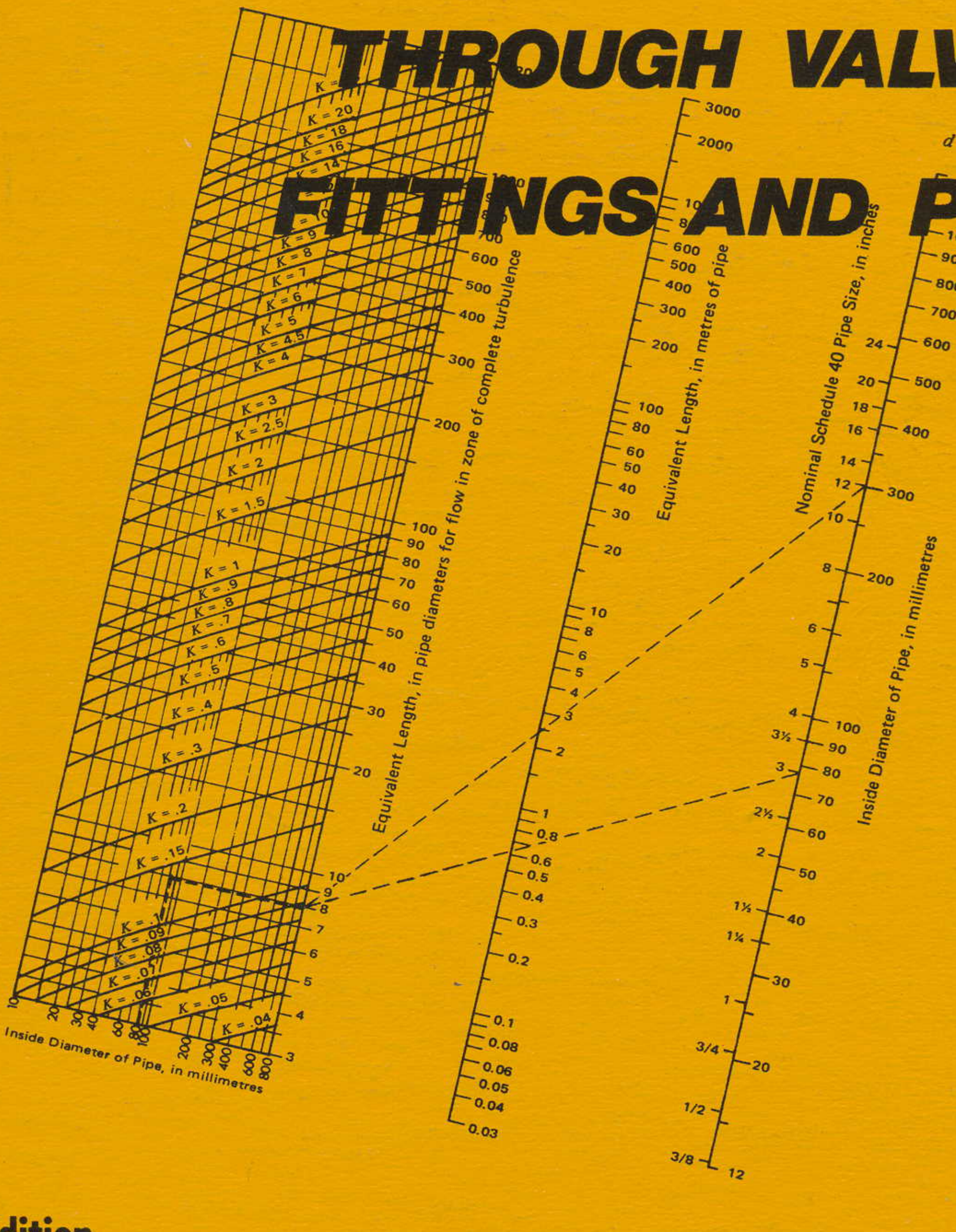
Flow of Fluids

THROUGH VALVES, FITTINGS AND PIPE



Metric Edition

Technical Paper No. 410 M

CRANE®

FLOW OF FLUIDS

THROUGH

VALVES, FITTINGS, AND PIPE

METRIC EDITION – SI UNITS

CRANE®

CRANE CO.
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Bibliography

[1] R. A. Dodge & M. J. Thompson, "Fluid Mechanics"; McGraw-Hill Book Company, Inc., 1937; pages 193, 288, and 407.

[2] H. Rouse, "Elementary Mechanics of Fluids"; John Wiley & Sons, Inc., New York, 1946.

[3] B. F. Grizzle, "Simplification of Gas Flow Calculations by Means of a New Special Slide Rule"; *Petroleum Engineer*, September, 1945.

[4] H. Kirchbach, "Loss of Energy in Miter Bends"; *Transactions of the Munich Hydraulic Institute*, Bulletin No. 3, American Society of Mechanical Engineers, New York, 1935.

[5] "Dowtherm Handbook"; Dow Chemical Co., Midland, Michigan, 1954; page 10.

[6] R. J. S. Pigott, "Pressure Losses in Tubing, Pipe, and Fittings"; *Transactions of the American Society of Mechanical Engineers*, Volume 72, 1950; pages 679 to 688.

[7] National Engineering Laboratory, "Steam Tables 1964"; HMSO Edinburgh, UK.

[8] R. F. Stearns, R. M. Jackson, R. R. Johnson, and C. A. Larson, "Flow Measurement with Orifice Meters"; D. Van Nostrand Company, Inc., New York, 1951.

[9] "Fluid Meters"; American Society of Mechanical Engineers, Part 1–6th Edition, New York, 1971.

[10] R. G. Cunningham, "Orifice Meters with Supercritical Compressible Flow"; ASME Paper No. 50-A-45.

[11] "Air Conditioning Refrigerating Data Book–Design," American Society of Refrigerating Engineers, 9th Edition, New York, 1955.

[12] W. L. Nelson, "Petroleum Refinery Engineering"; McGraw-Hill Book Co., New York, 1949.

[13] Lionel S. Marks, "Mechanical Engineers Handbook"; McGraw-Hill Book Co., New York, 1951.

[14] Y. R. Mayhew & G. F. C. Rogers, "Thermodynamic and Transport Properties of Fluids"; Basil Blackwell, Oxford, UK, 1972.

[15] J. B. Maxwell, "Data Book on Hydrocarbons"; D. Van Nostrand Company, Inc., New York, 1950.

[16] C. I. Corp and R. O. Ruble, "Loss of Head in Valves and Pipes of One-Half to Twelve Inches Diameter"; *University of Wisconsin Experimental Station Bulletin*, Volume 9, No. 1, 1922.

[17] G. L. Tuve and R. E. Sprenkle, "Orifice Discharge Coefficients for Viscous Liquids"; *Instruments*, November, 1933; page 201.

[18] L. F. Moody, "Friction Factors for Pipe Flow"; *Transactions of the American Society of Mechanical Engineers*, Volume 66, November, 1944; pages 671 to 678.

[19] A. H. Shapiro, "The Dynamics and Thermodynamics of Compressible Fluid Flow"; The Ronald Press Company, 1953, Chapter 6.

[20] ASME Steam Tables, 1967.

[21] K. H. Beij, "Pressure Losses for Fluid Flow in 90 Degree Pipe Bends"; *Journal of Research of the National Bureau of Standards*, Volume 21, July, 1938.

[22] "Marks' Standard Handbook for Mechanical Engineers" Seventh Edition 1966, McGraw-Hill Book Co., New York

[23] Bingham, E. C. and Jackson, R. F., *Bureau of Standards Bulletin 14*; pages 58 to 86 (S.P. 298, August, 1916) (1919).

[24] T. R. Weymouth, *Transactions of the American Society of Mechanical Engineers*, Volume 34, 1912; page 197.

[25] R. J. S. Pigott, "The Flow of Fluids in Closed Conduits," *Mechanical Engineering*, Volume 55, No. 8, August 1933 page 497.

[26] Emory Kemler, "A Study of Data on the Flow of Fluids in Pipes," *Transactions of the American Society of Mechanical Engineers*, Vol. 55, 1933, HYD-55-2.

[27] "Handbook of Chemistry and Physics," 44th Edition, 1962-1963 Chemical Rubber Publishing Co., Cleveland.

[28] V. L. Streeter, "Fluid Mechanics", 1st Edition, 1951.

[29] "Standards of Hydraulic Institute", Eighth Edition, 1947.

[30] International Gas Union, Appendix 1 of report "Problems arising from interchangeability of second family gases"; May, 1976.

FOREWORD

The more complex industry becomes, the more vital becomes the role played by fluids in the industrial machine. One hundred years ago water was the only important fluid which was conveyed from one point to another in pipe. Today, almost every conceivable fluid is handled in pipe during its production, processing, transportation, or utilization. The age of atomic energy and rocket power has added fluids such as liquid metals . . . . i.e., sodium, potassium, and bismuth, as well as liquid oxygen, nitrogen, etc. . . . to the list of more common fluids such as oil, water, gases, acids, and liquors that are being transported in pipe today. Nor is the transportation of fluids the only phase of hydraulics which warrants attention now. Hydraulic and pneumatic mechanisms are used extensively for the controls of modern aircraft, sea-going vessels, automotive equipment, machine tools, earth-moving and road-building machines, and even in scientific laboratory equipment where precise control of fluid flow is required.

So extensive are the applications of hydraulics and fluid mechanics that almost every engineer has found it necessary to familiarize himself with at least the elementary laws of fluid flow. To satisfy a demand for a simple and practical treatment of the subject of flow in pipe, Crane Co. published in 1935, a booklet entitled Flow of Fluids and Heat Transmission. A revised edition on the subject of Flow of Fluids Through Valves, Fittings, and Pipe was published in 1942. Technical Paper No. 410, a completely new edition with an all-new format was introduced in 1957. In T.P. 410, Crane has endeavoured to present the latest available information on flow of fluids, in summarized form with all auxiliary data necessary to the solution of all but the most unusual fluid flow problems.

From 1957 until the present, there have been numerous printings of Technical Paper No. 410. Each successive printing is updated, as necessary, to reflect the latest flow information available. This continual updating, we believe, serves the best interests of the users of this publication.

The fifteenth printing (1976 edition) presented a conceptual change regarding the values of Equivalent Length "*L/D*" and Resistance Coefficient "*K*" for valves and fittings relative to the friction factor in pipes. This change had relatively minor effect on most problems dealing with flow conditions that result in Reynolds numbers falling in the turbulent zone. However, for flow in the laminar zone, the change avoided a significant overstatement of pressure drop. Consistent with the conceptual revision, the resistance to flow through valves and fittings was expressed in terms of resistance coefficient "*K*" instead of equivalent length "*L/D*", and the coverage of valve and fitting types was expanded.

Further important revisions included the updating of steam viscosity data, orifice coefficients, and nozzle coefficients.

T.P. 410M was introduced in early 1977 as a metric version of the fifteenth printing of T.P. 410. Technical data, with certain exceptions, are presented in terms of SI metric units. Exceptions occur in instances where present units outside the SI system (e.g. nominal pipe sizes in inches) are expected to continue in use for an indefinite period, or where agreement has not yet been reached on the specific metric units to be used (as for flow coefficients).

Successive printings of T.P. 410M, like T.P. 410, are updated as necessary to reflect latest flow information available. Arrangement of material is alike in both editions. Theory is presented in Chapters 1 and 2 . . . practical application to flow problems in Chapters 3 and 4 . . . physical properties of fluids and flow characteristics of valves, fittings, and pipe in Appendix A . . . and conversion units and other useful engineering data in Appendix B.

Most of the data on flow through valves and fittings were obtained by carefully conducted experiments in the Crane Engineering Laboratories. Liberal use has been made, however, of other reliable sources of data on this subject and due credit has been given these sources in the text. The bibliography of references will provide a source for further study of the subject presented.

CRANE CO.

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APPENDIX A

Physical Properties of Fluids and Flow Characteristics of Valves, Fittings, and Pipe

APPENDIX B

Engineering Data

MISCELLANEOUS

Nomenclature

Unless otherwise stated, all symbols used
in this book are defined as follows:

A = cross sectional area of pipe or orifice, in square metres

a = cross sectional area of pipe or orifice, or flow area in valve, in square millimetres

B = rate of flow in barrels (42 US gallons) per hour

C = flow coefficient for orifices and nozzles = discharge coefficient corrected for velocity of approach = $C_d / \sqrt{1-\beta^4}$

C_d = discharge coefficient for orifices and nozzles

C_v = flow coefficient for valves

D = internal diameter of pipe, in metres

d = internal diameter of pipe, in millimetres

e = base of natural logarithm = 2.718

f = friction factor in formula $h_L = fLv^2/D\,2g_n$

f_T = friction factor in zone of complete turbulence

g_n = acceleration of gravity = 9.81 metres per second per second

H = total head, in metres of fluid

h = static pressure head existing at a point, in metres of fluid

h_L = loss of static pressure head due to fluid flow, in metres of fluid

h_w = static pressure head, in millimetres of water

K = resistance coefficient or velocity head loss in the formula, $h_L = Kv^2/2g_n$

L = length of pipe, in metres

L/D = equivalent length of a resistance to flow, in pipe diameters

L_m = length of pipe, in kilometres

M = molecular weight (molecular mass)

P = pressure, in newtons per square metre (pascals) gauge

P' = pressure, in newtons per square metre (pascals) absolute

(see page 1-5 for diagram showing relationship between gauge and absolute pressure)

p = pressure, in bars gauge

p' = pressure, in bars absolute

Q = rate of flow, in litres per minute

q = rate of flow, in cubic metres per second at flowing conditions

q' = rate of flow, in cubic metres per second at metric standard conditions (MSC)—1.013 25 bar absolute and 15°C

q'_d = rate of flow, in millions of cubic metres per day at MSC

q'_h = rate of flow, in cubic metres per hour at MSC

q_m = rate of flow, in cubic metres per minute at flowing conditions

q'_m = rate of flow, in cubic metres per minute at MSC

R_o = universal gas constant = 8314 J/kg–mol K

R = individual gas constant = R_o/M J/kg K (where M = molecular weight of the gas)

R_e = Reynolds number

R_H = hydraulic radius, in metres

r_c = critical pressure ratio for compressible flow

S = specific gravity of liquids at specified temperature relative to water at standard temperature (15°C) – (relative density)

S_g = specific gravity of a gas relative to air = the ratio of the molecular weight of the gas to that of air (relative density)

T = absolute temperature, in kelvins (273 + t)

t = temperature, in degrees Celsius

$\overline{V}$ = specific volume of fluid, in cubic metres per kilogram

V = mean velocity of flow, in metres per minute

V_a = volume, in cubic metres

v = mean velocity of flow, in metres per second

v_s = sonic (or critical) velocity of flow of a gas, in metres per second

W = rate of flow, in kilograms per hour

w = rate of flow, in kilograms per second

w_a = mass, in kilograms

Y = net expansion factor for compressible flow through orifices, nozzles, or pipe

Z = potential head or elevation above reference level, in metres

Greek Letters

Beta

β = ratio of small to large diameter in orifices and nozzles, and contractions or enlargements in pipes

Gamma

γ = ratio of specific heat at constant pressure to specific heat at constant volume = c_p/c_v

Delta

Δ = differential between two points

Epsilon

ϵ = absolute roughness or effective height of pipe wall irregularities, in millimetres

Mu

μ = dynamic (absolute) viscosity, in centipoise

μ' = dynamic viscosity, in newton seconds per square metre (pascal seconds)

Nu

ν = kinematic viscosity, in centistokes

ν' = kinematic viscosity, metres squared per second

Rho

ρ = weight density of fluid, kilograms per cubic metre

ρ' = density of fluid, grams per cubic centimetre

Sigma

Σ = summation

Theta

θ = angle of convergence or divergence in enlargements or contractions in pipes

Subscripts for Diameter

(1) ...defines smaller diameter

(2) ...defines larger diameter

Subscripts for Fluid Property

(1) ...defines inlet (upstream) condition

(2) ...defines outlet (downstream) condition

Theory of Flow In Pipe

CHAPTER 1

The most commonly employed method of transporting fluid from one point to another is to force the fluid to flow through a piping system. Pipe of circular section is most frequently used because that shape offers not only greater structural strength, but also greater cross sectional area per unit of wall surface than any other shape. Unless otherwise stated, the word "pipe" in this book will always refer to a closed conduit of circular section and constant internal diameter.

Only a few special problems in fluid mechanics . . . . laminar flow in pipe, for example . . . . can be entirely solved by rational mathematical means; all other problems require methods of solution which rest, at least in part, on experimentally determined coefficients. Many empirical formulas have been proposed for the problem of flow in pipe, but these are often extremely limited and can be applied only when the conditions of the problem closely approach the conditions of the experiments from which the formulas were derived.

Because of the great variety of fluids being handled in modern industrial processes, a single equation which can be used for the flow of any fluid in pipe offers obvious advantages. Such an equation is the Darcy* formula. The Darcy formula can be derived rationally by means of dimensional analysis; however, one variable in the formula . . . . the friction factor . . . . must be determined experimentally. This formula has a wide application in the field of fluid mechanics and is used extensively throughout this paper.

*The Darcy formula is also known as the Weisbach formula or the Darcy-Weisbach formula; also, as the Fanning formula, sometimes modified so that the friction factor is one-fourth the Darcy friction factor.

Physical Properties of Fluids

The solution of any flow problem requires a knowledge of the physical properties of the fluid being handled. Accurate values for the properties affecting the flow of fluids . . . namely, viscosity and mass density . . . have been established by many authorities for all commonly used fluids and many of these data are presented in the various tables and charts in Appendix A.

Viscosity: Viscosity expresses the readiness with which a fluid flows when it is acted upon by an external force. The coefficient of absolute viscosity or, simply, the absolute viscosity of a fluid, is a measure of its resistance to internal deformation or shear. Molasses is a highly viscous fluid; water is comparatively much less viscous; and the viscosity of gases is quite small compared to that of water.

Although most fluids are predictable in their viscosity, in some, the viscosity depends upon the previous working of the fluid. Printer's ink, wood pulp slurries, and catsup are examples of fluids possessing such thixotropic properties of viscosity.

Considerable confusion exists concerning the units used to express viscosity; therefore, proper units must be employed whenever substituting values of viscosity into formulas.

Dynamic or Absolute Viscosity: The coherent SI unit of dynamic viscosity is the pascal second (Pa s) which may also be expressed as the newton second per square metre (N s/m²), or as the kilogram per metre second kg/(m s). This unit has also been called the poiseuille (Pl) in France but it should be noted that it is not the same as the poise (P) described below.

The poise is the corresponding unit in the CGS system of units and has the dimensions of dyne seconds per square centimetre or of grams per centimetre second. The submultiple centipoise (cP), 10^{-2} poise, is the unit most commonly used at present to express dynamic viscosity and this situation appears likely to continue for some time. For this reason, and since most handbooks and tables follow the same procedure, all viscosity data in this paper are expressed in centipoise. The relationship between pascal second and centipoise is:

$$1 \text{ Pa s} = 1 \text{ N s/m}^2 = 1 \text{ kg/(m s)} = 10^3 \text{ cP}$$
$$1 \text{ cP} = 10^{-3} \text{ Pa s}$$

In this paper the symbol μ is used for viscosity measured in centipoise and μ' for viscosity measured in pascal second units. The viscosity of water at temperature of 20°C is very nearly 1 centipoise* or 0.001 pascal seconds.

Kinematic Viscosity: This is the ratio of the dynamic viscosity to the density. In the SI system the unit of kinematic viscosity is the metre squared per second (m²/s). The corresponding CGS unit is the stokes (St), dimensions, centimetres squared per second and the centistoke (cSt), 10^{-2} stokes, is the submultiple commonly used.

$$1 \text{ m}^2\text{/s} = 10^6 \text{ cSt}$$
$$1 \text{ cSt} = 10^{-6} \text{ m}^2\text{/s}$$

$$\nu \text{ (Centistokes)} = \frac{\mu \quad \text{(centipoise)}}{\rho' \text{ (grams per cubic cm)}}$$

Factors for conversion between the SI and CGS units described above and also for Imperial units of dynamic and kinematic viscosity are given on page B-3 of Appendix B.

The measurement of the absolute viscosity of fluids (especially gases and vapours) requires elaborate equipment and considerable experimental skill. On the other hand, a rather simple instrument in the form of a tube viscometer or viscosimeter can be used for measuring the kinematic viscosity of oils and other viscous liquids. With this type of instrument the time required for a small volume of liquid to flow through an orifice is determined and the measurement of kinematic viscosity expressed in terms of seconds.

Various forms of tube viscosimeters are used resulting in empirical scales such as Saybolt Universal, Saybolt Furol (for very viscous liquids), Redwood No 1 and No 2 and Engler. Information on the relationships between these empirical viscosities and kinematic and dynamic viscosities in absolute units is included in Appendix B.

The ASTM standard viscosity temperature chart for liquid petroleum products, reproduced on page B-6 is used to determine the Saybolt Universal viscosity of a petroleum product at any temperature when the viscosities at two different temperatures are known. The viscosities of some of the most common fluids are given on pages A-2 to A-5. It will be noted that, with a rise in temperature, the viscosity of liquids decreases, whereas the viscosity of gases increases. The effect of pressure on the viscosity of liquids and perfect gases is so small that it is of no practical interest in most flow problems. Conversely, the viscosity of saturated, or only slightly superheated,vapours is appreciably altered by pressure changes, as indicated on page A-2 showing the viscosity of steam. Unfortunately, the data on vapours are incomplete and, in some cases, contradictory. Therefore, it is expedient when dealing with vapours other than steam to neglect the effect of pressure because of the lack of adequate data.

*Actually the viscosity of water at 20°C is 1.002 centipoise ("Handbook of Chemistry and Physics" 54th Edition 1973-4 CRC Press)

Physical Properties of Fluids – continued

Density, specific volume and specific gravity: The density of a substance is its mass per unit volume. The coherent SI unit of density is the kilogram per cubic metre (kg/m³) and the symbol designation used in this paper is ρ (Rho).

Other commonly used metric units are:

gram per cubic centimetre (g/cm³) or gram per millilitre (g/ml)	1 g/cm³ or 1 g/ml = 1000 kg/m³

The coherent SI unit of specific volume $\bar{V}$, which is the reciprocal of density, is the cubic metre per kilogram (m³/kg)

$$\bar{V} = \frac{1}{\rho} \qquad \rho = \frac{1}{\bar{V}}$$

Other commonly used metric units for specific volume are:

litre per kilogram (litre/kg) or cubic decimetre per kilogram (dm³/kg)	1 litre/kg or 1 dm³/kg = 0.001 m³/kg

The variations in density and other properties of water with changes in temperature are shown on page A-6. The densities of other common liquids are shown on page A-7. Unless very high pressures are being considered the effect of pressure on the density of liquids is of no practical importance in flow problems.

The densities of gases and vapours, however, are greatly altered by pressure changes. For the so-called "perfect" gases, the density can be computed from the formula.

$$\rho = \frac{P'}{RT} \quad \text{or} \quad \frac{10^5 p'}{RT}$$

The individual gas constant R is equal to the universal gas constant R_o (8314 J/kg–mol K) divided by the molecular weight M of the gas,

$$R = \frac{R_o}{M} = \frac{8314}{M} \text{ J/kg K}$$

Values of R, as well as other useful gas constants, are given on page A-8. The density of air for various conditions of temperature and pressure can be found on page A-10.

Specific volume is commonly used in steam flow computations and values are listed in the steam tables shown on pages A-13 to A-17. A chart for determining the density and specific volume of gases is given on page A-11.

Specific gravity (or relative density) is a relative measure of density. Since pressure has an insignificant effect upon the density of liquids, temperature is the only condition that must be considered in designating the basis for specific gravity. The specific gravity of a liquid is the ratio of its density at a specified temperature to that of water at some standard temperature. Usually the temperatures are the same and 60°F/60°F (15.6°C/15.6°C) is commonly used. Rounding off to 15°C/15°C does not create any significant error.

$$S = \frac{\rho \text{ any liquid at specified temperature}}{\rho \text{ water at } 60°\text{F } (15.6°\text{C})}$$

A hydrometer can be used to measure the specific gravity of a liquid directly. Two hydrometer scales in common use are:

- API scale, used for oils.
- Baumé scales. There are two kinds in use: one for liquids heavier than water and one for liquids lighter than water.

The relationships between these hydrometer scales and specific gravity are:

For oils,

$$S\,(60°\text{F}/60°\text{F}) = \frac{141.5}{131.5 + \text{deg. API}}$$

For liquids lighter than water,

$$S\,(60°\text{F}/60°\text{F}) = \frac{140}{130 + \text{deg. Baumé}}$$

For liquids heavier than water,

$$S\,(60°\text{F}/60°\text{F}) = \frac{145}{145 - \text{deg. Baumé}}$$

For converting hydrometer readings to more useful units refer to table on page B-7.

The specific gravity of gases is defined as the ratio of the molecular weight of the gas to that of air, and as the ratio of the individual gas constant of air to that of gas.

$$S_g = \frac{R(\text{air})}{R(\text{gas})} = \frac{M(\text{gas})}{M(\text{air})}$$

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$$\bar{V} = \frac{1}{\rho} \qquad \rho = \frac{1}{\bar{V}}$$

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The specific gravity of gases is defined as the ratio of the molecular weight of the gas to that of air, and as the ratio of the individual gas constant of air to that of gas.

$$S_g = \frac{R(\text{air})}{R(\text{gas})} = \frac{M(\text{gas})}{M(\text{air})}$$

Nature of Flow in Pipe – Laminar and Turbulent

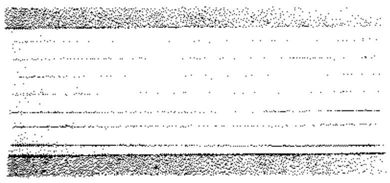


Figure 1-1
Laminar Flow
Actual photograph of coloured filaments being carried along undisturbed by a stream of water.

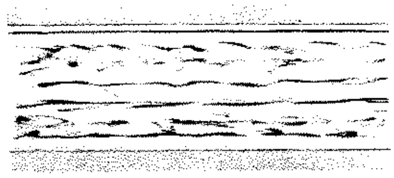


Figure 1-2
Flow in Critical Zone, Between Laminar and Transition Zones
At the critical velocity, the filaments begin to break up, indicating flow is becoming turbulent.

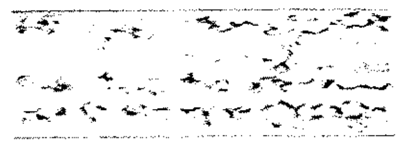


Figure 1-3
Turbulent Flow
This illustration shows the turbulence in the stream completely dispersing the coloured filaments a short distance downstream from the point of injection.

A simple experiment (illustrated above) will readily show there are two entirely different types of flow in pipe. The experiment consists of injecting small streams of a coloured fluid into a liquid flowing in a glass pipe and observing the behaviour of these coloured streams at different sections downstream from their points of injection.

If the discharge or average velocity is small, the streaks of coloured fluid flow in straight lines, as shown in Figure 1-1. As the flow rate is gradually increased, these streaks will continue to flow in straight lines until a velocity is reached when the streaks will waver and suddenly break into diffused patterns, as shown in Figure 1-2. The velocity at which this occurs is called the "critical velocity". At velocities higher than "critical", the filaments are dispersed at random throughout the main body of the fluid, as shown in Figure 1-3.

The type of flow which exists at velocities lower than "critical" is known as laminar flow and, sometimes, as viscous or streamline flow. Flow of this nature is characterized by the gliding of concentric cylindrical layers past one another in orderly fashion. Velocity of the fluid is at its maximum at the pipe axis and decreases sharply to zero at the wall.

At velocities greater than "critical", the flow is turbulent. In turbulent flow, there is an irregular random motion of fluid particles in directions transverse to the direction of the main flow. The velocity distribution in turbulent flow is more uniform across the pipe diameter than in laminar flow. Even though a turbulent motion exists throughout the greater portion of the pipe diameter, there is always a thin layer of fluid at the pipe wall . . . . known as the "boundary layer" or "laminar sub-layer" . . . . which is moving in laminar flow.

Mean velocity of flow: The term "velocity", unless otherwise stated, refers to the mean, or average, velocity at a given cross section, as determined by the continuity equation for steady state flow:

$$v = \frac{q}{A} = \frac{w}{A\rho} = \frac{w\bar{V}}{A} \qquad \textbf{Equation 1-1}$$

(For nomenclature, see page preceding Chapter 1)

"Reasonable" velocities for use in design work are given on pages 3-6 and 3-16.

Reynolds number: The work of Osborne Reynolds has shown that the nature of flow in pipe . . . . that is, whether it is laminar or turbulent . . . . depends on the pipe diameter, the density and viscosity of the flowing fluid, and the velocity of flow. The numerical value of a dimensionless combination of these four variables, known as the Reynolds number, may be considered to be the ratio of the dynamic forces of mass flow to the shear stress due to viscosity. Reynolds number is:

$$R_e = \frac{Dv\rho}{\mu'} \quad \text{or} \quad \frac{dv\rho}{\mu} \qquad \textbf{Equation 1-2}$$

(other forms of this equation; page 3-2.)

For engineering purposes, flow in pipes is usually considered to be laminar if the Reynolds number is less than 2000, and turbulent if the Reynolds number is greater than 4000. Between these two values lies the "critical zone" where the flow . . . . being laminar, turbulent, or in the process of change, depending upon many possible varying conditions . . . . is unpredictable. Careful experimentation has shown that the laminar zone may be made to terminate at a Reynolds number as low as 1200 or extended as high as 40,000, but these conditions are not expected to be realized in ordinary practice.

Hydraulic radius: Occasionally a conduit of non-circular cross section is encountered. In calculating the Reynolds number for this condition, the equivalent diameter (four times the hydraulic radius) is substituted for the circular diameter. Use friction factors given on pages A-24 and A-25.

$$R_H = \frac{\text{cross sectional flow area}}{\text{wetted perimeter}}$$

This applies to any ordinary conduit (circular conduit not flowing full, oval, square or rectangular) but not to extremely narrow shapes such as annular or elongated openings, where width is small relative to length. In such cases, the hydraulic radius is approximately equal to one-half the width of the passage.

To determine quantity of flow in following formula:

$$Q = 0.2087d^2\sqrt{\frac{h_L D}{fL}}$$

the value of d^2 is based upon an equivalent diameter of actual flow area and $4R_H$ is substituted for D.

General Energy Equation

Bernoulli's Theorem

The Bernoulli theorem is a means of expressing the application of the law of conservation of energy to the flow of fluids in a conduit. The total energy at any particular point, above some arbitrary horizontal datum plane, is equal to the sum of the elevation head, the pressure head, and the velocity head, as follows:

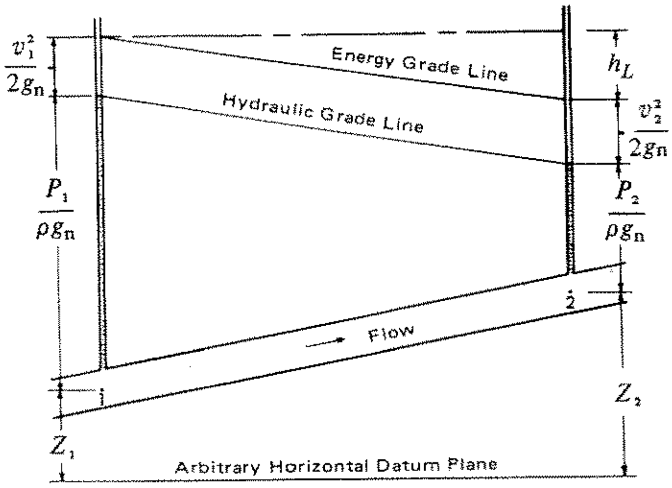


Figure 1-4
Energy Balance for Two Points in a Fluid

Adapted from *Fluid Mechanics*[1]* by R. A. Dodge and M. J. Thompson. Copyright 1937; McGraw-Hill Book Company, Inc.

$$Z + \frac{P}{\rho g_n} + \frac{v^2}{2g_n} = H$$

If friction losses are neglected and no energy is added to, or taken from, a piping system (i.e., pumps or turbines), the total head, H, in the above equation will be a constant for any point in the fluid. However, in actual practice, losses or energy increases or decreases are encountered and must be included in the Bernoulli equation. Thus, an energy balance may be written for two points in a fluid, as shown in the example in Figure 1-4.

Note the pipe friction loss from point 1 to point 2 (h_L) may be referred to as the head loss in metres of fluid. The equation may be written as follows:

Equation 1-3

$$Z_1 + \frac{P_1}{\rho_1 g_n} + \frac{v_1^2}{2g_n} = Z_2 + \frac{P_2}{\rho_2 g_n} + \frac{v_2^2}{2g_n} + h_L$$

All practical formulas for the flow of fluids are derived from Bernoulli's theorem, with modifications to account for losses due to friction.

Measurement of Pressure

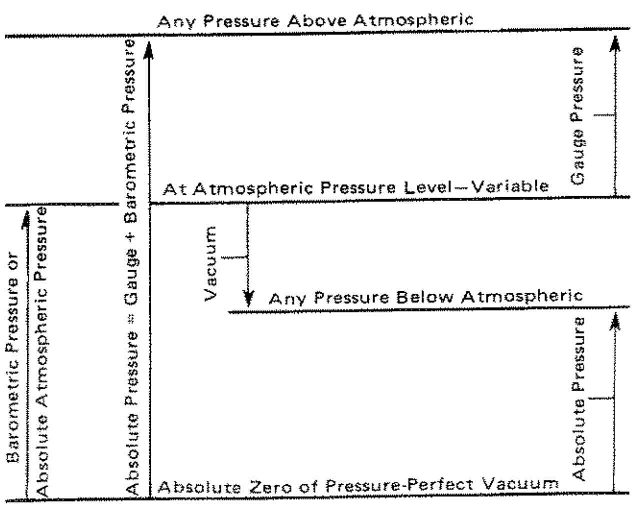


Figure 1-5
Relationship Between Gauge and Absolute Pressures

Figure 1-5 graphically illustrates the relationship between gauge and absolute pressures. Perfect vacuum cannot exist on the surface of the earth, but it nevertheless makes a convenient datum for the measurement of pressure.

Barometric pressure is the level of the atmospheric pressure above perfect vacuum.

"Standard" atmospheric pressure is 1.013 25 bar (14.6959 lbf/in²) or 760 millimetres of mercury.

Gauge pressure is measured above atmospheric pressure, while absolute pressure always refers to perfect vacuum as a base.

Vacuum is the depression of pressure below the atmospheric level. Reference to vacuum conditions is often made by expressing the absolute pressure in terms of the height of a column of mercury or of water. Millimetre of mercury, micrometre (micron) of mercury, inch of water and inch of mercury, are some of the commonly used conventional units.

**All superior figures used as reference marks refer to the Bibliography*

Darcy's Formula

General Equation for Flow of Fluids

Flow in pipe is always accompanied by friction of fluid particles rubbing against one another, and consequently, by loss of energy available for work; in other words, there must be a pressure drop in the direction of flow. If ordinary Bourdon tube pressure gauges were connected to a pipe containing a flowing fluid, as shown in Figure 1-6, gauge P_1 would indicate a higher static pressure than gauge P_2.

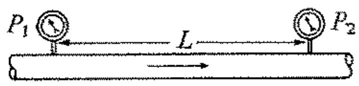


Figure 1-6

The general equation for pressure drop, known as Darcy's formula and expressed in metres of fluid, is $h_L = fLv^2/D\ 2g_n$. This equation may be written to express pressure drop in newtons per square metre (pascals) by substitution of proper units, as follows:

$$\Delta P = \frac{\rho f L v^2}{2D} \quad (\text{since } \Delta P = h_L \times \rho \times g_n) \qquad \textbf{Equation 1-4}$$

For other forms of this equation, see page 3-2

The Darcy equation is valid for laminar or turbulent flow of any liquid in a pipe. However, when extreme velocities occurring in a pipe cause the downstream pressure to fall to the vapour pressure of the liquid, cavitation occurs and calculated flow rates will be inaccurate. With suitable restrictions, the Darcy equation may be used when gases and vapours (compressible fluids) are being handled. These restrictions are defined on page 1-7.

Equation 1-4 gives the loss in pressure due to friction and applies to pipe of constant diameter carrying fluids of reasonably constant density in straight pipe, whether horizontal, vertical, or sloping. For inclined pipe, vertical pipe, or pipe of varying diameter, the change in pressure due to changes in elevation, velocity, and density of the fluid must be made in accordance with Bernoulli's theorem (page 1-5). For an example using this theorem, see page 4-8.

Friction factor: The Darcy formula can be rationally derived by dimensional analysis, with the exception of the friction factor, f, which must be determined experimentally. The friction factor for laminar flow conditions ($R_e < 2000$) is a function of Reynolds number only; whereas, for turbulent flow ($R_e > 4000$), it is also a function of the character of the pipe wall.

A region known as the "critical zone" occurs between Reynolds number of approximately 2000 and 4000. In this region, the flow may be either laminar or turbulent depending upon several factors; these include changes in section or direction of flow and obstructions, such as valves, in the upstream piping. The friction factor in this region is indeterminate and has lower limits based on laminar flow and upper limits based on turbulent flow conditions.

At Reynolds numbers above approximately 4000, flow conditions again become more stable and definite friction factors can be established. This is important because it enables the engineer to determine the flow characteristics of any fluid flowing in a pipe, providing the viscosity and density at flowing conditions are known. For this reason, Equation 1-4 is recommended in preference to some of the commonly known empirical equations for the flow of water, oil, and other liquids, as well as for the flow of compressible fluids when restrictions previously mentioned are observed.

If the flow is laminar ($R_e < 2000$), the friction factor may be determined from the equation:

$$f = \frac{64}{R_e} = \frac{64\,\mu'}{D v \rho} = \frac{64\,\mu}{d v \rho}$$

If this quantity is substituted into Equation 1-4, the pressure drop in newtons per square metre is:

$$\Delta P = 32\,000 \frac{\mu L v}{d^2} \qquad \textbf{Equation 1-5}$$

which is Poiseuille's law for laminar flow.

When the flow is turbulent ($R_e > 4000$), the friction factor depends not only upon the Reynolds number but also upon the relative roughness, ϵ/d .... the roughness of the pipe walls (ϵ), as compared to the diameter of the pipe (d). For very smooth pipes such as drawn brass tubing and glass, the friction factor decreases more rapidly with increasing Reynolds number than for pipe with comparatively rough walls.

Since the character of the internal surface of commercial pipe is practically independent of the diameter, the roughness of the walls has a greater effect on the friction factor in the small sizes. Consequently, pipe of small diameter will approach the very rough condition and, in general, will have higher friction factors than large pipe of the same material.

The most useful and widely accepted data of friction factors for use with the Darcy formula have been presented by L. F. Moody[18] and are reproduced on pages A-23 to A-25. Professor Moody improved upon the well-established Pigott and Kemler[25,26] friction factor diagram, incorporating more recent investigations and developments of many outstanding scientists.

The friction factor, f, is plotted on page A-24 on the basis of relative roughness obtained from the chart on page A-23 and the Reynolds number. The value of f is determined by horizontal projection from the intersection of the ϵ/d curve under consideration with the calculated Reynolds number to the left hand vertical scale of the chart on page A-24. Since most calculations involve

Darcy's Formula

General Equation for Flow of Fluids – continued

commercial steel or wrought iron pipe, the chart on page A-25 is furnished for a more direct solution. It should be kept in mind that these figures apply to clean new pipe.

Effect of age and use on pipe friction: Friction loss in pipe is sensitive to changes in diameter and roughness of pipe. For a given rate of flow and a fixed friction factor, the pressure drop per metre of pipe varies inversely with the fifth power of the diameter. Therefore, a 2% reduction of diameter causes an 11% increase in pressure drop; a 5% reduction of diameter increases pressure drop 29%. In many services, the interior of pipe becomes encrusted with scale, dirt, tubercules or other foreign matter; thus, it is often prudent to make allowance for expected diameter changes.

Authorities[2] point out that roughness may be expected to increase with use (due to corrosion or incrustation) at a rate determined by the pipe material and nature of the fluid. Ippen[18], in discussing the effect of aging, cites a 4-inch galvanized steel pipe which had its roughness doubled and its friction factor increased 20% after three years of moderate use.

Principles of Compressible Flow in Pipe

An accurate determination of the pressure drop of a compressible fluid flowing through a pipe requires a knowledge of the relationship between pressure and specific volume; this is not easily determined in each particular problem. The usual extremes considered are adiabatic flow ($P'V_a^{\gamma}$ = constant) and isothermal flow ($P'V_a$ = constant). Adiabatic flow is usually assumed in short, perfectly insulated pipe. This would be consistent since no heat is transferred to or from the pipe, except for the fact that the minute amount of heat generated by friction is added to the flow.

Isothermal flow or flow at constant temperature is often assumed, partly for convenience but more often because it is closer to fact in piping practice. The most outstanding case of isothermal flow occurs in natural gas pipe lines. Dodge and Thompson[3] show that gas flow in insulated pipe is closely approximated by isothermal flow for reasonably high pressures.

Since the relationship between pressure and volume may follow some other relationship ($P'V_a^n$ = constant) called polytropic flow, specific information in each individual case is almost an impossibility.

The density of gases and vapours changes considerably with changes in pressure; therefore, if the pressure drop between P_1 and P_2 in Figure 1-6 is great, the density and velocity will change appreciably.

When dealing with compressible fluids, such as air, steam, etc., the following restrictions should be observed in applying the Darcy formula:

1. If the calculated pressure drop ($P_1 - P_2$) is less than about 10% of the inlet pressure P_1, reasonable accuracy will be obtained if the specific volume used in the formula is based upon either the upstream or downstream conditions, whichever are known.

2. If the calculated pressure drop ($P_1 - P_2$) is greater than about 10%, but less than about 40% of inlet pressure P_1, the Darcy equation may be used with reasonable accuracy by using a specific volume based upon the average of upstream and downstream conditions; otherwise, the method given on page 1-9 may be used.

3. For greater pressure drops, such as are often encountered in long pipe lines, the methods given on the next two pages should be used.

(continued on the next page)

Principles of Compressible Flow in Pipe – continued

Complete isothermal equation: The flow of gases in long pipe lines closely approximates isothermal conditions. The pressure drop in such lines is often large relative to the inlet pressure, and solution of this problem falls outside the limitations of the Darcy equation. An accurate determination of the flow characteristics falling within this category can be made by using the complete isothermal equation:

Equation 1-6

$$w^2 = \left[\frac{A^2}{\bar{V}_1\left(\frac{fL}{D} + 2\log_e \frac{P_1'}{P_2'}\right)}\right]\left[\frac{(P_1')^2 - (P_2')^2}{P_1'}\right]$$

The formula is developed on the basis of these assumptions:

1. Isothermal flow.
2. No mechanical work is done on or by the system.
3. Steady flow or discharge unchanged with time.
4. The gas obeys the perfect gas laws.
5. The velocity may be represented by the average velocity at a cross section.
6. The friction factor is constant along the pipe.
7. The pipe line is straight and horizontal between end points.

Simplified Compressible Flow–Gas Pipe Line Formula: In the practice of gas pipe line engineering, another assumption is added to the foregoing:

8. Acceleration can be neglected because the pipe line is long.

Then, the formula for discharge in a horizontal pipe may be written:

$$w^2 = \left[\frac{DA^2}{\bar{V}_1 fL}\right]\left[\frac{(P_1')^2 - (P_2')^2}{P_1'}\right] \qquad \text{Equation 1-7}$$

This is equivalent to the complete isothermal equation if the pipe line is long and also for shorter lines if the ratio of pressure drop to initial pressure is small.

Since gas flow problems are usually expressed in terms of cubic metres per hour at standard conditions, it is convenient to rewrite Equation 1-7 as follows:

Equation 1-7a

$$q'_h = 1.361 \times 10^{-7} \sqrt{\left[\frac{(P_1')^2 - (P_2')^2}{f L_m T S_g}\right] d^5}$$

Other commonly used formulas for compressible flow in long pipe lines:

Weymouth formula[24]:

Equation 1-8

$$q'_h = 2.61 \times 10^{-8}\, d^{2.667} \sqrt{\left[\frac{(P_1')^2 - (P_2')^2}{S_g L_m}\right] \frac{288}{T}}$$

Panhandle formula[3] for natural gas pipe lines 6 to 24-inch diameter, Reynolds numbers 5 x 10^6 to 14 x 10^6, and $S_g = 0.6$:

Equation 1-9

$$q'_h = 2.044 \times 10^{-8}\, E\, d^{2.6182} \left[\frac{(P_1')^2 - (P_2')^2}{L_m}\right]^{0.5394}$$

The flow efficiency factor E is defined as an experience factor and is usually assumed to be 0.92 or 92% for average operating conditions. Suggested values for E for other operating conditions are given on page 3-3.

Note: The pressures P_1' P_2' in all the foregoing equations are in terms of newtons per square metre. For equations in terms of pressures in bars, p_1' p_2' refer to page 3-3.

Comparison of formulas for compressible flow in pipe lines: Equations 1-7, 1-8, and 1-9 are derived from the same basic formula, but differ in the selection of data used for the determination of the friction factors.

Friction factors in accordance with the Moody[18] diagram are normally used with the Simplified Compressible Flow formula (Equation 1-7). However, if the same friction factors employed in the Weymouth or Panhandle formulas are used in the Simplified formula, identical answers will be obtained.

The Weymouth friction factor[24] is defined as:

$$f = \frac{0.094}{d^{1/3}}$$

This is identical to the Moody friction factor in the fully turbulent flow range for 20-inch I.D. pipe only. Weymouth friction factors are greater than Moody factors for sizes less than 20-inch, and smaller for sizes larger than 20-inch.

The Panhandle friction factor[3] is defined as:

$$f = 0.0454 \left(\frac{d}{q'_h S_g}\right)^{0.1461}$$

In the flow range to which the Panhandle formula is limited, this results in friction factors that are lower than those obtained from either the Moody data or the Weymouth friction formula. As a result, flow rates obtained by solution of the Panhandle formula are usually greater than those obtained by employing either the Simplified Compressible Flow formula with Moody friction factors, or the Weymouth formula.

An example of the variation in flow rates which may be obtained for a specific condition by employing these formulas is given on page 4-11.

Principles of Compressible Flow in Pipe – continued

Limiting flow of gases and vapours: The feature not evident in the preceding formulas (Equations 1-4 and 1-6 to 1-9 inclusive) is that the weight rate of flow (e.g. kg/sec) of a compressible fluid in a pipe, with a given upstream pressure will approach a certain maximum rate which it cannot exceed, no matter how much the downstream pressure is further reduced.

The maximum velocity of a compressible fluid in pipe is limited by the velocity of propagation of a pressure wave which travels at the speed of sound in the fluid. Since pressure falls off and velocity increases as fluid proceeds downstream in pipe of uniform cross section, the maximum velocity occurs in the downstream end of the pipe. If the pressure drop is sufficiently high, the exit velocity will reach the velocity of sound. Further decrease in the outlet pressure will not be felt upstream because the pressure wave can only travel at sonic velocity, and the "signal" will never translate upstream. The "surplus" pressure drop obtained by lowering the outlet pressure after the maximum discharge has already been reached takes place beyond the end of the pipe. This pressure is lost in shock waves and turbulence of the jetting fluid.

The maximum possible velocity in the pipe is sonic velocity, which is expressed as:

Equation 1-10

$$v_s = \sqrt{\gamma RT} = \sqrt{\gamma P' \bar{V}}$$

The value of γ the ratio of specific heats at constant pressure to constant volume, is 1.4 for most diatomic gases; see pages A-8 and A-9 for values of γ for gases and steam respectively. This velocity will occur at the outlet end or in a constricted area, when the pressure drop is sufficiently high. The pressure, temperature, and specific volume are those occurring at the point in question. When compressible fluids discharge from the end of a reasonably short pipe of uniform cross section into an area of larger cross section, the flow is usually considered to be adiabatic. This assumption is supported by experimental data on pipe having lengths of 220 and 130 pipe diameters discharging air to atmosphere. Investigation of the complete theoretical analysis of adiabatic flow[19] has led to a basis for establishing correction factors, which may be applied to the Darcy equation for this condition of flow.

Since these correction factors compensate for the changes in fluid properties due to expansion of the fluid, they are identified as Y net expansion factors; see page A-22.

The Darcy formula, including the Y factor, is:

$$w = 1.111 \times 10^{-6}\, Y d^2 \sqrt{\frac{\Delta P}{K \bar{V}_1}}$$

Equation 1-11*

(Resistance coefficient K is defined on page 2-8)

It should be noted that the value of K in this equation is the total resistance coefficient of the pipe line, including entrance and exit losses when they exist, and losses due to valves and fittings.

The pressure drop, ΔP, in the ratio $\Delta P/P'_1$ which is used for the determination of Y from the charts on page A-22, is the measured difference between the inlet pressure and the pressure in the area of larger cross section. In a system discharging compressible fluids to atmosphere, this ΔP is equal to the inlet gauge pressure, or the difference between absolute inlet pressure and atmospheric pressure. This value of ΔP is also used in Equation 1-11, whenever the Y factor falls within the limits defined by the resistance factor K curves in the charts on page A-22. When the ratio of $\Delta P/P'_1$, using ΔP as defined above, falls beyond the limits of the K curves in the charts, sonic velocity occurs at the point of discharge or at some restriction within the pipe, and the limiting values for Y and ΔP, as determined from the tabulations to the right of the charts on page A-22, must be used in Equation 1-11.

Application of Equation 1-11 and the determination of values for K, Y, and ΔP in the formula is demonstrated in examples on pages 4-13 and 4-14.

The charts on page A-22 are based upon the general gas laws for perfect gases and, at sonic velocity conditions at the outlet end, will yield accurate results for all gases which approximately follow the perfect gas laws. An example of this type of flow problem is presented on page 4-13.

This condition of flow is comparable to the flow through nozzles and venturi tubes, covered on page 2-15, and the solutions of such problems are similar.

*For equation in terms of pressure drop in bars (Δp) see page 3-4.

Steam

General Discussion

Water under normal atmospheric conditions exists in the form of a liquid. When a body of water is heated by means of some external medium, the temperature of the water rises and soon small bubbles, which break and form continuously, are noted on the surface. This phenomenon is described as "boiling".

There are three distinct stages in the process of converting water to superheated steam. The water must be boiling before steam can be formed and superheated steam cannot be formed until the steam has been completely dried.

In stage one, heat is added to raise the temperature of the water to the boiling point corresponding to the pressure conditions under which the heat is added. The boiling point is usually referred to as the generation or saturation temperature. The amount of heat required to raise the temperature of the water from 0°C to the saturation temperature is known as the enthalpy of the water or sensible heat.

In the second stage heat is added to the boiling water and under constant pressure conditions the water is changed to steam without any increase in temperature. This is the evaporation or latent heat stage. At this stage, with the steam in contact with liquid water, the steam is in the condition known as Saturated. It may be "dry" or "wet" depending on the generating conditions. "Dry" saturated steam is steam free from mechanically mixed water particles. "Wet" saturated steam contains water particles in suspension. Saturated steam at any pressure has a definite temperature.

If the water is heated in a closed vessel not completely filled, the pressure will rise after steam begins to form accompanied by an increase in temperature.

Stage three commences when steam at any given pressure is heated to a temperature higher than the temperature of saturated steam at that pressure. The steam is then said to be Superheated.

Heat is one of the forms of energy and the SI unit for all forms is the joule (J). This is a very small unit of energy and it is often more convenient to use the kilojoule (kJ) or even larger multiple, megajoule (MJ).

The SI unit for energy per unit mass is the joule per kilogram (J/kg) or some multiple of this unit and the steam tables provided on pages A-13 to A-17 give detailed information on the specific enthalpy of steam, in terms of kilojoules per kilogram (kJ/kg), over a wide range of pressure and temperature conditions. The datum is taken as 0°C. From the table on page A-13 the specific enthalpy (sensible heat) of water at 1 bar absolute is seen to be 417.5 kJ/kg and the specific enthalpy of evaporation (latent heat) 2257.9 kJ/kg. Consequently, the total heat or energy of the vapour, formed when water boils at 1 bar pressure is the sum of these two quantities, i.e. 2675.4 kJ/kg.

The relationship between the joule and the British thermal unit (Btu) is defined by the equation:

$$1 \text{ Btu/lb} = 2.326 \text{ J/g} = 2.326 \text{ kJ/kg}$$

Flow of Fluids Through Valves and Fittings

CHAPTER 2

The preceding chapter has been devoted to the theory and formulas used in the study of fluid flow in pipes. Since industrial installations usually contain a considerable number of valves and fittings, a knowledge of their resistance to the flow of fluids is necessary to determine the flow characteristics of a complete piping system.

Many texts on hydraulics contain no information on the resistance of valves and fittings to flow, while others present only a limited discussion of the subject. In realization of the need for more complete detailed information on the resistance of valves and fittings to flow, Crane Co. has conducted extensive tests in their Engineering Laboratories and has also sponsored investigations in other laboratories. These tests have been supplemented by a thorough study of all published data on this subject. Appendix A contains data from these many separate tests and the findings have been combined to furnish a basis for calculating the pressure drop through valves and fittings.

Representative resistances to flow of various types of piping components are given in the "K" Factor Table; see pages A-26 thru A-29.

The chart on page A-30 illustrates the relationship between equivalent length in pipe diameters and in metres of pipe for flow in the zone of complete turbulence, resistance coefficient K, and pipe size.

A discussion of the equivalent length and resistance coefficient K, as well as the flow coefficient C_V methods of calculating pressure drop through valves and fittings is presented on pages 2-8 to 2-10.

Types of Valves and Fittings used in Pipe Systems

Valves: The great variety of valve designs precludes any thorough classification.

If valves were classified according to the resistance they offer to flow, those exhibiting a straight-thru flow path such as gate, ball, plug, and butterfly valves would fall in the low resistance class, and those having a change in flow path direction such as globe and angle valves would fall in the high resistance class.

For photographic illustrations of some of the most commonly used valve designs, refer to pages A-18 and A-19. For line illustrations of typical fittings and pipe bends, as well as valves, see pages A-27 to A-29.

Fittings: Fittings may be classified as branching, reducing, expanding, or deflecting. Such fittings as tees, crosses, side outlet elbows, etc., may be called branching fittings.

Reducing or expanding fittings are those which change the area of the fluid passageway. In this class are reducers and bushings. Deflecting fittings.......bends, elbows, return bends, etc. ....are those which change the direction of flow.

Some fittings, of course, may be combinations of any of the foregoing general classifications. In addition, there are types such as couplings and unions which offer no appreciable resistance to flow and, therefore, need not be considered here.

Pressure Drop Chargeable To Valves and Fittings

When a fluid is flowing steadily in a long straight pipe of uniform diameter, the flow pattern, as indicated by the velocity distribution across the pipe diameter, will assume a certain characteristic form. Any impediment in the pipe which changes the direction of the whole stream, or even part of it, will alter the characteristic flow pattern and create turbulence, causing an energy loss greater than that normally accompanying flow in straight pipe. Because valves and fittings in a pipeline disturb the flow pattern, they produce an additional pressure drop.

The loss of pressure produced by a valve (or fitting) consists of:

1. The pressure drop within the valve itself.
2. The pressure drop in the upstream piping in excess of that which would normally occur if there were no valve in the line. This effect is small.
3. The pressure drop in the downstream piping in excess of that which would normally occur if there were no valve in the line. This effect may be comparatively large.

From the experimental point of view it is difficult to measure the three items separately. Their combined effect is the desired quantity, however, and this can be accurately measured by well known methods.

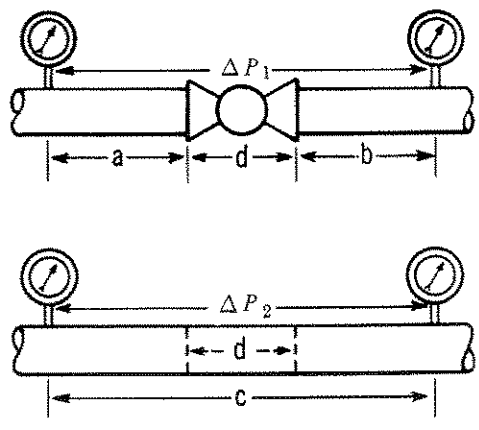


Figure 2-1

Figure 2-1 shows two sections of a pipe line of the same diameter and length. The upper section contains a globe valve. If the pressure drops, ΔP_1 and ΔP_2, were measured between the points indicated, it would be found that ΔP_1 is greater than ΔP_2.

Actually, the loss chargeable to a valve of length "d" is ΔP_1 minus the loss in a section of pipe of length "a + b". The losses, expressed in terms of resistance coefficient "K" of various valves and fittings as given on pages A-26 to A-29 include the loss due to the length of the valve or fitting.

Crane Flow Tests

Crane Engineering Laboratories have facilities for conducting water, steam, and air flow tests for many sizes and types of valves and fittings. Although a detailed discussion of all the various tests performed is beyond the scope of this paper, a brief description of some of the apparatus will be of interest.

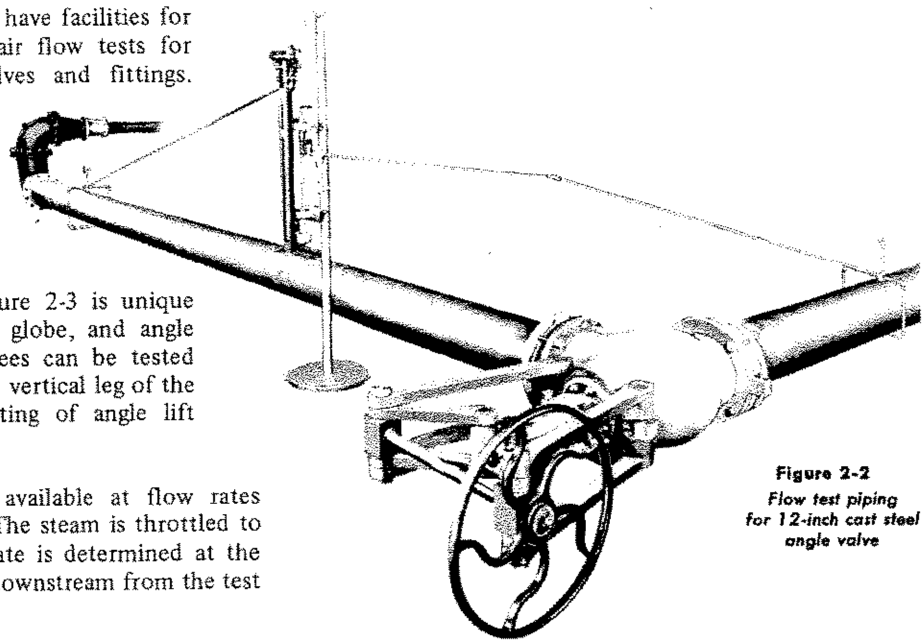


Figure 2-2
Flow test piping for 12-inch cast steel angle valve

The test piping shown in Figure 2-3 is unique in that 150 mm (6 inch) gate, globe, and angle valves or 90 degree ells and tees can be tested with either water or steam. The vertical leg of the angle test section permits testing of angle lift check and stop check valves.

Saturated steam at 10 bar is available at flow rates up to 50 000 kilograms/hour. The steam is throttled to the desired pressure and its state is determined at the meter as well as upstream and downstream from the test specimen.

For tests on water, a steam-turbine driven pump supplies water at rates up to 4.5 cubic metres/minute through the test piping.

Static pressure differential is measured by means of a manometer connected to piezometer rings upstream and downstream from test position 1 in the angle test section, or test position 2 in the straight test section. The downstream piezometer for the angle test section serves as the upstream piezometer for the straight test section. Measured pressure drop for the pipe alone between piezometer stations is subtracted from the pressure drop through the valve plus pipe to ascertain the pressure drop chargeable to the valve alone.

Results of some of the flow tests conducted in the Crane Engineering Laboratories are plotted in Figures 2-4 to 2-7 shown on the two pages following.

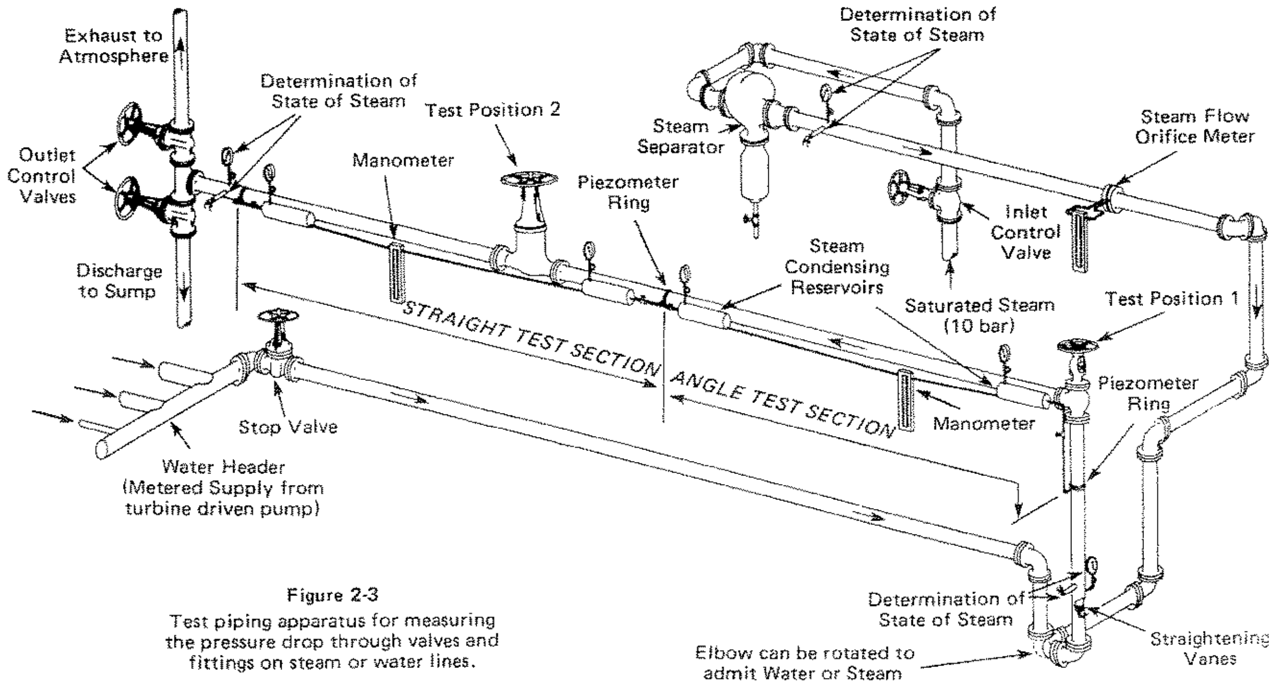


Figure 2-3
Test piping apparatus for measuring the pressure drop through valves and fittings on steam or water lines.

Crane Water Flow Tests

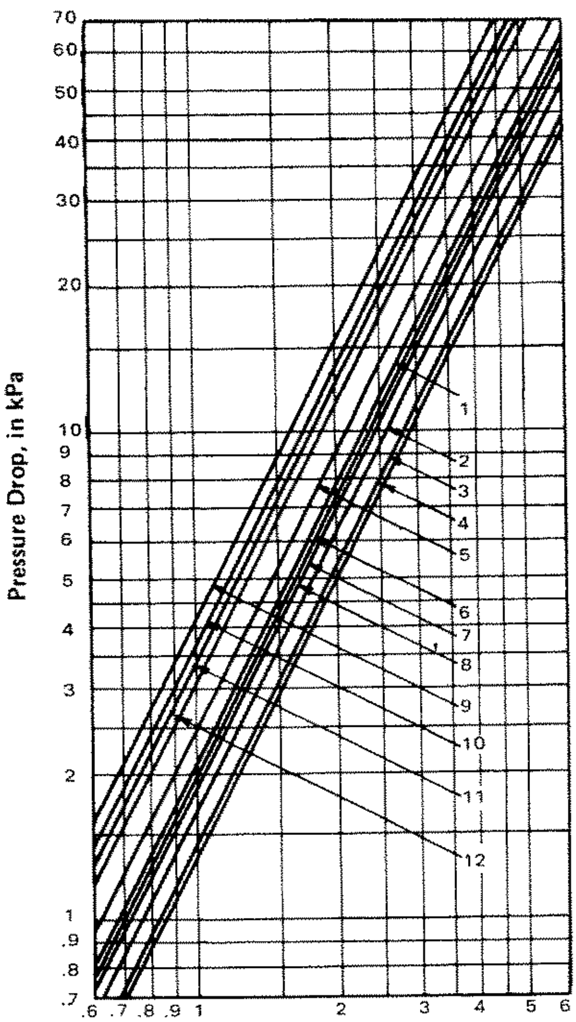


Figure 2-4

1 kPa = 0.01 bar

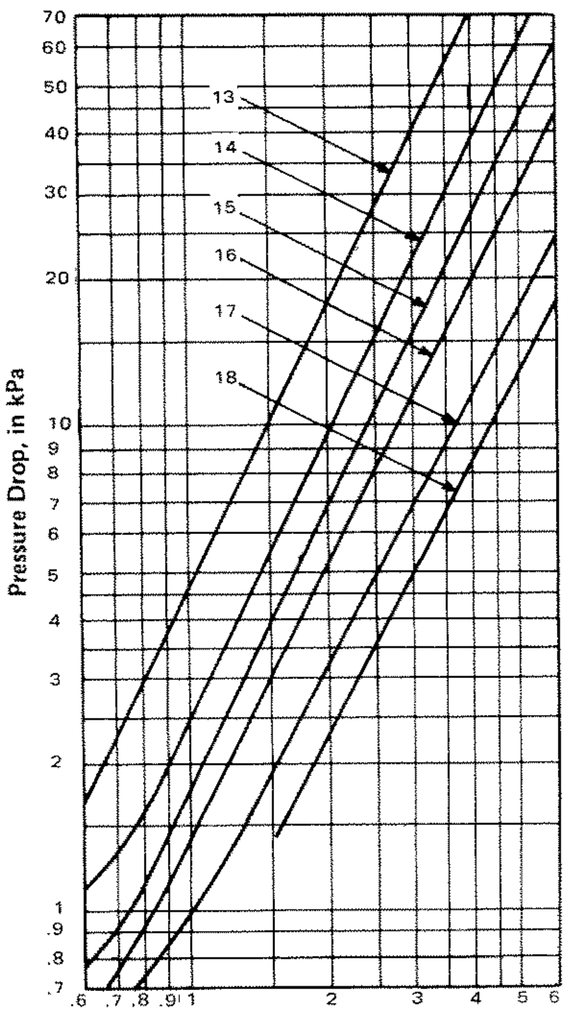


Figure 2-5

Water Flow Tests — Curves 1 to 18

Fluid	Figure No.	Curve No.	Nominal Size in.	Nominal Size mm	Valve Type *
Water	Figure 2-4	1 2 3 4	3/4 2 4 6	20 50 100 150	Class 150 Cast Iron Y-Pattern Globe Valve, Flat Seat
		5 6 7 8	1 1/2 2 2 1/2 3	40 50 65 80	Class 150 Brass Angle Valve with Composition Disc, Flat Seat
		9 10 11 12	1 1/2 2 2 1/2 3	40 50 65 80	Class 150 Brass Conventional Globe Valve with Composition Disc – Flat Seat
	Figure 2-5	13 14 15 16 17	3/8 1/2 3/4 1 1/4 2	10 15 20 32 50	Class 200 Brass Swing Check Valve
		18	6	150	Class 125 Iron Body Swing Check Valve

*Except for check valves at lower velocities where curves (14 to 17) bend, all valves were tested with disc fully lifted.

Crane Steam Flow Tests

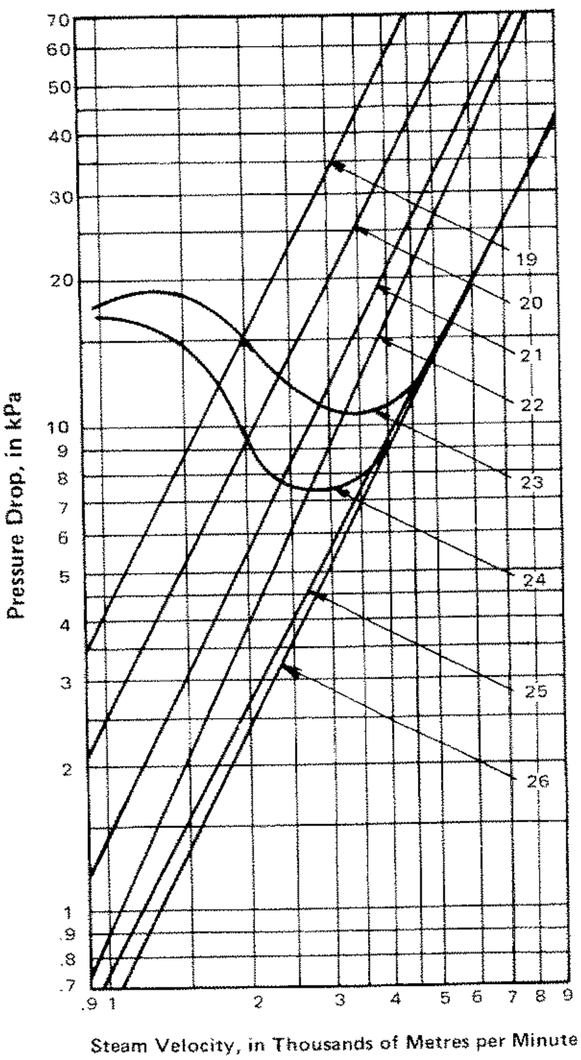


Figure 2-6

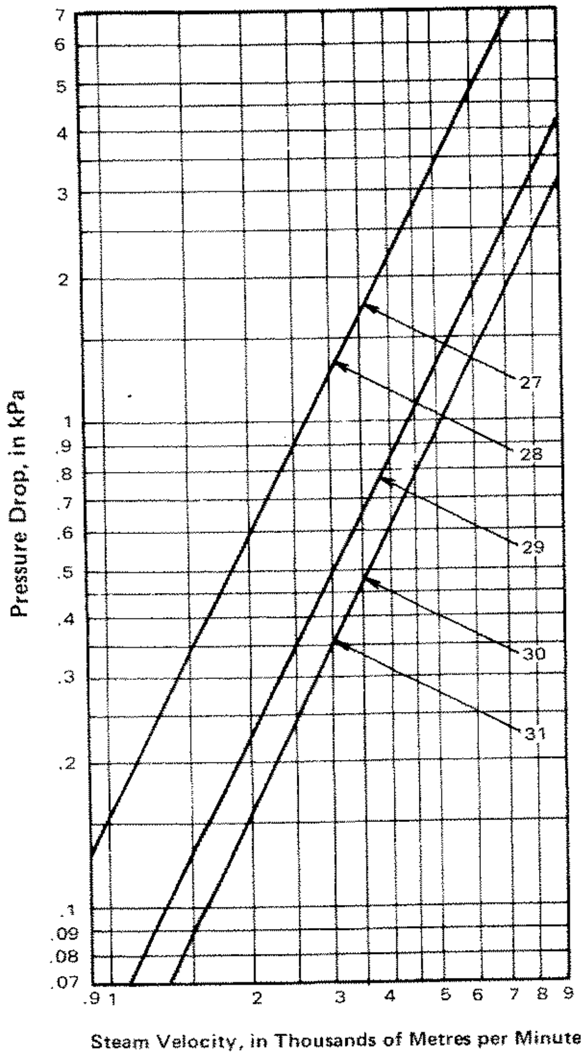


Figure 2-7

1 kPa = 0.01 bar

Steam Flow Tests – Curves 19 to 31

Fluid	Figure No.	Curve No.	Nominal Size in	Nominal Size mm	Valve* or Fitting Type
Saturated steam 3·5 bar gauge	Figure 2-6	19	2	50	Class 300 Brass Conventional Globe Valve . . . . Plug Type Seat
		20	6	150	Class 300 Steel Conventional Globe Valve . . . . Plug Type Seat
		21	6	150	Class 300 Steel Angle Valve . . . . Plug Type Seat
		22	6	150	Class 300 Steel Angle Valve . . . . Ball to Cone Seat
		23	6	150	Class 600 Steel Angle Stop-Check Valve
		24	6	150	Class 600 Steel Y-Pattern Globe Stop-Check Valve
		25	6	150	Class 600 Steel Angle Valve
		26	6	150	Class 600 Steel Y-Pattern Globe Valve
	Figure 2-7	27	2	50	90° Short Radius Elbow for Use with Schedule 40 Pipe
		28	6	150	Class 250 Cast Iron Flanged Conventional 90° Elbow
		29	6	150	Class 600 Steel Gate Valve
		30	6	150	Class 125 Cast Iron Gate Valve
		31	6	150	Class 150 Steel Gate Valve

*Except for check valves at lower velocities where curves (23 and 24) bend, all valves were tested with disc fully lifted.

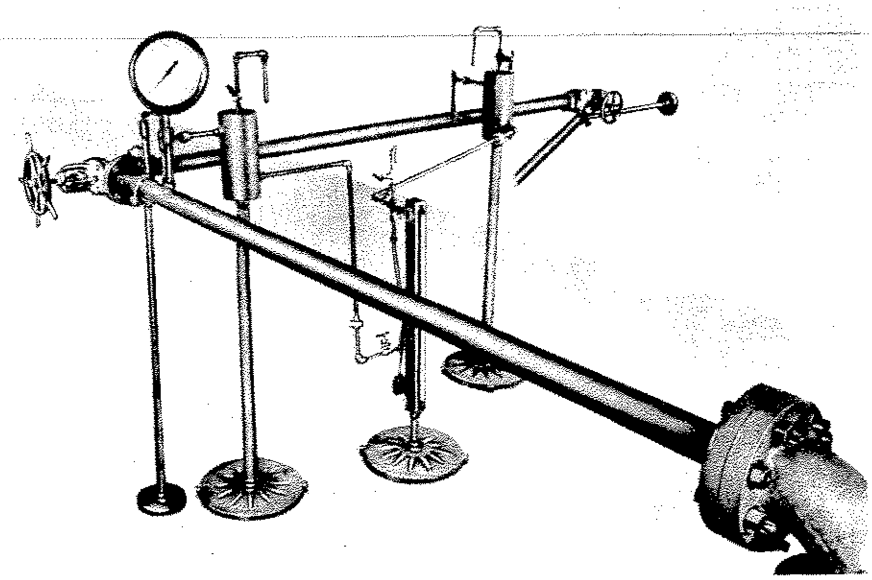


Figure 2-8
Flow test piping for 2½ inch (65 mm) cast steel angle valve.

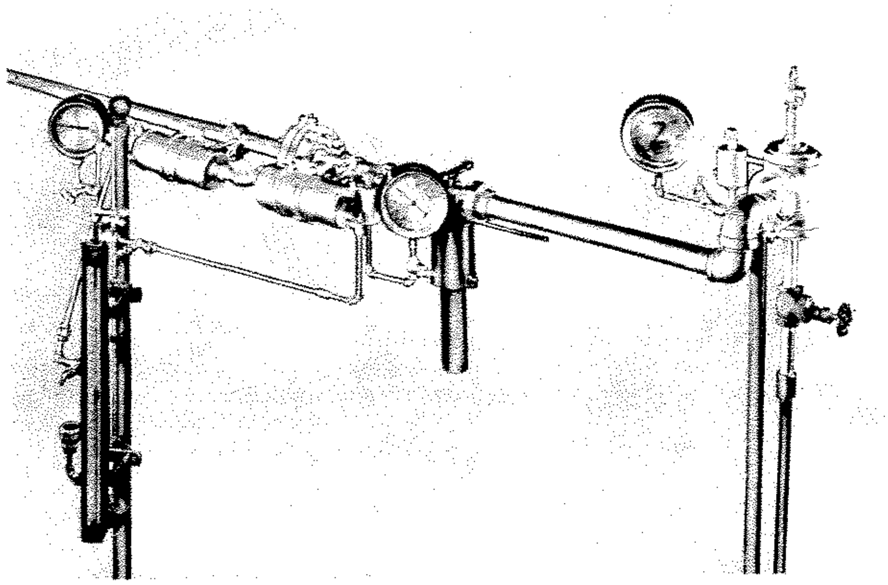


Figure 2-9
Steam capacity test of a ½ inch (15 mm) brass relief valve.

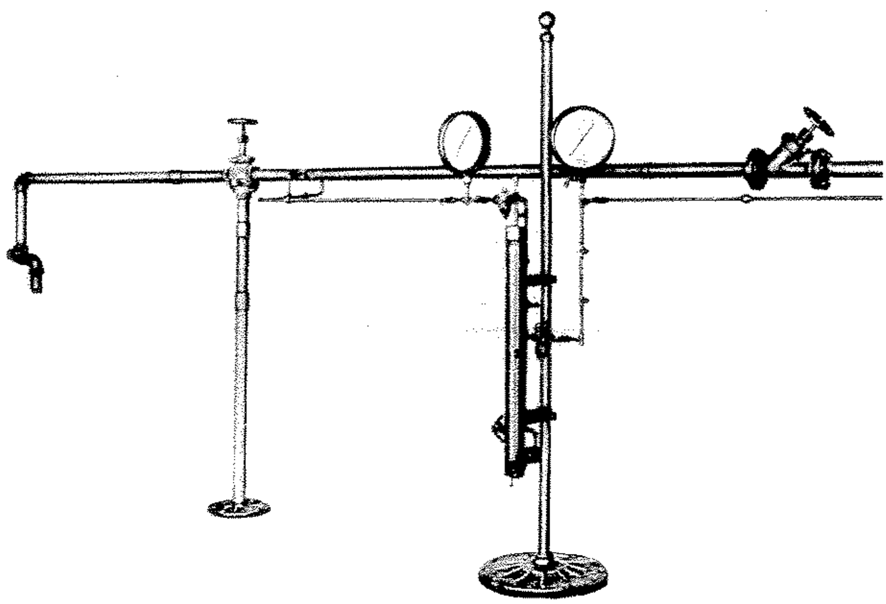


Figure 2-10
Flow test piping for 2 inch (50 mm) fabricated steel y-pattern globe valve.

Relationship of Pressure Drop to Velocity of Flow

Many experiments have shown that the head loss due to valves and fittings is proportional to a constant power of the velocity. When pressure drop or head loss is plotted against velocity on logarithmic co-ordinates, the resulting curve is therefore a straight line. In the turbulent flow range, the value of the exponent of v has been found to vary from about 1.8 to 2.1 for different designs of valves and fittings. However, for all practical purposes, it can be assumed that the pressure drop or head loss due to the flow of fluids in the turbulent range through valves and fittings varies as the square of the velocity.

This relationship of pressure drop to velocity of flow is valid for check valves, only if there is sufficient flow to hold the disc in a wide open position. The point of deviation of the test curves from a straight line, as illustrated in Figures 2-5 and 2-6, defines the flow conditions necessary to support a check valve disc in the wide open position.

Most of the difficulties encountered with check valves, both lift and swing types, have been found to be due to oversizing which results in noisy operation and premature wear of the moving parts.

Referring again to Figure 2-6, it will be noted that the velocity of 3.5 bar saturated steam, at the point where the two curves deviate from a straight line, is about 4000 to 4500 metres/minute. Lower velocities are not sufficient to lift the disc through its full stroke and hold it in a stable position against the stops, and can actually result in an increase in pressure drop as indicated by the curves. Under these conditions, the disc fluctuates with each minor flow pulsation, causing noisy operation and rapid wear of the contacting moving parts.

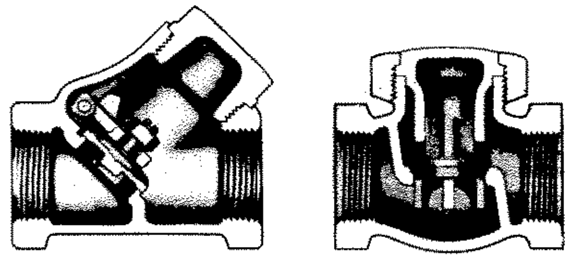


Figure 2-11

Y-Pattern Swing Check Valve

Lift Check Valve

The minimum velocity required to lift the disc to the full-open and stable position has been determined by tests for numerous types of check and foot valves, and is given in the "K" Factor Table (see pages A-26 thru A-29). It is expressed in terms of a constant times the square root of the specific volume of the fluid being handled, making it appliable for use with any fluid.

Sizing of check valves in accordance with the specified minimum velocity for full disc lift will often result in valves smaller in size than the pipe in which they are installed; however, the actual pressure drop will be little, if any, higher than that of a full size valve which is used in other than the wide-open position. The advantages are longer valve life and quieter operation. The losses due to sudden or gradual contraction and enlargement which will occur in such installations with bushings, reducing flanges, or tapered reducers can be readily calculated from the data given in the "K" Factor Table.

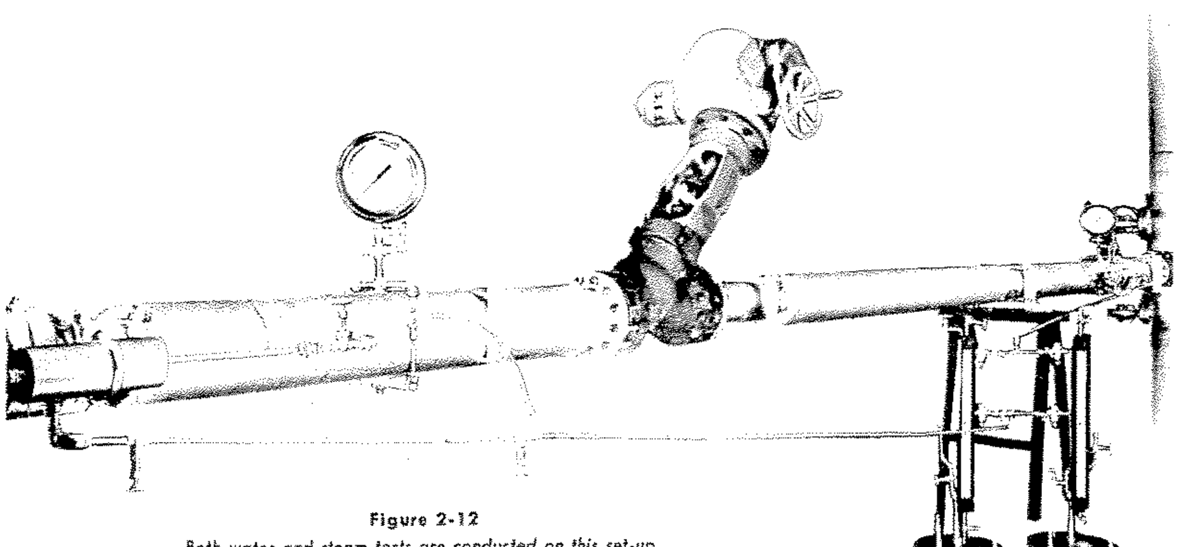


Figure 2-12

Both water and steam tests are conducted on this set-up.

Resistance Coefficient K, Equivalent Length L/D And Flow Coefficient

Pressure loss test data for a wide variety of valves and fittings are available from the work of numerous investigators. Extensive studies in this field have been conducted by Crane Laboratories. However, due to the time-consuming and costly nature of such testing, it is virtually impossible to obtain test data for every size and type of valve and fitting.

It is therefore desirable to provide a means of reliably extrapolating available test information to envelope those items which have not been or cannot readily be tested. Commonly used concepts for accomplishing this are the "equivalent length L/D", "resistance coefficient K", and "flow coefficient C_v or K_v".

Pressure losses in a piping system result from a number of system characteristics, which may be categorized as follows:

1. Pipe friction, which is a function of the surface roughness of the interior pipe wall, the inside diameter of the pipe, and the fluid velocity, density and viscosity. Friction factors are discussed on pages 1-6 and 1-7. For friction data, see pages A-23 thru A-25.
2. Changes in direction of flow path.
3. Obstructions in flow path.
4. Sudden or gradual changes in the cross-section and shape of flow path.

Velocity in a pipe is obtained at the expense of static head, and decrease in static head due to velocity is,

$$h_L = \frac{v^2}{2g_n} \qquad \text{Equation 2-1}$$

which is defined as the "velocity head". Flow through a valve or fitting in a pipe line also causes a reduction in static head which may be expressed in terms of velocity head. The resistance coefficient K in the equation

$$h_L = K\frac{v^2}{2g_n} \qquad \text{Equation 2-2}$$

therefore, is defined as the number of velocity heads lost due to a valve or fitting. It is always associated with the diameter in which the velocity occurs. In most valves or fittings, the losses due to friction (Category 1 above) resulting from actual length of flow path are minor compared to those due to one or more of the other three categories listed.

The resistance coefficient K is therefore considered as being independent of friction factor or Reynolds number, and may be treated as a constant for any given obstruction (i.e., valve or fitting) in a piping system under all conditions of flow, including laminar flow.

The same loss in straight pipe is expressed by the Darcy equation

$$h_L = \left(f\frac{L}{D}\right)\frac{v^2}{2g_n} \qquad \text{Equation 2-3}$$

It follows that

$$K = \left(f\frac{L}{D}\right) \qquad \text{Equation 2-4}$$

The ratio L/D is the equivalent length, in pipe diameters of straight pipe, that will cause the same pressure drop as the obstruction under the same flow conditions. Since the resistance coefficient K is constant for all conditions of flow, the value of L/D for any given valve or fitting must necessarily vary inversely with the change in friction factor for different flow conditions.

The resistance coefficient K would theoretically be a constant for all sizes of a given design or line of valves and fittings if all sizes were geometrically similar. However, geometric similarity is seldom, if ever, achieved because the design of valves and fittings is dictated by manufacturing economies, standards, structural strength, and other considerations.

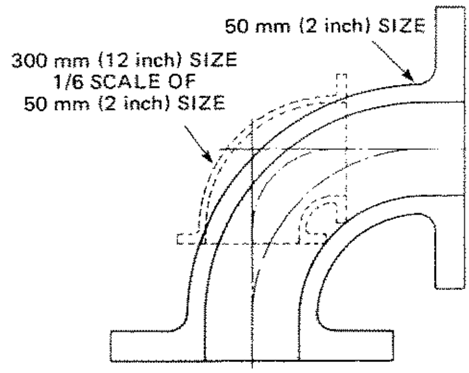


Figure 2-13
Geometrical dissimilarity between 50 mm (2 inch) and 300 mm (12 inch) standard cast iron flanged elbows

An example of geometric dissimilarity is shown in Figure 2-13 where a 300 mm (12 inch) standard elbow has been drawn to 1/6 scale of a 50 mm (2 inch) standard elbow, so that their port diameters are identical. The flow paths through the two fittings drawn to these scales would also have to be identical to have geometric similarity; in addition, the relative roughness of the surfaces would have to be similar.

Figure 2-14 is based on the analysis of extensive test data from various sources. The K coefficients for a number of lines of valves and fittings have been plotted against size. It will be noted that the K curves show a definite tendency to follow the same slope as the

(continued on next page)

Resistance Coefficient K, Equivalent Length L/D, And Flow Coefficient - continued

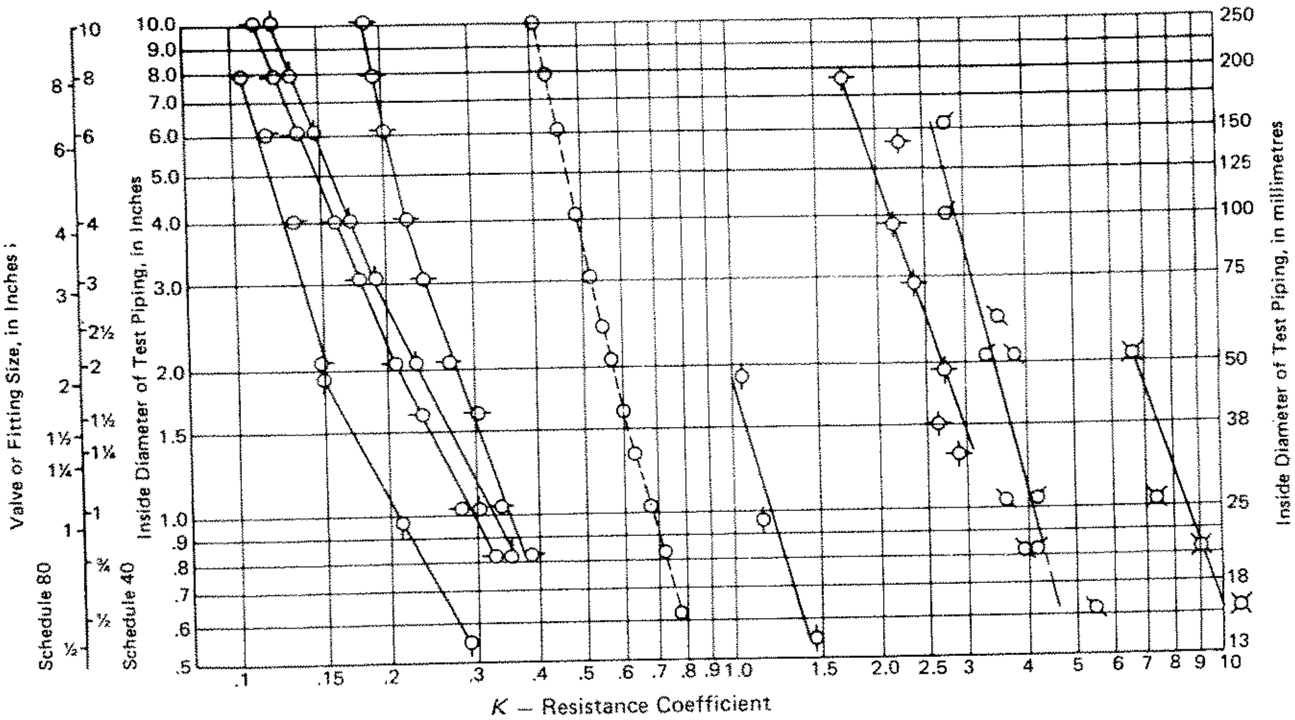


Figure 2-14, Variations of Resistance Coefficient K ($= f\ L/D$) with Size

Symbol	Product Tested	Authority
	Schedule 40 Pipe, 30 Diameters Long ($K = 30\ f_T$)*	Moody A.S.M.E. Trans., Nov.-1944[18]
	Class 125 Iron Body Wedge Gate Valves	Univ. of Wisc. Exp. Sta. Bull., Vol. 9, No. 1, 1922[16]
	Class 600 Steel Wedge Gate Valves	Crane Tests
	90 Degree Pipe Bends, $R/D = 2$	Pigott A.S.M.E. Trans., 1950[6]
	90 Degree Pipe Bends, $R/D = 3$	Pigott A.S.M.E. Trans., 1950[6]
	90 Degree Pipe Bends, $R/D = 1$	Pigott A.S.M.E. Trans., 1950[6]
	Class 600 Steel Wedge Gate Valves, Seat Reduced	Crane Tests
	Class 300 Steel Venturi Ball-Cage Gate Valves	Crane-Armour Tests
	Class 125 Iron Body Y-Pattern Globe Valves	Crane-Armour Tests
	Class 125 Brass Angle Valves, Composition Disc	Crane Tests
	Class 125 Brass Globe Valves, Composition Disc	Crane Tests

*f_T = friction factor for flow in the zone of complete turbulence: see page A-26.

(continued from the preceding page)

$f(L/D)$ curve for straight clean commercial steel pipe at flow conditions resulting in a constant friction factor. It is probably coincidence that the effect of geometric dissimilarity between different sizes of the same line of valves or fittings upon the resistance coefficient K is similar to that of relative roughness, or size of pipe, upon friction factor.

Based on the evidence presented in Figure 2-14, it can be said that the resistance coefficient K, for a given line of valves or fittings, tends to vary with size as does the friction factor, f, for straight clean commercial steel pipe at flow conditions resulting in a constant friction factor, and that the equivalent length L/D tends toward a constant for the various sizes of a given line of valves or fittings at the same flow conditions.

On the basis of this relationship, the resistance coefficient K for each illustrated type of valve and fitting is presented on pages A-26 thru A-29. These coefficients are given as the product of the friction factor for the desired size of clean commercial steel pipe with flow in the zone of complete turbulence, and a constant, which represents the equivalent length L/D for the valve or fitting in pipe diameters for the same flow conditions, on the basis of test data. This equivalent length, or constant, is valid for all sizes of the valve or fitting type with which it is identified.

Resistance Coefficient K, Equivalent Length L/D, And Flow Coefficient - continued

The friction factors for clean commercial steel pipe with flow in the zone of complete turbulence (f_T), for nominal sizes from ½ to 24-inch (15 to 600 mm), are tabulated at the beginning of the "K" Factor Table (page A-26) for convenience in converting the algebraic expressions of K to arithmetic quantities.

There are some resistances to flow in piping, such as sudden and gradual contractions and enlargements, and pipe entrances and exits, that have geometric similarity between sizes. The resistance coefficients (K) for these items are therefore independent of size as indicated by the absence of a friction factor in their values given in the "K" Factor Table.

As previously stated, the resistance coefficient K is always associated with the diameter in which the velocity in the term $v^2/2g_n$ occurs. The values in the "K" Factor Table are associated with the internal diameter of the following pipe schedule numbers for the various ANSI Classes of valves and fittings.

Class 300 and lower	Schedule 40
Class 400 and 600	Schedule 80
Class 900	Schedule 120
Class 1500	Schedule 160
Class 2500 (sizes ½ to 6")	XXS
Class 2500 (sizes 8" and up)	Schedule 160

When the resistance coefficient K is used in flow equation 2-2, or any of its equivalent forms given in Chapter 3 as Equations 3-14, 3-16, 3-19 and 3-20, the velocity and internal diameter dimensions used in the equation must be based on the dimensions of these schedule numbers regardless of the pipe with which the valve may be installed.

An alternate procedure which yields identical results for Equation 2-2 is to adjust K in proportion to the fourth power of the diameter ratio, and to base values of velocity or diameter on the internal diameter of the connecting pipe.

$$K_a = K_b \left(\frac{d_a}{d_b}\right)^4 \qquad \text{Equation 2-5}$$

Subscript "a" defines K and d with reference to the internal diameter of the connecting pipe.

Subscript "b" defines K and d with reference to the internal diameter of the pipe for which the values of K were established, as given in the foregoing list of pipe schedule numbers.

When a piping system contains more than one size of pipe, valves, or fittings, Equation 2-5 may be used to express all resistances in terms of one size. For this case, subscript "a" relates to the size with reference to which all resistances are to be expressed, and subscript "b" relates to any other size in the system. For sample problem, see Example 4-14.

It is convenient in some branches of the valve industry, particularly in connection with control valves, to express the valve capacity and the valve flow characteristics in terms of a flow coefficient. In the USA and UK the flow coefficient at present in use is designated C_v and is defined as:

C_v = Rate of flow of water, in either US or UK gallons per minute, at 60F, at a pressure drop of one pound per square inch across the valve. **(See Equation 3-16, page 3-4).**

Another coefficient, K_v, is used in some countries, particularly in Europe, and this is defined as:

K_v = Rate of flow of water in cubic metres per hour (m^3/h) at a pressure drop of one kilogram force per square centimetre (kgf/cm^2) across the valve.

One kgf/cm^2 is equal to 0.980 665 bar (exactly) and in some continental countries the name kilopond (kp) is used in place of kilogram force, i.e. 1 kp/cm^2 = 1 kgf/cm^2.

At the time of preparation of this paper there is no agreed international definition for a flow coefficient in terms of SI units. Liquid flow capacity in metric units can be converted to C_v as defined above. For example:

$$C_v = 0.0694\, Q \sqrt{\frac{\rho}{\Delta p\,(999)}} \quad \text{(in U.S. gallons)}$$

where:

Q = rate of flow, litres/min.
ρ = density of fluid, kg/m^3
Δp = bar

Laminar Flow Conditions

In the usual piping installation, the flow will change from laminar to turbulent in the range of Reynolds numbers from 2000 to 4000, defined on pages A-24 and A-25 as the critical zone. The lower critical Reynolds number of 2000 is usually recognized as the upper limit for the application of Poiseuille's law for laminar flow in straight pipes,

$$h_L = 3263\left(\frac{\mu L v}{d^2 \rho}\right) \qquad \text{Equation 2-8}$$

which is identical to Equation 2-3 when the value of the fraction factor for laminar flow, $f = 64/R_e$, is factored into it. Laminar flow at Reynolds numbers above 2000 is unstable, and the critical zone and lower range of the transition zone, turbulent mixing and laminar motion may alternate unpredictably.

Equation 2-2 ($h_L = Kv^2/2g_n$) is valid for computing the head loss due to valves and fittings for all conditions of flow, including laminar flow, using resistance coefficient K as given in the "K" Factor Table. When this equation is used to determine the losses in straight pipe, it is necessary to compute the Reynolds number in order to establish the friction factor, f, to be used to determine the value of the resistance coefficient K for the pipe in accordance with Equation 2-4 ($K = fL/D$). See examples on pages 4-4 and 4-5.

Contraction and Enlargement

The resistance to flow due to sudden enlargements may be expressed by,

$$K_1 = \left(1 - \frac{d_1^2}{d_2^2}\right)^2 \qquad \text{Equation 2-9}$$

and the resistance due to sudden contractions, by

$$K_1 = 0.5\left(1 - \frac{d_1^2}{d_2^2}\right) \qquad \text{Equation 2-10}$$

Subscripts 1 and 2 define the internal diameters of the small and large pipes respectively.

It is convenient to identify the ratio of diameters of the small to large pipes by the Greek letter β (beta). Using this notation, these equations may be written,

Sudden Enlargement

$$K_1 = (1 - \beta^2)^2 \qquad \text{Equation 2-9.1}$$

Sudden Contraction

$$K_1 = 0.5(1 - \beta^2) \qquad \text{Equation 2-10.1}$$

Equation 2-9 is derived from the momentum equation together with the Bernoulli equation. Equation 2-10 uses the derivation of Equation 2-9 together with the continuity equation and a close approximation of the contraction coefficients determined by Julius Weisbach.[28]

The value of the resistance coefficient in terms of the larger pipe is determined by dividing Equations 2-9 and 2-10 by β^4.

$$K_2 = \frac{K_1}{\beta^4} \qquad \text{Equation 2-11}$$

The losses due to gradual enlargements in pipes were investigaged by A.H. Gibson,[29] and may be expressed as a coefficient, C_e, applied to Equation 2-9. Approximate averages of Gibson's coefficients for different included angles of divergence, θ, are defined by the equations:

$$\text{For } \theta \mathrel{\overline{\lessgtr}} 45^\circ \ldots\ldots\ldots C_e = 2.6 \sin\frac{\theta}{2} \qquad \text{Equation 2-12}$$

$$\text{For } 45^\circ < \theta \mathrel{\overline{\lessgtr}} 180^\circ \ldots C_e = 1 \qquad \text{Equation 2-12.1}$$

The losses due to gradual contractions in pipes were established by the analysis of Crane test data, using the same basis as that of Gibson for gradual enlargements, to provide a contraction coefficient, C_c to be applied to Equation 2-10. The approximate averages of these coefficients for different included angles of convergence, θ, are defined by the equations:

$$\text{For } \theta \mathrel{\overline{\lessgtr}} 45^\circ \ldots\ldots C_c = 1.6 \sin\frac{\theta}{2} \qquad \text{Equation 2-13}$$

$$\text{For } 45^\circ < \theta \mathrel{\overline{\lessgtr}} 180^\circ \ldots C_c = \sqrt{\sin\frac{\theta}{2}} \qquad \text{Equation 2-13.1}$$

The resistance coefficient K for sudden and gradual enlargements and contractions, expressed in terms of the large pipe, is established by combining equations 2-9 to 2-13 inclusive.

Sudden and Gradual Enlargements

$$\theta \mathrel{\overline{\lessgtr}} 45^\circ \ldots\ldots\ldots\ldots K_2 = \frac{2.6 \sin\frac{\theta}{2}\,(1 - \beta^2)^2}{\beta^4} \qquad \text{Equation 2-14}$$

$$45^\circ < \theta \mathrel{\overline{\lessgtr}} 180^\circ \ldots\ldots K_2 = \frac{(1 - \beta^2)^2}{\beta^4} \qquad \text{Equation 2-14.1}$$

Sudden and Gradual Contractions

$$\theta \mathrel{\overline{\lessgtr}} 45^\circ \ldots\ldots\ldots\ldots K_2 = \frac{0.8 \sin\frac{\theta}{2}\,(1 - \beta^2)}{\beta^4} \qquad \text{Equation 2-15}$$

$$45^\circ < \theta \mathrel{\overline{\lessgtr}} 180^\circ \ldots\ldots K_2 = \frac{0.5\sqrt{\sin\frac{\theta}{2}}\,(1 - \beta^2)}{\beta^4} \qquad \text{Equation 2-15.1}$$

Valves with Reduced Seats

Valves are often designed with reduced seats, and the transition from seat to valve ends may be either abrupt or gradual. Straight-through types, such as gate and ball valves, so designed with gradual transition are sometimes referred to as venturi valves. Analysis of tests on such straight-through valves indicates an excellent correlation between test results and calculated values of K based on the summation of Equations 2-11, 2-14 and 2-15.

Valves which exhibit a change in direction of the flow path, such as globe and angle valves, are classified as high resistance valves. Equations 2-14 and 2-15 for gradual contractions and enlargements cannot be readily applied to these configurations because the angles of convergence and divergence are variable with respect to different planes of reference. The entrance and exit losses for reduced seat globe and angle valves are judged to fall short of those due to sudden expansion and contraction (Equations 2-14.1 and 2-15.1 at $\theta = 180°$) if the approaches to the seat are gradual. Analysis of available test data indicates that the factor β applied to Equations 2-14 and 2-15 for sudden contraction and enlargement will bring calculated K values for reduced seat globe and angle valves into reasonably close agreement with test results. In the absence of actual test data, the resistance coefficients for reduced seat globe and angle valves may thus be computed as the summation of Equation 2-11 and β times Equations 2-14.1 and 2-15.1 at $\theta = 180°$.

The procedure for determining K for reduced seat globe and angle valves is also applicable to throttled globe and angle valves. For this case the value of β must be based upon the square root of the ratio of areas,

$$\beta = \sqrt{\frac{a_1}{a_2}}$$

where:

a_1 . . . . . defines the area at the most restricted point in the flow path

a_2 . . . . . defines the internal area of the connecting pipe.

Resistance of Bends

Secondary flow: The nature of the flow of liquids in bends has been thoroughly investigated and many interesting facts have been discovered. For example, when a fluid passes around a bend in either viscous or turbulent flow, there is established in the bend a condition known as "secondary flow". This is rotating motion, at right angles to the pipe axis, which is superimposed upon the main motion in the direction of the axis. The frictional resistance of the pipe walls and the action of centrifugal force combine to produce this rotation. Figure 2-15 illustrates this phenomenon.

Resistance of bends to flow: The resistance or head loss in a bend is conventionally assumed to consist of — (1) the loss due to curvature; (2) the excess loss in the downstream tangent; and (3) the loss due to length, thus:

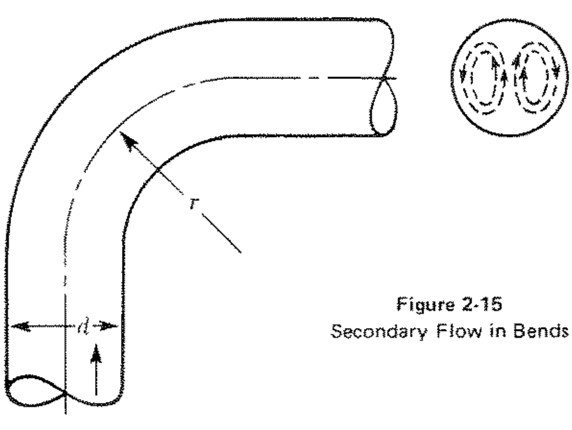


Figure 2-15
Secondary Flow in Bends

$$h_t = h_p + h_e + h_L \qquad \text{Equation 2-16}$$

where:

h_t = total loss, in metres of fluid

h_p = excess loss in downstream tangent, in metres of fluid

h_c = loss due to curvature, in metres of fluid

h_L = loss in bend due to length, in metres of fluid

if:

$$h_b = h_p + h_c \qquad \text{Equation 2-17}$$

then:

$$h_t = h_b + h_L$$

However, the quantity h_b can be expressed as a function of velocity head in the forumula:

$$h_b = K_b \frac{v^2}{2g_n} \qquad \text{Equation 2-18}$$

where:

K_b = the bend coefficient

v = velocity through pipe, metres per second

g_n = 9.81 metres per second per second

Resistance of Bends – continued

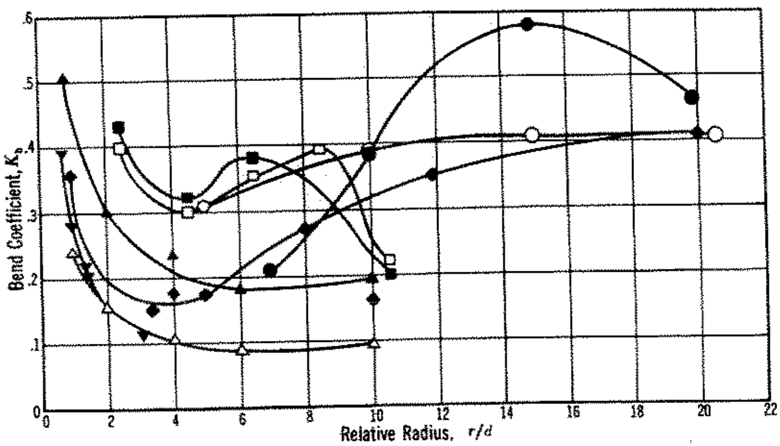


Figure 2-16, Bend Coefficients Found by Various Investigators (Beij[21])
From "Pressure Losses for Fluid Flow in 90° Pipe Bends" by K.H. Beij
Courtesy of Journal of Research of National Bureau of Standards

Investigator	Diameter inches	Symbol	Diameter mm
Balch	3	●	80
Davis	2	○	50
Brightmore	3	■	80
Brightmore	4	□	100
Hofmann	1.7 (rough pipe)	▲	43 (rough pipe)
Hofmann	1.7 (smooth pipe)	△	43 (smooth pipe)
Vogel	6, 8 and 10	▼	150, 200, 250
Beij	4	◆	100

The relationship between K_b and r/d (relative radius*) is not well defined, as can be observed by reference to Figure 2-16 (taken from the work of Beij[21]). The curves in this chart indicate that K_b has a minimum value when r/d is between 3 and 5.

Values of K for 90 degree bends with various bend ratios (r/d) are listed on page A-29. The values (also based on the work of Beij) represent average conditions of flow in 90 degree bends.

The loss due to continuous bends greater than 90 degrees, such as pipe coils or expansion bends, is less than the summation of losses in the total number of 90 degree bends contained in the coil, considered separately, because the loss h_p in Equation 2-16 occurs only once in the coil.

The loss due to length in terms of K is equal to the developed length of the bend, in pipe diameters, multiplied by the friction factor f_T as previously described and as tabulated on page A-26.

$$K_{length} = .5\, f_T \pi \left(\frac{r}{d}\right) \qquad \textbf{Equation 2-19}$$

In the absence of experimental data, it is assumed that $h_p = h_c$ in Equation 2-16. On this basis, the total value of K for a pipe coil or expansion bend made up of continuous 90 degree bends can be determined by multiplying the number (n) of 90 degree bends less one contained in the coil by the value of K due to length, plus one-half of the value of K due to bend resistance, and adding the value of K for one 90 degree bend (page A-29).

$$K_B = (n\text{-}1)\left(0.25\, f_T \pi \frac{r}{d} + 0.5\, K_1\right) + K_1 \qquad \textbf{Equation 2-20}$$

Subscript 1 defines the value of K (see page A-29) for one 90 degree bend.

Example:
A 2" Schedule 40 pipe coil contains five complete turns, i.e., twenty (n) 90 degree bends. The relative radius (r/d) of the bends is 16, and the resistance coefficient K_1 of one 90 degree bend is $42 f_T$ (42 x .019 = .80) per page A-29.

Find the total resistance coefficient (K_B) for the coil.

$$K_B = (20\text{-}1)\,(0.25 \times 0.019\pi \times 16 + 0.5 \times 0.8) + 0.8$$
$$= 13$$

Resistance of mitre bends: The equivalent length of mitre bends, based on the work of H. Kirchbach[4], is also shown on page A-29.

*The relative radius of a bend is the ratio of the radius of the bend axis to the internal diameter of the pipe. Both dimensions must be in the same units.

Flow Through Nozzles and Orifices

Orifices and nozzles are used principally to meter rate of flow. A portion of the theory is covered here. For more complete data, refer to Bibliography sources 8, 9, and 10. For installation or operation of commercial meters, refer to information supplied by the meter manufacturer.

Orifices are also used to restrict flow or to reduce pressure. For liquid flow, several orifices are sometimes used to reduce pressure in steps so as to avoid cavitation. Overall resistance coefficient K for an orifice is given on page A-20. For a sample problem, see page 4-7.

The rate of flow of any fluid through an orifice or nozzle, neglecting the velocity of approach, may be expressed by:

$$q = C_d A \sqrt{2 g_n h_L} \qquad \text{Equation 2-21}$$

Velocity of approach may have considerable effect on the quantity discharged through a nozzle or orifice. The factor correcting for velocity of approach.

$$\frac{1}{\sqrt{1 - \beta^4}}$$

may be incorporated in Equation 2-21 as follows:

$$q = \frac{C_d A}{\sqrt{1 - \beta^4}} \sqrt{2 g_n h_L} \qquad \text{Equation 2-22}$$

The quantity

$$\frac{C_d}{\sqrt{1 - \beta^4}}$$

is defined as the flow coefficient C. Values of C for nozzles and orifices are shown on page A-20. Use of the flow coefficient C eliminates the necessity for calculating the velocity of approach, and Equation 2-22 may now be written:

$$q = C A \sqrt{2 g_n h_L} = C A \sqrt{\frac{2\,\Delta p}{\rho}} \qquad \text{Equation 2-23}$$

Orifices and nozzles are normally used in piping systems as metering devices and are installed with flange taps or pipe taps in accordance with ASME or other standard specifications. The values of h_L and Δp in Equation 2-23 are the measured differential static head or pressure across pipe taps located 1 diameter upstream and 0.5 diameter downstream from the inlet face of the orifice plate or nozzle, when values of C are taken from page A-20. The flow coefficient C is plotted for Reynolds numbers based on the internal diameter of the upstream pipe.

Flow of liquids: For nozzles and orifices discharging incompressible fluids to atmosphere, C values may be taken from page A-20 if h_L or Δp in Equation 2-23 is taken as the upstream head or gauge pressure.

Flow of gases and vapors: The flow of compressible fluids through nozzles and orifices can be expressed by the same equation used for liquids except the net expansion factor Y must be included.

$$q = YCA \sqrt{\frac{2\,\Delta p}{\rho}} \qquad \text{Equation 2-24}$$

The expansion factor Y is a function of:

1. The specific heat ratio γ.
2. The ratio (β) of orifice or throat diameter to inlet diameter.
3. Ratio of downstream to upstream absolute pressures.

This factor[9,10] has been experimentally determined on the basis of air, which has a specific heat ratio of 1.4, and steam having specific heat ratios of approximately 1.3. The data is plotted on page A-21.

Values of γ for some of the common vapors and gases are given on pages A-8 and A-9. The specific heat ratio γ may vary slightly for different pressures and temperatures but for most practical problems the values given will provide reasonably accurate results.

Equation 2-24 may be used for orifices discharging compressible fluids to atmosphere by using:

1. Flow coefficient C given on page A-20 in the Reynolds number range where C is a constant for the given diameter ratio, β.
2. Expansion factor Y per page A-21.
3. Differential pressure Δp, equal to the inlet gauge pressure.

This also applies to nozzles discharging compressible fluids to atmosphere only if the absolute inlet pressure is less than the absolute atmospheric pressure divided by the critical pressure ratio r_c; this is discussed on the next page. When the absolute inlet pressure is greater than this amount, flow through nozzles should be calculated as outlined on the following page.

Flow Through Nozzles and Orifices – continued

Maximum flow of compressible fluids in a nozzle: A smoothly convergent nozzle has the property of being able to deliver a compressible fluid up to the velocity of sound in its minimum cross section or throat, providing the available pressure drop is sufficiently high. Sonic velocity is the maximum velocity that may be attained in the throat of a nozzle (supersonic velocity is attained in a gradually divergent section following the convergent nozzle, when sonic velocity exists in the throat).

The critical pressure ratio is the largest ratio of downstream pressure to upstream pressure capable of producing sonic velocity. Values of critical pressure ratio r_c which depend upon the ratio of nozzle diameter to upstream diameter as well as the specific heat ratio γ are given on page A-21

Flow through nozzles and venturi meters is limited by critical pressure ratio and minimum values of Y to be used in Equation 2-24 for this condition, are indicated on page A-21 by the termination of the curves at $P'_2/P'_1 = r_c$.

Equation 2-24 may be used for discharge of compressible fluids through a nozzle to atmosphere, or to a downstream pressure lower than indicated by the critical pressure ratio r_c, by using values of:

Y . . . . minimum per page A-21
C . . . . page A-20
ΔP . . . . . . $P'_1(1 - r_c)$; r_c per page A-21
ρ . . . . density at upstream condition

Flow through short tubes: Since complete experimental data for the discharge of fluids to atmosphere through short tubes (L/D is less than, or equal to, 2.5 pipe diameters)[1] are not available, it is suggested that reasonably accurate approximations may be obtained by using Equations 2-23 and 2-24, with values of C somewhere between those for orifices and nozzles, depending upon entrance conditions.

If the entrance is well rounded, C values would tend to approach those for nozzles, whereas short tubes with square entrance would have characteristics similar to those for square edged orifices.

Discharge of Fluids Through Valves, Fittings, and Pipe

Liquid flow: To determine the flow of liquid through pipe, the Darcy formula is used. Equation 1-4 (page 1-6) has been converted to more convenient terms in Chapter 3 and has been rewritten as Equation 3-14. Expressing this equation in terms of flow rate in litres per minute:

$$h_L = \frac{22 \cdot 96\,KQ^2}{d^4}$$

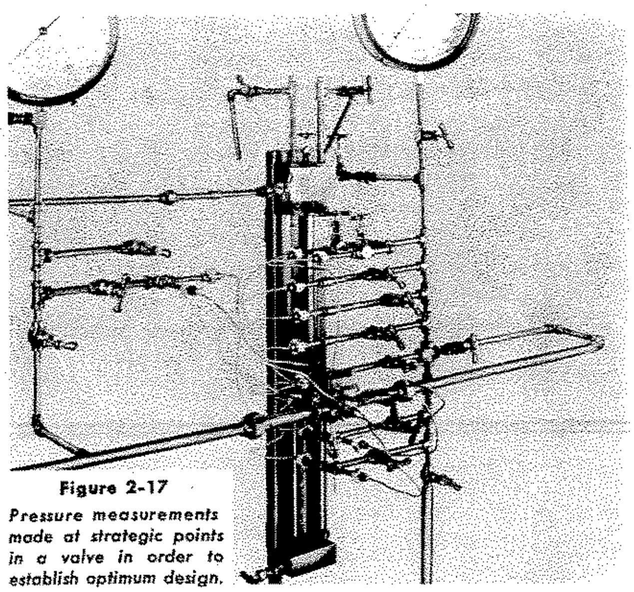


Figure 2-17
Pressure measurements made at strategic points in a valve in order to establish optimum design.

Solving for Q, the equation can be rewritten,

$$Q = 0.2087\,d^2 \sqrt{\frac{h_L}{K}} \qquad \text{Equation 2-25}$$

Equation 2-25 can be employed for valves, fittings, and pipe where K would be the sum of all the resistances in the piping system, including entrance and exit losses when they exist. Examples of problems of this type are shown on page 4-12.

Compressible flow: When a compressible fluid flows from a piping system into an area of larger cross section that that of the pipe, as in the case of discharge to atmosphere, a modified form of the Darcy formula, Equation 1-11 developed on page 1-9, is used.

$$w = 1.111 \times 10^{-6}\,Y d^2 \sqrt{\frac{\Delta P}{K\bar{V}_1}}$$

The determination of values of K, Y, and ΔP in this equation is described on page 1-9 and is illustrated in the examples on pages 4-13 and 4-14. This equation is also given in Chapter 3, page 3-5, Equation 3-22, in terms of pressure drop in bars (Δp).

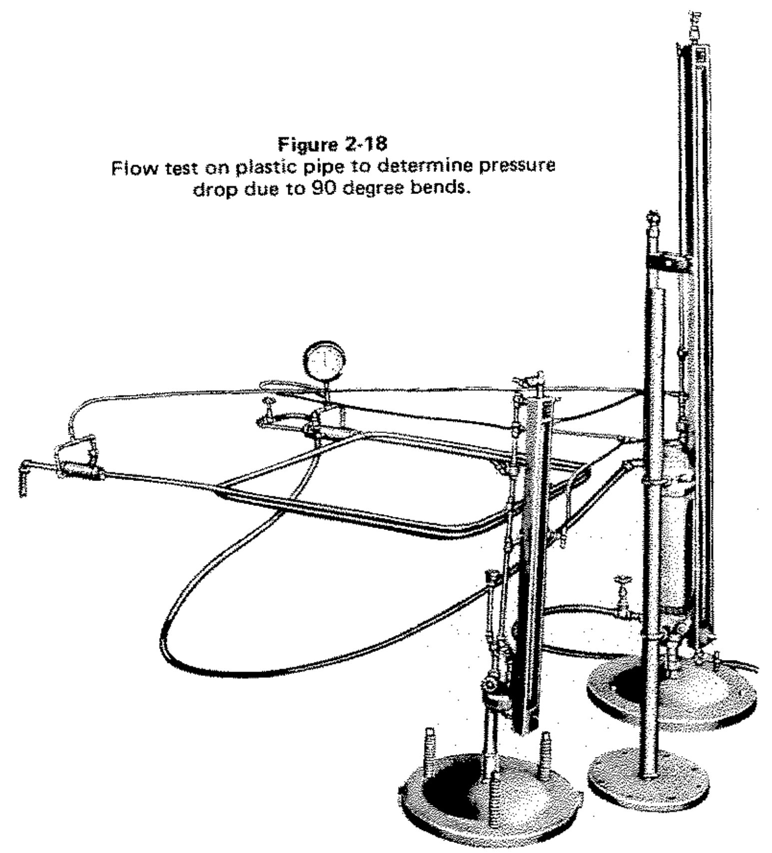


Figure 2-18
Flow test on plastic pipe to determine pressure drop due to 90 degree bends.

Formulas and Nomographs For Flow Through Valves, Fittings, and Pipe

CHAPTER 3

Only basic formulas needed for the presentation of the theory of fluid flow through valves, fittings, and pipe were presented in the first two chapters of this paper. In the summary of formulas given in this chapter, the basic formulas are rewritten in terms of the SI metric units which it is anticipated will be commonly used following the change-over to the metric system or, where this is already in being, the adoption of SI units.

In each case a choice of equations is given enabling the user to select the formula most suited to the available data.

Nomographs presented in this chapter are graphical solutions of the flow formulas applying to pipe. Valve and fitting flow problems may also be solved by means of these nomographs by determining their equivalent length in terms of metres of straight pipe.

Due to the wide variety of terms and the variation in the physical properties of liquids and gases, it was necessary to divide the nomographs into two parts: the first part (pages 3-6 to 3-15) pertains to liquid flow, and the second part (pages 3-16 to 3-27), pertains to compressible flow.

All nomographs for the solution of pressure drop problems are based upon Darcy's formula, since it is a general formula which is applicable to all fluids and can be applied to all types of pipe through the use of the Moody Friction Factor Diagram. Darcy's formula also provides a means of solving problems of flow through valves and fittings on the basis of equivalent length or resistance coefficient. Nomographs provide simple, rapid, practical, and reasonably accurate solutions to flow formulas and the decimal point is accurately located.

Accuracy of a nomograph is limited by the available page space, length of scales, number of units provided on each scale, and the angle at which the connecting line crosses the scale. Whenever the solution of a problem falls beyond the range of a nomograph, the solution of the formula must be obtained by calculation.

Summary of Formulas

To eliminate needless duplication, formulas have been written in terms of either specific volume $\bar{V}$ or density ρ, but not in terms of both, since one is the reciprocal of the other.

$$\bar{V} = \frac{1}{\rho} \qquad \rho = \frac{1}{\bar{V}}$$

These equations may be substituted in any of the formulas shown in this paper whenever necessary.

- **Bernoulli's theorem:** Equation 3-1

$$Z + \frac{P}{\rho g_n} + \frac{v^2}{2g_n} = H$$

$$Z_1 + \frac{P_1}{\rho_1 g_n} + \frac{v_1^2}{2g_n} = Z_2 + \frac{P_2}{\rho_2 g_n} + \frac{v_2^2}{2g_n} + h_L$$

- **Mean velocity of flow in pipe:** (Continuity Equation) Equation 3-2

$$v = \frac{q}{A} = 1273\,000\,\frac{q}{d^2} = 21.22\,\frac{Q}{d^2}$$

$$v = 56.23\,\frac{B}{d^2} = 1273\,000\,\frac{w\bar{V}}{d^2} = 354\,\frac{W\bar{V}}{d^2}$$

$$v = 1.243\,\frac{q_h' T}{p' d^2} = 433\,\frac{q_h' S_g}{\rho d^2}$$

$$V = \frac{q_m}{A} = 16\,670\,\frac{W\bar{V}}{a} = 21\,220\,\frac{W\bar{V}}{d^2}$$

$$V = 74.55\,\frac{q_h' T}{p' d^2} = 25\,970\,\frac{q_h' S_g}{\rho d^2}$$

- **Reynolds number of flow in pipe:** Equation 3-3

$$R_e = \frac{Dv\rho}{\mu'} = \frac{dv\rho}{1000\mu'} = \frac{dv\rho}{\mu}$$

$$R_e = 1\,273\,000\,\frac{q\rho}{d\mu} = 318.3\,\frac{q\rho}{R_H\mu} = 21.22\,\frac{Q\rho}{d\mu}$$

$$R_e = 354\,\frac{W}{d\mu} = 432\,\frac{q_h' S_g}{d\mu} = 56.23\,\frac{B\rho}{d\mu}$$

$$R_e = \frac{Dv}{\nu'} = \frac{dv}{1000\nu'} = 1000\,\frac{dv}{\nu}$$

$$R_e = 1273 \times 10^6\,\frac{q}{d\nu} = 21\,220\,\frac{Q}{d\nu} = 354\,000\,\frac{W\bar{V}}{d\nu}$$

- **Viscosity equivalents:** Equation 3-4

$$\nu = \frac{\mu}{\rho'} = \frac{\mu}{S}$$

- **Head loss and pressure drop in straight pipe:**

Pressure loss due to flow is the same in a sloping, vertical, or horizontal pipe. However, the difference in pressure due to the difference in head must be considered in pressure drop calculations: see page 1-5.

Darcy's formula: Equation 3-5

$$h_L = f\frac{L}{D}\frac{v^2}{2g_n} = 51\,\frac{fLv^2}{d}$$

$$h_L = 8265 \times 10^{10}\,\frac{fLq^2}{d^5} = 22\,950\,\frac{fLQ^2}{d^5}$$

$$h_L = 161\,200\,\frac{fLB^2}{d^5} = 6\,376\,000\,\frac{fLW^2\bar{V}^2}{d^5}$$

$$\Delta p = 0.005\,\frac{fL\rho v^2}{d} = 0.000\,001\,39\,\frac{fL\rho V^2}{d}$$

$$\Delta p = 81\,055 \times 10^5\,\frac{fL\rho q^2}{d^5} = 2.252\,\frac{fL\rho Q^2}{d^5}$$

$$\Delta p = 15.81\,\frac{fL\rho B^2}{d^5} = 625.3\,\frac{fLW^2\bar{V}}{d^5}$$

$$\Delta p = 2.69\,\frac{fLT(q_h')^2 S_g}{d^5 p'}$$

$$\Delta p = 936.5\,\frac{fL(q_h')^2 S_g^2}{d^5 \rho}$$

- **Head loss and pressure drop with laminar flow in straight pipe:**

For laminar flow conditions ($R_e < 2000$), the friction factor is a direct mathematical function of the Reynolds number only, and can be expressed by the formula: $f = 64/R_e$. Substituting this value of f in the Darcy formula, it can be rewritten:

Equation 3-6

$$h_L = 3263\,\frac{\mu L v}{d^2 \rho}$$

$$h_L = 41\,550 \times 10^5\,\frac{\mu L q}{d^4 \rho} = 69\,220\,\frac{\mu L Q}{d^4 \rho}$$

$$h_L = 183\,500\,\frac{\mu L B}{d^4 \rho} = 1\,154\,000\,\frac{\mu L W}{d^4 \rho^2}$$

$$\Delta p = 0.32\,\frac{\mu L v}{d^2} = 407\,400\,\frac{\mu L q}{d^4}$$

$$\Delta p = 6.79\,\frac{\mu L Q}{d^4} = 18\,\frac{\mu L B}{d^4}$$

$$\Delta p = 113.2\,\frac{\mu L W}{d^4 \rho}$$

Summary of Formulas – continued

• Limitations of Darcy formula

Non-compressible flow; liquids:

The Darcy formula may be used without restriction for the flow of water, oil, and other liquids in pipe. However, when extreme velocities occurring in pipe cause the downstream pressure to fall to the vapour pressure of the liquid, cavitation occurs and calculated flow rates are inaccurate.

Compressible flow; gases and vapours:

When pressure drop is less than 10% of p_1, use ρ or $\bar{V}$ based on either inlet or outlet conditions.

When pressure drop is greater than 10% of p_1 but less than 40% of p_1, use the average of ρ or $\bar{V}$ based on inlet and outlet conditions, or use Equation 3-20.

When pressure drop is greater than 40% of p_1, use the rational or empirical formulas given on this page for compressible flow, or use Equation 3-20 (for theory, see page 1-9).

• Isothermal flow of gas in pipe lines

Equation 3-7

$$w = 316.23 \sqrt{\frac{A^2}{\bar{V}_1\left(f\frac{L}{D} + 2\log_e \frac{p_1'}{p_2'}\right)}\left(\frac{(p_1')^2 - (p_2')^2}{p_1'}\right)}$$

$$w = 0.000\,2484 \sqrt{\frac{d^4}{\bar{V}_1\left(f\frac{L}{D} + 2\log_e \frac{p_1'}{p_2'}\right)}\left(\frac{(p_1')^2 - (p_2')^2}{p_1'}\right)}$$

• Simplified compressible flow for long pipe lines

Equation 3-7a

$$w = 316.23 \sqrt{\left(\frac{A^2}{\bar{V}_1\, f\frac{L}{D}}\right)\left[\frac{(p_1')^2 - (p_2')^2}{p_1'}\right]}$$

$$w = 0.000\,007\,855 \sqrt{\left(\frac{d^5}{\bar{V}_1\, f\, L}\right)\left[\frac{(p_1')^2 - (p_2')^2}{p_1'}\right]}$$

$$q'_h = 0.013\,61 \sqrt{\left(\frac{(p_1')^2 - (p_2')^2}{f\, L_m\, T\, S_g}\right) d^5}$$

• Maximum (sonic) velocity of compressible fluids in pipe

The maximum possible velocity of a compressible fluid in a pipe is equivalent to the speed of sound in the fluid; this is expressed as:

Equation 3-8

$$v_s = \sqrt{\gamma R T}$$

$$v_s = \sqrt{\gamma P' \bar{V}} = 316.2\sqrt{\gamma p' \bar{V}}$$

• Empirical formulas for the flow of water, steam, and gas

Although the rational method (using Darcy's formula) for solving flow problems has been recommended in this paper, some engineers prefer to use empirical formulas.

Hazen and Williams formula for flow of water: Equation 3-9

$$Q = 0.000\,599\, d^{2.63}\, c \left(\frac{p_1 - p_2}{L}\right)^{0.54}$$

where:
c = 140 for new steel pipe
c = 130 for new cast iron pipe
c = 110 for riveted pipe

Equation 3-10 (deleted)

Spitzglass formula for low pressure gas: (pressure less than 7000 N/m² (7 kPa)) Equation 3-11

$$q'_h = 0.003\,38 \sqrt{\frac{\Delta h_w\, d^5}{S_g L\left(1 + \frac{91.5}{d} + 0.001\,18\, d\right)}}$$

Flowing temperature is 15°C

Weymouth formula for high pressure gas: Equation 3-12

$$q'_h = 0.002\,61\, d^{2.667} \sqrt{\left(\frac{(p_1')^2 - (p_2')^2}{S_g L_m}\right)\left(\frac{288}{T}\right)}$$

Panhandle formula[3] for natural gas pipe lines 150 to 600 mm diameter and R_e = (5 x 10⁶) to (14 x 10⁶): Equation 3-13

$$q'_h = 0.005\,06\, E\, d^{2.6182}\left(\frac{(p_1')^2 - (p_2')^2}{L_m}\right)^{0.5394}$$

where: gas temperature = 15°C
S_g = 0.6
E = flow efficiency
E = 1.00 (100%) for brand new pipe without any bends, elbows, valves, and change of pipe diameter or elevation
E = 0.95 for very good operating conditions
E = 0.92 for average operating conditions
E = 0.85 for unusually unfavourable operating conditions

Summary of Formulas – continued

- **Head loss and pressure drop through valves and fittings**

Head loss through valves and fittings is generally given in terms of resistance coefficient K which indicates static head loss through a valve in terms of "velocity head", or, equivalent length in pipe diameters L/D that will cause the same head loss as the valve.

From Darcy's formula, head loss through a pipe is:

$$h_L = f \frac{L}{D} \frac{v^2}{2g_n} \qquad \text{Equation 3-5}$$

and head loss through a valve is:

$$h_L = K \frac{v^2}{2g_n} \qquad \text{Equation 3-14}$$

therefore: $K = f \frac{L}{D}$ **Equation 3-15**

To eliminate needless duplication of formulas, the following are all given in terms of K. Whenever necessary, substitute $(f\,L/D)$ for (K).

$$h_L = 8265 \times 10^7 \frac{Kq^2}{d^4} = 22.96 \frac{KQ^2}{d^4} \qquad \text{Equation 3-14}$$

$$h_L = 161.2 \frac{KB^2}{d^4} = 6377 \frac{KW^2 \bar{V}^2}{d^4}$$

$$\Delta p = 0.000\,005\, K\rho v^2 = 0.000\,1389 \times 10^{-5}\, K\rho V^2$$

$$\Delta p = 8105\,500 \frac{K\rho q^2}{d^4} = 0.002\,25 \frac{K\rho Q^2}{d^4}$$

$$\Delta p = 0.0158 \frac{K\rho B^2}{d^4}$$

$$\Delta p = 0.6253 \frac{KW^2 \bar{V}}{d^4}$$

$$\Delta p = 0.002\,69 \frac{K (q'_h)^2\, T S_g}{d^4\, p'}$$

$$\Delta p = 0.9365 \frac{K\, (q'_h)^2\, S_g{}^2}{d^4\, \rho}$$

For compressible flow with h_L or Δp greater than approximately 10% of inlet absolute pressure, the denominator should be multiplied by Y^2. For values of Y, see page A–22.

- **Flow coefficient**

As explained on page 2-10 there is not yet an agreed definition for a flow coefficient in terms of SI units. The equations given below relate to C_v as expressed in Imperial units with flow rate in UK or US gallons per minute.

Flow rate Q in UK gal/min: **Equation 3-16**

$$C_v = Q \sqrt{\frac{\rho}{\Delta P\,(62.4)}} = \frac{24.9\, d^2}{\sqrt{f\,L/D}} = \frac{24.9\, d^2}{\sqrt{K}}$$

Flow rate Q in US gal/min:

$$C_v = Q \sqrt{\frac{\rho}{\Delta P\,(62.4)}} = \frac{29.9\, d^2}{\sqrt{f\,L/D}} = \frac{29.9\, d^2}{\sqrt{K}}$$

where ρ = density of liquid in lb/ft³
ΔP = pressure drop, in lbf/in²
d = internal diameter, in inches
L/D = equivalent length of valve in pipe diameters
f = friction factor
K = resistance coefficient

- **Resistance coefficient, K, for sudden and gradual enlargements in pipes**

For $\theta \leqq 45°$,

$$K_1 = 2.6 \sin\frac{\theta}{2}(1 - \beta^2)^2 \qquad \text{*Equation 3-17}$$

For $45° < \theta \leqq 180°$,

$$K_1 = (1 - \beta^2)^2 \qquad \text{*Equation 3-17.1}$$

- **Resistance coefficient, K, for sudden and gradual contractions in pipes**

For $\theta \leqq 45°$,

$$K_1 = 0.8 \sin\frac{\theta}{2}(1 - \beta^2) \qquad \text{*Equation 3-18}$$

For $45° < \theta \leqq 180°$,

$$K_1 = 0.5 \sqrt{\sin\frac{\theta}{2}(1 - \beta^2)} \qquad \text{*Equation 3-18.1}$$

***Note:** The values of the resistance coefficients (K) in equations 3-17, 3-17.1, 3-18, and 3-18.1 are based on the velocity in the small pipe. To determine K values in terms of the greater diameter, divide the equations by β^4.

- **Discharge of fluid through valves, fittings, and pipe; Darcy's formula**

Liquid flow: **Equation 3-19**

$$q = 0.000\,003\,478\, d^2 \sqrt{\frac{h_L}{K}} = 0.000\,3512\, d^2 \sqrt{\frac{\Delta p}{K\rho}}$$

$$Q = 0.2087\, d^2 \sqrt{\frac{h_L}{K}} = 21.07\, d^2 \sqrt{\frac{\Delta p}{K\rho}}$$

$$w = 0.000\,003\,478\, \rho d^2 \sqrt{\frac{h_L}{K}} = 0.000\,3512\, d^2 \sqrt{\frac{\Delta p\rho}{K}}$$

$$W = 0.012\,52\, \rho d^2 \sqrt{\frac{h_L}{K}} = 1.265\, d^2 \sqrt{\frac{\Delta p\rho}{K}}$$

Compressible flow:

$$q'_h = 19.31\, Yd^2 \sqrt{\frac{\Delta p p'_1}{K T_1 S_g}} \qquad \text{Equation 3-20}$$

$$q'_h = 1.0312 \frac{Yd^2}{S_g} \sqrt{\frac{\Delta p \rho_1}{K}}$$

$$q'_m = 0.3217\, Yd^2 \sqrt{\frac{\Delta p p'_1}{K T_1 S_g}} = 0.01719 \frac{Yd^2}{S_g} \sqrt{\frac{\Delta p \rho_1}{K}}$$

$$q' = 0.005\,363\, Yd^2 \sqrt{\frac{\Delta p p'_1}{K T_1 S_g}} = 0.000\,2864 \frac{Yd^2}{S_g} \sqrt{\frac{\Delta p \rho_1}{K}}$$

$$w = 0.000\,3512\, Yd^2 \sqrt{\frac{\Delta p}{K \bar{V}_1}} \qquad W = 1.265\, Yd^2 \sqrt{\frac{\Delta p}{K \bar{V}_1}}$$

Values of Y are shown on page A–22. For K, Y, and Δp determination, see examples on pages 4-13 and 4-14.

Summary of Formulas – concluded

- **Flow through nozzles and orifices**
  (h_L and Δp measured across taps at 1 diameter and 0.5 diameter)

Liquid: Equation 3-21

$$q = Av = AC\sqrt{2g_n h_L} = AC\sqrt{\frac{2\,\Delta p}{\rho}}$$

$$q = 0.000\,003\,48\, d_1^2 C\sqrt{h_L} = 0.000\,3512\, d_1^2\, C\sqrt{\frac{\Delta p}{\rho}}$$

$$Q = 0.2087\, d_1^2\, C\sqrt{h_L} = 21.07\, d_1^2\, C\sqrt{\frac{\Delta p}{\rho}}$$

$$w = 0.000\,003\,48\, d_1^2\, C\sqrt{h_L \rho^2} = 0.000\,3512\, d_1^2\, C\sqrt{\Delta p \rho}$$

$$W = 0.012\,52\, d_1^2\, C\sqrt{h_L \rho^2} = 1.265\, d_1^2\, C\sqrt{\Delta p \rho}$$

Values of C are shown on page A-20
d_1 = nozzle or orifice diameter

Compressible fluids: Equation 3-22

$$q'_h = 19.31\, Y d_1^2\, C\sqrt{\frac{\Delta p p'_1}{T_1 S_g}}$$

$$q'_h = 1.0312\,\frac{Y d_1^2\, C}{S_g}\sqrt{\Delta p \rho_1}$$

$$q'_m = 0.3217\, Y d_1^2\, C\sqrt{\frac{\Delta p p'_1}{T_1 S_g}}$$

$$q'_m = 0.01719\,\frac{Y d_1^2\, C}{S_g}\sqrt{\Delta p \rho_1}$$

$$q = 0.005\,363\, Y d_1^2\, C\sqrt{\frac{\Delta p p'_1}{T_1 S_g}}$$

$$q' = 0.000\,2864\,\frac{Y d_1^2\, C}{S_g}\sqrt{\Delta p \rho_1}$$

$$w = 0.000\,3512\, Y d_1^2\, C\sqrt{\frac{\Delta p}{\bar{V}_1}}$$

$$W = 1.265\, Y d_1^2\, C\sqrt{\frac{\Delta p}{\bar{V}_1}}$$

Values of C are shown on page A-20
Values of Y are shown on page A-21
d_1 = nozzle or orifice diameter

- **Equivalents of head loss and pressure drop** Equation 3-23

$$h_L = \frac{10200\,\Delta p}{\rho} \qquad \Delta p = \frac{h_L \rho}{10200}$$

- **Changes in resistance coefficient K required to compensate for different pipe inside diameter**

Equation 3-24 (see page A-30)

$$K_a = K_b \left(\frac{d_a}{d_b}\right)^4$$

Subscript a refers to pipe in which valve will be installed.
Subscript b refers to pipe for which the resistance coefficient K was established.

- **Specific gravity of liquids**

Any liquid: Equation 3-25

$$S = \frac{\rho \;(\text{any liquid at 60 F (15.6 C) unless otherwise specified})}{\rho \;(\text{water at 60 F (15.6 C)})}$$

Oils: Equation 3-26

$$S\,(60\,\text{F}/60\,\text{F}) = \frac{141.5}{131.5 + \text{Deg API}}$$

Liquids lighter than water: Equation 3-27

$$S\,(60\,\text{F}/60\,\text{F}) = \frac{140}{130 + \text{Deg Baumé}}$$

Liquids heavier than water: Equation 3-28

$$S\,(60\,\text{F}/60\,\text{F}) = \frac{145}{145 - \text{Deg Baumé}}$$

- **Specific gravity of gases** Equation 3-29

$$S_g = \frac{R\,(\text{air})}{R\,(\text{gas})} = \frac{287}{R\,(\text{gas})}$$

$$S_g = \frac{M\,(\text{gas})}{M\,(\text{air})} = \frac{M\,(\text{gas})}{29}$$

- **General gas laws for perfect gases**

$$P'V_a = w_a RT \qquad \text{Equation 3-30}$$

$$\rho = \frac{w_a}{V_a} = \frac{P'}{RT} = \frac{10^5 p'}{RT} \qquad \text{Equation 3-31}$$

$$R = \frac{8314}{M} = \frac{P'}{\rho T} \qquad \text{Equation 3-32}$$

$$P'V_a = n_a MRT = n_a\, 8314T = \frac{w_a}{M}\, 8314T \qquad \text{Equation 3-33}$$

Equation 3-34

$$\rho = \frac{w_a}{V_a} = \frac{P'M}{8314T} = \frac{P'S_g}{287T} = \frac{348.4\, p'S_g}{T}$$

where:
$n_a = w_a/M$ = number of mols of a gas

- **Hydraulic radius*** Equation 3-35

$$R_H = \frac{\text{cross sectional flow area (square metres)}}{\text{wetted perimeter (metres)}}$$

Equivalent diameter relationship:
$D = 4R_H$
$d = 4000R_H$

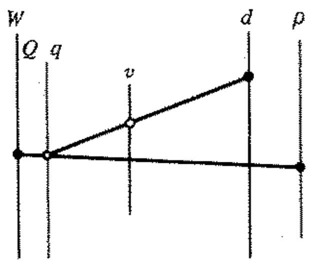
* See page 1-4 for limitations

Velocity of Liquids in Pipe

The mean velocity of any flowing liquid can be calculated from the following formula, or, from the nomograph on the opposite page. The nomograph is a graphical solution of the formula.

$$v = 1273.2 \times 10^3 \frac{q}{d^2} = 21.22 \frac{Q}{d^2} = 353.7 \frac{W}{d^2 \rho}$$

The pressure drop per 100 metres and the velocity in Schedule 40 pipe, for water at 15°C, have been calculated for commonly used flow rates for pipe sizes of 1/8 to 24 inch; these values are tabulated on page B-13.



Example 1

Given: No 3 Fuel Oil at 15°C flows through a 2 inch Schedule 40 pipe at the rate of 20,000 kilograms per hour.

Find: The rate of flow in litres per minute and the mean velocity in the pipe.

Solution:

1. $\rho = 897$ . . . . .page A-7

	Connect		Read
2.	$W = 20{,}000$	$\rho = 897$	$Q = 375$
3.	$Q = 375$	2″ Sched 40	$v = 2.9$

Example 2

Given: Maximum flow rate of a liquid will be 1400 litres per minute with maximum velocity limited to 3 metres per second.

Find: The smallest suitable size of steel pipe to ISO 336.

Solution:

	Connect		Read
1.	$Q = 1400$	$v = 3$	$d = 100$

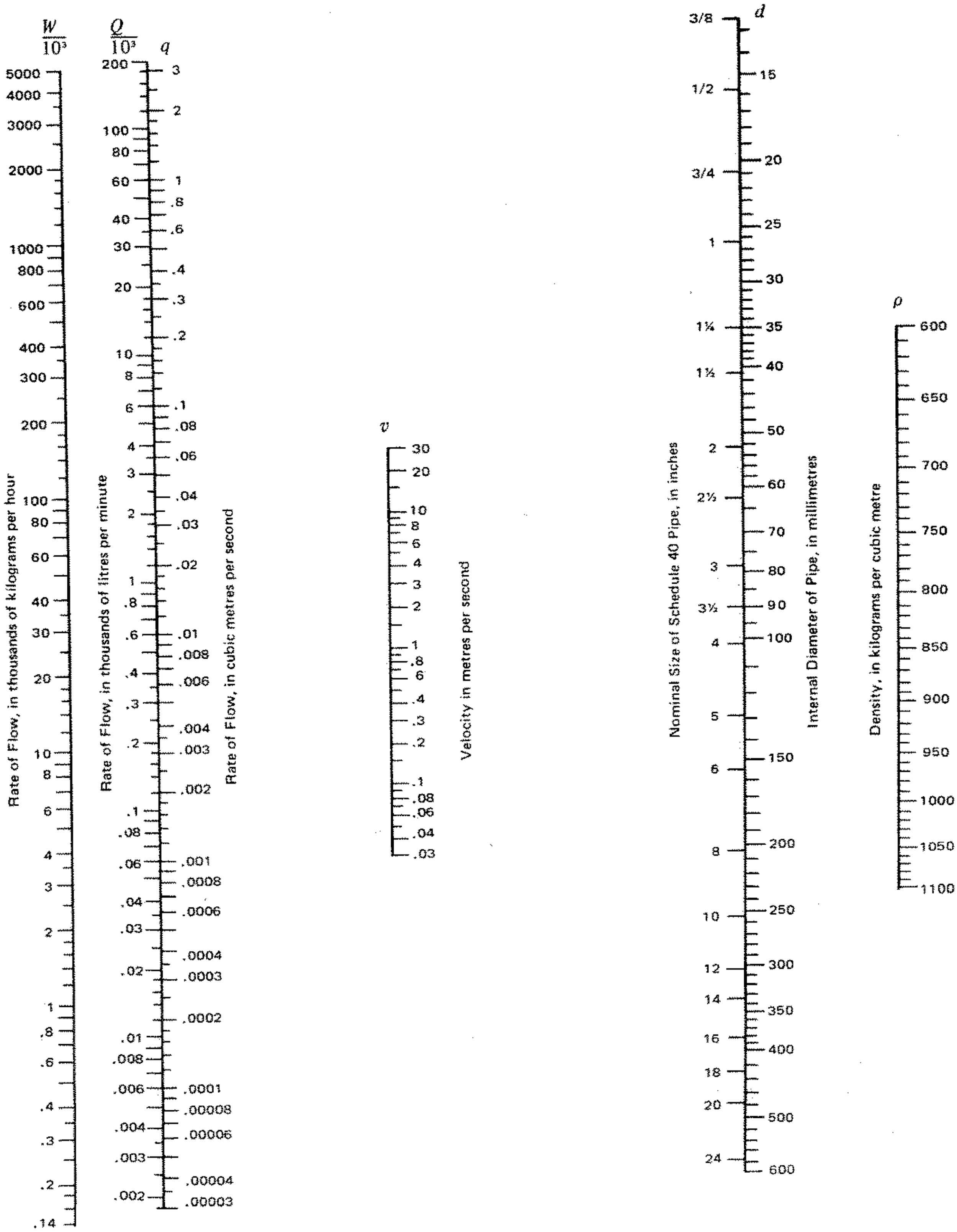
2. From the table on page B-19 the smallest suitable size of steel pipe to ISO 336 is seen to be nominal size 4″, inside diameter 100.1 mm.

Reasonable Velocities
for the Flow of water through Pipe

Service Condition	Reasonable Velocity
Boiler Feed.	2.4 to 4.6 metres per second
Pump Suction and Drain Lines.	1.2 to 2.1 metres per second
General Service	1.2 to 3.0 metres per second
City	to 2.1 metres per second

Velocity of Liquids in Pipe

(continued)



Reynolds Number for Liquid Flow

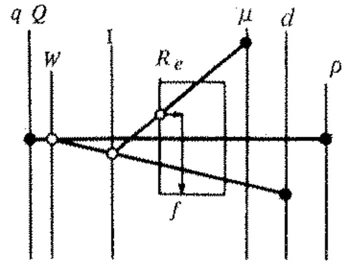
Friction Factor for Clean Steel Pipe

Reynolds number may be calculated from the formula below, or, from the nomograph on the opposite page. The nomograph is a graphical solution of the formula.

$$R_e = 1273 \times 10^3 \frac{q\rho}{d\mu} = 21.22 \frac{Q\rho}{d\mu} = 354 \frac{W}{d\mu}$$

(For values of d see pages B-16 to B-21)

The friction factor for clean steel pipe can be obtained from the chart in the centre of the nomograph.
Friction factors for other types of pipe can be determined by using the Reynolds number obtained from the nomograph or by calculation and referring to pages A-23 and A-24.



Example 1

Given: Water at 90°C flows through a 4-inch Schedule 40 steel pipe at a rate of 1590 litres per minute.

Find: The flow rate in kilograms per hour, the Reynolds number and the friction factor.

Solution:

1. ρ = 965 . . . . page A-6
2. μ = 0.31 . . . . page A-3
3. d = 102.3 . . . . page B-16

	Connect		Read
4.	Q = 1590	ρ = 965	W = 92 000
5.	W = 92 000	4″ Sched 40	Index
6.	Index	μ = 0.31	R_e = 1 000 000
7.	R_e = 1 000 000	horizontally to d = 102	f = 0.017

Example 2

Given: Oil of density 897 kg/m³ and viscosity 9.4 centipoise flows through a 51 mm inside diameter steel pipe at a rate of 0.006 cubic metres per second.

Find: The flow rate in kilograms per hour, the Reynolds number and the friction factor.

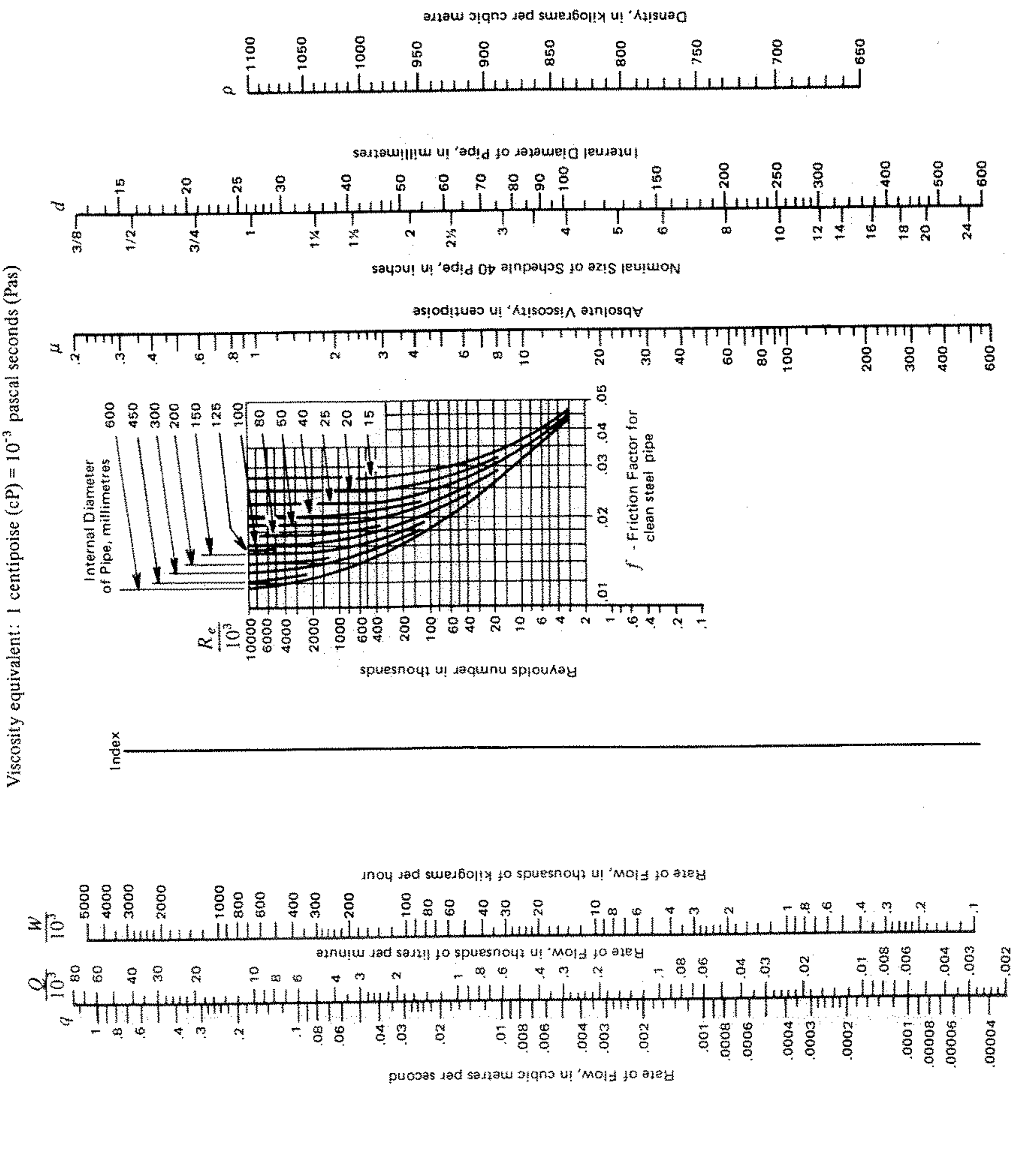
Solution:

	Connect		Read
1.	q = 0.006	ρ = 897	W = 19 000
2.	W = 19 000	d = 51	Index
3.	Index	μ = 9.4	R_e = 14 500
4.	R_e = 14 500	horizontally to d = 51	f = 0.03

Reynolds Number for Liquid Flow

Friction Factor for Clean Steel Pipe

(continued)



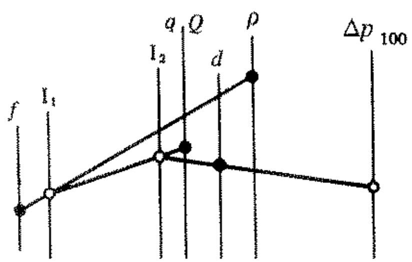
Pressure Drop in Liquid Lines for Turbulent Flow

The pressure drop of flowing liquids can be calculated from the Darcy formula that follows, or, from the nomograph on the opposite page. The nomograph is a graphical solution of the formula.

$$\Delta p_{100} = 0.5 \frac{f \rho v^2}{d} = 81\,055 \times 10^7 \frac{f \rho q^2}{d^5}$$

$$\Delta p_{100} = 225 \frac{f \rho Q^2}{d^5} = 62\,530 \frac{f W^2}{d^5 \rho}$$

(For values of d see pages B-16 to B-21)



When flow rate is given in kilograms per hour (W), use the following equations to convert to litres per minute (Q) or cubic metres per second (q), or use the nomograph on the preceding page.

$$Q = \frac{W}{0.06\rho} \quad ; \quad q = \frac{W}{3600\rho}$$

For Reynolds number less than 2000, flow is considered laminar and the nomograph on page 3-13 should be used.

The pressure drop per 100 metres and the velocity in Schedule 40 pipe, for water at 15°C, have been calculated for commonly used flow rates for pipe sizes of 1/8 to 24 inch; these values are tabulated on page B-13.

Example 1

Given: Water at 90°C flows through a 4-inch Schedule 40 new steel pipe at a rate of 92 000 kilograms per hour.

Find: The pressure drop per 100 metres of pipe.

Solution:

1. $\rho = 965$. . . . . page A-6
2. $\mu = 0.31$ . . . . page A-3
3. $f = 0.017$. . . . . Example 1, page 3-8
4. $Q = 1590$. . . . . Example 1, page 3-8

	Connect		Read
5.	$f = 0.017$	$\rho = 965$	Index 1
6.	Index 1	$Q = 1590$	Index 2
7.	Index 2	4″ Sched 40	$\Delta p_{100} = 0.85$

Example 2

Given: Oil of density 897 kg/m³ flows through a 51 mm inside diameter pipe at a velocity of 3 metres per second.

Find: The pressure drop per 100 metres of pipe.

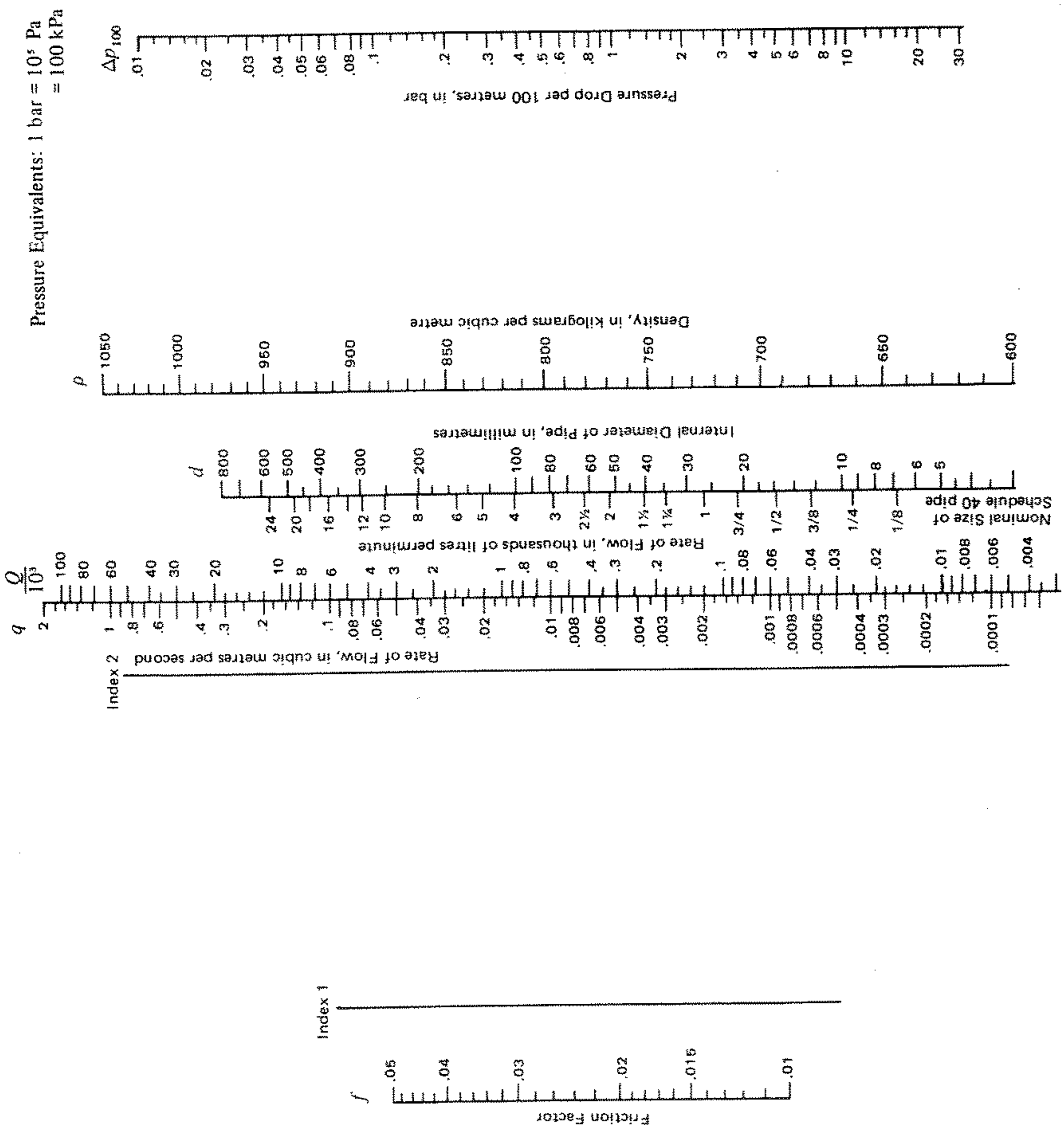
Solution:

1. $\rho = 897$
2. $q = .006$ . . . . nomograph, page 3-7
3. $f = 0.03$ . . . . Example 2, page 3-8

	Connect		Read
4.	$\rho = 897$	$f = 0.03$	Index 1
5.	Index 1	$q = 0.006$	Index 2
6.	Index 2	$d = 51$	$\Delta p_{100} = 2.4$

Pressure Drop in Liquid Lines for Turbulent Flow

(continued)



Pressure Drop in Liquid Lines for Laminar Flow

Pressure drop can be calculated from the formula below, or, from the nomograph on the opposite page, only when the flow is laminar. The nomograph is a graphical solution of the formula.

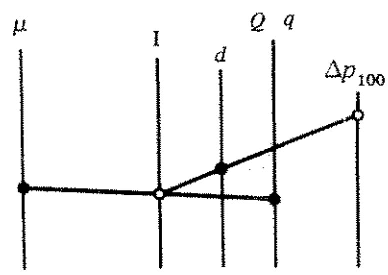
Flow is considered to be laminar at Reynolds number of 2000 or less; therefore, before using the formula or nomograph, determine the Reynolds number from the formula on page 3-2 or the nomograph on page 3-9.

$$\Delta p_{100} = 32\frac{\mu v}{d^2} = 4074 \times 10^4 \frac{\mu q}{d^4}$$

$$\Delta p_{100} = 679\frac{\mu Q}{d^4}$$

Where Δp_{100} is the pressure drop in bar for 100 metres of pipe.

(For values of d see pages B-16 to B-21)



Example 1

Given: A lubricating oil of density 897 kg/m³ and viscosity 450 centipoise flows through a 6 inch Schedule 40 steel pipe at a rate of 3000 litres per minute.

Find: The pressure drop per 100 metres of pipe.

Solution:

1. ρ = 897
2. μ = 450
3. R_e = 825. . . . . page 3-9
4. Since $R_e < 2000$, the flow is laminar and the nomograph on the opposite page may be used.

	Connect		Read
5.	μ = 450	Q = 3000	Index
6.	Index	6″ Sched 40	Δp_{100} = 1.63

Example 2

Given: Oil having a density of 875 kg/m³ and viscosity 95 centipoise flows through a steel pipe 79 mm inside diameter at a velocity of 2 metres per second.

Find: The flow rate in litres per minute and the pressure drop in 40 metres of pipe.

Solution:

1. ρ = 875
2. μ = 95
3. Q = 590. . . . . page 3-7
4. R_e = 1450. . . . . page 3-9
5. Since $R_e < 2000$, the flow is laminar and the nomograph on the opposite page may be used.

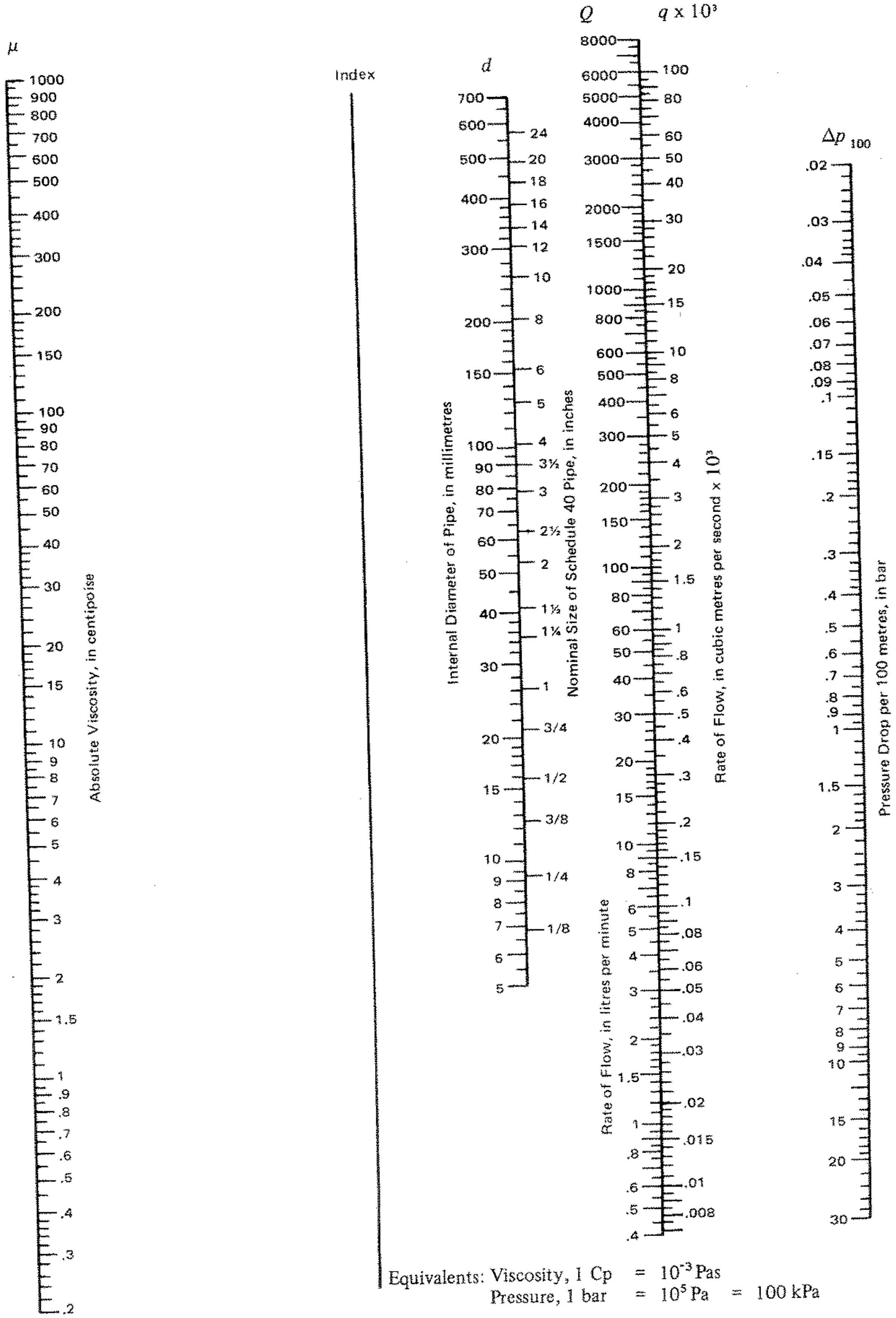
	Connect		Read
6.	μ = 95	Q = 590	Index
7.	Index	d = 79	Δp_{100} = 1

8. For 40 metres of pipe the pressure drop

$$\Delta p_{40} = \frac{40}{100} \times 1 = 0.4$$

Pressure Drop in Liquid Lines for Laminar Flow

(continued)



Equivalents: Viscosity, 1 Cp = 10^{-3} Pas
Pressure, 1 bar = 10^5 Pa = 100 kPa

Flow of Liquids Through Nozzles and Orifices

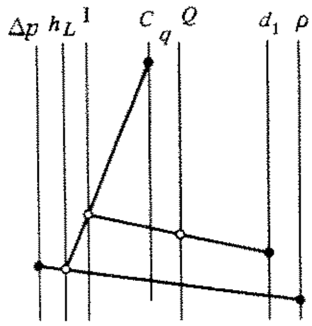
The flow of liquids through nozzles and orifices can be determined from the following formula, or, from the nomograph on the opposite page. The nomograph is a graphical solution of the formula.

$$q = 3.48 \times 10^{-6}\ d_1^2\ C\sqrt{h_L} = 3.51 \times 10^{-4}\ d_1^2\ C\sqrt{\frac{\Delta p}{\rho}}$$

$$Q = 0.209\ d_1^2\ C\sqrt{h_L} = 21.07\ d_1^2\ C\sqrt{\frac{\Delta p}{\rho}}$$

d_1 = nozzle or orifice diameter

Head loss or pressure drop is measured across taps located 1 diameter upstream and 0.5 diameter downstream.



Example 1

Given: A differential pressure of 0.2 bar is measured across taps of a 50 mm inside diameter nozzle assembled in 3-inch Schedule 80 steel pipe carrying water at 15°C.

Find: The flow rate in litres per minute

Solution:

1. d_2 (inlet diam) 73.7 . . . . 3″ Sched 80 pipe; page B-16
2. $\beta = \frac{d_1}{d_2} = (50 \div 73.7) = 0.68$
3. C = 1.12 . turbulent flow assumed; page A-20
4. ρ = 999 . . . . page A-6

	Connect		Read
5.	$\Delta p = 0.2$	$\rho = 999$	$h_L = 2.1$
6.	$h_L = 2.1$	$C = 1.12$	Index
7.	Index	$d_1 = 50$	$Q = 830$

8. Calculate R_e based on I.D. of pipe (73.66 mm)
9. μ = 1.1 . . . . page A-3
10. R_e = 220 000 . . . . page 3-9
11. C = 1.12 correct for R_e = 220 000; page A-20
12. When the C factor assumed in Step 3 is not in agreement with page A-20 for the Reynolds number based on the calculated flow the factor must be adjusted until reasonable agreement is reached by repeating Steps 3 to 11 inclusive.

Example 2

Given: The flow of water, at 15°C through a 6-inch pipe, 150.7 mm I.D., is to be restricted to 850 litres per minute by means of a square edged orifice, across which there will be a differential head of 1.2 metres of water.

Find: The size of the orifice opening.

Example 2 — cont.

Solution:

1. ρ = 999 . . . . page A-6
2. u = 1.1 . . . . page A-3
3. R_e = 110 000 . . . . page 3-9
4. Assume a β ratio of say 0.50
5. d_2 (inlet diam) = 150.7
6. $d_1 = 0.50\ d_2 = 0.50 \times 150.7 = 75.35$
7. C = 0.62 . . . . page A-20

	Connect		Read
8.	h_L = 1.2	C = 0.62	Index
9.	Index	Q = 850	d_1 = 77

10. An orifice diameter of 77 mm will be satisfactory, since this is reasonably close to the assumed value in Step 6.
11. If the value of d_1 determined from the nomograph is smaller than the assumed value used in Step 6 repeat Steps 6 to 10 inclusive, using reduced assumed values for d_1 until it is in reasonable agreement with the value determined in Step 9.

Example 3

Given: A differential pressure of 3.5 kilopascals is measured across taps of a 25 mm inside diameter square edged orifice assembled in 1-1/2-inch Schedule 80 steel pipe carrying lubricating oil of 897 kg/m³ density and 450 centipoise viscosity.

Find: The flow rate in cubic metres per second.

Solution:

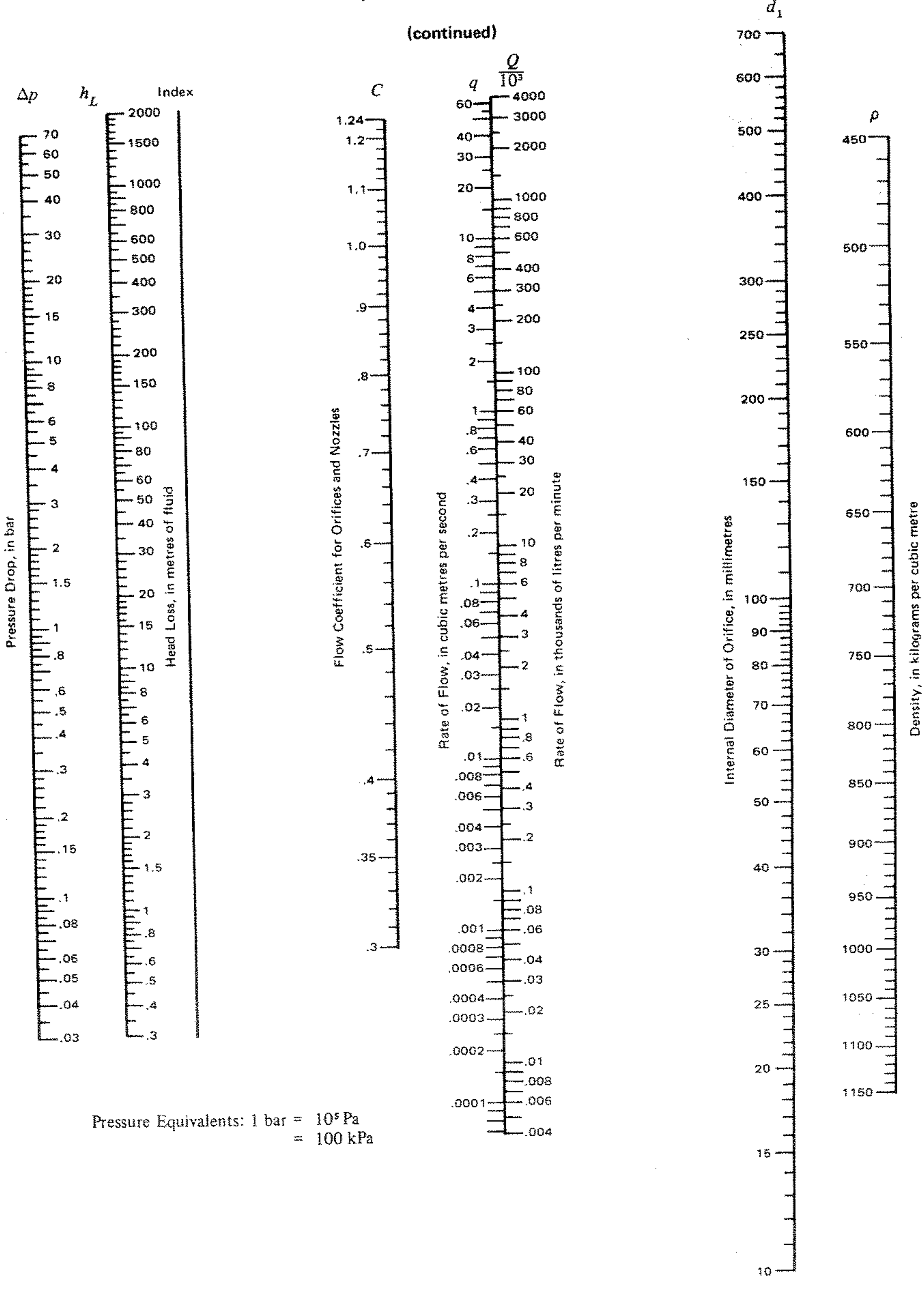
1. Δp = 3.5 kPa = 0.035 bar
2. ρ = 897
3. d_1 (inlet diam) = 38.1 . . . . page B-16
4. $\beta = (25 \div 38.1) = 0.656$
5. μ = 450 suspect flow is laminar since viscosity is high; . . . . page A-3
6. C = 0.85 . . . . assumed; page A-20

	Connect		Read
7.	Δp = 0.035	ρ = 897	h_L = 0.4
8.	h_L = 0.4	C = 0.85	Index
9.	Index	d_1 = 25	q = .0012

10. Calculate R_e based on I.D. of pipe (38.14 mm)
11. R_e = 80 . . . . page 3-8
12. C = 0.84 for R_e = 80 . . . . page A-20
    This is in reasonable agreement with the assumed value in Step 6.
13. When the C factor assumed in Step 6 is not in agreement with page A-20 for the Reynolds number based on the calculated flow it must be adjusted until reasonable agreement is reached by repeating Steps 6 to 12 inclusive.

Flow of Liquids Through Nozzles and Orifices

(continued)

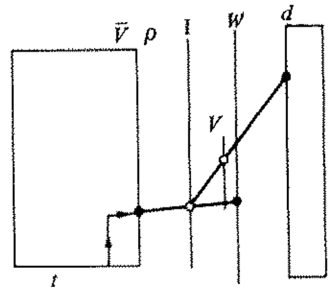


Pressure Equivalents: 1 bar = 10^5 Pa
= 100 kPa

Velocity of Compressible Fluids in Pipe

The mean velocity of compressible fluids in pipe can be computed by means of the following formula, or, by using the nomograph on the opposite page. The nomograph is a graphical solution of the formula.

$$V = \frac{21\,220\, W \bar{V}}{d^2} = \frac{21\,220\, W}{d^2 \rho}$$



Example 1

Given: Steam at 45 bar gauge and 450°C is to flow through a Schedule 80 pipe at a rate of 15 000 kilograms per hour with the velocity limited to 2 500 metres per minute.

Find: The suitable pipe size and the velocity through the pipe.

Solution:

	Connect		Read
1.	450°C	vertically to	45 bar g.
2.	45 bar g.	horizontally to	$\bar{V}$ = 0.069
3.	$\bar{V}$ = 0.069	W = 15 000	Index
4.	Index	V = 2500	d = 94
5.	4″ Schedule 80 is suitable		
6.	Index	4″ Sched 80 pipe	V = 2300

Example 2

Given: Air at 30 bar gauge and 15°C flows through a steel pipe 40.3 mm inside diameter at a rate of 4000 cubic metres per hour at metric standard conditions (1.013 25 bar and 15°C)

Find: The flow rate in kilograms per hour and the velocity in metres per minute.

Solution:

1. W = 4900, using S_g = 1.0. . . . . page B-2

2. ρ = 37.5 . . . . page A-10

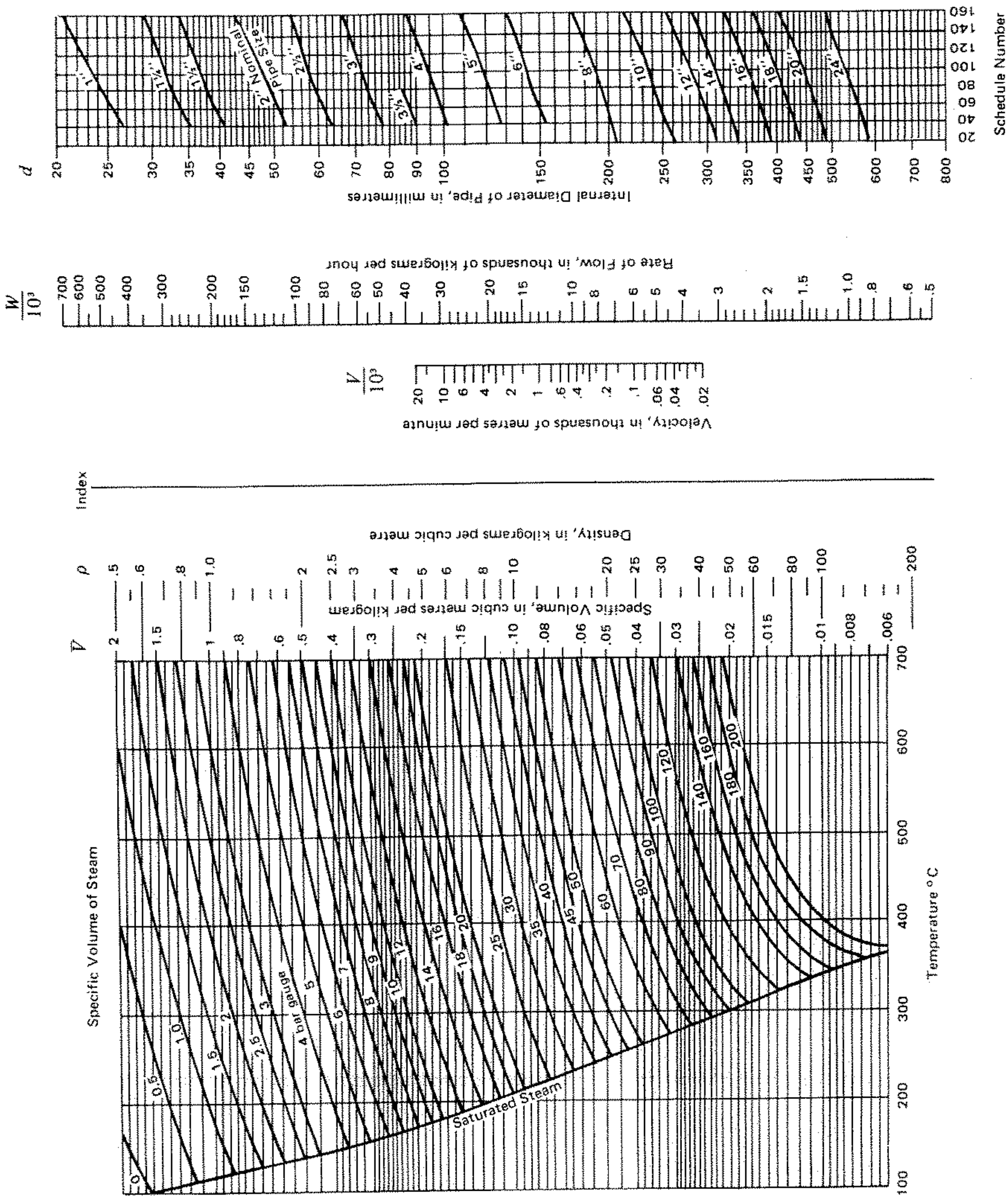
	Connect		Read
3.	ρ = 37.5	W = 4900	Index
4.	Index	d = 40.3	V = 1700

Reasonable Velocities for Flow of Steam through Pipe

Condition of Steam	Pressure (p) bar	Service	Reasonable Velocity (V) metres per minute
Saturated	0 to 1.7	Heating (short lines)	1200 to 1800
	1.7 and up	Power house equipment, process piping, etc.	1800 to 3000
Superheated	14 and up	Boiler and turbine leads, etc.	2000 to 6000

Velocity of Compressible Fluids in Pipe

(continued)



Reynolds Number for Compressible Flow

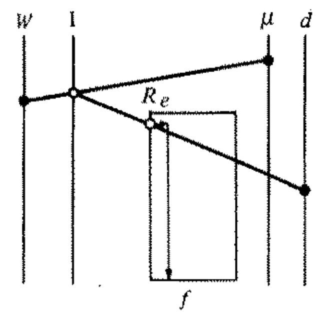
Friction Factor for Clean Steel Pipe

The Reynolds number may be determined from the formula below or from the nomograph on the opposite page. The nomograph is a graphical solution of the formula.

The friction factor for clean steel pipe can be obtained from the chart in the centre of the nomograph. Friction factor for other types of pipe can be determined by using the calculated Reynolds number and referring to pages A-23 and A-24

$$R_e = 354 \frac{W}{d\mu} = 432 \frac{q'_h S_g}{d\mu}$$

For values of d, see pages B-16 to B-21



Example 1

Given: Natural Gas at 17 bar gauge and 15°C with a specific gravity of 0.62, flows through a steel pipe 200 mm inside diameter at a rate of 34 000 standard cubic metres per hour.

Find: The flow rate in kilograms per hour, the Reynolds number and the friction factor.

Solution:

1. W = 26,000, using $S_g = 0.62$. . . . . page B-2
2. μ = 0.012 . . . . page A-5

	Connect		Read
3.	W = 26 000	μ = 0.012	Index
4.	Index	d = 200	R_e = 4 000 000
5.	R_e = 4 000 000	horizontally to 200 mm I.D.	f = 0.014

Note: Flowing pressure of gases has a negligible effect upon viscosity, Reynolds number, and friction factor.

Example 2

Given: Steam at 40 bar and 450°C flows through a 4-inch Schedule 80 pipe at a rate of 14 000 kilograms per hour.

Find: The Reynolds number and the friction factor.

Solution:

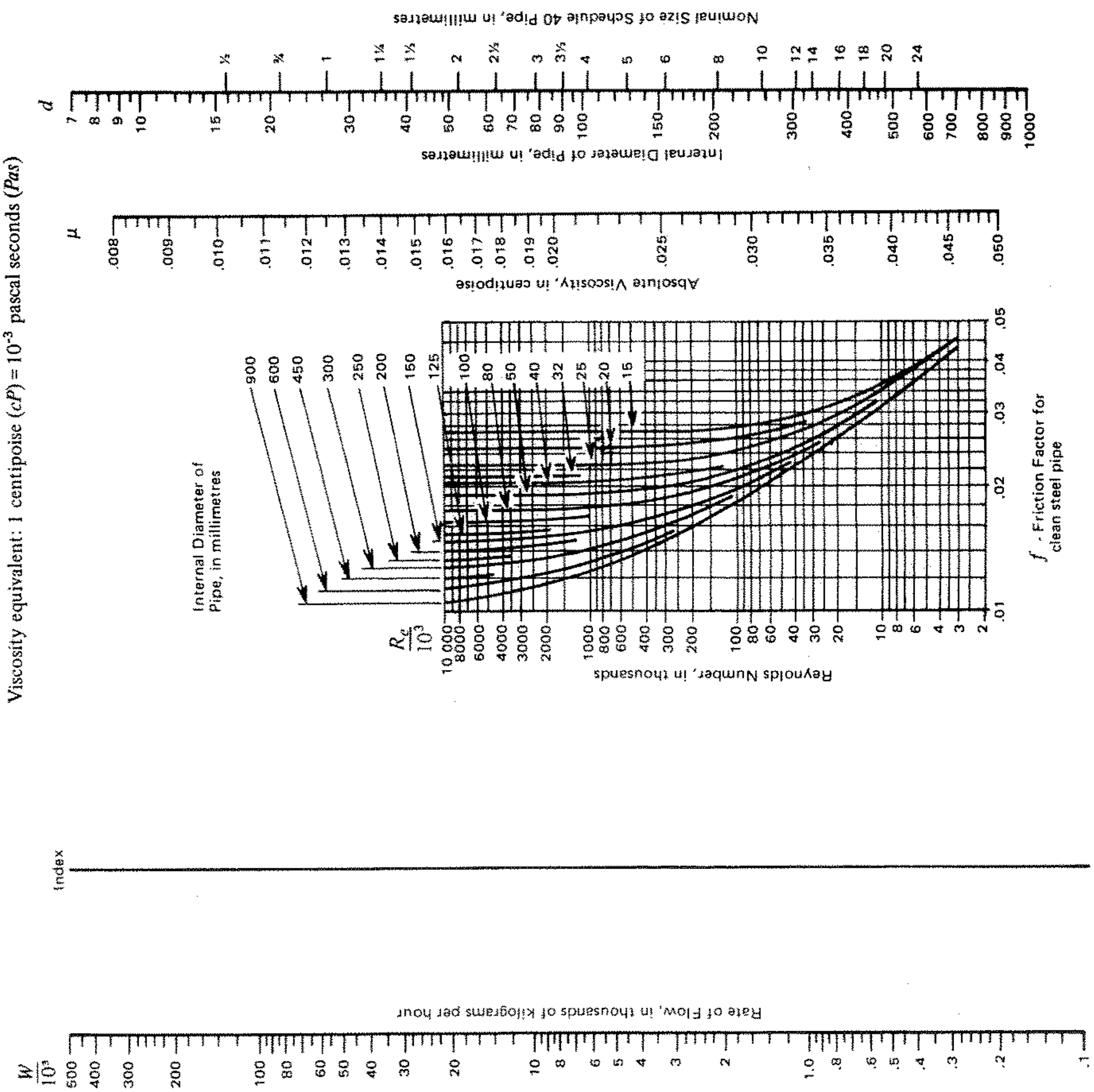
1. d = 97.2 . . . . page B-16
2. μ = 0.029 . . . . page A-2

	Connect		Read
3.	W = 14 000	μ = 0.029	Index
4.	Index	d = 97.2	R_e = 1 750 000
5.	R_e = 1 750 000	horizontally to 97 mm I.D.	f = 0.017

Reynolds Number for Compressible Flow

Friction Factor for Clean Steel Pipe

(continued)



Pressure Drop in Compressible Flow Lines

The pressure drop of flowing compressible fluids can be calculated from the Darcy formula below, or, from the nomograph on the opposite page. The nomograph is a graphical solution of the formula.

$$\Delta p_{100} = 62\,530 \frac{f W^2 \bar{V}}{d^5} = 62\,530 \frac{f W^2}{d^5 \rho}$$

$$\Delta p_{100} = 93\,650 \frac{f (q'_h)^2 S_g{}^2}{d^5 \rho}$$

(For values of d, see pages B-16 to B-21)

When the flow rate is given in cubic metres per hour at standard conditions (q'_h), use the following equation or the nomograph on page B-2 to convert to kilograms per hour (W).

$$W = 1.225\, q'_h\, S_g$$

Air: For pressure drop in bar per 100 metres of Schedule 40 pipe for air at 7 bar gauge and 15°C, see page B-14.

Example 1

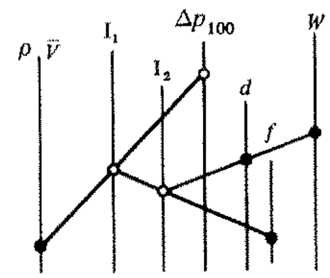
Given: Steam at 40 bar gauge and 450°C flows through a 4-inch Schedule 80 pipe at a rate of 14 000 kilograms per hour.

Find: The pressure drop per 100 metres of pipe.

Solution:

1. d = 97.2 . . . . page B-16
2. μ = 0.029 . . . . page A-2
3. f = 0.017 . . . . page 3-19
4. $\bar{V}$ = 0.078 . . . . page 3-17 or A-15

	Connect		Read
5.	W = 14 000	d = 97.2	Index 2
6.	Index 2	f = 0.017	Index 1
7.	Index 1	$\bar{V}$ = 0.078	Δp_{100} = 1.88



Example 2

Given: Natural Gas at 17 bar gauge and 15°C flows through a steel pipe 200 mm inside diameter at a rate of 34 000 standard cubic metres per hour; its specific gravity is 0.62.

Find: The flow rate in kilograms per hour and the pressure drop per 100 metres of pipe.

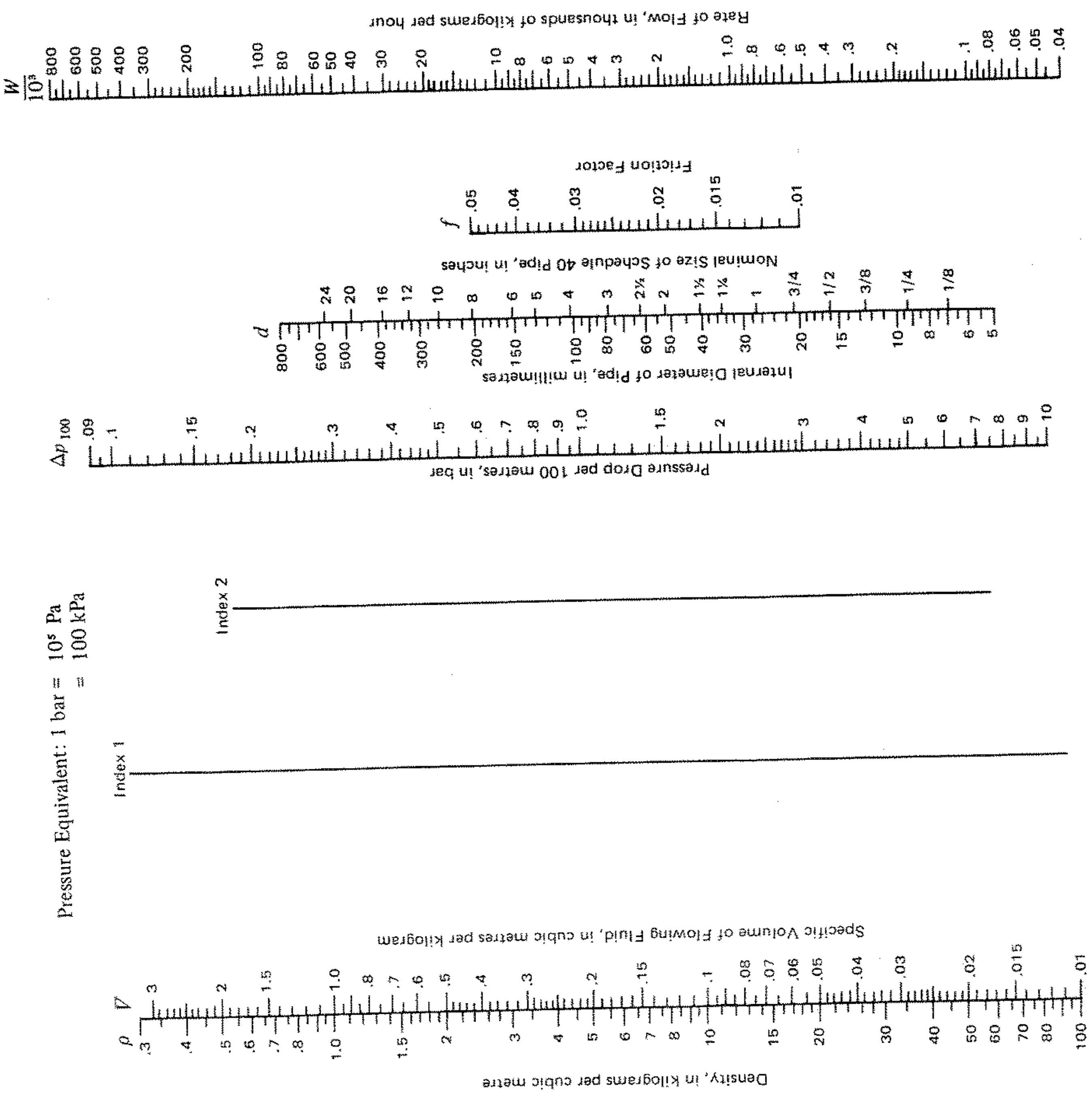
Solution:

1. W = 26 000. . . . . page B-2
2. μ = 0.12 . . . . page A-5
3. f = 0.014. . . . . page 3-19
4. ρ = 13.5 . . . . page A-10

	Connect		Read
5.	W = 26 000	d = 200	Index 2
6.	Index 2	f = 0.014	Index 1
7.	Index 1	ρ = 13.5	Δp_{100} = 0.135

Pressure Drop in Compressible Flow Lines

(continued)



Simplified Flow Formula for Compressible Fluids

Pressure Drop, Rate of Flow, and Pipe Size

The simplified flow formula for compressible fluids is accurate for fully turbulent flow; in addition, its use provides a good approximation in calculations involving compressible fluid flow through commercial steel pipe for most normal flow conditions.

If velocities are low, friction factors assumed in the simplified formula may be too low; in such cases, the formula and nomograph shown on pages 3-20 and 3-21 may be used to provide greater accuracy.

The Darcy formula can be written in the following form;

$$\Delta P_{100} = \frac{62\,530\,f\,W^2\,\bar{V}}{d^5} = \left(\frac{W^2}{10^8}\right)\left(\frac{62\,530 \times 10^8 f}{d^5}\right)\bar{V}$$

Let $C_1 = \frac{W^2}{10^8}$ and $C_2 = \frac{62\,530 \times 10^8\,f}{d^5}$

The simplified flow formula can then be written:

$$\Delta P_{100} = C_1\,C_2\,\bar{V} = \frac{C_1\,C_2}{\rho}$$

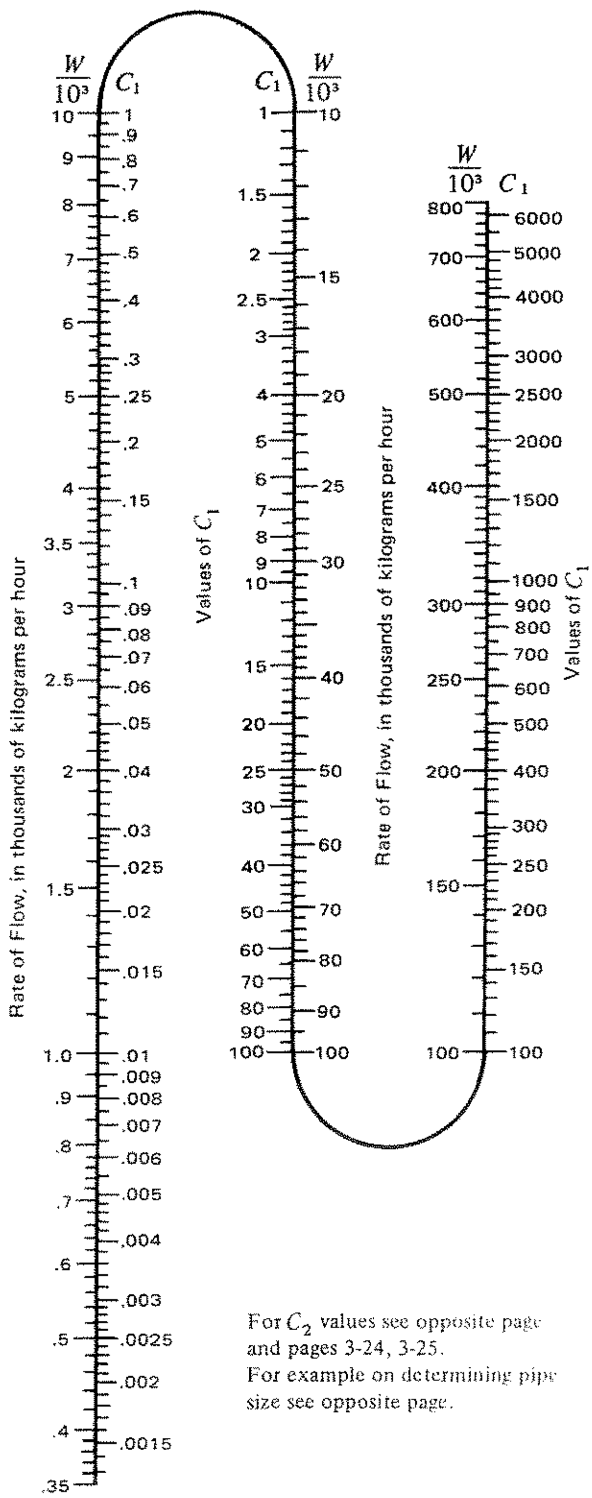
$$C_1 = \frac{\Delta P_{100}}{C_2\,\bar{V}} = \frac{\Delta P_{100}\,\rho}{C_2} \qquad C_2 = \frac{\Delta P_{100}}{C_1\,\bar{V}} = \frac{\Delta P_{100}\,\rho}{C_1}$$

C_1 = discharge factor, from chart at right

C_2 = size factor from tables on pages 3-23 to 3-25

The limitations of the Darcy formula for compressible flow, as outlined on page 3-3 apply also to the simplified flow formula.

Values of C_1 (metric)



For C_2 values see opposite page and pages 3-24, 3-25.
For example on determining pipe size see opposite page.

Example 1

Given: Steam at 24 bar absolute and 250°C flows through an 8-inch Schedule 40 pipe at a rate of 100 000 kilograms per hour.

Find: The pressure drop per 100 metres of pipe.

Solution:
C_1 = 100
C_2 = 0.257 . . . . facing page
$\bar{V}$ = 0.091 m³/kg. . . . . . . .page 3-17 or A-15
ΔP_{100} = 100 x 0.257 x 0.091 = 2.34 bar

Example 2

Given: Pressure drop is 1 bar with 7 bar gauge air at 30°C flowing through 100 metres of 4 inch nominal size ISO steel pipe, 6.3 mm wall thickness.

Find: The flow rate in cubic metres per minute at metric standard conditions (1.013 25 bar and 15°C).

Solution:
ΔP_{100} = 1
C_2 = 9.42 . . . . page 3-24
ρ = 9.21 . . . . page A-10
$C_1 = \frac{1 \times 9.21}{9.42} = 0.978$
W = 9 900
$q'_m = W \div (73.5\,S_g)$ . . . . page B-2
$q'_m = 9\,900 \div (73.5 \times 1) = 134.7$ m³/min

Simplified Flow Formula for Compressible Fluids (continued)

Values of C_2 (metric)

For steel pipes to ANSI B36.10: 1970 and BS1600: Part 2: 1970.

Nominal Pipe Size Inches	Schedule Number	Value of C_2
1/8	40 s	13 940 000
	80 x	46 100 000
¼	40 s	2 800 000
	80 x	7 550 000
3/8	40 s	561 000
	80 x	1 260 000
½	40 s	164 600
	80 x	327 500
	160	756 800
	... xx	19 680 000
¾	40 s	37 300
	80 x	65 000
	160	176 200
	... xx	1 104 000
1	40 s	10 470
	80 x	17 000
	160	39 600
	... xx	200 800
1¼	40 s	2 480
	80 x	3 720
	160	6 140
	... xx	24 000
1½	40 s	1 100
	80 x	1 590
	160	2 920
	... xx	8 150
2	40 s	297
	80 x	415
	160	859
	... xx	1 582
2½	40 s	117
	80 x	162
	160	257
	... xx	669
3	40 s	37.7
	80 x	50.5
	160	85.0
	... xx	170.0
3½	40 s	17.6
	80 x	23.2
4	40 s	9.10
	80 x	11.88
	120	15.73
	160	20.77
	... xx	32.72

Nominal Pipe Size Inches	Schedule Number	Value of C_2
5	40 s	2.798
	80 x	3.590
	120	4.734
	160	6.318
	... xx	8.677
6	40 s	1.074
	80 x	1.404
	120	1.786
	160	2.422
	... xx	3.275
8	20	0.234
	30	0.243
	40 s	0.257
	60	0.287
	80 x	0.326
	100	0.371
	120	0.444
	140	0.509
	... xx	0.558
	160	0.586
10	20	0.0699
	30	0.0741
	40 s	0.0787
	60 x	0.0905
	80	0.1001
	100	0.1148
	120	0.1325
	140	0.1593
	160	0.1852
12	20	0.0276
	30	0.0296
	... s	0.0308
	40	0.0317
	... x	0.0343
	60	0.0363
	80	0.0407
	100	0.0470
	120	0.0546
	140	0.0616
	160	0.0744
14	10	0.016 70
	20	0.017 53
	30 s	0.018 41
	40	0.019 34
	... x	0.020 33
	60	0.021 89
	80	0.024 92
	100	0.029 16
	120	0.033 40
	140	0.038 37
	160	0.044 35

Nominal Pipe Size Inches	Schedule Number	Value of C_2
16	10	0.008 15
	20	0.008 50
	30 s	0.008 87
	40 x	0.009 66
	60	0.010 77
	80	0.012 32
	100	0.014 15
	120	0.016 30
	140	0.019 34
	160	0.021 89
18	10	0.004 35
	20	0.004 51
	.. s	0.004 68
	30	0.004 86
	.. x	0.005 05
	40	0.005 24
	60	0.005 90
	80	0.006 64
	100	0.007 66
	120	0.008 87
	140	0.010 08
	160	0.011 77
20	10	0.002 48
	20 s	0.002 65
	30 x	0.002 83
	40	0.002 98
	60	0.003 36
	80	0.003 82
	100	0.004 42
	120	0.005 05
	140	0.005 89
	160	0.006 78
24	10	0.000 940
	20 s	0.000 994
	.. x	0.001 051
	30	0.001 081
	40	0.001 146
	60	0.001 304
	80	0.001 470
	100	0.001 711
	120	0.001 970
	140	0.002 242
	160	0.002 600

Note

The letters s, x, xx, in the columns of Schedule Numbers indicate Standard, Extra Strong, and Double Extra Strong pipe respectively.

Example 3

Given: A 6 bar gauge saturated steam line with 9000 kilograms per hour flow is permitted a maximum pressure drop of 2.4 bar per 100 metres of pipe.

Find: The smallest size of ISO 336 steel pipe suitable.

Solution: $\Delta p_{100} = 2.4$ $\bar{V} = 0.273$ ..... page 3-17 or A-12

$C_1 = 0.81$ $C_2 = \dfrac{2.4}{0.81 \times 0.273} = 10.85$

Reference to the table of C_2 values for ISO 336 pipes on page 3-24 shows that a 4 inch nominal size pipe with 7.1 mm wall thickness has the C_2 value nearest to, but less than, 10.85

The actual pressure drop per 100 metres of 4 inch, 7.1 mm wall thickness, pipe is;

$$\Delta p_{100} = C_1\, C_2\, \bar{V} = 0.81 \times 10.22 \times 0.273 = 2.26 \text{ bar}$$

Simplified Flow Formula for Compressible Fluids (continued)

Values of C_2 (metric)

For steel pipes to ISO 336 – 1974

Nominal Pipe Size Inches	Wall Thickness mm	Value of C_2
1/8	1.6	12 700 000
	1.8	17 500 000
	2.0	24 600 000
	2.3	42 800 000
¼	1.8	2 010 000
	2.0	2 530 000
	2.3	3 620 000
	2.6	5 290 000
	2.9	7 940 000
3/8	2.0	436 000
	2.3	562 000
	2.6	732 000
	2.9	967 000
	3.2	1 300 000
½	2.6	151 000
	2.9	186 000
	3.2	229 000
	3.6	309 000
	4.0	423 000
	4.5	591 000
	5.0	955 000
	5.4	1 380 000
¾	2.6	31 700
	2.9	36 800
	3.2	42 900
	3.6	53 100
	4.0	66 400
	4.5	83 800
	5.0	116 000
	5.4	148 000
	5.6	166 000
	5.9	208 000
	6.3	289 000
	7.1	539 000
1	3.2	9 390
	3.6	11 000
	4.0	13 000
	4.5	15 400
	5.0	19 400
	5.4	23 000
	5.6	25 000
	5.9	29 300
	6.3	36 700
	7.1	55 400
	8.0	86 400
	8.8	143 000
1¼	3.2	2 200
	3.6	2 480
	4.0	2 800
	4.5	3 170
	5.0	3 750
	5.4	4 250
	5.6	4 500
	5.9	5 040
	6.3	5 910
	7.1	7 850
	8.0	10 600
	8.8	14 800
	10.0	26 300

Nominal Pipe Size Inches	Wall Thickness mm	Value of C_2
1½	3.2	990
	3.6	1 100
	4.0	1 220
	4.5	1 350
	5.0	1 560
	5.4	1 730
	5.6	1 820
	5.9	2 000
	6.3	2 290
	7.1	2 900
	8.0	3 730
	8.8	4 880
	10.0	7 720
2	3.6	283
	4.0	307
	4.5	333
	5.0	371
	5.4	402
	5.6	418
	5.9	449
	6.3	496
	7.1	592
	8.0	711
	8.8	864
	10.0	1 190
	11.0	1 600
2½	5.0	88.6
	5.4	94.1
	5.6	96.8
	5.9	102.
	6.3	110.
	7.1	125.
	8.0	144.
	8.8	166.
	10.0	209.
	11.0	258.
	12.5	354.
	14.2	495.
3	5.4	37.1
	5.6	38.0
	5.9	39.8
	6.3	42.3
	7.1	47.1
	8.0	52.7
	8.8	59.2
	10.0	71.5
	11.0	84.9
	12.5	109.4
	14.2	143.1
	16.0	191.2
3½	5.6	17.2
	5.9	17.9
	6.3	18.9
	7.1	20.7
	8.0	22.8
	8.8	25.2
	10.0	29.6
	11.0	34.2
	12.5	42.3
	14.2	52.8
	16.0	66.9
	17.5	85.5

Nominal Pipe Size Inches	Wall Thickness mm	Value of C_2
4	5.6	8.71
	5.9	9.00
	6.3	9.42
	7.1	10.22
	8.0	11.10
	8.8	12.11
	10.0	13.91
	11.0	15.77
	12.5	18.88
	14.2	22.80
	16.0	27.86
	17.5	34.30
	20.0	48.61
5	5.9	2.83
	6.3	2.94
	7.1	3.14
	8.0	3.35
	8.8	3.59
	10.0	4.00
	11.0	4.41
	12.5	5.08
	14.2	5.87
	16.0	6.84
	17.5	8.01
	20.0	10.37
6	6.3	1.02
	7.1	1.08
	8.0	1.13
	8.8	1.20
	10.0	1.31
	11.0	1.42
	12.5	1.59
	14.2	1.79
	16.0	2.02
	17.5	2.28
	20.0	2.79
	22.2	3.35
8	6.3	0.234
	7.1	0.244
	8.0	0.254
	8.8	0.265
	10.0	0.283
	11.0	0.300
	12.5	0.326
	14.2	0.355
	16.0	0.388
	17.5	0.425
	20.0	0.490
	22.2	0.559
	25.0	0.677
10	6.3	0.069 9
	7.1	0.072 1
	8.0	0.074 4
	8.8	0.076 9
	10.0	0.081 0
	11.0	0.084 8
	12.5	0.090 5
	14.2	0.096 7
	16.0	0.103 6
	17.5	0.111 0
	20.0	0.124 1
	22.2	0.137 3
	25.0	0.159 1
	28.0	0.179 6
	30.0	0.198 3

Simplified Flow Formula for Compressible Fluids (continued)

Values of C_2 (metric)

For steel pipes to ISO 336 – 1974

Nominal Pipe Size Inches	Wall Thickness mm	Value of C_2
12	6.3	0.027 6
	7.1	0.028 4
	8.0	0.029 2
	8.8	0.030 0
	10.0	0.031 3
	11.0	0.032 5
	12.5	0.034 3
	14.2	0.036 3
	16.0	0.038 4
	17.5	0.040 7
	20.0	0.044 6
	22.2	0.048 4
	25.0	0.054 5
	28.0	0.060 1
	30.0	0.065 1
	32.0	0.070 5
	36.0	0.083 2
14	6.3	0.016 7
	7.1	0.017 1
	8.0	0.017 5
	8.8	0.018 0
	10.0	0.018 7
	11.0	0.019 3
	12.5	0.020 3
	14.2	0.021 4
	16.0	0.022 5
	17.5	0.023 7
	20.0	0.025 7
	22.2	0.027 7
	25.0	0.030 8
	28.0	0.033 6
	30.0	0.036 1
	32.0	0.038 8
	36.0	0.044 9

Nominal Pipe Size Inches	Wall Thickness mm	Value of C_2
16	6.3	0.008 14
	7.1	0.008 31
	8.0	0.008 49
	8.8	0.008 68
	10.0	0.008 98
	11.0	0.009 26
	12.5	0.009 66
	14.2	0.010 09
	16.0	0.010 55
	17.5	0.011 03
	20.0	0.011 83
	22.2	0.012 61
	25.0	0.013 83
	28.0	0.014 90
	30.0	0.015 83
	32.0	0.016 83
	36.0	0.019 06
	40.0	0.021 48
	45.0	0.025 30
18	6.3	0.004 34
	7.1	0.004 42
	8.0	0.004 51
	8.8	0.004 59
	10.0	0.004 74
	11.0	0.004 86
	12.5	0.005 05
	14.2	0.005 24
	16.0	0.005 45
	17.5	0.005 67
	20.0	0.006 03
	22.2	0.006 38
	25.0	0.006 91
	28.0	0.007 38
	30.0	0.007 78
	32.0	0.008 21
	36.0	0.009 14
	40.0	0.010 14
	45.0	0.011 67
	50.0	0.013 50

Nominal Pipe Size Inches	Wall Thickness mm	Value of C_2
20	6.3	0.002 48
	7.1	0.002 52
	8.0	0.002 56
	8.8	0.002 61
	10.0	0.002 68
	11.0	0.002 74
	12.5	0.002 83
	14.2	0.002 93
	16.0	0.003 03
	17.5	0.003 14
	20.0	0.003 32
	22.2	0.003 49
	25.0	0.003 75
	28.0	0.003 97
	30.0	0.004 16
	32.0	0.004 37
	36.0	0.004 80
	40.0	0.005 27
	45.0	0.005 97
	50.0	0.006 79
	55.0	0.007 74
24	6.3	0.000 939
	7.1	0.000 952
	8.0	0.000 966
	8.8	0.000 980
	10.0	0.001 002
	11.0	0.001 021
	12.5	0.001 051
	14.2	0.001 081
	16.0	0.001 112
	17.5	0.001 144
	20.0	0.001 198
	22.2	0.001 248
	25.0	0.001 324
	28.0	0.001 388
	30.0	0.001 442
	32.0	0.001 500
	36.0	0.001 621
	40.0	0.001 746
	45.0	0.001 930
	50.0	0.002 137
	55.0	0.002 372
	60.0	0.002 624

Notes.

(1) The values of C_2 for ISO steel pipes given above and on page 3–24 have been determined by interpolation based on the values of C_2 established for ANSI Schedule pipes shown on page 3 — 23.

(2) The sizes of ISO pipes included in the above table and the table on page 3–24 also cover most of the pipe sizes contained in BS 3600: 1973, within the same ranges of wall thicknesses.

Flow of Compressible Fluids Through Nozzles and Orifices

The flow of compressible fluids through nozzles and orifices can be determined from the following formula, or, by using the nomograph on the next page. The nomograph is a graphical solution of the formula.

$$w = 3.512 \times 10^{-4}\ Y d_1^2 C \sqrt{\Delta p \rho_1} = 3.512 \times 10^{-4}\ Y d_1^2\ C \sqrt{\frac{\Delta p}{\bar{V}_1}}$$

$$W = 1.265\ Y d_1^2 C \sqrt{\Delta p \rho_1} = 1.265\ Y d_1^2 C \sqrt{\frac{\Delta p}{\bar{V}_1}}$$

d_1 = nozzle or orifice diameter.

(Pressure drop is measured across taps located 1 diameter upstream and 0.5 diameter downstream from the inlet face of the nozzle or orifice).

Example 1

Given: A differential pressure of 0.8 bar is measured across taps located 1 diameter upstream and 0.5 diameter downstream from the inlet face of a 25 mm inside diameter nozzle assembled in a 2-inch Schedule 40 steel pipe, in which, dry carbon dioxide (CO_2) gas is flowing at 7 bar gauge pressure and 90°C.

Find: The flow rate in cubic metres per hour at metric standard conditions (MSC = 1.013 25 bar and 15°C).

Solution:

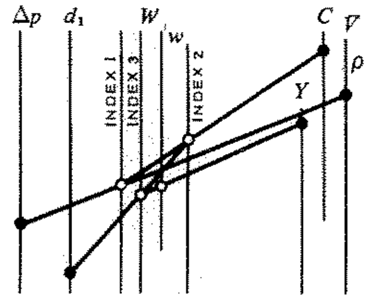
1. R = 189
2. S_g = 1.529 . . . . for CO_2 gas; page A-8
3. γ = 1.3

Steps 3 through 7 are used to determine the Y factor.

4. $p_1' = p + 1.013 = 7 + 1.013 = 8.013$
5. $\Delta p/p_1' = 0.8 \div 8.013 = 0.0998$
6. d_2 (inlet diam) = 52.5 . . 2″ Sched 40 pipe; page B-16
7. $\beta = d_1/d_2 = 25 \div 52.5 = 0.476$
8. Y = 0.93 . . . . page A-21
9. C = 1.02 . turbulent flow assumed; page A-20
10. $T = 273 + t = 273 + 90 = 363$
11. ρ_1 = 11.76 . . . . page A-10

	Connect		Read
12.	Δp = 0.8	ρ_1 = 11.76	Index 1
13.	Index 1	C = 1.02	Index 2
14.	Index 2	d_1 = 25	Index 3
15.	Index 3	Y = 0.93	W = 2300

16. q'_h = 1220 m³/h at MSC . . . . page B-2
17. μ = 0.018 . . . . page A-5
18. R_e = 860 000 or 8.6×10^5 . . . . page 3-2
19. C = 1.02 is correct for $R_e = 8.6 \times 10^5$ page A-20
20. When the C factor assumed in Step 9 is not in agreement with page A-20, for the Reynolds number based on the calculated flow, it must be adjusted until reasonable agreement is reached by repeating Steps 9 through 19.



Example 2

Given: A differential pressure of 0.2 bar is measured across taps located 1 diameter up-stream and 0.5 diameter downstream from the inlet face of an 18 mm inside diameter square edged orifice assembled in a 25.7 mm inside diameter steel pipe, in which, dry ammonia (NH_3) gas is flowing at 2.75 bar gauge pressure and 10°C.

Find: The flow rate in kilograms per second and in cubic metres per minute at metric standard conditions (1.013 25 bar and 15°C).

Solution:

1. R = 490
2. S_g = 0.596 . . . . for NH_3 gas; page A-8
3. γ = 1.32

Steps 3 through 7 are used to determine the Y factor.

4. $p_1' = p + 1.013 = 2.75 + 1.013 = 3.763$
5. $\Delta p/p_1' = 0.2 \div 3.763 = 0.0531$
6. $\beta = d_1/d_2 = 18 \div 25.7 = 0.700$
   (d_1 = orifice diameter, d_2 = inlet diameter)
7. Y = 0.98 . . . . page A-21
8. C = 0.70 turbulent flow assumed; . . page A-20
9. $T = 273 + t = 273 + 10 = 283$
10. ρ_1 = 2.76 . . . . page A-10 or 3-5

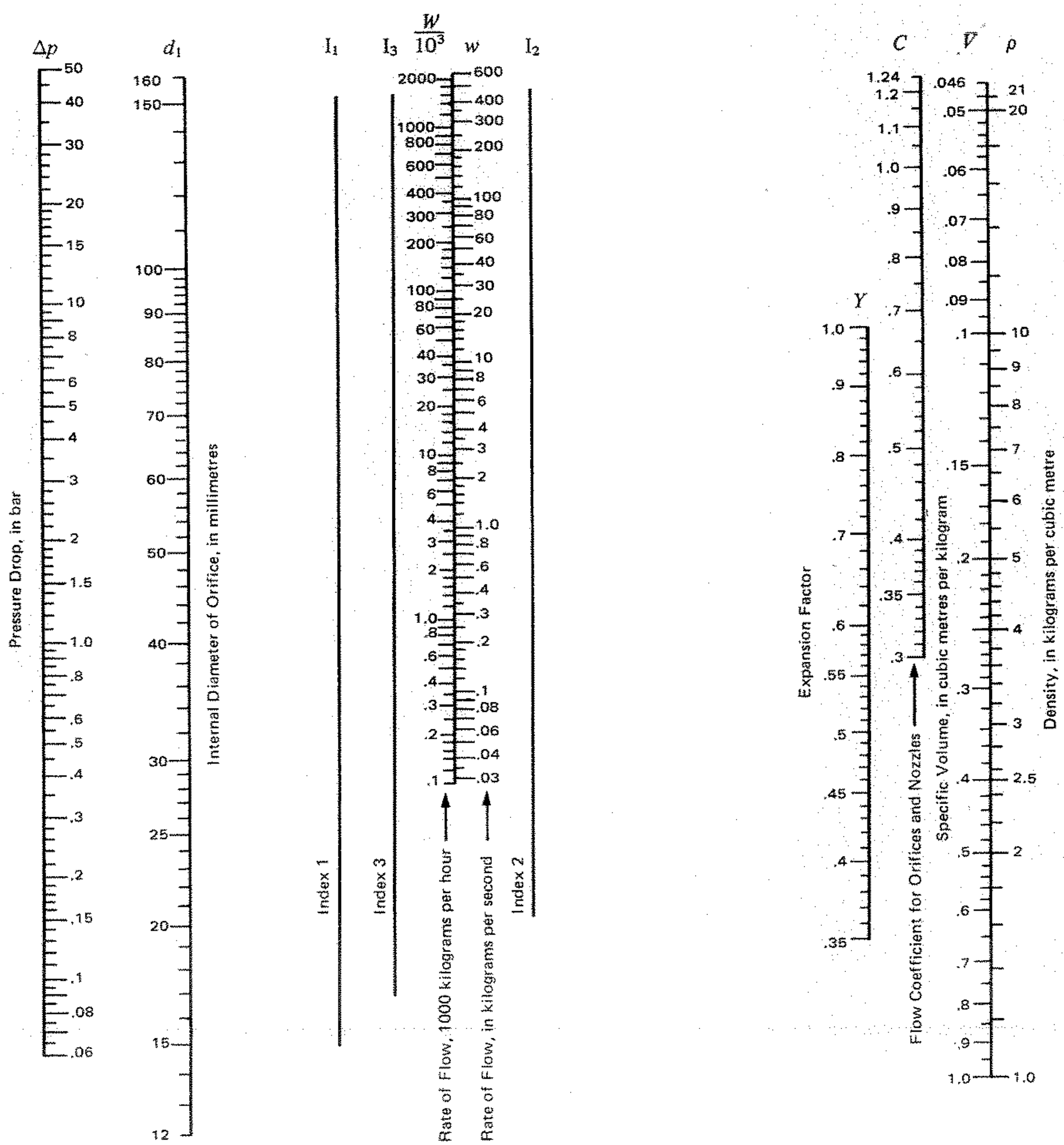
	Connect		Read
11.	Δp = 0.2	ρ_1 = 2.76	Index 1
12.	Index 1	C = 0.70	Index 2
13.	Index 2	d_1 = 18	Index 3
14.	Index 3	Y = 0.98	w = 0 .058
15.	Index 3	Y = 0.98	W = 205

16. $q'_m = \frac{W}{73.5\ S_g} = \frac{205}{73.5 \times 0.596} = 4.68$ page B-2
17. μ = 0.010 . . . . page A-5
18. R_e = 282 000 or 2.82×10^5 . . . . page 3-2
19. C = 0.70 is correct for $R_e = 2.82 \times 10^5$ page A-20
20. When the C factor assumed in Step 8 is not in agreement with page A-20, for the Reynolds number based on the calculated flow, it must be adjusted until reasonable agreement is reached by repeating Steps 8 to 19.

Flow of Compressible Fluids

through Nozzles and Orifices

(continued)



Examples of Flow Problems

CHAPTER 4

Theory and answers to questions regarding proper application of formulas to flow problems can be presented to good advantage by the solution of practical problems. A few simple flow problems were presented in Chapter 3 to illustrate the use of the nomographs. Other problems, both simple and complex, are presented in this chapter.

Many of the examples given in this chapter employ the basic formulas of Chapters 1 and 2; these formulas were rewritten in more commonly used terms for Chapter 3. Use of nomographs, when applicable, are indicated in the solution of these problems.

The controversial subject regarding the selection of a formula most applicable to the flow of gas through long pipe lines is analyzed in Chapter 1. It is shown that the three commonly used formulas are basically identical, the only difference being in the selection of friction factors. A comparison of results obtained, using the three formulas, is presented in this chapter.

An original method has been developed for the solution of problems involving the discharge of compressible fluids from pipe systems. Illustrative examples applying this method demonstrate the simplicity of handling these, heretofore complex, problems.

Reynolds Number and Friction Factor For Pipe Other Than Steel

The example below shows the procedure in obtaining the Reynolds number and friction factor for smooth pipe (plastic). The same procedure applies for any pipe other than steel or wrought iron, such as concrete, wood stave, riveted steel, etc. For relative roughness of these and other piping materials, see page A-23.

Example 4-1 . . . Smooth Pipe (Plastic)

Given: Water at 30 C is flowing through 20 metres of 2-inch standard wall plastic pipe (smooth wall) at a rate of 200 litres per minute.

Find: The Reynolds number and friction factor.

Solution:

1. $R_e = \dfrac{21.22\ Q\rho}{d\mu}$ . . . . .page 3-2
2. $\rho = 995.6$ .page A-6
3. $d = 52.5$ .page B-17
4. $\mu = 0.8$ .page A-3
5. $R_e = \dfrac{21.22 \times 200 \times 995.6}{52.5 \times 0.8}$

   R_e = **100 600** or **1.006** $\times$ **10**^{5}
6. $f = 0.0177$ for smooth pipe . . . . .page A-24

Determination of Valve Resistance In L, L/D, K, and Flow Coefficient C_v

Example 4-2 . . . *L, L/D,* and *K* from C_v for Conventional Type Valves

Given:

A 150 mm (6-inch) Class 125 iron Y-pattern globe valve has a flow coefficient, C_v, of 600 (US gal/min).

Find: Resistance coefficient K and equivalent lengths L/D and L for flow in zone of complete turbulence.

Solution:

1. K, L/D, and L should be given in terms of 6-inch Schedule 40 pipe; see page 2-10.

2. $C_v = \dfrac{29.9\, d^2}{\sqrt{K}}$ or $K = \dfrac{891\, d^4}{(C_v)^2}$ . . . . page 3-4

In this equation d is in inches (1 inch = 25.4 mm).

3. $d = 154.1$ mm $\div 25.4 = 6.067''$ . . . . . . page B-16

4. $K = \dfrac{891 \times 6.067^4}{600^2} = 3.35$ . . . . based on 6" Sched 40 pipe

5. $\dfrac{L}{D} = \dfrac{K}{f}$ . . . . page 3-4

6. $f = 0.015$ . . . for 154 mm I.D. pipe in fully turbulent flow range; page A-25

7. $\dfrac{L}{D} = \dfrac{K}{f} = \dfrac{3.35}{0.015} = 223$

$D = 154.1 \div 1000 = 0.1541$ metres

8. $L = \left(\dfrac{L}{D}\right) D = 223 \times 0.1541 = 34.4$ metres

Example 4-3 . . . *L, L/D* and *K* for Conventional Type Valves

Given:

A 100 mm (4-inch) Class 600 steel conventional angle valve with full area seat.

Find: Resistance coefficient K and equivalent lengths L/D and L for flow in zone of complete turbulence.

Solution:

1. K, L/D, and L should be given in terms of 4-inch Schedule 80 pipe; see page 2-10.

2. $K = 150\, f_T$ . . . . page A-27

$K = f\dfrac{L}{D}$; or $\dfrac{L}{D} = \dfrac{K}{f_T}$ . . . . page 3-4

(subscript "T" refers to flow in zone of complete turbulence)

3. $d = 97.2$ . . . . page B-16

$f_T = 0.017$ . . . . page A-26

4. $K = 150 \times 0.017 = 2.55$ . . . . based on 4" Sched. 80 pipe

Example 4-3 . . . continued

5. $\dfrac{L}{D} = \dfrac{2.55}{0.017} = 150$ . . . . . for graphical solutions of steps 5 and 6, use page A-30

6. $L = \left(\dfrac{L}{D}\right) D = \dfrac{150 \times 97.2}{1000} = 14.6$ metres

Example 4-4 . . . Venturi Type Valves

Given:

A 150 × 100 mm (6 × 4-inch) Class 600 steel gate valve with inlet and outlet ports conically tapered from back of body rings to valve ends. Face-to-face dimension is 560 mm and back of seat ring to back of seat ring is about 150 mm.

Find: K_2 for any flow condition, and L/D and L for flow in zone of complete turbulence.

Solution:

1. K_2, L/D, and L should be given in terms of 6-inch Schedule 80 pipe; see page 2-10.

2. $K_1 = 8\, f_T$ . . . . page A-27

$$K_2 = \frac{K_1 + \sin\frac{\theta}{2}\left[0.8\,(1-\beta^2) + 2.6\,(1-\beta^2)^2\right]}{\beta^4}$$

. . . . page A-26

$K = f\dfrac{L}{D}$ or $\dfrac{L}{D} = \dfrac{K}{f_T}$ . . . . page 3-4

$\beta = \dfrac{d_1}{d_2}$ . . . . page A-26

3. $d_1 = 101.6$ . . . . Valve Seat Bore

$d_2 = 146.4$ . . . . 6" Sched. 80 pipe; page B-16

$f_T = 0.015$ . . . . for 6" size; page A-26

4. $\beta = \dfrac{101.6}{146.4} = 0.69$ $\beta^2 = 0.48$ $\beta^4 = 0.23$

$\tan\dfrac{\theta}{2} = \dfrac{0.5(146.4 - 101.6)}{0.5(560 - 150)}$

$\tan\dfrac{\theta}{2} = 0.11 = \sin\dfrac{\theta}{2}$ approx.

5. $K_2 = \dfrac{8 \times 0.015 + 0.11(0.8 \times 0.52 + 2.6 \times 0.52^2)}{0.23}$

$K_2 = 1.06$

6. $\dfrac{L}{D} = \dfrac{1.06}{0.015} = 70$ . . . . diameters 6" Sched. 80 pipe

7. $L = \dfrac{70 \times 146.4}{1000} = 10$ metres of 6" Sched. 80 pipe

(For graphical solution of Steps 6 and 7, see page A-30.)

Check Valves
Determination of Size

Example 4-5 . . . Lift Check Valves

Given: A globe type lift check valve with a wing-guided disc is required in a 3-inch Schedule 40 horizontal pipe carrying 20 C water at the rate of 300 litres per minute.

Find: The proper size check valve and the pressure drop. The valve should be sized so that the disc is fully lifted at the specified flow; see page 2-7 for discussion.

Solution:

1. $v_{min} = 50\sqrt{\bar{V}}$ . . . . page A-27

$v = \dfrac{21.22Q}{d^2}$ . . . . page 3-2

$\Delta p = \dfrac{0.002\,25\,K\rho Q^2}{d^4}$ . . . . page 3-4

$K_1 = 600\,f_T$ . . . . page A-27

$K_2 = \dfrac{K_1 + \beta\,[0.5\,(1-\beta^2) + (1-\beta^2)^2]}{\beta^4}$ page A-27

$\beta = \dfrac{d_1}{d_2}$ . . . . page A-26

2. $d_1 = 62.7$ . . . for 2½" Sched. 40 pipe; page B-16

$d_2 = 77.9$ . . . for 3" Sched. 40 pipe; page B-16

$\bar{V} = 0.001\,002$ . . . . 20 C water; page A-6

$\rho = 998.2$ . . . . 20 C water; page A-6

$f_T = 0.018$ . . . . for 2½" or 3" size; page A-26

3. $v_{min} = 50\sqrt{0.001} = 1.585$

$v = \dfrac{21.22 \times 300}{77 \times 92} = 1.05$ for 3" valve

In as much as v is less than v_{min}, a 3-inch valve will be too large. Try a 2½-inch size.

$v = \dfrac{21.22 \times 300}{62.7^2} = 1.62$ . . . . for 2½" valve

Based on above, a 2½-inch valve installed in 3-inch Schedule 40 pipe with reducers is advisable.

4. $\beta = \dfrac{62.7}{77.9} = 0.80$

$\beta^2 = 0.64$

$\beta^4 = 0.41$

5. $K_2 = \dfrac{600 \times 0.018 + 0.8\,[0.5\,(1-0.64) + (1-0.64)^2]}{0.41}$

$K_2 = 27$

6. $\Delta p = \dfrac{0.002\,25 \times 27 \times 998.2 \times 300^2}{77.9^4} = 0.148$ bar

Reduced Port Valves
Velocity and Rate of Discharge

Example 4-6 . . . Reduced Port Ball Valve

Given: Water at 60 F discharges from a tank with 7 metres average head to atmosphere through:

60 metres — 3" Schedule 40 pipe; 6-3" standard 90° threaded elbows; 1-3" flanged ball valve having a 60mm diameter seat, 16° conical inlet, and 30° conical outlet end. Sharp-edged entrance is flush with inside of tank.

Find: Velocity of flow in the pipe and rate of discharge in litres per minute.

Solution:

1. $h_L = K\dfrac{v^2}{2g_n}$ or $v = \sqrt{\dfrac{2g_n h_L}{K}}$ . . . . page 3-4

$v = 21.22\dfrac{Q}{d^2}$ or $Q = 0.047vd^2$ . . . . page 3-2

2. $K = 0.5$ . . . . entrance; page A-29

$K = 1.0$ . . . . exit; page A-29

$f_T = 0.018$ . . . . page A-26

3. For K (ball valve), page A-28 indicates use of Formula 5. However, when inlet and outlet angles (θ) differ, Formula 5 must be expanded to:

$$K_2 = \frac{K_1 + .8\sin\frac{\theta}{2}\,(1-\beta^2) + 2.6\sin\frac{\theta}{2}\,(1-\beta^2)^2}{\beta^4}$$

4. $\beta = \dfrac{d_1}{d_2} = \dfrac{60}{77.9} = 0.77$ . . . . . . page A-26

5. $\sin\theta/2 = \sin 8° = 0.14$ . . . . valve inlet

6. $\sin\theta/2 = \sin 15° = 0.26$ . . . . valve outlet

7. $K_2 = \dfrac{3 \times .018 + 0.8 \times 0.14\,(1-0.77^2)}{0.77^4} +$

$\dfrac{2.6 \times 0.26\,(1-0.77^2)^2}{0.77^4} = 0.58$ . . . . . valve

$K = 6 \times 30f_T = 180 \times 0.018 = 3.24$ 6 elbows; p. A-29

$K = f\dfrac{L}{D} = \dfrac{0.018 \times 60 \times 1000}{77.9} = 13.9$ pipe; p. 3-4

8. Then, for entire system (entrance, pipe, ball valve, six elbows, and exit),

$K = 0.5 + 13.9 + 0.58 + 3.24 + 1.0 = 19.2$

9. $v = \sqrt{(19.62 \times 7) \div 19.2} = 2.675$ m/s

$Q = 0.047 \times 2.675 \times 77.9^2 = 763$ litres/min.

10. Calculate Reynolds number to verify that friction factor of 0.018 (zone of complete turbulence) is correct for flow condition . . . or, use "vd" scale at top of Friction Factor chart on page A-25.

$vd = 2.675 \times 77.9 = 208$

11. Enter chart on page A-25 at $vd = 208$. Note f for 3-inch pipe is less than 0.02. Therefore, flow is in the transition zone (slightly less than fully turbulent) but the difference is small enough to forego any correction of K for the pipe.

Laminar Flow in Valves, Fittings, and Pipe

In flow problems where viscosity is high, calculate the Reynolds Number to determine whether the flow is laminar or turbulent.

Example 4-7

Given: S.A.E. 10 Lube Oil at 15 C flows through the system described in Example 4-6 at the same differential head.

Find: The velocity in the pipe and rate of flow in litres per minute.

Solution:

1. $h_L = K \frac{v^2}{2g_n}$ .... page 3-4

$v = \sqrt{\frac{2g_n h_L}{K}}$

$v = 21.22 \frac{Q}{d^2}$ .... page 3-2

$Q = 0.047\, vd^2$

$R_e = \frac{dv\rho}{\mu}$ .... page 3-2

$f = \frac{64}{R_e}$ ...... pipe, laminar flow; page 3-2

$K = f\frac{L}{D}$ .... pipe; page 3-4

2. $K_2 = 0.58$ .... valve; Example 4-6

$K = 3.24$ .... 6 elbows; Example 4-6

$K = 0.5$ .... entrance; Example 4-6

$K = 1.0$ .... exit; Example 4-6

$\rho = 875.2$ .... page A-7

$\mu = 100$ .... page A-3

$h_L = 7$ .... Example 4-6

3. *Assume laminar flow with $v = 1.5$

$R_e = \frac{77.9 \times 1.5 \times 875.2}{100} = 1020$

$f = 64 \div 1020 = 0.063$ .... pipe

$K = \frac{0.063 \times 60 \times 1000}{77.9} = 48.5$ ...... pipe

$K = 48.5 + 0.58 + 3.24 + 0.5 + 1.0$

$K = 53.8$ .... entire system

4. $v = \sqrt{\frac{19.62 \times 7}{53.8}} = 1.6$ m/s

5. $Q = 0.047 \times 1.6 \times 77.9^2 = 456$ litres/min.

**Note:* This problem has two unknowns and, therefore, requires a trial-and-error solution. Two or three trial assumptions will usually bring the solution and final assumption into agreement within desired limits.

Example 4-8

Given: S.A.E. 70 Lube Oil at 40 C is flowing at the rate of 600 barrels per hour through 60 metres of 8-inch Schedule 40 pipe, in which an 8-inch conventional globe valve with full area seat is installed.

Find: The pressure drop due to flow through the pipe and valve.

Solution:

1. $\Delta p = \frac{0.0158\, K\rho B^2}{d^4}$ .... page 3-4

$R_e = \frac{56.23\, \rho B}{d\mu}$ .... page 3-2

$K_1 = 340\, f_T$ .... valve; page A-27

$K = f\frac{L}{D}$ .... pipe; page 3-4

$f = \frac{64}{R_e}$ .... pipe

2. S = 0.916 at 60 F (15.6 C) ...... page A-7

S = 0.90 at 40 C .... page A-7

$d = 202.7$ .... 8" Sched. 40 pipe; page B-16

$\mu = 450$ .... page A-3

$f_T = 0.014$ .... page A-26

3. $\rho = 999 \times 0.9 = 899$ .... page A-6, A-7

$R_e = \frac{56.23 \times 899 \times 600}{202.7 \times 450} = 332$

$R_e < 2000$; therefore flow is laminar.

4. $f = \frac{64}{332} = 0.193$ .... pipe

$K_1 = 340 \times 0.014 = 4.76$ .... valve

$K = \frac{0.193 \times 60 \times 1000}{202.7} = 57.13$ .... pipe

$K = 4.76 + 57.13 = 61.89$ ...... total system

5. $\Delta p = \frac{0.0158 \times 61.89 \times 899 \times 600^2}{202.7^4}$

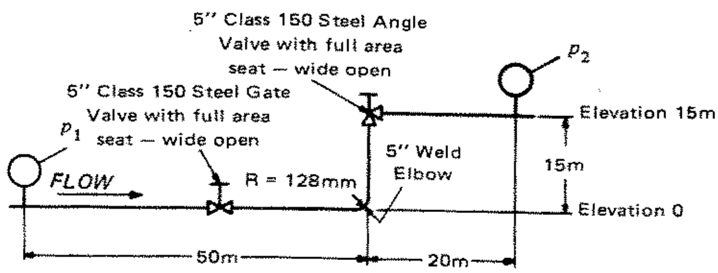
$\Delta p = 0.188$ bar

Laminar Flow in Valves, Fittings, and Pipe – continued

In flow problems where viscosity is high, calculate the Reynolds Number to determine whether the flow is laminar or turbulent.

Example 4-9

Given: S.A.E. 70 Lube Oil at 40 C is flowing through 5-inch Schedule 40 pipe at a rate of 2300 litres per minute, as shown in the following sketch.



Find: The velocity in metres per second and pressure difference between gauges p_1 and p_2.

Solution:

1. $v = \dfrac{21.22Q}{d^2}$ . . . . page 3-2

$R_e = \dfrac{21.22Q\rho}{d\mu}$ . . . . page 3-2

$\Delta p = \dfrac{0.002\,25\,K\rho Q^2}{d^4}$ loss due to flow; page 3-4

$\Delta p = \dfrac{h_L \rho}{10\,200}$ loss due to elevation change; page 3-5

2. $K_1 = 8\,f_T$ . . . . gate valve; page A-27

$K_1 = 150\,f_T$ . . . . angle valve; page A-27

$K = 20\,f_T$ . . . . elbow; page A-29

$K = f\,\dfrac{L}{D}$ . . . . pipe; page 3-4

$f = \dfrac{64}{R_e}$ . . . . pipe; page 3-2

3. $d = 128.2$ . . . . . 5" Sched. 40 pipe; page B-16

S = 0.916 at 60 F (15.6 C) . . . . . page A-7

S = 0.90 at 40 C . . . . page A-7

$\mu = 450$ . . . . page A-3

$\rho = 999 \times 0.9 = 899$ . . . . page A-6, A-7

$f_T = 0.016$ . . . . page A-26

4. $R_e = \dfrac{21.22 \times 2300 \times 899}{128.2 \times 450} = 760$

$R_e < 2000$; therefore flow is laminar.

5. $f = \dfrac{64}{760} = 0.084$

6. Summarizing K for the entire system (gate valve, angle valve, elbow, and pipe),

$$K = (8 \times 0.016) + (150 \times 0.016) + (20 \times 0.016) + \frac{(0.084 \times 85 \times 1000)}{128.2} = 55.7$$

7. $v = \dfrac{21.22 \times 2300}{128.2^2} = 2.97$ m/s

8. $\Delta p = \dfrac{0.002\,25 \times 55.7 \times 899 \times 2300^2}{128.2^4} + \dfrac{15 \times 899}{10\,200}$

$\Delta p = 3.53$ bar . . . . total

Pressure Drop and Velocity in Piping Systems

Example 4-10 . . . Piping Systems – Steam

Given: 40 bar abs. steam at 460 C flows through 120 metres of horizontal 6-inch Schedule 80 pipe at a rate of 40 000 kilograms per hour.

The system contains three 90 degree weld elbows having a relative radius of 1.5, one fully-open 6 x 4-inch Class 600 venturi gate valve as described in Example 4-4, and one 6-inch Class 600 y-pattern globe valve. Latter has a seat diameter equal to 0.9 of the inside diameter of Schedule 80 pipe, disc fully lifted.

Find: The pressure drop through the system.

Solution:

1. $\Delta p = \dfrac{0.6253\, K W^2 \bar{V}}{d^4}$ . . . . page 3-4

2. For globe valve (see page A-27),

$$K_2 = \frac{K_1 + \beta\,[0.5\,(1-\beta^2) + (1-\beta^2)^2]}{\beta^4}$$

$K_1 = 55\, f_T$

$\beta = 0.9$

3. $K = 14\, f_T$ . . . . . . 90° weld elbows; page A-29

$K = f\,\dfrac{L}{D}$ . . . . pipe; page 3-4

$R_e = 354\,\dfrac{W}{d\mu}$ . . . . page 3-2

4. $d = 146.4$ . . . . 6" Sched. 80 pipe; page B-16

$\bar{V} = 0.081$ . . . 40 bar steam 460 C; page A-16

$\mu = 0.027$ . . . . page A-2

$f_T = 0.015$ . . . . page A-26

5. For globe valve,

$$K_2 = \frac{55 \times .015 + .9\,[.5\,(1-.9^2) + (1-.9^2)^2]}{.9^4}$$

$K_2 = 1.44$

6. $R_e = \dfrac{354 \times 40\,000}{146.4 \times 0.027} = 3.58 \times 10^6$

$f = 0.015$ . . . . pipe; page A-25

$K = \dfrac{0.015 \times 120 \times 1000}{146.4} = 12.3$ . . . . . . pipe

$K = 3 \times 14 \times 0.015 = 0.63$ 3 elbows; page A-29

$K_2 = 1.44$ . . . . . . 6 x 4" gate valve; Example 4-4

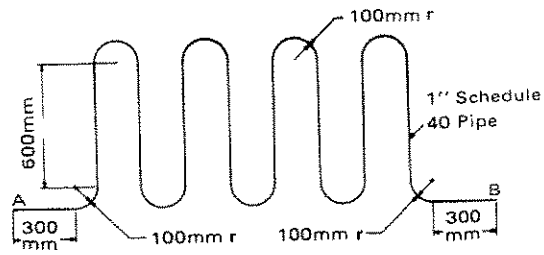
7. Summarizing K for the entire system (globe valve, pipe, venturi gate valve, and elbows),

$K = 1.44 + 12.3 + 0.63 + 1.44 = 15.8$

8. $\Delta p = \dfrac{0.6253 \times 15.8 \times 40\,000^2 \times 0.081}{146.4^4} = 2.8$ bar

Example 4-11 . . . Flat Heating Coils – Water

Given: Water at 80 C is flowing through a flat heating coil, shown in the sketch below, at a rate of 60 litres per minute.



Find: The pressure drop from Point A to B.

Solution:

1. $\Delta p = \dfrac{0.002\,25\, K \rho Q^2}{d^4}$ . . . . page 3-4

$R_e = \dfrac{21.22\, Q \rho}{d\mu}$ . . . . page 3-2

$K = f\,\dfrac{L}{D}$ . . . . straight pipe; page 3-4

$r/d = 4$ . . . . pipe bends

$K_{90} = 14\, f_T$ . . . . 90° bends; page A-29

$K_B = (n-1)\,(.25\,\pi f_T\,\dfrac{r}{d} + .5\, K_{90}) + K_{90}$

. . . . 180° bends; page A-29

2. $\rho = 971.8$ . . . . water 40 C; page A-6

$\mu = 0.35$ . . . . water 40 C; page A-3

$d = 26.6$ . . . . . . 1" Sched. 40 pipe; page B-16

$f_T\ 0.023$ . . . . . . 1" Sched. 40 pipe; page A-26

3. $R_e = \dfrac{21.22 \times 60 \times 971.8}{26.6 \times 0.35} = 1.33 \times 10^5$

$f = 0.024$ . . . . pipe

$K = \dfrac{0.024 \times 5.4 \times 1000}{26.6} = 4.87$ 5.4m straight pipe

$K = 2 \times 14 \times 0.023 = 0.64$ . . . . . two 90° bends

4. For seven 180° bends,

$K_B = 7\,[(2-1)\,(0.25\pi \times 0.023 \times 4) + (0.5 \times 0.32) + 0.32] = 3.87$

5. $K_{TOTAL} = 4.87 + 0.64 + 3.87 = 9.38$

6. $\Delta p = \dfrac{0.002\,25 \times 9.38 \times 971.8 \times 60^2}{26.6^4} = 0.152$ bar

Pressure Drop and Velocity in Piping Systems – continued

Example 4-12 . . . Orifice Size for Given Pressure Drop and Velocity

Given: A 12 inch nominal size, ISO 336 steel pipe, 11 mm. wall thickness, 18 metres long containing a standard gate valve discharges 15 C water to atmosphere from a reservoir. The entrance projects inward into the reservoir and its centre line is 3.5 metres below the water level in the reservoir.

Find: The diameter of thin-plate orifice that must be installed in the pipe to restrict the velocity of flow to 3 metres per second when the gate valve is wide open.

Solution:

1. $h_L = K \dfrac{v^2}{2g_n}$ or System $K = \dfrac{2g_n h_L}{v^2}$ page 3-4

   $R_e = \dfrac{dv\rho}{\mu}$ . . . . page 3-2

2. $K = 0.78$ . . . . entrance; page A-29

   $K = 1.0$ . . . . exit; page A-29

   $K_1 = 8f_T$ . . . . gate valve; page A-27

   $K = f\dfrac{L}{D}$ . . . . pipe; page 3-4

3. $d = 301.9$ . . . . pipe; page B-20

   $f_T = 0.013$ . . . . pipe; page A-26

   $\rho = 999.0$ . . . . page A-6

   $\mu = 1.1$ . . . . page A-3

4. $R_e = \dfrac{301.9 \times 3 \times 999}{1.1} = 8.2 \times 10^5$

   $f = 0.014$ . . . . page A-25

5. Total K required $= 19.62 \times 3.5 \div 3^2 = 7.63$

   $K_1 = 8 \times 0.013 = 0.10$ . . . . gate valve

   $K = \dfrac{18 \times 1000}{301.9} \times 0.013 = 0.84$ . . . . pipe

   Then, exclusive of orifice,

   $K_{total} = 0.78 + 1.0 + 0.1 + 0.84 = 2.72$

6. $K_{orifice} = 7.63 - 2.72 = 4.91$

7. $K_{orifice} \simeq \dfrac{1 - \beta^2}{C^2\beta^4}$ . . . . .page A-20

8. Assume $\beta = 0.7$ $\therefore$ $C = 0.7$ page A-20
   then $K \simeq 4.3$ $\therefore$ β is too large

9. Assume $\beta = 0.65$ $\therefore$ $C = 0.67$ page A-20
   then $K \simeq 7.1$ $\therefore$ β is too small

10. Assume $\beta = 0.69$ $\therefore$ $C = 0.687$ page A-20
    then $K \simeq 4.9$ $\therefore$ use $\beta = 0.69$

11. Orifice size $\simeq 0.69 \times 301.9 = 208$ mm

Example 4-13 . . . Flow Given in Traditional Units

Given: Fuel oil, with a specific gravity of 0.815 and a kinematic viscosity of 2.7 centistokes flows through a 2-inch Schedule 40 steel pipe, 100 feet long, at a rate of 2 US gallons per second.

Find: The pressure drop in bars and in pounds force per square inch.

Solution:

1. $\Delta p = 2.252 \dfrac{fL\rho Q^2}{d^5}$ . . . . page 3-2 or 3-10

   $R_e = 21\,220 \dfrac{Q}{\nu d}$ . . . . page 3-2

2. Convert units given to those used in this paper; refer to page B-10.

   1 ft = 0.3048 m

   1 US gallon = 3.785 litres

3. $L = 100$ ft $= 100 \times 0.3048 = 30.48$ m

4. $d = 52.5$ mm . . . . page B-16

5. $\rho = 999 \times S = 999 \times 0.815$ . . . . . . page A-7

   $\rho = 814$ kg/m^3

6. 2 US gallons $= 2 \times 3.785 = 7.57$ litres

7. $Q = \left(\dfrac{7.57 \text{ litres}}{\cancel{\text{sec}}}\right)\left(\dfrac{60\ \cancel{\text{sec}}}{\text{min}}\right) = 454.2$ litres/min

8. $\nu = 2.7$ centistokes

9. $R_e = \dfrac{21\,220 \times 454.2}{2.7 \times 52.5} = 68\,000$ or 6.8×10^4

10. $f = 0.0230$ . . . . page A-25

11. $\Delta p = \dfrac{2.252 \times 0.0230 \times 30.48 \times 814 \times 454.2^2}{52.5^5}$

    $\Delta p = 0.665$ bar

12. Pressure drop in pounds force per square inch

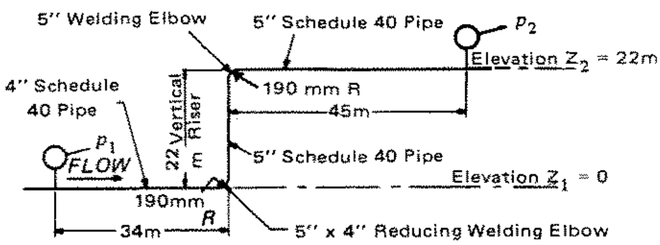
    $= 0.665 \times 14.5$ . . . . page B-12

    $= 9.64$ lbf/in^2

Pressure Drop and Velocity in Piping Systems – continued

Example 4-14 . . . Bernoulli's Theorem – Water

Given: Water at 15 C is flowing through the piping system, shown in the sketch below, at a rate of 1500 litres per minute.



Find: The velocity in both the 4 and 5-inch pipe sizes and the pressure differential between gauges p_1 and p_2.

Solution:

1. Use Bernouilli's theorem (see page 3-2):

$$Z_1 + \frac{10^5 p_1}{\rho_1 g_n} + \frac{v^2{}_1}{2g_n} = Z_2 + \frac{10^5 p_2}{\rho_2 g_n} + \frac{v^2{}_2}{2g_n} + h_L$$

Since, $p_1 = p_2$

$$p_1 - p_2 = \frac{\rho g_n}{10^5} \quad (Z_2 - Z_1) + \frac{v^2{}_2 - v^2{}_1}{2g_n} + h_L$$

2. $h_L = \dfrac{22.96KQ^2}{d^4}$ . . . . page 3-4

$R_e = \dfrac{21.22Q\rho}{d\mu}$ . . . . page 3-2

$K = f\,\dfrac{L}{D}$ . . . . page 3-4

$K = \dfrac{fL}{D\beta^4}$ . . . . small pipe, in terms of larger pipe; page 2-11

$K = 14f_T$ 90° elbow; page A-29

$K = 14f_T + \dfrac{(1-\beta^2)^2}{\beta^4}$ reducing 90° elbow; page A-26

Note: In the absence of test data for increasing elbows, the resistance is conservatively estimated to be equal to the summation of the resistance due to a straight size 5" elbow and a sudden enlargement (4" to 5").

$\beta = \dfrac{d_1}{d_2}$ . . . . page A-26

3. $\rho = 999.0$ . . . . page A-6

$\mu = 1.1$ . . . . page A-3

$d_1 = 102.3$ . . . . 4" Sched. 40 pipe; page B-16

$d_2 = 128.2$ . . . . 5" Sched. 40 pipe; page B-16

$f_T = 0.016$ . . . . 5" size; page A-26

4. $\beta = \dfrac{102.3}{128.2} = 0.80$

$Z_2 - Z_1 = 22 - 0 = 22$ metres

$v_1 = 3.04$ . . . . 4" pipe. page B-13

$v_2 = 1.94$ . . . . 5" pipe, page B-13

$$\frac{v^2{}_2 - v^2{}_1}{2g_n} = \frac{1.936^2 - 3.041^2}{2 \times 9.81} = -0.28 \text{ metres}$$

5. For Schedule 40 pipe,

$R_e = \dfrac{21.22 \times 1500 \times 999}{102.3 \times 1.1} = 2.83 \times 10^5$ . . . . 4" pipe

$R_e = \dfrac{21.22 \times 1500 \times 999}{128.2 \times 1.1} = 2.25 \times 10^5$ . . . . 5" pipe

$f = 0.018$ . . . . 4 or 5" pipe

6. $K = \dfrac{0.018 \times 67 \times 1000}{128.2}$

$K = 9.4$ . . . . for 67 m of 5" Sched. 40 pipe

$K = \dfrac{0.018 \times 34 \times 1000}{102.3}$

$K = 6.0$ . . . . for 34 m of 4" Sched. 40 pipe

With reference to velocity in 5" pipe,

$K_2 = 6.0 \div 0.8^4 = 14.6$ . . . . page 2-11

$K = 14 \times 0.016 = 0.22$ . . . . 5" 90° elbow

$K = 0.22 + \dfrac{0.36^2}{0.8^4} = 0.54$ . . . . . 5x4" 90° elbow

7. Then, in terms of 5-inch pipe,

$K_{TOTAL} = 9.4 + 14.6 + 0.22 + 0.54 = 24.8$

8. $h_L = \dfrac{22.96 \times 24.8 \times 1500^2}{128.2^4} = 4.74$

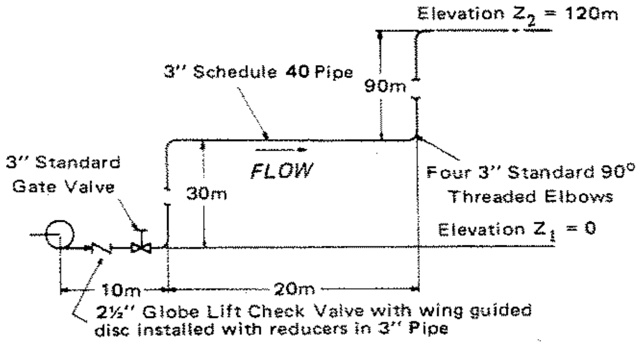
9. $p_1 - p_2 = \dfrac{999 \times 9.81}{10^5} \; (22 - 0.28 + 4.74)$

$p_1 - p_2 = 2.6$ bar

Pressure Drop and Velocity in Piping Systems — continued

Example 4-15 . . . Power Required for Pumping

Given: Water at 20 C is pumped through the piping system below at a rate of 400 litres per minute.



Find: The total discharge head *(H)* at flowing conditions and the power demand (brake power) required for a pump having an efficiency (e_p) of 70 per cent.

Solution: 1. Use Bernoulli's theorem (see page 3-2):

$$Z_1 + \frac{10^5 p_1}{\rho_1 g_n} + \frac{v_1^2}{2g_n} = Z_2 + \frac{10^5 p_2}{\rho_2 g_n} + \frac{v_2^2}{2g_n} + h_L$$

2. Since $\rho_1 = \rho_2$ and $v_1 = v_2$, the equation can be rewritten to establish the pump head, *H:*

$$\frac{10^5}{\rho g_n}(p_1 - p_2) = (Z_2 - Z_1) + h_L$$

3. $h_L = \dfrac{22.96\,KQ^2}{d^4}$ . . . . page 3-4

$R_e = \dfrac{dv\rho}{\mu}$ . . . . page 3-2

$v = \dfrac{21.22Q}{d^2}$ . . . . page 3-2

Power demand (kW) = $\dfrac{QH\rho}{6116 \times 10^3 \times e_p}$ page B-21

4. $K = 30f_T$ . . . . 90° elbow; page A-29

$K_1 = 8f_T$ . . . . gate valve; page A-27

$K = f\dfrac{L}{D}$ . . . . straight pipe; page 3-4

$K = 1.0$ . . . . exit; page A-29

5. $d = 77.9$ . . . . 3" Sched. 40 pipe; page B-16

$\rho = 998.2$ . . . . page A-6

$\mu = 0.98$ . . . . page A-3

$f_T = 0.018$ . . . . page A-26

6. $v = \dfrac{21.22 \times 400}{77.9^2} = 1.4$

$R_e = \dfrac{77.9 \times 1.4 \times 998.2}{0.98} = 1.1 \times 10^5$

$f = 0.021$ . . . . page A-25

7. $K = 4 \times 30 \times 0.018 = 2.16$ . . . . . four 90° elbows

$K_1 = 8 \times 0.018 = 0.14$ . . . . gate valve

$K = 27.0$. lift check with reducers; Example 4-5

For 150 metres of 3-inch Schedule 40 pipe,

$$K = \frac{0.021 \times 150 \times 1000}{77.9} = 40.4 \quad \text{and,}$$

$$K_{TOTAL} = 2.16 + 0.14 + 27.0 + 40.4 + 1 = 70.7$$

8. $h_L = \dfrac{22.96 \times 70.7 \times 400^2}{77.9^4} = 7$

9. $H = 120 + 7 = 127$ metres

Power demand = $\dfrac{400 \times 127 \times 998.2}{6116 \times 10^3 \times 0.7} = 11.84$ kW

Example 4-16 . . . Air Lines

Given: Air at 5 bar gauge and 40 C is flowing through 25 metres of 1-inch Schedule 40 pipe at a rate of 3 standard (MSC) cubic metres per minute (see page B-12).

Find: The pressure drop and the velocity at both upstream and downstream gauges.

Solution: 1. Referring to the table on page B-14 read pressure drop of 0.565 bar for 7 bar, 15 C air at a flow rate of 3 cubic metres per minute through 100 metres of 1-inch Schedule 40 pipe.

2. Correction for length, pressure, and temperature (page B-15):

$$\Delta p = 0.565\left(\frac{25}{100}\right)\left(\frac{7 + 1.013}{5 + 1.013}\right)\left(\frac{273 + 40}{288}\right)$$

$\Delta p = 0.205$ bar

3. To find the velocity, the rate of flow in cubic metres per minute at flowing conditions must be determined from page B-15.

$$q_m = q'_m\left(\frac{1.013}{1.013 + p}\right)\left(\frac{273 + t}{288}\right)$$

At upstream gauge:

$$q_m = 3\left(\frac{1.013}{1.013 + 5}\right)\left(\frac{273 + 40}{288}\right) = 0.549$$

At downstream gauge:

$$q_m = 3\left[\frac{1.013}{1.013 + (5 - 0.205)}\right]\left(\frac{273 + 40}{288}\right) = 0.569$$

4. $V = \dfrac{q_m}{A}$ . . . . page 3-2

5. $d = 26.6$ . . . . page B-16

6. $A = 0.7854\left(\dfrac{26.6}{1000}\right)^2 = 0.000\,556$

7. $V = \dfrac{0.549}{0.000\,556} = 987$ m/min. *(upstream)*

$V = \dfrac{0.569}{0.000\,556} = 1023$ m/min. *(downstream)*

Note: Example 4-16 may also be solved by use of the pressure drop formula and nomograph shown on pages 3-2 and 3-21 respectively or the velocity formula and nomograph shown on pages 3-2 and 3-17 respectively.

Pipe Line Flow Problems

Example 4-17 . . . Sizing of Pump for Oil Pipe Lines

Given: Crude oil 30 degree API at 15.6 C with a viscosity of 75 Universal Saybolt seconds is flowing through a BS 1600, 12 inch, Schedule 30 steel pipe at a rate of 1900 barrels per hour. The pipe line is 80 kilometres long with discharge at an elevation of 600 metres above the pump inlet. Assume the pump has an efficiency of 67 per cent.

Find: The power demand of the pump.

Solution:

1. $\Delta p = 15.81 \dfrac{fL\rho B^2}{d^5}$ ... Equation 3-5 on page 3-2 or, after converting B to Q, use nomograph on page 3-11

   $R_e = 56.23 \dfrac{B\rho}{d\mu}$ .... page 3-2 or 3-8

   $h_L = \dfrac{10\,200\,\Delta p}{\rho}$ .... page 3-5

   power demand (kW) = $\dfrac{QH\rho}{6116 \times 10^3 \times e_p}$ page B-21

2. $t = 15.6$ C
3. $\rho = 875.3$ .... page B-7

   $S = 0.8762$ .... page B-7
4. $d = 307.1$ .... page B-16
5. 75USS = 12.5 centipoise .... page B-5
6. $R_e = \dfrac{56.23 \times 1900 \times 875.3}{307.1 \times 12.5} = 24\,360$
7. $f = 0.025$ .... page A-25
8. $\Delta p = \dfrac{15.81 \times 0.025 \times 80\,000 \times 875.3 \times 1900^2}{307.1^5}$

   $\Delta p = 36.58$
9. $h_L = \dfrac{10\,200 \times 36.58}{875.3} = 426.3$
10. The total discharge head at the pump is:

    $H = 426.3 + 600 = 1026.3$
11. $Q = \left(\dfrac{1900 \text{ bbl}}{\text{h}}\right) \times \left(\dfrac{159 \text{ litres}}{\text{bbl}}\right) \times \left(\dfrac{\text{h}}{60 \text{ min}}\right) = 5035$
12. Then the power demand is:

    $\dfrac{5035 \times 1026.3 \times 875.3}{6116 \times 10^3 \times 0.67} = 1104$, say 1110 kW

Pipe Line Flow Problems — continued

Example 4-18 . . . Gas

Given: A natural gas pipe line made of BS 3600 14-inch pipe, wall thickness 11 mm, is 160 kilometres long. The inlet pressure is 90 bar absolute, the outlet pressure is 20 bar absolute and the average temperature is 4°C.

The gas consists of 75% methane (CH_4), 21% ethane (C_2H_6), and 4% propane (C_3H_8).

Find: The flow rate in millions of cubic metres per day at Metric Standard Conditions (MSC).

Solutions: Three solutions to this example are presented for the purpose of illustrating the variations in results obtained by use of the Simplified Compressible Flow formula, the Weymouth formula and the Panhandle, formula.

Simplified Compressible Flow Formula
(see page 3-3)

1. $$q'_h = 0.013\,61 \sqrt{\left[\frac{(p'_1)^2 - (p'_2)^2}{fL_m T S_g}\right] d^5}$$

2. $d = 333.6$ . . . . page B-20.

3. $f = 0.0128$ turbulent flow assumed; page A-25

4. $T = 273 + t = 273 + 4 = 277$

5. Approximate atomic weights:

   Carbon . . . . $C = 12.0$

   Hydrogen . . . . . . $H = 1.0$

6. Approximate molecular weights:

   Methane (CH_4)

   $M = (1 \times 12.0) + (4 \times 1.0) = 16$

   Ethane (C_2H_6)

   $M = (2 \times 12.0) + (6 \times 1.0) = 30$

   Propane (C_3H_8)

   $M = (3 \times 12.0) + (8 \times 1.0) = 44$

   Natural Gas

   $M = (16 \times 0.75) + (30 \times 0.21) + (44 \times 0.04)$

   $M = 20.06$, or say 20.1

7. $$S_g = \frac{M\,(\text{gas})}{M\,(\text{air})} = \frac{20.1}{29} = 0.693 \qquad \text{page 3-5}$$

8. $$q'_h = 0.013\,61 \sqrt{\frac{(90^2 - 20^2) \times 333.6^5}{0.0128 \times 160 \times 277 \times 0.693}}$$

   $q'_h = 122\,400$

9. $$q'_d = \left(\frac{122\,400 \text{ m}^3}{1\,000\,000 \cancel{\text{hr}}}\right)\left(\frac{24 \cancel{\text{hr}}}{\text{day}}\right) = 2.938$$

10. $$R_e = \frac{432 q'_h S_g}{d\mu}$$ . . . . page 3-2

11. $\mu = 0.011$ . . . . estimated; page A-5

12. $$R_e = \frac{432 \times 122\,400 \times 0.693}{333.6 \times 0.011}$$

    $R_e = 9\,986\,000$ or 9.986×10^6

13. $f = 0.0128$ . . . . page A-25

14. Since the assumed friction factor ($f = 0.0128$) is correct, the flow rate is 2.938 million m^3/d at MSC. If the assumed friction factor were incorrect, it would have to be adjusted and Steps 8, 9, 12, and 13 repeated until the assumed friction factor was in reasonable agreement with that based upon the calculated Reynolds number.

Weymouth Formula
(see page 3-3)

15. $$q'_h = 0.002\,61\, d^{2.667} \sqrt{\left[\frac{(p'_1)^2 - (p'_2)^2}{S_g L_m}\right]\left(\frac{288}{T}\right)}$$

16. $d^{2.667} = 5\,363\,000$

17. $$q'_h = 13\,997 \sqrt{\frac{(90^2 - 20^2)}{0.693 \times 160}\left(\frac{288}{277}\right)}$$

    $q'_h = 118\,930$

18. $$q'_d = \left(\frac{118\,930}{1\,000\,000 \cancel{\text{hr}}}\right)\left(\frac{24 \cancel{\text{hr}}}{\text{day}}\right) = 2.854$$

Panhandle Formula
(see page 3-3)

19. $$q'_h = 0.005\,06 E d^{2.6182} \left[\frac{(p'_1)^2 - (p'_2)^2}{L_m}\right]^{0.5394}$$

20. Assume average operation conditions; then efficiency is 92 per cent:

    $E = 0.92$

21. $d^{2.6182} = 4\,038\,000$

22. $$q'_h = 18\,798 \left(\frac{90^2 - 20^2}{160}\right)^{0.5394}$$

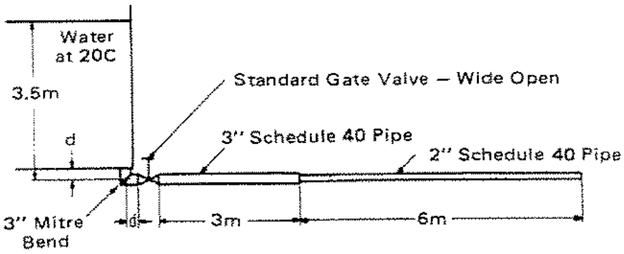
    $q'_h = 151\,910$

23. $$q'_d = \left(\frac{151\,910}{1\,000\,000 \cancel{\text{hr}}}\right)\left(\frac{24 \cancel{\text{hr}}}{\text{day}}\right) = 3.646$$

Discharge of Fluids from Piping Systems

Example 4-19 . . . Water

Given: Water at 20 C is flowing from a reservoir through the piping system below. The reservoir has a constant head of 3.5 metres.



Find: The flow rate in litres per minute.

Solution: 1. $Q = 0.2087\, d^2 \sqrt{\frac{h_L}{K}}$ .. page 3-4

$R_e = \frac{21.22\, Q\rho}{d\mu}$ .... page 3-2

$\beta = d_1/d_2$ .... page A-26

2. $K = 0.5$ .... entrance; page A-29

$K = 60 f_T$ .... mitre bend; page A-29

$K_1 = 8 f_T$ .... gate valve; page A-27

$K = f\frac{L}{D}$ .... straight pipe; page 3-4

$K_2 = \frac{0.5\,(1-\beta^2)\sqrt{\sin\frac{\theta}{2}}}{\beta^4}$ ... sudden contraction; page A-26

$K = \frac{fL}{D\beta^4}$ small pipe, in terms of larger pipe; page 2-5

$K = \frac{1}{\beta^4}$ exit from small pipe in terms of larger pipe

3. $d = 52.5$ ...... 2" Sched. 40 pipe; page B-16

$d = 77.9$ ...... 3" Sched. 40 pipe; page B-16

$\mu = 1.1$ .... page A-3

$\rho = 998.2$ .... page A-6

$f_T = 0.019$ .... 2" pipe; page A-26

$f_T = 0.018$ .... 3" pipe; page A-26

4. $\beta = 52.5 \div 77.9 = 0.67$

$K = 0.5$ .... 3" entrance

$K = 60 \times 0.018 = 1.08$ ...... 3" mitre bend

$K_1 = 8 \times 0.018 = 0.14$ .... 3" gate valve

$K = \frac{0.018 \times 3 \times 1000}{77.9} = 0.69$ 3 metres, 3" pipe

For 6 metres of 2-inch pipe, in terms of 3-inch pipe,

$K = \frac{0.019 \times 6 \times 1000}{52.5 \times 0.67^4} = 10.8$

For 2-inch exit, in terms of 3-inch pipe,

$K = 1 \div 0.67^4 = 5.0$

For sudden contraction,

$K_2 = \frac{0.5\,(1-0.67^2)\,(1)}{0.67^4} = 1.37$

and, $K_{TOTAL} = 0.5 + 1.08 + 0.14 + 0.69 + 10.8 + 5.0 + 1.37 = 19.58$

5. $Q = 0.2087 \times 77.9^2 \sqrt{3.5 \div 19.58} = 535$

(this solution assumes flow in fully turbulent zone)

6. Calculate Reynolds numbers and check friction factors for flow in straight pipe of the 2-inch size:

$R_e = \frac{21.22 \times 535 \times 998.2}{52.5 \times 1.1} = 1.96 \times 10^5$

$f = 0.021$ .... page A-25

and for flow in straight pipe of the 3-inch size:

$R_e = \frac{21.22 \times 535 \times 998.2}{77.9 \times 1.1} = 1.32 \times 10^5$

$f = 0.020$ .... page A-25

7. Since assumed friction factors used for straight pipe in Step 4 are not in agreement with those based on the approximate flow rate, the K factors for these items and the total system should be corrected accordingly.

$K = \frac{0.020 \times 3 \times 1000}{77.9} = 0.77$ 3 metres, 3" pipe

For 6-metres of 2-inch pipe, in terms of 3-inch pipe,

$K = \frac{0.021 \times 6 \times 1000}{52.5 \times 0.67^4} = 11.9$

and, $K_{TOTAL} = 0.5 + 1.08 + 0.14 + 0.77 + 11.9 + 5.0 + 1.37 = 20.76$

8. $Q = 0.2087 \times 77.9^2 \sqrt{3.5 \div 20.76} = 520$ litres/min

Discharge of Fluids from Piping Systems – continued

Example 4-20 . . . Steam at Sonic Velocity

Given: A header with 12 bar absolute saturated steam is feeding a pulp stock digester through 10 metres of 2-inch, ISO 336 steel pipe, 4 mm wall thickness, which includes one standard 90 degree elbow and a fully-open conventional plug type disc globe valve. The initial pressure in the digester is atmospheric.

Find: The initial flow rate in kilograms per hour, using both the modified Darcy formula and the sonic velocity and continuity equations.

Solutions – for theory, see page 1-9:

Modified Darcy Formula

1. $W = 1.265 Y d^2 \sqrt{\dfrac{\Delta p}{K \overline{V}_1}}$ . . . . . . page 3-4

$K = f \dfrac{L}{D}$ . . . . pipe; page 3-4

2. $K_l = 340 f_T$ . . . . globe valve; page A-27

$K = 30 f_T$ . . . . 90° elbow; page A-29

$K = 0.5$ . . . . entrance from header; page A-29

$K = 1.0$ . . . . exit to digester; page A-29

3. $\gamma = 1.3$ . . . . page A-9

$d = 52.3$ . . . . page B-19

$f_T = 0.019$ . . . . page A-26

$\overline{V}_1 = 0.1632$ . . . . page A-13

4. $K = \dfrac{0.019 \times 10 \times 1000}{52.3} = 3.63$ 10 metres pipe

$K_l = 340 \times 0.019 = 6.46$ . . . . 2" globe valve

$K = 30 \times 0.019 = 0.57$ . . . . 2" 90° elbow

and, for the entire system,

$K = 3.63 + 6.46 + 0.57 + 0.5 + 1.0 = 12.16$

5. $\dfrac{\Delta p}{p_1'} = \dfrac{12 - 1.013}{12} = \dfrac{10.987}{12} = 0.916$

6. Using the chart on page A-22 for $\gamma = 1.3$, it is found that for $K = 12.16$ the maximum $\Delta p/p_1'$ is 0.786 (interpolated from table on page A-22). Since $\Delta p/p_1'$ is less than indicated in Step 5, sonic velocity occurs at the end of the pipe, and Δp in the equation of Step *1* is:

$\Delta p = 0.786 \times 12 = 9.432$, say 9.43

7. $Y = 0.710$ interpolated from table; page A-22

8. $W = 1.265 \times 0.71 \times 52.3^2 \sqrt{\dfrac{9.43}{12.16 \times 0.1632}}$

$W = 5356$ kg/h.

Sonic Velocity and Continuity Equations

9. $v_s = 316.2 \sqrt{\gamma p' \overline{V}}$ . . . . page 3-3

$W = \dfrac{v d^2}{354 \overline{V}}$ . . . . Equation 3-2; page 3-2

10. $p' = p_1' - \Delta p$

$p' = 12 - 9.43 = 2.57$

Δp determined in Step 6.

11. $h_g = 2782.7$ . . 12 bar abs. sat. steam; page A-13

12. At 2.57 bar abs. the temperature of steam with total heat of 2782.7 kJ/kg equals 159 C and

$\overline{V} = 0.7558$

13. $v_s = 316.2 \sqrt{1.3 \times 2.57 \times 0.7558}$

$v_s = 502.4$

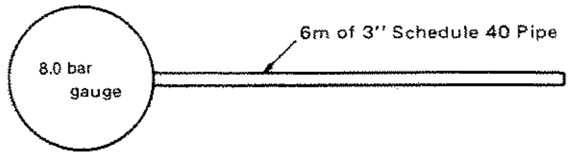
$W = \dfrac{502.4 \times 52.3^2}{354 \times 0.7558} = 5136$ kg/h

NOTE: In Steps 11 and 12 constant total heat h_g is assumed. But the increase in specific volume from inlet to outlet requires that the velocity must increase. Source of the kinetic energy increase is the internal heat energy of the fluid. Consequently, the heat energy actually decreases toward the outlet. Calculation of the correct h_g at the outlet will yield a flow rate commensurate to the answer in Step 8.

Discharge of Fluids from Piping Systems – continued

Example 4-21 . . . Gases at Sonic Velocity

Given: Coke oven gas having a specific gravity of 0.42, a header pressure of 8.0 bar gauge and a temperature of 60 C is flowing through 6 metres of 3-inch Schedule 40 pipe before discharging to atmosphere. Assume ratio of specific heats, $\gamma = 1.4$.



Find: The flow rate in cubic metres per hour at Metric Standard Conditions.

Solution – for theory, see page 1-9:

1. $q'_h = 19.31\, Yd^2 \sqrt{\frac{\Delta p\, p'_1}{K T_1 S_g}}$ .... page 3-4

   $K = f \frac{L}{D}$ .... page 3-4

2. $p'_1 = 8.0 + 1.013 = 9.013$
3. $f = 0.0175$ .... page A-25

   Note: The Reynolds number need not be calculated since gas discharged to atmosphere through a short pipe will have a high R_e and flow will always be in a fully turbulent range, in which the friction factor is constant.

4. $d = 77.9$; $D = 0.0779$ .... page B-16
5. $K = f \frac{L}{D} = \frac{0.0175 \times 6}{0.0779} = 1.35$ ..... for pipe

   $K = 0.5$ .... for entrance; page A-29

   $K = 1.0$ .... for exit; page A-29

   $K = 1.35 + 0.5 + 1.0 = 2.85$ .... total

6. $\frac{\Delta p}{p'_1} = \frac{9.013 - 1.013}{9.013} = \frac{8}{9.013} = 0.888$

7. Using the chart on page A-22 for $\gamma = 1.4$, it is found that for $K = 2.85$, the maximum $\Delta p / p'_1$ is 0.655 (interpolated from table on page A-22). Since $\Delta p / p'_1$ is less than indicated in Step 6, sonic velocity occurs at the end of the pipe and Δp in Step *1* is:

   $\Delta p = 0.655\, p'_1 = 0.655 \times 9.013 = 5.9$

8. $T_1 = 60 + 273 = 333$
9. $Y = 0.636$ interpolated from table; page A-22
10. q'_h is equal to:

    $19.31 \times 0.636 \times 77.9^2 \sqrt{\frac{5.9 \times 9.013}{2.85 \times 333 \times 0.42}}$

    $q'_h = 27\,200 \text{ m}^3/\text{h}$

Example 4-22 . . . Compressible Fluids at Subsonic Velocity

Given: Air at a pressure of 1.33 bar gauge and a temperature of 40 C is measured at a point 3 metres from the outlet of a ½-inch Schedule 80 pipe discharging to atmosphere.

Find: The flow rate in cubic metres per minute at Metric Standard Conditions.

Solution:

1. $q'_m = 0.3217\, Yd^2 \sqrt{\frac{\Delta p\, p'_1}{K T_1 S_g}}$ ... page 3-4

   $K = f \frac{L}{D}$ .... page 3-4

2. $p'_1 = 1.33 + 1.013 = 2.343$
3. $\Delta p = 1.33$
4. $d = 13.8$; $D = 0.0138$ .... page B-16
5. $f = 0.0275$ ......fully turbulent flow; page A-25
6. $K = f \frac{L}{D} = \frac{0.0275 \times 3}{0.0138} = 5.98$ .... for pipe

   $K = 1.0$ .... for exit; page A-29

   $K = 5.98 + 1 = 6.98$ .... total

7. $\frac{\Delta p}{p'_1} = \frac{1.33}{2.343} = 0.568$
8. $Y = 0.76$ .... page A-22
9. $T_1 = 273 + t_1 = 273 + 40 = 313$
10. $q'_m = 0.3217 \times 0.76 \times 13.8^2 \sqrt{\frac{1.33 \times 2.343}{6.98 \times 313 \times 1.0}}$

    $q'_m = 1.76 \text{ m}^3/\text{min}$

Flow Through Orifice Meters

Example 4-23 . . . Liquid Service

Given: A square edged orifice of 50 mm diameter is installed in a 102.5 mm inside diameter pipe having a mercury manometer connected between the pipe taps 1 diameter upstream and 0.5 diameter downstream.

Find: (a) The theoretical calibration constant for the meter when used on 15 C water and for the flow range where the orifice flow coefficient C is constant . . . and (b), the flow rate of 15 C water when the mercury deflection is 110 millimetres.

Solution – (a)

1. $Q = 21.07\, d_1^2\, C \sqrt{\dfrac{\Delta p}{\rho}}$ ..... page 3-5 or 3-15

$R_e = \dfrac{21.22\, Q\rho}{d\mu}$ .... page 3-2 or 3-8

2. To determine differential pressure across the taps,

$\Delta p = \dfrac{\Delta h_m\, \rho}{1000 \times 10\,200}$ .... page 3-5

where: Δh_m = differential head in millimetres of mercury

3. The weight density of mercury under water equals $\rho_W\,(S_{Hg} - S_W)$, where (at 15 C):

ρ_W = density of water = 999.0 ... page A-6

S_{Hg} = specific gravity of mercury = 13.57 ... page A-7

S_W specific gravity of water = 1.00 ... page A-6

4. And ρ of Hg under H_2O = 999 (13.57 – 1.00) = 12 557 kg/m³

5. $\Delta p = \dfrac{\Delta h_m\,(12\,557)}{1000 \times 10\,200} = 0.00123\, \Delta h_m$

6. d_2 (larger diam.) = 102.5

7. $\dfrac{d_1}{d_2} = \dfrac{50}{102.5} = 0.49$

8. $C = 0.625$ .... page A-20

9. $Q = 21.07 \times 50^2 \times 0.625 \sqrt{\dfrac{0.00123\, \Delta h_m}{999}}$

$Q = 36.5 \sqrt{\Delta h_m}$ .... calibration constant

Solution – (b):

10. $Q = 36.5 \sqrt{\Delta h_m} = 36.5 \sqrt{110} = 383$

11. $\mu = 1.1$ .... page A-3

12. $R_e = \dfrac{21.22 \times 383 \times 999}{102.5 \times 1.1}$

R_e = 72 000 or 7.2 x 10^4

13. $C = 0.625$ is correct for $R_e = 7.2 \times 10^4$, per page A-20; therefore, the flow rate through the pipe is 383 litres per minute.

14. When the C factor on page A-20 is incorrect, for the Reynolds number based on calculated flow, it must be adjusted until reasonable agreement is reached by repeating Steps *9*, *10*, and *12*.

Example 4-24 . . . Laminar Flow

In flow problems where the viscosity is high, calculate the Reynolds number to determine the type of flow.

Given: SAE 10 Lube Oil at 32 C is flowing through a 3-inch Schedule 40 pipe and produces 2.8 kPa pressure differential between the pipe taps of a 55 mm I.D. square edged orifice.

Find: The flow rate in litres per minute.

Solution:

1. $Q = 21.07 d_1^2\, C \sqrt{\dfrac{\Delta p}{\rho}}$ ...... page 3-5 or 3-15

$R_e = \dfrac{21.22 Q\rho}{d\mu}$ .... page 3-2 or 3-8

2. $\Delta p = 2.8 \div 100 = 0.028$ bar

3. $\mu = 38$ .... suspect laminar flow; page A-3

4. d_2 (larger diam.) = 77.9 .... page B-16

5. $\dfrac{d_1}{d_2} = \dfrac{55}{77.9} = 0.706$

6. $C = 0.8$ page A-20, assumed value based on laminar flow

7. $S = 0.876$ at 15 C .... page A-7

$S = 0.87$ at 32 C .... page A-7

8. $\rho = 999 \times 0.87 = 869$ .... page A-7

9. $Q = 21.07 \times 55^2 \times 0.8 \sqrt{\dfrac{0.028}{869}} = 289.5$

10. $R_e = \dfrac{21.22 \times 289.5 \times 869}{77.9 \times 38} = 1803$

11. $C = 0.9$ for $R_e = 1803$ .... page A-20

Since the assumed C value of 0.8 is not correct, it must be adjusted by repeating Steps *6*, *7*, *8* and *9*.

12. $C = 0.87$ .... assumed; page A-20

13. $Q = 21.07 \times 55^2 \times 0.87 \sqrt{\dfrac{0.028}{869}} = 315$

14. $R_e = \dfrac{21.22 \times 315 \times 869}{77.9 \times 38} = 1960$

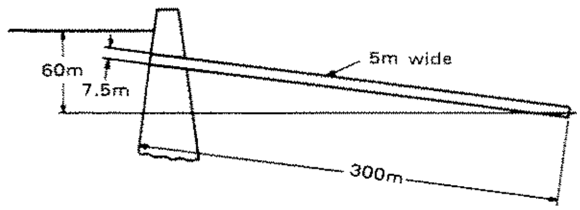
15. $C = 0.87$ for $R_e = 1960$ .... page A-20

Since $C = 0.87$ is correct for the flow, the flow through the meter is 315 litres per minute.

Application of Hydraulic Radius to Flow Problems

Example 4-25 . . . Rectangular Duct

Given: A rectangular concrete overflow aqueduct 7.6 metres high and 5 metres wide, has an absolute roughness (ϵ) of 3 millimetres.



Find: The discharge rate in cubic metres per second when the liquid in the reservoir has reached the maximum height indicated in the above sketch. Assume the average temperature of the water is 15 C.

Solution:

1. $$h_L = \frac{v^2}{2g_n}(K_e + K_a) = \frac{v^2}{2g_n}\left(K_e + \frac{fL}{4R_H}\right)$$

2. $$v = \frac{q}{A}$$

3. $$q = 3.478 \times 10^{-6}\, d^2 \sqrt{\frac{h_L}{K_e + K_a}} \quad \text{.. page 3-4}$$

$$q = 4.428A \sqrt{\frac{h_L}{K_e + K_a}}$$

$$q = 4.428A \sqrt{\frac{h_L}{K_e + f\frac{L}{4R_H}}}$$

where: K_e = resistance of entrance and exit
K_a = resistance of aqueduct

To determine the friction factor from the Moody diagram, an equivalent diameter four times the hydraulic radius is used; refer to page 3-5.

$$R_H = \frac{\text{cross sectional flow area}}{\text{wetted perimeter}}$$

$$R_e = 318.3\,\frac{q\rho}{R_H\mu} \quad \text{............. page 3-2}$$

4. Assuming a sharp edged entrance,
$K = 0.5$ .... page A-29
Assuming a sharp edged exit to atmosphere,
$K = 1.0$ .... page A-29
Then, resistance of entrance and exit,
$K_e = 0.5 + 1.0 = 1.5$

5. $$R_H = \frac{5 \times 7.5}{2(5 + 7.5)} = 1.5 \text{ m}$$

6. Equivalent diameter relationship:
$D = 4R_H = 4 \times 1.5 = 6$ .... page 3-5
$d = 4000\,R_H = 4000 \times 1.5 = 6000$ page 3-5

7. Relative roughness, $\epsilon/d = 0.0005$ . . . page A-23

8. $f = 0.017$ fully turbulent flow assumed; page A-23

9. $$q = 4.428 \times 7.5 \times 5 \sqrt{\frac{60}{1.5 + \frac{0.017 \times 300}{6}}}$$

$q = 839\ m^3/s$

10. Calculate R_e
and check, $f = 0.017$ for $q = 839\ m^3/s$ flow

11. $\rho = 999$ .... page A-6

12. $\mu = 1.1$ .... page A-3

13. $$R_e = \frac{318.3 \times 839 \times 999}{1.5 \times 1.1}$$

$R_e = 162\ 000\ 000$ or 1.62×10^8

14. $f = 0.017$ .... for calculated R_e; page A-24

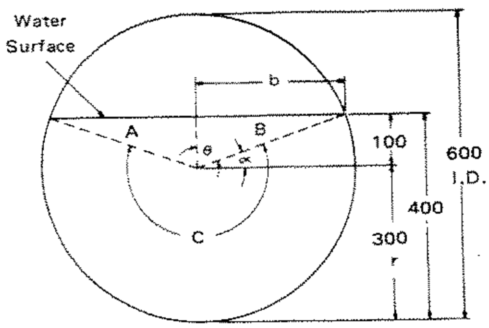
15. Since the friction factor assumed in Step *8* and that determined in Step *14* are in agreement, the discharge flow will be 839 m^3/s

16. If the assumed friction factor and the friction factor based on the calculated Reynolds number were not in reasonable agreement, the former should be adjusted and calculations repeated until reasonable agreement is reached.

Application of Hydraulic Radius to Flow Problems — continued

Example 4-26 . . . Pipe Partially Filled With Flowing Water

Given: A cast iron pipe is two-thirds full of steady, uniform flowing water (15 C). The pipe has an inside diameter of 600 mm and a slope of 1 in 16. See sketch below.



Dimensions in millimetres

Find: The flow rate in litres per minute.

Solution:

1. $Q = 0.2087 d^2 \sqrt{\frac{h_L D}{fL}}$ . . . . page 3-4

   Since pipe is flowing partially full an equivalent diameter based upon hydraulic radius is substituted for D in Equation 1 (see page 1-4).

   $D = 4R_H$ . . . . page 3-5

2. $Q = 0.2087 d^2 \sqrt{\frac{h_L\, 4R_H}{fL}} = 0.4174 d^2 \sqrt{\frac{h_L R_H}{fL}}$

3. $R_H = \frac{\text{cross sectional flow area}}{\text{wetted perimeter}}$ . . page 3-5

4. $R_e = 0.0053 \frac{Q\rho}{R_H \mu}$ . . . . page 3-2

5. Depth of flowing water equals:

   $\frac{2}{3}(600) = 400$ mm

6. $\text{Cos } \theta = \frac{100}{300} = 0.333$

   $\theta = 70°32'$

   $\alpha = 90° - 70°32' = 19°28' = 19.47°$

7. $\text{Area C} = \frac{\pi d^2}{4} \left[\frac{180 + (2 \times 19.47)}{360}\right]$

   $\text{Area C} = \frac{\pi\, 600^2}{4} \left(\frac{218.94}{360}\right) = 172\,000 \text{ mm}^2$

8. $b = \sqrt{300^2 - 100^2} = 283$ mm

9. Area A = Area B = ½ (100 x 283)

   Area A or B = 14 150 mm^2

10. The cross sectional flow area equals:

    A+B+C = (2 x 14 150) + 172 000

    A+B+C = 200 300 mm^2 or 0.2003 m^2

11. $d^2 = \frac{4a}{\pi} = \frac{4 \times 200\,300}{\pi} = 255\,000$

12. $h_L = \Delta h = \frac{1}{16} = 0.0625$ metre per metre

13. The wetted perimeter equals:

    $\pi d \left(\frac{218.94}{360}\right)$

    $\pi\, 600 \left(\frac{218.94}{360}\right) = 1146$ mm $= 1.146$ m

14. $R_H = \frac{0.2003}{1.146} = 0.175$ m

15. Equivalent diameter $d = 4000\, R_H$ . . page 3-5

    $d = 4000 \times 0.175 = 700$

16. Relative roughness $\frac{\epsilon}{d} = 0.00036$ . . . page A-23

17. $f = 0.0156$ (assuming fully turbulent flow; page A-23)

18. $Q = 0.4174 \times 255\,000 \sqrt{\frac{0.0625 \times 0.175}{0.0156 \times 1}}$

    $Q = 89\,000$ litres/min.

19. Calculate the Reynolds number to check the friction factor assumed in Step 17.

20. $\rho = 999$ . . . . page A-6

21. $\mu = 1.1$ . . . . page A-3

22. $R_e = \frac{0.0053 \times 89\,000 \times 999}{0.175 \times 1.1}$

    $R_e = 2\,450\,000$ or 2.45×10^6

23. $f = 0.0156$ . . . . page A-24

24. Since the friction factor assumed in Step 17 and that determined in Step 23 are in agreement, the flow rate will be 89 000 litres/min.

25. If the assumed friction factor and the friction factor based on the calculated Reynolds number, were not in reasonable agreement, the former should be adjusted and the calculations repeated until reasonable agreement is reached.

Physical Properties of Fluids and Flow Characteristics of Valves, Fittings, and Pipe

APPENDIX A

The physical properties of many commonly used fluids are required for the solution of flow problems. This appendix presents a compilation of such properties obtained from various reference sources. In those cases where the information given by the source reference is in Imperial units this has been converted and is presented here in terms of SI units.

Most texts on the subject of fluid mechanics cover in detail the flow through pipe, but the flow characteristics of valves and fittings are given little, if any, attention, probably because the information has not been available. This appendix includes a presentation of data which provides a basis for calculating the resistance coefficient *'K'* for various types of valves and fittings and the method of employing this coefficient to obtain pressure drop or head loss through valves and fittings is explained in Chapter 2.

The *Y* net expansion factors for discharge of compressible fluids from piping systems, which are presented here, provide means for a greatly simplified solution of a heretofore complex problem.

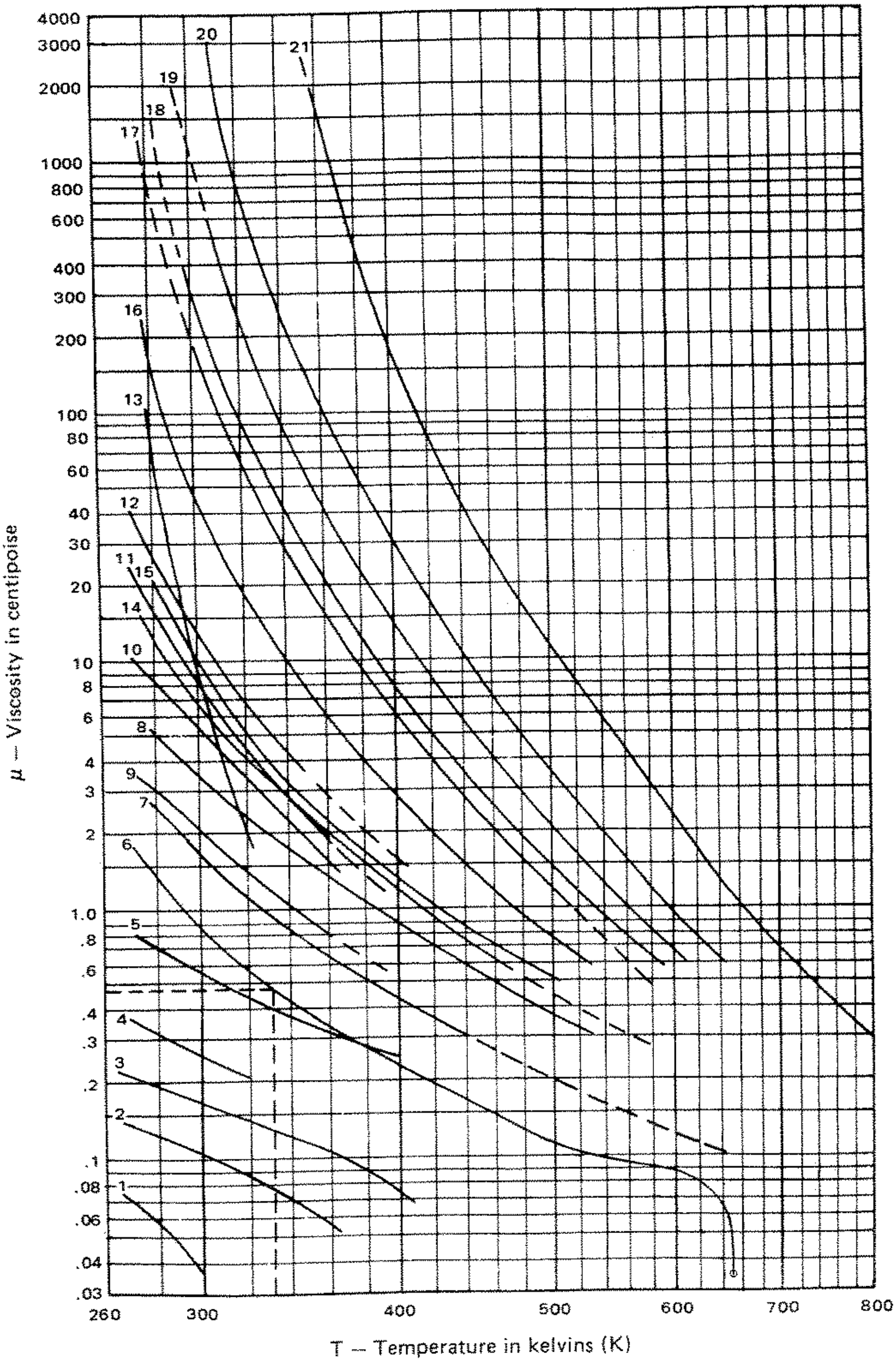
Viscosity of Water and Steam[7] — in centipoise (μ)

Temp. °C	Pressure, Bar Absolute 1	5	10	25	50	75	100	150	200	300	400	500	600	700	800
0	1.750	1.750	1.750	1.750	1.750	1.750	1.750	1.740	1.740	1.740	1.730	1.720	1.720	1.710	1.710
50	.544	.544	.544	.544	.545	.545	.545	.546	.546	.547	.548	.549	.550	.551	.552
100	.012	.279	.279	.280	.280	.280	.281	.282	.283	.285	.287	.289	.291	.293	.295
150	.014	.181	.181	.182	.182	.183	.183	.184	.186	.188	.190	.192	.194	.197	.199
200	.016	.016	.016	.134	.135	.135	.136	.137	.138	.140	.143	.145	.148	.150	.152
250	.018	.018	.018	.018	.107	.108	.108	.110	.111	.113	.116	.118	.121	.123	.126
300	.020	.020	.020	.020	.020	.020	.090	.092	.093	.095	.098	.101	.103	.106	.108
350	.022								.073	.078	.082	.085	.087	.089	.091
375	.023	.023	.023	.024	.024	.024	.025	.026	.029⊙	.066	.072	.076	.079	.082	.085
400	.024	.024	.024	.025	.025	.025	.026	.027	.029	.046	.063	.069	.074	.077	.080
425	.025	.025	.025	.026	.026	.026	.027	.028	.029	.034	.050	.061	.067	.071	.075
450	.026	.026	.026	.027	.027	.027	.028	.028	.030	.033	.041	.052	.060	.065	.069
475	.027	.027	.027	.028	.028	.028	.029	.029	.030	.033	.038	.046	.053	.060	.064
500	.028	.028	.028	.029	.029	.029	.029	.030	.031	.033	.037	.042	.048	.054	.060
550	.030	.030	.030	.031	.031	.031	.031	.032	.033	.035	.037	.040	.044	.048	.053
600	.032	.032	.033	.033	.033	.033	.033	.034	.034	.036	.038	.040	.043	.046	.049
650	.034	.034	.035	.035	.035	.035	.035	.036	.036	.038	.039	.041	.043	.045	.048
700	.036	.037	.037	.037	.037	.037	.037	.038	.038	.039	.041	.042	.044	.046	.048

Notes. (1) The entry shown for 0°C and 1 bar relates to a metastable liquid state. The stable state is here solid.
(2) ⊙ Critical point, 374.15°C, 221.2 bar.

Source of data: NEL Steam Tables 1964 (HMSO, Edinburgh)[7]

Viscosity of Water and Liquid Petroleum Products

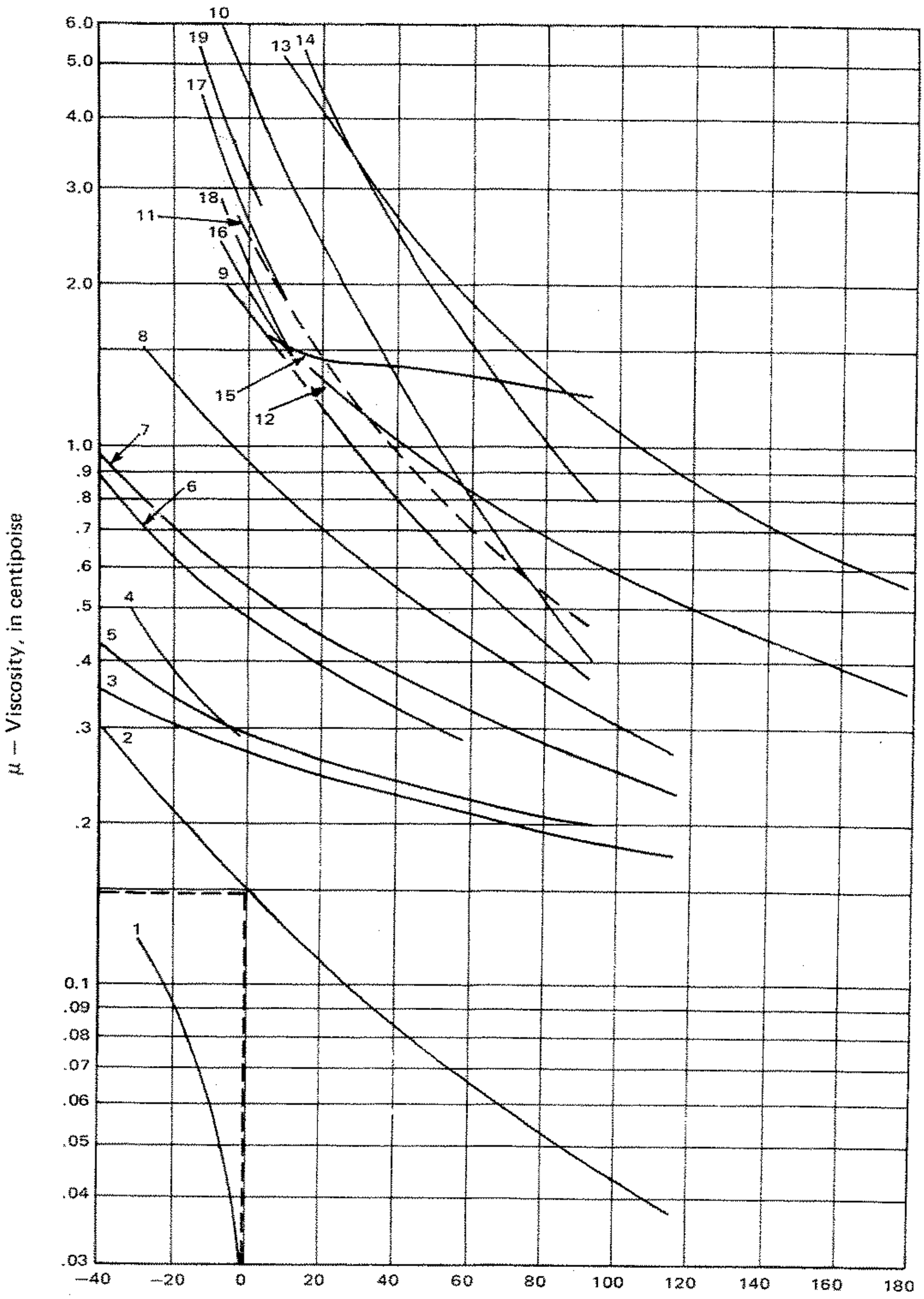


1. Ethane (C_2H_6)
2. Propane (C_3H_8)
3. Butane (C_4H_{10})
4. Natural Gasoline
5. Gasoline
6. Water
7. Kerosene
8. Distillate
9. 48 Deg. API Crude
10. 40 Deg. API Crude
11. 35.6 Deg. API Crude
12. 32.6 Deg. API Crude
13. Salt Creek Crude
14. Fuel 3 (Max.)
15. Fuel 5 (Min.)
16. SAE 10 Lube (100 V.I.)
17. SAE 30 Lube (100 V.I.)
18. Fuel 5 (Max.) or Fuel 6 (Min.)
19. SAE 70 Lube (100 V.I.)
20. Bunker C Fuel (Max.) and M.C. Residuum
21. Asphalt

Adapted from data extracted from Bibliography references 8, 12 and 23

Example: Find the viscosity of water at 60°C
Solution: 60°C = 273 + 60 = 333 K
Viscosity of water at 333 K = 0.47 centipoise (curve 6)

Viscosity of Various Liquids



1. Carbon Dioxide . . CO_2
2. Ammonia . . . . . . NH_3
3. Methyl Chloride . CH_3Cl
4. Sulphur Dioxide . SO_2
5. Freon 12 . . . . F-12
6. Freon 114 . . . . . . F-114
7. Freon 11 . . . . F-11
8. Freon 113 . . . . . . F-113
9. Ethyl Alcohol
10. Isopropyl Alcohol
11. 20% Sulphuric Acid . . . . . 20% H_2SO_4
12. Dowtherm E
13. Dowtherm A
14. 20% Sodium Hydroxide . . 20% NaOH
15. Mercury
16. 10% Sodium Chloride Brine . . . 10% NaCl
17. 20% Sodium Chloride Brine . . . 20% NaCl
18. 10% Calcium Chloride Brine. . . 10% $CaCl_2$
19. 20% Calcium Chloride Brine. . . 20% $CaCl_2$

Example: The viscosity of ammonia at 0°C is 0.15 centipoise.

Adapated from data extracted from Bibliography references 5, 8, 11

Viscosity of Gases and Vapours

The curves for hydrocarbon vapours and natural gases in the chart at the upper right are adapted from data taken from Maxwell[15]; the curves for all other gases (except helium[27]) in the chart are based upon Sutherland's formula, as follows:

$$\mu = \mu_0 \left(\frac{T_0 + C}{T + C}\right) \left(\frac{T}{T_0}\right)^{3/2}$$

where:

μ = viscosity, in centipoise at temperature T.

μ_0 = viscosity, in centipoise at temperature T_0.

T = absolute temperature, in Kelvin (273 + °C), for which viscosity is required.

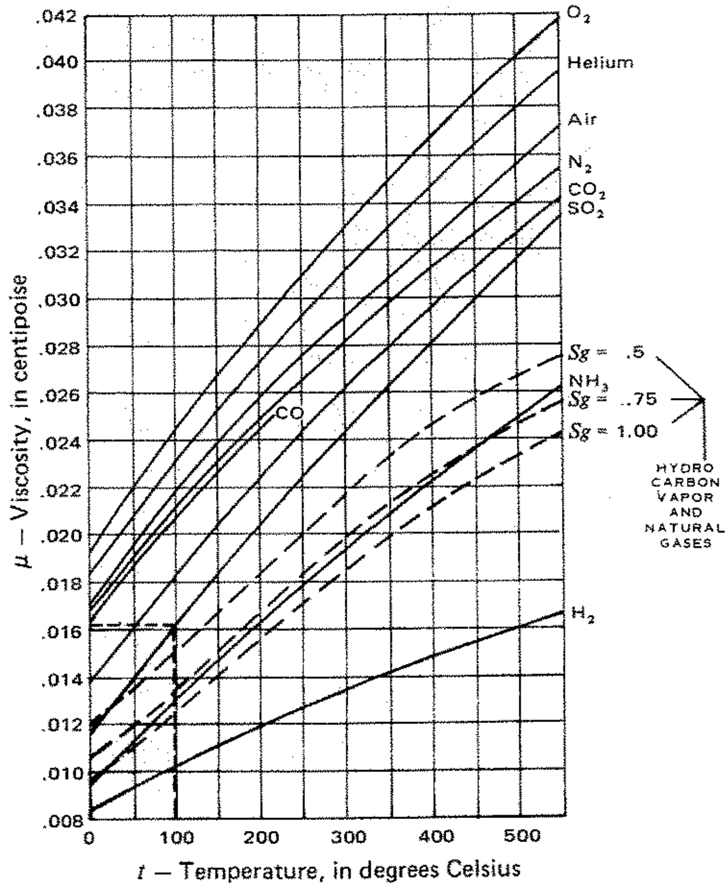
T_0 = absolute temperature, in Kelvin, for which viscosity is known.

C = Sutherland's constant.

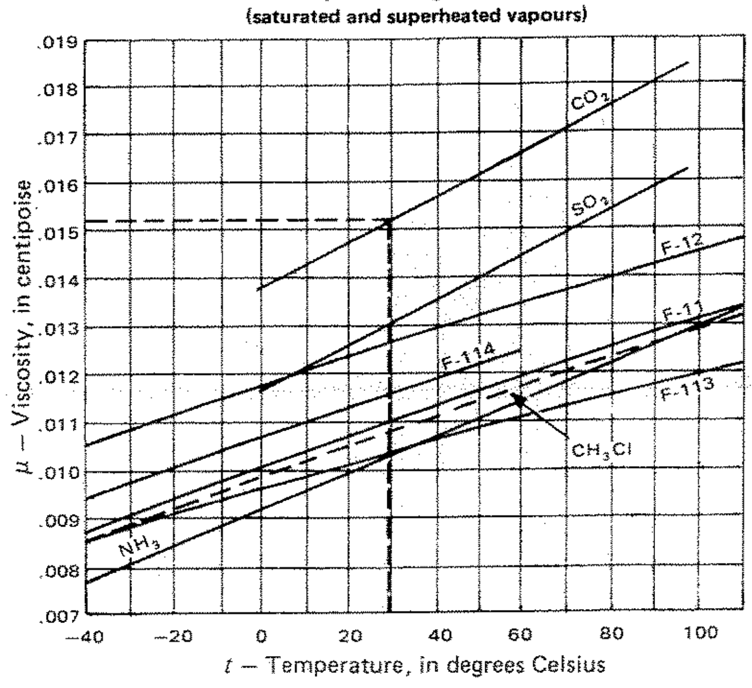
Note: The variation of viscosity with pressure is small for most gases. For gases given on this page, the correction of viscosity for pressure is less than 10 per cent for pressures up to 35 bar.

Fluid	Approximate Values of "C"
O_2	127
Air	120
N_2	111
CO_2	240
CO	118
SO_2	416
NH_3	370
H_2	72

Viscosity of Various Gases



Viscosity of Refrigerant Vapours
(saturated and superheated vapours)



Upper chart example: The viscosity of sulphur dioxide gas (SO_2) at 100°C is 0.0162 centipoise.

Lower chart example: The viscosity of carbon dioxide gas (CO_2) at about 30°C is 0.0152 centipoise.

Physical Properties of Water

Temperature of Water t Degrees Celsius	Saturation Pressure p' Bar Absolute	Specific Volume $\bar{V} \times 10^3$ Cubic Decimetres per Kilogram	Density ρ Kilograms per Cubic Metre
.01	.006112	1.0002	999.8
5	.008719	1.0001	999.9
10	.012271	1.0003	999.7
15	.017041	1.0010	999.0
20	.023368	1.0018	998.2
25	.031663	1.0030	997.0
30	.042418	1.0044	995.6
35	.056217	1.0060	994.0
40	.073750	1.0079	992.2
45	.09582	1.0099	990.2
50	.12335	1.0121	988.0
55	.15740	1.0145	985.7
60	.19919	1.0171	983.2
65	.25008	1.0199	980.5
70	.31160	1.0228	977.7
75	.38547	1.0258	974.8
80	.47359	1.0290	971.8
85	.57803	1.0324	968.6
90	.70109	1.0359	965.3
95	.84526	1.0396	961.9
100	1.01325	1.0435	958.3
110	1.4326	1.0515	951.0
120	1.9853	1.0603	943.1
130	2.7012	1.0697	934.8
140	3.6136	1.0798	926.1
150	4.7597	1.0906	916.9
160	6.1805	1.1021	907.4
170	7.9203	1.1144	897.3
180	10.0271	1.1275	886.9
190	12.552	1.1415	876.0
200	15.551	1.1565	864.7
225	25.504	1.1992	833.9
250	39.776	1.2512	799.2
275	59.49	1.3168	759.4
300	85.92	1.4036	712.5
325	120.57	1.5289	654.1
350	165.37	1.741	574.4
374.15	221.20	3.170	315.5

To convert Specific Volume from cubic decimetres per kilogram (dm^3/kg) to cubic metres per kilogram (m^3/kg) divide values in table by 10^3.

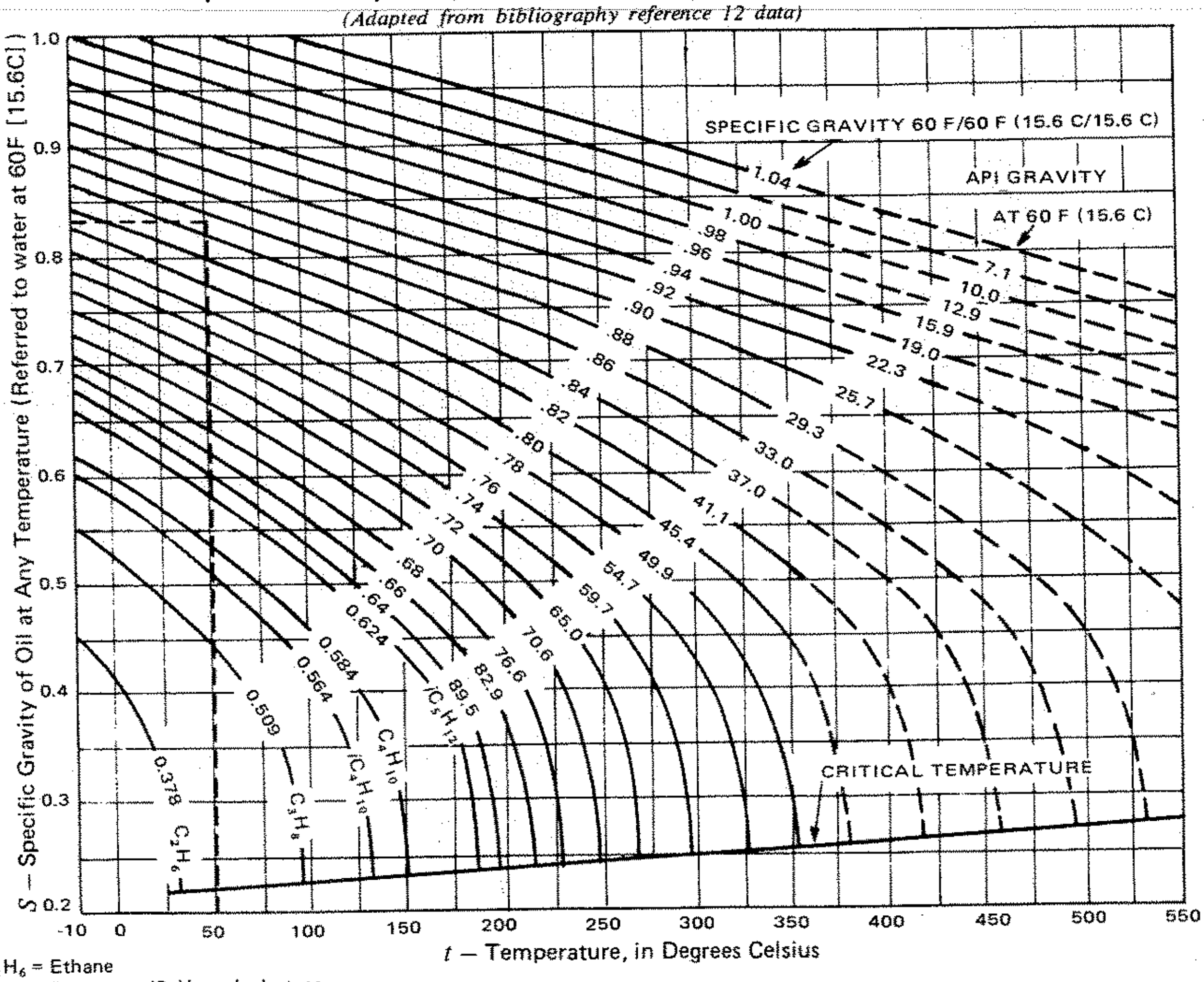
To convert Density from kilograms per cubic metre (kg/m^3) to kilograms per litre (kg/litre) divide values in table by 10^3.

Specific gravity of water at 15°C = 1.00.

Data on pressure and volume abstracted from UK National Engineering Laboratory "Steam Tables 1964" with permission of HMSO.

Specific Gravity-Temperature Relationship for Petroleum Oils

(Adapted from bibliography reference 12 data)



C_2H_6 = Ethane
C_3H_8 = Propane iC_4H_{10} = Isobutane
C_4H_{10} = Butane iC_5H_{12} = Isopentane

Example: The specific gravity of an oil at 15.6 C is 0.85. The specific gravity at 50 C = 0.83.

To find the density in kilograms/cubic metre of a petroleum oil at its flowing temperature when the specific gravity at 60 F/60 F (15.6 C/15.6 C) is known, multiply the specific gravity of the oil at flowing temperature (see chart above) by 999, the density of water at 60 F (15.6 C).

Density and Specific Gravity* of Various Liquids

Liquid	Temp. t °F	Temp. t °C	Density ρ kg/m³	Specific Gravity S	Liquid	Temp. t °F	Temp. t °C	Density ρ kg/m³	Specific Gravity S
Acetone	60	15.6	791.3	0.792	Mercury	20	-6.7	13 612	13.623
Ammonia, Saturated	10	-12.2	655.2	0.656	Mercury	40	4.4	13 584	13.596
Benzene	32	0	898.6	0.899	Mercury	60	15.6	13 557	13.568
Brine, 10% Ca Cl	32	0	1090.1	1.091	Mercury	80	26.7	13 530	13.541
Brine, 10% Na Cl	32	0	1077.1	1.078	Mercury	100	37.8	13 502	13.514
Bunkers C Fuel Max.	60	15.6	1013.2	1.014	Milk	...	...	†	...
Carbon Disulphide	32	0	1291.1	1.292	Olive Oil	59	15.0	917.9	0.919
Distillate	60	15.6	848.8	0.850	Pentane	59	15.0	623.1	0.624
Fuel 3 Max.	60	15.6	897.4	0.898	SAE 10 Lube‖	60	15.6	875.3	0.876
Fuel 5 Min.	60	15.6	964.8	0.966	SAE 30 Lube‖	60	15.6	897.4	0.898
Fuel 5 Max.	60	15.6	991.9	0.993	SAE 70 Lube‖	60	15.6	915.0	0.916
Fuel 6 Min.	60	15.6	991.9	0.993	Salt Creek Crude	60	15.6	841.9	0.843
Gasoline	60	15.6	749.8	0.751	32.6° API Crude	60	15.6	861.3	0.862
Gasoline, Natural	60	15.6	679.5	0.680	35.6° API Crude	60	15.6	845.9	0.847
Kerosene	60	15.6	814.5	0.815	40° API Crude	60	15.6	824.2	0.825
M. C. Residuum	60	15.6	934.2	0.935	48° API Crude	60	15.6	787.5	0.788

* Liquid at specified temperature relative to water at 15.6°C (60°F)
† Milk has a density of 1028 to 1035 kg/m³
‖ 100 Viscosity Index

Values in above table are based on *Smithsonian Physical Tables*, Mark's *Engineers' Handbook* and [12]Nelson's *Petroleum Refinery Engineering*.

Physical Properties of Gases

(Approximate values at 20°C and 1.01325 bar)

c_p = specific heat at constant pressure
c_v = specific heat at constant volume

Name of Gas	Chemical Formula or Symbol	Approx. Molecular Weight	Density kg/m³	Specific Gravity Relative to Air	Individual Gas Constant J/kg K	Specific Heat at Room Temperature J/kg K		Heat Capacity per Cubic Metre J/m³ K		γ equal to c_p/c_v
		M	ρ	S_g	R	c_p	c_v	c_p	c_v	
Acetylene (ethyne)	C_2H_2	26.0	1.0925	0.907	320	1465	1127	1601	1231	1.30
Air	–	29.0	1.2045	1.000	287	1009	721	1215	868	1.40
Ammonia	NH_3	17.0	0.7179	0.596	490	2190	1659	1572	1191	1.32
Argon	A	39.9	1.6610	1.379	208	519	311	862	517	1.67
n-Butane	C_4H_{10}	58.1	2.4897	2.067	143	1654	1490	4118	3710	1.11
Carbon dioxide	CO_2	44.0	1.8417	1.529	189	858	660	1580	1216	1.30
Carbon monoxide	CO	28.0	1.1648	0.967	297	1017	726	1185	846	1.40
Chlorine	Cl_2	70.9	2.9944	2.486	117	481	362	1440	1084	1.33
Ethane	C_2H_6	30.0	1.2635	1.049	277	1616	1325	2042	1674	1.22
Ethylene	C_2H_4	28.0	1.1744	0.975	296	1675	1373	1967	1612	1.22
Helium	He	4.0	0.1663	0.1381	2078	5234	3153	870	524	1.66
Hydrogen Chloride	HCl	36.5	1.5273	1.268	228	800	567	1222	866	1.41
Hydrogen	H_2	2.0	0.0837	0.0695	4126	14319	10155	1199	850	1.41
Hydrogen sulphide	H_2S	34.1	1.4334	1.190	243	1017	782	1458	1121	1.30
Methane	CH_4	16.0	0.6673	0.554	519	2483	1881	1657	1255	1.32
Methyl Chloride	CH_3Cl	50.5	2.1500	1.785	165	1005	838	2161	1800	1.20
Natural gas (a)	–	19.5	0.8034	0.667	426	2345	1846	1884	1483	1.27
Nitric Oxide	NO	30.0	1.2491	1.037	277	967	691	1208	863	1.40
Nitrogen	N_2	28.0	1.1648	0.967	297	1034	733	1204	854	1.41
Nitrous oxide	N_2O	44.0	1.8429	1.530	189	925	706	1705	1301	1.31
Oxygen	O_2	32.0	1.3310	1.105	260	909	649	1210	864	1.40
Propane	C_3H_8	44.1	1.8814	1.562	188	1645	1430	3095	2690	1.15
Propene propylene	C_3H_6	42.1	1.7477	1.451	198	1499	1315	2620	2298	1.14
Sulphur dioxide	SO_2	64.1	2.7270	2.264	129	645	512	1759	1396	1.26

(a) Representative values; exact characteristics require knowledge of exact constitutents.

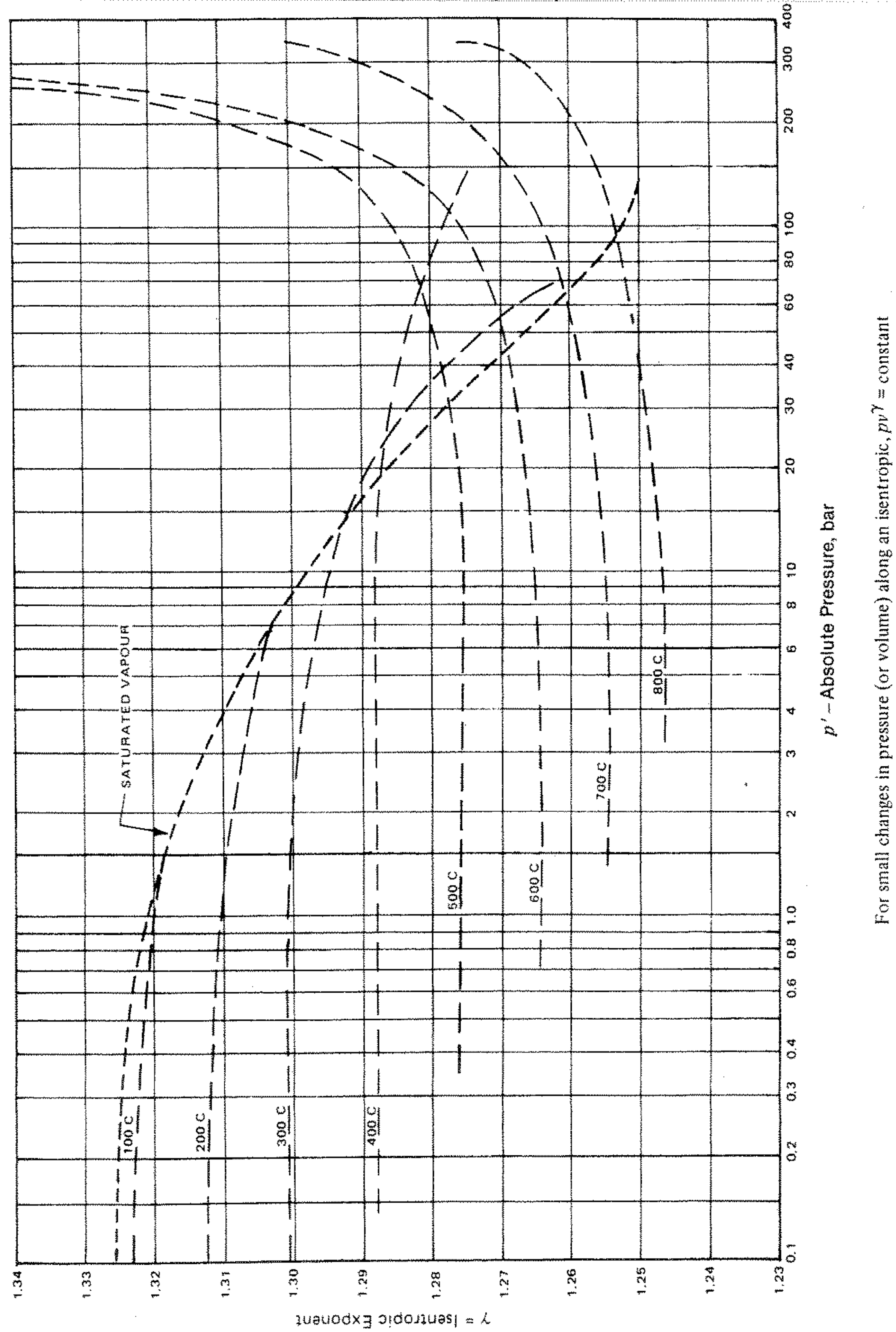
Notes. To obtain density values at 15°C, 1.01325 bar, multiply table values by 1.0174.

Where the Kelvin (K) appears in the above table it may be replaced by the degree Celsius (°C) i.e. kJ/kg K may be written kJ/kg°C.

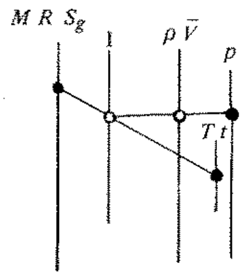
Values of Molecular Weight, Specific Gravity, Individual Gas Constant and Specific Heat abstracted from or based on Table 24 in Mark's "Standard Handbook for Mechanical Engineers", Seventh Edition, 1966 – approximate values adapted from a number of sources.[22]

Values of Densities obtained by multiplying density of dry air at 20°C, 1.01325 bar, by specific gravity of gas, i.e. 1.2045 x S_g. Density of air, from "Thermodynamic and Transport Properties of Fluids", Y. R. Mayhew and G. F. C. Rogers, 1972.[14]

Steam – Values of Isentropic Exponent, γ [20]



Density and Specific Volume
Of Gases and Vapours



The chart on page A-11 is based on the formula:

$$\rho = \frac{10^5 p'}{RT} = \frac{12.03 M p' Sg}{T} = \frac{349 p' Sg}{T}$$

where: $p' = 1.013 + p'$
$T = 273 + t$

Universal Gas Constant = 8314

Molecular weight of air = 29

Problem: What is the density of dry CH_4 if the temperature is 40°C and the gauge pressure is 1 bar?

Solution: Refer to the table on page A-8 for molecular weight, specific gravity or individual gas constant. Connect 519 of the R scale with 40 on the temperature scale, t, and mark the intersection with the index scale. Connect this point with 1 on the pressure scale, p. Read the answer, 1.24 kilograms per cubic metre, on the density scale, ρ.

Density of Air

Air Temp. °C	Density of Air in Kilograms per Cubic Metre For Pressures in Bar Gauge Indicated (Based on an atmospheric pressure of 1.013 25 bar and a molecular weight of 28.97)																		
	0 bar	0.5 bar	1 bar	2 bar	3 bar	4 bar	5 bar	6 bar	7 bar	8 bar	9 bar	10 bar	11 bar	12 bar	13 bar	14 bar	15 bar	16 bar	17 bar
0°	1.293	1.930	2.568	3.844	5.12	6.39	7.67	8.95	10.22	11.50	12.77	14.05	15.32	16.60	17.88	19.15	20.43	21.70	22.98
5	1.269	1.896	2.522	3.775	5.03	6.28	7.53	8.78	10.04	11.29	12.54	13.80	15.05	16.30	17.55	18.81	20.06	21.31	22.56
10	1.247	1.862	2.477	3.708	4.93	6.17	7.40	8.63	9.86	11.09	12.32	13.55	14.78	16.01	17.24	18.47	19.71	20.94	22.17
15	1.225	1.830	2.435	3.644	4.85	6.06	7.27	8.48	9.69	10.90	12.11	13.32	14.53	15.74	16.95	18.15	19.36	20.57	21.78
20	1.204	1.799	2.393	3.581	4.77	5.96	7.15	8.34	9.52	10.71	11.90	13.09	14.28	15.47	16.66	17.84	19.03	20.22	21.41
25	1.184	1.768	2.353	3.522	4.69	5.86	7.03	8.20	9.37	10.53	11.70	12.87	14.04	15.21	16.38	17.55	18.71	19.88	21.05
30	1.165	1.739	2.314	3.463	4.61	5.76	6.91	8.06	9.21	10.36	11.51	12.66	13.81	14.96	16.11	17.26	18.41	19.55	20.70
35	1.146	1.711	2.277	3.407	4.54	5.67	6.80	7.93	9.06	10.19	11.32	12.45	13.58	14.72	15.85	16.98	18.11	19.24	20.37
40	1.127	1.684	2.240	3.353	4.47	5.58	6.69	7.80	8.92	10.03	11.14	12.25	13.37	14.48	15.59	16.71	17.82	18.93	20.04
50	1.093	1.632	2.171	3.249	4.33	5.41	6.48	7.56	8.64	9.72	10.80	11.88	12.95	14.03	15.11	16.19	17.27	18.35	19.42
60	1.060	1.583	2.106	3.152	4.20	5.24	6.29	7.33	8.38	9.43	10.47	11.52	12.56	13.61	14.66	15.70	16.75	17.79	18.84
70	1.028	1.537	2.044	3.060	4.08	5.09	6.11	7.12	8.14	9.15	10.17	11.18	12.20	13.21	14.23	15.24	16.26	17.28	18.29
80	1.0	1.493	1.986	2.973	3.960	4.95	5.93	6.92	7.91	8.89	9.88	10.87	11.85	12.84	13.83	14.81	15.80	16.79	17.77
90	0.972	1.452	1.932	2.891	3.851	4.81	5.77	6.73	7.69	8.65	9.61	10.57	11.53	12.49	13.45	14.41	15.36	16.32	17.28
100	0.946	1.413	1.880	2.814	3.748	4.68	5.62	6.55	7.48	8.42	9.35	10.28	11.22	12.15	13.09	14.02	14.95	15.89	16.82
120	0.898	1.342	1.784	2.671	3.557	4.44	5.33	6.21	7.10	7.99	8.87	9.76	10.65	11.53	12.42	13.31	14.19	15.08	15.97
140	0.855	1.276	1.698	2.541	3.385	4.23	5.07	5.91	6.76	7.60	8.45	9.29	10.13	10.97	11.82	12.66	13.51	14.35	15.19
160	0.815	1.217	1.620	2.424	3.229	4.03	4.84	5.64	6.45	7.25	8.06	8.86	9.66	10.47	11.27	12.08	12.88	13.69	14.49
180	0.779	1.164	1.548	2.317	3.086	3.855	4.62	5.39	6.16	6.93	7.70	8.47	9.24	10.01	10.77	11.54	12.31	13.08	13.85
200	0.746	1.114	1.483	2.219	2.955	3.692	4.43	5.16	5.90	6.64	7.37	8.11	8.85	9.58	10.32	11.06	11.79	12.53	13.26
220	0.716	1.069	1.423	2.129	2.836	3.542	4.25	4.96	5.66	6.37	7.08	7.78	8.49	9.20	9.90	10.61	11.31	12.02	12.73
240	0.688	1.027	1.367	2.046	2.725	3.404	4.08	4.76	5.44	6.12	6.80	7.48	8.16	8.84	9.51	10.19	10.87	11.55	12.23
260	0.662	0.989	1.316	1.969	2.623	3.277	3.930	4.58	5.24	5.89	6.54	7.20	7.85	8.51	9.16	9.81	10.47	11.12	11.77
280	0.638	0.953	1.268	1.898	2.528	3.158	3.788	4.42	5.05	5.68	6.31	6.94	7.57	8.20	8.83	9.46	10.09	10.72	11.35
300	0.616	0.920	1.224	1.832	2.440	3.048	3.656	4.26	4.87	5.48	6.09	6.70	7.30	7.91	8.52	9.13	9.74	10.34	10.95

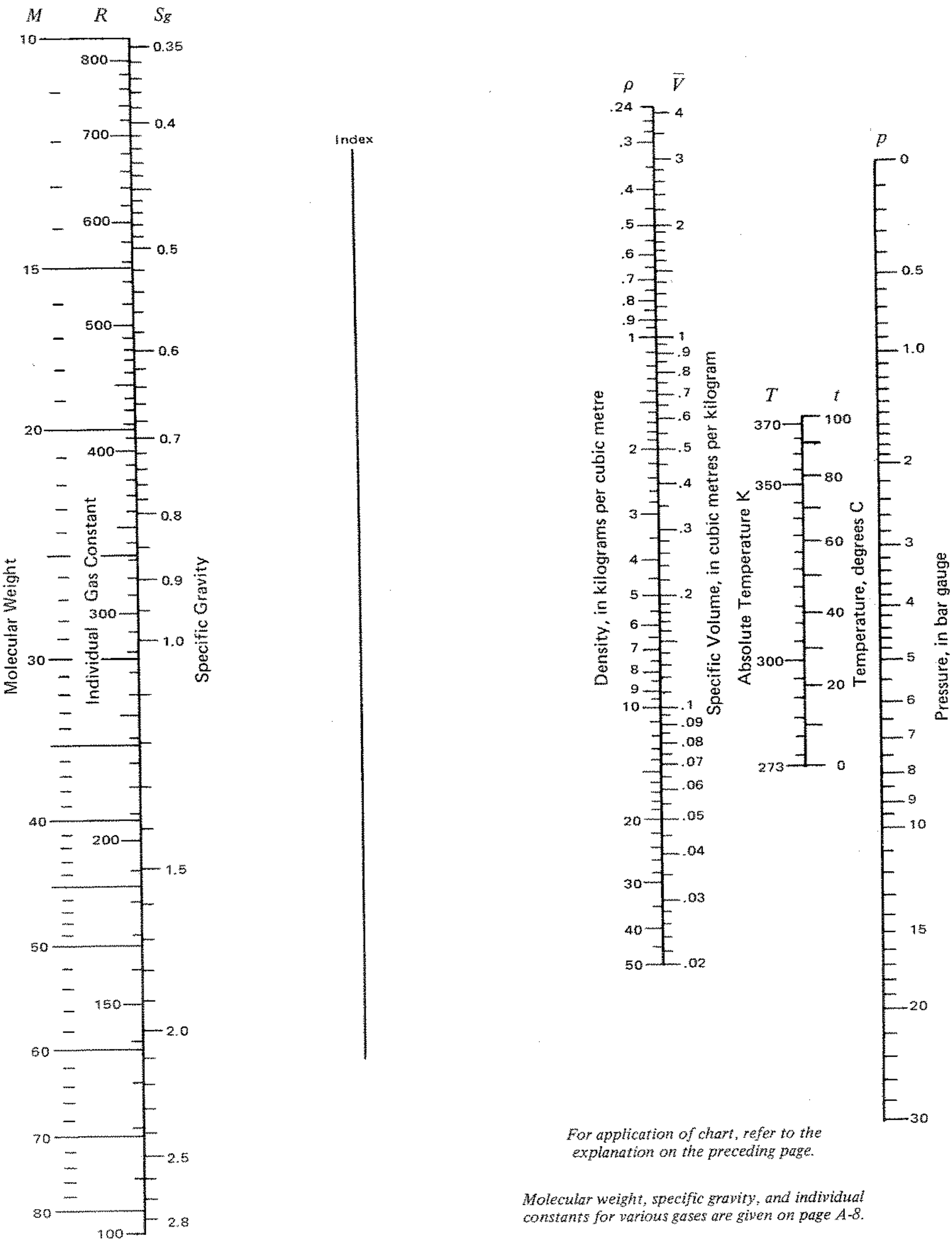
Air Temp. °C	18 bar	19 bar	20 bar	30 bar	40 bar	50 bar	60 bar	70 bar	80 bar
0°	24.25	25.53	26.81	39.6	52.3	65.1	77.8	90.6	103.3
5	23.82	25.07	26.32	38.8	51.4	63.9	76.4	89.0	101.5
10	23.40	24.63	25.86	38.2	50.5	62.8	75.1	87.4	99.7
15	22.99	24.20	25.41	37.5	49.6	61.7	73.8	85.9	98.0
20	22.56	23.79	24.98	36.9	48.7	60.6	72.5	84.4	96.3
25	22.22	23.39	24.56	36.2	47.9	59.6	71.3	83.0	94.7
30	21.85	23.00	24.15	35.6	47.1	58.6	70.1	81.6	93.1
35	21.50	22.63	23.76	35.1	46.4	57.7	69.0	80.3	91.6
40	21.16	22.27	23.38	34.5	45.6	56.8	67.9	79.0	90.1
50	20.50	21.58	22.66	33.4	44.2	55.0	65.8	76.6	87.4
60	19.88	20.93	21.98	32.4	42.9	53.4	63.8	74.3	84.7
70	19.31	20.32	21.34	31.5	41.6	51.8	61.9	72.1	82.3
80	18.76	19.75	20.73	30.6	40.5	50.3	60.2	70.1	79.9
90	18.24	19.20	20.16	29.76	39.4	48.9	58.5	68.1	77.7
100	17.75	18.69	19.62	28.96	38.3	47.6	57.0	66.3	75.6
120	16.85	17.74	18.62	27.49	36.4	45.2	54.1	62.9	71.8
140	16.04	16.88	17.72	26.17	34.6	43.0	51.5	59.9	68.3
160	15.30	16.10	16.91	24.95	33.0	41.0	49.1	57.1	65.2
180	14.62	15.34	16.16	23.85	31.5	39.2	46.9	54.6	62.3
200	14.00	14.74	15.47	22.84	30.2	37.6	44.9	52.3	59.7
220	13.43	14.14	14.85	21.91	28.98	36.0	43.1	50.2	57.2
240	12.91	13.59	14.27	21.06	27.85	34.6	41.4	48.2	55.0
260	12.43	13.08	13.73	20.27	26.81	33.3	39.9	46.4	53.0
280	11.98	12.61	13.24	19.54	25.83	32.1	38.4	44.7	51.0
300	11.56	12.17	12.78	18.86	24.94	31.0	37.1	43.2	49.3

Air Density Table

The table at the left is calculated for the perfect gas law shown at the top of the page. Correction for super-compressibility, the deviation from the perfect gas law, would be less than three percent and has not been applied.

The density of gases other than air can be determined from this table by multiplying the density listed for air by the specific gravity of the gas relative to air, as listed in the tables on page A-8.

Density and Specific Volume of Gases and Vapours – continued



For application of chart, refer to the explanation on the preceding page.

Molecular weight, specific gravity, and individual constants for various gases are given on page A-8.

Volumetric Composition and Specific Gravity* of Gaseous Fuels[13, 30]

	Type of Gas	Chemical Composition Percent by Volume: Hydrogen	Carbon Monoxide	Methane	Ethane	Propane	Pentanes and above	Butane	Ethylene	Benzine	Oxygen	Nitrogen	Carbon Dioxide	Specific Gravity relative to Air S_g
1	Natural Gas, Pittsburgh			83.4	15.8							0.8		0.61
2	Producer Gas from Bituminous Coal	14.0	27.0	3.0							0.6	50.9	4.5	0.86
3	Blast Furnace Gas	1.0	27.5									60.0	11.5	1.02
4	Blue Water Gas from Coke	47.3	37.0	1.3							0.7	8.3	5.4	0.57
5	Carbureted Water Gas	40.5	34.0	10.2					6.1	2.8	0.5	2.9	3.0	0.63
6	Coal Gas (Cont. Vertical Retorts)	54.5	10.9	24.2					1.5	1.3	0.2	4.4	3.0	0.42
7	Coke-Oven Gas	46.5	6.3	32.1					3.5	0.5	0.8	8.1	2.2	0.44
8	Refinery Oil Gas (Vapour Phase)	13.1	1.2	23.3	21.7			21.7	39.6		1.0		0.1	0.89
9	Oil Gas, Pacific Coast	48.6	12.7	26.3					2.7	1.1	0.3	3.6	4.7	0.47
	Typical North Sea Gases –													
10	West Sole			94.0	3.3	0.6	0.2	0.2				1.2	0.5	0.594
11	Leman Bank			94.8	3.0	0.6	0.2	0.2				1.2	0.0	0.588
12	Indefatigable			91.4	3.6	0.9	0.2	0.4				3.0	0.5	0.609
13	Hewett (Lower Bunter)			92.6	3.6	0.9	0.3	0.4				2.2	0.0	0.603
14	Hewett (Upper Bunter)			81.9	6.0	2.5	0.2	0.4				8.9	0.1	0.657
15	Viking			90.8	4.3	1.1	0.3	0.5				2.5	0.5	0.616

*Relative Density

Gases 1 to 9 reproduced by permission from 'Mechanical Engineers' Handbook' by L S Marks, 5th Edition, McGraw-Hill Book Company, Inc.[13]

Gases 10 to 15 – data extracted from a report prepared by a Working Group of the IGU on Gas Interchangeability, May 1976.[30]

Properties of Saturated Steam

S.I. Units

Abs. Press. bar	Temp. °C	Specific Vol. dm³/kg	Specific Enthalpy kJ/kg			Abs. Press. bar	Temp. °C	Specific Vol. dm³/kg	Specific Enthalpy kJ/kg		
p'_s	t_s	$\bar{v}_g$	h_f	h_{fg}	h_g	p'_s	t_s	$\bar{v}_g$	h_f	h_{fg}	h_g
0.1	45.833	14674.6	191.8	2392.9	2584.8	6.0	158.838	315.47	670.4	2085.0	2755.5
0.2	60.086	7649.8	251.5	2358.4	2609.9	6.2	160.123	305.85	676.0	2080.9	2756.9
0.3	69.124	5229.3	289.3	2336.1	2625.4	6.4	161.376	296.81	681.5	2076.8	2758.2
0.4	75.886	3993.4	317.7	2319.2	2636.9	6.6	162.598	288.30	686.8	2072.7	2759.5
						6.8	163.791	280.27	692.0	2068.8	2760.8
0.5	81.345	3240.2	340.6	2305.4	2646.0	7.0	164.956	272.68	697.1	2064.9	2762.0
0.6	85.954	2731.8	359.9	2293.6	2653.6	7.2	166.095	265.50	702.0	2061.1	2763.2
0.7	89.959	2364.7	376.8	2283.3	2660.1	7.4	167.209	258.70	706.9	2057.4	2764.3
0.8	93.512	2087.0	391.7	2274.0	2665.8	7.6	168.300	252.24	711.7	2053.7	2765.4
0.9	96.713	1869.2	405.2	2265.6	2670.9	7.8	169.368	246.10	716.3	2050.1	2766.4
1.0	99.632	1693.7	417.5	2257.9	2675.4	8.0	170.415	240.26	720.9	2046.5	2767.5
1.1	102.317	1549.2	428.8	2250.8	2679.6	8.2	171.441	234.69	725.4	2043.0	2768.5
1.2	104.808	1428.1	439.4	2244.1	2683.4	8.4	172.448	229.38	729.9	2039.6	2769.4
1.3	107.133	1325.1	449.2	2237.8	2687.0	8.6	173.436	224.30	734.2	2036.2	2770.4
1.4	109.315	1236.3	458.4	2231.9	2690.3	8.8	174.405	219.45	738.5	2032.8	2771.3
1.5	111.372	1159.0	467.1	2226.2	2693.4	9.0	175.358	214.81	742.6	2029.5	2772.1
1.6	113.320	1091.1	475.4	2220.9	2696.2	9.2	176.294	210.36	746.8	2026.2	2773.0
1.7	115.170	1030.9	483.2	2215.7	2699.0	9.4	177.214	206.10	750.8	2023.0	2773.8
1.8	116.933	977.23	490.7	2210.8	2701.5	9.6	178.119	202.01	754.8	2019.8	2774.6
1.9	118.617	929.00	497.8	2206.1	2704.0	9.8	179.009	198.07	758.7	2016.7	2775.4
2.0	120.231	885.44	504.7	2201.6	2706.3	10.0	179.884	194.29	762.6	2013.6	2776.2
2.1	121.780	845.90	511.3	2197.2	2708.5	10.5	182.015	185.45	772.0	2005.9	2778.0
2.2	123.270	809.89	517.6	2193.0	2710.6	11.0	184.067	177.38	781.1	1998.5	2779.7
2.3	124.705	776.81	523.7	2188.9	2712.6	11.5	186.048	169.99	789.9	1991.3	2781.3
2.4	126.091	746.45	529.6	2184.9	2714.5	12.0	187.961	163.20	798.4	1984.3	2782.7
2.5	127.430	718.44	535.3	2181.0	2716.4	12.5	189.814	156.93	806.7	1977.4	2784.1
2.6	128.727	692.51	540.9	2177.3	2718.2	13.0	191.609	151.13	814.7	1970.7	2785.4
2.7	129.984	668.44	546.2	2173.6	2719.9	13.5	193.350	145.74	822.5	1964.2	2786.6
2.8	131.203	646.04	551.4	2170.1	2721.5	14.0	195.042	140.72	830.1	1957.7	2787.8
2.9	132.388	625.13	556.5	2166.6	2723.1	14.5	196.688	136.04	837.5	1951.4	2788.9
3.0	133.540	605.56	561.4	2163.2	2724.7	15.0	198.289	131.66	844.7	1945.2	2789.9
3.1	134.661	587.22	566.2	2159.9	2726.1	15.5	199.850	127.55	851.7	1939.2	2790.8
3.2	135.753	569.99	570.9	2156.7	2727.6	16.0	201.372	123.69	858.6	1933.2	2791.7
3.3	136.819	553.76	575.5	2153.5	2729.0	16.5	202.857	120.05	865.3	1927.3	2792.6
3.4	137.858	538.46	579.9	2150.4	2730.3	17.0	204.307	116.62	871.8	1921.5	2793.4
3.5	138.873	524.00	584.3	2147.4	2731.6	17.5	205.725	113.38	878.3	1915.9	2794.1
3.6	139.865	510.32	588.5	2144.4	2732.9	18.0	207.111	110.32	884.6	1910.3	2794.8
3.7	140.835	497.36	592.7	2141.4	2734.1	18.5	208.468	107.41	890.7	1904.7	2795.5
3.8	141.784	485.05	596.8	2138.6	2735.3	19.0	209.797	104.65	896.8	1899.3	2796.1
3.9	142.713	473.36	600.8	2135.7	2736.5	19.5	211.099	102.03	902.8	1893.9	2796.7
4.0	143.623	462.22	604.7	2133.0	2737.6	20.0	212.375	99.536	908.6	1888.6	2797.2
4.2	145.390	441.50	612.3	2127.5	2739.8	21.0	214.855	94.890	920.0	1878.2	2798.2
4.4	147.090	422.60	619.6	2122.3	2741.9	22.0	217.244	90.652	931.0	1868.1	2799.1
4.6	148.729	405.28	626.7	2117.2	2743.9	23.0	219.552	86.769	941.6	1858.2	2799.8
4.8	150.313	389.36	633.5	2112.2	2745.7	24.0	221.783	83.199	951.9	1848.5	2800.4
5.0	151.844	374.68	640.1	2107.4	2747.5	25.0	223.943	79.905	962.0	1839.0	2800.9
5.2	153.327	361.08	646.5	2102.7	2749.3	26.0	226.037	76.856	971.7	1829.6	2801.4
5.4	154.765	348.46	652.8	2098.1	2750.9	27.0	228.071	74.025	981.2	1820.5	2801.7
5.6	156.161	336.71	658.8	2093.7	2752.5	28.0	230.047	71.389	990.5	1811.5	2802.0
5.8	157.518	325.74	664.7	2089.3	2754.0	29.0	231.969	68.928	999.5	1802.6	2802.2

Refer to page A-14 for units and notations.

Properties of Saturated Steam

S.I. Units – continued

Abs. Press. bar	Temp. °C	Specific Vol. dm^3/kg	Specific Enthalpy kJ/kg			Abs. Press. bar	Temp. °C	Specific Vol. dm^3/kg	Specific Enthalpy kJ/kg		
p_s'	t_s	v_g	h_f	h_{fg}	h_g	p_s'	t_s	v_g	h_f	h_{fg}	h_g
30.0	233.841	66.626	1008.4	1793.9	2802.3	90.0	303.306	20.495	1363.7	1380.9	2744.6
31.0	235.666	64.467	1017.0	1785.4	2802.3	92.0	304.887	19.964	1372.8	1368.6	2741.4
32.0	237.445	62.439	1025.4	1776.9	2802.3	94.0	306.443	19.455	1381.7	1356.3	2738.0
33.0	239.183	60.529	1033.7	1768.6	2802.3	96.0	307.973	18.965	1390.6	1344.1	2734.7
34.0	240.881	58.728	1041.8	1760.3	2802.1	98.0	309.479	18.494	1399.3	1331.9	2731.2
35.0	242.541	57.025	1049.8	1752.2	2802.0	100.0	310.961	18.041	1408.0	1319.7	2727.7
36.0	244.164	55.415	1057.6	1744.2	2801.7	104.0	313.858	17.184	1425.2	1295.3	2720.6
37.0	245.754	53.888	1065.2	1736.2	2801.4	108.0	316.669	16.385	1442.2	1270.9	2713.1
38.0	247.311	52.438	1072.7	1728.4	2801.1	112.0	319.402	15.639	1458.9	1246.5	2705.4
39.0	248.836	51.061	1080.1	1720.6	2800.8	116.0	322.059	14.940	1475.4	1222.0	2697.4
40.0	250.333	49.749	1087.4	1712.9	2800.3	120.0	324.646	14.283	1491.8	1197.4	2689.2
41.0	251.800	48.500	1094.6	1705.3	2799.9	124.0	327.165	13.664	1508.0	1172.6	2680.6
42.0	253.241	47.307	1101.6	1697.8	2799.4	128.0	329.621	13.078	1524.0	1147.6	2671.6
43.0	254.656	46.168	1108.5	1690.3	2798.9	132.0	332.018	12.523	1540.0	1122.3	2662.3
44.0	256.045	45.080	1115.4	1682.9	2798.3	136.0	334.357	11.996	1555.8	1096.7	2652.5
45.0	257.411	44.037	1122.1	1675.6	2797.7	140.0	336.641	11.495	1571.6	1070.7	2642.4
46.0	258.753	43.039	1128.8	1668.3	2797.0	144.0	338.874	11.017	1587.4	1044.4	2631.8
47.0	260.074	42.081	1135.3	1661.1	2796.4	148.0	341.057	10.561	1603.1	1017.6	2620.7
48.0	261.373	41.161	1141.8	1653.9	2795.7	152.0	343.193	10.125	1618.9	990.3	2609.2
49.0	262.652	40.278	1148.2	1646.8	2794.9	156.0	345.282	9.7072	1634.7	962.6	2597.3
50.0	263.911	39.429	1154.5	1639.7	2794.2	160.0	347.328	9.3076	1650.5	934.3	2584.9
52.0	266.373	37.824	1166.8	1625.7	2792.6	164.0	349.332	8.9248	1666.5	905.6	2572.1
54.0	268.763	36.334	1178.9	1611.9	2790.8	168.0	351.295	8.5535	1683.0	873.3	2556.3
56.0	271.086	34.947	1190.8	1598.2	2789.0	172.0	353.220	8.1912	1700.4	842.6	2543.0
58.0	273.347	33.651	1202.3	1584.7	2787.0	176.0	355.106	7.8395	1717.6	811.1	2528.7
60.0	275.550	32.438	1213.7	1571.3	2785.0	180.0	356.957	7.4977	1734.8	778.6	2513.4
62.0	277.697	31.300	1224.8	1558.0	2782.9	184.0	358.771	7.1647	1752.1	745.0	2497.1
64.0	279.791	30.230	1235.7	1544.9	2780.6	188.0	360.552	6.8386	1769.7	710.0	2479.7
66.0	281.837	29.223	1246.5	1531.9	2778.3	192.0	362.301	6.5173	1787.8	673.3	2461.0
68.0	283.835	28.272	1257.0	1518.9	2775.9	196.0	364.107	6.1979	1806.6	634.2	2440.7
70.0	285.790	27.373	1267.4	1506.0	2773.5	200.0	365.701	5.8767	1826.5	591.9	2418.4
72.0	287.702	26.522	1277.6	1493.3	2770.9	204.0	367.356	5.5485	1848.1	545.2	2393.3
74.0	289.574	25.715	1287.7	1480.5	2768.3	208.0	368.982	5.2051	1872.5	491.7	2364.3
76.0	291.408	24.949	1297.6	1467.9	2765.5	212.0	370.580	4.8314	1901.5	427.4	2328.9
78.0	293.205	24.220	1307.4	1455.3	2762.8	216.0	372.149	4.3919	1939.9	341.6	2281.6
80.0	294.968	23.525	1317.1	1442.8	2759.9	220.0	373.692	3.7279	2011.1	184.5	2195.6
82.0	296.697	22.863	1326.6	1430.3	2757.0						
84.0	298.394	22.231	1336.1	1417.9	2754.0	221.2	374.150	3.1700	2107.4	0.0	2107.4
86.0	300.060	21.627	1345.4	1405.5	2750.9						
88.0	301.697	21.049	1354.6	1393.2	2747.8						

These tables of properties of saturated and superheated steam have been extracted from "Steam Tables in S.I. Units–Thermodynamic Properties of Water and Steam" by permission of the authors and publishers, the Central Electricity Generating Board.

Units and Notation

Quantity	Symbol	Unit
Pressure	p'	bar ($10^5 N/m^2$) abs.
Temperature	t	°C
Specific Volume	$\bar{v}$	dm^3/kg ($10^{-3} m^3/kg$)
Specific Enthalpy	h	kJ/kg(10^3 J/kg)

The following suffixes are used for saturation values:

s	saturation
f	saturated liquid
g	saturated vapour
fg	evaporation increment

Absolute pressure = Gauge pressure + 1.013 bar approx.

One bar = $10^5 N/m^2$ = 14.5 lbf/in² approx.

Properties of Superheated Steam

S.I. Units

Abs. Press. bar p'	Sat. Temp. °C t_s		Total Temperature: Degrees Celsius t°C										
			160	180	200	220	250	300	350	400	450	550	650
1.0	99.6	$\bar{v}$	1983.8	2078.3	2172.3	2266.0	2406.1	2638.7	2870.8	3102.5	3334.0	3796.5	4258.8
		h	2796.2	2835.8	2875.4	2915.0	2974.5	3074.5	3175.6	3278.2	3382.4	3595.6	3815.7
1.2	104.8	$\bar{v}$	1650.5	1729.7	1808.4	1886.7	2003.7	2197.9	2391.5	2584.7	2777.7	3163.4	3548.7
		h	2794.8	2834.6	2874.4	2914.1	2973.9	3074.0	3175.3	3277.9	3382.1	3595.4	3815.5
1.4	109.3	$\bar{v}$	1412.5	1480.7	1548.4	1615.7	1716.3	1883.0	2049.1	2214.9	2380.4	2711.1	3041.5
		h	2793.4	2833.5	2873.4	2913.3	2973.2	3073.5	3174.9	3277.6	3381.3	3595.2	3815.4
1.8	116.9	$\bar{v}$	1095.1	1148.7	1201.7	1254.4	1333.0	1463.1	1592.6	1721.8	1850.7	2108.1	2365.2
		h	2790.5	2831.1	2871.5	2911.7	2971.9	3072.6	3174.1	3277.0	3381.8	3594.9	3815.1
2.2	123.3	$\bar{v}$	893.09	937.36	981.13	1024.5	1089.1	1195.9	1302.1	1408.0	1513.6	1724.4	1934.9
		h	2787.7	2828.8	2869.5	2910.0	2970.6	3071.6	3173.4	3276.4	3380.8	3594.5	3814.8
2.6	128.7	$\bar{v}$	753.19	791.04	828.38	865.34	920.27	1010.9	1101.0	1190.7	1280.2	1458.7	1637.0
		h	2784.8	2826.4	2867.5	2908.3	2969.2	3070.6	3172.6	3275.8	3380.3	3594.1	3814.5
3.0	133.5	$\bar{v}$	650.57	683.72	716.35	748.59	796.44	875.29	953.52	1031.4	1109.0	1263.9	1418.5
		h	2781.8	2824.0	2865.5	2906.6	2967.9	3069.7	3171.9	3275.2	3379.8	3593.7	3814.2
4.0	143.6	$\bar{v}$	483.71	509.26	534.26	558.85	595.19	654.85	713.85	772.50	830.92	947.35	1063.4
		h	2774.2	2817.8	2860.4	2902.3	2964.5	3067.2	3170.0	3273.6	3378.5	3592.8	3813.5
5.0	151.8	$\bar{v}$	383.47	404.51	424.96	444.97	474.43	522.58	570.05	617.16	664.05	757.41	850.42
		h	2766.4	2811.4	2855.1	2898.0	2961.1	3064.8	3168.1	3272.1	3377.2	3591.8	3812.8
6.0	158.8	$\bar{v}$	316.55	334.61	352.04	369.02	393.91	434.39	474.19	513.61	552.80	630.78	708.41
		h	2758.2	2804.8	2849.7	2893.5	2957.6	3062.3	3166.2	3270.6	3376.0	3590.9	3812.1
7.0	165.0	$\bar{v}$		284.61	299.92	314.75	336.37	371.39	405.71	439.64	473.34	540.33	606.97
		h		2798.0	2844.2	2888.9	2954.0	3059.8	3164.3	3269.0	3374.7	3589.9	3811.4
8.0	170.4	$\bar{v}$		247.06	260.79	274.02	293.21	324.14	354.34	384.16	413.74	472.49	530.89
		h		2791.1	2838.6	2884.2	2950.4	3057.3	3162.4	3267.5	3373.4	3589.0	3810.7
9.0	175.4	$\bar{v}$		217.71	230.32	242.31	259.63	287.39	314.39	341.01	367.39	419.73	471.72
		h		2783.9	2832.7	2879.5	2946.8	3054.7	3160.5	3265.9	3372.1	3588.1	3810.0
10.0	179.9	$\bar{v}$		194.36	205.92	216.93	232.75	257.98	282.43	306.49	330.30	377.52	424.38
		h		2776.5	2826.8	2874.6	2943.0	3052.1	3158.5	3264.4	3370.8	3587.1	3809.3
11.0	184.1	$\bar{v}$			185.92	196.14	210.75	233.91	256.28	278.24	299.96	342.98	385.65
		h			2820.7	2869.6	2939.3	3049.6	3156.6	3262.9	3369.5	3586.2	3808.5
12.0	188.0	$\bar{v}$			169.23	178.80	192.40	213.85	234.49	254.70	274.68	314.20	353.38
		h			2814.4	2864.5	2935.4	3046.9	3154.6	3261.3	3368.2	3585.2	3807.8
13.0	191.6	$\bar{v}$			155.09	164.11	176.87	196.87	216.05	234.79	253.28	289.85	326.07
		h			2808.0	2859.3	2931.5	3044.3	3152.7	3259.7	3366.9	3584.3	3807.1
14.0	195.0	$\bar{v}$			142.94	151.50	163.55	182.32	200.24	217.72	234.95	268.98	302.66
		h			2801.4	2854.0	2927.6	3041.6	3150.7	3258.2	3365.6	3583.3	3806.4
16.0	201.4	$\bar{v}$				130.98	141.87	158.66	174.54	189.97	205.15	235.06	264.62
		h				2843.1	2919.4	3036.2	3146.7	3255.0	3363.0	3581.4	3805.0
18.0	207.1	$\bar{v}$				114.96	124.99	140.24	154.55	168.39	181.97	208.68	235.03
		h				2831.7	2911.0	3030.7	3142.7	3251.9	3360.4	3579.5	3803.6
20.0	212.4	$\bar{v}$				102.09	111.45	125.50	138.56	151.13	163.42	187.57	211.36
		h				2819.9	2902.4	3025.0	3138.6	3248.7	3357.8	3577.6	3802.1
22.0	217.2	$\bar{v}$				91.520	100.35	113.43	125.47	137.00	148.25	170.30	192.00
		h				2807.5	2893.4	3019.3	3134.5	3245.5	3355.2	3575.7	3800.7
24.0	221.8	$\bar{v}$					91.075	103.36	114.55	125.22	135.61	155.91	175.86
		h					2884.2	3013.4	3130.3	3242.3	3352.6	3573.8	3799.3

$\bar{v}$ = specific volume, cubic decimetres per kilogram
h = specific enthalpy (total heat), kilojoules per kilogram
Note. To convert $\bar{v}$ dm³/kg to $\bar{V}$ m³/kg divide values of $\bar{v}$ by 10^3

Properties of Superheated Steam

S.I. Units — continued

Abs. Press. bar p'	Sat. Temp. °C t_s		Total Temperature: Degrees Celsius t °C										
			260	280	300	320	340	380	420	460	500	550	650
26.0	226.0	$\bar{v}$	85.671	90.370	94.830	99.117	103.28	111.33	119.14	126.81	134.38	143.74	162.21
		h	2903.0	2956.7	3007.4	3056.0	3103.0	3194.3	3283.5	3372.1	3460.6	3571.9	3797.9
27.0	228.1	$\bar{v}$	82.111	86.695	91.036	95.199	99.232	107.03	114.58	121.99	129.30	138.33	156.14
		h	2898.7	2953.1	3004.4	3053.4	3100.8	3192.5	3282.0	3370.8	3459.5	3571.0	3797.1
28.0	230.0	$\bar{v}$	78.800	83.280	87.510	91.560	95.476	103.03	110.35	117.52	124.58	133.30	150.50
		h	2894.2	2949.5	3001.3	3050.8	3098.5	3190.7	3280.5	3369.5	3458.4	3570.0	3796.4
29.0	232.0	$\bar{v}$	75.714	80.098	84.226	88.170	91.978	99.315	106.41	113.35	120.18	128.62	145.26
		h	2889.7	2945.8	2998.2	3048.1	3096.2	3188.9	3279.0	3368.2	3457.3	3569.1	3795.7
30.0	233.8	$\bar{v}$	72.829	77.124	81.159	85.005	88.713	95.844	102.73	109.46	116.08	124.26	140.36
		h	2885.1	2942.0	2995.1	3045.4	3093.9	3187.0	3277.5	3367.0	3456.2	3568.1	3795.0
31.0	235.7	$\bar{v}$	70.125	74.340	78.287	82.043	85.657	92.596	99.286	105.82	112.24	120.17	135.78
		h	2880.5	2938.2	2991.9	3042.7	3091.5	3185.2	3276.0	3365.7	3455.1	3567.2	3794.3
32.0	237.4	$\bar{v}$	67.587	71.727	75.593	79.264	82.791	89.552	96.058	102.41	108.65	116.34	131.48
		h	2875.8	2934.4	2988.7	3040.0	3089.2	3183.4	3274.5	3364.4	3454.0	3566.2	3793.6
33.0	239.2	$\bar{v}$	65.198	69.269	73.061	76.652	80.098	86.691	93.026	99.200	105.27	112.74	127.45
		h	2871.0	2930.5	29.855	3037.3	3086.8	3181.5	3273.0	3363.1	3452.8	3565.3	3792.9
34.0	240.9	$\bar{v}$	62.945	66.954	70.675	74.193	77.563	83.998	90.171	96.183	102.09	109.36	123.65
		h	2866.2	2926.6	2982.2	3034.5	3084.4	3179.7	3721.5	3361.8	3451.7	3564.3	3792.1
36.0	244.2	$\bar{v}$	58.804	62.700	66.297	69.681	72.911	79.059	84.938	90.652	96.255	103.15	116.69
		h	2856.3	2918.6	2975.6	3028.9	3079.6	3175.9	3268.4	3359.2	3449.5	3562.4	3790.7
38.0	247.3	$\bar{v}$	55.082	58.885	62.372	65.639	68.746	74.638	80.255	85.702	91.038	97.596	110.46
		h	2846.1	2910.4	2968.9	3023.3	3074.8	3172.2	3265.4	3356.6	3447.2	3560.5	3789.3
40.0	250.3	$\bar{v}$	51.716	55.440	58.833	61.996	64.994	70.658	76.039	81.247	86.341	92.597	104.86
		h	2835.6	2902.0	2962.0	3017.5	3069.8	3168.4	3263.3	3354.0	3445.0	3558.6	3787.9
42.0	253.2	$\bar{v}$	48.654	52.314	55.625	58.696	61.597	67.055	72.224	77.216	82.092	88.075	99.787
		h	2824.8	2893.5	2955.0	3011.6	3064.8	3164.5	3259.2	3351.4	3442.7	3556.7	3786.4
44.0	256.0	$\bar{v}$	45.853	49.463	52.702	55.692	58.505	63.779	68.755	73.551	78.229	83.963	95.177
		h	2813.6	2884.7	2947.8	3005.7	3059.7	3160.6	3256.0	3348.8	3440.5	3554.7	3785.0
46.0	258.8	$\bar{v}$	43.278	46.849	50.027	52.944	55.679	60.785	65.587	70.204	74.702	80.209	90.967
		h	2802.0	2875.6	2940.5	2999.6	3054.6	3156.7	3252.9	3346.2	3438.2	3552.8	3783.6
48.0	261.4	$\bar{v}$		44.443	47.569	50.421	53.085	58.040	62.682	67.136	71.469	76.768	87.109
		h		2866.4	2933.1	2993.4	3049.4	3152.8	3249.7	3343.5	3435.9	3550.9	3782.1
50.0	263.9	$\bar{v}$		42.219	45.301	48.097	50.697	55.513	60.009	64.313	68.494	73.602	83.559
		h		2856.9	2925.5	2987.2	3044.1	3148.8	3246.5	3340.9	3433.7	3549.0	3780.7
52.0	266.4	$\bar{v}$		40.156	43.201	45.947	48.489	53.178	57.540	61.707	65.747	70.679	80.282
		h		2847.1	2917.8	2980.8	3038.7	3144.8	3243.3	3338.2	3431.4	3547.1	3779.3
54.0	268.8	$\bar{v}$		38.235	41.251	43.952	46.442	51.016	55.254	59.293	63.204	67.973	77.248
		h		2837.0	2909.8	2974.3	3033.3	3140.7	3240.1	3335.5	3429.1	3545.1	3777.8
56.0	271.1	$\bar{v}$		36.439	39.434	42.096	44.539	49.006	53.130	57.051	60.843	65.460	74.430
		h		2826.7	2901.7	2967.7	3027.7	3136.6	3236.9	3332.9	3426.8	3543.2	3776.4
58.0	273.3	$\bar{v}$		34.756	37.736	40.364	42.764	47.134	51.152	54.964	58.644	63.120	71.807
		h		2816.0	2893.5	2961.0	3022.2	3132.4	3233.6	3330.2	3424.5	3541.2	3775.0
60.0	275.5	$\bar{v}$		33.173	36.145	38.744	41.105	45.385	49.306	53.016	56.591	60.937	69.359
		h		2804.9	2885.0	2954.2	3016.5	3128.3	3230.3	3327.4	3422.2	3539.3	3773.5
64.0	279.8	$\bar{v}$		30.265	33.241	35.796	38.092	42.212	45.957	49.483	52.871	56.978	64.922
		h		2781.6	2867.5	2940.3	3004.9	3119.8	3223.7	3322.0	3417.6	3535.4	3770.7
68.0	283.8	$\bar{v}$			30.652	33.180	35.423	39.407	42.999	46.364	49.588	58.486	61.007
		h			2849.0	2925.8	2993.1	3111.1	3216.9	3316.5	3412.9	3531.5	3767.8
72.0	287.7	$\bar{v}$			28.321	30.839	33.041	36.910	40.368	43.591	46.668	50.381	57.527
		h			2829.5	2910.7	2980.8	3102.3	3210.1	3310.9	3408.2	3527.6	3764.9

$\bar{v}$ = specific volume, cubic decimetres per kilogram
h = specific enthalpy (total heat), kilojoules per kilogram
Note. To convert $\bar{v}$ dm^3/kg to $\bar{V}$ m^3/kg divide values of $\bar{v}$ by 10^3

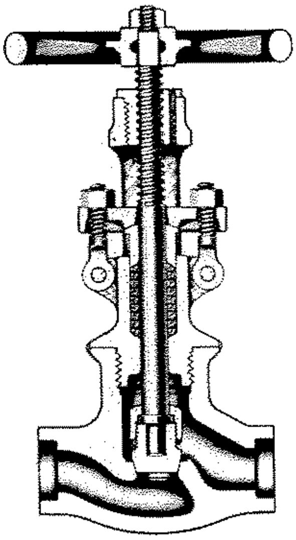
Properties of Superheated Steam

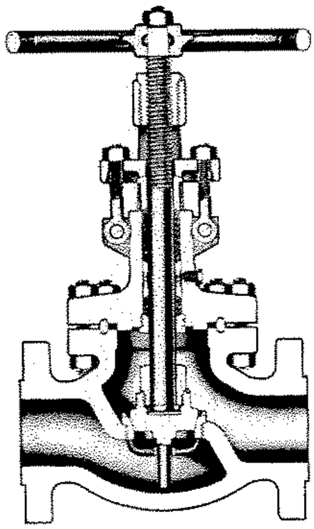
S.I. Units – continued

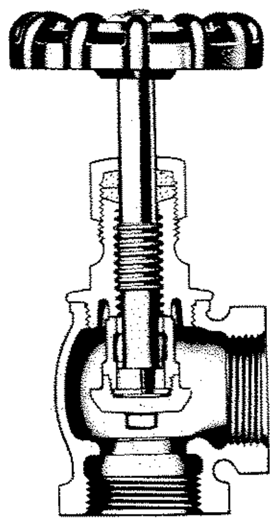
Abs. Press. bar p'	Sat. Temp. °C t_s		Total Temperature: Degrees Celsius t °C										
			340	360	380	400	420	440	460	500	550	600	650
76.0	291.4	$\bar{v}$	30.901	32.858	34.671	36.380	38.011	39.583	41.109	44.056	47.603	51.045	54.413
		h	2968.2	3033.4	3093.3	3149.6	3203.2	3254.9	3305.3	3403.5	3523.7	3642.9	3762.1
80.0	295.0	$\bar{v}$	28.965	30.885	32.652	34.310	35.888	37.405	38.874	41.704	45.102	48.394	51.611
		h	2955.3	3022.7	3084.2	3141.6	3196.2	3248.7	3299.7	3398.8	3519.7	3639.5	3759.2
84.0	298.4	$\bar{v}$	27.203	29.094	30.821	32.435	33.965	35.432	36.850	39.576	42.839	45.996	49.076
		h	2941.9	3011.7	3074.8	3133.5	3189.1	3242.3	3293.9	3394.0	3515.8	3636.2	3756.3
88.0	301.7	$\bar{v}$	25.592	27.459	29.153	30.727	32.215	33.638	35.009	37.640	40.782	43.815	46.771
		h	2928.0	3000.4	3065.3	3125.3	3181.9	3235.9	3288.2	3389.2	3511.8	3632.8	3753.4
92.0	304.9	$\bar{v}$	24.110	25.961	27.625	29.165	30.615	31.997	33.328	35.872	38.904	41.824	44.667
		h	2913.7	2988.9	3055.7	3117.0	3174.6	3229.4	3282.4	3384.4	3507.8	3629.4	3750.5
96.0	308.0	$\bar{v}$	22.740	24.581	26.221	27.730	29.146	30.493	31.785	34.252	37.182	39.999	42.738
		h	2898.8	2977.0	3045.8	3108.5	3167.2	3222.9	3276.5	3379.5	3503.9	3626.1	3747.6
100.0	311.0	$\bar{v}$	21.468	23.305	24.926	26.408	27.793	29.107	30.365	32.760	35.597	38.320	40.963
		h	2883.4	2964.8	3035.7	3099.9	3159.7	3216.2	3270.5	3374.6	3499.8	3622.7	3744.7
105.0	314.6	$\bar{v}$	19.997	21.838	23.440	24.893	26.245	27.521	28.741	31.054	33.786	36.401	38.935
		h	2863.1	2949.1	3022.8	3089.0	3150.2	3207.9	3263.1	3368.4	3494.8	3618.5	3741.1
110.0	318.0	$\bar{v}$	18.639	20.494	22.083	23.512	24.834	26.078	27.262	29.503	32.139	34.656	37.091
		h	2841.7	2932.8	3009.6	3077.8	3140.5	3199.4	3255.5	3362.2	3489.7	3614.2	3737.5
115.0	321.4	$\bar{v}$	17.376	19.255	20.838	22.247	23.543	24.758	25.911	28.086	30.635	33.063	35.408
		h	2819.0	2915.8	2996.0	3066.4	3130.7	3190.7	3247.8	3356.0	3484.7	3610.0	3733.9
120.0	324.6	$\bar{v}$	16.193	18.108	19.691	21.084	22.357	23.546	24.672	26.786	29.256	31.603	33.865
		h	2794.7	2898.1	2982.0	3054.8	3120.7	3182.0	3240.0	3349.6	3479.6	3605.7	3730.2
125.0	327.8	$\bar{v}$	15.077	17.041	18.629	20.010	21.264	22.429	23.530	25.590	27.987	30.259	32.446
		h	2768.7	2879.6	2967.6	3042.9	3110.5	3173.1	3232.2	3343.3	3474.4	3601.4	3726.6
130.0	330.8	$\bar{v}$	14.015	16.041	17.641	19.015	20.252	21.397	22.474	24.485	26.816	29.019	31.135
		h	2740.6	2860.2	2952.7	3030.7	3100.2	3164.1	3224.2	3336.8	3469.3	3597.1	3722.9
135.0	333.8	$\bar{v}$	12.994	15.102	16.720	18.090	19.313	20.439	21.496	23.461	25.731	27.870	29.922
		h	2709.9	2839.7	2937.3	3018.3	3089.7	3155.0	3216.2	3330.4	3464.1	3592.8	3719.3
140.0	336.6	$\bar{v}$	11.997	14.213	15.858	17.227	18.438	19.549	20.586	22.509	24.723	26.804	28.795
		h	2675.7	2818.1	2921.4	3005.6	3079.0	3145.8	3208.1	3323.8	3458.8	3588.5	3715.6
150.0	342.1	$\bar{v}$		12.562	14.282	15.661	16.857	17.940	18.946	20.795	22.909	24.884	26.768
		h		2770.8	2887.7	2979.1	3057.0	3126.9	3191.5	3310.6	3448.3	3579.8	3708.3
160.0	347.3	$\bar{v}$		11.036	12.871	14.275	15.464	16.527	17.506	19.293	21.320	23.203	24.994
		h		2716.5	2851.1	2951.3	3034.2	3107.5	3174.5	3297.1	3437.7	3571.0	3700.9
170.0	352.3	$\bar{v}$		9.5837	11.588	13.034	14.225	15.274	16.232	17.966	19.918	21.721	23.428
		h		2652.4	2811.0	2921.7	3010.5	3087.5	3157.2	3283.5	3427.0	3562.2	3693.5
180.0	357.0	$\bar{v}$		8.1042	10.405	11.913	13.115	14.155	15.096	16.785	18.670	20.403	22.037
		h		2568.7	2766.6	2890.3	2985.8	3066.9	3139.4	3269.6	3416.1	3553.4	3686.1
190.0	361.4	$\bar{v}$			9.2983	10.889	12.111	13.148	14.075	15.726	17.554	19.223	20.792
		h			2716.8	2856.7	2960.0	3045.6	3121.3	3255.4	3405.2	3544.5	3678.6
200.0	365.7	$\bar{v}$			8.2458	9.9470	11.197	12.236	13.154	14.771	16.548	18.161	19.672
		h			2660.2	2820.5	2932.9	3023.7	3102.7	3241.1	3394.1	3535.5	3671.1
210.0	369.8	$\bar{v}$			7.2076	9.0714	10.360	11.405	12.316	13.907	15.638	17.201	18.658
		h			2593.1	2781.3	2904.5	3001.0	3083.6	3226.5	3382.9	3526.5	3663.6
220.0	373.7	$\bar{v}$			6.1105	8.2510	9.5883	10.645	11.552	13.119	14.810	16.327	17.737
		h			2504.5	2738.8	2874.6	2977.5	3064.0	3211.7	3371.6	3517.4	3656.1

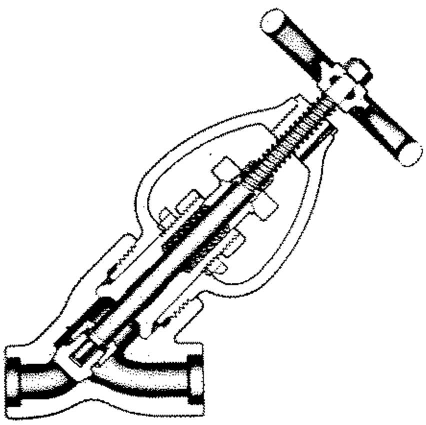
$\bar{v}$ = specific volume, cubic decimetres per kilogram
h = specific enthalpy (total heat), kilojoules per kilogram
Note. To convert $\bar{v}$ dm³/kg to $\bar{V}$ m³/kg divide values of $\bar{v}$ by 10^3

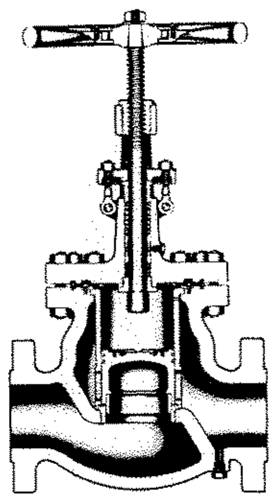
Types of Valves

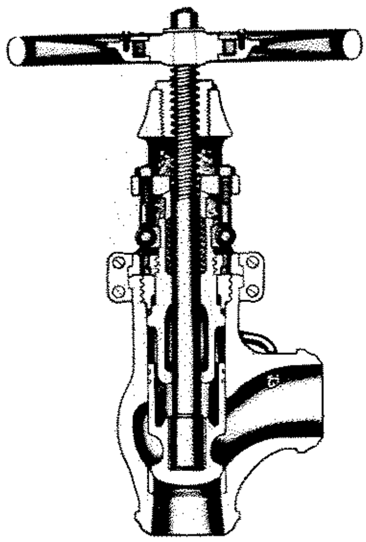

Conventional Globe Valve

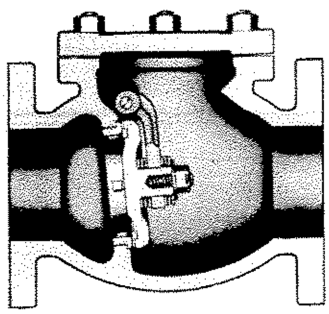

Conventional Globe Valve
With Disc Guide

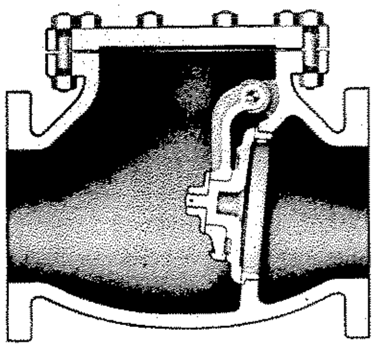

Conventional Angle Valve

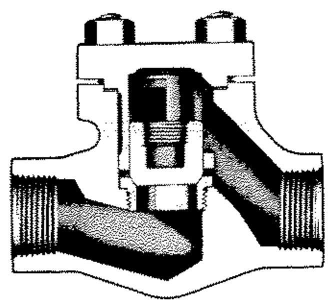

Y-Pattern Globe Valve
With Stem 45 degrees from Run


Globe Stop-Check Valve

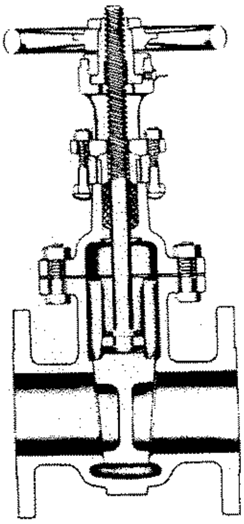

Angle Stop-Check Valve


Conventional Swing Check Valve

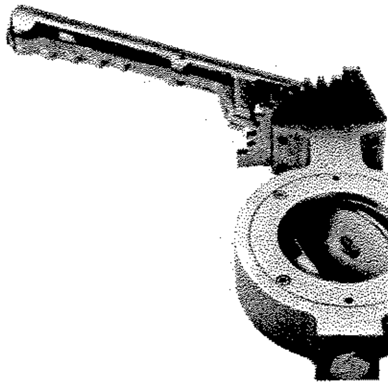

Clearway Swing Check Valve


Globe Type Lift Check Valve

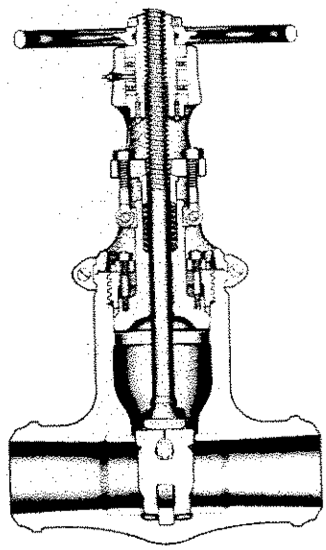
Types of Valves



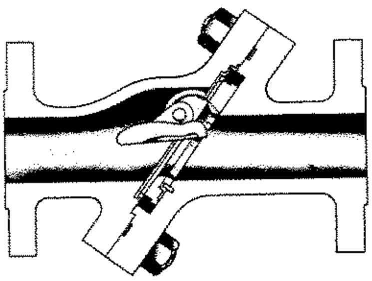
Wedge Gate Valve
(Bolted Bonnet)



High Performance Butterfly Valve

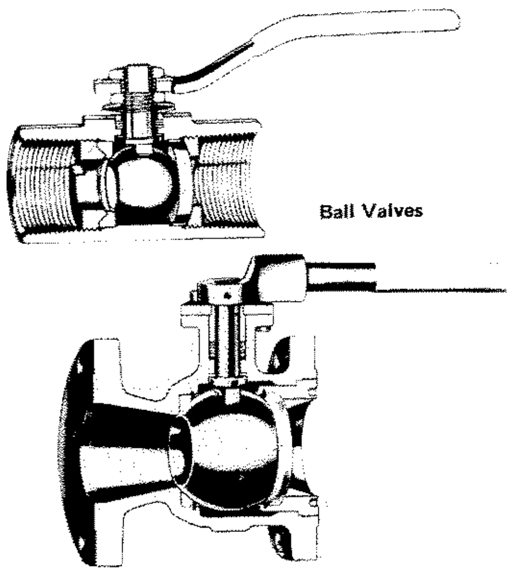


Flexible Wedge Gate Valve
(Pressure-Seal Bonnet)

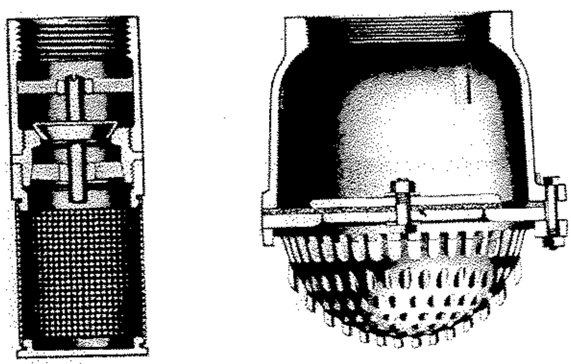


Tilting Disc Check Valve

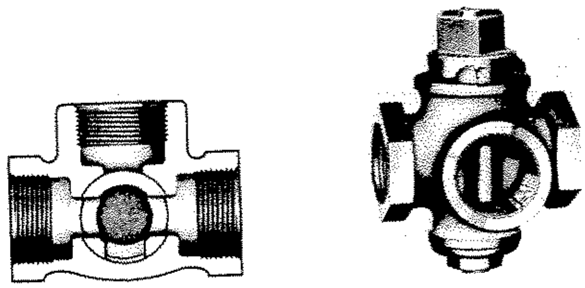
Butterfly Wafer Valve



Ball Valves

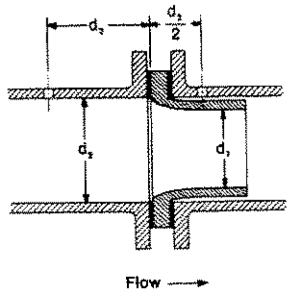


Foot Valves
Poppet and Hinged Types



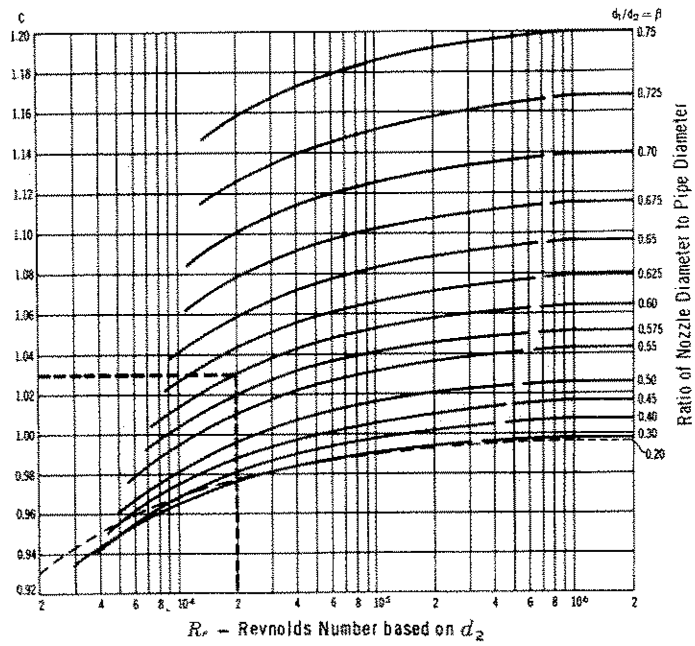
Three-Way Cock
Sectional and Outside Views

Flow Coefficient C for Nozzles[9]

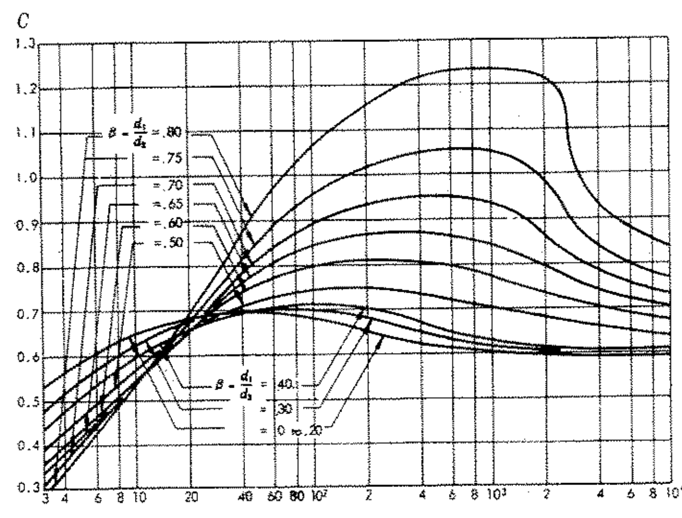


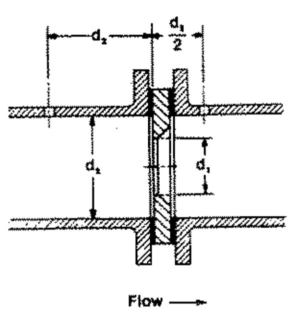
$$C = \frac{C_d}{\sqrt{1-\beta^4}}$$

Example: The flow coefficient C for a diameter ratio β of 0.60 at a Reynolds number of 20 000 (2×10^4) equals 1.03.



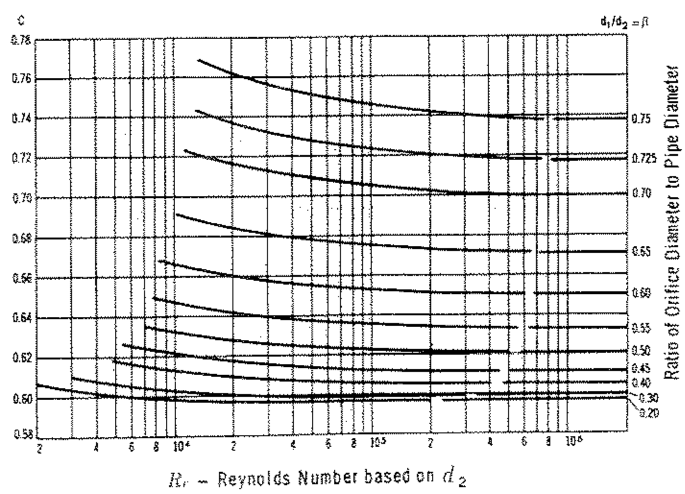
Flow Coefficient C for Square-Edge Orifices[9,17]





$$C = \frac{C_d}{\sqrt{1-\beta^4}}$$

$$K_{orifice} \simeq \frac{1-\beta^2}{C^2\beta^4}$$

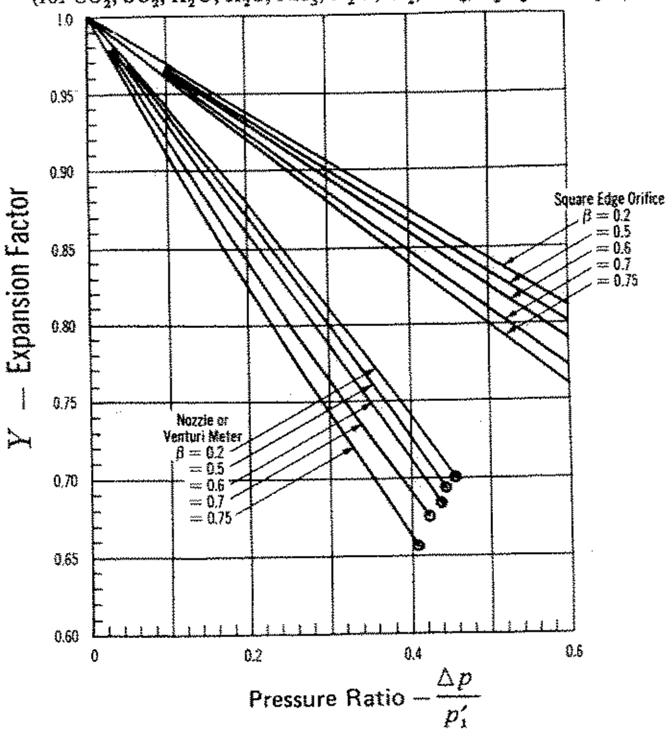


Net Expansion Factor, Y

For Compressible Flow through Nozzles and Orifices[9]

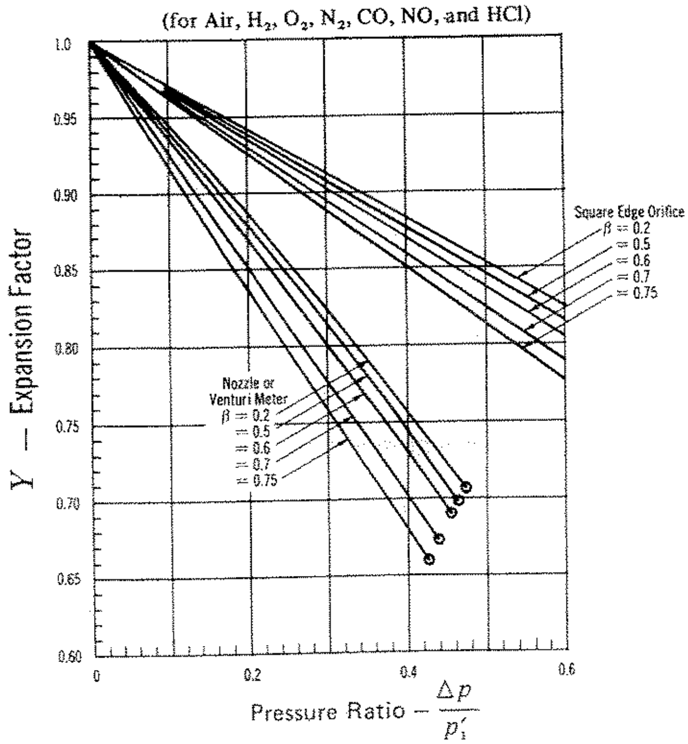
γ = **1.3** approximately

(for CO_2, SO_2, H_2O, H_2S, NH_3, N_2O, Cl_2, CH_4, C_2H_2, and C_2H_4)



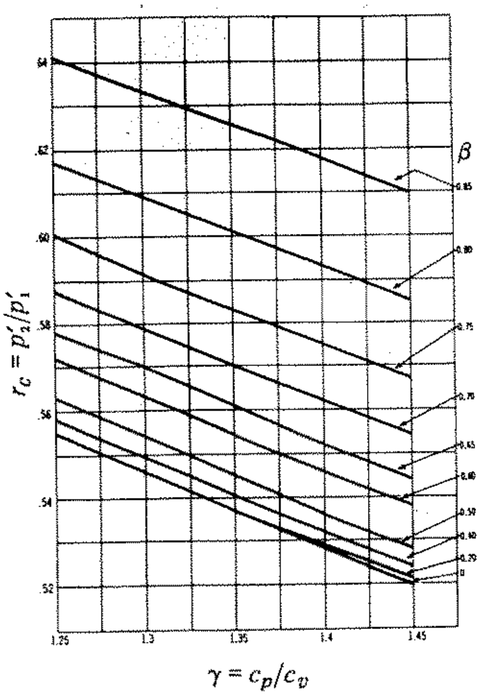
γ = **1.4** approximately

(for Air, H_2, O_2, N_2, CO, NO, and HCl)



Critical Pressure Ratio, r_c

For Compressible Flow through Nozzles and Venturi Tubes[9]

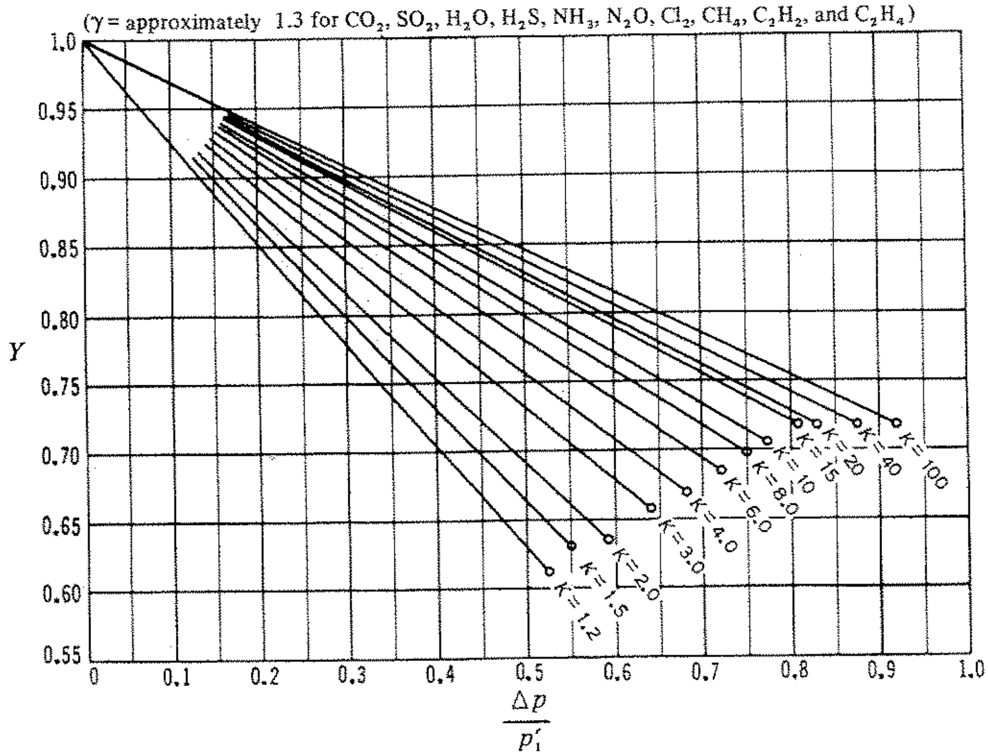


$$\frac{\Delta p}{p'_1} = \frac{\Delta P}{P'_1} \qquad \frac{p'_2}{p'_1} = \frac{P'_2}{P'_1}$$

Net Expansion Factor Y for Compressible Flow Through Pipe to a Larger Flow Area

$\gamma = 1.3$

(γ = approximately 1.3 for CO_2, SO_2, H_2O, H_2S, NH_3, N_2O, Cl_2, CH_4, C_2H_2, and C_2H_4)



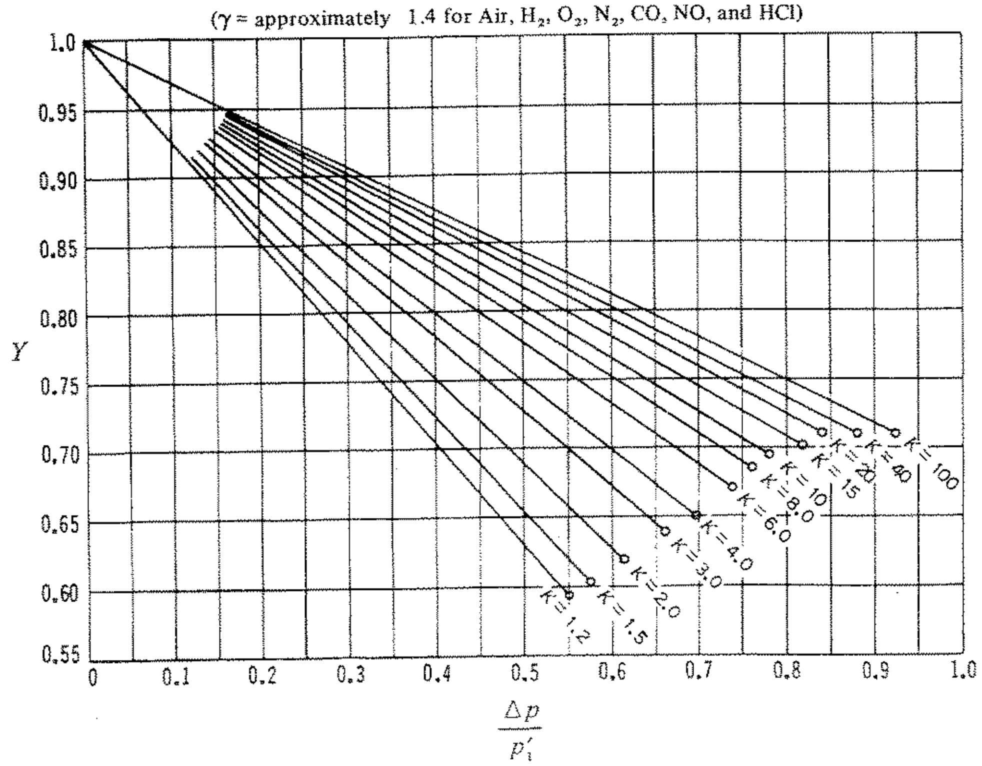
Limiting Factors For Sonic Velocity

$\gamma = 1.3$

K	$\frac{\Delta p}{p'_1}$	Y
1.2	.525	.612
1.5	.550	.631
2.0	.593	.635
3	.642	.658
4	.678	.670
6	.722	.685
8	.750	.698
10	.773	.705
15	.807	.718
20	.831	.718
40	.877	.718
100	.920	.718

$\gamma = 1.4$

(γ = approximately 1.4 for Air, H_2, O_2, N_2, CO, NO, and HCl)



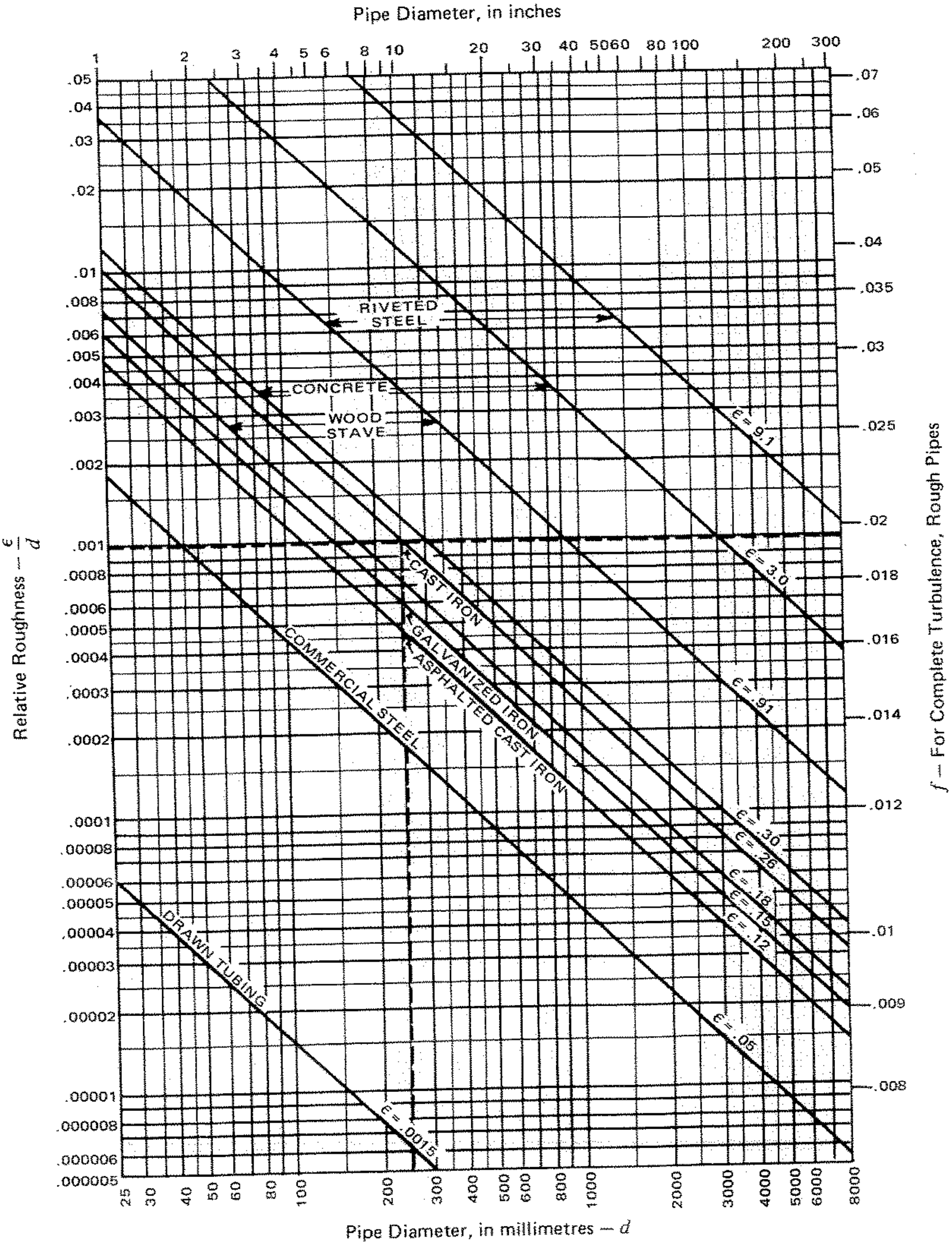
Limiting Factors For Sonic Velocity

$\gamma = 1.4$

K	$\frac{\Delta p}{p'_1}$	Y
1.2	.552	.588
1.5	.576	.606
2.0	.612	.622
3	.662	.639
4	.697	.649
6	.737	.671
8	.762	.685
10	.784	.695
15	.818	.702
20	.839	.710
40	.883	.710
100	.926	.710

$$\frac{\Delta p}{p'_1} = \frac{\Delta P}{P'_1}$$

Relative Roughness of Pipe Materials and Friction Factors
For Complete Turbulence



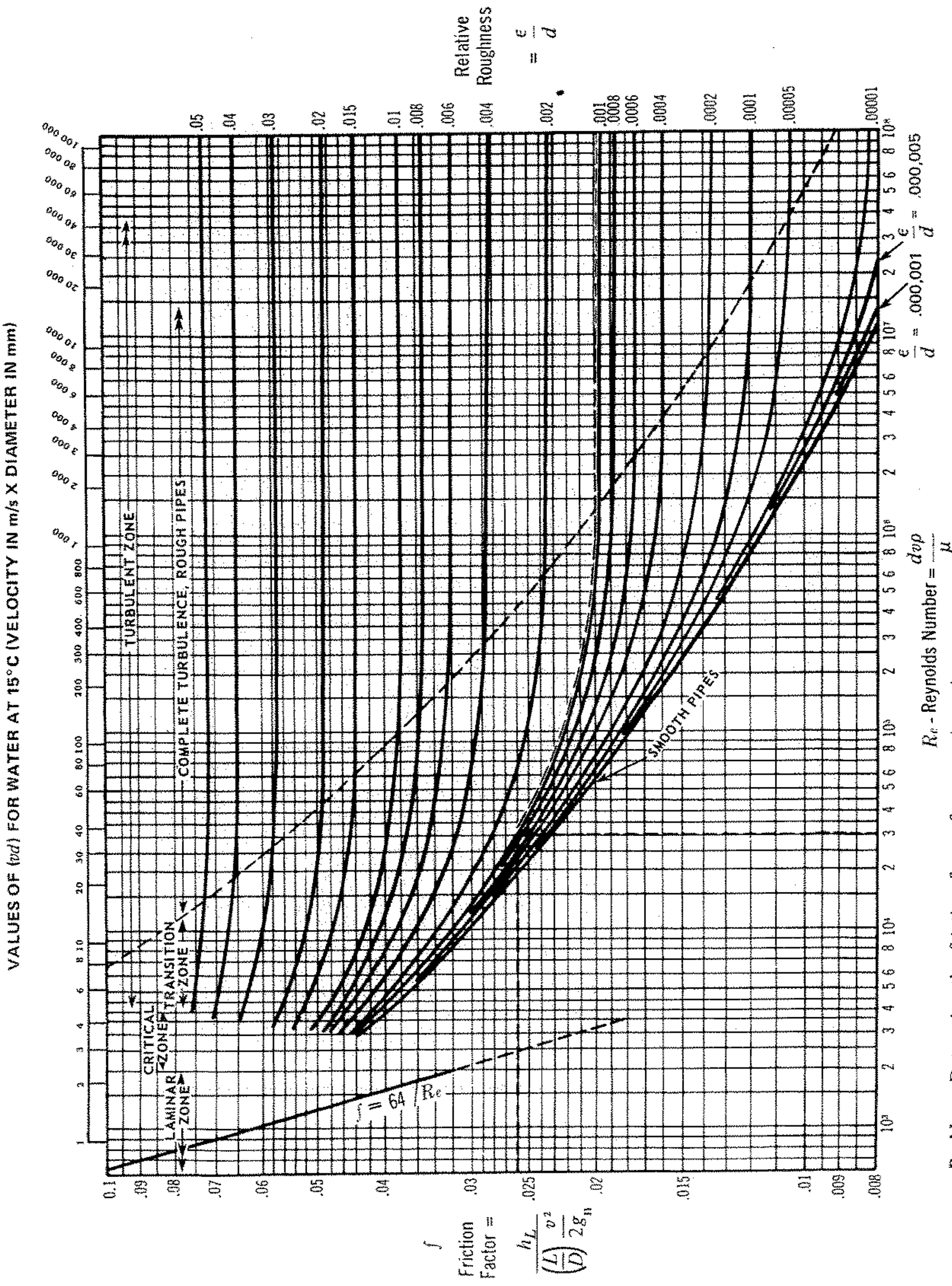
(Absolute Roughness is in millimetres)

Adapted from data extracted from Bibliography reference 18

Problem: Determine absolute and relative roughness, and friction factor, for fully turbulent flow in a cast iron pipe, 250 mm int. diam.

Solution: Absolute roughness (ϵ) = 0.26 . . . . . Relative roughness (ϵ/d) = 0.001 . . . . . Friction factor at fully turbulent flow (f) = 0.0196.

Friction Factors for Any Type of Commercial Pipe



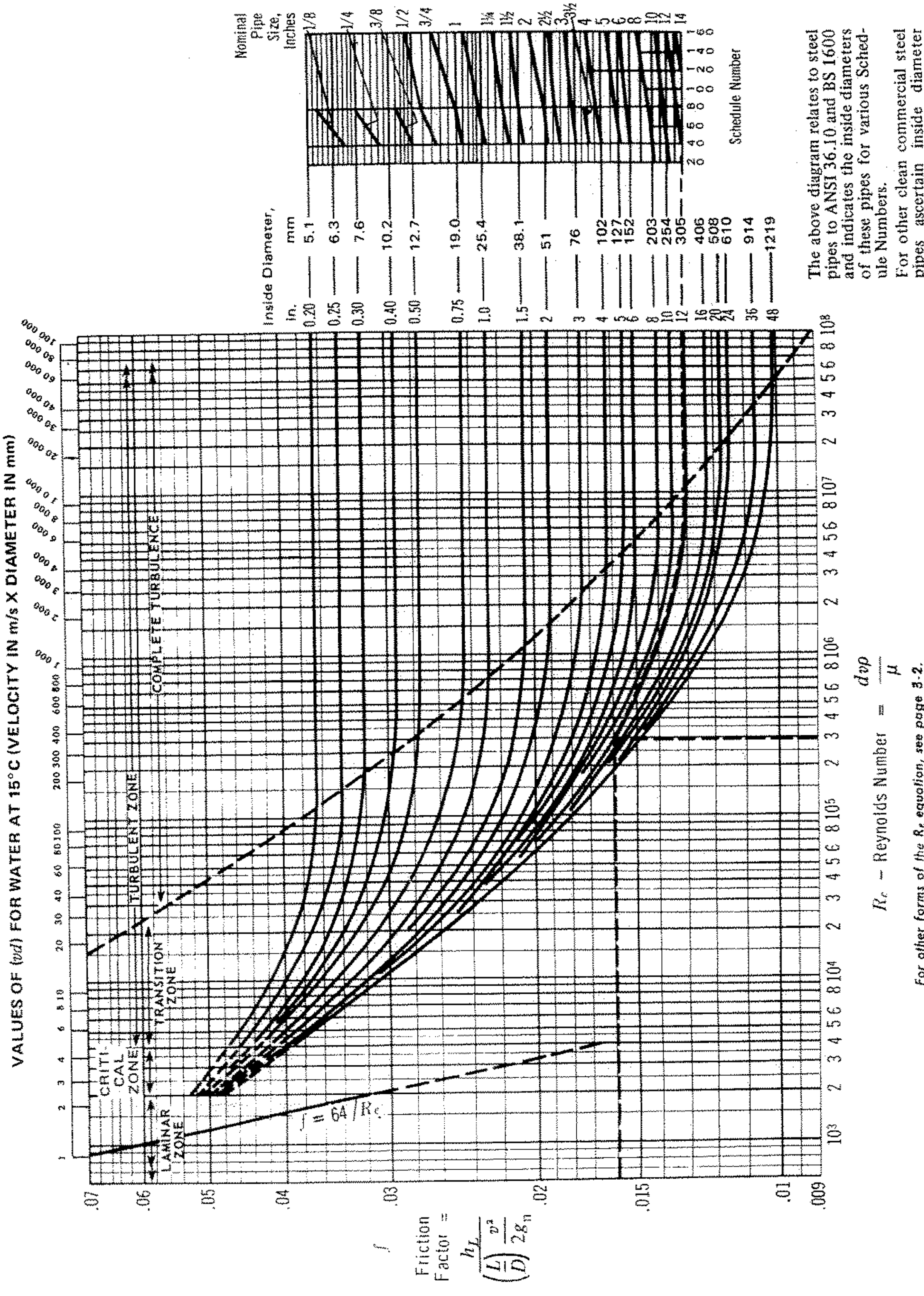
Problem: Determine the friction factor for a cast iron pipe 250 mm int. diam. at a Reynolds number flow of 30,000.

Solution: The relative roughness (see page A-23) is 0.001. Then, the friction factor (f) equals 0.026.

For other forms of the R_e equation, see page 3-2.

Adapted from data extracted from Bibliography reference 18.

Friction Factors for Clean Commercial Steel Pipes



The above diagram relates to steel pipes to ANSI 36.10 and BS 1600 and indicates the inside diameters of these pipes for various Schedule Numbers.

For other clean commercial steel pipes ascertain inside diameter and use main chart only.

Adapted from data extracted from Bibliography reference 18.

Problem: Determine the friction factor for 12-inch Schedule 40 pipe at a flow having a Reynolds number of 300 000.

Solution: The friction factor (f) equals 0.016.

"K" FACTOR TABLE — SHEET 1 of 4

Representative Resistance Coefficients (K) for Valves and Fittings

("K" is based on use of schedule pipe as listed on page 2-10)

PIPE FRICTION DATA FOR CLEAN COMMERCIAL STEEL PIPE WITH FLOW IN ZONE OF COMPLETE TURBULENCE

Nominal Size													
mm	15	20	25	32	40	50	65, 80	100	125	150	200, 250	300-400	450-600
in.	½	¾	1	1¼	1½	2	2½, 3	4	5	6	8, 10	12-16	18-24
Friction Factor (f_T)	.027	.025	.023	.022	.021	.019	.018	.017	.016	.015	.014	.013	.012

FORMULAS FOR CALCULATING "K" FACTORS* FOR VALVES AND FITTINGS WITH REDUCED PORT (Ref. pages 2-11 and 3-4)

Formula 1

$$K = \frac{0.8\left(\sin\frac{\theta}{2}\right)(1-\beta^2)}{\beta^4} = \frac{K_1}{\beta^4}$$

Formula 2

$$K_2 = \frac{0.5\,(1-\beta^2)\sqrt{\sin\frac{\theta}{2}}}{\beta^4} = \frac{K_1}{\beta^4}$$

Formula 3

$$K_2 = \frac{2.6\left(\sin\frac{\theta}{2}\right)(1-\beta^2)^2}{\beta^4} = \frac{K_1}{\beta^4}$$

Formula 4

$$K_2 = \frac{(1-\beta^2)^2}{\beta^4} = \frac{K_1}{\beta^4}$$

Formula 5

$$K_2 = \frac{K_1}{\beta^4} + \text{Formula 1} + \text{Formula 3}$$

$$K_2 = \frac{K_1 + \sin\frac{\theta}{2}\,[0.8\,(1-\beta^2) + 2.6\,(1-\beta^2)^2]}{\beta^4}$$

Formula 6

$$K_2 = \frac{K_1}{\beta^4} + \text{Formula 2} + \text{Formula 4}$$

$$K_2 = \frac{K_1 + 0.5\sqrt{\sin\frac{\theta}{2}}\,(1-\beta^2) + (1-\beta^2)^2}{\beta^4}$$

$$K_2 = \frac{K_1}{\beta^4} + \beta\,(\text{Formula 2} + \text{Formula 4}) \text{ when } \theta = 180^\circ$$

$$K_2 = \frac{K_1 + \beta\,[0.5\,(1-\beta^2) + (1-\beta^2)^2]}{\beta^4}$$

$$\beta = \frac{d_1}{d_2}$$

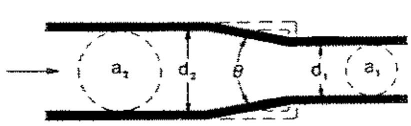
$$\beta^2 = \left(\frac{d_1}{d_2}\right)^2 = \frac{a_1}{a_2}$$

Subscript 1 defines dimensions and coefficients with reference to the smaller diameter.

Subscript 2 refers to the larger diameter.

Use K furnished by valve or fitting supplier when available

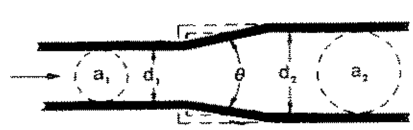
SUDDEN AND GRADUAL CONTRACTION



If: $\theta \leq 45^\circ$ .... K_2 = Formula 1

$45^\circ < \theta \leq 180^\circ$ .... K_2 = Formula 2

SUDDEN AND GRADUAL ENLARGEMENT



If: $\theta \leq 45^\circ$ .... K_2 = Formula 3

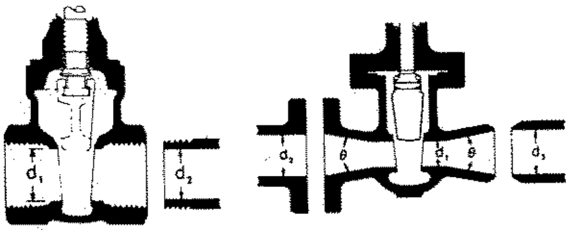
$45^\circ < \theta \leq 180^\circ$ .... K_2 = Formula 4

"K" FACTOR TABLE – SHEET 2 of 4

Representative Resistance Coefficients (K) for Valves and Fittings

(for formulas and friction data, see page A-26)
("K" is based on use of schedule pipe as listed on page 2-10)

GATE VALVES
Wedge Disc, Double Disc, or Plug Type

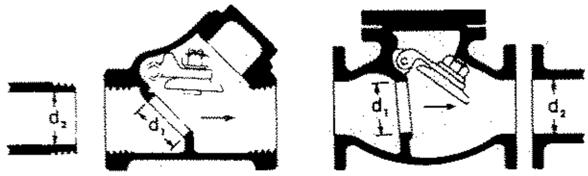


If: $\beta = 1, \theta = 0$ .... $K_1 = 8 f_T$

$\beta < 1$ and $\theta \leqq 45°$ .... K_2 = Formula 5

$\beta < 1$ and $45° < \theta \leqq 180°$ .... K_2 = Formula 6

SWING CHECK VALVES



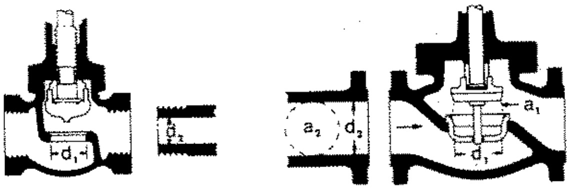
$K = 100 f_T$ | $K = 50 f_T$

Minimum pipe velocity (mps) for full disc lift

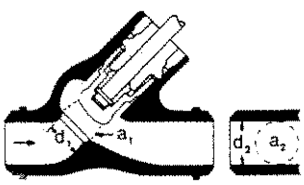
$= 45\sqrt{\bar{V}}$ | $= 75\sqrt{\bar{V}}$ except

U/L listed $= 120\sqrt{\bar{V}}$

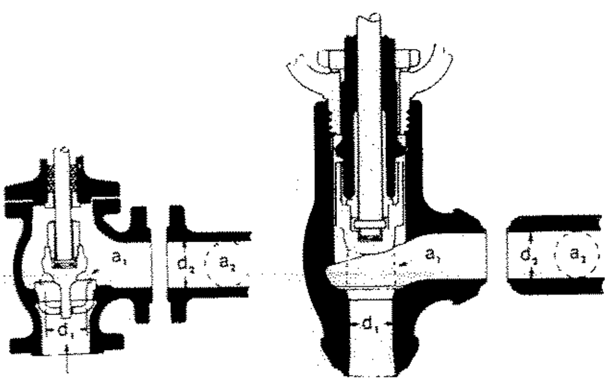
GLOBE AND ANGLE VALVES



If: $\beta = 1 \quad K_1 = 340 f_t$



If: $\beta = 1 \ldots . K_1 = 55 f_T$

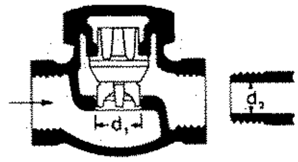


If: $\beta = 1 \ldots K_1 = 150 f_T$ If: $\beta = 1 \ldots K_1 = 55 f_T$

All globe and angle valves,
whether reduced seat or throttled,

If: $\beta < 1 \ldots . K_2$ = Formula 7

LIFT CHECK VALVES

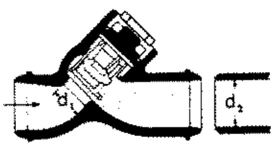


If: $\beta = 1 \ldots . K_1 = 600 f_T$

$\beta < 1 \ldots . K_2$ = Formula 7

Minimum pipe velocity (mps) for full disc lift

$= 50 \beta^2 \sqrt{\bar{V}}$



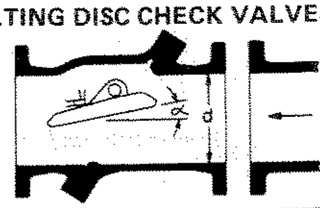
If: $\beta = 1 \ldots . K_1 = 55 f_T$

$\beta < 1 \ldots . K_2$ = Formula 7

Minimum pipe velocity (mps) for full disc lift

$= 170 \beta^2 \sqrt{\bar{V}}$

TILTING DISC CHECK VALVES



Sizes	$\alpha = 5°$	$\alpha = 15°$
50 mm (2") to 200 mm (8") K =	$40 f_T$	$120 f_T$
250 mm (10") to 350 mm (14") K =	$30 f_T$	$90 f_T$
400 mm (16") to 1200 mm (48") K =	$20 f_T$	$60 f_T$
Minimum pipe velocity (mps) for full disc lift =	$100\sqrt{\bar{V}}$	$40\sqrt{\bar{V}}$

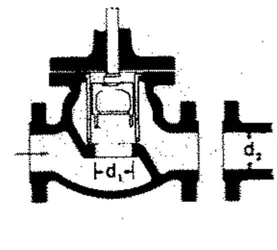
Note. mps = metres per second

"K" FACTOR TABLE – SHEET 3 of 4

Representative Resistance Coefficients (K) for Valves and Fittings

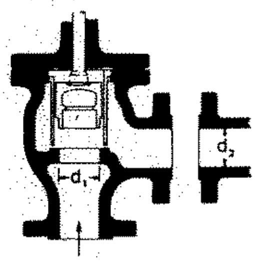
(for formulas and friction data, see page A-26)
("K" is based on use of schedule pipe as listed on page 2-10)

STOP-CHECK VALVES
(Globe and Angle Types)



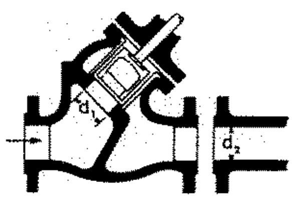
If:
$\beta = 1 \ldots.\ K_1 = 400 f_T$
$\beta < 1 \ldots.\ K_2 =$ Formula 7

Minimum pipe velocity (mps) for full disc lift
$= 70\,\beta^2\,\sqrt{\bar{V}}$

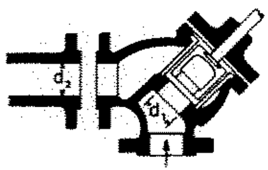


If:
$\beta = 1 \ldots.\ K_1 = 200 f_T$
$\beta < 1 \ldots.\ K_2 =$ Formula 7

Minimum pipe velocity (mps) for full disc lift
$= 95\,\beta^2\,\sqrt{\bar{V}}$

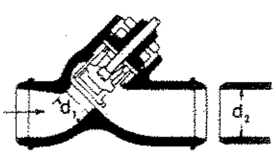


If:
$\beta = 1 \ldots.\ K_1 = 300 f_T$
$\beta < 1 \ldots.\ K_2 =$ Formula 7

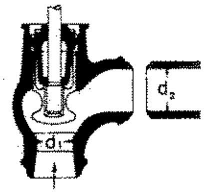


If:
$\beta = 1 \ldots.\ K_1 = 350 f_T$
$\beta < 1 \ldots.\ K_2 =$ Formula 7

Minimum pipe velocity (mps) for full disc lift
$= 75\,\beta^2\,\sqrt{\bar{V}}$



$\beta = 1 \ldots.\ K_1 = 55 f_T$
$\beta < 1 \ldots.\ K_2 =$ Formula 7



$\beta = 1 \ldots.\ K_1 = 55 f_T$
$\beta < 1 \ldots.\ K_2 =$ Formula 7

Minimum pipe velocity (mps) for full disc lift
$= 170\,\beta^2\,\sqrt{\bar{V}}$

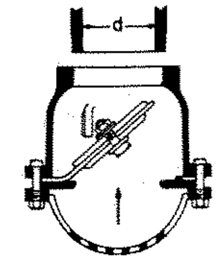
FOOT VALVES WITH STRAINER

Poppet Disc

$K = 420 f_T$

Minimum pipe velocity (mps) for full disc lift
$= 20\,\sqrt{\bar{V}}$

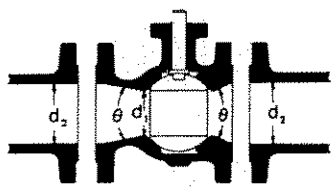
Hinged Disc



$K = 75 f_T$

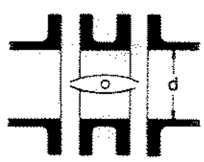
Minimum pipe velocity (mps) for full disc lift
$= 45\,\sqrt{\bar{V}}$

BALL VALVES



If: $\beta = 1, \theta = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ K_1 = 3 f_T$
$\beta < 1$ and $\theta \lessapprox 45° \ldots\ldots\ldots\ldots\ K_2 =$ Formula 5
$\beta < 1$ and $45° < \theta \lessapprox 180° \ldots\ldots\ K_2 =$ Formula 6

BUTTERFLY VALVES



Sizes 50 mm (2") to 200 mm (8") .... $K = 45 f_T$
Sizes 250 mm (10") to 350 mm (14") ..... $K = 35 f_T$
Sizes 400 mm (16") to 600 mm (24") ..... $K = 25 f_T$

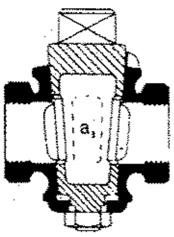
"K" FACTOR TABLE – SHEET 4 of 4

Representative Resistance Coefficients (K) for Valves and Fittings

(for formulas and friction data, see page A-26)
("K" is based on use of schedule pipe as listed on page 2-10)

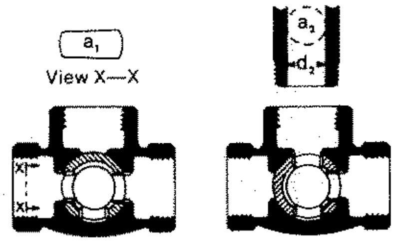
PLUG VALVES AND COCKS

Straight-Way



If: $\beta = 1$,
$K_1 = 18 f_T$

3-Way

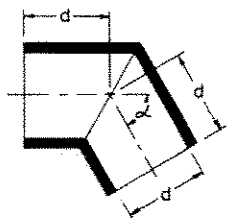


If: $\beta = 1$,
$K_1 = 30 f_T$

If: $\beta = 1$,
$K_1 = 90 f_T$

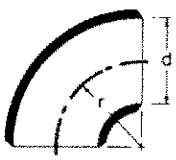
If: $\beta < 1$ K_2 = Formula 6

MITRE BENDS



∝	K
0°	$2 f_T$
15°	$4 f_T$
30°	$8 f_T$
45°	$15 f_T$
60°	$25 f_T$
75°	$40 f_T$
90°	$60 f_T$

90° PIPE BENDS AND FLANGED OR BUTT-WELDING 90° ELBOWS



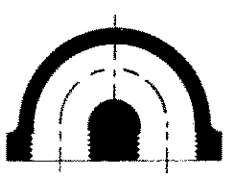
r/d	K	r/d	K
1	$20 f_T$	8	$24 f_T$
1.5	$14 f_T$	10	$30 f_T$
2	$12 f_T$	12	$34 f_T$
3	$12 f_T$	14	$38 f_T$
4	$14 f_T$	16	$42 f_T$
6	$17 f_T$	20	$50 f_T$

The resistance coefficient, K_B, for pipe bends other than 90° may be determined as follows:

$$K_B = (n-1)\left(0.25\,\pi f_T \frac{r}{d} + 0.5\,K\right) + K$$

n = number of 90° bends
K = resistance coefficient for one 90° bend (per table)

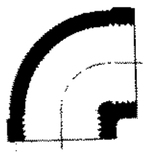
CLOSE PATTERN RETURN BENDS



$K = 50 f_T$

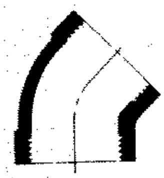
STANDARD ELBOWS

90°



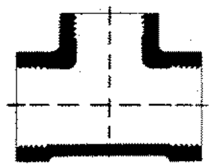
$K = 30 f_T$

45°



$K = 16 f_T$

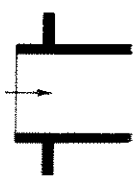
STANDARD TEES



Flow thru run.......... $K = 20 f_T$
Flow thru branch....... $K = 60 f_T$

PIPE ENTRANCE

Inward Projecting

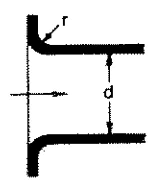


$K = 0.78$

r/d	K
0.00*	0.5
0.02	0.28
0.04	0.24
0.06	0.15
0.10	0.09
0.15 & up	0.04

*Sharp-edged

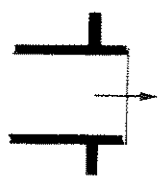
Flush



For K, see table

PIPE EXIT

Projecting



$K = 1.0$

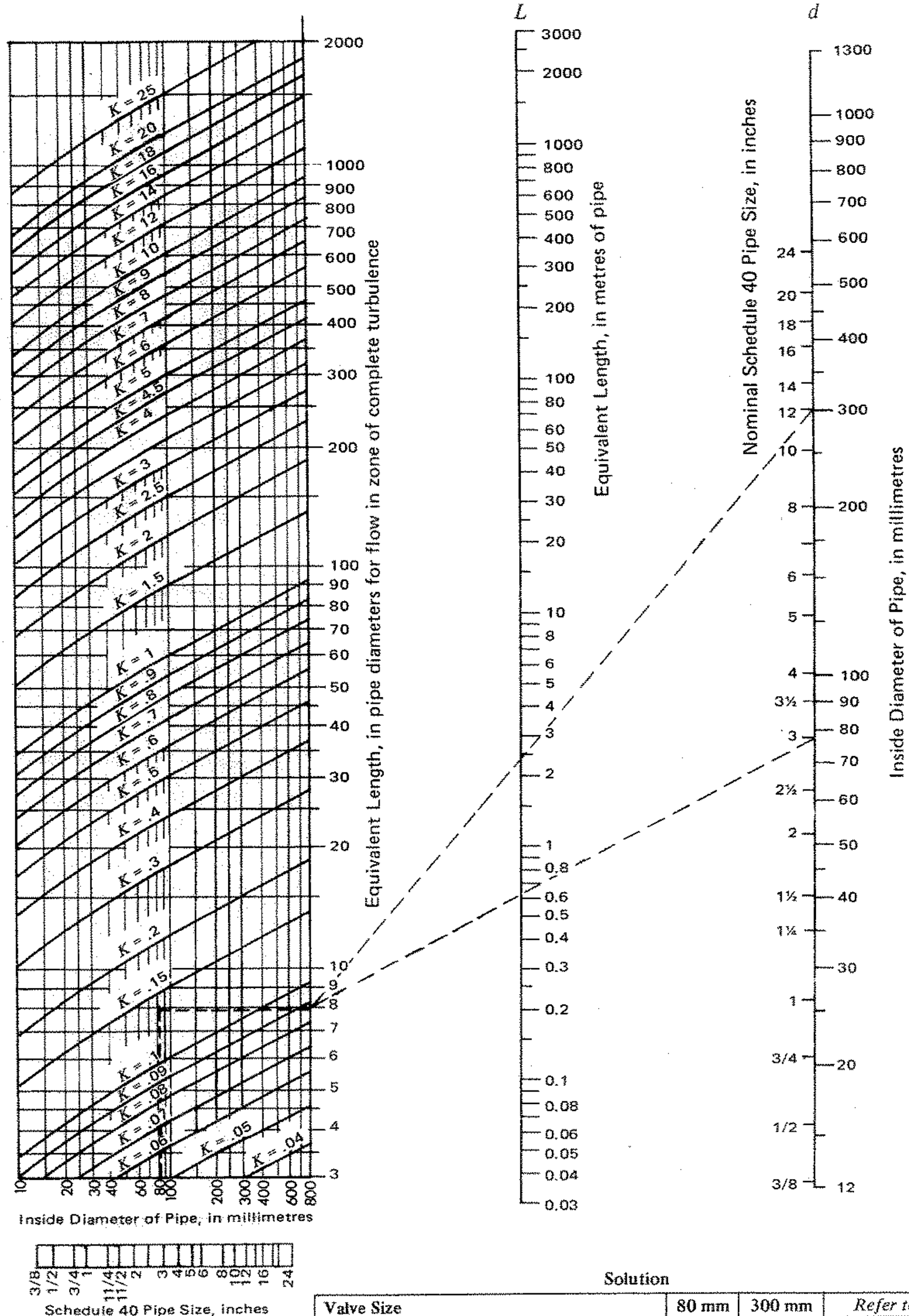
Sharp-Edged

$K = 1.0$

Rounded

$K = 1.0$

Equivalent Lengths L and L/D and Resistance Coefficient K



Problem: Find the equivalent length in pipe diameters and metres of Schedule 40 clean commercial steel pipe, and the resistance factor K for 80 mm and 300 mm fully opened gate valves, ANSI Class 300, with flow in zone of complete turbulence.

Solution

Valve Size	80 mm	300 mm	*Refer to*
Equivalent length, pipe diameters	8	8	Page A-27
Equivalent length, metres of Sched. 40 pipe	0.62	2.43	Dotted lines
Resist Factor K, based on Sched. 40 pipe	0.14	0.10	on chart

For discussion on L/D and K see pages 2-8 to 2-10

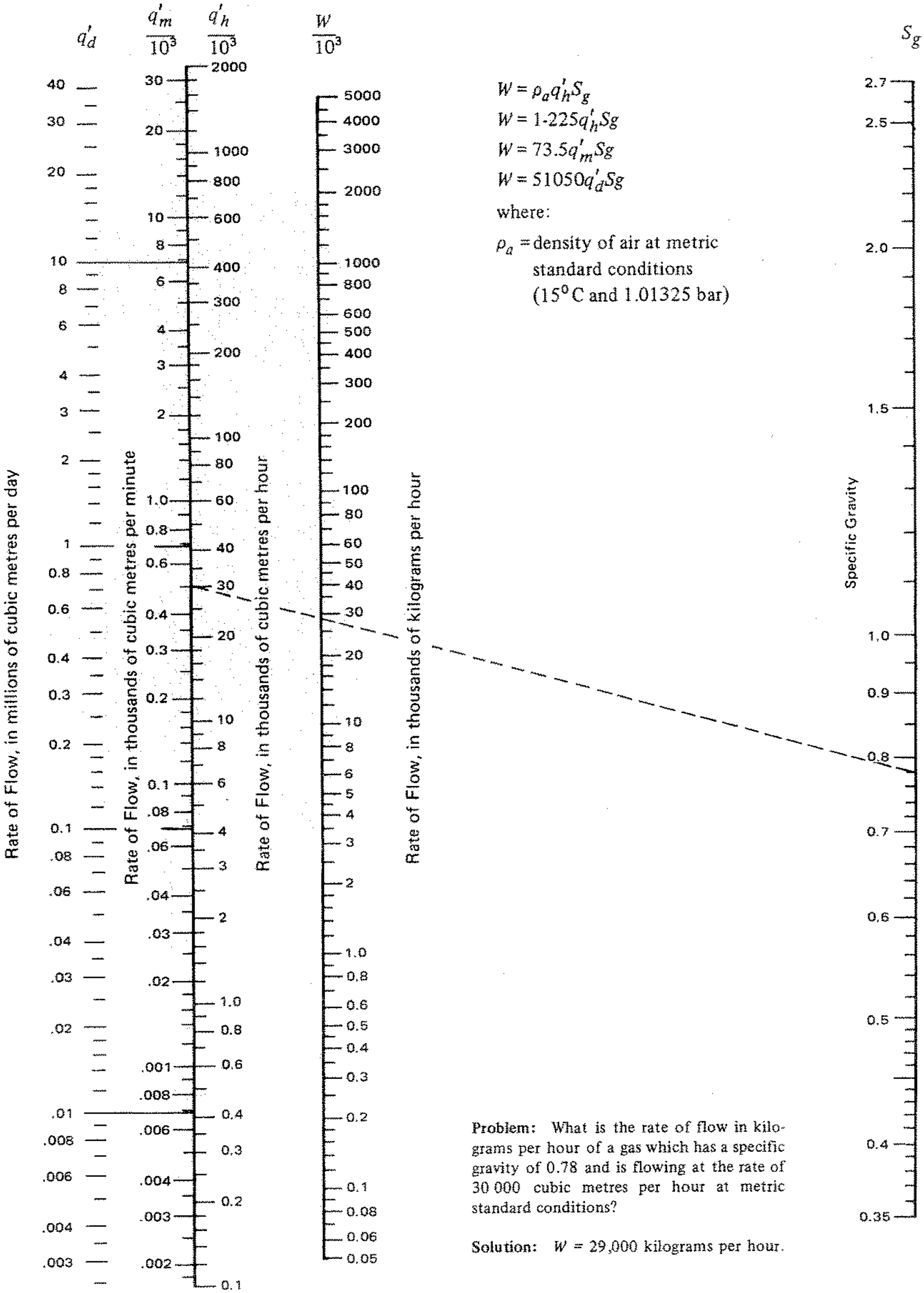
Engineering Data

APPENDIX B

This section includes a number of tables and nomographs for conversion to units other than the SI units generally used in this paper. A summary of SI units, prefixes and symbols is also presented.

Tables of dimensions of steel pipe to ANSI, BS and ISO standards are provided as well as complete solutions of water and air flow pressure drop problems.

Equivalent Volume and Mass Flow Rates of Compressible Fluids at Metric Standard Conditions



$W = \rho_a q'_h S_g$

$W = 1{\cdot}225 q'_h Sg$

$W = 73.5 q'_m Sg$

$W = 51050 q'_d Sg$

where:

ρ_a = density of air at metric standard conditions (15°C and 1.01325 bar)

Problem: What is the rate of flow in kilograms per hour of a gas which has a specific gravity of 0.78 and is flowing at the rate of 30 000 cubic metres per hour at metric standard conditions?

Solution: W = 29,000 kilograms per hour.

Equivalents of Absolute (Dynamic) Viscosity

TO OBTAIN → / MULTIPLY ↓ BY ↘	Pascal second Pa s	Centipoise cP	Poundal second per square foot pdl s/ft²	Pound-force second per square foot lbf s/ft²	Kilogram-force second per square metre kgf s/m²
1 pascal second (= 1 N s/m²) Pa s =	1	1000	0.672	2.09×10^{-2}	0.102
1 centipoise cP =	0.001	1	6.72×10^{-4}	2.09×10^{-5}	1.02×10^{-4}
1 poundal second per square foot (= 1 lb/(ft s)) pdl s/ft² =	1.488	1488	1	0.031	0.152
1 pound-force second per square foot (= 1 slug/(ft s)) lbf s/ft² =	47.88	47 880	32.174	1	4.882
1 kilogram-force second per square metre kgf s/m² =	9.807	9807	6.590	0.205	1

To convert absolute or dynamic viscosity from one set of units to another, locate the given set of units in the left hand column and multiply the numerical value by the factor shown horizontally to the right under the set of units desired.

Example. Convert an absolute viscosity of 0.0014 slugs/foot second to centipoise. The conversion factor is seen to be 47 880. Then 0.0014 times 47 880 = 67 centipoise.

Equivalents of Kinematic Viscosity

TO OBTAIN → / MULTIPLY ↓ BY ↘	Metre squared per second m²/s	Centistokes cSt	Inch squared per second in²/s	Foot squared per second ft²/s
1 metre squared per second m²/s =	1	1×10^{6}	1550	10.764
1 centistokes cSt =	1×10^{-6}	1	1.55×10^{-3}	1.0764×10^{-5}
1 inch squared per second in²/s =	6.452×10^{-4}	645.2	1	6.944×10^{-3}
1 foot squared per second ft²/s =	9.290×10^{-2}	92 903	144	1

To convert kinematic viscosity from one set of units to another, locate the given set of units in the left hand column and multiply the numerical value by the factor shown horizontally to the right, under the set of units desired.

Example. Convert a kinematic viscosity of 0.5 foot squared/second to centistokes. The conversion factor is seen to be 92 903. Then 0.5 times 92 903 = 46 451 centistokes.

For conversion from kinematic to absolute viscosity, see page B-5.

Equivalents of Kinematic and Saybolt Universal Viscosity

Kinematic Viscosity, Centistokes ν	Equivalent Saybolt Universal Viscosity, Sec — At 100 F (38C) Basic Values	At 210 F (99 C)
1.83	32.01	32.23
2.0	32.62	32.85
4.0	39.14	39.41
6.0	45.56	45.88
8.0	52.09	52.45
10.0	58.91	59.32
15.0	77.39	77.93
20.0	97.77	98.45
25.0	119.3	120.1
30.0	141.3	142.3
35.0	163.7	164.9
40.0	186.3	187.6
45.0	209.1	210.5
50.0	232.1	233.8
55.0	255.2	257.0
60.0	278.3	280.2
65.0	301.4	303.5
70.0	324.4	326.7
75.0	347.6	350.0
80.0	370.8	373.4
85.0	393.9	396.7
90.0	417.1	420.0
95.0	440.3	443.4
100.0	463.5	466.7
120.0	556.2	560.1
140.0	648.9	653.4
160.0	741.6	
180.0	834.2	
200.0	926.9	
220.0	1019.6	
240.0	1112.3	
260.0	1205.0	
280.0	1297.7	
300.0	1390.4	
320.0	1483.1	
340.0	1575.8	
360.0	1668.5	Saybolt Seconds equal centistokes times 4.6673
380.0	1761.2	
400.0	1853.9	
420.0	1946.6	
440.0	2039.3	
460.0	2132.0	
480.0	2224.7	
500.0	2317.4	
Over 500	Saybolt Seconds equal centistokes times 4.6347	

Note: To obtain the Saybolt Universal viscosity equivalent to a kinematic viscosity determined at t, multiply the equivalent Saybolt Universal viscosity at 100 F by $1 + (t - 100)\ 0.000\ 064$.

For example, 10 ν at 210 F are equivalent to 58.91 multiplied by 1.0070 or 59.32 sec Saybolt Universal at 210 F.
(In this formula temperature t must be in °F.)

These tables are reprinted with the permission of the American Society for Testing Materials (ASTM) The table at the left was abstracted from Table 1, D2161-63T. The table at the right was abstracted from Table 3, D2161-63T.

Equivalents of Kinematic and Saybolt Furol Viscosity

Kinematic Viscosity, Centistokes ν	Equivalent Saybolt Furol Viscosity, Sec — At 122 F (50 C)	At 210 F (99 C)
48	25.3	
50	26.1	25.2
60	30.6	29.8
70	35.1	34.4
80	39.6	39.0
90	44.1	43.7
100	48.6	48.3
125	60.1	60.1
150	71.7	71.8
175	83.8	83.7
200	95.0	95.6
225	106.7	107.5
250	118.4	119.4
275	130.1	131.4
300	141.8	143.5
325	153.6	155.5
350	165.3	167.6
375	177.0	179.7
400	188.8	191.8
425	200.6	204.0
450	212.4	216.1
475	224.1	228.3
500	235.9	240.5
525	247.7	252.8
550	259.5	265.0
575	271.3	277.2
600	283.1	289.5
625	294.9	301.8
650	306.7	314.1
675	318.4	326.4
700	330.2	338.7
725	342.0	351.0
750	353.8	363.4
775	365.5	375.7
800	377.4	388.1
825	389.2	400.5
850	400.9	412.9
875	412.7	425.3
900	424.5	437.7
925	436.3	450.1
950	448.1	462.5
975	459.9	474.9
1000	471.7	487.4
1025	483.5	499.8
1050	495.2	512.3
1075	507.0	524.8
1100	518.8	537.2
1125	530.6	549.7
1150	542.4	562.2
1175	554.2	574.7
1200	566.0	587.2
1225	577.8	599.7
1250	589.5	612.2
1275	601.3	624.8
1300	613.1	637.3
Over 1300	*	†

*OVER 1300 CENTISTOKES AT 122 F (50 C);
Saybolt Fluid Sec = centistokes x 0.4717

†OVER 1300 CENTISTOKES AT 210 F (99 C);
Log (Saybolt Furol Sec – 2.87) = 1.0276 [Log (centistokes)] – 0.3975

Equivalents of Kinematic, Saybolt Universal, Saybolt Furol, and Absolute Viscosity

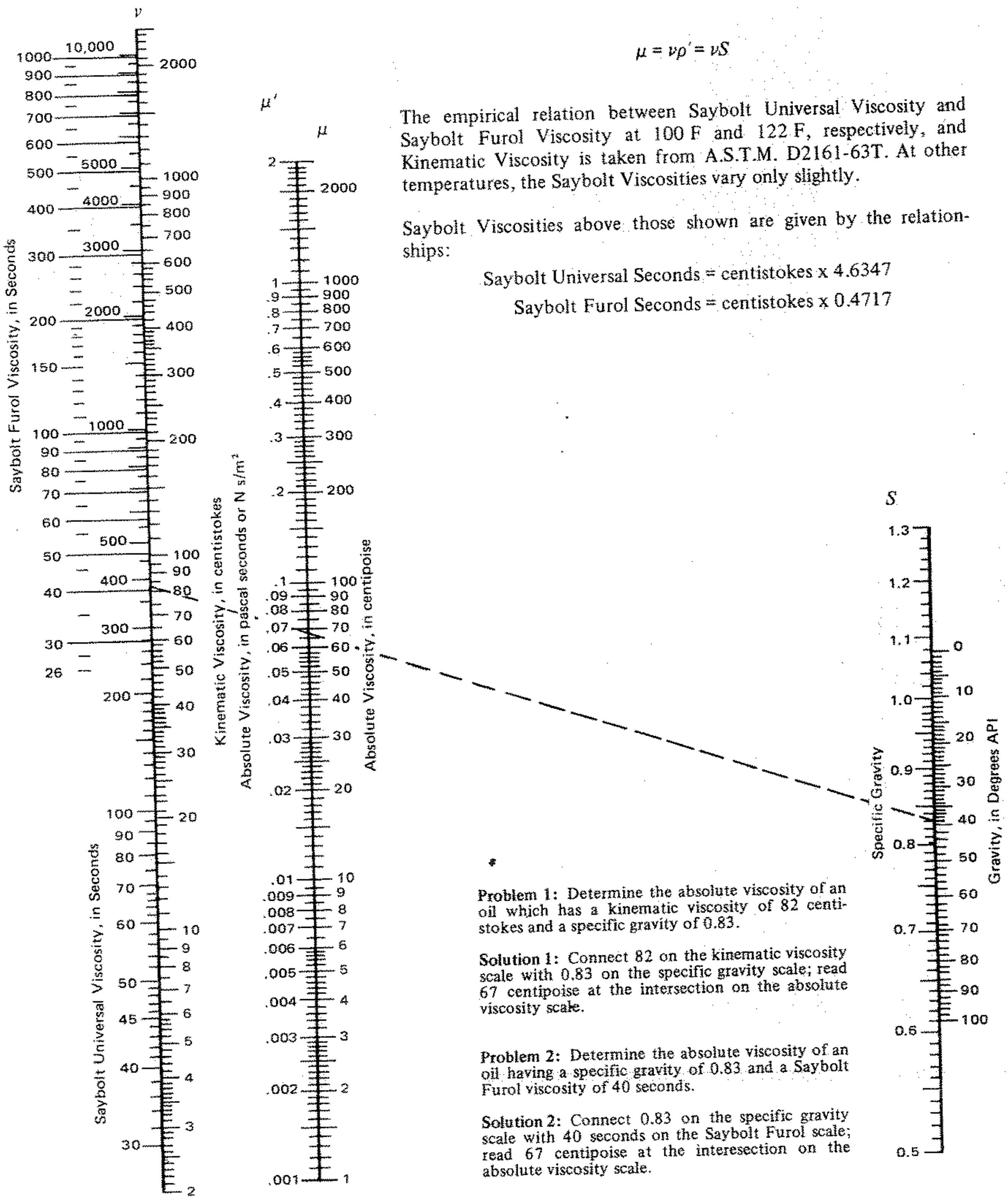
$$\mu = \nu\rho' = \nu S$$

The empirical relation between Saybolt Universal Viscosity and Saybolt Furol Viscosity at 100 F and 122 F, respectively, and Kinematic Viscosity is taken from A.S.T.M. D2161-63T. At other temperatures, the Saybolt Viscosities vary only slightly.

Saybolt Viscosities above those shown are given by the relationships:

Saybolt Universal Seconds = centistokes x 4.6347

Saybolt Furol Seconds = centistokes x 0.4717



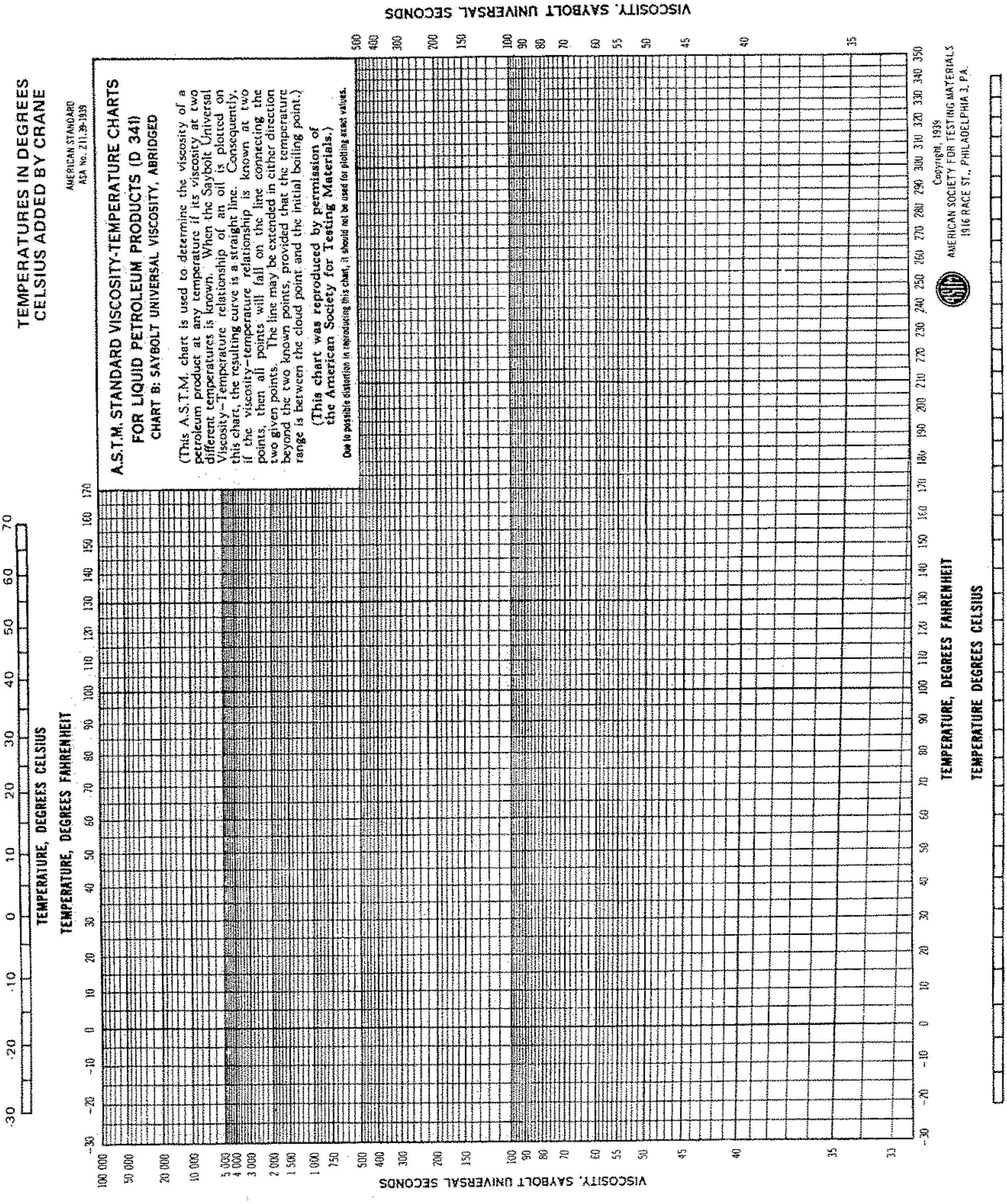
Problem 1: Determine the absolute viscosity of an oil which has a kinematic viscosity of 82 centistokes and a specific gravity of 0.83.

Solution 1: Connect 82 on the kinematic viscosity scale with 0.83 on the specific gravity scale; read 67 centipoise at the intersection on the absolute viscosity scale.

Problem 2: Determine the absolute viscosity of an oil having a specific gravity of 0.83 and a Saybolt Furol viscosity of 40 seconds.

Solution 2: Connect 0.83 on the specific gravity scale with 40 seconds on the Saybolt Furol scale; read 67 centipoise at the interesection on the absolute viscosity scale.

Saybolt Universal Viscosity Chart



Equivalents of Degrees API, Degrees Baumé, Specific Gravity and Density at 60F/60F (15.6 C/15.6 C)

Degrees on API or Baumé Scale	Values for API Scale Oil		Values for Baumé Scale: Liquids Lighter than Water		Values for Baumé Scale: Liquids Heavier than Water	
	Specific Gravity S	Density kg/m³ ρ	Specific Gravity S	Density kg/m³ ρ	Specific Gravity S	Density kg/m³ ρ
0	...	...	...	...	1.0000	998.9
2	...	...	...	...	1.0140	1013.0
4	...	...	...	...	1.0284	1027.4
6	...	...	...	...	1.0432	1042.2
8	...	...	...	...	1.0584	1057.4
10	1.0000	998.9	1.0000	998.9	1.0741	1073.1
12	0.9861	985.1	0.9859	985.0	1.0902	1089.1
14	0.9725	971.5	0.9722	971.2	1.1069	1105.8
16	0.9593	958.4	0.9589	957.9	1.1240	1122.9
18	0.9465	945.6	0.9459	944.9	1.1417	1140.5
20	0.9340	933.1	0.9333	932.3	1.1600	1158.8
22	0.9218	927.0	0.9211	920.1	1.1789	1177.7
24	0.9100	909.0	0.9091	908.2	1.1983	1197.1
26	0.8984	897.5	0.8974	896.6	1.2185	1217.2
28	0.8871	886.1	0.8861	885.2	1.2393	1238.1
30	0.8762	875.3	0.8750	874.1	1.2609	1259.7
32	0.8654	864.5	0.8642	863.4	1.2832	1282.0
34	0.8550	854.1	0.8537	852.8	1.3063	1305.0
36	0.8448	844.0	0.8434	842.6	1.3303	1328.9
38	0.8348	833.9	0.8333	832.5	1.3551	1353.7
40	0.8251	824.3	0.8235	822.7	1.3810	1379.7
42	0.8155	814.7	0.8140	813.1	1.4078	1406.4
44	0.8063	805.4	0.8046	803.8	1.4356	1434.1
46	0.7972	796.4	0.7955	794.7	1.4646	1463.1
48	0.7883	787.5	0.7865	785.7	1.4948	1493.2
50	0.7796	778.8	0.7778	777.1	1.5263	1524.8
52	0.7711	770.3	0.7692	768.4	1.5591	1557.5
54	0.7628	762.0	0.7609	760.1	1.5934	1591.8
56	0.7547	754.0	0.7527	751.9	1.6292	1627.5
58	0.7467	746.0	0.7447	743.9	1.6667	1665.0
60	0.7389	738.1	0.7368	736.1	1.7059	1704.2
62	0.7313	730.6	0.7292	728.5	1.7470	1745.2
64	0.7238	723.1	0.7216	720.8	1.7901	1788.3
66	0.7165	715.7	0.7143	713.6	1.8354	1833.5
68	0.7093	708.5	0.7071	706.4	1.8831	1881.2
70	0.7022	701.5	0.7000	699.4	1.9333	1931.4
72	0.6953	694.6	0.6931	692.3	...	...
74	0.6886	687.8	0.6863	685.6	...	...
76	0.6819	681.3	0.6796	678.9	...	...
78	0.6754	674.7	0.6731	672.5	...	...
80	0.6690	668.3	0.6667	666.0	...	...
82	0.6628	662.0	0.6604	659.8	...	...
84	0.6566	656.0	0.6542	653.6	...	...
86	0.6506	649.9	0.6482	647.5	...	...
88	0.6446	643.9	0.6422	641.5	...	...
90	0.6388	638.2	0.6364	635.8	...	...
92	0.6331	632.4	0.6306	630.0	...	...
94	0.6275	626.8	0.6250	624.4	...	...
96	0.6220	621.4	0.6195	618.8	...	...
98	0.6166	615.9	0.6140	613.3	...	...
100	0.6112	610.6	0.6087	608.1	...	...

To obtain density in kilograms per litre (kg/litre) divide density in kg/m³ by 10^3

For formulas, see page 1-3.

INTERNATIONAL SYSTEM OF UNITS (SI)

The name Système International d'Unités (International System of Units), with abbreviation SI, was adopted by the 11th General Conference of Weights and Measures in 1960.

This system includes three classes of units:

(1) base units
(2) supplementary units
(3) derived units

Together these form the coherent system of SI units.

BASE UNITS

Quantity	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mol

SUPPLEMENTARY UNITS

Quantity	Name	Symbol
Plain Angle	radian	rad
Solid Angle	steradian	sr

DERIVED UNITS

Quantity	Name	Symbol	Equivalents
frequency	hertz	Hz	1 Hz = 1 cycle/s
force	newton	N	1 N = 1 kg/m/s²
pressure and stress	pascal	Pa	1 Pa = 1 N/m²
work, energy, quantity of heat	joule	J	1 J = 1 N m
power	watt	W	1 W = 1 J/s
quantity of electricity	coulomb	C	1 C = 1 A s
electric potential, potential difference, tension, electromotive force	volt	V	1 V = 1 W/A
electric capacitance	farad	F	1 F = 1 A s/v
electric resistance	ohm	Ω	1 Ω = 1 V/A
electric conductance	siemens	S	1 S = 1 Ω^{-1}
flux of magnetic induction, magnetic flux	weber	Wb	1 Wb = 1 V s
magnetic flux density, magnetic induction	tesla	T	1 T = 1 Wb/m²
inductance	henry	H	1 H = 1 V s/A
luminous flux	lumen	lm	1 lm = 1 cd sr
illumination	lux	lx	1 lx = 1 lm/m²

INTERNATIONAL SYSTEM OF UNITS (SI) (Cont'd)

EXCEPTIONS

Certain units which are outside the SI system but have international recognition and use, will continue to be used. The most important of these are:

TIME: In addition to the second (s) the following units will also continue in use:

Name	Symbol
minute	min
hour	h
day	d

Other units such as week, month and year will also continue in use.

PLANE ANGLE:
In addition to the radian (rad) the following units will continue to be used:

Name	Symbol
degree	°
minute	′
second	″

TEMPERATURE:
In addition to the kelvin (K), which relates to the absolute or thermodynamic scale, customary temperatures will be measured in degrees Celsius (° C), formerly called centigrade. The degree intervals on the Kelvin and Celsius scales are identical, but, whereas 0 Kelvin is absolute zero, 0 degrees Celsius is the temperature of melting ice.

DECIMAL MULTIPLES AND SUB-MULTIPLES OF SI UNITS – PREFIXES:

Factor		
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

When a prefix is added to a unit it's considered to be combined with that unit, forming a new unit symbol which can be raised to a positive or negative power and which can be combined with other unit symbols to form compound units. When a combined prefix and symbol is raised to a positive (or negative) power they must be considered as one whole individual unit and not as separate entities.

WRITTEN USE OF SYMBOLS AND PREFIXES

Primary units are spaced apart,

e.g. N m (newton metre)
kW h (kilowatt hour)

Prefixes are placed immediately adjacent to the unit.

e.g. MN (meganewton)
kJ (kilojoule)

Conversion Equivalents

The conversion equivalents given on this page and pages B – 11, B – 12, are based generally on British Standard 350 : Part 1 : 1974. In some cases the degree of rounding has been adjusted to an extent considered to be of value to a practical engineer.

Length

millimetre mm	centimetre cm	metre m	inch in	foot ft	yard yd
1	0.1	0.001	0.0394	0.0033	0.0011
10	1	0.01	0.3937	0.0328	0.0109
1000	100	1	39.3701	3.2808	1.0936
25.4	2.54	0.0254	1	0.0833	0.0278
304.8	30.48	0.3048	12	1	0.3333
914.4	91.44	0.9144	36	3	1

1 kilometre = 1000 metres = 0.62137 miles
1 mile = 1609.34 metres = 1.60934 kilometres

Area

square millimetre mm^2	square centimetre cm^2	square metre m^2	square inch in^2	square foot ft^2	square yard yd^2
1	0.01	10^{-6}	1.55×10^{-3}	1.076×10^{-5}	1.196×10^{-6}
100	1	10^{-4}	0.155	1.076×10^{-3}	1.196×10^{-4}
10^6	10 000	1	1550	10.764	1.196
645.16	6.4516	6.452×10^{-4}	1	6.944×10^{-3}	7.716×10^{-4}
92 903	929.03	0.093	144	1	0.111
836 127	8361.27	0.836	1296	9	1

Volume

cubic millimetre mm^3	cubic centimetre cm^3	cubic metre m^3	cubic inch in^3	cubic foot ft^3	cubic yard yd^3
1	0.001	10^{-9}	6.1×10^{-5}	3.531×10^{-8}	1.308×10^{-9}
1000	1	10^{-6}	0.061	3.531×10^{-5}	1.308×10^{-6}
10^9	10^6	1	61 024	35.31	1.308
16 387	16.39	1.639×10^{-5}	1	5.787×10^{-4}	2.143×10^{-5}
2.832×10^7	2.832×10^4	0.0283	1728	1	0.0370
7.646×10^8	7.646×10^5	0.7646	46 656	27	1

Liquid Measure

cubic metre m^3	litre l	millilitre ml	U.K. gallon U.K. gal	U.S. gallon U.S. gal	cubic foot ft^3
1	1000	10^6	220	264.2	35.3147
0.001	1	1000	0.22	0.2642	0.0353
10^{-6}	0.001	1	2.2×10^{-4}	2.642×10^{-4}	3.53×10^{-5}
0.00455	4.546	4546	1	1.201	0.1605
0.00378	3.785	3785	0.8327	1	0.1337
0.0283	28.317	28 317	6.2288	7.4805	1

1 U.S. Barrel = 42 U.S. gallons (petroleum measure)
1 litre = 10^6 mm^3 = 10^3 cm^3 or 1 cubic decimetre (1 dm^3)
1 litre = 1.76 U.K. pints = 2.113 U.S. pints
U.K. gallon and U.K. pint also called Imperial gallon and Imperial pint

Conversion Equivalents — continued

Velocity

metre per second m/s	foot per second ft/s	metre per minute m/min	foot per minute ft/min	kilometre per hour km/h	mile per hour mile/h
1	3.281	60	196.85	3.6	2.2369
0.305	1	18.288	60	1.0973	0.6818
0.017	0.055	1	3.281	0.06	0.0373
0.005	0.017	0.305	1	0.0183	0.01136
0.278	0.911	16.667	54.68	1	0.6214
0.447	1.467	26.822	88	1.6093	1

Mass

kilogram kg	pound lb	hundredweight cwt	tonne t	U.K. ton	U.S. ton sh ton
1	2.205	0.0197	0.001	9.84×10^{-4}	0.0011
0.454	1	0.0089	4.54×10^{-4}	4.46×10^{-4}	5.0×10^{-4}
50.802	112	1	0.0508	0.05	0.056
1000	2204.6	19.684	1	0.9842	1.1023
1016	2240	20	1.0161	1	1.12
907.2	2000	17.857	0.9072	0.8929	1

Mass Flow Rate

kilogram per second kg/s	pound per second lb/s	kilogram per hour kg/h	pound per hour lb/h	U.K. ton/hour ton/h	tonne t/h
1	2.205	3600	7936.64	3.5431	3.6
0.454	1	1633	3600	1.607	1.633
2.78×10^{-4}	6.12×10^{-4}	1	2.205	9.84×10^{-4}	0.001
1.26×10^{-4}	2.78×10^{-4}	0.454	1	4.46×10^{-4}	4.54×10^{-4}
0.282	0.622	1016	2240	1	1.016
0.278	0.612	1000	2204.6	0.9842	1

Volumetric Rate of Flow

litre per second l/s	litre per minute l/min	cubic metre per hour m^3/h	cubic foot per hour ft^3/h	cubic foot per minute ft^3/min	U.K. gallon per minute U.K.gal/min	U.S.gallon per minute US gal/min	U.S. barrel per day US barrel/d
1	60	3.6	127.133	2.1189	13.2	15.85	543.439
0.017	1	0.06	2.1189	0.0353	0.22	0.264	9.057
0.278	16.667	1	35.3147	0.5886	3.666	4.403	150.955
0.008	0.472	0.0283	1	0.0167	0.104	0.125	4.275
0.472	28.317	1.6990	60	1	6.229	7.480	256.475
0.076	4.546	0.2728	9.6326	0.1605	1	1.201	41.175
0.063	3.785	0.2271	8.0209	0.1337	0.833	1	34.286
0.002	0.110	0.0066	0.2339	0.0039	0.024	0.029	1

Force

newton N	kilonewton kN	kilogram force* kgf	pound force lbf
1	0.001	0.102	0.225
1000	1	101.97	224.81
9.807	0.0098	1	2.205
4.448	0.0044	0.454	1

* The kilogram force is sometimes called the kilopond (kp)

Conversion Equivalents – continued

Pressure and Liquid Head

newton per square metre N/m^2	millibar $(10^2 N/m^2)$ mbar	bar $(10^5 N/m^2)$ bar	kilogram force per square centimetre kgf/cm^2	pound force per square inch lbf/in^2	foot of water $ft\ H_2O$	metre of water $m\ H_2O$	millimetre of mercury mm Hg	inch of mercury in Hg
1	0.01	10^{-5}	1.02×10^{-5}	1.45×10^{-4}	3.3×10^{-4}	1.02×10^{-4}	0.0075	2.95×10^{-4}
100	1	0.001	1.02×10^{-3}	0.0145	0.033	0.0102	0.75	0.029
10^5	1000	1	1.02	14.5	33.455	10.2	750.1	29.53
98 067	980.7	0.981	1	14.22	32.808	10.0	735.6	28.96
6895	68.95	0.069	0.0703	1	2.307	0.703	51.71	2.036
2989	29.89	0.03	0.0305	0.433	1	0.305	22.42	0.883
9807	98.07	0.098	0.1	1.42	3.28	1	73.55	2.896
133.3	1.333	0.0013	0.0014	0.019	0.045	0.014	1	0.039
3386	33.86	0.0338	0.0345	0.491	1.133	0.345	25.4	1

The special name 'pascal' (symbol Pa) has been given to the unit N/m^2 (1 Pa = 1 N/m^2).
1 mm Hg is also known by the name 'torr'.
The international standard atmosphere (1 atm) = 101 325 pascals or 1.013 25 bar. This is equal to 1.033 23 kgf/cm^2 or 14.6959 lbf/in^2.
The technical (metric) atmosphere (1 at) = 1 kgf/cm^2 or 0.980 66 bar. This is equal to 14.2233 lbf/in^2.
The conventional reference conditions known as 'standard temperature and pressure' (stp) are: 1.01325 bar at 0°C = 14.6959 lbf/in^2 at 0°C.
The standard reference conditions (st) for gas are 1.013 25 bar at 15°C and dry, as defined by the International Gas Union. These may also be referred to as Metric Standard Conditions (MSC).

Energy, Work, Heat

joule J	kilojoule kJ	megajoule MJ	foot pound force ft lbf	British thermal unit B.t.u.	therm	kilowatt hour kW h
1	0.001	10^{-6}	0.737	9.48×10^{-4}	9.48×10^{-9}	2.78×10^{-7}
1000	1	0.001	737.56	0.9478	9.48×10^{-6}	2.78×10^{-4}
10^6	1000	1	737 562	947.82	9.48×10^{-3}	0.2778
1.356	1.36×10^{-3}	1.36×10^{-6}	1	1.28×10^{-3}	1.28×10^{-8}	3.77×10^{-7}
1055.1	1.0551	1.05×10^{-3}	778.17	1	10^{-5}	2.931×10^{-4}
1.0551×10^8	105 510	105.51	7.78×10^7	100 000	1	29.307
3.6×10^6	3600	3.6	2.65×10^6	3412.1	0.03412	1

1 joule = 1 newton metre

Power

Watt W	kilogram force metre per second kgf m/s	metric horsepower	foot pound force per second ft lbf/s	horsepower hp
1	0.102	0.00136	0.738	0.0013
9.806	1	0.0133	7.233	0.0131
735.5	75	1	542.476	0.9863
1.356	0.138	1.84×10^{-3}	1	1.82×10^{-3}
745.70	76.04	1.0139	550.0	1

1 watt = 1 joule per sec = 1 newton metre per sec.
The metric horsepower is called 'cheval vapeur' (ch) or (CV) in France.
In Germany it is called the 'Pferdestärke' (PS).

Density. 1 g/cm^3 = 1000 kg/m^3 = 0.0361 lb/in^3
1 kg/m^3 = 0.001 g/cm^3 = 0.0624 lb/ft^3

Specific Volume. 1 cm^3/g = 0.001 m^3/kg = 27.68 in^3/lb
1 m^3/kg = 1000 cm^3/g = 16.0185 ft^3/lb

Flow of Water Through Schedule 40 Steel Pipe

Discharge	Pressure Drop per 100 metres and Velocity in Schedule 40 Pipe for Water at 15 C															
Litres per Minute	Velocity Metres per Second	Press. Drop bars	Velocity Metres per Second	Press. Drop bars	Velocity Metres per Second	Press. Drop bars	Velocity Metres per Second	Press. Drop bars	Velocity Metres per Second	Press. Drop bars	Velocity Metres per Second	Press. Drop bars	Velocity Metres per Second	Press. Drop bars	Velocity Metres per Second	Press. Drop bars
	1/8"		1/4"		3/8"		1/2"		3/4"		1"					
1	0.459	0.726	0.251	0.17												
2	0.918	2.59	0.501	0.60	0.272	0.136	0.170	0.044								
3	1.38	5.59	0.752	1.22	0.407	0.29	0.255	0.091	0.144	0.023						
4	1.84	9.57	1.00	2.09	0.543	0.48	0.340	0.151	0.192	0.038	0.120	0.012				
5	2.29	14.45	1.25	3.18	0.679	0.70	0.425	0.223	0.241	0.057	0.150	0.017				
													1 1/4"		1 1/2"	
6	2.75	20.29	1.50	4.46	0.815	0.98	0.510	0.309	0.289	0.077	0.180	0.024				
8	3.67	35.16	2.01	7.36	1.09	1.69	0.680	0.524	0.385	0.129	0.240	0.041	0.138	0.011		
10			2.51	11.81	1.36	2.52	0.850	0.798	0.481	0.193	0.300	0.061	0.172	0.015	0.127	0.008
15			3.76	25.67	2.04	5.37	1.28	1.69	0.722	0.403	0.450	0.124	0.258	0.032	0.190	0.015
20					2.72	9.24	1.70	2.84	0.962	0.683	0.600	0.210	0.344	0.054	0.254	0.026
	2"		2 1/2"													
30	0.231	0.016					2.55	6.17	1.44	1.45	0.900	0.442	0.517	0.114	0.380	0.053
40	0.308	0.027	0.216	0.010			3.40	10.72	1.92	2.50	1.20	0.758	0.689	0.193	0.507	0.091
50	0.385	0.039	0.270	0.017					2.41	3.83	1.50	1.14	0.861	0.290	0.634	0.135
60	0.462	0.055	0.324	0.023					2.89	5.41	1.80	1.61	1.03	0.400	0.761	0.187
70	0.539	0.098	0.378	0.031					3.37	7.27	2.10	2.15	1.21	0.541	0.888	0.248
					3"		3 1/2"									
80	0.616	0.092	0.432	0.039	0.280	0.014			3.85	9.27	2.40	2.76	1.38	0.690	1.01	0.315
90	0.693	0.115	0.486	0.048	0.315	0.017	0.235	0.008			2.70	3.47	1.55	0.862	1.14	0.397
100	0.770	0.141	0.540	0.059	0.350	0.020	0.261	0.010			3.00	4.25	1.72	1.05	1.27	0.488
									4"							
150	1.15	0.295	0.810	0.125	0.524	0.042	0.392	0.021	0.304	0.011	4.50	9.30	2.58	2.26	1.90	1.03
200	1.54	0.512	1.08	0.212	0.699	0.072	0.523	0.036	0.405	0.019			3.44	3.91	2.54	1.81
											5"		6"			
250	1.92	0.773	1.35	0.322	0.874	0.108	0.653	0.053	0.507	0.028					3.17	2.74
300	2.31	1.10	1.62	0.449	1.05	0.152	0.784	0.074	0.608	0.040	0.387	0.014			3.80	3.82
350	2.69	1.47	1.89	0.606	1.22	0.203	0.915	0.099	0.710	0.053	0.452	0.018			4.44	5.18
400	3.08	1.92	2.16	0.780	1.40	0.264	1.05	0.128	0.811	0.068	0.516	0.023	0.357	0.009	5.07	6.69
450	3.46	2.39	2.43	0.979	1.57	0.329	1.18	0.161	0.912	0.084	0.581	0.028	0.402	0.012	5.71	8.45
500	3.85	2.95	2.70	1.20	1.75	0.403	1.31	0.196	1.01	0.101	0.646	0.034	0.447	0.014		
550	4.23	3.55	2.97	1.44	1.92	0.479	1.44	0.232	1.11	0.122	0.710	0.041	0.491	0.016		
600	4.62	4.20	3.24	1.69	2.10	0.566	1.57	0.273	1.22	0.146	0.775	0.047	0.536	0.019		
650	5.00	6.88	3.51	1.97	2.27	0.658	1.70	0.319	1.32	0.169	0.839	0.055	0.581	0.022		
700	5.39	5.63	3.78	2.28	2.45	0.759	1.83	0.368	1.42	0.194	0.904	0.063	0.625	0.025		
															8"	
750	5.77	6.44	4.05	2.60	2.62	0.863	1.96	0.420	1.52	0.218	0.968	0.072	0.670	0.029		
800			4.32	2.95	2.80	0.977	2.09	0.473	1.62	0.246	1.03	0.081	0.715	0.032		
850			4.59	3.31	2.97	1.09	2.22	0.528	1.72	0.277	1.10	0.091	0.760	0.036	0.439	0.009
900					3.15	1.22	2.35	0.585	1.82	0.308	1.16	0.010	0.804	0.041	0.465	0.010
950					3.32	1.35	2.48	0.649	1.93	0.342	1.23	0.111	0.849	0.045	0.491	0.012
1000					3.5	1.50	2.61	0.714	2.03	0.377	1.29	0.122	0.894	0.049	0.516	0.013
1100					3.85	1.75	2.87	0.860	2.23	0.452	1.42	0.147	0.983	0.059	0.568	0.015
1200					4.20	2.14	3.14	1.02	2.43	0.534	1.55	0.172	1.07	0.069	0.620	0.018
1300							3.40	1.19	2.64	0.627	1.68	0.200	1.16	0.080	0.671	0.021
1400							3.66	1.37	2.84	0.722	1.81	0.232	1.25	0.091	0.723	0.024
	10"															
1500							3.92	1.56	3.04	0.818	1.94	0.264	1.34	0.105	0.775	0.027
1600							4.18	1.78	3.24	0.924	2.07	0.297	1.43	0.118	0.826	0.031
1700							4.44	1.99	3.45	1.04	2.19	0.331	1.52	0.132	0.878	0.035
1800	0.590	0.012							3.65	1.16	2.32	0.369	1.61	0.147	0.930	0.039
1900	0.622	0.014							3.85	1.28	2.45	0.410	1.70	0.163	0.981	0.042
			12"													
2000	0.655	0.015							4.05	1.41	2.58	0.452	1.79	0.181	1.03	0.046
2200	0.721	0.018							4.46	1.70	2.84	0.545	1.97	0.217	1.14	0.056
2400	0.786	0.021									3.10	0.645	2.14	0.253	1.24	0.065
2600	0.852	0.025	0.600	0.010							3.36	0.749	2.32	0.296	1.34	0.076
2800	0.917	0.028	0.646	0.012							3.61	0.859	2.50	0.339	1.45	0.087
					14"		16"									
3000	0.983	0.032	0.692	0.013	0.573	0.008					3.87	0.982	2.68	0.387	1.55	0.099
3500	1.15	0.043	0.810	0.018	0.668	0.011					4.52	1.33	3.13	0.526	1.81	0.134
4000	1.31	0.055	0.923	0.023	0.764	0.014					5.16	1.72	3.57	0.673	2.07	0.172
4500	1.47	0.068	1.04	0.029	0.860	0.018	0.658	0.009					4.02	0.853	2.32	0.214
5000	1.64	0.084	1.15	0.034	0.955	0.022	0.731	0.011					4.47	1.04	2.58	0.262
									18"							
6000	1.96	0.118	1.38	0.049	1.15	0.031	0.877	0.016					5.36	1.47	3.10	0.373
7000	2.29	0.158	1.61	0.065	1.34	0.042	1.02	0.021	0.808	0.012			6.25	2.0	3.61	0.499
8000	2.62	0.204	1.84	0.085	1.53	0.054	1.17	0.027	0.924	0.015			7.15	2.59	4.13	0.650
9000	2.95	0.256	2.08	0.107	1.72	0.067	1.31	0.033	1.04	0.019					4.65	0.816
10 000	3.28	0.313	2.31	0.130	1.91	0.081	1.46	0.041	1.15	0.023					5.16	0.992
											20"		24"			
12 000	3.93	0.447	2.77	0.184	2.29	0.114	1.75	0.057	1.38	0.032	1.11	0.019			6.20	1.41
14 000	4.59	0.600	3.23	0.246	2.67	0.153	2.05	0.077	1.62	0.044	1.30	0.025			7.23	1.91
16 000	5.24	0.776	3.69	0.317	3.06	0.198	2.34	0.099	1.85	0.056	1.49	0.032	1.03	0.013	8.26	2.48
18 000	5.90	0.975	4.15	0.398	3.44	0.246	2.63	0.124	2.08	0.069	1.67	0.040	1.16	0.016		
20 000	6.55	1.19	4.61	0.487	3.82	0.302	2.92	0.152	2.31	0.084	1.86	0.049	1.28	0.020		
25 000	8.19	1.83	5.77	0.758	4.77	0.469	3.65	0.234	2.89	0.130	2.32	0.076	1.61	0.030		
30 000			6.92	1.08	5.73	0.669	4.38	0.332	3.46	0.183	2.79	0.108	1.93	0.043		
35 000			8.07	1.46	6.68	0.903	5.12	0.446	4.04	0.248	3.25	0.144	2.25	0.057		
40 000			9.23	1.90	7.64	1.17	5.85	0.578	4.62	0.319	3.72	0.186	2.57	0.074		
45 000			10.38	2.39	8.59	1.47	6.58	0.726	5.19	0.400	4.18	0.233	2.89	0.092		
50 000					9.55	1.81	7.31	0.888	5.77	0.491	4.64	0.284	3.21	0.113		
55 000							8.04	1.07	6.35	0.594	5.11	0.343	3.53	0.136		
60 000							8.77	1.27	6.93	0.708	5.58	0.411	3.86	0.161		
65 000							9.5	1.49	7.50	0.822	6.04	0.475	4.18	0.189		
70 000							10.2	1.70	8.08	0.955	6.51	0.552	4.50	0.216		
75 000							11.0	1.98	8.66	1.10	6.97	0.628	4.82	0.246		

1 cubic metre = 1000 litres.

For pressure drop and velocity for pipe other than Schedule 40 and other than 100 metres long, see explanations on page B-15.

Flow of Air Through Schedule 40 Steel Pipe

Free Air q'_m Cubic Metres per Minute at 15 C and 1.013 bar abs	Compressed Air Cubic Metres per Minute at 15 C and 7 bar gauge	Pressure Drop of Air In Bars per 100 Metres of Schedule 40 Pipe — For Air at 7 bar gauge pressure and 15 C Temperature								
		1/8"	1/4"	3/8"	1/2"					
0.03	0.0038	0.093	0.021	0.0045						
0.06	0.0076	0.337	0.072	0.016	0.0051					
0.09	0.0114	0.719	0.154	0.033	0.011	3/4"				
0.12	0.0152	1.278	0.267	0.058	0.018					
0.15	0.0190	1.942	0.405	0.087	0.027	0.0067	1"			
0.2	0.0253	3.357	0.698	0.146	0.047	0.011	0.0035			
0.3	0.0379	7.554	1.57	0.319	0.099	0.024	0.0073	1¼"		
0.4	0.0506		2.71	0.548	0.170	0.041	0.012			
0.5	0.0632		4.10	0.842	0.257	0.062	0.018			
0.6	0.0759		5.90	1.19	0.370	0.088	0.026	0.0066	1½"	
0.7	0.0885		8.03	1.62	0.494	0.117	0.035	0.0086	0.0041	
0.8	0.101			2.12	0.634	0.150	0.044	0.011	0.0053	
0.9	0.114			2.64	0.803	0.187	0.055	0.014	0.0065	
1.0	0.126			3.26	0.991	0.231	0.067	0.017	0.0079	2"
1.25	0.158			4.99	1.55	0.353	0.102	0.026	0.012	
1.5	0.190			7.20	2.19	0.499	0.147	0.036	0.017	0.0048
1.75	0.221	2½"		9.79	2.98	0.679	0.196	0.047	0.022	0.0064
2.0	0.253				3.82	0.871	0.257	0.062	0.029	0.0082
2.25	0.284	0.0042			4.84	1.10	0.325	0.076	0.036	0.010
2.5	0.316	0.0051			5.97	1.36	0.393	0.094	0.045	0.012
3.0	0.379	0.0073			8.6	1.92	0.565	0.135	0.063	0.018
3.5	0.442	0.0097	3"			2.61	0.754	0.184	0.086	0.024
4.0	0.506	0.012				3.41	0.984	0.236	0.110	0.030
4.5	0.569	0.016	0.0051			4.32	1.25	0.298	0.136	0.038
5.0	0.632	0.019	0.0063	3½"		5.34	1.54	0.368	0.164	0.046
6	0.759	0.027	0.0090			7.68	2.17	0.518	0.236	0.066
7	0.885	0.036	0.012	0.0059			2.95	0.689	0.321	0.090
8	1.011	0.047	0.015	0.0075			3.85	0.900	0.419	0.115
9	1.138	0.058	0.019	0.0094			4.88	1.14	0.530	0.145
10	1.264	0.072	0.023	0.011	4"		6.02	1.41	0.640	0.179
11	1.391	0.085	0.028	0.014	0.0073		7.29	1.71	0.774	0.217
12	1.517	0.101	0.033	0.016	0.0085		8.67	2.02	0.921	0.252
13	1.643	0.119	0.039	0.019	0.0098			2.38	1.08	0.295
14	1.770	0.138	0.045	0.022	0.011			2.76	1.25	0.343
15	1.896	0.158	0.051	0.025	0.013			3.13	1.44	0.393
16	2.023	0.178	0.058	0.028	0.015			3.57	1.64	0.443
17	2.149	0.200	0.065	0.031	0.016			4.01	1.85	0.500
18	2.276	0.223	0.072	0.035	0.018	5"		4.49	2.07	0.558
19	2.402	0.247	0.081	0.039	0.020			5.01	2.31	0.618
20	2.528	0.266	0.089	0.043	0.022	0.0072		5.49	2.53	0.685
22	2.781	0.328	0.107	0.052	0.027	0.0086		6.65	3.07	0.825
24	3.034	0.388	0.126	0.061	0.032	0.010	6"	7.91	3.61	0.982
26	3.287	0.455	0.148	0.071	0.037	0.012		9.28	4.22	1.15
28	3.540	0.525	0.171	0.082	0.043	0.014	0.0054		4.86	1.33
30	3.793	0.603	0.197	0.094	0.049	0.016	0.0061		5.62	1.52
32	4.046	0.682	0.222	0.106	0.055	0.018	0.0069		6.39	1.73
34	4.298	0.770	0.251	0.119	0.062	0.020	0.0078		7.22	1.94
36	4.551	0.863	0.280	0.134	0.070	0.022	0.0087		8.09	2.17
38	4.804	0.957	0.312	0.148	0.077	0.024	0.0096			2.41
40	5.057	1.05	0.346	0.164	0.086	0.027	0.011			2.67
45	5.689	1.33	0.435	0.207	0.107	0.034	0.013	8"		3.36
50	6.321	1.65	0.534	0.254	0.132	0.042	0.016			4.15
60	7.585	2.37	0.765	0.363	0.188	0.059	0.023	0.0058		5.98
70	8.850	3.23	1.03	0.495	0.254	0.080	0.031	0.0077		8.14
80	10.11	4.22	1.35	0.639	0.332	0.104	0.040	0.010	10"	
90	11.38	5.34	1.70	0.808	0.418	0.130	0.051	0.013	0.0041	
100	12.64	6.59	2.10	0.992	0.513	0.160	0.062	0.015	0.0050	
110	13.91	7.97	2.54	1.19	0.621	0.192	0.075	0.019	0.0060	
120	15.17	9.49	3.02	1.42	0.739	0.228	0.089	0.022	0.0071	
130	16.43		3.55	1.67	0.862	0.267	0.103	0.026	0.0082	
140	17.70		4.12	1.93	1.00	0.308	0.120	0.029	0.0095	12"
150	18.96		4.73	2.22	1.15	0.353	0.138	0.034	0.011	0.0045
200	25.28		8.4	3.94	2.03	0.628	0.243	0.059	0.019	0.0078
250	31.61			6.16	3.17	0.975	0.378	0.090	0.029	0.012
300	37.93			8.88	4.56	1.40	0.540	0.129	0.041	0.017
350	44.25				6.21	1.90	0.735	0.174	0.056	0.023
400	50.57				8.11	2.48	0.960	0.227	0.072	0.030
450	56.89					3.14	1.215	0.286	0.091	0.037
500	63.21					3.88	1.50	0.352	0.112	0.046
550	69.53					4.69	1.82	0.424	0.134	0.055
600	75.85					5.58	2.16	0.504	0.160	0.066
650	82.17					6.55	2.54	0.592	0.188	0.076
700	88.50					7.60	2.94	0.686	0.218	0.089
750	94.82					8.72	3.38	0.788	0.248	0.101
800	101.1						3.84	0.896	0.282	0.115
850	107.5						4.34	1.01	0.319	0.130

For calculations for pipe other than Schedule 40 and other than 100 metres long, and for other temperature/pressure conditions, see facing page.

Flow of Water through Schedule 40 Steel Pipe, continued from page B — 13

Pressure Drop for lengths of pipe other than 100 metres

For lengths of pipe other than 100 metres the pressure drop is proportional to the length. Thus, for 50 metres of pipe, the pressure drop is approximately one-half the value given in the table . . . for 300 metres, three times the given value, etc.

Velocity

Velocity is a function of the cross sectional flow area; thus, it is constant for a given flow rate and is independent of pipe length.

Pressure Drop and Velocity for pipe other than Schedule 40

To determine the velocity or pressure drop of water through pipe other than Schedule 40, use the following formulas:

$$v_a = v_{40}\left(\frac{d_{40}}{d_a}\right)^2$$

$$\Delta p_a = \Delta p_{40}\left(\frac{d_{40}}{d_a}\right)^5$$

Subscript "*a*" refers to the Schedule of pipe through which velocity or pressure drop is desired.

Subscript "40" refers to the velocity or pressure drop through Schedule 40 pipe, as given in the tables on page B-13.

Flow of Air through Schedule 40 Steel Pipe, continued from facing page

Pressure Drop for lengths of pipe other than 100 metres

For lengths of pipe other than 100 metres the pressure drop is proportional to the length. Thus, for 50 metres of pipe, the pressure drop is approximately one-half the value given in the table . . . for 300 metres, three times the given value, etc.

The pressure drop is also inversely proportional to the absolute pressure and directly proportional to the absolute temperature.

Therefore, to determine the pressure drop for inlet or average pressures other than 7 bar and at temperatures other than 15 C, multiply the values given in the table by the ratio:

$$\left(\frac{7 + 1.013}{p + 1.013}\right)\left(\frac{273 + t}{288}\right)$$

where:

"*p*" is the inlet or average gauge pressure in bars, and,

"*t*" is the temperature in degrees Celsius under consideration.

Pressure Drop through pipe other than Schedule 40

To determine the pressure drop through pipe other than Schedule 40, use the following formula:

$$\Delta p_a = \Delta p_{40}\left(\frac{d_{40}}{d_a}\right)^5$$

Subscript "*a*" refers to the Schedule of pipe through which pressure drop is desired.

Subscript "40" refers to the pressure drop through Schedule 40 pipe, as given in the table on facing page.

Flow Rate of compressed air at temperature and pressure other than Metric Standard Conditions (MSC)

The cubic metres per minute of compressed air at any pressure is inversely proportional to the absolute pressure and directly proportional to the absolute temperature.

To determine the cubic metres per minute of compressed air at any temperature and pressure other than standard conditions (MSC), multiply the value of cubic metres per minute of free air by the ratio:

$$\left(\frac{1.013}{1.013 + p}\right)\left(\frac{2.73 + t}{288}\right)$$

Commercial Steel Pipe

Based on ANSI B36.10: 1970 and BS 1600: Part 2: 1970

Schedule Wall Thicknesses

Schedule	Nominal Pipe Size (Inches)	Outside Diameter (mm)	Thickness (mm)	Inside Diameter (mm)
Schedule 10	14	355.6	6.35	342.9
	16	406.4	6.35	393.7
	18	457.2	6.35	444.5
	20	508.0	6.35	495.3
	24	609.6	6.35	596.9
	30	762.0	7.92	746.2
Schedule 20	8	219.1	6.35	206.4
	10	273.0	6.35	260.3
	12	323.9	6.35	311.2
	14	355.6	7.92	339.8
	16	406.4	7.92	390.6
	18	457.2	7.92	441.4
	20	508.0	9.52	489.0
	24	609.6	9.52	590.6
	30	762.0	12.70	736.6
Schedule 30	8	219.1	7.04	205.0
	10	273.0	7.80	257.4
	12	323.9	8.38	307.1
	14	355.6	9.52	336.6
	16	406.4	9.52	387.4
	18	457.2	11.13	434.9
	20	508.0	12.70	482.6
	24	609.6	14.27	581.1
	30	762.0	15.88	730.2
Schedule 40	1/8	10.3	1.73	6.8
	1/4	13.7	2.24	9.2
	3/8	17.1	2.31	12.5
	1/2	21.3	2.77	15.8
	3/4	26.7	2.87	21.0
	1	33.4	3.38	26.6
	1¼	42.2	3.56	35.1
	1½	48.3	3.68	40.9
	2	60.3	3.91	52.5
	2½	73.0	5.16	62.7
	3	88.9	5.49	77.9
	3½	101.6	5.74	90.1
	4	114.3	6.02	102.3
	5	141.3	6.55	128.2
	6	168.3	7.11	154.1
	8	219.1	8.18	202.7
	10	273.0	9.27	254.5
	12	323.9	10.31	303.3
	14	355.6	11.13	333.3
	16	406.4	12.70	381.0
	18	457.2	14.27	428.7
	20	508.0	15.09	477.8
	24	609.6	17.48	574.6
Schedule 60	8	219.1	10.31	198.5
	10	273.0	12.70	247.6
	12	323.9	14.27	295.4
	14	355.6	15.09	325.4
	16	406.4	16.64	373.1
	18	457.2	19.05	419.1
	20	508.0	20.62	466.8
	24	609.6	24.61	560.4
Schedule 80	1/8	10.3	2.41	5.5
	1/4	13.7	3.02	7.7
	3/8	17.1	3.20	10.7
	1/2	21.3	3.73	13.8
	3/4	26.7	3.91	18.9
	1	33.4	4.55	24.3
	1¼	42.2	4.85	32.5
	1½	48.3	5.08	38.1
	2	60.3	5.54	49.2
	2½	73.0	7.01	59.0
	3	88.9	7.62	73.7
Schedule 80–cont.	3½	101.6	8.08	85.4
	4	114.3	8.56	97.2
	5	141.3	9.52	122.3
	6	168.3	10.97	146.4
	8	219.1	12.70	193.7
	10	273.0	15.09	242.8
	12	323.9	17.47	289.0
	14	355.6	19.05	317.5
	16	406.4	21.44	363.5
	18	457.2	23.82	409.6
	20	508.0	26.19	455.6
	24	609.6	30.96	547.7
Schedule 100	8	219.1	15.09	188.9
	10	273.0	18.26	236.5
	12	323.9	21.44	281.0
	14	355.6	23.82	308.0
	16	406.4	26.19	354.0
	18	457.2	29.36	398.5
	20	508.0	32.54	442.9
	24	609.6	38.89	531.8
Schedule 120	4	114.3	11.13	92.0
	5	141.3	12.70	115.9
	6	168.3	14.27	139.8
	8	219.1	18.26	182.6
	10	273.0	21.44	230.1
	12	323.9	25.40	273.1
	14	355.6	27.79	300.0
	16	406.4	30.96	344.5
	18	457.2	34.92	387.4
	20	508.0	38.10	431.8
	24	609.6	46.02	517.6
Schedule 140	8	219.1	20.62	177.9
	10	273.0	25.40	222.2
	12	323.9	28.58	266.7
	14	355.6	31.75	292.1
	16	406.4	36.52	333.4
	18	457.2	39.69	377.8
	20	508.0	44.45	419.1
	24	609.6	52.39	504.8
Schedule 160	1/2	21.3	4.78	11.7
	3/4	26.7	5.56	15.6
	1	33.4	6.35	20.7
	1¼	42.2	6.35	29.5
	1½	48.3	7.14	34.0
	2	60.3	8.74	42.8
	2½	73.0	9.52	54.0
	3	88.9	11.13	66.6
	4	114.3	13.49	87.3
	5	141.3	15.88	109.5
	6	168.3	18.26	131.8
	8	219.1	23.01	173.1
	10	273.0	28.58	215.8
	12	323.9	33.34	257.2
	14	355.6	35.71	284.2
	16	406.4	40.49	325.4
	18	457.2	45.24	366.7
	20	508.0	50.01	408.0
	24	609.6	59.54	490.5

Commercial Steel Pipe

Based on ANSI B36.10: 1970 and BS 1600 : Part 2 : 1970

Standard Wall Pipe

Nominal Pipe Size Inches	Outside Diameter mm	Thickness mm	Inside Diameter mm
1/8	10.3	1.73	6.8
¼	13.7	2.24	9.2
3/8	17.1	2.31	12.5
½	21.3	2.77	15.8
¾	26.7	2.87	21.0
1	33.4	3.38	26.6
1¼	42.2	3.56	35.1
1½	48.3	3.68	40.9
2	60.3	3.91	52.5
2½	73.0	5.16	62.7
3	88.9	5.49	77.9
3½	101.6	5.74	90.1
4	114.3	6.02	102.3
5	141.3	6.55	128.2
6	168.3	7.11	154.1
8	219.1 S	8.18	202.7
10	273.0 S	9.27	254.5
12	323.9 S	9.52	304.9

Extra Strong Pipe

Nominal Pipe Size Inches	Outside Diameter mm	Thickness mm	Inside Diameter mm
1/8	10.3	2.41	5.5
¼	13.7	3.02	7.7
3/8	17.1	3.20	10.7
½	21.3	3.73	13.8
¾	26.7	3.91	18.9
1	33.4	4.55	24.3
1¼	42.2	4.85	32.5
1½	48.3	5.08	38.1
2	60.3	5.54	49.2
2½	73.0	7.01	59.0
3	88.9	7.62	73.7
3½	101.6	8.08	85.4
4	114.3	8.56	97.2
5	141.3	9.52	122.3
6	168.3	10.97	146.4
8	219.1	12.70	193.7
10	273.0	12.70	247.6
12	323.9	12.70	298.5

Double Extra Strong Pipe

Nominal Pipe Size Inches	Outside Diameter mm	Thickness mm	Inside Diameter mm
½	21.3	7.47	6.4
¾	26.7	7.82	11.1
1	33.4	9.09	15.2
1¼	42.2	9.70	22.8
1½	48.3	10.16	28.0
2	60.3	11.07	38.2
2½	73.0	14.02	45.0
3	88.9	15.24	58.4
4	114.3	17.12	80.1
5	141.3	19.05	103.2
6	168.3	21.95	124.4
8	219.1	22.22	174.7
10	273.0	25.40	222.2
12	323.9	25.40	273.1

Stainless Steel Pipe

Based on ANSI B36.19-1965 and BS 1600 : Part 2 : 1970

Schedule 5 S

Nominal Pipe Size Inches	Outside Diameter mm	Thickness mm	Inside Diameter mm
½	21.3	1.65	18.0
¾	26.7	1.65	23.4
1	33.4	1.65	30.1
1¼	42.2	1.65	38.9
1½	48.3	1.65	45.0
2	60.3	1.65	57.0
2½	73.0	2.11	68.8
3	88.9	2.11	84.7
3½	101.6	2.11	97.4
4	114.3	2.11	110.1
5	141.3	2.77	135.8
6	168.3	2.77	162.8
8	219.1	2.77	213.6
10	273.0	3.40	266.2
12	323.9	3.96	316.0

Schedule 10 S

Nominal Pipe Size Inches	Outside Diameter mm	Thickness mm	Inside Diameter mm
⅛	10.3	1.24	7.8
¼	13.7	1.65	10.4
⅜	17.1	1.65	13.8
½	21.3	2.11	17.1
¾	26.7	2.11	22.5
1	33.4	2.77	27.9
1¼	42.2	2.77	36.7
1½	48.3	2.77	42.8
2	60.3	2.77	54.8
2½	73.0	3.05	66.9
3	88.9	3.05	82.8
3½	101.6	3.05	95.5
4	114.3	3.05	108.2
5	141.3	3.40	134.5
6	168.3	3.40	161.5
8	219.1	3.76	211.6
10	273.0	4.19	264.6
12	323.9	4.57	314.8

Schedule 40 S

⅛ to 12	Values are the same, size for size, as those shown on page B – 17 for Standard Wall Pipe

Schedule 80 S

⅛ to 12	Values are the same, size for size, as those shown on page B – 17 for Extra Strong Pipe.

Commercial Steel Pipe

Selected from ISO 336 - 1974 and BS 3600 : 1973

Nominal Pipe Size (Inches)	Outside Diameter (mm)	Thickness (mm)	Inside Diameter (mm)
⅛	10.2	1.6	7.0
		1.8	6.6
		2.0	6.2
		2.3	5.6
¼	13.5	1.8	9.9
		2.0	9.5
		2.3	8.9
		2.6	8.3
		2.9	7.7
⅜	17.2	2.0	13.2
		2.3	12.6
		2.6	12.0
		2.9	11.4
		3.2	10.8
½	21.3	2.6	16.1
		2.9	15.5
		3.2	14.9
		3.6	14.1
		4.0	13.3
		4.5	12.3
		5.0	11.3
		5.4	10.5
¾	26.9	2.6	21.7
		2.9	21.1
		3.2	20.5
		3.6	19.7
		4.0	18.9
		4.5	17.9
		5.0	16.9
		5.4	16.1
		5.6	15.7
		5.9	15.1
		6.3	14.3
		7.1	12.7
1	33.7	3.2	27.3
		3.6	26.5
		4.0	25.7
		4.5	24.7
		5.0	23.7
		5.4	22.9
		5.6	22.5
		5.9	21.9
		6.3	21.1
		7.1	19.5
		8.0	17.7
		8.8	16.1
1¼	42.4	3.2	36.0
		3.6	35.2
		4.0	34.4
		4.5	33.4
		5.0	32.4
		5.4	31.6
		5.6	31.2
		5.9	30.6
		6.3	29.8
		7.1	28.2
		8.0	26.4
		8.8	24.8
		10.0	22.4*
1½	48.3	3.2	41.9
		3.6	41.1
		4.0	40.3
		4.5	39.3
		5.0	38.3
		5.4	37.5
		5.6	37.1
		5.9	36.5
		6.3	35.7
		7.1	34.1
		8.0	32.3
		8.8	30.7
		10.0	28.3

Nominal Pipe Size (Inches)	Outside Diameter (mm)	Thickness (mm)	Inside Diameter (mm)
2	60.3	3.6	53.1
		4.0	52.3
		4.5	51.0
		5.0	50.3
		5.4	49.5
		5.6	49.1
		5.9	48.5
		6.3	47.7
		7.1	46.1
		8.0	44.3
		8.8	42.7
		10.0	40.3
		11.0	38.3
2½	76.1	5.0	66.1
		5.4	65.3
		5.6	64.9
		5.9	64.3
		6.3	63.5
		7.1	61.9
		8.0	60.1
		8.8	58.5
		10.0	56.1
		11.0	54.1
		12.5	51.1
		14.2	47.7
3	88.9	5.4	78.1
		5.6	77.7
		5.9	77.1
		6.3	76.3
		7.1	74.7
		8.0	72.9
		8.8	71.3
		10.0	68.9
		11.0	66.9
		12.5	63.9
		14.2	60.5
		16.0	56.9
3½	101.6	5.6	90.4
		5.9	89.8
		6.3	89.0
		7.1	87.4
		8.0	85.6
		8.8	84.0
		10.0	81.6
		11.0	79.6
		12.5	76.6
		14.2	73.2
		16.0	69.6
		17.5	66.6
4	114.3	5.6	103.1
		5.9	102.5
		6.3	101.7
		7.1	100.1
		8.0	98.3
		8.8	96.7
		10.0	94.3
		11.0	92.3
		12.5	89.3
		14.2	85.9
		16.0	82.3
		17.5	79.3
		20.0	74.3
5	139.7	5.9	127.9
		6.3	127.1
		7.1	125.5
		8.0	123.7
		8.8	122.1
		10.0	119.7
		11.0	117.7
		12.5	114.7
		14.2	111.3
		16.0	107.7
		17.5	104.7
		20.0	99.7

* Not included in BS 3600 : 1973

Commercial Steel Pipe – continued

Nominal Pipe Size Inches	Outside Diameter mm	Thickness mm	Inside Diameter mm
6	168.3	6.3	155.7
		7.1	154.1
		8.0	152.3
		8.8	150.7
		10.0	148.3
		11.0	146.3
		12.5	143.3
		14.2	139.9
		16.0	136.3
		17.5	133.3
		20.0	128.3
		22.2	123.9
8	219.1	6.3	206.5
		7.1	204.9
		8.0	203.1
		8.8	201.5
		10.0	199.1
		11.0	197.1
		12.5	194.1
		14.2	190.7
		16.0	187.1
		17.5	184.1
		20.0	179.1
		22.2	174.7
		25.0	169.1
10	273.0	6.3	260.4
		7.1	258.8
		8.0	257.0
		8.8	255.4
		10.0	253.0
		11.0	251.0
		12.5	248.0
		14.2	244.6
		16.0	241.0
		17.5	238.0
		20.0	233.0
		22.2	228.6
		25.0	223.0
		28.0	217.0*
		30.0	213.0*
12	323.9	6.3	311.3
		7.1	309.7
		8.0	307.9
		8.8	306.3
		10.0	303.9
		11.0	301.9
		12.5	298.9
		14.2	295.5
		16.0	291.9
		17.5	288.9
		20.0	283.9
		22.2	279.5
		25.0	273.9
		28.0	267.9*
		30.0	263.9*
		32.0	259.9*
		36.0	251.9*
14	355.6	6.3	343.0
		7.1	341.4
		8.0	339.6
		8.8	338.0
		10.0	335.6
		11.0	333.6
		12.5	330.6
		14.2	327.2
		16.0	323.6
		17.5	320.6
		20.0	315.6
		22.2	311.2
		25.0	305.6
		28.0	299.6*
		30.0	295.6*
		32.0	291.6*
		36.0	283.6*
16	406.4	6.3	393.8
		7.1	392.2
		8.0	390.4
		8.8	388.8
		10.0	386.4
		11.0	384.4
		12.5	381.4
		14.2	378.0
		16.0	374.4
		17.5	371.4
		20.0	366.4
		22.2	362.0
		25.0	356.4
		28.0	350.4*
		30.0	346.4*
		32.0	342.4*
		36.0	334.4*
		40.0	326.4*
		45.0	316.4*
18	457.0	6.3	444.4
		7.1	442.8
		8.0	441.0
		8.8	439.4
		10.0	437.0
		11.0	435.0
		12.5	432.0
		14.2	428.6
		16.0	425.0
		17.5	422.0
		20.0	417.0
		22.2	412.6
		25.0	407.0
		28.0	401.0*
		30.0	397.0*
		32.0	393.0*
		36.0	385.0*
		40.0	377.0*
		45.0	367.0*
		50.0	357.0*
20	508.0	6.3	495.4
		7.1	493.8
		8.0	492.0
		8.8	490.4
		10.0	488.0
		11.0	486.0
		12.5	483.0
		14.2	479.6
		16.0	476.0
		17.5	473.0
		20.0	468.0
		22.2	463.6
		25.0	458.0
		28.0	452.0*
		30.0	448.0*
		32.0	444.0*
		36.0	436.0*
		40.0	428.0*
		45.0	418.0*
		50.0	408.0*
		55.0	398.0*
24	610.0	6.3	597.4
		7.1	595.8
		8.0	594.0
		8.8	592.4
		10.0	590.0
		11.0	588.0
		12.5	585.0
		14.2	581.6
		16.0	578.0
		17.5	575.0
		20.0	570.0
		22.2	565.6
		25.0	560.0
		28.0	554.0*
		30.0	550.0*
		32.0	546.0*
		36.0	538.0*
		40.0	530.0*
		45.0	520.0*
		50.0	510.0*
		55.0	500.0*
		60.0	490.0*

* Not included in BS 3600 : 1973

Power Required for Pumping

Litres per Min.	Theoretical Power in kilowatts (kW) to Raise Water (at 15 C) to Different Heights														
	Metres														
	2	4	6	8	10	12	14	16	18	20	25	30	35	40	45
20	0.007	0.013	0.020	0.026	0.033	0.039	0.046	0.052	0.059	0.065	0.082	0.098	0.114	0.131	0.147
40	0.013	0.026	0.039	0.052	0.065	0.078	0.091	0.105	0.118	0.131	0.163	0.196	0.229	0.261	0.294
60	0.020	0.039	0.059	0.078	0.098	0.118	0.137	0.157	0.176	0.196	0.245	0.294	0.343	0.392	0.441
80	0.026	0.052	0.078	0.105	0.131	0.157	0.183	0.209	0.235	0.261	0.327	0.392	0.457	0.523	0.588
100	0.033	0.065	0.098	0.131	0.163	0.196	0.229	0.261	0.294	0.327	0.408	0.490	0.572	0.653	0.735
120	0.039	0.078	0.118	0.157	0.196	0.235	0.274	0.314	0.353	0.392	0.490	0.588	0.686	0.784	0.882
140	0.046	0.091	0.137	0.183	0.229	0.274	0.320	0.366	0.412	0.457	0.572	0.686	0.800	0.915	1.029
160	0.052	0.105	0.157	0.209	0.261	0.314	0.366	0.418	0.470	0.523	0.653	0.784	0.915	1.045	1.176
180	0.059	0.118	0.176	0.235	0.294	0.353	0.412	0.470	0.529	0.588	0.735	0.882	1.029	1.176	1.323
200	0.065	0.131	0.196	0.261	0.327	0.392	0.457	0.523	0.588	0.653	0.817	0.980	1.143	1.307	1.470
250	0.082	0.163	0.245	0.327	0.408	0.490	0.572	0.653	0.735	0.817	1.021	1.225	1.429	1.633	1.838
300	0.098	0.196	0.294	0.392	0.490	0.588	0.686	0.784	0.882	0.980	1.225	1.470	1.715	1.960	2.205
350	0.114	0.229	0.343	0.457	0.572	0.686	0.800	0.915	1.029	1.143	1.429	1.715	2.001	2.287	2.573
400	0.131	0.261	0.392	0.523	0.653	0.784	0.915	1.045	1.176	1.307	1.633	1.960	2.287	2.614	2.940
450	0.147	0.294	0.441	0.588	0.735	0.882	1.029	1.176	1.323	1.470	1.838	2.205	2.573	2.940	3.308
500	0.163	0.327	0.490	0.653	0.817	0.980	1.143	1.307	1.470	1.633	2.042	2.450	2.859	3.267	3.675
600	0.196	0.392	0.588	0.784	0.980	1.176	1.372	1.568	1.764	1.960	2.450	2.940	3.430	3.920	4.410
700	0.229	0.457	0.686	0.915	1.143	1.372	1.601	1.829	2.058	2.287	2.859	3.430	4.002	4.574	5.145
800	0.261	0.523	0.784	1.045	1.307	1.568	1.829	2.091	2.352	2.614	3.267	3.920	4.574	5.227	5.880
900	0.294	0.588	0.882	1.176	1.470	1.764	2.058	2.352	2.646	2.940	3.675	4.410	5.145	5.880	6.615
1000	0.327	0.653	0.980	1.307	1.633	1.960	2.287	2.614	2.940	3.267	4.084	4.900	5.717	6.534	7.351
1250	0.408	0.817	1.225	1.633	2.042	2.450	2.859	3.267	3.675	4.084	5.105	6.125	7.146	8.167	9.188
1500	0.490	0.980	1.470	1.960	2.450	2.940	3.430	3.920	4.410	4.900	6.125	7.351	8.576	9.801	11.03
2000	0.653	1.307	1.960	2.614	3.267	3.920	4.574	5.227	5.880	6.534	8.167	9.801	11.43	13.07	14.70

Litres per Min.	Metres						
	50	55	60	70	80	90	100
20	0.163	0.180	0.196	0.229	0.261	0.294	0.327
40	0.327	0.359	0.392	0.457	0.523	0.588	0.653
60	0.490	0.539	0.588	0.686	0.784	0.882	0.980
80	0.653	0.719	0.784	0.915	1.045	1.176	1.307
100	0.817	0.898	0.980	1.143	1.307	1.470	1.633
120	0.980	1.078	1.176	1.372	1.568	1.764	1.960
140	1.143	1.258	1.372	1.601	1.829	2.058	2.287
160	1.307	1.437	1.568	1.829	2.091	2.352	2.614
180	1.470	1.617	1.764	2.058	2.352	2.646	2.940
200	1.633	1.797	1.960	2.287	2.614	2.940	3.267
250	2.042	2.246	2.450	2.859	3.267	3.675	4.084
300	2.450	2.695	2.940	3.430	3.920	4.410	4.900
350	2.859	3.144	3.430	4.002	4.574	5.145	5.717
400	3.267	3.594	3.920	4.574	5.227	5.880	6.534
450	3.675	4.043	4.410	5.145	5.880	6.615	7.351
500	4.084	4.492	4.900	5.717	6.534	7.351	8.167
600	4.900	5.390	5.880	6.861	7.841	8.821	9.801
700	5.717	6.289	6.861	8.004	9.147	10.29	11.43
800	6.534	7.187	7.841	9.147	10.45	11.76	13.07
900	7.351	8.086	8.821	10.29	11.76	13.23	14.70
1000	8.167	8.984	9.801	11.43	13.07	14.70	16.33
1250	10.21	11.23	12.25	14.29	16.33	18.38	20.42
1500	12.25	13.48	14.70	17.15	19.60	22.05	24.50
2000	16.33	17.97	19.60	22.87	26.14	29.40	32.67

$$\text{Theoretical Power} = \frac{QH\rho}{6116 \times 10^3} = \frac{Qp}{600} \text{ kilowatts}$$

$$\text{Power Demand (Brake Power)} = \frac{\text{Theoretical Power}}{e_p}$$

where: Q = Flow rate in litres per minute
H = Pump head in metres
ρ = Density of liquid in kg/m^3
p = Pressure in bar gauge
e_p = Pump efficiency

Overall efficiency (e_o) takes into account all losses in the pump and driver.

$$e_o = e_p \, e_D \, e_T$$

where: e_D = driver efficiency
e_T = transmission efficiency
e_V = volumetric efficiency

$$e_V (\%) = \frac{\text{actual pump displacement } (Q)\ (100)}{\text{theoretical pump displacement } (Q)}$$

Note: For fluids other than water, multiply table values by specific gravity. In pumping liquids with a viscosity considerably higher than that of water, the pump capacity and head are reduced. To calculate the power required for such fluids, pipe friction head must be added to the elevation head to obtain the total head; this value is inserted in the first power equation given above.

Specific gravity of water . . . . *page A-6*
Specific gravity of liquids other than water . . . . *page A-7*

TEMPERATURE CONVERSION

-460° to 0°			1° to 60°			61° to 290°			300° to 890°			900° to 3000°		
C	C / F	F	C	C / F	F	C	C / F	F	C	C / F	F	C	C / F	F
-273	-460		-17.2	1	33.8	16.1	61	141.8	149	300	572	482	900	1652
-268	-450		-16.7	2	35.6	16.7	62	143.6	154	310	590	488	910	1670
-262	-440		-16.1	3	37.4	17.2	63	145.4	160	320	608	493	920	1688
-257	-430		-15.6	4	39.2	17.8	64	147.2	166	330	626	499	930	1706
-251	-420		-15.0	5	41.0	18.3	65	149.0	171	340	644	504	940	1724
-246	-410		-14.4	6	42.8	18.9	66	150.8	177	350	662	510	950	1742
-240	-400		-13.9	7	44.6	19.4	67	152.6	182	360	680	516	960	1760
-234	-390		-13.3	8	46.4	20.0	68	154.4	188	370	698	521	970	1778
-229	-380		-12.8	9	48.2	20.6	69	156.2	193	380	716	527	980	1796
-223	-370		-12.2	10	50.0	21.1	70	158.0	199	390	734	532	990	1814
-218	-360		-11.7	11	51.8	21.7	71	159.8	204	400	752	538	1000	1832
-212	-350		-11.1	12	53.6	22.2	72	161.6	210	410	770	549	1020	1868
-207	-340		-10.6	13	55.4	22.8	73	163.4	216	420	788	560	1040	1904
-201	-330		-10.0	14	57.2	23.3	74	165.2	221	430	806	571	1060	1940
-196	-320		-9.4	15	59.0	23.9	75	167.0	227	440	824	582	1080	1976
-190	-310		-8.9	16	60.8	24.4	76	168.8	232	450	842	593	1100	2012
-184	-300		-8.3	17	62.6	25.0	77	170.6	238	460	860	604	1120	2048
-179	-290		-7.8	18	64.4	25.6	78	172.4	243	470	878	616	1140	2084
-173	-280		-7.2	19	66.2	26.1	79	174.2	249	480	896	627	1160	2120
-169	-273	-460	-6.7	20	68.0	26.7	80	176.0	254	490	914	638	1180	2156
-168	-270	-454	-6.1	21	69.8	27.2	81	177.8	260	500	932	649	1200	2192
-162	-260	-436	-5.6	22	71.6	27.8	82	179.6	266	510	950	660	1220	2228
-157	-250	-418	-5.0	23	73.4	28.3	83	181.4	271	520	968	671	1240	2264
-151	-240	-400	-4.4	24	75.2	28.9	84	183.2	277	530	986	682	1260	2300
-146	-230	-382	-3.9	25	77.0	29.4	85	185.0	282	540	1004	693	1280	2336
-140	-220	-364	-3.3	26	78.8	30.0	86	186.8	288	550	1022	704	1300	2372
-134	-210	-346	-2.8	27	80.6	30.6	87	188.6	293	560	1040	732	1350	2462
-129	-200	-328	-2.2	28	82.4	31.1	88	190.4	299	570	1058	760	1400	2552
-123	-190	-310	-1.7	29	84.2	31.7	89	192.2	304	580	1076	788	1450	2642
-118	-180	-292	-1.1	30	86.0	32.2	90	194.0	310	590	1094	816	1500	2732
-112	-170	-274	-0.6	31	87.8	32.8	91	195.8	316	600	1112	843	1550	2822
-107	-160	-256	0.0	32	89.6	33.3	92	197.6	321	610	1130	871	1600	2912
-101	-150	-238	0.6	33	91.4	33.9	93	199.4	327	620	1148	899	1650	3002
-96	-140	-220	1.1	34	93.2	34.4	94	201.2	332	630	1166	927	1700	3092
-90	-130	-202	1.7	35	95.0	35.0	95	203.0	338	640	1184	954	1750	3182
-84	-120	-184	2.2	36	96.8	35.6	96	204.8	343	650	1202	982	1800	3272
-79	-110	-166	2.8	37	98.6	36.1	97	206.6	349	660	1220	1010	1850	3362
-73	-100	-148	3.3	38	100.4	36.7	98	208.4	354	670	1238	1038	1900	3452
-68	-90	-130	3.9	39	102.2	37.2	99	210.2	360	680	1256	1066	1950	3542
-62	-80	-112	4.4	40	104.0	37.8	100	212.0	366	690	1274	1093	2000	3632
-57	-70	-94	5.0	41	105.8	43	110	230	371	700	1292	1121	2050	3722
-51	-60	-76	5.6	42	107.6	49	120	248	377	710	1310	1149	2100	3812
-46	-50	-58	6.1	43	109.4	54	130	266	382	720	1328	1177	2150	3902
-40	-40	-40	6.7	44	111.2	60	140	284	388	730	1346	1204	2200	3992
-34	-30	-22	7.2	45	113.0	66	150	302	393	740	1364	1232	2250	4082
-29	-20	-4	7.8	46	114.8	71	160	320	399	750	1382	1260	2300	4172
-23	-10	14	8.3	47	116.6	77	170	338	404	760	1400	1288	2350	4262
-17.8	0	32	8.9	48	118.4	82	180	356	410	770	1418	1316	2400	4352
			9.4	49	120.2	88	190	374	416	780	1436	1343	2450	4442
			10.0	50	122.0	93	200	392	421	790	1454	1371	2500	4532
			10.6	51	123.8	99	210	410	427	800	1472	1399	2550	4622
			11.1	52	125.6	100	212	413.6	432	810	1490	1427	2600	4712
			11.7	53	127.4	104	220	428	438	820	1508	1454	2650	4802
			12.2	54	129.2	110	230	446	443	830	1526	1482	2700	4892
			12.8	55	131.0	116	240	464	449	840	1544	1510	2750	4982
			13.3	56	132.8	121	250	482	454	850	1562	1538	2800	5072
			13.9	57	134.6	127	260	500	460	860	1580	1566	2850	5162
			14.4	58	136.4	132	270	518	466	870	1598	1593	2900	5252
			15.0	59	138.2	138	280	536	471	880	1616	1621	2950	5342
			15.6	60	140.0	143	290	554	477	890	1634	1649	3000	5432

Locate temperature in middle column. If in degrees Celsius, read Fahrenheit equivalent in right hand column; if in degrees Fahrenheit, read Celsius equivalent in left hand column.