temperature operation, this may consist of a steam-heated tempering coil, while for high-temperature drying, a direct-fired (oil or gas) combustion furnace directly connected to the dryer supplies hot combustion gas to the dryer. Where product contamination by the combustion gas is a possibility, an indirect-fired heating unit is used. The hot gas is forced through the drying cylinder by an induced-draft centrifugal-type fan which is appropriately arranged to provide either cocurrent or countercurrent flow, that is, in the direction of product flow or in a direction counter to product flow. Typically, a dust collector (cyclone type, or filters and scrubbers) recovers the fines from the exhaust gas.

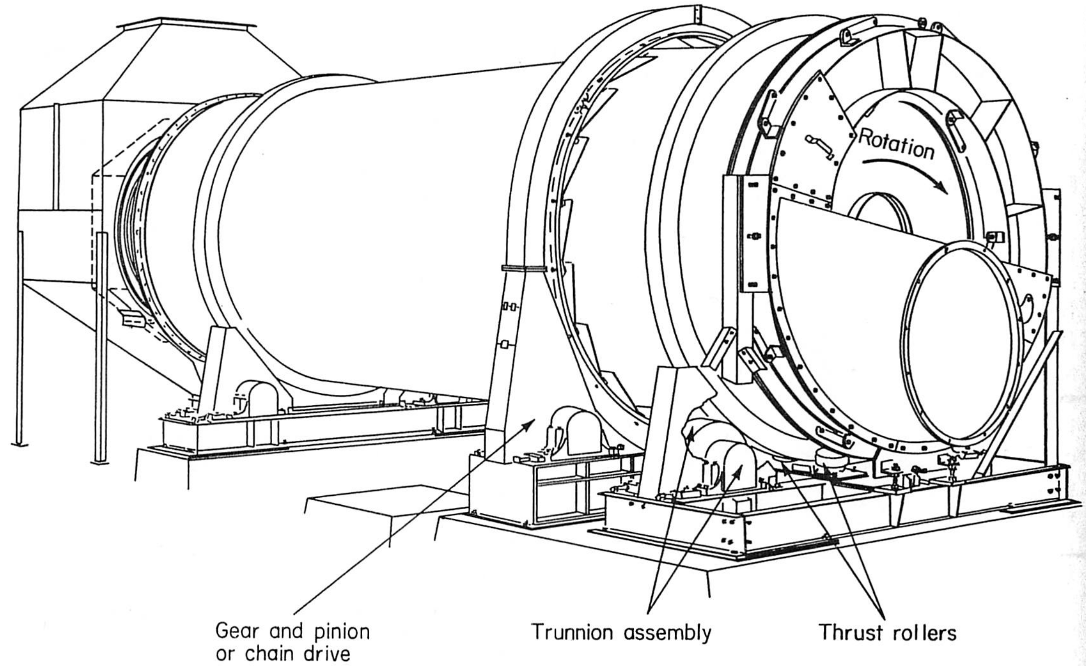

Fig. 9 Rotary dryer. *(FMC Corporation.)*

In the case of indirect rotary dryers, the material is dried by direct contact with a hot metal surface, such as steam- or hot-water-heated tubes, over which the product flows in a thin layer. A sufficient flow of air is maintained through the dryer to remove the water vapor. Indirect rotary dryers are applicable in the situation where the material undergoing drying cannot be exposed to combustion gases, or where excessive dust carry-over in the combustion gas will occur.

Design Equations: Retention Time An estimation of product residence time is difficult to obtain because of the complex interaction of the following factors:

Percentage loading
Number of flights
Design of flights
Slope of the dryer from the horizontal
Speed of rotation of the dryer shell
Length of dryer (effective)
Diameter of dryer
Physical properties of the material
Air velocity within the dryer

The effect of each of the above factors on the residence time is discussed qualitatively by Williams-Gardner.[5] Empirical expressions, based on experimental work, for the residence time are:

$$t = \frac{KL}{nDS} + Yv \tag{13}$$

where t = retention time, min
L = effective length of dryer, ft

9.5E Moisture Movements in Solids During Drying in the Falling-Rate Period

When drying occurs by evaporation of moisture from the exposed surface of a solid, moisture must move from the depths of the solid to the surface. The mechanisms of this movement affect the drying during the constant-rate and falling-rate periods. Some of the theories advanced to explain the various types of falling-rate curves will be briefly reviewed.

1. Liquid diffusion theory. According to this theory, diffusion of liquid moisture occurs when there is a concentration difference between the depths of the solid and the surface. This method of transport of moisture is usually found in nonporous solids where single-phase solutions are formed with the moisture, such as in paste, soap, gelatin, and glue. It is also found in drying the last portions of moisture from clay, flour, wood, leather, paper, starches, and textiles. In drying many food materials, the movement of water in the falling-rate period also occurs by diffusion.

The shapes of the moisture-distribution curves in the solid at given times are qualitatively consistent with the unsteady-state diffusion equations given in Chapter 7. The moisture diffusivity D_{AB} usually decreases with decreased moisture content, so that the diffusivities are usually average values over the range of concentrations used. Materials drying in this way are usually said to be drying by diffusion, although the actual mechanisms may be quite complicated. Since the rate of evaporation from the surface is quite fast, that is, the resistance is quite low, compared to the diffusion rate through the solid in the falling-rate period, the moisture content at the surface is at the equilibrium value.

The shape of a diffusion-controlled curve in the falling-rate period is similar to Fig. 9.5-2a. If the initial constant-rate drying is quite high, the first falling-rate period of unsaturated surface evaporation may not appear. If the constant-rate drying is quite low, the period of unsaturated surface evaporation is usually present in region CD in Fig. 9.5-1b and the diffusion-controlled curve is in region DE. Equations for calculating drying in this period where diffusion controls are given in Section 9.9. Also, Problem 7.1-4 for the drying of clay and Problem 7.1-6 for the drying of wood using diffusion theory are given in the Chapter 7 Problems.

2. Capillary movement in porous solids. When granular and porous solids such as clays, sand, soil, paint pigments, and minerals are being dried, unbound or free moisture moves

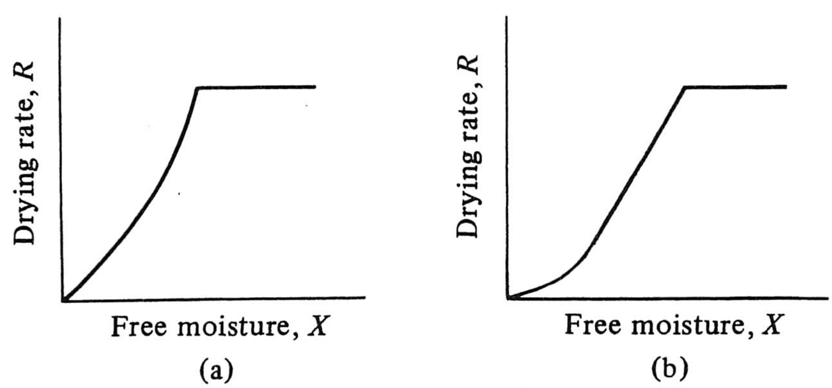

FIGURE 9.5-2. *Typical drying-rate curves: (a) diffusion-controlled falling-rate period, (b) capillary-controlled falling-rate period in a fine porous solid.*

most competent to make this decision. The process of scaling up the laboratory test drying time to the commercial drying time is subject to considerable uncertainties and subjective factors, the effects of which are not quantitatively predictable. Thus, the magnitude of the scale-up factor is based primarily on experience and is a function of the specific dryer type being simulated and of the drying and physical characteristics of the material being dried. The value of the scale-up factor can vary from about 1.2 to 2.0 or greater, depending on variables such as the degree of uniformity of the feed and the rapidity of drying. The designer should consult the vendor for an appropriate scale-up factor for typical drying systems.

Once the most appropriate dryer type has been determined, an efficient laboratory testing program should be designed to establish the optimal operating conditions. An effective experimental plan will elicit the critical data required by the designer and will ensure that the ultimate commercial system is the one most suited to meet the client's requirements.

DRYER DESIGN AND PERFORMANCE

Tray Dryer

Tray dryers are adaptable to the drying of almost any material that can be contained in a tray. A variation of this is the rack-type dryer. Generally, batch operation is used; however, there are many continuous tray or rack dryers in industry today. Figure 3 illustrates the air circulation system and tray arrangement in a typical batch atmospheric tray dryer. Heat is usually supplied by steam coils or gas burners located inside the dryer, and the heated air is recirculated over the surface of the stacked trays. Drying times may vary from hours to days. Because of the labor required to load and unload the trays, materials that exhibit short drying times are not normally dried in a tray dryer except where production is very limited or of an experimental nature. Figure 4 shows a typical truck-tray dryer arrangement.

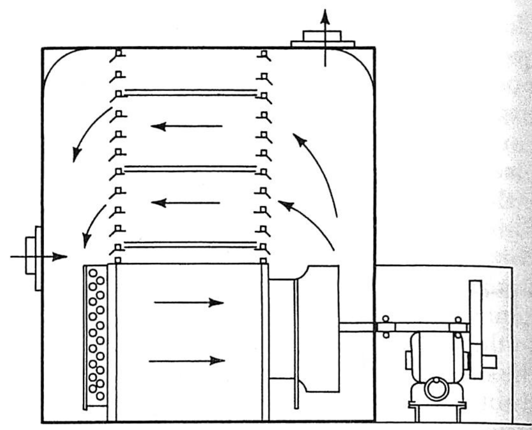

Fig. 3 Typical cross-circulation tray dryer. *(Proctor & Schwartz, Inc.)*

Design Equations In the typical design problem it is desired to determine the amount of tray area required for a specified production rate. The necessary data (usually obtained from the laboratory tests) are the drying time for the given initial and final moisture contents and the desired tray loading. The design equation is

$$A = \frac{P(t + t_d)}{L}$$

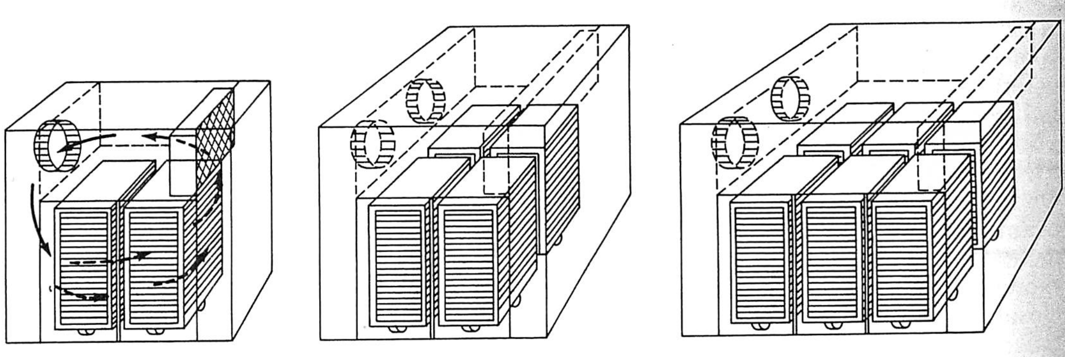

Fig. 4 Typical truck dryer arrangement. *(Proctor & Schwartz, Inc.)*

2. *Plot of rate-of-drying curve.* In Fig. 9.5-1b the rate-of-drying curve for constant-drying conditions is shown. At zero time the initial free moisture content is shown at point A. In the beginning the solid is usually at a colder temperature than its ultimate temperature, and the evaporation rate will increase. Eventually, at point B, the surface temperature rises to its equilibrium value. Alternatively, if the solid is quite hot to start with, the rate may start at point A'. This initial unsteady-state adjustment period is usually quite short and it is often ignored in the analysis of times of drying.

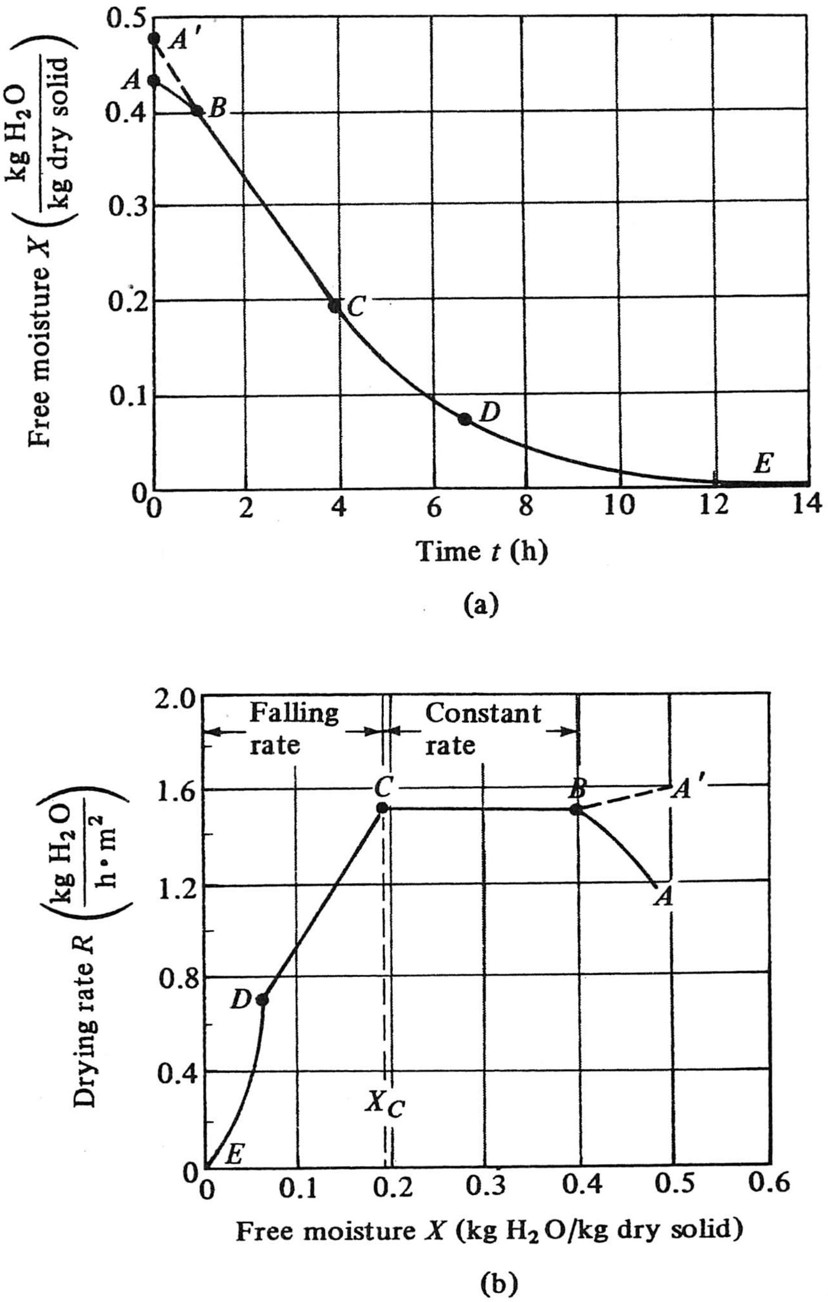

FIGURE 9.5-1. *Typical drying-rate curve for constant drying conditions: (a) plot of data as free moisture versus time, (b) rate of drying curve as rate versus free moisture content.*

9.1B General Methods of Drying

Drying methods and processes can be classified in several different ways. Drying processes can be classified as *batch,* where the material is inserted into the drying equipment and drying proceeds for a given period of time, or as *continuous,* where the material is continuously added to the dryer and dried material is continuously removed.

Drying processes can also be categorized according to the physical conditions used to add heat and remove water vapor: (1) in the first category, heat is added by direct contact with heated air at atmospheric pressure, and the water vapor formed is removed by the air; (2) in vacuum drying, the evaporation of water proceeds more rapidly at low pressures, and the heat is added indirectly by contact with a metal wall or by radiation (low temperatures can also be used under vacuum for certain materials that may discolor or decompose at higher temperatures); and (3) in freeze-drying, water is sublimed from the frozen material.

9.2 EQUIPMENT FOR DRYING

9.2A Tray Dryer

In *tray dryers,* which are also called shelf, cabinet, or compartment dryers, the material, which may be a lumpy solid or a pasty solid, is spread uniformly on a metal tray to a depth of 10 to 100 mm. Such a typical tray dryer, shown in Fig. 9.2-1, contains removable trays loaded in a cabinet.

Steam-heated air is recirculated by a fan over and parallel to the surface of the trays. Electrical heat is also used, especially for low heating loads. About 10 to 20% of the air passing over the trays is fresh air, the remainder being recirculated air.

After drying, the cabinet is opened and the trays are replaced with a new batch of trays. A modification of this type is the tray–truck type, where trays are loaded on trucks which are pushed into the dryer. This saves considerable time, since the trucks can be loaded and unloaded outside the dryer.

In the case of granular materials, the material can be loaded on screens which form the bottom of each tray. Then, in this through-circulation dryer, heated air passes through the permeable bed, yielding shorter drying times because of the greater surface area exposed to the air.

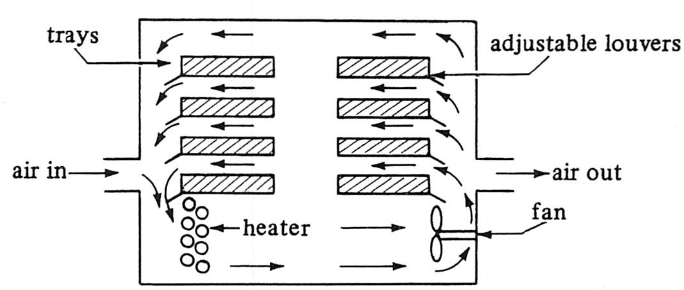

FIGURE 9.2-1. *Tray or shelf dryer.*

9.2B Vacuum-Shelf Indirect Dryers

Vacuum-shelf dryers are indirectly heated batch dryers similar to tray dryers. Such a dryer consists of a cabinet made of cast-iron or steel plates with tightly fitted doors so that it can be operated under vacuum. Hollow shelves of steel are fastened permanently inside the chamber and are connected in parallel to inlet and outlet steam headers. The trays containing the solids to be dried rest upon the hollow shelves. The heat is conducted through the metal walls and aided by radiation from the shelf above. For low-temperature operation, circulating warm water is used instead of steam for furnishing the heat to vaporize the moisture. The vapors usually pass to a condenser.

These dryers are used to dry expensive or temperature-sensitive or easily oxidizable materials. They are useful for handling materials with toxic or valuable solvents.

9.2C Continuous Tunnel Dryers

Continuous tunnel dryers are often batch truck or tray compartments operated in series, as shown in Fig. 9.2-2a. The solids are placed on trays or on trucks which move continuously through a tunnel with hot gases passing over the surface of each tray. The hot air flow can be countercurrent, cocurrent, or a combination. Many foods are dried in this way.

When granular particles of solids are to be dried, perforated or screen-belt continuous conveyors are often used, as in Fig. 9.2-2b. The wet granular solids are conveyed as a layer 25

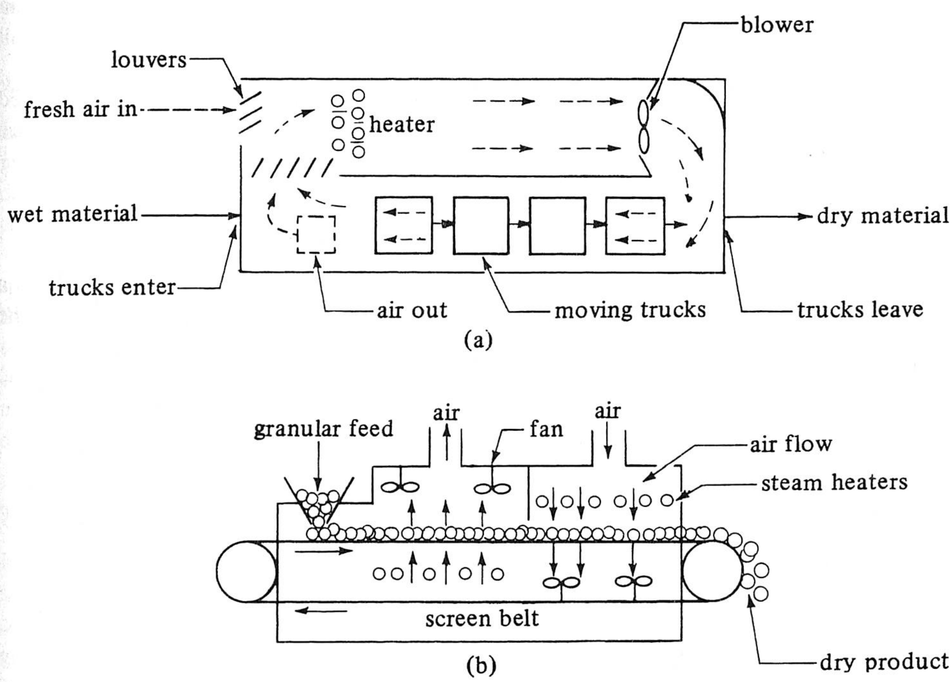

FIGURE 9.2-2. *Continuous tunnel dryers: (a) tunnel dryer trucks with countercurrent air flow, (b) through-circulation screen conveyor dryer.*

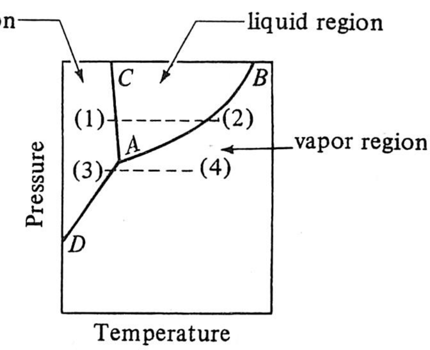

FIGURE 9.3-1. *Phase diagram for water.*

If a pan of water is held at 65.6°C in a room at 101.3 kPa abs pressure, the vapor pressure of water will again be 25.7 kPa. This illustrates an important property of the vapor pressure of water, which is not influenced by the presence of an inert gas such as air; that is, the vapor pressure of water is essentially independent of the total pressure of the system.

9.3B Humidity and Humidity Chart

1. Definition of humidity. The humidity H of an air–water vapor mixture is defined as the kg of water vapor contained in 1 kg of dry air. The humidity so defined depends only on the partial pressure p_A of water vapor in the air and on the total pressure P (assumed throughout this chapter to be 101.325 kPa, 1.0 atm abs, or 760 mm Hg). Using the molecular weight of water (A) as 18.02 and of air as 28.97, the humidity H in kg H_2O/kg dry air, or in English units as lb H_2O/lb dry air, is as follows:

$$H \frac{\text{kg } H_2O}{\text{kg dry air}} = \frac{p_A}{P - p_A} \frac{\text{kg mol } H_2O}{\text{kg mol air}} \times \frac{18.02 \text{ kg } H_2O}{\text{kg mol } H_2O} \times \frac{1}{28.97 \text{ kg air/kg mol air}} \tag{9.3-1}$$

$$H = \frac{18.02}{28.97} \frac{p_A}{P - p_A}$$

Saturated air is air in which the water vapor is in equilibrium with liquid water at the given conditions of pressure and temperature. In this mixture the partial pressure of the water vapor in the air–water mixture is equal to the vapor pressure p_{AS} of pure water at the given temperature. Hence, the saturation humidity H_S is

$$H_S = \frac{18.02}{28.97} \frac{p_{AS}}{P - p_{AS}} \tag{9.3-2}$$

2. Percentage humidity. The percentage humidity H_P is defined as 100 times the actual humidity H of the air divided by the humidity H_S if the air were saturated at the same temperature and pressure:

$$H_P = 100 \frac{H}{H_S} \tag{9.3-3}$$

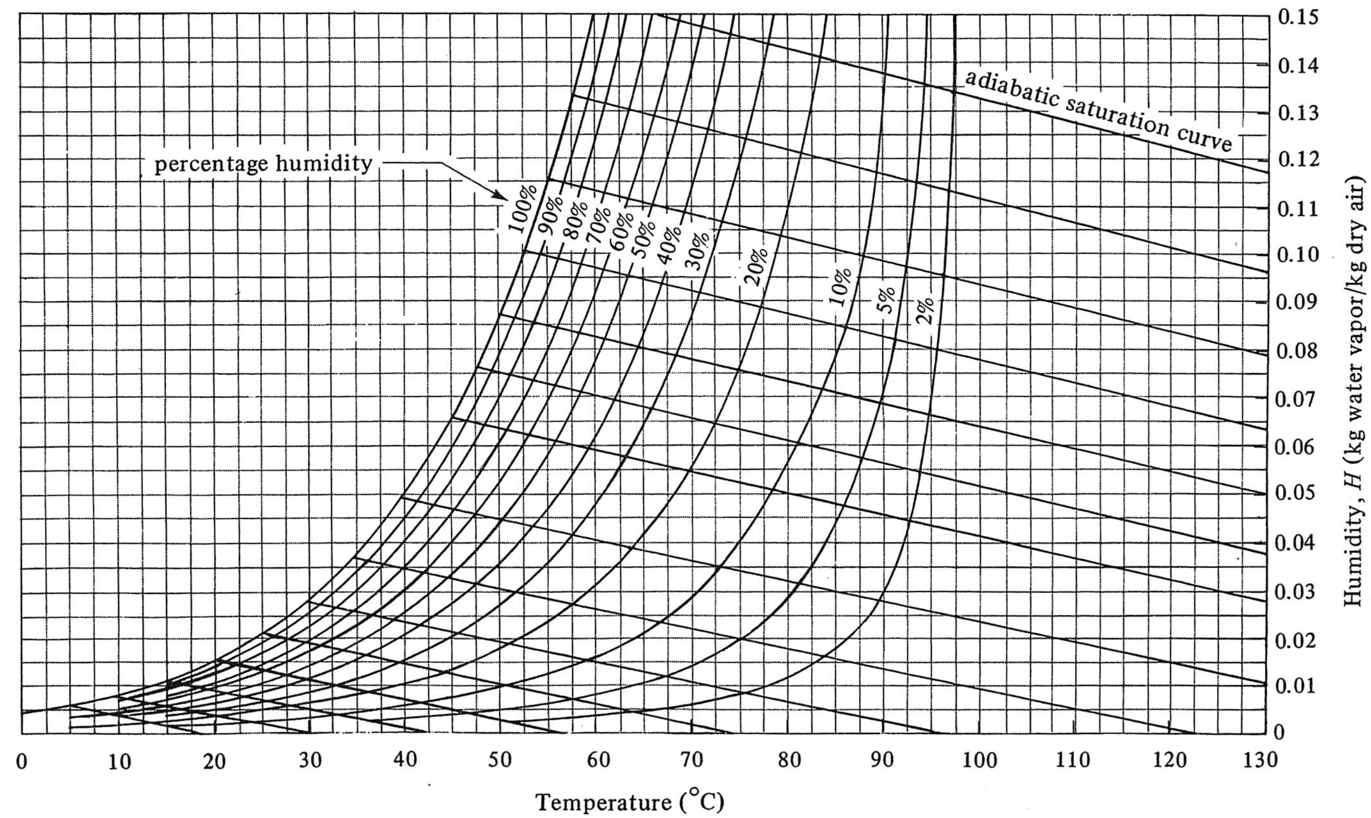

FIGURE 9.3-2. *Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)*

For some solids the value of the equilibrium moisture content depends on the direction from which equilibrium is approached. A different value for the equilibrium moisture content is obtained according to whether a wet sample is allowed to dry by desorption or a dry sample adsorbs moisture by adsorption. For drying calculations it is the desorption equilibrium that is the larger value and is of particular interest.

9.4B Experimental Data of Equilibrium Moisture Content for Inorganic and Biological Materials

1. Typical data for various materials. If the material contains more moisture than its equilibrium value in contact with a gas of a given humidity and temperature, it will dry until it reaches its equilibrium value. If the material contains less moisture than its equilibrium value, it will adsorb water until it reaches its equilibrium value. For air having 0% humidity, the equilibrium moisture value of all materials is zero.

The equilibrium moisture content varies greatly with the type of material for any given percent relative humidity, as shown in Fig. 9.4-1 for some typical materials at room tempera-

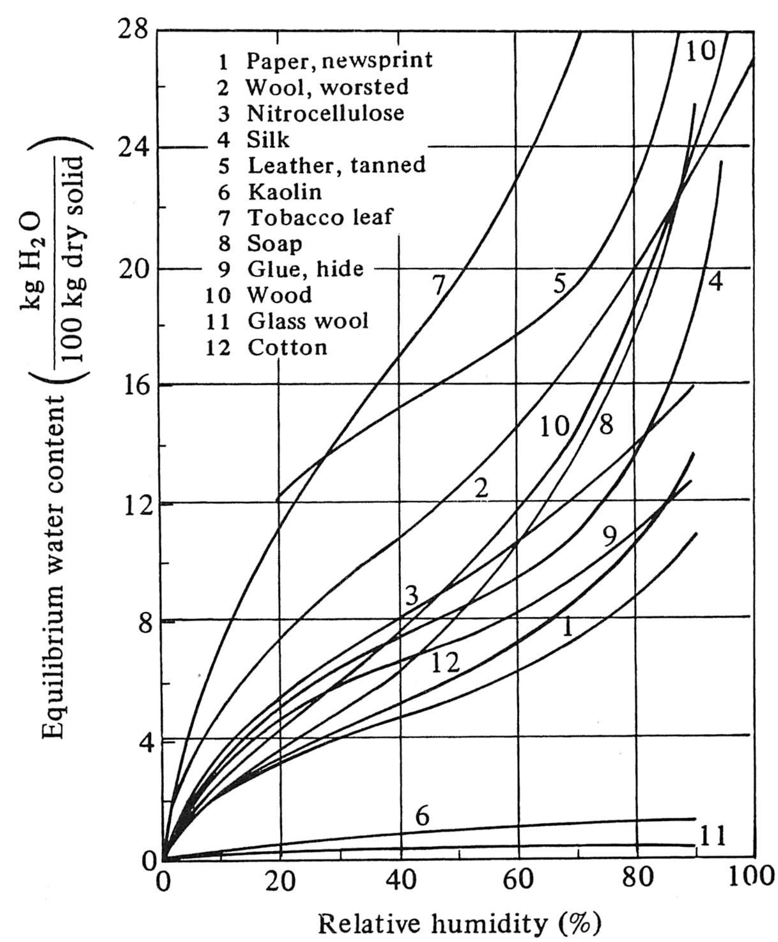

FIGURE 9.4-1. *Typical equilibrium moisture contents of some solids at approximately 298 K (25°C). [From National Research Council, International Critical Tables, Vol. II. New York: McGraw-Hill Book Company, 1929. Reproduced with permission of the National Academy of Sciences.]*

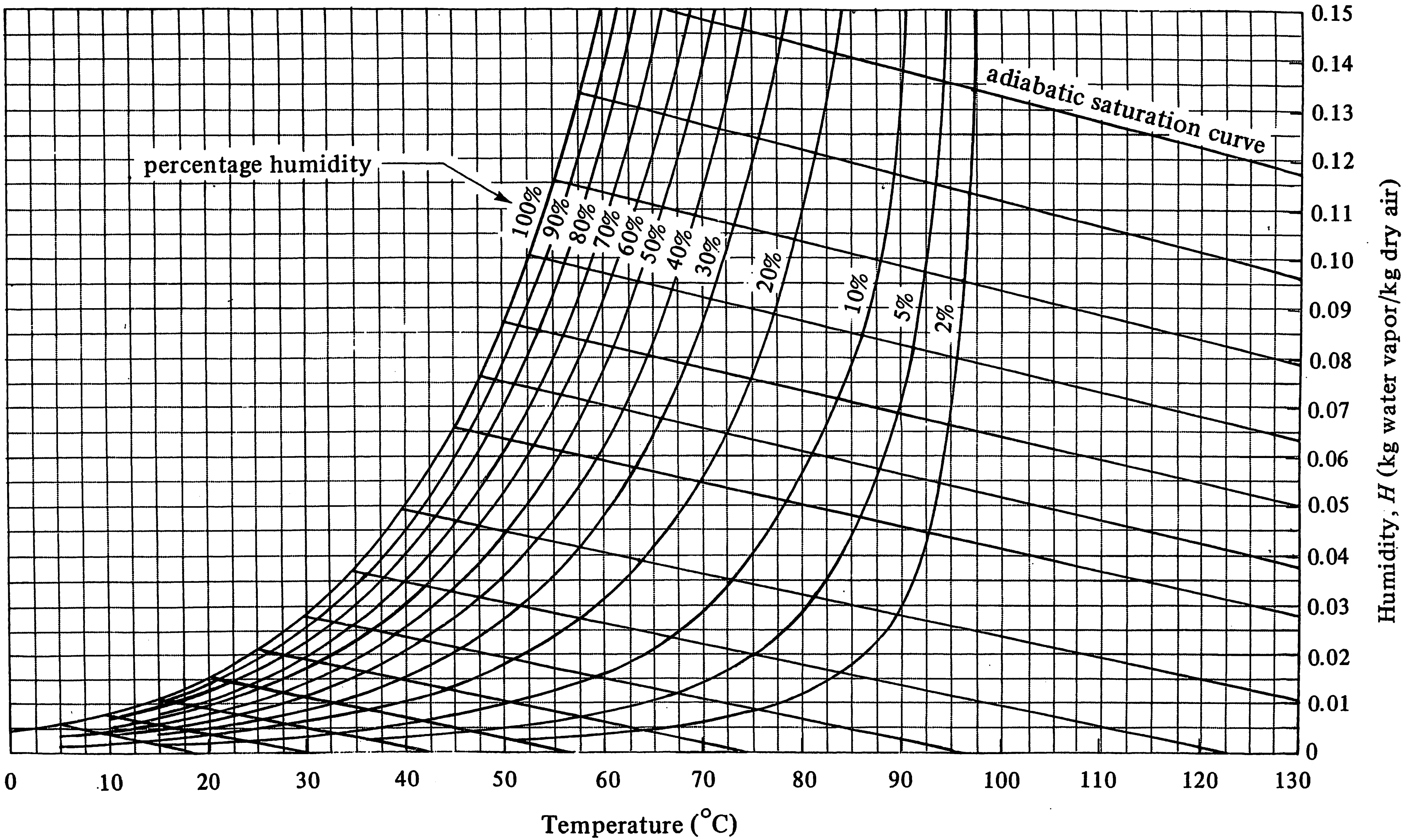

FIGURE 9.3-2. *Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)*

upward through the center of the chamber to leave at the top. The product is sprayed into the rising air stream. This type of flow pattern results in high evaporative capacity and relatively low entrainment of dust.

Atomization System. Three types of atomizers are in general use. Single-fluid pressure nozzles atomize the liquid by virtue of the high pressure of the feed delivered by the pump. Pressures may range from 400 to 10,000 lb/in². The higher the pressure, the finer is the atomization and the higher is the capacity of the nozzle. Nozzle orifice diameters may vary from 0.013 to 0.15 in. Two-fluid nozzles, appropriate for low-capacity operations, require a second fluid (air or steam) at 60 to 100 lb/in² (gage) to atomize the feed. Disk atomizers use a whirling disk to atomize the feed. Disk diameters range from 2 to 14 in and rotation speeds from 3000 to 50,000 r/min. Capacities up to 60,000 lb/h of feed can be obtained from a single atomizer. Disk atomization is generally applicable to suspensions and pastes that would erode and plug nozzles.

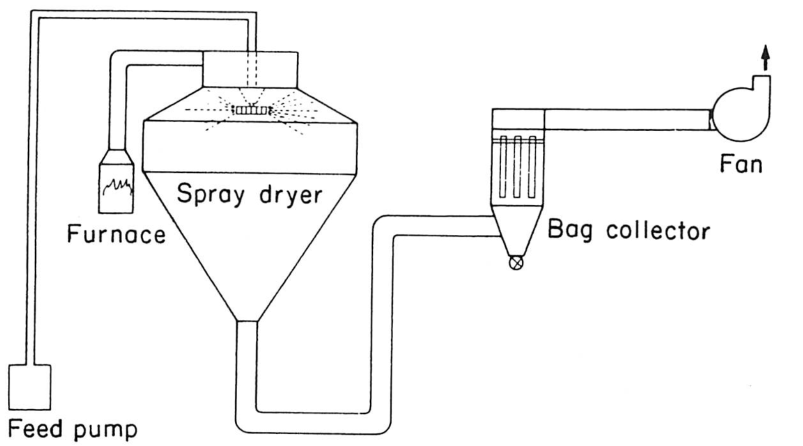

Fig. 11 Disk-atomization spray dryer. *(Proctor & Schwartz, Inc.)*

Separation System. Two systems are in general use to separate the dry product from the air. In the first, the dry material is allowed to settle in the coned-shaped bottom of the drying chamber where it is discharged by a rotary valve. The exhaust air containing some entrained product flows to a cyclone collector, bag filter, wet scrubber, or an elecrostatic precipitator, or combinations of the foregoing. In the second system, the exhaust air containing all of the product is discharged from the drying chamber and sent to the separation equipment where total recovery of the product occurs.

Product Characteristics An important advantage of spray drying is related to the physical properties of the dried product. The formation of a spherical particle, solid or hollow, is a desirable and unique feature of the spray-drying process. This shape is conducive to a free-flowing product of controlled bulk density. Moreover, a hollow, spherical product correlates with a low bulk density and high solubility. The properties of particle size distribution, bulk density, and agglomeration are usually of greatest interest and can be controlled within limits by appropriate manipulation of the design variables.

Performance Characteristics Performance data for a typical spray drying system are presented in Table 1. Volumetric evaporative capacities generally lie in the range 1 to 5 kg/(h)(m³) for drying temperatures between 150°C and 200°C.

Estimation of Drying Time. Particle residence times may range up to 30 s. Actual drying times can be crudely estimated from the theoretical expression for the drying time of a pure liquid drop of fixed diameter D_p:

$$\theta = \frac{\lambda W \rho_s D_p^2}{12 k_f (T_a - T_s)}$$

where θ = drying time, h
λ = latent heat of evaporation, Btu/lb
W = moisture content of the drop, lb/lb of dry solid
ρ_s = density of dry particle, lb/ft³
$T_a - T_s$ = temperature difference between drop and gas, °F

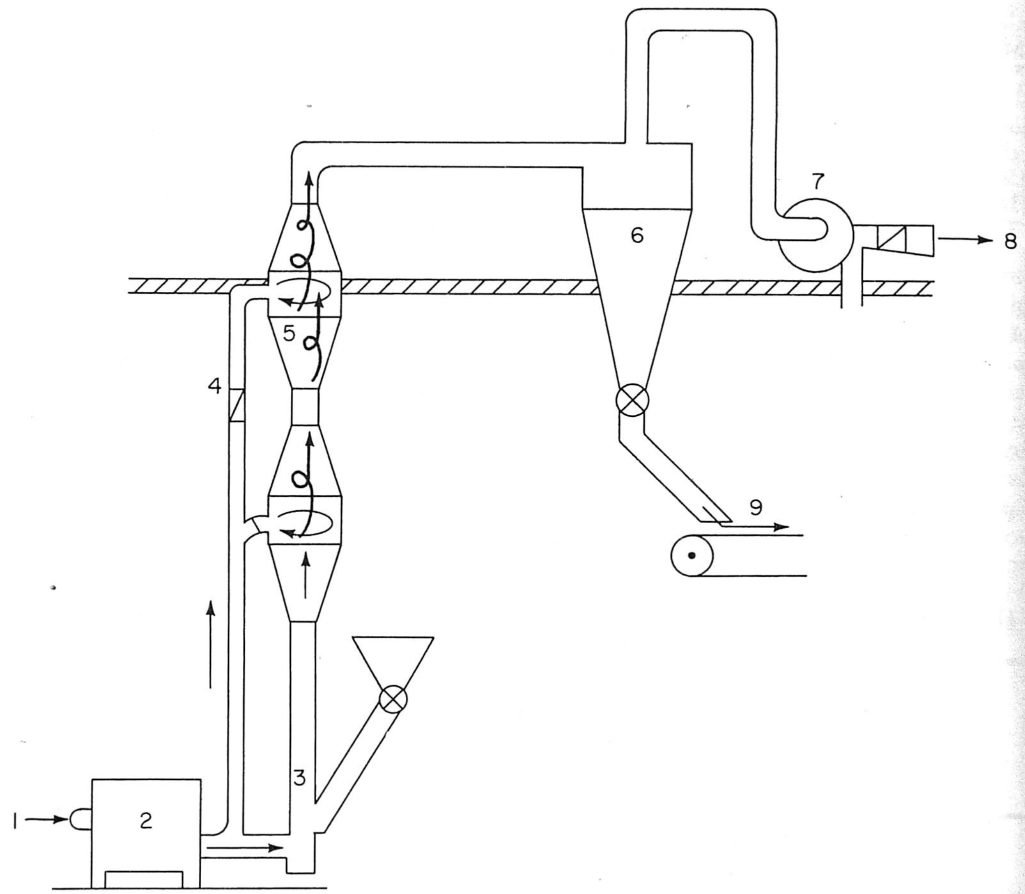

Fig. 12 Typical flash dryer. (1) Fresh air inlet; (2) air heater; (3) mainstream drying air; (4) auxiliary drying air; (5) dryer; (6) separator; (7) main circulating fan; (8) exhaust air outlet; (9) product delivery. *(Proctor & Schwartz, Inc.)*

DESIGN EXAMPLE

It is desired to dry a particular product in a flash dryer. The production rate is 2500 lb bone-dry solid per hour. Design conditions established from laboratory studies on a test unit are tabulated below.

Initial moisture content, dry basis	54%
Final moisture content, dry basis	19%
Inlet air temperature, °F	600
Outlet air temperature, °F	200
Average residence time, s	1.2
Product temperature, °F	150
Maximum allowable product temperature, °F	175
Inlet air humidity, lb water/lb dry air	0.01

Calculate:

1. Volumetric flow rate of air
2. Energy consumption
3. Overall thermal efficiency
4. Size of drying chamber

Solution

1. Assuming a 5% heat loss (heat lost to surroundings by radiation and sensible heat leaving in the dry product), one first calculates the enthalpies of the inlet and outlet air streams. Thus,

Inlet air enthalpy (Based on a reference state of liquid water at 32°F and dry air at 0°F):

$$H_{in} = 0.24T + Y_{in}[1075.5 + 0.45(T - 32)]$$

where H = enthalpy, Btu/lb dry air and Y = humidity, lb water vapor/lb dry air.

$$\begin{aligned} H_{in} &= 0.24(600) + 0.01[1075.5 + 0.45(600 - 32)] \\ &= 157.31 \text{ Btu/lb dry air} \end{aligned}$$

Fluidizing Velocity The normal operating range of the superficial gas velocity is about 25 to 300 ft/min. A consideration of the relation between the pressure drop across the bed and the superficial gas velocity through the bed is essential to the understanding of the operation of the fluid-bed dryer. As the gas velocity is increased from zero, the bed undergoes a transformation from a fixed bed to a partially or completely fluidized bed. The incipient fluidizing velocity corresponds to that velocity for which the pressure drop is sufficient to support the weight of the bed. A plot of the log of pressure drop against the

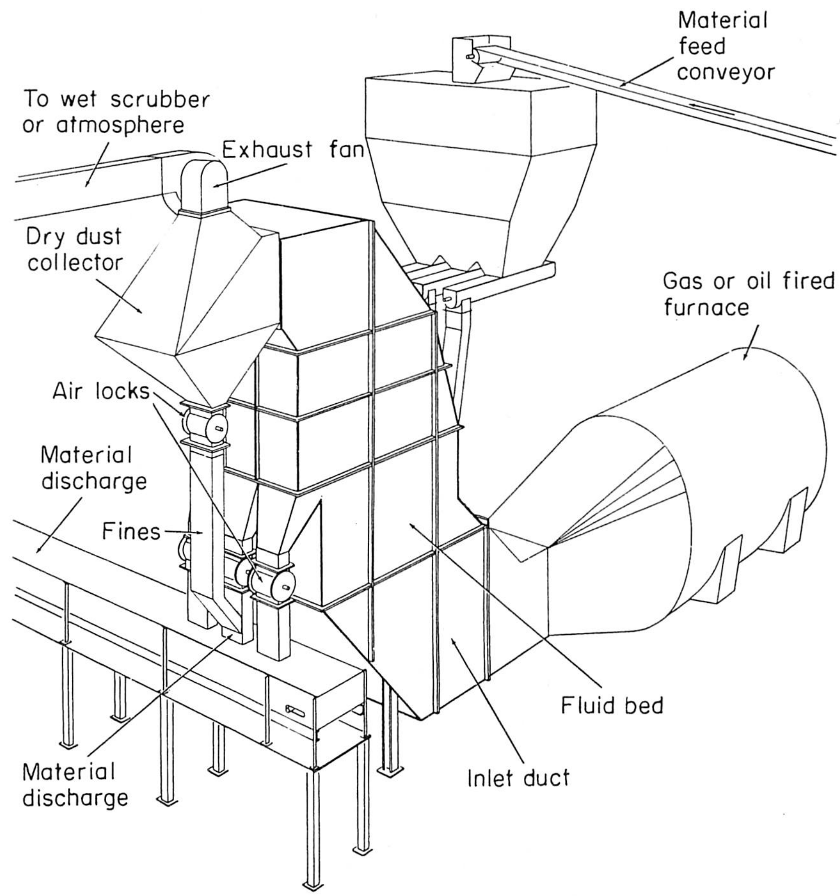

Fig. 13 Typical fluid-bed dryer. *(FMC Corporation.)*

log of the superficial velocity yields a straight line of positive slope over that range of operation corresponding to fixed-bed drying. Beyond the incipient fluidizing velocity, the bed markedly expands at constant pressure drop as the velocity is increased. The bed is now said to be in a state of aggregative fluidization. The flow regimes of the aggregative fluidized system are characterized by "bubbling" followed by "slugging" at gas velocities much greater than the incipient fluidizing velocity. In the bubbling regime, bubbles of the gas rise through the fluidized bed and burst at the top, thereby creating a circulation flow of particles in the bed. As the gas velocity increases further, the bubbles grow in size and in frequency of appearance, causing greater expansion of the bed. When the diameter of the bubble is equal to the diameter of the containing column, the behavior of the system is referred to as "slugging." A further increase of velocity causes particles to be carried out of the container by the gas stream. At this point the void fraction of the bed may be as high as 0.98 and the behavior is termed dilute-phase fluidization. For best results, the fluid-bed dryer is operated with a superficial gas velocity that is about twice the incipient fluidizing velocity. This places the system in the "bubbling" regime corresponding to dense-phase fluidization.

In lieu of an experimental determination, the following expression gives the theoretical value of the incipient velocity:

$$\mathrm{Re}_0 = 25.7[(1 + 5.53 \times 10^{-5} G_a)^{0.5} - 1]$$

where

$$\mathrm{Re}_0 = \frac{V_0\, d_p}{\mu}$$

is the Reynolds number at incipient fluidization point, and

$$G_a = \rho_f(\rho_s - \rho_f)g\, d_p^3/\mu^2 \equiv \text{Galileo number.}$$

where d_p is the equivalent spherical diameter of the particle. However, it is recommended that the optimum operating gas velocity for a specific case be determined experimentally.

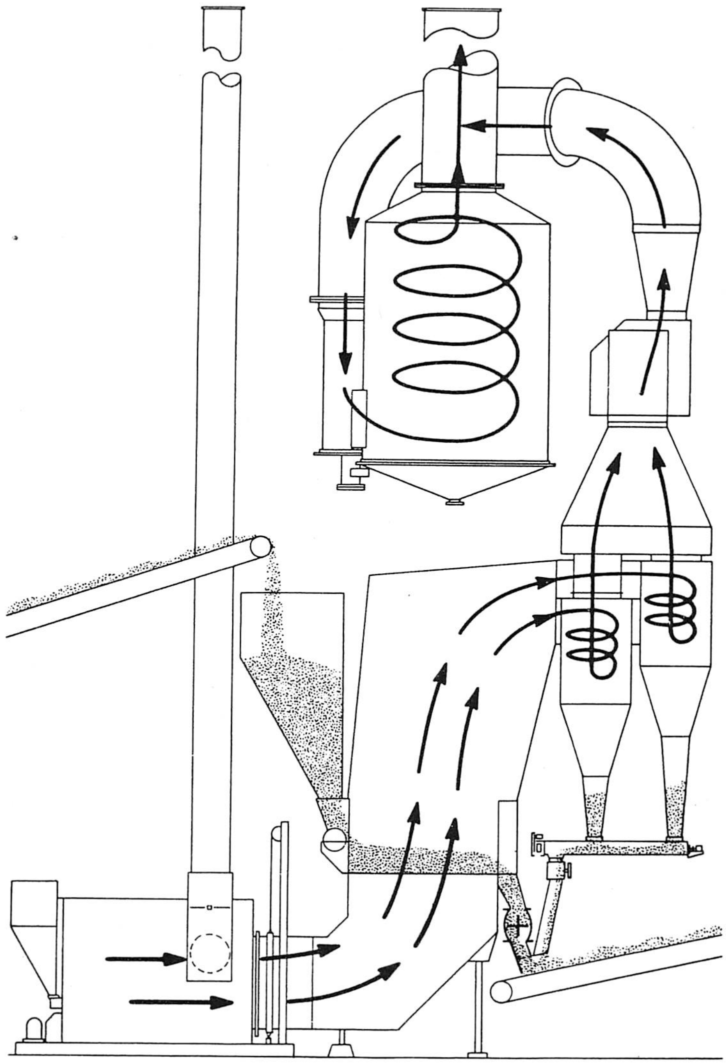

Fig. 14 Flow pattern of fluid-bed dryer. *(FMC Corporation.)*

Design Procedure The minimum bed area is calculated on the basis of the specified inlet air temperature, the total evaporation rate, and the operating gas velocity. The temperature and humidity of the exit gas will correspond to the equilibrium gas conditions for the product moisture content. Thus, by writing material and heat balances, one obtains the volumetric flow rate of the gas, and this number divided by the minimum fluidizing velocity gives the minimum cross-sectional area of the drying chamber. The design area of the chamber will be in excess of this value and is evaluated from the experimental conditions.

Two basic spray-drying systems are illustrated diagrammatically in Figs. 10 and 11. The feed is pumped from the product feed tank to the atomization unit which consists of either a number of small orifice nozzles or a spinning disk. The purpose of this device is to create a uniform spray of small droplets (usually in the 10 to 20 μm range). Air or gas is forced through a direct-fired combustion chamber, or over steam-heated coils, by a centrifugal blower, and is delivered to the drying chamber inlet at a temperature ranging between 200 and 1400°F. The contact between the finely dispersed droplets and the hot gas results in rapid drying (drying time can be on the order of a fraction of a second). The dry particles settle through the drying chamber and are pneumatically conveyed from the product discharge, often at the bottom of the drying chamber, to a cyclone or bag collector where the product is separated from the carrier air.

The relative flow direction of air and product can be varied to provide several different airflow configurations. Figure 10 depicts cocurrent operation. In countercurrent flow, the hot air enters at the opposite end of the chamber from the product atomization point. Although this design maximizes the value of the mean temperature driving force, it has the disadvantage, in the case of temperature-sensitive materials, that a lower inlet-gas temperature must be used than that in the cocurrent dryer. In the mixed-flow dryer, the hot air enters tangentially, spirals down the side of the cone, reverses direction, and flows

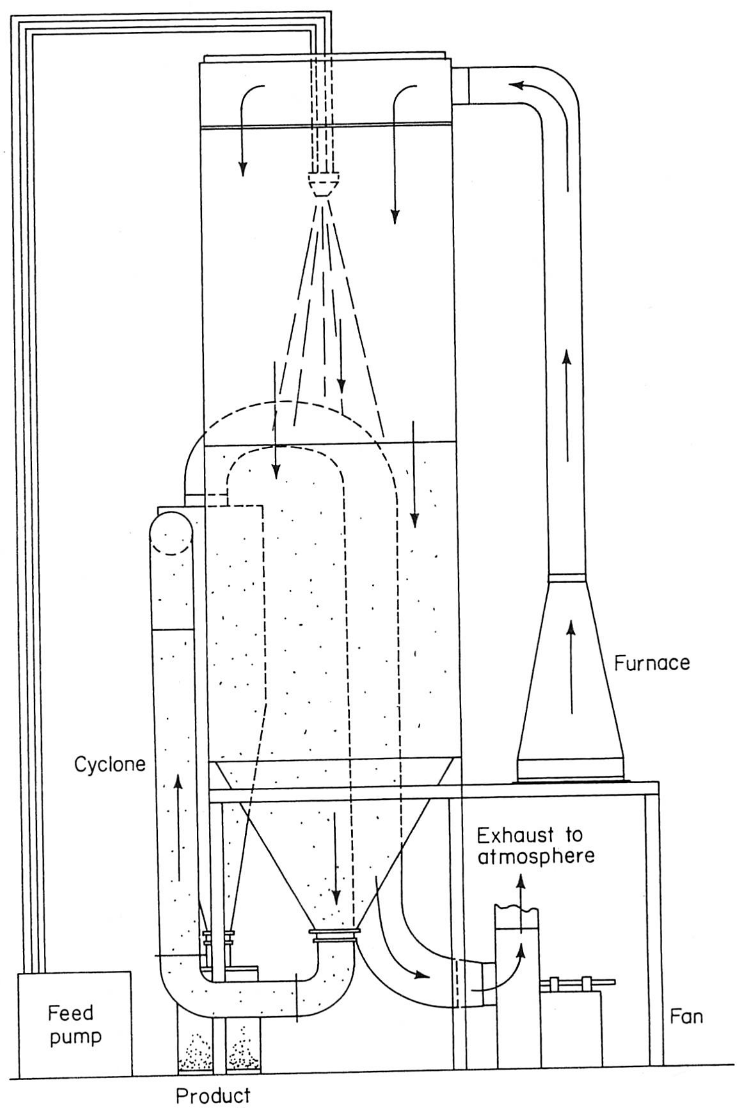

Fig. 10 Nozzle-atomization spray dryer. *(Proctor & Schwartz, Inc.)*

Summary of Calculations

Compartment	1	2	3	Grand totals
Total heat load per compartment, Btu/h	6,226,000	5,200,000	3,845,000	15,271,000
Exhaust air rate, lb/h dry air	27,000	21,800	16,100	64,900
Exhaust, ft³/min at cond.	9360	7993	6359	23,800
Recycle ratio	0.72	0.77	0.83	0.70
Btu/lb water evaporated				1629

Rotary Dryer

This type of dryer is suitable for free-flowing, nonsticking materials of relatively small particle size. Rotary dryers are of two general types—direct and indirect. A direct-heat continuous rotary dryer consists of a rotating cylindrical shell, slightly inclined to the horizontal, through which hot gas flows in cocurrent or in countercurrent direction to the flow of the product. The rotating shell is typically up to 10 ft in diameter and between 4 and 15 diameters in length, and may be equipped with internal, longitudinal flights spaced about the circumference of the cylinder. Various flight designs are used, depending upon the handling characteristics of the product. For example, the flights may extend continuously the entire length of the dryer, or they may be offset every 2 to 6 ft. Since the purpose of the flight is to lift and shower the wet material through the hot gas, the shape of the flights is an important design consideration. For free-flowing granular materials, a radial flight with a 90° lip is effective, whereas, for sticky materials, a straight radial flight is satisfactory. In operation, the shell rotates at 4 to 5 r/min and the retention time of the product varies from 5 min to 2 h. The gas velocity throughout the cylinder varies from 4.9 to 9.8 ft/s. Figures 8 and 9 illustrate the mechanical features of a typical direct rotary dryer. The feed system may consist of an inclined chute fed from a rotary valve, a vibrating feeder, or a belt conveyor—or, for very wet material, a screw conveyor may be used. The dried product is normally discharged through a counterbalanced flap or rotary valve into the collecting device. The drying air is heated in a heat exchanger; in moderate- and low-

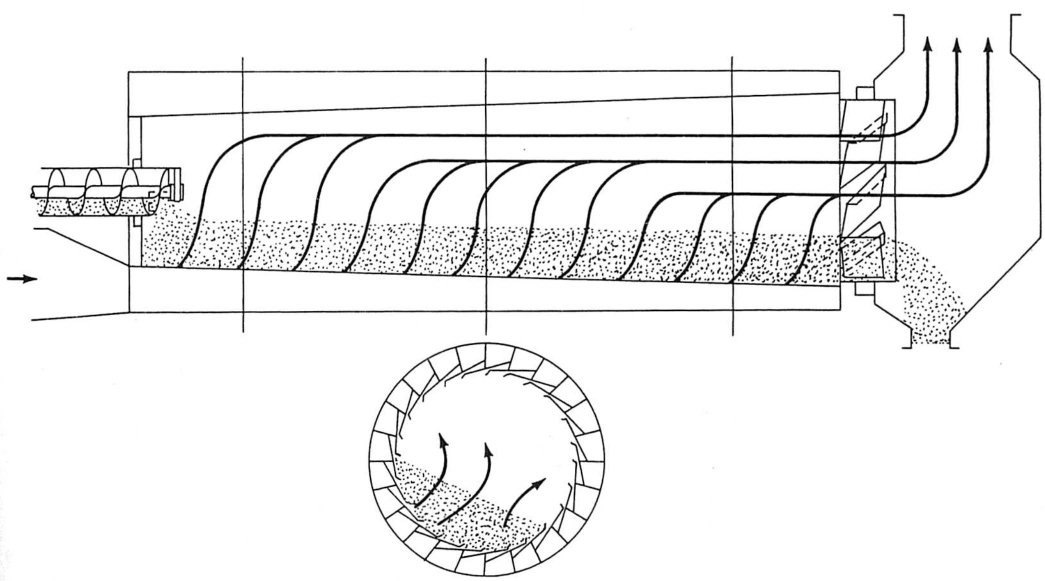

Fig. 8 Typical rotary dryer. *(FMC Corporation.)*