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# (CONTINUED)

# Perry's Chemical Engineers' Handbook

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# PERRY'S CHEMICAL ENGINEERS' HANDBOOK

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Water inlet, °F = 110

Water outlet, °F = 90

From the nomograph, $P = 68$ and $Q = 1.07$, giving an area required of 73 ft²/(gal·min). Area for 10,000 gal/min is thus 730,000 ft², or 17 acres.

With a depth of 5 ft, total volume of the pond would amount to a 45.5-h holdup, which is more than the 24-h holdup required to maintain a fairly constant discharge temperature throughout the day.

Table 12-5 presents typical values of solar radiation on a horizontal surface, Btu/(h·ft²), based on analysis of Weather Bureau records for a number of stations throughout the United States. These are clear-day values, rarely exceeded even in the high arid regions. The normal or actual average monthly values are only 50 to 60 percent of the tabulated figures for most of the eastern United States and 80 to 90 percent in the arid southwest. Also, the solar radiation should be multiplied by the absorption coefficient for the pond, which appears to exceed 95 percent.

# SOLIDS-DRYING FUNDAMENTALS*

**General References:** Cook and DuMont, *Process Drying Practice*, McGraw-Hill, 1991. *Drying Technology—An International Journal*, Marcel Dekker, N.Y., 1982. Hall, *Dictionary of Drying*, Marcel Dekker, N.Y., 1979. Keey, *Introduction to Industrial Drying Operations*, Pergamon, N.Y., 1978. Masters, *Spray Drying Handbook*, Wiley, N.Y., 1990. Mujumdar, *Handbook of Industrial Drying*, Marcel Dekker, N.Y., 1987. Nonhebel and Moss, *Drying of Solids in the Chemical Industry*, CRC Press, Ohio, 1971. van't Land, *Industrial Drying Equipment*, Marcel Dekker, N.Y., 1991.

## INTRODUCTION

The material on solids drying is divided into two subsections, "Solids-Drying Fundamentals," and "Solids-Drying Equipment." In this introductory part some elementary definitions are given. In solids-gas contacting equipment, the solids bed can exist in any of the following four conditions.

***Static*** This is a dense bed of solids in which each particle rests upon another at essentially the settled bulk density of the solids phase. Specifically, *there is no relative motion among solids particles* (Fig. 12-26).

***Moving*** This is a slightly expanded bed of solids in which the particles are separated only enough to flow one over another. Usually the flow is downward under the force of gravity, but upward motion by mechanical lifting or agitation may also occur within the process vessel. In some cases, lifting of the solids is accomplished in separate equipment, and solids flow in the presence of the gas phase is downward only. The latter is a moving bed as usually defined in the petroleum industry. In this definition, *solids motion is achieved by either mechanical agitation or gravity force* (Fig. 12-27).

***Fluidized*** This is an expanded condition in which the solids particles are supported by drag forces caused by the gas phase passing through the interstices among the particles at some critical velocity. It is an unstable condition in that the superficial gas velocity upward is less than the terminal setting velocity of the solids particles; the gas velocity is not sufficient to entrain and convey continuously all the solids. At the same time, there exist, within the stream of gas, eddies traveling at high enough velocities to lift the particles temporarily. Particle motion is continually upward and falling back. Specifically, the solids phase and the gas phase are intermixed and *together behave like a boiling fluid* (Fig. 12-28).



**FIG. 12-26** Solids bed in static condition (tray dryer).

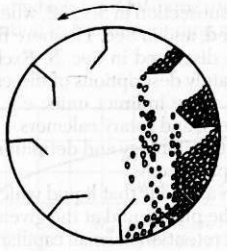


**FIG. 12-27** Moving solids bed in a rotary dryer with lifters.

***Dilute*** This is a fully expanded condition in which the solids particles are so widely separated that they exert essentially no influence upon each other. Specifically, the solids phase is so fully dispersed in the gas that *the density of the suspension is essentially that of the gas phase alone* (Fig. 12-29). Commonly, this situation exists when the gas velocity at all points in the system exceeds the terminal settling velocity of the solids and the particles can be lifted and continuously conveyed by the gas; however, this is not always true. Gravity settling chambers such as prilling towers and countercurrent-flow spray dryers are two exceptions in which gas velocity is insufficient to entrain the solids completely.

**Gas-Solids Contacting** Terms used in this section to describe the method by which gas may contact a bed of solids are the following:

1. *Parallel flow.* The direction of gas flow is parallel to the surface of the solids phase. Contacting is primarily at the interface between phases, with possibly some penetration of gas into the voids among the solids near the surface. The solids bed is usually in a static condition (Fig. 12-30).

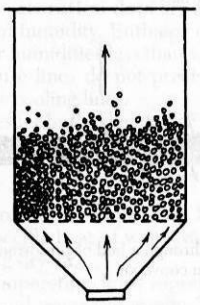


**FIG. 12-28** Fluidized solids bed.

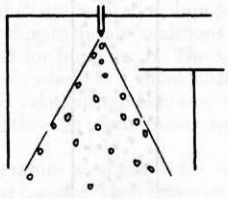


**FIG. 12-29** Solids in a dilute condition near the top of a spray dryer.

* The contribution of George A. Schurr, E. I. du Pont de Nemours & Co., to material that was used from the sixth edition is acknowledged. (Solids Drying)

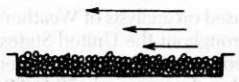


**FIG. 12-30** Parallel gas flow over a static bed of solids.

2. *Perpendicular flow.* The direction of gas flow is normal to the phase interface. The gas impinges on the solids bed. Again the solids bed is usually in a static condition (Fig. 12-31).
3. *Through circulation.* The gas penetrates and flows through interstices among the solids, circulating more or less freely around the individual particles (Fig. 12-32). This may occur when solids are in static, moving, fluidized, or dilute conditions.

Three additional terms require definition.

1. *Cocurrent gas flow.* The gas phase and solids particles both flow in the same direction (Fig. 12-33).
2. *Countercurrent gas flow.* The direction of gas flow is exactly opposite to the direction of solids movement.
3. *Cross-flow of gas.* The direction of gas flow is at a right angle to that of solids movement, across the solids bed (Fig. 12-34).

Because in a gas-solids-contacting operation heat transfer and mass transfer take place at the solids' surfaces, maximum process efficiency can be expected with a maximum exposure of solids surface to the gas phase, together with thorough mixing of gas and solids. Both are important. Within any arrangement of particulate solids, gas is present in the voids among the particles and contacts all surfaces except at the points of particle contact. When the solids bed is in a static or slightly moving condition, however, gas within the voids is cut off from the main body of the gas phase. Some transfer of energy and mass may occur by diffusion, but it is usually insignificant.

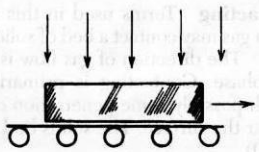


**FIG. 12-31** Circulating gas impinging on a large solid object in perpendicular flow, in a roller-conveyor furnace.

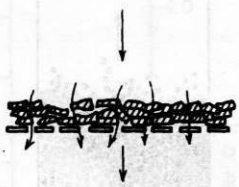


**FIG. 12-32** Gas passing through a bed of preformed solids, in through circulation on a perforated-apron conveyor.

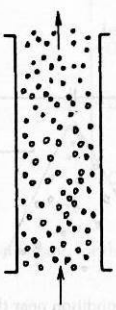


**FIG. 12-33** Cocurrent gas-solids flow in a vertical-lift dilute-phase pneumatic conveyor.

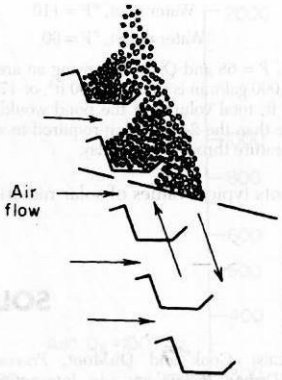



**FIG. 12-34** Cross-flow of gas and solids in a cascade-type gravity dryer. (*Link-Belt Co., Multi-Louvre principle.*)

Equipment design and selection are governed by two factors:

1. Mechanical considerations
2. Solids flow and surface characteristics.

The former usually involves process temperature or isolation. Solids surface characteristics are important in that they control the extent to which an operation is diffusion-limited, i.e., diffusion into and out of the pores of a given solids particle, not through the voids among separate particles. The size of the solids particles, the surface-to-mass ratio, is also important in the evaluation of surface characteristics and the diffusion problem.

**Gas-Solids Separations** After the solids and gas have been brought together and mixed in a gas-solids contactor, it becomes necessary to separate the two phases. If the solids are sufficiently coarse and the gas velocity sufficiently low, it is possible to effect a complete gravitational separation in the primary contactor. Applications of this type are rare, however, and supplementary dust-collection equipment is commonly required. The recovery step may even dictate the type of primary contacting device selected. For example, when treating an extremely friable solid material, a deep fluidized-solids contactor might overload the collection system with fines, whereas the more gentle contacting of a traveling-screen contactor would be expected to produce a minimum of fines by attrition. Therefore, although gas-solids separation is usually considered as separate and distinct from the primary contacting operation, it is usually desirable to evaluate the separation problem at the same time that contacting methods are evaluated.

**Definitions** Drying generally refers to the removal of a liquid from a solid by **evaporation.** Mechanical methods for separating a liquid from a solid are not generally considered drying, although they often precede a drying operation, since it is less expensive and frequently easier to use mechanical methods than to use thermal methods.

This subsection presents the theory and fundamental concepts of the drying of solids.

Equipment commonly employed for the drying of solids is described both in this subsection in Sec. 12, where indirect heat transfer devices are discussed, and in Sec. 17 where fluidized beds are covered. Dryer control is discussed in Sec. 8. Excluding fluid beds this subsection contains mainly descriptions of direct-heat-transfer equipment. It also includes some indirect units; e.g., vacuum dryers, furnaces, steam-tube dryers, and rotary calciners.

Generally accepted terminology and definitions are given alphabetically in the following paragraphs.

**Bound moisture** in a solid is that liquid which exerts a vapor pressure less than that of the pure liquid at the given temperature. Liquid may become bound by retention in small capillaries, by solution in cell or fiber walls, by homogeneous solution throughout the solid, and by chemical or physical adsorption on solid surfaces.

**Capillary flow** is the flow of liquid through the interstices and over the surface of a solid, caused by liquid-solid molecular attraction.

**Constant-rate period** is that drying period during which the rate of water removal per unit of drying surface is constant.

**Critical moisture content** is the average moisture content when the constant-rate period ends.

**Dry-weight basis** expresses the moisture content of wet solid as kilograms of water per kilogram of bone-dry solid.

**Equilibrium moisture content** is the limiting moisture to which a given material can be dried under specific conditions of air temperature and humidity.

**Falling-rate period** is a drying period during which the instantaneous drying rate continually decreases.

**Fiber-saturation point** is the moisture content of cellular materials (e.g., wood) at which the cell walls are completely saturated while the cavities are liquid-free. It may be defined as the equilibrium moisture content as the humidity of the surrounding atmosphere approaches saturation.

**Free-moisture content** is that liquid which is removable at a given temperature and humidity. It may include bound and unbound moisture.

**Funicular state** is that condition in drying a porous body when capillary suction results in air being sucked into the pores.

**Hygroscopic material** is material that may contain bound moisture.

**Initial moisture distribution** refers to the moisture distribution throughout a solid at the start of drying.

**Internal diffusion** may be defined as the movement of liquid or vapor through a solid as the result of a concentration difference.

**Moisture content** of a solid is usually expressed as moisture quantity per unit weight of the dry or wet solid.

**Moisture gradient** refers to the distribution of water in a solid at a given moment in the drying process.

**Nonhygroscopic material** is material that can contain no bound moisture.

**Pendular state** is that state of a liquid in a porous solid when a continuous film of liquid no longer exists around and between discrete particles so that flow by capillary cannot occur. This state succeeds the funicular state.

**Unaccomplished moisture change** is the ratio of the free moisture present at any time to that initially present.

**Unbound moisture** in a hygroscopic material is that moisture in excess of the equilibrium moisture content corresponding to saturation humidity. All water in a nonhygroscopic material is unbound water.

**Wet-weight basis** expresses the moisture in a material as a percentage of the weight of the wet solid. Use of a dry-weight basis is recommended since the percentage change of moisture is constant for all moisture levels. When the wet-weight basis is used to express moisture content, a 2 or 3 percent change at high moisture contents (above 70 percent) actually represents a 15 to 20 percent change in evaporative load. See Fig. 12-35 for the relationship between the dry- and wet-weight bases.

## APPLICATION OF PSYCHROMETRY TO DRYING

In any drying process, if an adequate supply of heat is assumed, the temperature and rate at which liquid vaporization occurs will depend on the vapor concentration in the surrounding atmosphere.

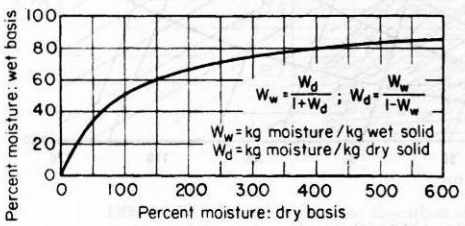



**FIG. 12-35** Relationship between wet-weight and dry-weight bases.

In vacuum drying or other processes containing atmospheres of 100 percent vapor, the temperature of liquid vaporization will equal or exceed the saturation temperature of the liquid at the system pressure. (When a free liquid or wetted surface is present, drying will occur at the saturation temperature, just as free water at 101.325 kPa vaporizes in a 100 percent steam atmosphere at 100°C.)

On the other hand, when evolved vapor is purged from the dryer environment by using a second (inert) gas, the temperature at which vaporization occurs will depend on the concentration of vapor in the surrounding gas. In effect, the liquid must be heated to a temperature at which its vapor pressure equals or exceeds the partial pressure of vapor in the purge gas. In the reverse situation, condensation will occur.

In most drying operations, water is the liquid evaporated and air is the normally employed purge gas. For drying purposes, a psychrometric chart found very useful is that reproduced in Fig. 12-36.

1. The **wet-bulb or saturation temperature line** gives the maximum weight of water vapor that 1 kg of dry air can carry at the intersecting **dry-bulb temperature** shown on the abscissa at saturation humidity. The partial pressure of water in air equals the water-vapor pressure at that temperature. The saturation humidity is defined by

$$H_s = p_s/(P - p_s)18/28.9 \qquad (12\text{-}17)$$

where $H_s$ = saturation humidity (kg/kg dry air), $p_s$ = vapor pressure of water at temperature $t_s$, $P$ = absolute pressure, and 18/28.9 = ratio of molecular weights of water (18) and air (28.9). Similarly, the humidity at any condition less than saturation is given by

$$H = p/(P - p)18/28.9 \qquad (12\text{-}18)$$

2. The percent relative humidity is defined by

$$H_R = 100(p/p_s) \qquad (12\text{-}19)$$

where $p$ = partial pressure of water vapor in the air, $p_s$ = vapor pressure of water at the same temperature, and $H_R$ = percent relative humidity.

3. Humid volumes are given by the curves entitled "Volume $m^3$/kg dry air." The volumes are plotted as functions of absolute humidity and temperature. The difference between dry-air specific volume and humid-air volume at a given temperature is the volume of water vapor.

4. Enthalpy data are given on the basis of kilojoules per kilogram of dry air. **Enthalpy-at-saturation data** are accurate only at the saturation temperature and humidity. Enthalpy deviation curves permit enthalpy corrections for humidities less than saturation and show how the wet-bulb-temperature lines do not precisely coincide with constant-enthalpy, adiabatic cooling lines.

5. There are no lines for humid heats on Fig. 12-36. These may be calculated by

$$C_s = 1.0 + 1.87H \qquad (12\text{-}20)$$

where $C_s$ = humid heat of moist air, kJ/(kg·K); 1.0 = specific heat of dry air, kJ/(kg·K), 1.87 = specific heat of water vapor, kJ/(kg·K); and $H$ = absolute humidity, kg/kg dry air.

6. The wet-bulb-temperature lines represent also the adiabatic-saturation lines for air and water vapor only. These are based on the relationship

$$H_s - H = (C_s/\lambda)(t - t_s) \qquad (12\text{-}21)$$

where $H_s$ and $t_s$ = adiabatic saturation humidity and temperature respectively, corresponding to the air conditions represented by $H$ and $t$, and $C_s$ = humid heat for humidity $H$. The slope of the adiabatic-saturation curve is $C_s/\lambda$, where $\lambda$ = latent heat of evaporation at $t_s$. These lines show the relationship between the temperature and humidity of air passing through a continuous dryer operating adiabatically.

The wet-bulb temperature is established by a dynamic equilibrium between heat and mass transfer when liquid evaporates from a small mass, such as the wet bulb of a thermometer, into a very large mass of gas such that the latter undergoes no temperature or humidity change. It is expressed by the relationship

$$h_c(t - t_w) = k'_g\lambda(H_w - H_a) \qquad (12\text{-}22)$$

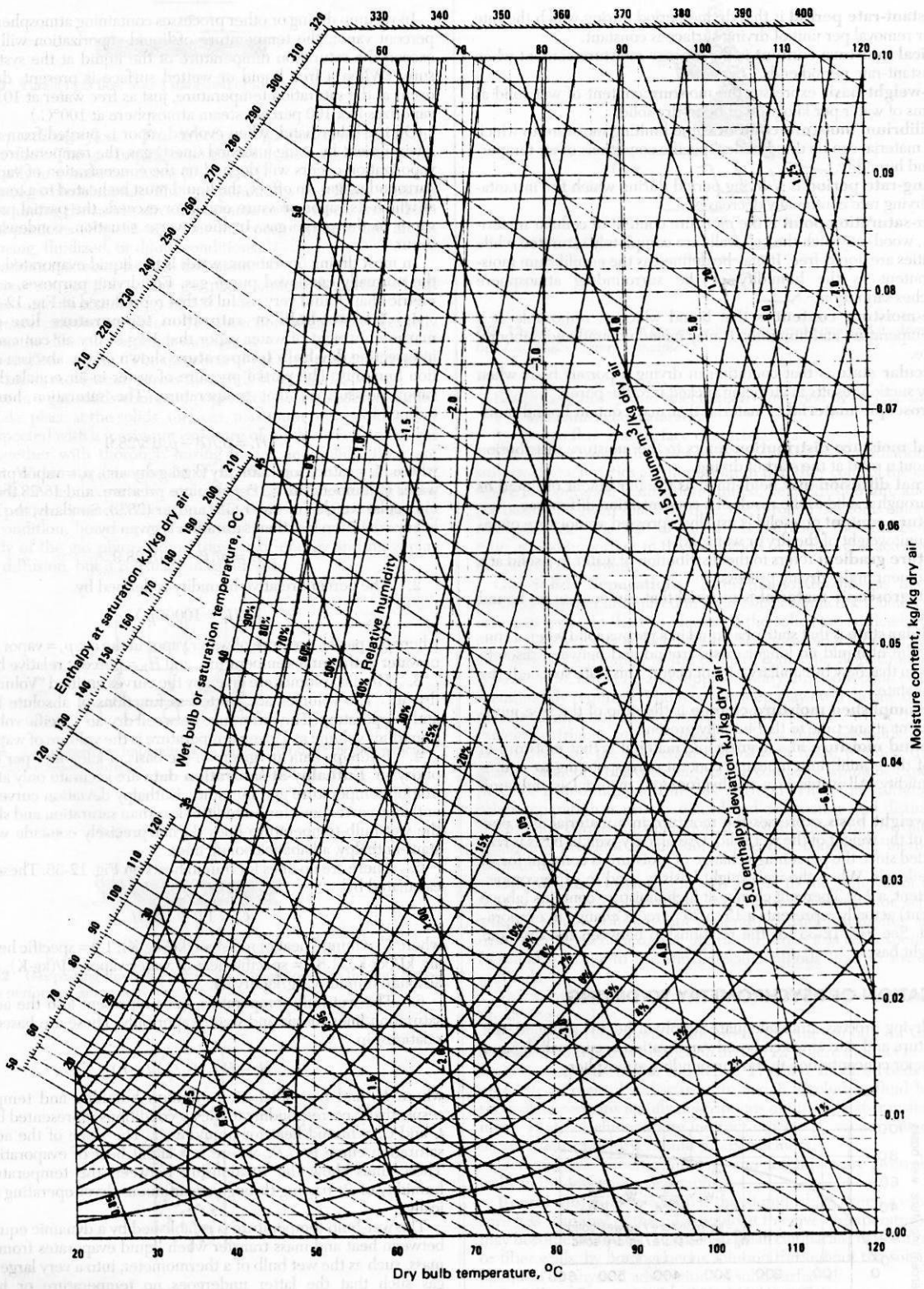



**FIG. 12-36** Psychrometric chart: properties of air and water-vapor mixtures from 20 to 120°C. (*Carrier Corp.*)

where $h_c$ = heat-transfer coefficient by convection, J/(m²·s·K) [Btu/(h·ft²·°F)]; $t$ = air temperature, K; $t_w$ = wet-bulb temperature of air, K; $k'_g$ = mass-transfer coefficient, kg/(s·m²) (kg/kg) [lb/(h·ft²)(lb/lb)]; $\lambda$ = latent heat of evaporation at $t_w$, J/kg (Btu/lb); $H_w$ = saturated humidity at $t_w$ = kg/kg of dry air; and $H_a$ = humidity of the surrounding air, kg/kg of dry air.

For air–water-vapor mixtures, it so happens that $h_c/k'_g = C_s$ approximately, although there is no theoretical reason for this. Hence, since the ratio $(H_w - H_a)/(t_w - t)$ equals $h_c/k'_g/\lambda$, which represents the slope of the wet-bulb-temperature lines, it is also equal to $C_s/\lambda$, the slope of the adiabatic-saturation lines as shown previously.

A given humidity chart is precise only at the pressure for which it is evaluated. Most air–water-vapor charts are based on a pressure of 1 atm. Humidities read from these charts for given values of wet- and dry-bulb temperature apply only at an atmospheric pressure of 760 mmHg. If the total pressure is different from 760 mmHg, the humidity at a given wet-bulb and dry-bulb temperature must be corrected according to the following relationship.

$$H_a = H_o + 0.622 p_w \left( \frac{1}{P - p_w} - \frac{1}{760 - p_w} \right) \qquad (12\text{-}23)$$

where $H_a$ = humidity of air at pressure $P$, kg/kg of dry air; $H_o$ = humidity of air as read from a humidity chart based on 760-mm pressure at the observed wet- and dry-bulb temperatures, kg/kg dry air, $p_w$ = vapor pressure of water at the observed wet-bulb temperature, mmHg; and $P$ = the pressure at which the wet- and dry-bulb readings were taken. Similar corrections can be derived to correct specific volume, the saturation-humidity curve, and the relative-humidity curves.

## HUMIDITY CHARTS FOR SOLVENT VAPORS

Humidity charts for other solvent vapors may be prepared in an analogous manner. There is one important difference involved, however, in that the wet-bulb temperature differs considerably from the adiabatic-saturation temperatures for vapors other than water.

Figures 12-37 to 12-39 show humidity charts for carbon tetrachloride, benzene, and toluene. The lines on these charts have been calculated in the manner outlined for air–water vapor except for the wet-bulb-temperature lines. The determination of these lines depends on data for the psychrometric ratio $h_c/k'_g$, as indicated by Eq. (12-22). For the charts shown, the wet-bulb-temperature lines are based on the following equation:

$$H_w - H = (\alpha h_c/\lambda_w k'_g)(t - t_w) \qquad (12\text{-}24)$$

where $\alpha$ = radiation correction factor, a value of 1.06 having been used for these charts. Values of $h_c/k'_g$, obtained from values of $h_c/k'_g C_s$ as presented by Walker, Lewis, McAdams, and Gilliland (*Principles of Chemical Engineering*, 3d ed., McGraw-Hill, New York, 1937), where $C_s$ = humid heat of air with respect to the vapor involved, are as follows:

| Material | Carbon tetrachloride | Benzene | Toluene |
|---|---|---|---|
| $h_c/k'_g C_s$ | 0.51 | 0.54 | 0.47 |

A discussion of the theory of the relationship between $h_c$ and $k'_g$ may be found in the psychrometry part of this section. Because both theoretical and experimental values of $h_c/k'_g$ apply only to dilute gas mixtures, the wet-bulb lines at high concentrations have been omitted. For a discussion of the precautions to be taken in making psychrometric determinations of solvent vapors at low solvent wet-bulb temperatures in the presence of water vapor, see the paper by Sherwood and Comings [*Trans. Am. Inst. Chem. Eng.*, **28,** 88 (1932)].

## GENERAL CONDITIONS FOR DRYING

Solids drying encompasses two fundamental and simultaneous processes: (1) heat is transferred to evaporate liquid, and (2) mass is

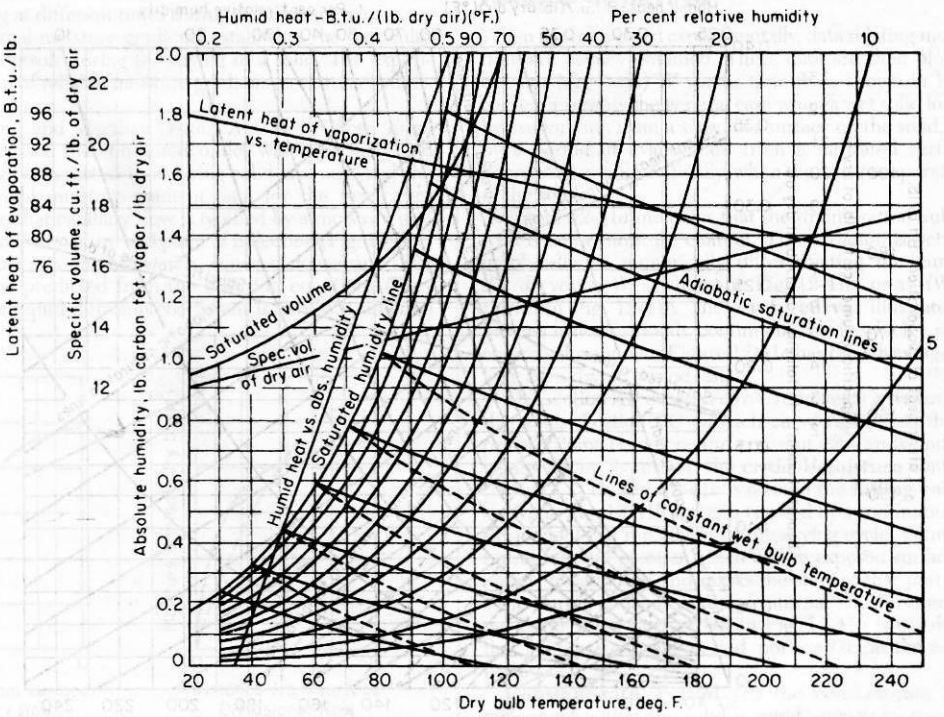



**FIG. 12-37** Humidity chart for air-carbon tetrachloride vapor mixture. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

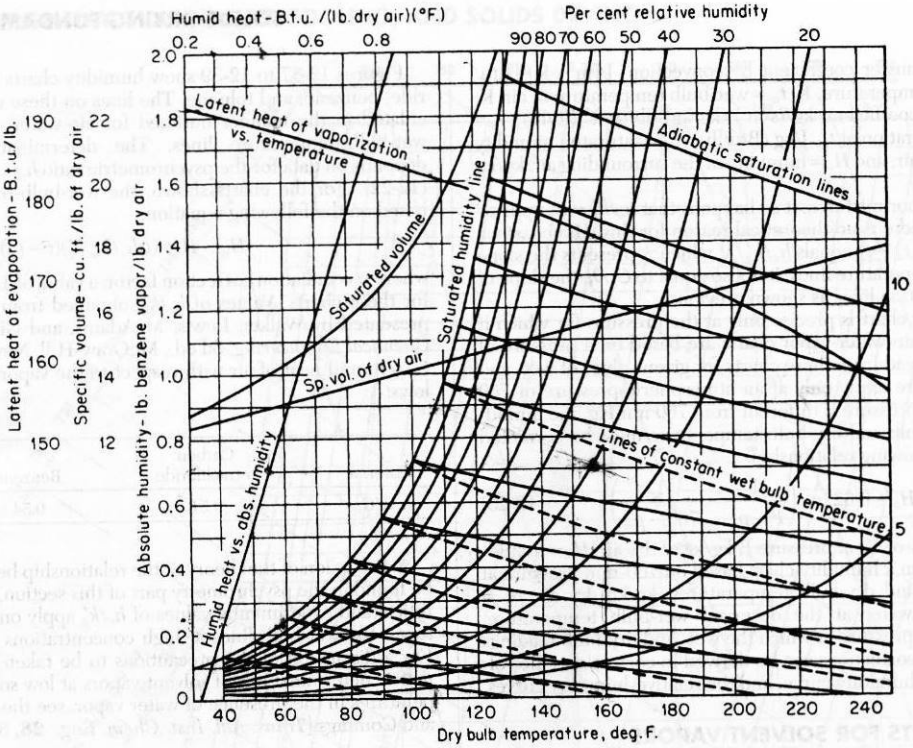



**FIG. 12-38** Humidity chart for air-benzene-vapor mixture. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

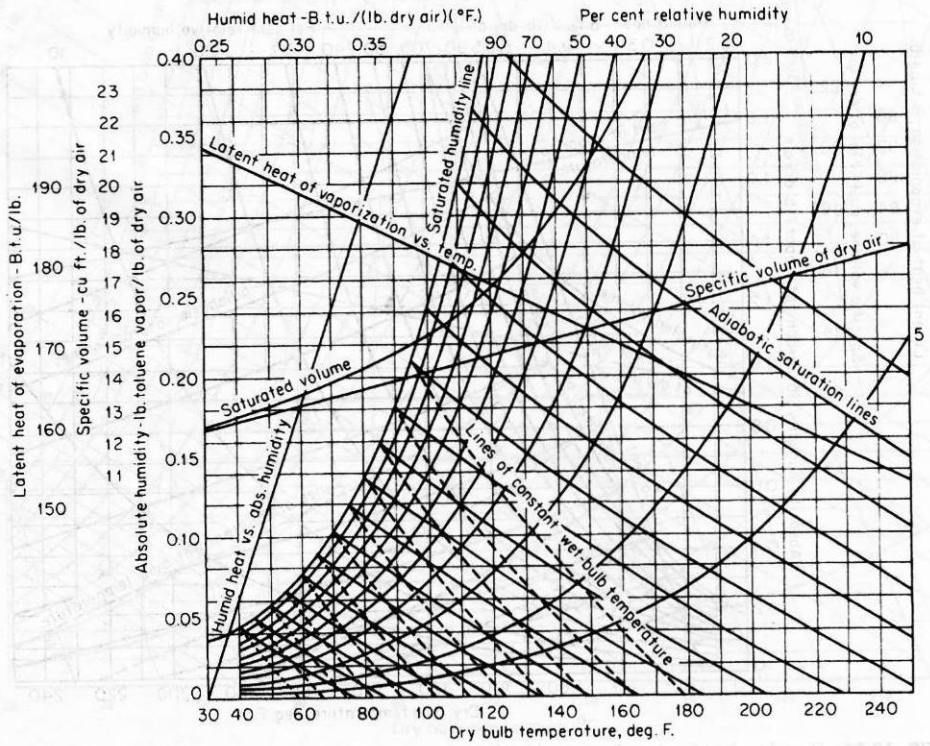



**FIG. 12-39** Humidity chart for air-toluene-vapor mixture. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

transferred as a liquid or vapor within the solid and as a vapor from the surface. The factors governing the rates of these processes determine the drying rate.

Commercial dryers differ fundamentally by the methods of heat transfer employed (see classification of dryers, Fig. 12-45). These industrial-dryer operations may utilize heat transfer by convection, conduction, radiation, or a combination of these. In each case, however, heat must flow to the outer surface and then into the interior of the solid. The single exception is dielectric and microwave drying, in which high-frequency electricity generates heat internally and produces a high temperature within the material and on its surface.

Mass is transferred in drying as a liquid and vapor within the solid and as vapor from the exposed surfaces. Movement within the solid results from a concentration gradient which is dependent on the characteristics of the solid. A solid to be dried may be porous or nonporous. It can also be hygroscopic or nonhygroscopic. Many solids fall intermediately between these two extremes, but it is generally convenient to consider the solid to be one or the other.

A study of how a solid dries may be based on the **internal** mechanism of liquid flow or on the effect of the **external** conditions of temperature, humidity, air flow, state of subdivision, etc., on the drying rate of the solids. The former procedure generally requires a fundamental study of the internal condition. The latter procedure, although less fundamental, is more generally used because the results have greater immediate application in equipment design and evaluation.

## INTERNAL MECHANISM OF LIQUID FLOW

The structure of the solid determines the mechanism for which internal liquid flow may occur. These mechanisms can include (1) **diffusion** in continuous, homogeneous solids, (2) **capillary flow** in granular and porous solids, (3) flow caused by **shrinkage** and **pressure** gradients, (4) flow caused by **gravity,** and (5) flow caused by a **vaporization-condensation** sequence.

In general, one mechanism predominates at any given time in a solid during drying, but it is not uncommon to find different mechanisms predominating at different times during the drying cycle.

The study of internal moisture gradients establishes the particular mechanism which controls during the drying of a solid. The experimental determination of reliable moisture gradients is extremely difficult.

Hougen, McCauley, and Marshall [*Trans. Am. Inst. Chem. Eng.*, **36,** 183 (1940)] discussed the conditions under which capillary and diffusional flow may be expected in a drying solid and analyzed the published experimental moisture-gradient data for the two cases. Their curves indicate that capillary flow is typified by a moisture gradient involving a double curvature and point of inflection (Fig. 12-40*a*) while diffusional flow is a smooth curve, concave downward (Fig. 12-40*b*), as would be predicted from the diffusion equations. They also showed that the liquid-diffusion coefficient is usually a function of moisture content which decreases with decreasing moisture. The effect of variable diffusivity is illustrated in Fig. 12-40*b*, where the dashed line is calculated for constant diffusivity and the solid line is experimental for the case in which the diffusion coefficient is moisture-dependent. Thus, the integrated diffusion equations assuming constant diffusivity only approximate the actual behavior.

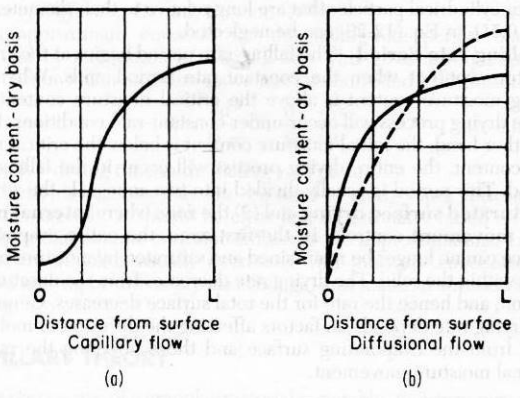



**FIG. 12-40** Two types of internal moisture gradients obtained in drying solids.

These authors classified solids on the basis of capillary and diffusional flow:

**Capillary Flow** Moisture which is held in the interstices of solids, as liquid on the surface, or as free moisture in cell cavities, moves by gravity and capillarity, provided that passageways for continuous flow are present. In drying, liquid flow resulting from capillarity applies to liquids not held in solution and to all moisture above the fiber-saturation point, as in textiles, paper, and leather, and to all moisture above the equilibrium moisture content at atmospheric saturations, as in fine powders and granular solids, such as paint pigments, minerals, clays, soil, and sand.

**Vapor Diffusion** Moisture may move by vapor diffusion through the solid, provided that a temperature gradient is established by heating, thus creating a vapor-pressure gradient. Vaporization and vapor diffusion may occur in any solid in which heating takes place at one surface and drying from the other and in which liquid is isolated between granules of solid.

**Liquid Diffusion** The movement of liquids by diffusion in solids is restricted to the equilibrium moisture content below the point of atmospheric saturation and to systems in which moisture and solid are mutually soluble. The first class applies to the last stages in the drying of clays, starches, flour, textiles, paper, and wood; the second class includes the drying of soaps, glues, gelatins, and pastes.

**External Conditions** The principal external variables involved in any drying study are temperature, humidity, air flow, state of subdivision of the solid, agitation of the solid, method of supporting the solid, and contact between hot surfaces and wet solid. All these variables will not necessarily occur in one problem.

## PERIODS OF DRYING

When a solid is dried experimentally, data relating moisture content to time are usually obtained. These data are then plotted as moisture content (dry basis) $W$ versus time $\theta$, as shown in Fig. 12-41*a*. This curve represents the general case when a wet solid loses moisture first by evaporation from a saturated surface on the solid, followed in turn by a period of evaporation from a saturated surface of gradually decreasing area, and, finally, when the latter evaporates in the interior of the solid.

Figure 12-41*a* indicates that the drying rate is subject to variation with time or moisture content. This variation is better illustrated by graphically or numerically differentiating the curve and plotting $dW/d\theta$ versus $W$, as shown in Fig. 12-41*b*, or as $dW/d\theta$ versus $\theta$, as shown in Fig. 12-41*c*. These **rate curves** illustrate that the drying process is not a smooth, continuous one in which a single mechanism controls throughout. Figure 12-41*c* has the advantage of showing how long each drying period lasts.

The section $AB$ on each curve represents a **warming-up** period of the solids. Section $BC$ on each curve represents the **constant-rate** period. Point $C$, where the constant rate ends and the drying rate begins falling, is termed the **critical-moisture** content. The curved portion $CD$ on Fig. 12-41*a* is termed the **falling-rate** period and, as shown in Fig. 12-41*b* and *c*, is typified by a continuously changing rate throughout the remainder of the drying cycle. Point $E$ (Fig. 12-41*b*) represents the point at which all the exposed surface becomes completely unsaturated and marks the start of that portion of the drying cycle during which the rate of internal moisture movement controls the drying rate. Portion $CE$ in Fig. 12-41*b* is usually defined as the first falling-rate drying period; portion $DE$, as the second falling-rate period.

**Constant-rate Period** In the constant-rate period moisture movement within the solid is rapid enough to maintain a saturated condition at the surface, and the rate of drying is controlled by the rate of heat transferred to the evaporating surface. Drying proceeds by diffusion of vapor from the saturated surface of the material across a

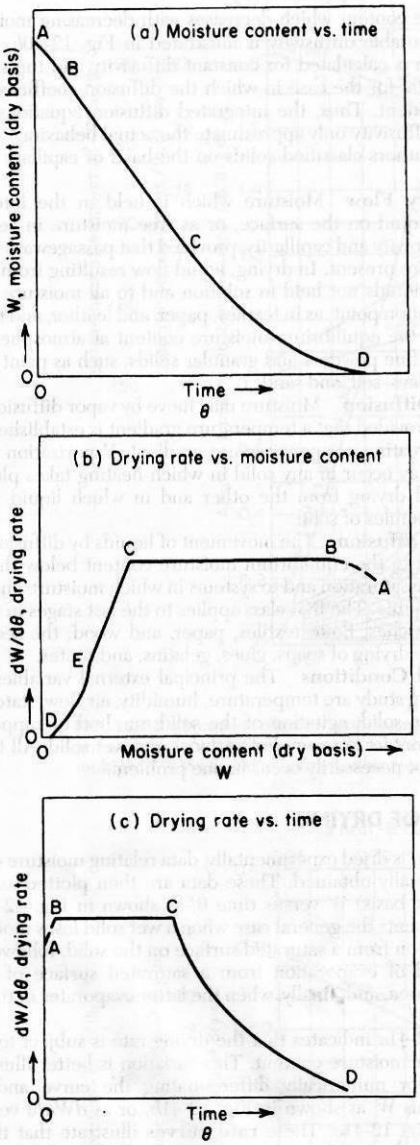



**FIG. 12-41** The periods of drying.

stagnant air film into the environment. The rate of mass transfer balances the rate of heat transfer, and the temperature of the saturated surface remains constant. The mechanism of moisture removal is equivalent to evaporation from a body of water° and is essentially independent of the nature of the solids.

If heat is transferred solely by convection and in the absence of other heat effects, the surface temperature approaches the wet-bulb temperature. However, when heat is transferred by radiation, convection, or a combination of these and convection, the temperature at the saturated surface is between the wet-bulb temperature and the boiling point of water. Under these conditions, the rate of heat transfer is increased and a higher drying rate results.

When heat is transferred to a wet solid by convection to hot surfaces and heat transfer by convection is negligible, the solids approach the boiling-point temperature rather than the wet-bulb temperature. This method of heat transfer is utilized in indirect dryers (see classification of dryers in Fig. 12-45). Radiation is also effective in increasing the constant rate by augmenting the convection heat transfer and raising the surface temperature above the wet-bulb temperature.

When the heat for evaporation in the constant-rate period is supplied by a hot gas, a dynamic equilibrium establishes the rate of heat transfer to the material and the rate of vapor removal from the surface:

$$dw/d\theta = h_t A\,\Delta t/\lambda = k_g A\,\Delta p \qquad (12\text{-}25)$$

where $dw/d\theta$ = drying rate, kg water/s; $h_t$ = total heat-transfer coefficient, J/(m²·s·K) [Btu/(h·ft²·°F)]; $A$ = area for heat transfer and evaporation, m²; $\lambda$ = latent heat of evaporation at $t'_s$, J/kg (Btu/lb); $k_g$ = mass-transfer coefficient, kg/(s·m²·atm) [(lb/(h·ft²·atm)]; $\Delta t = t - t'_s$, where $t$ = gas (dry-bulb) temperature, K; $p = p_s - p$, where $p_s$ = vapor pressure of water at surface temperature $t'_s$, atm; and $p$ = partial pressure of water vapor in the gas, atm.

The magnitude of the constant rate depends upon three factors:

1. The heat- or mass-transfer coefficient
2. The area exposed to the drying medium
3. The difference in temperature or humidity between the gas stream and the wet surface of the solid

All these factors are the external variables. The internal mechanism of liquid flow does not affect the constant rate.

For drying calculations, it is convenient to express Eq. (12-25) in terms of the decrease in moisture content rather than in the quantity of water evaporated. For evaporation from a tray of wet material, if no change in volume during drying is assumed, Eq. (12-25) becomes

$$dw/d\theta = (h/\rho_s\, d\lambda)(t - t'_s) \qquad (12\text{-}26)$$

where $dw/d\theta$ = drying rate, kg water/(s·kg dry solids); $h_t$ = total heat-transfer coefficient, J/(m²·s·K) [Btu/(h·ft²·°F)]; $\rho_s$ = bulk density dry material, kg/m³; $d$ = thickness of bed, m; $\lambda$ = latent heat of vaporization, J/kg (Btu/lb); $t$ = air temperature, K; and $t'_s$ = evaporating surface temperature, K. (Note that $dw/d\theta$ is inherently negative.)

A similar equation can be written for the through-circulation case:

$$dW/d\theta = (h_t a/\rho_s \lambda)(t - t'_s) \qquad (12\text{-}27)$$

where $a$ = m² of heat-transfer area/m³ of bed, 1/m; and other symbols are as in Eq. (12-26).

The values of $\rho_s$ and/or $a$ must be known in order to use Eqs. (12-26) and (12-27). The value of $a$ is difficult to estimate without experimental data. When the void fraction is known, $a$ can sometimes be estimated from the following relationships:

For spherical particles,

$$a = \frac{6(1 - F)}{(D_p)_m} \qquad (12\text{-}28)$$

For uniform cylindrical particles,

$$a = \frac{4(0.5D_0 + Z)(1 - F)}{D_0 Z} \qquad (12\text{-}29)$$

where $F$ = void fraction; $(D_p)_m$ = harmonic mean diameter of spherical particles, m; $D_0$ = diameter of cylinder, m; and Z = height of cylinder, m. For cylindrical particles that are long relative to their diameter, the term $0.5D_0$ in Eq. (12-29) can be neglected.

**Falling-rate Period** The falling-rate period begins at the critical moisture content when the constant-rate period ends. When the falling moisture content is above the critical moisture content, the whole drying process will occur under constant-rate conditions. If, on the other hand, the initial moisture content is below the critical moisture content, the entire drying process will occur in the falling-rate period. This period is usually divided into two zones: (1) the zone of **unsaturated surface drying** and (2) the zone where **internal moisture movement** controls. In the first zone, the entire evaporating surface can no longer be maintained and saturated by moisture movement within the solid. The drying rate decreases from the unsaturated portion, and hence the rate for the total surface decreases. Generally, the drying rate depends on factors affecting the diffusion of moisture away from the evaporating surface and those affecting the rate of internal moisture movement.

° The term "water" is used for convenience; this discussion applies equally to other liquids.

As drying proceeds, the point is reached where the evaporating surface is unsaturated. The point of evaporation moves into the solid, and the dry process enters the second falling-rate period. The drying rate is now governed by the rate of internal moisture movement; the influence of external variables diminishes. This period usually predominates in determining the overall drying time to lower moisture content.

## LIQUID DIFFUSION

Diffusion-controlled mass transfer is assumed when the vapor or liquid flow conforms to Fick's second law of diffusion. This is stated in the unsteady-state-diffusion equation using mass-transfer notation as

$$\delta c/\delta\theta = D_{AB}(\delta^2 C/dx) \tag{12-30}$$

where $c$ = concentration of one component in a two-component phase of $A$ and $B$, $\theta$ = diffusion time, $x$ = distance in the direction of diffusion, and $D_{AB}$ = binary diffusivity of the phase $AB$. This equation applies to diffusion in solids, stationary liquids, and stagnant gases.

The diffusion equation for the falling-rate drying period for a slab can be derived from the diffusion equation if one assumes that the surface is dry or at an equilibrium moisture content and that the initial moisture distribution is uniform. For these conditions, the following equation is obtained:

$$\frac{W - W_e}{W_c - W_e} = \frac{8}{\pi^2}\left[\sum_{n=0}^{n=\infty} \frac{1}{(2n+1)} e^{-(2n+1)^2 D_\ell \theta (\pi/2d)^2}\right] \tag{12-31}$$

where $W$, $W_c$, and $W_e$ = average moisture content (dry basis) at any time, $\theta$, at the start of the falling-rate period and in equilibrium with the environment respectively, kg/kg; $D_\ell$ = liquid diffusivity, $m^2/s$; $\theta$ = time from start of falling-rate period, s; and $d$ = one-half of the thickness of the solid layer through which diffusion occurs, m. When evaporation occurs from only one face, $d$ = total thickness, m.

Equation (12-31) assumes that $D_\ell$ is constant; however, $D_\ell$ is rarely constant but varies with moisture content, temperature, and humidity. For long drying times, Eq. (12-31) simplifies to a limiting form of the diffusion equation as

$$\frac{W - W_e}{W_c - W_e} = \frac{8}{\pi^2}\left[e^{-D_\ell \theta (\pi/2d)^2}\right] \tag{12-32}$$

Equation (12-32) may be differentiated to give the drying rate as

$$-\frac{dW}{d\theta} = \frac{\pi^2 D_\ell}{4d^2}(W - W_e) \tag{12-33}$$

where $dW/d\theta$ = drying rate, kg/s.

When Eq. (12-31) is plotted on semilogarithmic graph paper, a straight line is obtained for values of $(W - W_e)/(W_c - W_e) < 0.6$. It is in the straight-line portion that the approximate form [Eq. (12-33)] applies.

Equations (12-31), (12-32), and (12-33) hold only for a slab-sheet solid whose thickness is small relative to the other two dimensions. For other shapes, reference should be made to Crank (*The Mathematics of Diffusion*, Oxford, London, 1956).

An approximate equation for the falling-rate period may be obtained by integration of Eq. (12-33). This gives an equation for materials in which moisture movement is controlled by diffusion:

$$\theta_f = \frac{4d^2}{D_\ell \pi^2} \ln \frac{W_c - W_e}{W - W_e} \tag{12-34}$$

where $\theta_f$ = drying time in the falling-rate period.

Diffusion equations may also be used to study vapor diffusion in porous materials. It should be clear that all estimates based on relationships that assume constant diffusivity are approximations. Liquid diffusivity in solids usually decreases with moisture concentration. Liquid and vapor diffusivity also change, and material shrinks during drying.

## CAPILLARY THEORY

If the porous size of a granular material is suitable, moisture may move from a region of high to one of low concentration as the result of capillary action rather than by diffusion. The capillary theory assumes that a bed of nonporous spheres is composed of particles surrounding a space called a pore. These pores are connected by passages of various sizes. As water is progressively removed from the bed, the curvature of the water surface in the interstices of the top layer of spheres increases and a suction pressure resulting from curvature is set up. As the removal of water continues, the suction pressure attains a value in which air is drawn into the pore spaces between successive layers of spheres.

This entry suction or suction potential is a measure of the resultant forces tending to draw water from the interior of the bed to the surface. For a pore formed by regularly packed nonporous spheres, the suction potential is given by

$$P_s = x\sigma/r\rho g \tag{12-35}$$

where $P_s$ = suction potential, m of water; $\sigma$ = surface tension; dyn/m; $\rho$ = density of water, $kg/m^3$; $g = 9.8\ m/s^2$; $r$ = sphere radius, m; and $x$ is a packing factor equal to 12.9 for rhombohedral and 4.8 for cubical packing.

As drying proceeds, the surface moisture evaporates, causing retreat of the surface menisci until the suction potential reaches a value given by Eq. (12-35). At this point, the pores of the surface will open, air will enter, and the moisture will redistribute itself with a slight lowering of the suction potential. As evaporation proceeds, the suction potential again increases until a slightly higher entry value is reached, when a further redistribution occurs.

The drying rate curve (Fig. 12-41) can be analyzed in terms of capillary theory. In region $BC$, there is a loss of moisture with a gradual increase in suction and emptying of the bulk of the larger pores in the solid. In region $CE$, there is an increase in suction as the moisture content decreases and finer pores are opened. Section $ED$ represents a condition in which moisture is being removed by vapor diffusion from the interior of the body, although there is still sufficient water in the bed to give rise to capillary forces.

An approximate equation for use for materials in which moisture movement is controlled by capillary flow is given as

$$\theta_f = \frac{\rho_s d\lambda (W_c - W_e)}{h_t (t - t'_s)} \ln \frac{W_c - W_e}{W - W_e} \tag{12-36}$$

where $\theta_f$ = drying time in the falling-rate period.

Table 12-6 gives an approximate classification of materials that obey Eqs. (12-34) and (12-36).

## CRITICAL MOISTURE CONTENT

To use the preceding equations for estimating drying times in the falling-rate period, it is necessary to know values of critical moisture content $W_c$. Such values are difficult to obtain without making actual drying tests, which in themselves would give the required drying time and thereby obviate solving the equations. However, when drying tests are not feasible, some estimate of critical moisture content must be made.

Values of critical moisture contents for some representative materials are given in Table 12-7 for drying by cross circulation and in Table 12-15 for drying by through circulation. The tabulated values are only approximate, since critical moisture content depends on the drying history. It appears that the constant-rate period ends when the moisture content at the surface reaches a specific value. Since the critical

**TABLE 12-6 Materials Obeying Eqs. (12-34) and (12-38)**

| Materials obeying Eq. (12-34) | Materials obeying (Eq. 12-38) |
|---|---|
| 1. Single-phase solid systems such as soap, gelatin, and glue<br>2. Wood and similar solids below the fiber-saturation point<br>3. Last stages of drying starches, textiles, paper, clay, hydrophilic solids, and other materials when bound water is being removed | 1. Coarse granular solids such as sand, paint pigments, and minerals<br>2. Materials in which moisture flow occurs at concentrations above the equilibrium moisture content at atmospheric saturation or above the fiber-saturation point |

**TABLE 12-7 Approximate Critical Moisture Contents Obtained on the Air Drying of Various Materials, Expressed as Percentage Water on the Dry Basis**

| Material | Thickness, in. | Critical moisture, % water, dry basis |
|---|---|---|
| Barium nitrate crystals, on trays | 1.0 | 7 |
| Beaverboard | 0.17 | Above 120 |
| Brick clay | .62 | 14 |
| Carbon pigment | 1 | 40 |
| Celotex | 0.44 | 160 |
| Chrome leather | .04 | 125 |
| Copper carbonate (on trays) | 1–1.5 | 60 |
| English china clay | 1 | 16 |
| Flint clay refractory brick mix | 2.0 | 13 |
| Gelatin, initially 400 % water | 0.1–0.2 (wet) | 300 |
| Iron blue pigment (on trays) | 0.25–0.75 | 110 |
| Kaolin | | 14 |
| Lithol red | 1 | 50 |
| Lithopone press cake (in trays) | 0.25 | 6.4 |
| | .50 | 8.0 |
| | .75 | 12.0 |
| | 1.0 | 16.0 |
| Niter cake fines, on trays | | Above 16 |
| Paper, white eggshell | 0.0075 | 41 |
| Fine book | .005 | 33 |
| Coated | .004 | 34 |
| Newsprint | | 60–70 |
| Plastic clay brick mix | 2.0 | 19 |
| Poplar wood | 0.165 | 120 |
| Prussian blue | | 40 |
| Pulp lead, initially 140% water | | Below 15 |
| Rock salt (in trays) | 1.0 | 7 |
| Sand, 50–150 mesh | 2.0 | 5 |
| Sand, 200–325 mesh | 2.0 | 10 |
| Sand, through 325 mesh | 2.0 | 21 |
| Sea sand (on trays) | 0.25 | 3 |
| | .5 | 4.7 |
| | .75 | 5.5 |
| | 1.0 | 5.9 |
| | 2.0 | 6.0 |
| Silica brick mix | 2.0 | 8 |
| Sole leather | 0.25 | Above 90 |
| Stannic tetrachloride sludge | 1 | 180 |
| Subsoil, clay fraction 55.4% | | 21 |
| Subsoil, much higher clay content | | 35 |
| Sulfite pulp | 0.25–0.75 | 60–80 |
| Sulfite pulp (pulp lap) | 0.039 | 110 |
| White lead | | 11 |
| Whiting | 0.25–1.5 | 6.9 |
| Wool fabric, worsted | | 31 |
| Wool, undyed serge | | 8 |

moisture content is the average moisture through the material, its value depends on the rate of drying, the thickness of the material, and the factors influencing moisture movement and resulting gradients within the solid. As a result, the critical moisture content increases with increased drying rate and with increased thickness of the mass of material being dried.

## EQUILIBRIUM MOISTURE CONTENT

In drying solids it is important to distinguish between hygroscopic and nonhygroscopic materials. If a hygroscopic material is maintained in contact with air at constant temperature and humidity until equilibrium is reached, the material will attain a definite moisture content. This moisture is termed the equilibrium moisture content for the specified conditions. Equilibrium moisture may be adsorbed as a surface film or condensed in the fine capillaries of the solid at reduced pressure, and its concentration will vary with the temperature and humidity of the surrounding air. However, at low temperatures, e.g., 15 to 50°C, a plot of equilibrium moisture content versus percent relative humidity is essentially independent of temperature. At zero humidity the equilibrium moisture content of all materials is zero.

Equilibrium moisture content depends greatly on the nature of the solid. For nonporous, i.e., nonhygroscopic, materials, the equilibrium moisture content is essentially zero at all temperatures and humidities. For organic materials such as wood, paper, and soap, equilibrium moisture contents vary regularly over wide ranges as temperature and humidity change. In the special case of the dehydration of hydrated inorganic salts such as copper sulfate, sodium sulfate, or barium chloride, temperature and humidity control is very important in obtaining the desired degree of moisture removal, and the proper conditions must be determined from data on the water of hydration or crystallization as a function of air temperature and humidity.

Equilibrium moisture content of a solid is particularly important in drying because it represents the limiting moisture content for given conditions of humidity and temperature. If the material is dried to a moisture content less than it normally possesses in equilibrium with atmospheric air, it will return to its equilibrium value on storage unless special precautions are taken.

Equilibrium moisture content of a hygroscopic material may be determined in a number of ways, the only requirement being a source of constant-temperature and constant-humidity air. Determination may be made under static or dynamic conditions, although the latter case is preferred. A simple static procedure is to place a number of samples in ordinary laboratory desiccators containing sulfuric acid solutions of known concentrations which produce atmospheres of known relative humidity. The sample in each desiccator is weighed periodically until a constant weight is obtained. Moisture content at this final weight represents the equilibrium moisture content for the particular conditions.

The value of equilibrium moisture content, for many materials, depends on the direction in which equilibrium is approached. A different value is reached when a wet material loses moisture by desorption, as in drying, from that obtained when a dry material gains it by adsorption. For drying calculations the desorption values are preferred. In the general case, the equilibrum moisture content reached by losing moisture is higher than that reached by adsorbing it.

Equilibrium moisture content can be measured dynamically by placing the sample in a U tube through which is drawn a continuous flow of controlled-humidity air. Again the sample is weighed periodically until a constant weight is reached. Properly humidified air for such a procedure can be obtained by bubbling dry air through a large volume of a saturated salt solution which produces a definite degree of saturation of the air. Care must be taken to ensure that the air and salt solution reach equilibrium. Values of the humidity over various salt solutions may be found in Table 12-8. Several manufacturers supply chambers with dial-in temperature and humidity conditions for air-water systems.

## ESTIMATIONS FOR TOTAL DRYING TIME

Estimates of both the constant-rate and the falling-rate periods are needed to estimate the total drying time for a given drying operation. If estimates for these periods are available, the total drying time is estimated by summing as

$$\theta_t = \theta_c + \theta_f \qquad (12\text{-}37)$$

where $\theta_t$ = total drying time, h; $\theta_c$ = drying time for constant-rate period, h; and $\theta_f$ = drying time for falling-rate period, h. The difficulty in estimating critical moisture content greatly reduces the number of drying cases in which calculation of a good estimate is possible.

## ANALYSIS OF DRYING DATA TESTS ON PLANT DRYERS

When experiments are carried out to select a suitable dryer and to obtain design data, the effect of changes in various external variables is studied. These experiments should be conducted in an experimental unit that simulates the large-scale dryer from both the thermal and the material-handling aspects, and only material which is truly representative of full-scale production should be used.

Data expressing moisture content in terms of elapsed time should be obtained and the results plotted as shown in Fig. 12-42. For purposes of analysis, the moisture-time curve must be differentiated

**TABLE 12-8 Maintenance of Constant Humidity**

| Solid phase | Max. temp., °C. | % humidity |
|---|---|---|
| $H_3PO_4 \cdot \frac{1}{2}H_2O$ | 24.5 | 9 |
| $ZnCl_2 \cdot \frac{1}{2}H_2O$ | 20 | 10 |
| $KC_2H_3O_2$ | 168 | 13 |
| $LiCl \cdot H_2O$ | 20 | 15 |
| $KC_2H_3O_2$ | 20 | 20 |
| KF | 100 | 22.9 |
| NaBr | 100 | 22.9 |
| $CaCl_2 \cdot 6H_2O$ | 24.5 | 31 |
| $CaCl_2 \cdot 6H_2O$ | 20 | 32.3 |
| $CaCl_2 \cdot 6H_2O$ | 18.5 | 35 |
| $CrO_3$ | 20 | 35 |
| $CaCl_2 \cdot 6H_2O$ | 10 | 38 |
| $CaCl_2 \cdot 6H_2O$ | 5 | 39.8 |
| $K_2CO_3 \cdot 2H_2O$ | 24.5 | 43 |
| $K_2CO_3 \cdot 2H_2O$ | 18.5 | 44 |
| $Ca(NO_3)_2 \cdot 4H_2O$ | 24.5 | 51 |
| $NaHSO_4 \cdot H_2O$ | 20 | 52 |
| $Mg(NO_3)_2 \cdot 6H_2O$ | 24.5 | 52 |
| $NaClO_3$ | 100 | 54 |
| $Ca(NO_3)_2 \cdot 4H_2O$ | 18.5 | 56 |
| $Mg(NO_3)_2 \cdot 6H_2O$ | 18.5 | 56 |
| $NaBr \cdot 2H_2O$ | 20 | 58 |
| $Mg(C_2H_3O_2) \cdot 4H_2O$ | 20 | 65 |
| $NaNO_2$ | 20 | 66 |
| $(NH_4)_2SO_4$ | 108.2 | 75 |
| $(NH_4)_2SO_4$ | 20 | 81 |
| $NaC_2H_3O_2 \cdot 3H_2O$ | 20 | 76 |
| $Na_2S_2O_3 \cdot 5H_2O$ | 20 | 78 |
| $NH_4Cl$ | 20 | 79.5 |
| $NH_4Cl$ | 25 | 79.3 |
| $NH_4Cl$ | 30 | 77.5 |
| KBr | 20 | 84 |
| $Tl_2SO_4$ | 104.7 | 84.8 |
| $KHSO_4$ | 20 | 86 |
| $Na_2CO_3 \cdot 10H_2O$ | 24.5 | 87 |
| $K_2CrO_4$ | 20 | 88 |
| $NaBrO_3$ | 20 | 92 |
| $Na_2CO_3 \cdot 10H_2O$ | 18.5 | 92 |
| $Na_2SO_4 \cdot 10H_2O$ | 20 | 93 |
| $Na_2HPO_4 \cdot 12H_2O$ | 20 | 95 |
| NaF | 100 | 96.6 |
| $Pb(NO_3)_2$ | 20 | 98 |
| $TlNO_3$ | 100.3 | 98.7 |
| TlCl | 100.1 | 99.7 |

For a more complete list of salts, and for references to the literature see "International Critical Tables," vol. 1, p. 68.

graphically or numerically and the drying rates so obtained plotted to determine the nature and extent of the drying periods in the cycle. It is customary to plot drying rate versus moisture content as in Fig. 12-41*b*. Although instructive, this type of plot gives no information on duration of the drying periods. These are better shown by plots similar to Fig. 12-41*c*, in which drying rate is plotted as a function of time on either arithmetic or logarithmic coordinates. Logarithmic plots permit easy reading at low moisture contents or long times.

In order to determine whether a simple relationship exists in the falling-rate period, the unaccomplished moisture change, defined as ratio of free moisture in the solid at time $\theta$ to total free moisture present at start of the falling-rate period $(W - W_e)/(W_c - W_e)$, is plotted as a function of time on semilogarithmic paper. If a straight line is obtained such as curve *B* of Fig. 12-43 by using the upper scale of abscissa, either Eq. (12-34), for materials in which the moisture moves by diffusion, or Eq. (12-37), for materials in which the moisture movement is by capillary flow, may be applicable. If Eq. (12-37) applies, $K_1$, the slope of the falling-rate drying curve, is related to the constant drying rate. The latter is calculated from Eq. (12-38) and can be compared with the measured value. If the slopes agree, the moisture movement is by capillary flow. If the slopes do not agree, the moisture movement is by diffusion and the slope of the line should equal $\pi^2 D_\ell / 4d^2$.

The dependency of drying rate on material thickness must be established experimentally. With the effect of material thickness established, liquid diffusivity can be calculated as indicated here. For this calculation, the theoretical values for an infinite slab are required. These are:

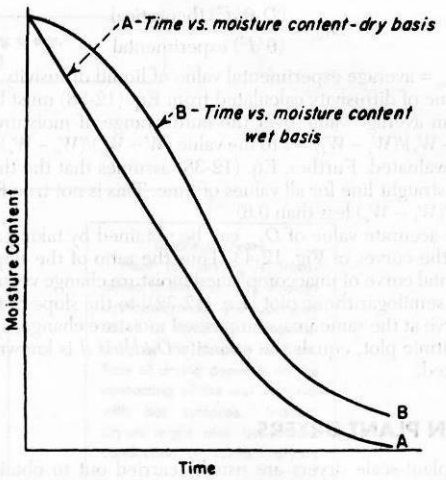



**FIG. 12-42** Drying-time curves.

| $\frac{D_\ell \theta}{d^2}$ | 0.02 | 0.05 | 0.10 | 0.15 | 0.20 | 0.30 | 0.50 | 1.0 |
|---|---|---|---|---|---|---|---|---|
| $\frac{W - W_e}{W_c - W_e}$ | 0.84 | 0.75 | 0.642 | 0.563 | 0.496 | 0.387 | 0.238 | 0.069 |

A plot of these values is shown as curve *A* in Fig. 12-43.

If a straight line such as curve *B* of Fig. 12-43 represents the experimental data and if it has been established that the drying time varies inversely as the square of the thickness, the average liquid diffusivity can be obtained as follows. At a given value of $(W - W_e)/(W_c - W_e)$, read the corresponding value of $D_\ell \theta / d^2$ from curve *A*, Eq. (12-32), Fig. 12-43. At the same value of $(W - W_e)/(W_c - W_e)$, read the corresponding experimental value of $\theta$ from curve *B* (upper scale). Then

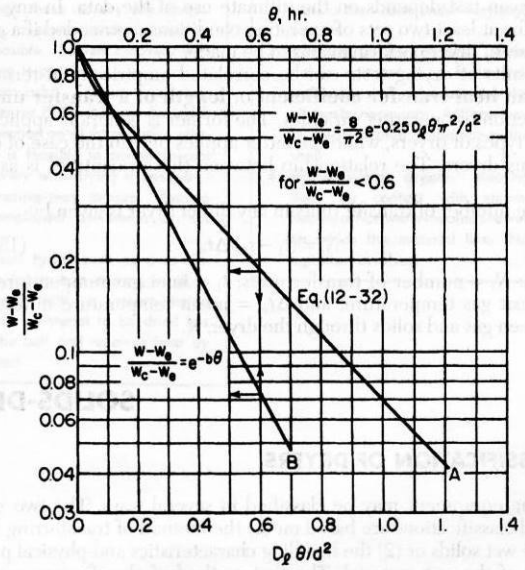



**FIG. 12-43** Analysis of drying data.

$$D_{\ell_{avg}} = \frac{(D_\ell \theta/d^2) \text{ theoretical}}{(\theta/d^2) \text{ experimental}} \qquad (12\text{-}38)$$

where $D_{\ell_{avg}}$ = average experimental value of liquid diffusivity, m²/h.

The value of diffusivity calculated from Eq. (12-38) must be recognized as an average value over the entire range of moisture change from $(W - W_e)/(W_c - W_e) = 1$ to the value $(W - W_e)/(W_c - W_e)$ at which $\theta/d^2$ was evaluated. Further, Eq. (12-38) assumes that the theoretical curve is a straight line for all values of time. This is not true for values $(W - W_e)/(W_c - W_e)$ less than 0.6.

A more accurate value of $D_{\ell_{avg}}$ can be obtained by taking a ratio of slopes of the curves of Fig. 12-43. Thus the ratio of the slope of the experimental curve of unaccomplished moisture change versus drying time on a semilogarithmic plot [Eq. (12-32)] to the slope of the theoretical curve at the same unaccomplished moisture change, again on a semilogaritmic plot, equals the quantity $D_\ell/d^2$. If $d$ is known, $D_\ell$ can be evaluated.

## TESTS ON PLANT DRYERS

Tests on plant-scale dryers are usually carried out to obtain design data for a specific material, to select a suitable dryer type, or to check present performance of an existing dryer with the objective of determining its capacity potential. In these tests overall performance data are obtained and the results used to make heat and material balances and to estimate overall drying rates or heat-transfer coefficients.

Generally, the minimum data to be taken in order to calculate the performance of a dryer are:

1. Inlet and outlet moisture contents
2. Inlet and outlet gas temperatures
3. Inlet and outlet material temperatures
4. Feed rate
5. Gas rate
6. Inlet and outlet humidities
7. Retention time or time of passage through the dryer
8. Fuel consumption

Whenever possible, moisture contents and temperatures should be measured at various points within the dryer.

Typical experimental and calculated results of a drying test for a continuous adiabatic convection dryer are shown in Fig. 12-44. Test data as elaborate as those shown are not usually justified economically except when basic studies, aimed at clarifying the effect of operating variables, are being carried out in order to arrive at a reliable design procedure. The completeness of the information which is sought in any given test depends on the ultimate use of the data. In any case data for at least two sets of operating conditions are needed if a good analysis of dryer performance is to be made.

Results of drying tests can be correlated empirically in terms of **overall heat-transfer coefficient** or **length of a transfer unit** as a function of operating variables. The former is generally applicable to all types of dryers, while the latter applies only in the case of continuous dryers. The relationship between these quantities is as follows.

The number of transfer units in any direct dryer is given by

$$N_t = (t_1 - t_2)/\Delta t_m \qquad (12\text{-}39)$$

where $N_t$ = number of transfer units; $t_1$ = inlet gas temperature, K; $t_2$ = exit gas temperature; and $\Delta t_m$ = mean temperature difference between gas and solids through the dryer, K.

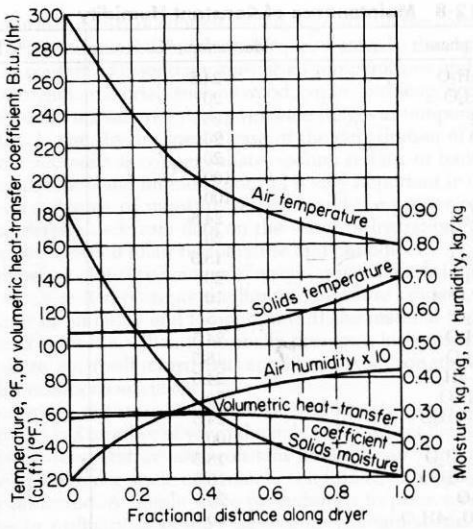



**FIG. 12-44** Typical results of dryer-performance tests. To convert British thermal units per hour-cubic foot-degree Fahrenheit to joules per cubic meter-second-kelvin, multiply by 1.73.

The volumetric heat-transfer coefficient is given by

$$U_v = \frac{q_d}{V_d \, \Delta t_m} = \frac{wc_s(t_2 - t_1)}{A_d L_d \, \Delta t_m} \qquad (12\text{-}40)$$

where $U_v$ = volumetric heat-transfer coefficient, J/(m³·s·K) [Btu/(h·ft³·°F)]; $q$ = cross-sectional area of dryer, m²; and $L_d$ = dryer length, m.

The volumetric heat-transfer coefficients along the dryer are lower at the discharge end (Fig. 12-44) because of the internal resistance to moisture movement in the later stages of drying. When drying data are expressed in terms of overall performance, care and judgment should be exercised in extrapolating the results to other conditions, particularly conditions of different feed and product moisture. If, for example, the overall heat-transfer coefficients, from the data of Fig. 12-44, were used to predict a dryer design for reducing the product moisture below 10 percent, the design would be in error. Obviously, this problem can be circumvented by making sure that the final moisture in the experiments is below that desired in the product.

In any capacity test to determine the potential of a plant dryer, the effects of the following variables should be studied:

1. **Effect of increased temperature.** This is often the simplest way to achieve increased capacity.
2. **Effect of increased final moisture.** Because of the marked increase in drying time required to dry to low moisture contents, the permissible maximum final moisture should always be established.
3. **Effect of increasing air velocity** should be determined. Frequently, higher air rates are necessary to provide the required additional heat at higher capacities.
4. **Uniformity of air flow** should be established. Air-flow maldistribution can seriously reduce dryer capacity and efficiency.
5. Possible benefits from **air recirculation** should be considered.

# SOLIDS-DRYING EQUIPMENT

## CLASSIFICATION OF DRYERS

Drying equipment may be classified in several ways. The two most useful classifications are based on (1) the method of transferring heat to the wet solids or (2) the handling characteristics and physical properties of the wet material. The first method of classification reveals differences in dryer design and operation, while the second method is most useful in the selection of a group of dryers for preliminary consideration in a given drying problem.

A classification chart of drying equipment on the basis of heat transfer is shown in Fig. 12-45. This chart classifies dryers as direct or indirect, with subclasses of continuous or batchwise operation.

**Direct Dryers** The general operating characteristics of direct dryers are these:

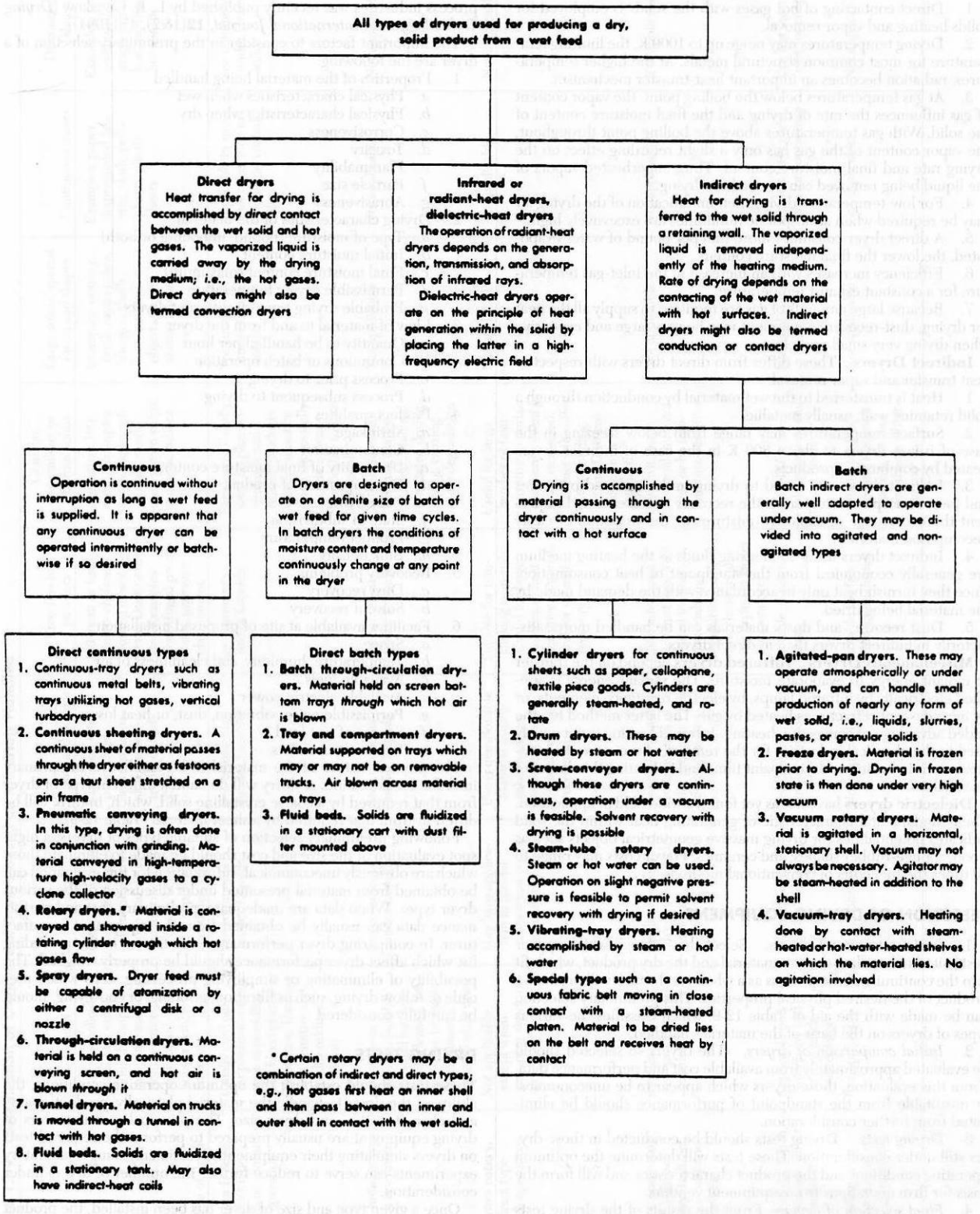



**FIG. 12-45** Classification of dryers, based on method of heat transfer. [*Revised from Marshall,* Heat, Piping Air Cond., *18, 71 (1946).*]

1. Direct contacting of hot gases with the solids is employed for solids heating and vapor removal.
2. Drying temperatures may range up to 1000 K, the limiting temperature for most common structural metals. At the higher temperatures, radiation becomes an important heat-transfer mechanism.
3. At gas temperatures below the boiling point, the vapor content of gas influences the rate of drying and the final moisture content of the solid. With gas temperatures above the boiling point throughout, the vapor content of the gas has only a slight retarding effect on the drying rate and final moisture content. Thus, superheated vapors of the liquid being removed can be used for drying.
4. For low-temperature drying, dehumidification of the drying air may be required when atmospheric humidities are excessively high.
5. A direct dryer consumes more fuel per pound of water evaporated, the lower the final moisture content.
6. Efficiency increases with an increase in the inlet-gas temperature for a constant exhaust temperature.
7. Because large amounts of gas are required to supply all the heat for drying, dust-recovery equipment may be very large and expensive when drying very small particles.

**Indirect Dryers** These differ from direct dryers with respect to heat transfer and vapor removal:

1. Heat is transferred to the wet material by conduction through a solid retaining wall, usually metallic.
2. Surface temperatures may range from below freezing in the case of freeze dryers to above 800 K in the case of indirect dryers heated by combustion products.
3. Indirect dryers are suited to drying under reduced pressures and inert atmospheres to permit the recovery of solvents and to prevent the occurrence of explosive mixtures or the oxidation of easily decomposed materials.
4. Indirect dryers using condensing fluids as the heating medium are generally economical from the standpoint of heat consumption, since they furnish heat only in accordance with the demand made by the material being dried.
5. Dust recovery and dusty materials can be handled more satisfactorily in indirect dryers than in direct dryers.

**Miscellaneous Dryers** **Infrared dryers** depend on the transfer of radiant energy to evaporate moisture. The radiant energy is supplied electrically by infrared lamps, by electric resistance elements, or by incandescent refractories heated by gas. The latter method has the added advantage of convection heating. Infrared heating is not widely used in the chemical industries for the removal of moisture. Its principal use is in baking or drying paint films and in heating thin layers of materials.

**Dielectric dryers** have not as yet found a wide field of application. Their fundamental characteristic of generating heat within the solid indicates potentialities for drying massive geometrical objects such as wood, sponge-rubber shapes, and ceramics. Power costs may range to 10 times the fuel costs of conventional methods.

## SELECTION OF DRYING EQUIPMENT

1. *Initial selection of dryers.* Select those dryers which appear best suited to handling the wet material and the dry product, which fit into the continuity of the process as a whole, and which will produce a product of the desired physical properties. This preliminary selection can be made with the aid of Table 12-9, which classifies the various types of dryers on the basis of the materials handled.
2. *Initial comparison of dryers.* The dryers so selected should be evaluated approximately from available cost and performance data. From this evaluation, those dryers which appear to be uneconomical or unsuitable from the standpoint of performance should be eliminated from further consideration.
3. *Drying tests.* Drying tests should be conducted in those dryers still under consideration. These tests will determine the optimum operating conditions and the product characteristics and will form the basis for firm quotations from equipment vendors.
4. *Final selection of dryer.* From the results of the drying tests and quotations, the final selection of the most suitable dryer can be made. A recent article describing dryer scale-up methodology in the process industries was recently published by L. R. Genskow [*Drying Technology—An International Journal*, **12**(1&2), 47 (1994)].

The important factors to consider in the preliminary selection of a dryer are the following:

1. Properties of the material being handled
   - *a.* Physical characteristics when wet
   - *b.* Physical characteristics when dry
   - *c.* Corrosiveness
   - *d.* Toxicity
   - *e.* Flammability
   - *f.* Particle size
   - *g.* Abrasiveness
2. Drying characteristics of the material
   - *a.* Type of moisture (bound, unbound, or both)
   - *b.* Initial moisture content
   - *c.* Final moisture content (maximum)
   - *d.* Permissible drying temperature
   - *e.* Probable drying time for different dryers
3. Flow of material to and from the dryer
   - *a.* Quantity to be handled per hour
   - *b.* Continuous or batch operation
   - *c.* Process prior to drying
   - *d.* Process subsequent to drying
4. Product qualities
   - *a.* Shrinkage
   - *b.* Contamination
   - *c.* Uniformity of final moisture content
   - *d.* Decomposition of product
   - *e.* Overdrying
   - *f.* State of subdivision
   - *g.* Product temperature
   - *h.* Bulk density
5. Recovery problems
   - *a.* Dust recovery
   - *b.* Solvent recovery
6. Facilities available at site of proposed installation
   - *a.* Space
   - *b.* Temperature, humidity, and cleanliness of air
   - *c.* Available fuels
   - *d.* Available electric power
   - *e.* Permissible noise, vibration, dust, or heat losses
   - *f.* Source of wet feed
   - *g.* Exhaust-gas outlets

The physical nature of the material to be handled is the primary item for consideration. A slurry will demand a different type of dryer from that required by a coarse crystalline solid, which, in turn, will be different from that required by a sheet material (Table 12-9).

Following preliminary selection of suitable types of dryers, a high-spot evaluation of the size and cost should be made to eliminate those which are obviously uneconomical. Information for this evaluation can be obtained from material presented under discussion of the various dryer types. When data are inadequate, preliminary cost and performance data can usually be obtained from the equipment manufacturer. In comparing dryer performance, the factors in the preceding list which affect dryer performance should be properly weighed. The possibility of eliminating or simplifying processing steps which precede or follow drying, such as filtration, grinding, or conveying, should be carefully considered.

## DRYING TESTS

These tests should establish the optimum operating conditions, the ability of the dryer to handle the material physically, product quality and characteristics, and dryer size. The principal manufacturers of drying equipment are usually prepared to perform the required tests on dryers simulating their equipment. Occasionally, simple laboratory experiments can serve to reduce further the number of dryers under consideration.

Once a given type and size of dryer has been installed, the product characteristics and drying capacity can be changed only within relatively narrow limits. Thus it is more economical and far more satisfac-

**TABLE 12-9 Classification of Commercial Dryers Based on Materials Handled**

| Type of dryer | Liquids | Slurries | Pastes and sludges | Free-flowing powders | Granular, crystalline, or fibrous solids | Large solids, special forms and shapes | Continuous sheets | Discontinuous sheets |
|---|---|---|---|---|---|---|---|---|
| | True and colloidal solutions; emulsions. Examples: inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex, etc. | Pumpable suspensions. Examples: pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates, etc. | Examples: filter-press cakes, sedimentation sludges, centrifuged solids, starch, etc. | 100 mesh or less. Relatively free flowing in wet state. Dusty when dry. Examples: centrifuged precipitates, pigments, clay, cement. | Larger than 100 mesh. Examples: rayon staple, salt crystals, sand, ores, potato strips, synthetic rubber. | Examples: pottery, brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber. | Examples: paper, impregnated fabrics, cloth, cellophane, plastic sheets. | Examples: veneer, wallboard, photograph prints, leather, foam rubber sheets. |
| **Vacuum freeze.** Indirect type, batch or continuous operation | Usually used only for pharmaceuticals such as penicillin and blood plasma. Expensive. Used on heat-sensitive and readily oxidized materials | See comments under Liquids | See comments under Liquids | See comments under Liquids | Expensive. Usually used on pharmaceuticals and related products which cannot be dried successfully by other means. Applicable to fine chemicals | See comments under Granular solids | Applicable in special cases such as emulsion-coated films | See comments under Granular solids |
| **Pan.** Indirect type, batch operation | Atmospheric or vacuum. Suitable for small batches. Easily cleaned. Solvents can be recovered. Material agitated while dried | See comments under Liquids | See comments under Liquids | See comments under Liquids | Suitable for small batches. Easily cleaned. Material is agitated during drying, causing some degradation | Not applicable | Not applicable | Not applicable |
| **Vacuum rotary.** Indirect type, batch operation | Not applicable, except when pumping slowly on dry "heel" | May have application in special cases when pumping onto dry "heel" | Use is questionable. Material usually cakes to dryer walls and agitator. Solvents can be recovered | Suitable for non-sticking materials. Useful for large batches of heat-sensitive materials and for solvent recovery | Useful for large batches of heat-sensitive materials or where solvent is to be recovered. Product will suffer some grinding action. Dust collectors may be required. | Not applicable | Not applicable | Not applicable |
| **Screw conveyor and indirect rotary.** Indirect type, continuous operation | Applicable with dry-product recirculation | Applicable with dry-product recirculation | Generally requires recirculation of dry product. Little dusting occurs | Chief advantage is low dust loss. Well suited to most materials and capacities, particularly those requiring drying at steam temperature | Low dust loss. Material must not stick or be temperature-sensitive | Not applicable | Not applicable | Not applicable |
| **Fluid beds.** Batch, continuous, direct, and indirect | Applicable only with inert bed or dry-solids recirculator | See comments under Liquids | See comments under Liquids | Suitable, if not too dusty | Suitable for crystals, granules, and short fibers | Not applicable | Use hot inert particles for contacting | Use hot inert particles for contacting |
| **Vibrating tray.** Indirect type, continuous operation | Not applicable | Not applicable | Not applicable | Suitable for free-flowing materials | Suitable for free-flowing materials that can be conveyed on a vibrating tray | Not applicable | Not applicable | Not applicable |

**TABLE 12-9 Classification of Commercial Dryers Based on Materials Handled** (*Concluded*)

| | Liquids | Slurries | Pastes and sludges | Free-flowing powders | Granular, crystalline, or fibrous solids | Large solids, special forms and shapes | Continuous sheets | Discontinuous sheets |
|---|---|---|---|---|---|---|---|---|
| **Drum.** Indirect type, continuous operation | Single, double or twin. Atm. or vacuum operation. Product flaky and usually dusty. Maintenance costs may be high | See comments under Liquids. Twin-drum dryers are widely used | Can be used only when paste or sludge can be made to flow. See comments under Liquids | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable |
| **Cylinder.** Indirect type, continuous operation | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Suitable for thin or mechanically weak sheets which can be dried in contact with a heated surface. Special surface effects obtainable | Suitable for materials which need not be dried flat and which will not be injured by contact with hot drum |
| **Infrared.** Batch or continuous operation | Only for thin films | See comments under Liquids | See comments under Liquids (only for thin layers) | Only for thin layers | Primarily suited to drying surface moisture. Not suited for thick layers | Specially suited for drying and baking paint and enamels | Usually used in conjunction with other methods. Useful when there are space limitations | Useful for laboratory work or in conjunction with other methods |
| **Dielectric.** Batch or continuous operation | Very expensive | See comments under Liquids | See comments under Liquids | Very expensive | Very expensive | Rapid drying of large objects suited to this method | Applications for final stages of paper dryers | Successful on foam rubber. Not fully developed on other materials |
| **Tray and compartment.** Direct type, batch operation | Not applicable | For very small batch production. Laboratory drying | Suited to batch operation. At large capacities, investment and operating costs are high. Long drying times | Dusting may be a problem. See comments under Pastes and Sludges | Suited to batch operation. At large capacities, investment and operating costs are high. Long drying times | See comments under Granular solids | Not applicable | See comments under Granular solids |
| **Batch through-circulation.** Direct type, batch operation | Not applicable | Not applicable | Suitable only if material can be preformed. Suited to batch operation. Shorter drying time than tray dryers | Not applicable | Usually not suited for materials smaller than 30 mesh. Suited to small capacities and batch operation | Primarily useful for small objects | Not applicable | Not applicable |
| **Tunnel. Continuous Tray.** Direct type, continuous operation | Not applicable | Not applicable | Suitable for small and large-scale production. | See comments under Pastes and Sludges. Vertical-turbo applicable | Essentially large-scale, semicontinuous tray drying. | Suited to a wide variety of shapes and forms. Operation can be made continuous. Widely used | Not applicable | Suited for leather, wallboard, veneer. |
| **Continuous through-circulation.** Direct type, continuous operation | Not applicable | Only crystal filter dryer may be suited | Suitable for materials that can be preformed. Will handle large capacities. Roto-louvre requires dry-product recirculation | Not generally applicable, except Roto-louvre in certain cases | Usually not suited for materials smaller than 30 mesh. Material does not tumble, except in Roto-louvre dryer. Latter operates at higher temperatures | Suited to smaller objects that can be loaded on each other. Can be used to convey materials through heated zones. Roto-louvre not suited. | Not applicable | Special designs are required. Suited to veneers. Roto-louvre not applicable |
| **Direct rotary.** Direct type, continuous operation | | Applicable with dry-product recirculation | Suitable only if product does not stick to walls and | Suitable for most materials and capacities, pro- | Suitable for most materials at most capacities. Dust- | Not applicable | Not applicable | Not applicable |

| Type of dryer | Applicable with dry-product recirculation | True and colloidal solutions; emulsions. Examples: inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex, etc. | Pumpable suspensions. Examples: pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates, etc. | does not dust. Recirculation of product may prevent sticking | Examples: filter-press cakes, sedimentation sludges, centrifuged solids, starch, etc. | vided that dusting is not too severe | 100 mesh or less. Relatively free flowing in wet state. Dusty when dry. Examples: centrifuged precipitates, pigments, clay, cement. | ing or crystal abrasion will limit its use | Larger than 100 mesh. Examples: rayon staple, salt crystals, sand, ores, potato strips, synthetic rubber. | Examples: pottery, brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber. | Examples: paper, impregnated fabrics, cloth, cellophane, plastic sheets. | Examples: veneer, wallboard, photograph prints, leather, foam rubber sheets. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pneumatic conveying.** Direct type, continuous operation | See comments under Slurries | Can be used only if product is recirculated to make feed suitable for handling | Usually requires recirculation of dry product to make suitable feed. Well suited to high capacities. Disintegration usually required | Suitable for materials that are easily suspended in a gas stream and lose moisture readily. Well suited to high capacities | Suitable for materials that are easily suspended in a gas streatm. Well suited to high capacities. Product may suffer physical degradation | Not applicable | Not applicable | Not applicable |
| **Spray.** Direct type, continuous operation | Suited for large capacities. Product is usually powdery, spherical, and free-flowing. High temperatures can be used with heat-sensitive materials. Product may have low bulk density | See comments under Liquids. Pressure-nozzle atomizers subject to erosion | Requires special pumping equipment to feed the atomizer. See comments under Liquids | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable |
| **Continuous sheeting.** Direct type, continuous operation | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Different types are available for different requirements. Suitable for drying without contacting hot surfaces | Not applicable |
| **Vacuum shelf.** Indirect type, batch operation | Not applicable | Applicable for small-batch production | Suitable for batch operation, small capacities. Useful for heat-sensitive or readily oxidizable materials. Solvents can be recovered | See comments under Pastes and Sludges | Suitable for batch operation, small capacities. Useful for heat-sensitive or readily oxidizable materials. Solvents can be recovered. | See comments under Granular solids | Not applicable | See comments under Granular solids |

tory to experiment in small-scale units than on the dryer that is finally installed.

On the basis of the results of the drying tests that establish size and operating characteristics, formal quotations and guarantees should be obtained from dryer manufacturers. Initial costs, installation costs, operating costs, product quality, dryer operability, and dryer flexibility can then be given proper weight in final evaluation and selection.

## BATCH TRAY AND DRYERS

**Description** A tray or compartment dryer is an enclosed, insulated housing in which solids are placed upon tiers of trays in the case of particulate solids or stacked in piles or upon shelves in the case of large objects. Heat transfer may be *direct* from gas to solids by circulation of large volumes of hot gas or *indirect* by use of heated shelves, radiator coils, or refractory walls inside the housing. In indirect-heat units, excepting vacuum-shelf equipment, circulation of a small quantity of gas is usually necessary to sweep moisture vapor from the compartment and prevent gas saturation and condensation. Compartment units are employed for the heating and drying of lumber, ceramics, sheet materials (supported on poles), painted and metal objects, and all forms of particulate solids.

**Field of Application** Because of the high labor requirements usually associated with loading or unloading the compartments, batch compartment equipment is rarely economical except in the following situations:

1. A long heating cycle is necessary because the size of the solid objects or permissible heating temperature requires a long holdup for internal diffusion of heat or moisture. This case may apply when the cycle will exceed 12 to 24 h.
2. The production of several different products requires strict batch identity and thorough cleaning of equipment between batches. This is a situation existing in many small color-pigment-drying plants.
3. The quantity of material to be processed does not justify investment in more expensive, continuous equipment. This case would apply in many pharmaceutical-drying operations.

Further, because of the nature of solids-gas contacting, which is usually by parallel flow and rarely by through circulation, heat transfer and mass transfer are comparatively inefficient. For this reason, use of tray and compartment equipment is restricted primarily to ordinary drying and heat-treating operations. Despite these harsh limitations, when the listed situations do exist, economical alternatives are difficult to develop.

**Auxiliary Equipment** If noxious gases, fumes, or dust are given off during the operation, dust- or fume-recovery equipment will be necessary in the exhaust-gas system. Wet scrubbers are employed for the recovery of valuable solvents from dryers. In order to minimize heat losses, thorough insulation of the compartment with brick, asbestos, or other insulating compounds is necessary. Modern fabricated dryer-compartment panels usually have 7.5 to 15 cm of blanket insulation placed between the internal and external sheet-metal walls. Doors and other access openings should be gasketed and tight. In the case of tray and truck equipment, it is usually desirable to have available extra trays and trucks so that they can be preloaded for rapid emptying and loading of the compartment between cycles. Air filters and gas dryers are occasionally employed on the inlet-air system for direct-heat units.

Vacuum-shelf dryers require auxiliary stream jets or other vacuum-producing devices, intercondensers for vapor removal, and occasionally wet scrubbers or (heated) bag-type dust collectors.

Uniform depth of loading in dryers and furnaces handling particulate solids is essential to consistent operation, minimum heating cycles, or control of final moisture. After a tray has been loaded, the bed should be leveled to a uniform depth. Special preform devices, noodle extruders, pelletizers, etc., are employed occasionally for preparing pastes and filter cakes so that screen bottom trays can be used and the advantages of through circulation approached.

Control of tray and compartment equipment is usually maintained by control of the circulating-air temperature (and humidity) and rarely by solids temperature. On vacuum units, control of the absolute pressure and heating-medium temperature is utilized. In direct dryers, cycle controllers are frequently employed to vary the air temperature or velocity across the solids during the cycle, e.g., high air temperatures may be employed during a constant-rate drying period while the solids surface remains close to the air wet-bulb temperature. During the falling-rate periods, this temperature may be reduced to prevent casehardening or other degrading effects caused by overheating the solids surfaces. In addition, higher air velocities may be employed during early drying stages to improve heat transfer; however, after surface drying has been completed, this velocity may need to be reduced to prevent dusting. Two-speed circulating fans are employed commonly for this purpose.

**Direct-Heat Tray Dryers** Satisfactory operation of tray-type dryers depends on maintaining a constant temperature and a uniform air velocity over all the material being dried.

Circulation of air at velocities of 1 to 10 m/s is desirable to improve the surface heat-transfer coefficient and to eliminate stagnant air pockets. Proper air flow in tray dryers depends on sufficient fan capacity, on the design of ductwork to modify sudden changes in direction, and on properly placed baffles. *Nonuniform air flow is one of the most serious problems in the operation of tray dryers.*

Tray dryers may be of the tray-truck or the stationary-tray type. In the former, the trays are loaded on trucks which are pushed into the dryer; in the latter, the trays are loaded directly into stationary racks within the dryer. Trucks may be fitted with flanged wheels to run on tracks or with flat swivel wheels. They may also be suspended from and moved on monorails. Trucks usually contain two tiers of trays, with 18 to 48 trays per tier, depending upon the tray dimensions.

Trays may be square or rectangular, with 0.5 to 1 $m^2$ per tray, and may be fabricated from any material compatible with corrosion and temperature conditions. When the trays are stacked in the truck, there should be a clearance of not less than 4 cm between the material in one tray and the bottom of the tray immediately above. When material characteristics and handling permit, the trays should have screen bottoms for additional drying area. Metal trays are preferable to nonmetallic trays, since they conduct heat more readily. Tray loadings range usually from 1 to 10 cm deep.

Steam is the usual heating medium, and a standard heater arrangement consists of a main heater before the circulating fan. When steam is not available or the drying load is small, electrical heat can be used. For temperatures above 450 K, products of combustion can be used, or indirect-fired air heaters.

Air is circulated by propeller or centrifugal fans; the fan is usually mounted within or directly above the dryer. Above 450 K, external or water-cooled bearings become necessary. Total pressure drop through the trays, heaters, and ductwork is usually in the range of 2.5 to 5 cm of water. Air recirculation is generally in the order of 80 to 95 percent except during the initial drying stage of rapid evaporation. Fresh air is drawn in by the circulating fan, frequently through dust filters. In most installations, air is exhausted by a separate small exhaust fan with a damper to control air-recirculation rates.

***Prediction of Heat- and Mass-Transfer Coefficients in Direct-Heat Tray Dryers*** In convection phenomena, heat-transfer coefficients depend on the geometry of the system, the gas velocity past the evaporating surface, and the physical properties of the drying gas. In estimating drying rates, the use of heat-transfer coefficients is preferred because they are usually more reliable than mass-transfer coefficients. In calculating mass-transfer coefficients from drying experiments; the partial pressure at the surface is usually inferred from the measured or calculated temperature of the evaporating surface. Small errors in temperature have negligible effect on the heat-transfer coefficient but introduce relatively large errors in the partial pressure and hence in the mass-transfer coefficient.

For many cases in drying, the heat-transfer coefficient can be expressed as

$$h_c = \alpha G^n / D_c p \qquad (12\text{-}41)$$

where $h_c$ = heat-transfer coefficient, $J/(m^2 \cdot s \cdot K)[Btu/(h \cdot ft^2 \cdot °F)]$; $G$ = mass velocity of drying gas, $kg/(s \cdot m^2)[lb/(h \cdot ft^2)]$; $D_c$ = characteristic dimension of the system, m; and $\alpha$, $n$, and $p$ are empirical constants. When radiation and conduction effects are negligible, the constant rate of drying from a surface is thus given by the following heat-transfer expression derived from Eqs. (12-26) and (12-41):

$$dw/d\theta = (\alpha G^n A/\lambda D_c^m)(t - t'_s) \qquad (12\text{-}42)$$

When the liquid is water and the drying gas is air, $t'_s$ is the wet-bulb temperature.

In order to estimate drying rates from Eq. (12-42) values of the empirical constants are required for the particular geometry under consideration. For flow parallel to plane plates, exponent $n$ has been reported to range from 0.35 to 0.8 [Chu, Lane, and Conklin, *Ind. Eng. Chem.*, **45,** 1856 (1953); Wenzel and White, *Ind. Eng. Chem.*, **51,** 275 (1958)]. The differences in exponent have been attributed to differences in flow pattern in the space above the evaporating surface. In the absence of applicable specific data, the heat-transfer coefficient for the parallel-flow case can be taken, for estimating purposes, as

$$h = 8.8G^{0.8}/D_e^{0.2} \qquad (12\text{-}43)$$

where the experimental data have been weighted in favor of an exponent of 0.8 in conformity with the usual Colburn $j$ factor and average values of the properties of air at 370 K have been incorporated.

Experimental data for drying from flat surfaces have been correlated by using the equivalent diameter of the flow channel or the length of the evaporating surface as the characteristic length dimension in the Reynolds number. However, the validity of one versus the other has not been established. The proper equivalent diameter probably depends at least on the geometry of the system, the roughness of the surface, and the flow conditions upstream of the evaporating surface. For most tray-drying calculations, the equivalent diameter (4 times the cross-sectional area divided by the perimeter of the flow channel) should be used.

For air flow impinging normally to the surface from slots, nozzles, or perforated plates, the heat-transfer coefficient can be obtained from the data of Friedman and Mueller (*Proceedings of the General Discussion on Heat Transfer,* Institution of Mechanical Engineers, London, and American Society of Mechanical Engineers, New York, 1951, pp. 138–142). These investigators give

$$h_c = \alpha G^{0.78} \qquad (12\text{-}44)$$

where the gas mass velocity $G$ is based on the total heat-transfer area and $\alpha$ is dependent on the plate open area, hole or slot size, and spacing between the plate, nozzle, or slot and the heat-transfer surface.

Most efficient performance is obtained with plates having open areas equal to 2 to 3 percent of the total heat-transfer area. The plate should be located at a distance equal to four to six hole (or equivalent) diameters from the heat-transfer surface.

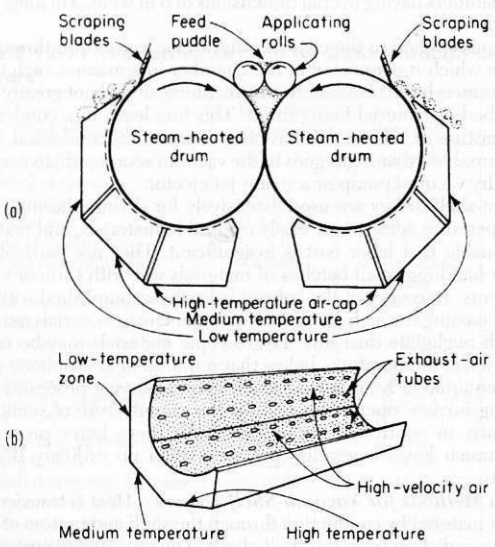



**FIG. 12-46** Example of the use of air impingement in drying as a secondary heat source on a double-drum dryer. [Chem. Eng., *197, (June 19, 1967).*]

Data from tests employing multiple slots, with a correction calculated for slot width, were reported by Korger and Kizek [*Int. J. Heat Mass Transfer,* London, **9,** 337 (1966)].

Air impingement is commonly employed for drying sheets, film, thin slabs, and coatings. Another application in which it is used is as a secondary heat source on drum and can dryers (see Fig. 12-46).

***Determination of the Temperature of the Evaporating Surface in Direct-Heat Tray Dryers*** When radiation and conduction are negligible, the temperature of the evaporating surface approaches the wet-bulb temperature and is readily obtained from the humidity and dry-bulb temperature. Frequently, however, radiation and conduction cause the temperature of the evaporating surface to exceed the wet-bulb temperature. When this occurs, the true surface temperature must be estimated.

Under steady-state conditions the temperature of the evaporating surface increases until the rate of sensible heat transfer to the surface equals the rate of heat removed by evaporation from the surface. To calculate this temperature, it is convenient to modify Eq. (12-26) in terms of humidity rather than partial-pressure difference, as follows:

$$k_g(p_s - p) = k'(H_s - H) \qquad (12\text{-}45)$$

where $k'$ = mass-transfer coefficient, kg/(s·m²)(unit humidity difference), and $k' = pk_g(M_a/M_w)$ is a suitable approximation at low humidities; $k_g$ = mass-transfer coefficient, kg/(s·m²·atm); $M_a$ = molecular weight of air; $M_w$ = molecular weight of the diffusing vapor; $p_s$ = vapor pressure of the liquid at the temperature of the evaporating surface, atm; $p$ = partial pressure of vapor in air, atm; $H_s$ = saturation humidity of the air at the temperature of the drying surface, kg/kg dry air; $H$ = humidity of the drying air, kg/kg dry air; and $p$ = total pressure, atm. For air-water mixtures $k'$ is approximately 1.6 $k_g$ at atmospheric pressure.

A rate balance between evaporation and heat transfer when radiation occurs may be modified by means of the psychrometric ratio for air-water vapor mixtures to give:

$$\frac{\lambda}{C_s}(H_s - H) = (t - t'_s) + \frac{h_r \epsilon}{h_c}(t_r - t'_s) \qquad (12\text{-}46)$$

where $\lambda$ = latent heat of evaporation, J/kg at $t'_s$; $C_s = h_c/k'$, where $h_c$ = convection heat-transfer coefficient, J/(s·m²·K), and $C_s$ = heat capacity of humid air, J/(kg dry air·K), as defined in the subsection "Application of Psychrometry to Drying"; $t$ = temperature of drying gases, K; $t'_s$ = temperature of the wet surface, K; $h_r$ = radiation heat-transfer coefficient, J/(s·m²·K); $h_c$ = convection heat-transfer coefficient, J/(s·m²·K); $t_r$ = temperature of source radiating heat to the wet surface, K; and $\epsilon$ = emissivity of surface receiving radiation.

Equation (12-46) may be solved by trial and error or graphically to estimate the true values of $H_s$ and $t'_s$ and, hence, the actual drying rate. The values of $\lambda$ and $h_r$ depend on the value of $t'_s$ but can generally be considered constant over the range of temperatures usually encountered in air drying.

Frequently, particularly in tray drying, heat arrives at the evaporating surface from the tray walls by conduction through the wet material. For this case, in which both radiation and conduction are significant, the total heat-transfer coefficient is given by Shepherd, Brewer, and Hadlock [*Ind. Eng. Chem.*, **30,** 388 (1938)] as

$$h_t = (h_c + h_r)\left[1 + \frac{A_u}{1 + d(h_c + h_r)/k}\right] \qquad (12\text{-}47)$$

where $h_t$ = total heat-transfer coefficient, J/(s·m²·K); $A_u$ = ratio of outside unwetted surface to evaporating surface area; $d$ = depth of material in tray, m; and $k$ = thermal conductivity of the wet material, J/[(s·m²)(K/m)]. Note that $h_c$ must be corrected for emissivity of the surface. For insulated trays, the arithmetic average of inside and outside unwetted area should be used.

Equation (12-47) assumes that all heat sources are at the same temperature and that the convection coefficients to the evaporating surface and to the unwetted portions of the tray are equal. When radiation occurs from a source at a different temperature, the radiation coefficient can be corrected to the same basis by multiplying by the ratio $(t - t'_s)/(t_r - t'_s)$, where $t$, $t'_s$, and $t_r$ are the drying-gas, evaporating-surface, and radiator temperatures respectively.

A relationship for estimating the surface temperature $t'_s$, based on the use of Eq. (12-47) to determine $h_t$, is as follows:

$$(H_s - H) = (h_t C_s / \lambda h_c)(t - t'_s) \qquad (12\text{-}48)$$

Equation (12-48) can be solved numerically or graphically. Figure 12-47 indicates how $H_s$ and $t'_s$ may be determined graphically on a humidity chart by the point of intersection on the saturation-humidity curve of a straight line of slope $h_t C_s / \lambda h_c$ passing through point $(H_s, t_s)$.

***Performance Data for Direct-Heat Tray Dryers*** A standard two-truck dryer is illustrated in Fig. 12-48. Adjustable baffles or a perforated distribution plate is normally employed to develop 0.3 to 1.3 cm of water-pressure drop at the wall through which air enters the truck enclosure. This will enhance the uniformity of air distribution, from top to bottom, among the trays. In three (or more) truck ovens, air-reheat coils may be placed between trucks if the evaporative load is high. Means for reversing air-flow direction may also be provided in multiple-truck units.

Performance data on some typical tray and compartment dryers are tabulated in Table 12-10. These indicate that an overall rate of evaporation of 0.0025 to 0.025 kg water/(s·m$^2$) of tray area may be expected from tray and tray-truck dryers. The thermal efficiency of this type of dryer will vary from 20 to 50 percent, depending on the drying temperature used and the humidity of the exhaust air. In drying to very low moisture contents under temperature restrictions, the thermal efficiency may be in the order of 10 percent. The major operating cost for a tray dryer is the labor involved in loading and unloading the trays. About two labor-hours are required to load and unload a standard two-truck tray dryer. In addition, about one-third to one-fifth of a worker's time is required to supervise the dryer during the drying period. Power for tray and compartment dryers will be approximately 1.1 kW per truck in the dryer. Maintenance will run from 3 to 5 percent of the installed cost per year.

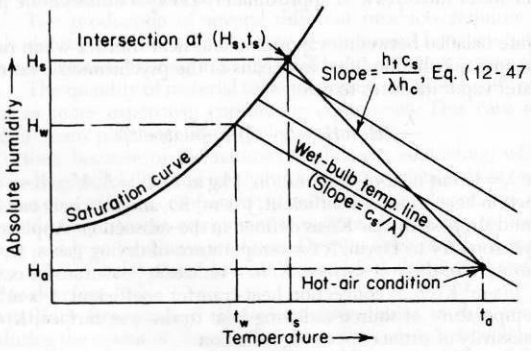



**FIG. 12-47** Graphical estimation of surface temperature during constant-rate period.

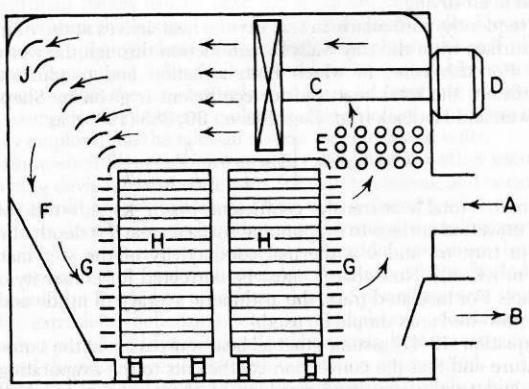



**FIG. 12-48** Double-truck dryer. (*A*) Air-inlet duct. (*B*) Air-exhaust duct with damper. (*C*) Adjustable-pitch fan 1 to 15 hp. (*D*) Fan motor. (*E*) Fin heaters. (*F*) Plenum chamber. (*G*) Adjustable air-blast nozzles. (*H*) Trucks and trays. (*J*) Turning vanes.

## BATCH THROUGH-CIRCULATION DRYERS

In one type of batch through-circulation dryer, heated air passes through a stationary permeable bed of the wet material placed on removable screen-bottom trays suitably supported in the dryer. This type is similar to a standard tray dryer except that hot air passes through the wet solid instead of across it. The pressure drop through the bed of material does not usually exceed about 2 cm of water. In another type, deep perforated-bottom trays are placed on top of plenum chambers in a closed-circuit hot-air-circulating system. In some food-drying plants, the material is placed in finishing bins with perforated bottoms; heated air passes up through the material and is removed from the top of the bin, reheated, and recirculated. The latter types involve a pressure drop through the bed of material of 1 to 8 cm of water at relatively low air rates. Table 12-11 gives performance data on three applications of batch through-circulation dryers. Batch through-circulation dryers are restricted in application to granular materials that permit free flow-through circulation of air. Drying times are usually much shorter than in parallel-flow tray dryers. Design methods are included in the subsection "Continuous Through-Circulation Dryers."

**Vacuum-Shelf Dryers** Vacuum-shelf dryers are indirect-heated batch dryers consisting of a vacuumtight chamber usually constructed of cast iron or steel plate, heated, supporting shelves within the chamber, a vacuum source, and usually a condenser. One or two doors are provided, depending on the size of the chamber. The doors are sealed with resilient gaskets of rubber or similar material (Fig. 12-49).

Hollow shelves of flat steel plate are fastened permanently inside the vacuum chamber and are connected in parallel to inlet and outlet headers. The heating medium, entering through one header and passing through the hollow shelves to the exit header, is generally steam, ranging in pressure from 700 kPa gauge to subatmospheric pressure for low-temperature operations. Low temperatures can be provided by circulating hot water, and high temperatures can be obtained by circulating hot oil or Dowtherm. Some small dryers employ electrically heated shelves. The material to be dried is placed in pans or trays on the heated shelves. The trays are generally of metal to ensure good heat transfer between the shelf and the tray.

Vacuum-shelf dryers may vary in size from 1 to 24 shelves, the largest chambers having overall dimensions of 6 m wide, 3 m long, and 2.5 m high.

Vacuum is applied to the chamber and vapor is removed through a large pipe which is connected to the chamber in a manner such that, if the vacuum is broken suddenly, the inrushing air will not greatly disturb the bed of material being dried. This line leads to a condenser where moisture or solvent that has been vaporized is condensed. The noncondensable exhaust gas goes to the vacuum source, which may be a wet or dry vacuum pump or a steam-jet ejector.

Vacuum-shelf dryers are used extensively for drying pharmaceuticals, temperature-sensitive or easily oxidizable materials, and materials so valuable that labor cost is insignificant. They are particularly useful for handling small batches of materials wet with toxic or valuable solvents. Recovery of the solvent is easily accomplished without danger of passing through an explosive range. Dusty materials may be dried with negligible dust loss. Hygroscopic materials may be completely dried at temperatures below that required in atmospheric dryers. The equipment is employed also for freeze-drying processes, for metallizing-furnace operations, and for the manufacture of semiconductor parts in controlled atmospheres. All these latter processes demand much lower operating pressures than do ordinary drying operations.

***Design Methods for Vacuum-Shelf Dryers*** Heat is transferred to the wet material by conduction through the shelf and bottom of the tray and by radiation from the shelf above. The critical moisture content will not be necessarily the same as for atmospheric tray drying [Ernst, Ridgway, and Tiller, *Ind. Eng. Chem.*, **30,** 1122 (1938)].

**TABLE 12-10 Manufacturer's Performance Data for Tray and Tray-Truck Dryers***

| Material | Color | Chrome yellow | Toluidine red | Half-finished Titone | Color |
|---|---|---|---|---|---|
| Type of dryer | 2-truck | 16-tray dryer | 16-tray | 3-truck | 2-truck |
| Capacity, kg product/h | 11.2 | 16.1 | 1.9 | 56.7 | 4.8 |
| Number of trays | 80 | 16 | 16 | 180 | 120 |
| Tray spacing, cm | 10 | 10 | 10 | 7.5 | 9 |
| Tray size, cm | 60 × 75 × 4 | 65 × 100 × 2.2 | 65 × 100 × 2 | 60 × 70 × 3.8 | 60 × 70 × 2.5 |
| Depth of loading, cm | 2.5 to 5 | 3 | 3.5 | 3 | |
| Initial moisture, % bone-dry basis | 207 | 46 | 220 | 223 | 116 |
| Final moisture, % bone-dry basis | 4.5 | 0.25 | 0.1 | 25 | 0.5 |
| Air temperature, °C | 85–74 | 100 | 50 | 95 | 99 |
| Loading, kg product/m² | 10.0 | 33.7 | 7.8 | 14.9 | 9.28 |
| Drying time, h | 33 | 21 | 41 | 20 | 96 |
| Air velocity, m/s | 1.0 | 2.3 | 2.3 | 3.0 | 2.5 |
| Drying, kg water evaporated/(h·m²) | 0.59 | 65 | 0.41 | 1.17 | 0.11 |
| Steam consumption, kg/kg water evaporated | 2.5 | 3.0 | — | 2.75 | |
| Total installed power, kW | 1.5 | 0.75 | 0.75 | 2.25 | 1.5 |

*Courtesy of Proctor & Schwartz, Inc.

During the constant-rate period, moisture is rapidly removed. Often 50 percent of the moisture will evaporate in the first hour of a 6- to 8-h cycle. The drying time has been found to be proportional to between the first and second power of the depth of loading. Shelf vacuum dryers operate in the range of 1 to 25 mmHg pressure. For size-estimating purposes, a heat-transfer coefficient of 20 J/(m²·s·K) may be used. The area employed in this case should be the shelf area in direct contact with the trays. Trays should be maintained as flatly as possible to obtain maximum area of contact with the heated shelves. For the same reason, the shelves should be kept free from scale and rust. Air vents should be installed on steam-heated shelves to vent noncondensable gases. The heating medium should not be applied to the shelves until after the air has been evacuated from the chamber in order to reduce the possibility of the material's overheating or boiling at the start of drying. Casehardening can sometimes be avoided by retarding the rate of drying in the early part of the cycle.

***Performance Data for Vacuum-Shelf Dryers*** The purchase price of a vacuum-shelf dryer depends upon the cabinet size and number of shelves per cabinet. For estimating purposes, typical prices (1985) and auxiliary-equipment requirements are given in Table 12-12. Installed cost of the equipment will be roughly 100 percent of the carbon steel purchase cost.

The thermal efficiency of a vacuum-shelf dryer is usually on the order of 60 to 60 percent. Table 12-13 gives operating data for one organic color and two inorganic compounds. Labor may constitute 50 percent of the operating cost; maintenance, 20 percent. Annual maintenance costs amount to 5 to 10 percent of the total installed cost. Actual labor costs will depend on drying time, facilities for loading and unloading trays, etc. The power required for these dryers is only that for the vacuum system; for vacuums of 680 to 735 mmHg the power requirements are in the order of 0.06 to 0.12 kW/m² tray surface.

**TABLE 12-11 Performance Data for Batch Through-Circulation Dryers***

| Kind of material | Granular polymer | Vegetable | Vegetable seeds |
|---|---|---|---|
| Capacity, kg product/h | 122 | 42.5 | 27.7 |
| Number of trays | 16 | 24 | 24 |
| Tray spacing, cm | 43 | 43 | 43 |
| Tray size, cm | 91.4 × 104 | 91.4 × 104 | 85 × 98 |
| Depth of loading, cm | 7.0 | 6 | 4 |
| Physical form of product | Crumbs | 0.6-cm diced cubes | Washed seeds |
| Initial moisture content, % dry basis | 11.1 | 669.0 | 100.0 |
| Final moisture content, % dry basis | 0.1 | 5.0 | 9.9 |
| Air temperature, °C | 88 | 77 dry-bulb | 36 |
| Air velocity, superficial, m/s | 1.0 | 0.6 to 1.0 | 1.0 |
| Tray loading, kg product/m² | 16.1 | 5.2 | 6.7 |
| Drying time, h | 2.0 | 8.5 | 5.5 |
| Overall drying rate, kg water evaporated/(h·m²) | 0.89 | 11.86 | 1.14 |
| Steam consumption, kg/kg water evaporated | 4.0 | 2.42 | 6.8 |
| Installed power, kW | 7.5 | 19 | 19 |

*Courtesy of Proctor & Schwartz, Inc.

**Batch Furnaces, Other Furnace Types, and Kilns** Batch furnaces are employed mainly for the heat treating of metals, such as annealing, normalizing, and "drawing" (tempering), and for the drying and calcination of ceramic articles. Many specialized furnaces have been designed for these purposes and may be either batch or continuous in operation. Batch furnaces are used in chemical processing for the same purposes as batch tray and truck dryers, when the drying or process temperature exceeds that which can be tolerated by unlined metal walls; ordinary tray and truck dryers are rarely employed when the circulating-gas temperature will exceed 600 to 700 K. They are employed for small-batch calcination, thermal decompositions, and other chemical reactions; these are the same as those reactions performed on a larger scale in rotary kilns, hearth furnaces, and shaft furnaces.

Design procedures and information on heat release in furnaces are given in Sec. 11. Tables indicating normal operating temperatures in various heating furnaces and the more common process furnaces are also included. Specialized designs of batch furnaces are shown in Figs. 12-50 to 12-53 and are described briefly in the following paragraphs. All may be heated by gas, oil, or electricity. **Standard oven furnaces** are similar in design to the small muffle furnace depicted in Fig. 12-53, but with the muffle housing eliminated.

**Forced-convection pit furnaces** are employed for heat-treating small metal parts in bulk. Small pieces are suspended in a mesh-bottom basket, while larger pieces are placed on racks. Air heating is by means of Nichrome electric coils set in refractory walls around the periphery of the pit. A high-velocity fan beneath the basket circulates heated air up past the coils and then down through the basket. Some heat is radiated to the outer basket shell, but most is transferred by direct convection from the circulating gas to the solids.

**Car-bottom furnaces** differ from standard types in that the charge is placed upon movable cars for running into the furnace enclosure. The top of the car is refractory-lined and forms the furnace hearth. The top only is exposed to heat, the lower metal structure being protected by the hearth brick, sand, and water seals at the sides and ends and by the circulation of cooling air around the car structure below the hearth. For use where floor space is limited **elevator furnaces** serve similar purposes.

The **rotary-hearth furnace** consists of a heating chamber lined with refractory brick within which is an annular-shaped refractory-lined rotating hearth. Around the periphery of the rotating hearth, sand or circulating liquid seals are employed to prevent air infiltration. It can be made semicontinuous in operation. The hearth speed can be

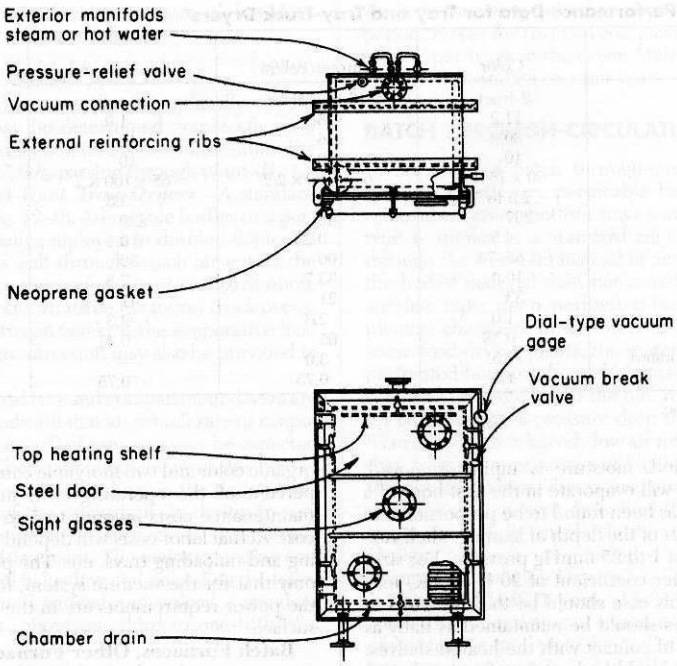



**FIG. 12-49** Vacuum-shelf dryer. (*Stokes Equipment Division, Pennwalt Corp.*)

**TABLE 12-12 Standard Vacuum-Shelf Dryers***

| Shelf area, $m^2$ | Floor space, $m^2$ | Weight average, kg | Pump capacity, $m^3/s$ | Pump motor, kW | Condenser area, $m^2$ | Price/$m^2$ (1995) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Carbon steel | 304 stainless steel |
| 0.4–1.1 | 4.5 | 540 | 0.024 | 1.12 | 1 | $110 | $170 |
| 1.1–2.2 | 4.5 | 680 | 0.024 | 1.12 | 1 | 75 | 110 |
| 2.2–5.0 | 4.6 | 1130 | 0.038 | 1.49 | 4 | 45 | 65 |
| 5.0–6.7 | 5.0 | 1630 | 0.038 | 1.49 | 4 | 36 | 65 |
| 6.7–14.9 | 6.4 | 3900 | 0.071 | 2.24 | 9 | 27 | 45 |
| 16.7–21.1 | 6.9 | 5220 | 0.071 | 2.24 | 9 | 22 | 36 |

*Stokes Vacuum, Inc.

varied to meet changing requirements in size, weight, and load of the charge. For gas and oil heating, the burners fire from the sides of the chamber, tangentially to the hearth.

Standard furnaces are usually direct-heated, in that the burner combustion gases circulate directly over the charge; occasionally the flame may be permitted to impinge on the charge. For bright annealing, tool hardening, powdered-metal sintering, and other work requiring protection of the charge by special atmospheres, **muffle-type furnaces** are frequently employed. In these, the charge is separated from the burners and combustion gases by a refractory arch. Heat is transferred by hot-gas radiation and convection to the arch and by radiation from the arch to the charge.

When used for **ceramic heating,** furnaces are called kilns. Operations include drying, oxidation, calcination, and vitrification. These kilns employ horizontal space burners with gaseous, liquid, or solid fuels. If product quality is not injured, ceramic ware may be exposed to flame and combustion gases; otherwise, muffle kilns are employed. Dutch ovens are used frequently for heat generation.

**Downdraft kilns** are the most common type, being used for brick, pipe, tile, and stoneware. The name is derived from the direction of combustion-gas flow when contacting the charge. The gases then flow up inside the walls to the top of the kiln and chimney. **Updraft kilns** are similar except in direction of gas flow, which is upward past the charge. They are employed commonly for pottery burning. **Stove kilns** are variations of updraft kilns used for burning common brick. The kiln is built of green brick and covered with a layer of burned brick. It is completely dismantled after each burning. **Clamp kilns** are another variation of updraft kilns used for common brick and temporary in nature. They have no tops or flue systems but consist only of sidewalls with arched spaces for combustion.

**TABLE 12-13 Performance Data of Vacuum-Shelf Dryers**

| Material | Sulfur black | Calcium carbonate | Calcium phosphate |
|---|---|---|---|
| Loading, kg dry material/$m^2$ | 25 | 17 | 33 |
| Steam pressure, kPa gauge | 410 | 410 | 205 |
| Vacuum, mmHg | 685–710 | 685–710 | 685–710 |
| Initial moisture content, % (wet basis) | 50 | 50.3 | 30.6 |
| Final moisture content, % (wet basis) | 1 | 1.15 | 4.3 |
| Drying time, h | 8 | 7 | 6 |
| Evaporation rate, kg/($s \cdot m^2$) | $8.9 \times 10^{-4}$ | $7.9 \times 10^{-4}$ | $6.6 \times 10^{-4}$ |

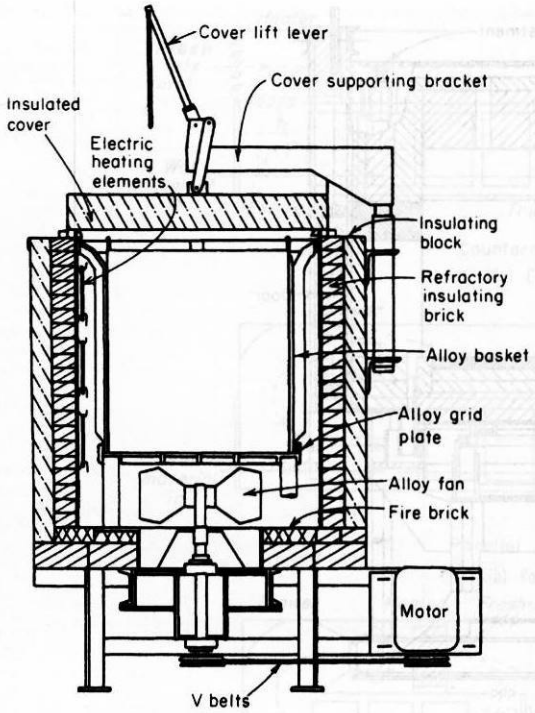



**FIG. 12-50** Pit furnace. (*W. S. Rockwell Co.*)

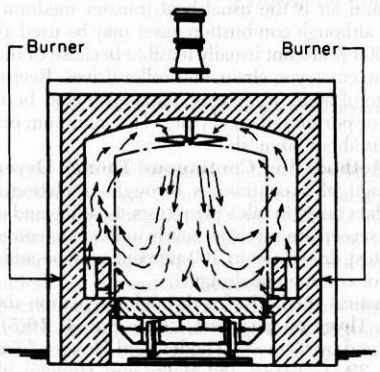



**FIG. 12-51** Car-bottom furnace. (*W. S. Rockwell Co.*)

## CONTINUOUS TUNNEL DRYERS

Continuous tunnels are in many cases **batch truck** or **tray compartments, operated in series.** The solids to be processed are placed in trays or on trucks which move progressively through the tunnel in contact with hot gases. Operation is **semicontinuous;** when the tunnel is filled, one truck is removed from the discharge end as each new truck is fed into the inlet end. In some cases, the trucks move on tracks or monorails, and they are usually conveyed mechanically, employing chain drives connecting to the bottom of each truck. Schematic diagrams of three typical tunnel arrangements are shown in Fig. 12-54. **Belt-conveyor and screen-conveyor tunnels are truly continuous** in operation, carrying a layer of solids on an endless conveyor.

Air flow can be totally **cocurrent, countercurrent,** or a combination of both as shown in Fig. 12-54. In addition, **cross-flow** designs are employed frequently, with the heating air flowing back and forth across the trucks in series. Reheat coils may be installed after each cross-flow pass to maintain constant-temperature operation; large propeller-type circulating fans are installed at each stage, and air may be introduced or exhausted at any desirable points. Tunnel equipment possesses maximum flexibility for any combination of air flow and temperature staging. When handling granular, particulate solids which do not offer high resistance to air flow, perforated or screen-type belt conveyors are employed with **through circulation** of gas to improve heat- and mass-transfer rates.

In tunnel equipment, the solids are usually heated by direct contact with hot gases. In high-temperature operations, radiation from walls and refractory lining may be significant also. The air in a direct-heat unit may be heated directly or indirectly by combustion or, at temperature below 475 K, by finned steam coils.

Applications of tunnel equipment are essentially the same as for batch tray and compartment units previously described, namely, practically all forms of particulate solids and large solid objects. In operation, they are more suitable for large-quantity production, usually representing investment and installation savings over (multiple) batch compartments. In the case of truck and tray tunnels, labor savings for loading and unloading are not significant compared with batch equipment. Belt and screen conveyors which are truly continuous represent major labor savings over batch operations but require additional investment for automatic feeding and unloading devices.

Auxiliary equipment and the special design considerations discussed for batch trays and compartments apply also to tunnel equipment. For size-estimating purposes, tray and truck tunnels and furnaces can be treated in the same manner as discussed for batch equipment.

**Continuous Through-Circulation Dryers** Continuous through-circulation dryers operate on the principle of blowing hot air through a permeable bed of wet material passing continuously through the dryer. Dryer rates are high because of the large area of contact and short distance of travel for the internal moisture.

The most widely used type is the **horizontal conveying-screen dryer** in which wet material is conveyed as a layer, 2 to 15 cm deep, on a horizontal mesh screen or perforated apron, while heated air is blown either upward or downward through the bed of material. Its drying characteristics were studied by Marshall and Hougen [*Trans. Am. Inst. Chem. Eng.*, **38,** 91 (1942)]. This dryer consists usually of a number of individual sections, complete with fan and heating coils, arranged in series to form a housing or tunnel through which the conveying screen travels. As shown in the sectional view in Fig. 12-55, the air circulates through the wet material and is reheated before reentering the bed. It is not uncommon to circulate the hot gas upward in the wet end and downward in the dry end. A portion of the air is exhausted continuously by one or two exhaust fans, not shown in the sketch, which handle air from several sections. Since each section can be operated independently, extremely flexible operation is possible, with high temperatures usually at the wet end, followed by lower temperatures; in some cases a unit with cooled or specially humidified air is employed for final conditioning. The **maximum pressure drop** that can be taken through the bed of solids without developing leaks or air bypassing is roughly 50 mm of water.

Through-circulation drying requires that the wet material be in a state of granular or pelleted subdivision so that hot air may be readily blown through it. Many materials meet this requirement without special preparation. Others require special and often elaborate pretreatment to render them suitable for through-circulation drying. The process of converting a wet solid into a form suitable for through circulation of air is called **preforming,** and often the success or failure of this contacting method depends on the preforming step. Fibrous, flaky, and coarse granular materials are usually amenable to drying without preforming. They can be loaded directly onto the conveying screen by suitable spreading feeders of the oscillating-belt or vibrating type or by spiked drums or belts feeding from bins. When materials must be preformed, several methods are available, depending on the physical state of the wet solid.

1. Relatively dry materials such as centrifuge cakes can sometimes be granulated to give a suitably porous bed on the conveying screen.

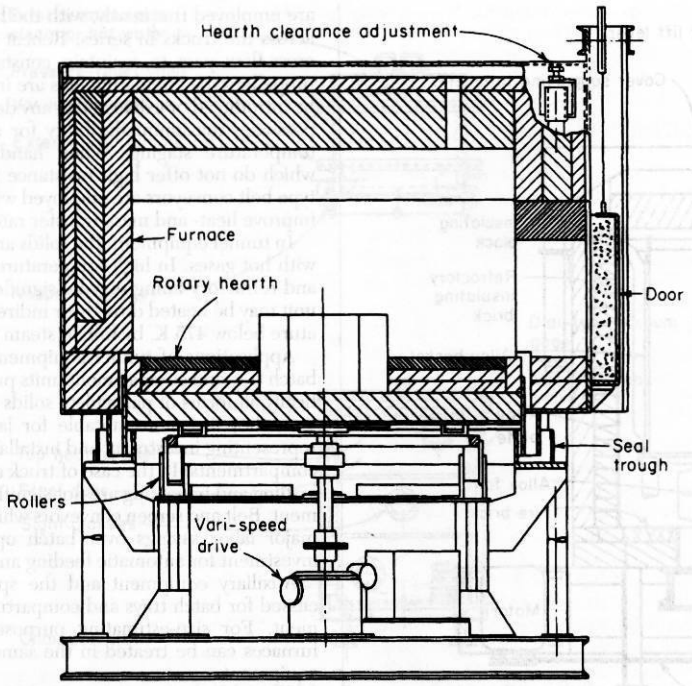



**FIG. 12-52** Rotary-hearth furnace. (*W. S. Rockwell Co.*)

2. Pasty materials can often be preformed by extrusion to form sphaghetti-like pieces, about 6 mm in diameter and several centimeters long.
3. Wet pastes that cannot be granulated or extruded may be predried and preformed on a steam-heated finned drum. Preforming on a finned drum may be desirable also in that some predrying is accomplished.
4. Thixotropic filter cakes from rotary vacuum filters that cannot be preformed by any of the above methods can often be scored by knives on the filter, the scored cake discharging in pieces suitable for through-circulation drying.
5. Material that shrinks markedly during drying is often reloaded during the drying cycle to 2 to 6 times the original loading depth. This is usually done after a degree of shrinkage which, by opening the bed, has destroyed the effectiveness of contact between the air and solids.
6. In a few cases, powders have been pelleted or formed in briquettes to eliminate dustiness and permit drying by through circulation. Table 12-14 gives a list of materials classified by preforming methods suitable for through-circulation drying.

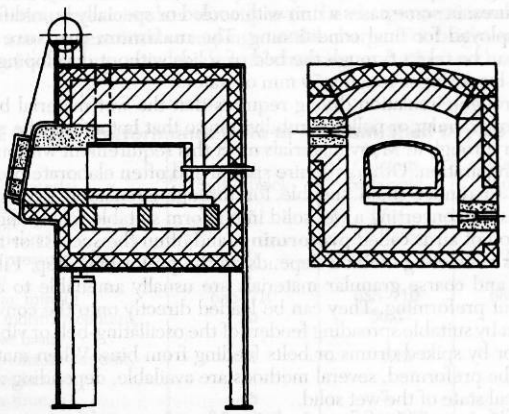


**FIG. 12-53** Small muffle furnace. (*W. S. Rockwell Co.*)

Steam-heated air is the usual heat-transfer medium employed in these dryers, although combustion gases may be used also. Temperatures above 600 K are not usually feasible because of the problems of lubricating the conveyor, chain, and roller drives. Recirculation of air is in the range of 60 to 90 percent. Conveyors may be made of wire-mesh screen or perforated-steel plate. The minimum practical screen opening size is about 30 mesh.

**Design Methods for Continuous Tunnel Dryers** In actual practice, design of a continuous through-circulation dryer is best based upon data taken in pilot-plant tests. Loading and distribution of solids on the screen are rarely as nearly uniform in commercial installations as in test dryers; 50 to 100 percent may be added to the test drying time for commercial design.

A mathematical method of a through-circulation dryer has been developed by Thygeson [*Am. Inst. Chem. Eng. J.*, **16**(5), 749 (1970)]. Results obtained by Gamson, Thodos, and Hougen [*Trans. Am. Inst. Chem. Eng.*, **39,** 1 (1943)] and Wilke and Hougen [ibid., **41,** 444 (1945)] for the rates of adiabatic evaporation of water from packed beds of porous solids are applicable when drying gases flow upward to downward. Use of average additive properties of the drying gas leads to

$$h_c = 0.11 \frac{G^{0.59}}{D_p^{0.41}} \quad \text{for} \quad \frac{D_p G}{\mu} > 350 \tag{12-49}$$

and

$$h_c = 0.15 \frac{G^{0.49}}{D_p^{0.51}} \quad \text{for} \quad \frac{D_p G}{\mu} < 350 \tag{12-50}$$

where $\mu$ = gas viscosity, lb/(ft·h); $D_p$ = diameter of sphere having the same surface area as particle, ft; and $G$ = mass velocity of drying gas, lb/(h·ft$^2$) [to convert from pounds per foot-hour to newtons per second-square meter, multiply by $4.133 \times 10^{-4}$; to convert from feet to meters, multiply by 0.3048; and to convert from pounds per hour-square foot to kilograms per second-square meter, multiply by $1.3562 \times 10^{-3}$].

**Performance and Cost Data for Continuous Tunnel Dryers** Experimental performance data are given in Table 12-15 for numer-

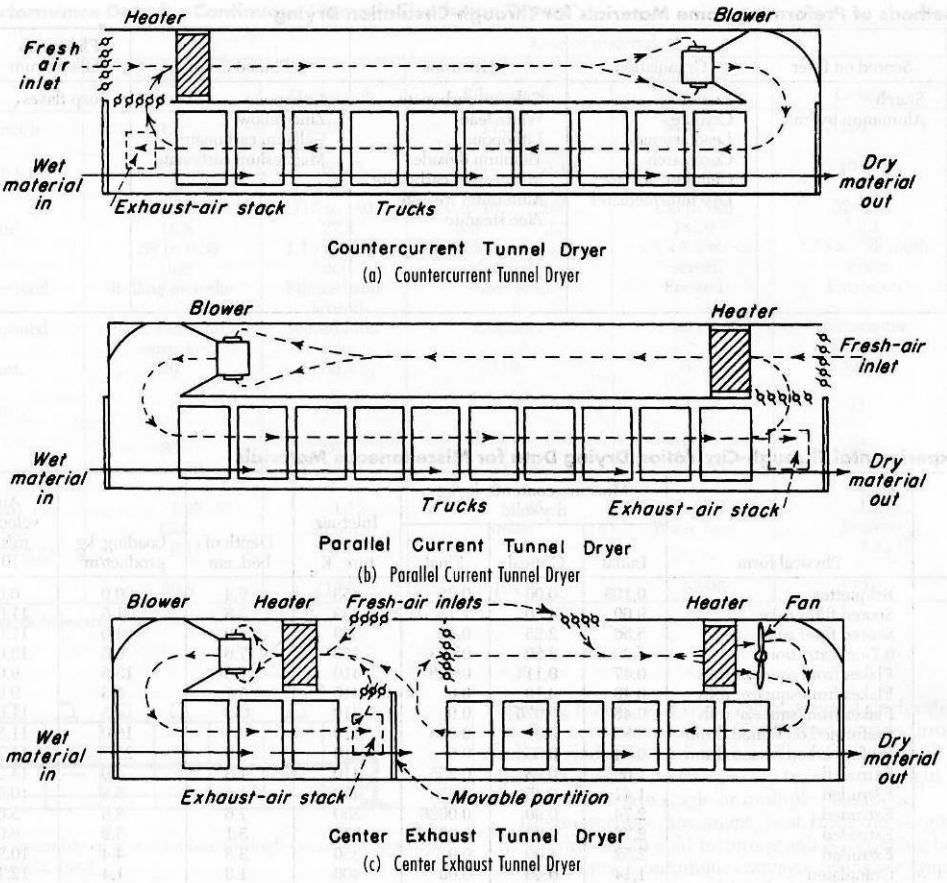



**FIG. 12-54** Three types of tunnel dryers. [*Van Arsdale*, Food Ind. ***14*** *(10), 43 (1942).*]

ous common materials. Performance data from several commercial through-circulation conveyor dryers are given in Table 12-16. Labor requirements vary depending on the time required for feed adjustments, inspection, etc. These dryers will consume from 0.9 to 1.1 kg of steam/kg of water evaporated. Thermal efficiency is a function of final moisture required and percent air recirculation.

Conveying-screen dryers are fabricated with conveyor widths from 0.3- to 4.4-m sections 1.6 to 2.5 m long. Each section consists of a sheet-metal enclosure, insulated sidewalls and roof, heating coils, a circulating fan, inlet-air distributor baffles, a fines catch pan under the conveyor, and a conveyor screeen (Fig. 12-56). Table 12-17 gives approximate purchase costs for equipment with type 304 stainless-steel hinged conveyor screens and includes steam-coil heaters, fans, motors, and a variable-speed conveyor drive. Cabinet- and auxiliary-equipment fabrication is of aluminized steel or stainless-steel materials. Prices do not include temperature controllers, motor starters, preform equipment, or auxiliary feed and discharge conveyors. These may add $55,000 to $135,000 to the dryer purchase cost (1995 costs).

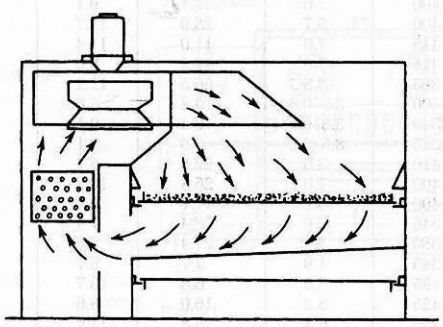


**FIG. 12-55** Section view of a continuous through-circulation conveyor dryer. (*Proctor & Schwartz, Inc.*)

A continuous conveyor dryer employing a combination of air impingement and through circulation is shown in Fig. 12-57.

**Continuous Furnaces** Continuous furnaces are employed for the same general duties cited for batch furnaces. Units are gas, oil, or electrically heated and utilize direct circulation of combustion gases or muffles for heat transfer. Continuous furnaces frequently have an extension added for **cooling** the charge before exposure to atmospheric air.

Conveyors may be of parallel-chain, mat, slat, woven wire-mesh belt, or cast-alloy type. Automatic tensioning devices are used to maintain belt tension during heating and cooling. The product may rest directly on the conveyor or on special supports built into it. Roller-conveyors are used for large pieces. **Flame curtains** are provided for sealing the ends and for protection of special treating atmospheres.

The pusher-type furnace is relatively free from mechanical problems because all mechanical parts are located outside the hot zone. It employs a roller-conveyor usually and will handle charges weighing considerably more per square meter than a belt-conveyor furnace. Pushers are driven by electric motors, compressed air, or hydraulic systems and can be automatically timed and synchronized with door-

**TABLE 12-14 Methods of Preforming Some Materials for Through-Circulation Drying**

| No preforming required | Scored on filter | Granulation | Extrusion | Finned drum | Flaking on chilled drum | Briquetting and squeezing |
|---|---|---|---|---|---|---|
| Cellulose acetate | Starch | Kaolin | Calcium carbonate | Lithopone | Soap flakes | Soda ash |
| Silica gel | Aluminum hydrate | Cryolite | White lead | Zinc yellow | | Cornstarch |
| Scoured wool | | Lead arsenate | Lithopone | Calcium carbonate | | Synthetic rubber |
| Sawdust | | Cornstarch | Titanium dioxide | Magnesium carbonate | | |
| Rayon waste | | Cellulose acetate | Magnesium carbonate | | | |
| Fluorspar | | Dye intermediates | Aluminum stearate | | | |
| Tapioca | | | Zinc stearate | | | |
| Breakfast food | | | | | | |
| Asbestos fiber | | | | | | |
| Cotton linters | | | | | | |
| Rayon staple | | | | | | |

**TABLE 12-15 Experimental Through-Circulation Drying Data for Miscellaneous Materials**

| Material | Physical form | Moisture contents, kg/kg dry solid | | | Inlet-air temperature, K | Depth of bed, cm | Loading, kg product/m$^2$ | Air velocity, m/s × $10^1$ | Experimental drying time, s × $10^{-2}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Critical | Final | | | | | |
| Alumina hydrate | Briquettes | 0.105 | 0.06 | 0.00 | 453 | 6.4 | 60.0 | 6.0 | 18.0 |
| Alumina hydrate | Scored filter cake | 9.60 | 4.50 | 1.15 | 333 | 3.8 | 1.6 | 11.0 | 90.0 |
| Alumina hydrate | Scored filter cake | 5.56 | 2.25 | 0.42 | 333 | 7.0 | 4.6 | 11.0 | 108.0 |
| Aluminum stearate | 0.7-cm extrusions | 4.20 | 2.60 | 0.003 | 350 | 7.6 | 6.5 | 13.0 | 36.0 |
| Asbestos fiber | Flakes from squeeze rolls | 0.47 | 0.11 | 0.008 | 410 | 7.6 | 13.6 | 9.0 | 5.6 |
| Asbestos fiber | Flakes from squeeze rolls | 0.46 | 0.10 | 0.0 | 410 | 5.1 | 6.3 | 9.0 | 3.6 |
| Asbestos fiber | Flakes from squeeze rolls | 0.46 | 0.075 | 0.0 | 410 | 3.8 | 4.5 | 11.0 | 2.7 |
| Calcium carbonate | Preformed on finned drum | 0.85 | 0.30 | 0.003 | 410 | 3.8 | 16.0 | 11.5 | 12.0 |
| Calcium carbonate | Preformed on finned drum | 0.84 | 0.35 | 0.0 | 410 | 8.9 | 25.7 | 11.7 | 18.0 |
| Calcium carbonate | Extruded | 1.69 | 0.98 | 0.255 | 410 | 1.3 | 4.9 | 14.3 | 9.0 |
| Calcium carbonate | Extruded | 1.41 | 0.45 | 0.05 | 410 | 1.9 | 5.8 | 10.2 | 12.0 |
| Calcium stearate | Extruded | 2.74 | 0.90 | 0.0026 | 350 | 7.6 | 8.8 | 5.6 | 57.0 |
| Calcium stearate | Extruded | 2.76 | 0.90 | 0.007 | 350 | 5.1 | 5.9 | 6.0 | 42.0 |
| Calcium stearate | Extruded | 2.52 | 1.00 | 0.0 | 350 | 3.8 | 4.4 | 10.2 | 24.0 |
| Cellulose acetate | Granulated | 1.14 | 0.40 | 0.09 | 400 | 1.3 | 1.4 | 12.7 | 1.8 |
| Cellulose acetate | Granulated | 1.09 | 0.35 | 0.0027 | 400 | 1.9 | 2.7 | 8.6 | 7.2 |
| Cellulose acetate | Granulated | 1.09 | 0.30 | 0.0041 | 400 | 2.5 | 4.1 | 5.6 | 10.8 |
| Cellulose acetate | Granulated | 1.10 | 0.45 | 0.004 | 400 | 3.8 | 6.1 | 5.1 | 18.0 |
| Clay | Granulated | 0.277 | 0.175 | 0.0 | 375 | 7.0 | 46.2 | 10.2 | 19.2 |
| Clay | 1.5-cm extrusions | 0.28 | 0.18 | 0.0 | 375 | 12.7 | 100.0 | 10.7 | 43.8 |
| Cryolite | Granulated | 0.456 | 0.25 | 0.0026 | 380 | 5.1 | 34.2 | 9.1 | 24.0 |
| Fluorspar | Pellets | 0.13 | 0.066 | 0.0 | 425 | 5.1 | 51.4 | 11.6 | 7.8 |
| Lead arsenate | Granulated | 1.23 | 0.45 | 0.043 | 405 | 5.1 | 18.1 | 11.6 | 18.0 |
| Lead arsenate | Granulated | 1.25 | 0.55 | 0.054 | 405 | 6.4 | 22.0 | 10.2 | 24.0 |
| Lead arsenate | Extruded | 1.34 | 0.64 | 0.024 | 405 | 5.1 | 18.1 | 9.4 | 36.0 |
| Lead arsenate | Extruded | 1.31 | 0.60 | 0.0006 | 405 | 8.4 | 26.9 | 9.2 | 42.0 |
| Kaolin | Formed on finned drum | 0.28 | 0.17 | 0.0009 | 375 | 7.6 | 44.0 | 9.2 | 21.0 |
| Kaolin | Formed on finned drum | 0.297 | 0.20 | 0.005 | 375 | 11.4 | 56.3 | 12.2 | 15.0 |
| Kaolin | Extruded | 0.443 | 0.20 | 0.008 | 375 | 7.0 | 45.0 | 10.16 | 18.0 |
| Kaolin | Extruded | 0.36 | 0.14 | 0.0033 | 400 | 9.6 | 40.6 | 15.2 | 12.0 |
| Kaolin | Extruded | 0.36 | 0.21 | 0.0037 | 400 | 19.0 | 80.7 | 10.6 | 30.0 |
| Lithopone (finished) | Extruded | 0.35 | 0.065 | 0.0004 | 408 | 8.2 | 63.6 | 10.2 | 18.0 |
| Lithopone (crude) | Extruded | 0.67 | 0.26 | 0.0007 | 400 | 7.6 | 41.1 | 9.1 | 51.0 |
| Lithopone | Extruded | 0.72 | 0.28 | 0.0013 | 400 | 5.7 | 28.9 | 11.7 | 18.0 |
| Magnesium carbonate | Extruded | 2.57 | 0.87 | 0.001 | 415 | 7.6 | 11.0 | 11.4 | 17.4 |
| Magnesium carbonate | Formed on finned drum | 2.23 | 1.44 | 0.0019 | 418 | 7.6 | 13.2 | 8.6 | 24.0 |
| Mercuric oxide | Extruded | 0.163 | 0.07 | 0.004 | 365 | 3.8 | 66.5 | 11.2 | 24.0 |
| Silica gel | Granular | 4.51 | 1.85 | 0.15 | 400 | 3.8–0.6 | 3.2 | 8.6 | 15.0 |
| Silica gel | Granular | 4.49 | 1.50 | 0.215 | 340 | 3.8–0.6 | 3.4 | 9.1 | 63.0 |
| Silica gel | Granular | 4.50 | 1.60 | 0.218 | 325 | 3.8–0.6 | 3.5 | 9.1 | 66.0 |
| Soda salt | Extruded | 0.36 | 0.24 | 0.008 | 410 | 3.8 | 22.8 | 5.1 | 51.0 |
| Starch (potato) | Scored filter cake | 0.866 | 0.55 | 0.069 | 400 | 7.0 | 26.3 | 10.2 | 27.0 |
| Starch (potato) | Scored filter cake | 0.857 | 0.42 | 0.082 | 400 | 5.1 | 17.7 | 9.4 | 15.0 |
| Starch (corn) | Scored filter cake | 0.776 | 0.48 | 0.084 | 345 | 7.0 | 26.4 | 7.4 | 54.0 |
| Starch (corn) | Scored filter cake | 0.78 | 0.56 | 0.098 | 380 | 7.0 | 27.4 | 7.6 | 24.0 |
| Starch (corn) | Scored filter cake | 0.76 | 0.30 | 0.10 | 345 | 1.9 | 7.7 | 6.7 | 15.0 |
| Titanium dioxide | Extruded | 1.2 | 0.60 | 0.10 | 425 | 3.0 | 6.8 | 13.7 | 6.3 |
| Titanium dioxide | Extruded | 1.07 | 0.65 | 0.29 | 425 | 8.2 | 16.0 | 8.6 | 6.0 |
| White lead | Formed on finned drum | 0.238 | 0.07 | 0.001 | 355 | 6.4 | 76.8 | 11.2 | 30.0 |
| White lead | Extruded | 0.49 | 0.17 | 0.0 | 365 | 3.8 | 33.8 | 10.2 | 27.0 |
| Zinc stearate | Extruded | 4.63 | 1.50 | 0.005 | 360 | 4.4 | 4.2 | 8.6 | 36.0 |

**TABLE 12-16 Performance Data for Continuous Through-Circulation Dryers***

| | Kind of material | | | | | |
|---|---|---|---|---|---|---|
| | Inorganic pigment | Cornstarch | Fiber staple | Charcoal briquettes | Gelatin | Inorganic chemical |
| Capacity, kg dry product/h | 712 | 4536 | 1724 | 5443 | 295 | 862 |
| | | | Stage A, Stage B | | | |
| Approximate dryer area, $m^2$ | 22.11 | 66.42 | 57.04 35.12 | 52.02 | 104.05 | 30.19 |
| Depth of loading, cm | 3 | 4 | | 16 | 5 | 4 |
| Air temperature, °C | 120 | 115 to 140 | 130 to 100 100 | 135 to 120 | 32 to 52 | 121 to 82 |
| Loading, kg product/$m^2$ | 18.8 | 27.3 | 3.5 3.3 | 182.0 | 9.1 | 33 |
| Type of conveyor, mm | 1.59 by 6.35 slots | 1.19 by 4.76 slots | 2.57-diameter holes, perforated plate | 8.5 × 8.5 mesh screen | 4.23 × 4.23 mesh screen | 1.59 × 6.35 slot |
| Preforming method or feed | Rolling extruder | Filtered and scored | Fiber feed | Pressed | Extrusion | Rolling extruder |
| Type and size of preformed particle, mm | 6.35-diameter extrusions | Scored filter cake | Cut fiber | 64 × 51 × 25 | 2-diameter extrusions | 6.35-diameter extrusions |
| Initial moisture content, % bone-dry basis | 120 | 85.2 | 110 | 37.3 | 300 | 111.2 |
| Final moisture content, % bone-dry basis | 0.5 | 13.6 | 9 | 5.3 | 11.1 | 1.0 |
| Drying time, min | 35 | 24 | 11 | 105 | 192 | 70 |
| Drying rate, kg water evaporated/($h \cdot m^2$) | 38.39 | 42.97 | 17.09 | 22.95 | 9.91 | 31.25 |
| Air velocity (superficial), m/s | 1.27 | 1.12 | 0.66 | 1.12 | 1.27 | 1.27 |
| Heat source per kg water evaporated, steam kg/kg gas ($m^3$/kg) | Gas 0.11 | Steam 2.0 | Steam 1.73 | Waste heat | Steam 2.83 | Gas 0.13 |
| Installed power, kW | 29.8 | 119.3 | 194.0 | 82.06 | 179.0 | 41.03 |

*Courtesy of Proctor & Schwartz, Inc.

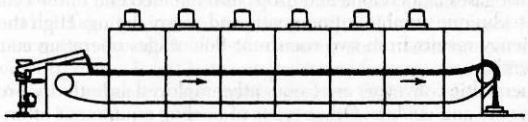


**FIG. 12-56** Section assembly of a continuous through-circulation conveyor dryer. (*Proctor & Schwartz, Inc.*)

**TABLE 12-17 Conveyor-Screen-Dryer Costs***

| Length | 2.4-m-wide conveyor | 3.0-m-wide conveyor |
|---|---|---|
| 7.5 m | $8600/$m^2$ | $7110/$m^2$ |
| 15 m | $6700/$m^2$ | $5600/$m^2$ |
| 22.5 m | $6200/$m^2$ | $5150/$m^2$ |
| 30 m | $5900/$m^2$ | $4950/$m^2$ |

*National Drying Machinery Company, 1996.

opening timers. For small solids, trays of perforated metal alloys are used to carry the product. These carriers ride through the tunnel on rollers, skid rails, and occasionally refractory skids, one tray pushing the next ahead. The charge may travel in a straight line or in counterflow movement in single or multiple chambers.

In counterflow movement, heat from the outgoing solids is transferred directly to cold incoming solids, reducing heat losses and fuel requirements. Continuous conveyor ovens are employed also for drying refractory shapes and for drying and baking enameled pieces. In many of these latter, the parts are suspended from overhead chain conveyors.

**Ceramic tunnel kilns** handling large irregular-shaped objects must be equipped for precise control of temperature and humidity conditions to prevent cracking and condensation on the product. The internal mechanism causing cracking when drying clay and ceramics has been studied extensively. Information on ceramic tunnel-kiln operation and design is reported fully in publications such as *The American Ceramic Society Bulletin*, *Ceramic Industry*, and *Transactions of the British Ceramic Society*.

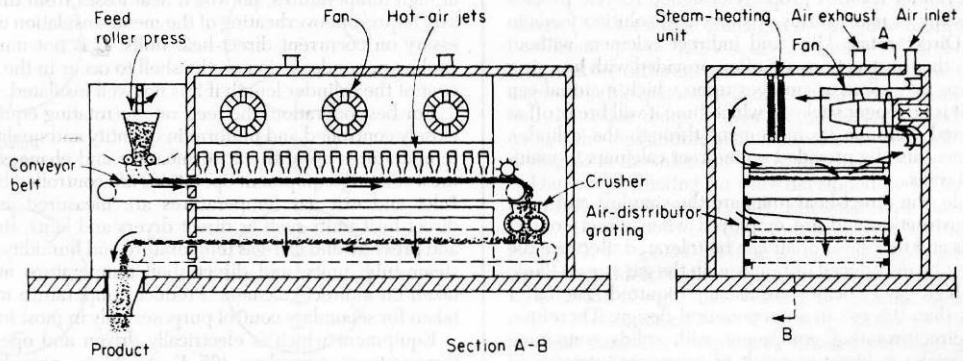



**FIG. 12-57** Special conveyor dryer with air jets impinging on surface of bed on first pass. Dried material is crushed and passed again through dryer, with air going through the now-permeable bed. [Chem. Eng., *192* (*June 19, 1967*).]

## ROTARY DRYERS

**Description** A rotary dryer consists of a cylinder, rotated upon suitable bearings and usually slightly inclined to the horizontal. The length of the cylinder may range from 4 to more than 10 times its diameter, which may vary from less than 0.3 to more than 3 m. Feed solids fed into one end of the cylinder progress through it by virtue of rotation, head effect, and slope of the cylinder and discharge as finished product at the other end. Gases flowing through the cylinder may retard or increase the rate of solids flow, depending upon whether gas flow is countercurrent or cocurrent with solids flow.

Rotary dryers have been classified as **direct, indirect-direct, indirect,** and **special types.** The terms refer to the method of heat transfer, being "direct" when heat is added to or removed from the solids by direct exchange between flowing gas and solids and being "indirect" when the heating medium is separated from physical contact with the solids by a metal wall or tube.

Only totally direct and totally indirect types will be discussed extensively here, as it must be recognized that an infinite number of variations between the two are possible. Their operating characteristics when performing heat- and mass-transfer operations make them suitable for the accomplishment of drying, chemical reactions, solvent recovery, thermal decompositions, mixing, sintering, and agglomeration of solids. The specific types included are the following:

*Direct rotary dryer (cooler).* This is usually a bare metal cylinder, with or without flights. It is suitable for low- and medium-temperature operations, the operating temperature being limited primarily by the strength characteristics of the metal employed in fabrication.

*Direct rotary kiln.* This is a metal cylinder lined on the interior with insulating block and/or refractory brick. It is suitable for high-temperature operations.

*Indirect steam-tube dryer.* This is a bare metal cylinder provided with one or more rows of metal tubes installed longitudinally in the shell. It is suitable for operation up to available steam temperatures or in processes requiring water cooling of the tubes.

*Indirect rotary calciner.* This is a bare metal cylinder surrounded on the outside by a fired or electrally heated furnace. It is suitable for operation at medium temperatures up to the maximum which can be tolerated by the metal wall of the cylinder, usually 650 to 700 K for carbon steel and 800 to 1025 K for stainless steel.

*Direct Roto-Louvre dryer.* This is one of the more important special types, differing from the direct rotary unit in that true *through circulation* of gas through the solids bed is provided. Like the direct rotary, it is suitable for low- and medium-temperature operation.

**Field of Application** Rotating equipment is applicable to batch or continuous processing solids which are relatively free-flowing and granular when discharged as product. Materials which are not completely free-flowing in their feed condition are handled in a special manner, either by recycling a portion of final product and premixing with the feed in an external mixer to form a uniform granular feed to the process or by maintaining a bed of free-flowing product in the cylinder at the feed end and, in essence, performing a premixing operation in the cylinder itself. A properly designed recycle process will permit processing of many forms of slurry and solution feeds in rotating vessels. Direct rotary kilns and indirect calciners without internal flights or other obstructions are often provided with **hanging link chains.** These may serve as surfaces upon which material can accumulate until it is no longer sticky, at which time it will break off as a granular solid and continue its movement through the cylinder. **Scraper chains** may also be provided on indirect calciners to maintain clean internal walls.

As a general rule, the direct-heat units are the simplest and most economical in construction and are employed when direct contact between the solids and flue gases or air can be tolerated. Because the total heat load must be introduced or removed in the gas stream, large gas volumes and high gas velocities are usually required. The latter will be rarely less than 0.5 m/s in an economical design. Therefore, employment of direct rotating equipment with solids containing extremely fine particles is likely to result in excessive entrainment losses in the exit-gas stream.

The indirect forms require only sufficient gas flow through the cylinder to remove vapors or otherwise complete the internal process. In addition, these can be sealed for processes requiring special gas atmospheres and exclusion of outside air.

**Auxiliary Equipment** On direct-heat rotating equipment, a combustion chamber is required for high temperatures and finned steam coils are used for low temperatures. If contamination of the product with combustion gases is undesirable on direct-heat units, indirect gas- or oil-fired air heaters may be employed to achieve temperatures in excess of available steam.

The *method of feeding* rotating equipment depends upon material characteristics and the location and type of upstream processing equipment. When the feed comes from above, a chute extending into the cylinder may be employed. For sealing purposes or if gravity feed is not convenient, a screw feeder is normally used. On cocurrent direct-heat units, cold-water jacketing of the feed chute or conveyor may be desirable if it is contacted by the inlet hot-gas stream. This will prevent overheating of the metal wall with resultant scaling or overheating of heat-sensitive feed materials.

Any type of solids conveyor may be suitable for **recycle** mixing; however, the most universally applicable is the double-shaft pug-mill-type paddle mixer. This conveyor or mixer should be insulated to prevent excessive heat losses from the hot, dry recycle product. To ensure uniformity in the recycle operation, a **surge storage** reserve of recycle solids should be installed for startup purposes and in the event of interruption of product discharge from the cylinder. In recycle operations, 50 to 60 percent product recirculation is found economical in many instances.

One method of feeding direct cocurrent drying equipment utilizes dryer exhaust gases to convey, mix, and predry wet feed. The latter is added to the exhaust gases, at high velocity, from the dryer. The wet feed, mixed with dust entrained from the dryer, separates from the exhaust gases in a cyclone and drops into the feed end of the cylinder. The technique combines pneumatic and rotary drying. High thermal efficiency results from two cocurrent-flow stages operating countercurrently.

Pneumatic conveyors are frequently employed as both dry-product conveyors and coolers. Other types of cooling equipment often used are screw conveyors, vibrating conveyors, and direct or indirect rotating coolers.

**Dust** entrained in the exit-gas stream is customarily removed in cyclone collectors. This dust may be discharged back into the process or separately collected. For expensive materials or extremely fine particles, bag collectors may follow a cyclone collector, provided fabric temperature stability is not limiting. When toxic gases or solids are present, the exit gas is at a high temperature, the gas is close to saturation as from a steam-tube dryer, or gas recirculation in a sealed system is involved, wet scrubbers may be used independently or following a cyclone. Cyclones and bag collectors in drying applications frequently require insulation and steam tracing. The exhaust fan should be located downstream from the collection system.

Rotating equipment, except brick-lined vessels, operated above ambient temperatures is usually insulated to reduce heat losses. Exceptions are direct-heat units of bare metal construction operating at high temperatures, on which heat losses from the shell are necessary to prevent overheating of the metal. Insulation is particularly necessary on cocurrent direct-heat units. It is not unusual for product cooling or condensation on the shell to occur in the last 10 to 50 percent of the cylinder length if it is not well insulated.

For best operation, the feed rate to rotating equipment should be closely controlled and uniform in quantity and quality. Because solids temperatures are difficult to measure and changes slowly detected, most rotating-equipment operations are controlled by indirect means. Inlet and exit gas temperatures are measured and controlled on direct-heat units such as direct dryers and kilns, steam temperature and pressure and exit-gas temperature and humidity are controlled on steam-tube units, and direct shell temperature measurements are taken on indirect calciners. Product temperature measurements are taken for secondary control purposes only in most instances.

Equipment which is electrically driven and operated with metal temperatures exceeding 425 K should be provided with auxiliary drives or power sources. Loss of rotation of a heated calciner or high-temperature dryer carrying a heavy bed of hot solids will quickly result in sagging of the cylinder due to nonuniform cooling.

**Direct-Heat Rotary Dryers** The direct-heat rotary dryer is usually equipped with **flights** on the interior for lifting and showering the solids through the gas stream during passage through the cylinder. These flights are usually offset every 0.6 to 2 m to ensure more continuous and uniform curtains of solids in the gas. The shape of the flights depends upon the handling characteristics of the solids. For free-flowing materials, a radial flight with a 90° lip is employed. For sticky materials, a flat radial flight without any lip is used. When materials change characteristics during drying, the flight design is changed along the dryer length. Many standard dryer designs employ flat flights with no lips in the first one-third of the dryer measured from the feed end, flights with 45° lips in the middle one-third, and flights with 90° lips in the final one-third of the cylinder. **Spiral flights** are usually provided in the first meter or so at the feed end to accelerate forward flow from under the feed chute or conveyor and to prevent leakage over the feed-end retainer ring into the gas seals.

When cocurrent gas-solids flow is used, flights may be left out to the final meter or so at the exit end to reduce entrainment of dry product in the exit gas. Showering of wet feed at the feed end of a countercurrent dryer will, on the other hand, frequently serve as an effective means for scrubbing dry entrained solids from the gas stream before it leaves the cylinder. Some dryers are provided with sawtooth flights to obtain uniform showering, while others use lengths of chain, attached to the underside of the flights, to scrape over and knock the walls of the cylinder, thereby removing sticky solids which might normally adhere to it. In kilns, the chains may contribute significantly to heat transfer; however, their use contributes to maintenance costs when flights are present in direct dryers. Solids sticking on flights and walls are usually removed more efficiently by **external shell knockers.** In dryers of large cross section, internal elements or partitions are sometimes used to increase the effectiveness of material distribution and reduce dusting and impact grinding. Use of internal members increases the difficulty of cleaning and maintenance unless sufficient free area is left between partitions for easy access of a person. Some examples of the more common flight arrangements are shown in Fig. 12-58. Component arrangements of countercurrent direct rotary dryers are shown in Fig. 12-59, and those of a cocurrent unit in Fig. 12-60.

Countercurrent flow of gas and solids gives greater **heat-transfer efficiency** with a given inlet-gas temperature, but cocurrent flow can be used more frequently to dry heat-sensitive materials at higher inlet-gas temperatures because of the rapid cooling of the gas during initial evaporation of surface moisture.

A number of different methods are employed to seal the rotating cylinder and prevent gas leakage through the annular opening between the rotating cylinder and the stationary throat pieces. *None is an effective solids seal,* nor will any function satisfactorily as a gas seal if solids leakage over the retaining ring on the cylinder is permitted.

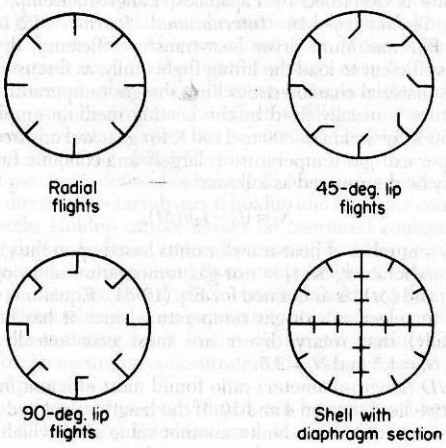



**FIG. 12-58** Alternative direct-heat rotary-dryer flight arrangements.

Three examples of ordinary gas seals are shown in Fig. 12-61. On direct rotary dryers, few gas seals are intended to be completely gastight, but by careful control of the internal pressure, generally between 0.25 and 2.5 mm of water below atmosphere, dusting to the outside is prevented and in-leakage of outside air is minimized.

Figure 12-61 also illustrates three basic types of **trunnion roll-bearing assemblies.** Antifriction pillow blocks are the most common on modern dryers; however, when the dryer load requires larger than a 12.7- to 15.2-cm-diameter bearing on the trunnion shaft, the dead-shaft antifriction bearing is substituted. This represents a considerable cost saving compared with the larger pillow blocks. They are completely sealed and continuously bathed in lubricant. Pillow-block bushings are less often used. The thrust washers are difficult to seal against dust, and they draw more power. Thrust roll mountings are depicted also in Fig. 12-61. These are usually dead-shaft.

Gases are forced through the cylinder by either an exhauster or an exhauster-blower combination. With the latter arrangement it is possible to maintain very precise control of internal pressure even when the total system pressure drop is high. When a low-pressure-drop air heater is employed, however, the exhauster alone is usually sufficient, as the major gas pressure losses are found in the exit-air ductwork and dust collectors. Use of a blower by itself to force gas through the cylinder is an unusual practice, because the internal pressure is above atmospheric and hot air and dust may be blown into the gas seals or out into the surrounding working areas.

Special designs of direct rotary dryers, such as the Renneburg DehydrO-Mat (Edward Renneburg & Sons Co.), are constructed especially to provide lower retention during the falling-rate drying period for the escape of internal moisture from the solids. The DehydrO-Mat is a cocurrent dryer employing a small-diameter shell at the feed end, where rapid evaporation of surface moisture in the stream of initially hot gas is accomplished with low holdup. At the solids- and gas-exit end, the shell diameter is increased to reduce gas velocities and provide increased holdup for the solids while they are exposed to the partially cooled gas stream.

The Louisville type P dryer is a cocurrent dryer developed for the drying of heat-sensitive polymers. It is designed for use on rather finely divided and bulky materials which are easily airborne since its basic design utilizes a discharge cone permitting pneumatic conveying of dried solids from the dryer. Its internal design provides additional retention time by slowing the progress of the material through the dryer cylinder, permitting a comparatively high velocity of the drying medium without excessive blow-through.

The Louisville type H dryer is a modified cocurrent dryer with "flash-drying" characteristics. Its internal arrangements consist of alternating disks and doughnuts which give high differential velocities between the drying medium and the solids being processed to increase the heat transfer and hence the rate of moisture removal.

***Design Methods for Direct-Heat Rotary Dryers*** Direct drying in a direct-heat rotary dryer is best expressed as a heat-transfer mechanism as follows:

$$Q_t = UaV(\Delta t)_m \qquad (12\text{-}51)$$

where $Q_t$ = total heat transferred, J/s; $Ua$ = volumetric heat-transfer coefficient, J/(s·m$^3$·K); $V$ = dryer volume, m$^3$; and $(\Delta t)_m$ = true mean temperature difference between the hot gases and material, K. When a considerable quantity of surface moisture is removed from the solids and the solids temperatures are unknown, a good approximation of $(\Delta t)_m$ is the logarithmic mean between the wet-bulb depressions of the drying air at the inlet and exit of the dryer.

Data for evaluating $Ua$ were developed by Miller [*Trans. Am. Inst. Chem. Eng.*, **38,** 841 (1942)], Friedman and Marshall [*Chem. Eng. Prog.*, **45,** 482, 573 (1949)], and Seaman and Mitchell [*Chem. Eng. Prog.*, **50,** 467 (1954)]. These authors all employed relationships that could be reduced to the form $Ua = KG^n/D$, where $K$ = a proportionality constant, $G$ = gas mass velocity, $D$ = diameter, and $n$ = a constant.

P. Y. McCormick [*Chem. Eng. Prog.*, **58**(6), 57 (1962)] compared all available data. The comparisons showed that flight geometry and shell speed should be accounted for in the value of $K$. He suggested that shell rotational speed and flight number and shape must affect the overall balance; however, data for evaluating these variables separately are not available. Also, it is not believed that the effect of gas velocity

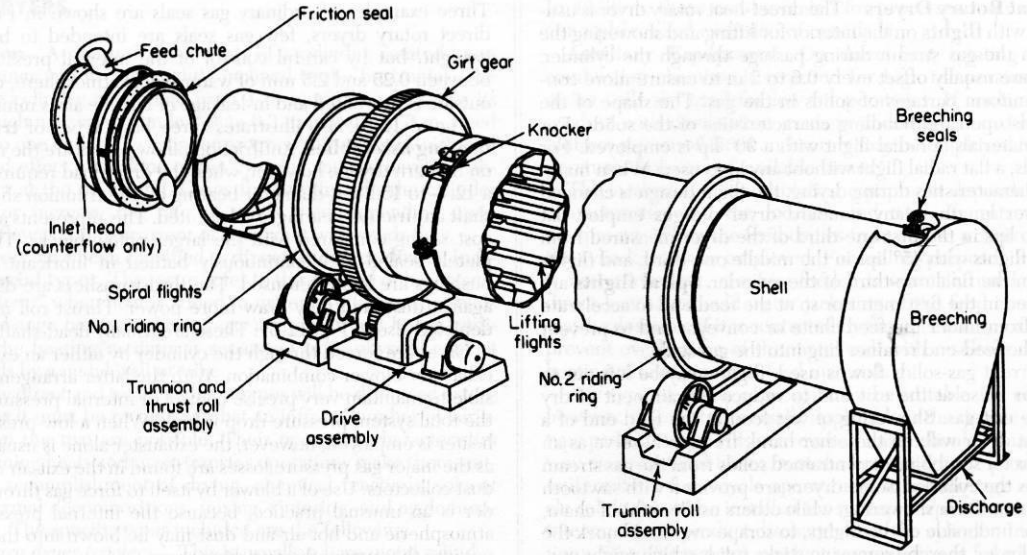



**FIG. 12-59** Component arrangements of a countercurrent direct-heat rotary dryer. (*ABB Raymond/Bartlett-Snow TM.*)

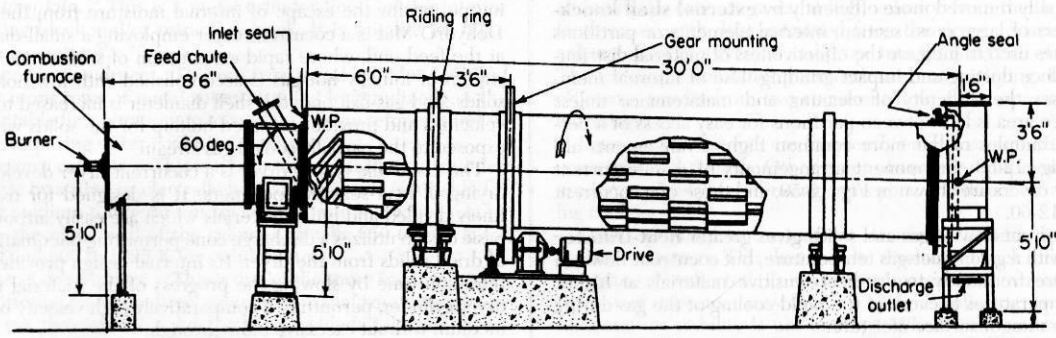



**FIG. 12-60** Elevation of a 60-in-diameter by 30-ft-long direct-heat cocurrent rotary dryer. To convert inches to centimeters, multiply by 2.54; to convert feet to meters, multiply by 0.3048. (*ABB Raymond/Bartlett-Snow TM.*)

is toward reducing the surface film thickness around each particle; rather, an increase in gas velocity more likely breaks up more effectively the showering curtains of solids and thereby exposes more solids surface; i.e., the effect is to increase the $a$ in $Ua$ rather than $U$.

The following relationship is recommended for commercial dryers now manufactured in the United States, which usually have a flight count per circle of 2.4 to 3.0 $D$ and operate at shell peripheral speeds of 60 to 75 ft/min:

$$Q_t = (0.5G^{0.67}/D)V\,\Delta t_m \qquad (12\text{-}52)$$

$$= 0.4LDG^{0.67}\,\Delta t_m \qquad (12\text{-}53)$$

where $Q_t$ = total heat transferred, Btu/h; $L$ = dryer length, ft; $D$ = dryer diameter, ft; $G$ = gas mass velocity, lb/(h·ft² of cross section); and $\Delta t_m$ = log mean of the drying-gas wet-bulb depression at the inlet end and exit end of the dryer shell.

Typical operating data for cocurrent rotary dryers are given in Table 12-18. (Note that the driving force $\Delta T_m$ must be based on wet-bulb depression and not on material temperatures. Use of material temperatures, particularly when the dry solids are superheated after drying, will yield conservative results.)

In most cases, direct-heat rotary dryers are still sized on the basis of pilot-plant tests, because rarely is all the moisture to be removed truly "free" moisture, and residence time for diffusion is frequently needed. A theoretical model simulating the operation of both cocurrent and countercurrent rotary dryers which relies on pilot and bench scale tests to determine parameters which describe solids transport and drying rate is described by Papadakis, Langrish, Kemp, and Bahu [*Drying Technology—An International Journal,* **12**(1&2), 259 (1994)]. For maximum dryer heat-transfer efficiency, dryer fillage must be sufficient to load the lifting flights fully, as discussed later.

Unless material characteristics limit the gas temperature, the inlet temperature is usually fixed by the heating medium employed; i.e., 400 to 450 K for steam or 800 to 1100 K for gas- and oil-fired burners. The proper exit-gas temperature is largely an economic function. Its value may be determined as follows:

$$N_t = (t_1 - t_2)/(\Delta t)_m \qquad (12\text{-}54)$$

where $N_t$ = number of heat-transfer units based upon the gas; $t_1$ = initial-gas temperature, K; $t_2$ = exit-gas temperature allowing for heat losses, K; and $(\Delta t)_m$ is as defined for Eq. (12-51). Equation (12-54) can be used to select an exit-gas temperature since it has been found (empirically) that rotary dryers are most economically operated between $N_t = 1.5$ and $N_t = 2.5$.

The $L/D$ (length-diameter) ratio found most efficient in commercial practice lies between 4 and 10. If the length calculated previously does not fall within these limits, another value of $N_t$ which will place $L/D$ in the proper range may be computed.

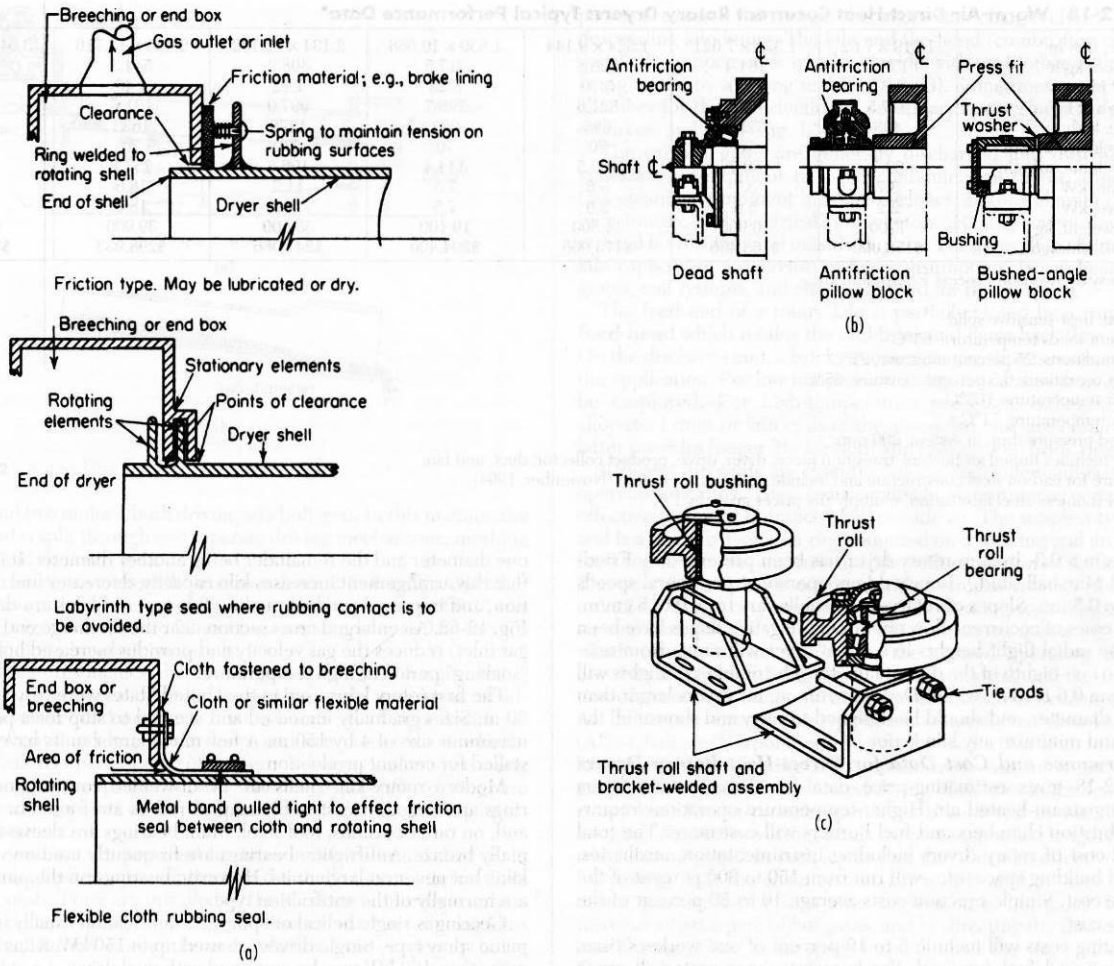



**FIG. 12-61** Rotary-dryer components. (*a*) Alternative rotary gas seals. (*b*) Alternative trunnion roll bearings. (*c*) Thrust roll assembly. (*ABB Raymond/Bartlett-Snow TM.*)

Rotary dryers usually operate with 10 to 15 percent of *their volume filled with material.* Lower fillage will be insufficient to utilize the lifters fully, while greater fillage creates the possibility of short-circuiting feed solids across the top of the bed. Under normal fillage conditions, the dryer usually can be made to hold solids long enough to complete the removal of *internal moisture.* If the holdup in the dryer is not great enough, the time of passage may be too short to remove all internal moisture, or because of incomplete flight fillage performance may be erratic. The effect of fillage on retention time and uniformity in rotary dryers has been studied by Miskell and Marshall [*Chem. Eng. Prog.*, **52,** 1 (1956)].

Time of passage is defined as holdup divided by feed rate. It can be measured directly in rotary dryers if holdup and feed rate can be measured directly. Holdup cannot always be measured conveniently on large plant dryers, however, unless a period of shutdown occurs when the dryer can be discharged and its contents weighed. Other methods have been resorted to, one of which consists of adding a pound or two of an inert detectable solid or a radioisotope of a feed constituent to the feed and analyzing for it in the discharged product. The time required for the maximum concentration to occur represents the average time of passage.

The time of passage in rotary dryers can be estimated by the relationships developed by Friedman and Marshall (op. cit.), as given here:

$$\theta = \frac{0.23L}{SN^{0.9}D} \pm 0.6\,\frac{BLG}{F} \qquad (12\text{-}55)$$

$$B = 5(D_p)^{-0.5} \qquad (12\text{-}56)$$

where $B$ = a constant depending upon the material being handled and approximately defined by Eq. (12-56); $D_p$ = weight average particle size of material being handled, μm; $F$ = feed rate to dryer, lb dry material/(h·ft² of dryer cross section); $\theta$ = time of passage, min; $S$ = slope, ft/ft; $N$ = speed, r/min; $L$ = dryer length, ft; $G$ = air-mass velocity, lb/(h·ft²); and $D$ = dryer diameter, ft. The plus sign refers to countercurrent flow and the negative sign to cocurrent flow. To convert from British thermal units per hour to watts, multiply by 0.293; to convert from pounds per hour-square foot of cross section to kilograms per second-square meter, multiply by 0.00135.

Air-mass velocities in rotary dryers usually range from 0.5 to 5.0 kg/(s·m²). It is customary to employ the highest air velocity possible without serious dusting. The amount of dusting occurring during operation is a complex function of the material being dried, its physical state, the air velocity employed, the holdup in the dryer, the number of flights, the rate of rotation, and the construction of the breeching at the end of the dryer. It can be predicted accurately only by experimental tests. An air rate of 1.4 kg/(s·m²) can usually be safely used with 35-mesh solids. Information on the dusting of a number of

**TABLE 12-18 Warm-Air Direct-Heat Cocurrent Rotary Dryers: Typical Performance Data***

| Dryer size, m × m | 1.219 × 7.62 | 1.372 × 7.621 | 1.524 × 9.144 | 1.839 × 10.668 | 2.134 × 12.192 | 2.438 × 13.716 | 3.048 × 16.767 |
|---|---|---|---|---|---|---|---|
| Evaporation, kg/h | 136.1 | 181.4 | 226.8 | 317.5 | 408.2 | 544.3 | 861.8 |
| Work, $10^5$ J/h | 3.61 | 4.60 | 5.70 | 8.23 | 1.12 | 1.46 | 2.28 |
| Steam, kg/h at kg/m² gauge | 317.5 | 408.2 | 521.6 | 725.7 | 997.9 | 131.5 | 2041 |
| Discharge, kg/h | 408 | 522 | 685 | 953 | 1270 | 1633 | 2586 |
| Exhaust velocity, m/min | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| Exhaust volume, m³/min | 63.7 | 80.7 | 100.5 | 144.4 | 196.8 | 257.7 | 399.3 |
| Exhaust fan, kW | 3.7 | 3.7 | 5.6 | 7.5 | 11.2 | 18.6 | 22.4 |
| Dryer drive, kW | 2.2 | 5.6 | 5.6 | 7.5 | 14.9 | 18.6 | 37.3 |
| Shipping weight, kg | 7700 | 10,900 | 14,500 | 19,100 | 35,800 | 39,900 | 59,900 |
| Price, FOB Chicago | $158,000 | $168,466 | $173,066 | $204,400 | $241,066 | $298,933 | $393,333 |

*Courtesy of Swenson Process Equipment Inc.

NOTE:
Material: heat-sensitive solid
Maximum solids temperature: 65°C
Feed conditions: 25 percent moisture, 27°C
Product conditions: 0.5 percent moisture, 65°C
Inlet-air temperature: 165°C
Exit-air temperature: 71°C
Assumed pressure drop in system: 200 mm.
System includes finned air heaters, transition piece, dryer, drive, product collector, duct, and fan.
Prices are for carbon steel construction and include entire dryer system (November, 1994).
For 304 stainless-steel fabrication, multiply the prices given by 1.5.

materials in a 0.3- by 2-m rotary dryer has been presented by Friedman and Marshall (ibid.). Rotary dryers operate at peripheral speeds of 0.25 to 0.5 m/s. Slopes of rotary-dryer shells vary from 0 to 8 cm/m. In some cases of cocurrent-flow operations, negative slopes have been used. The radial flight heights in a direct dryer will range from one-twelfth to one-eighth of the dryer diameter. The number of flights will range from 0.6 $D$ to $D$, where $D$ = diameter, m, for dryers larger than 0.6 m in diameter, and should be designed to carry and shower all the holdup and minimize any kiln action.

***Performance and Cost Data for Direct-Heat Rotary Dryers*** Table 12-18 gives estimating-price data for direct rotary dryers employing steam-heated air. Higher-temperature operations requiring combustion chambers and fuel burners will cost more. The total installed cost of rotary dryers including instrumentation, auxiliaries, allocated building space, etc., will run from 150 to 300 percent of the purchase cost. Simple erection costs average 10 to 20 percent of the purchase cost.

Operating costs will include 5 to 10 percent of one worker's time, plus power and fuel required. Yearly maintenance costs will range from 50 to 10 percent of total installed costs. Total power for fans, dryer drive, and feed and product conveyors will be in the range of 0.5 $D^2$ to 1.0 $D^2$. Thermal efficiency of a high-temperature direct-heat rotary dryer will range from 55 to 75 percent and, with steam-heated air, from 30 to 55 percent.

A representative list of materials dried in direct-heat rotary dryers is given in Table 12-19.

**Direct-Heat Rotary Kilns** One of the most important of the high-temperature process furnaces is the direct-fired rotary kiln. It replaces the ordinary rotary dryer when the wall temperature exceeds that which can be tolerated by a bare metal shell (650 to 700 K for carbon steel). Rotary-kiln shells are lined in part or for their entire length with a **refractory brick** to prevent overheating of the steel with resulting weakening. Occasionally two linings are used, the one next to the shell being an **insulating brick.** Insulation is infrequently used on the outside of the shell, and caution must be observed not to overheat the shell metal by this confinement. When wet feeds are applied to a kiln lining at the cold end, there may be leakage of liquid through the lining to the shell, which will cause trouble if the liquid is corrosive.

The feed is introduced into the upper end of the kiln by various methods, i.e., inclined chutes, overhung screw conveyors, slurry pipes, etc. Sometimes **ring dams** or chokes of a refractory material are installed within the kiln to build a deeper bed at one or more points, thus changing the flow pattern. The hot product is discharged from the lower end of the kiln into quench tanks, onto conveyors, or into cooling devices which may or may not recover its heat content. These cooling and heat-recovery devices include rotating inclined cylinders, inclined slow-moving grates, shaking grates, etc.

Some kilns have two or three diameters, part of the length being one diameter and the remainder being another diameter. It is claimed that this arrangement increases kiln capacity, decreases fuel consumption, and improves product quality. Two types of kilns are depicted in Fig. 12-62. An enlarged cross section near the discharge end (and hot-gas inlet) reduces the gas velocity and provides increased holdup for a "soaking" period at high temperature.

The first rotary kilns used in the United States were very small, 2 by 20 m. Sizes gradually increased and seemed to stop for a period at a maximum size of 4 by 150 m. A few much larger units have been installed for cement production.

Modern rotary-kiln shells are of all-welded construction. Riding rings are forged or cast steel; support rollers are forged or cast steel and, on rare occasions, tool steel. Main bearings are sleeve-type, normally bronze. Antifriction bearings are frequently used on very small kilns but never on large units. However, bearings on the pinion shafts are normally of the antifriction type.

Gearing is single helical or spur; gear lubrication usually is an automatic spray type. Single drives are used up to 150 kW. Kilns requiring more than 150 kW may be equipped with dual drives, i.e., two driving

**TABLE 12-19 Representative Materials Dried in Direct-Heat Rotary Dryers***

| Material dried | Moisture content, % (wet basis) | | Heat efficiency, % |
|---|---|---|---|
| | Initial | Final | |
| High-temperature: | | | |
| Sand | 10 | 0.5 | 61 |
| Stone | 6 | 0.5 | 65 |
| Fluorspar | 6 | 0.5 | 59 |
| Sodium chloride (vacuum salt) | 3 | 0.04 | 70–80 |
| Sodium sulfate | 6 | 0.1 | 60 |
| Ilmenite ore | 6 | 0.2 | 60–65 |
| Medium-temperature: | | | |
| Copperas | 7 | 1 (moles) | 55 |
| Ammonium sulfate | 3 | 0.10 | 50–60 |
| Cellulose acetate | 60 | 0.5 | 51 |
| Sodium chloride (grainer salt) | 25 | 0.06 | 35 |
| Cast-iron borings | 6 | 0.5 | 50–60 |
| Styrene | 5 | 0.1 | 45 |
| Low-temperature: | | | |
| Oxalic acid | 5 | 0.2 | 29 |
| Vinyl resins | 30 | 1 | 50–55 |
| Ammonium nitrate prills | 4 | 0.25 | 30–35 |
| Urea prills | 2 | 0.2 | 20–30 |
| Urea crystals | 3 | 0.1 | 50–55 |

*Taken from *Chem. Eng.*, June 19, 1967, p. 190, Table III.

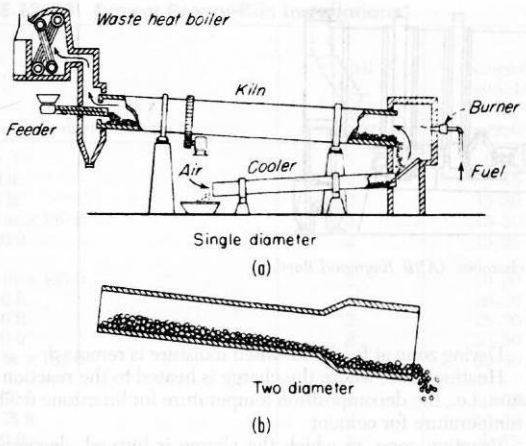



**FIG. 12-62** Rotary kilns.

pinions and two motors, both driving one bull gear. In this manner, the power load is split through two separate driving mechanisms, meshing with one and the same gear.

*Kiln inclination* varies wtih processes from 2 to 6 cm/m. *Speed of rotation* also varies from very slow, i.e., a peripheral speed of 0.15 m/s for a $TiO_2$ pigment kiln, or 0.22 m/s for a cement kiln, to 0.64 m/s for a unit calcining phosphate materials.

Special features include the discharge end designed for air cooling or kilns that operate at high temperatures, such as cement, dead-burned dolomite, and magnesia. Firing hoods are designed with retractable fronts and large side doors and are mounted on wheels. *Internal heat recuperators* are of numerous designs and are becoming more popular as fuel prices increase. *Thermocouple collector rings* are placed at various points on the shell for indicating and recording internal temperatures.

**Scoop systems** are provided for introducing collected dust or, in some cases, a feed component through the shell at some intermediate point or points. Ports are installed in the shell for admitting combustion air at points beyond the hot zone; these are used in reducing kilns for burning carbon monoxide and volatiles from materials being processed.

Firing may be accomplished at either end, depending on whether cocurrent or countercurrent flow of the charge and gases is desired. Sometimes a solid fuel is mixed with the charge and burned as it moves down the kiln. Gaseous, liquid, or powdered fuels may be used. The burner may be installed directly at the end of the kiln with combustion occurring inside it. In this case, the discharge-end housing usually consists of a fixed or movable kiln hood through which the fuel pipe enters the kiln. A center position for the fuel pipe is used when the flame is wanted off the charge. Some users prefer an off-center position toward the trough between the charge chord and the descending kiln lining. The kiln and the hood (combustion chamber) usually have open ends which coincide with each other with the gap being closed by a sliding seal (Fig. 12-63). Sometimes a special offset chamber for the introduction of secondary tempering air is provided on dryers and kilns (Fig. 12-64).

The exhaust gases are generally discharged into dust and fume knockdown equipment to avoid contamination of the atmosphere. Gas-cleaning equipment includes cyclones, settling chambers, scrubbing towers, and electrical precipitators. Heat-recovery devices are utilized both within and outside the kiln. These result in an increase in kiln capacity or a decrease in fuel consumption. Waste-heat boilers, grates, coil systems, and chains are used for this purpose.

The feed end of a rotary kiln is partially closed by a ring-shaped **feed head** which retains the end brick and dams back flow of solids. On the discharge end, a brick retaining-ring casting is made up to suit the application. For low temperatures, segmental alloy-iron rings may be employed. For high-temperature processes, either segmental alloy-steel rings or kiln ends of the air-cooled type are employed; the latter provides longer life for both kiln end and the brick ring.

Efficient **air seals** are essential for the controlled and economical operation of kilns. They reduce outside air entrance; certain types effectively prevent entrance of all outside air. The simplest type of air seal is a floating T-section ring mounted on a wearing pad around the feed end of the kiln and free to slide with expansion of the kiln shell. The web of the T ring is confined within circular retainer plates. Figure 12-65 shows two arrangements. The floating-type discharge-end air seal consists of a circular bar which floats on a wearing pad and which can be moved to provide the desired operating clearance between air seal and firing hood. The floating ring and the fixed portion of these seals can be furnished with renewable wearing surfaces. Air infiltration through this type of seal is usually less than 10 percent (Allis-Chalmers Corporation). For further reduction of air infiltration, lantern-ring-type floating seals, pressurized with inert gas or stack gases, are employed. Accelerated drying of slurries in the feed end of rotary kilns in wet-process operations is achieved by installation of *hanging chains*. Conveying spirals support suspended lengths of chain which are arranged in such a way that they form an effective pattern for drying. With the chain system, slurry is heated in three ways: by direct transfer from chains after suspension in hot gases, by lifting material into the path of hot gases, and by directing the flow of hot gas over the slurry bed in the space formed under the suspended chains. Frequently, the product forms into uniformly sized pellets which progress through the rest of the kiln in that form, resulting in improved heat transfer and reduced dust losses (Fig. 12-66).

***Design Methods for Rotary Kilns*** In rotary kilns, the material is not showered through the air stream but is retained in the lower part of the cylinder. Gas-solids contacting is much less efficient than in flighted units. Heat transfer is by radiation and convection from the flowing gas to the kiln brick and exposed bed surface and by radiation from the brick to the bed. For units employing separate combustion chambers, it can be assumed that at high temperatures the wall-film

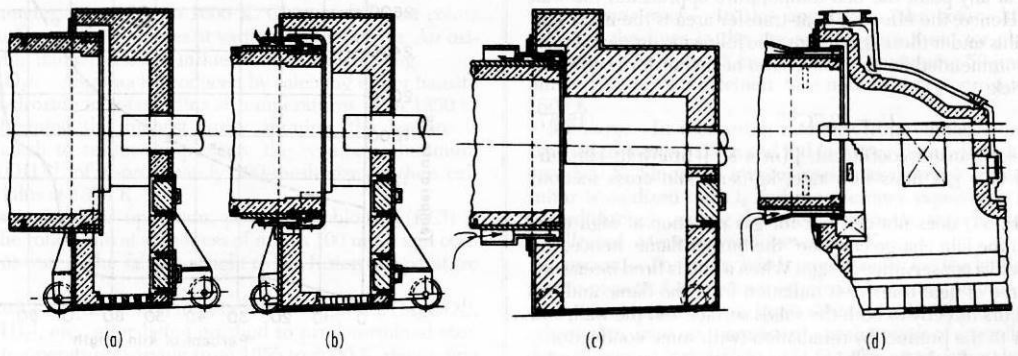



**FIG. 12-63** Alternative kiln firing hoods. *(a)* Plain firing hood. *(b)* Hood for high temperatures. *(c)* Hood with enlarged combustion-air passage. *(d)* Hood with cooler connection. *(Allis-Chalmers Corporation.)*

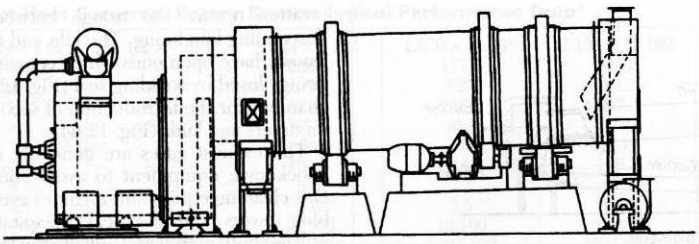


**FIG. 12-64** Dryer firing hood with air-tempering chamber. (*ABB Raymond/Bartlett-Snow TM.*)

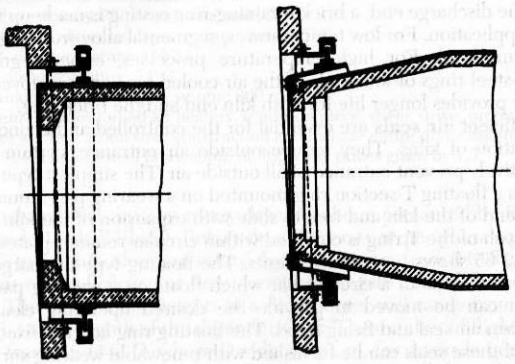



**FIG. 12-65** Kiln-seal arrangements. (*a*) Single-floating-type feed end air seal. (*b*) Single-floating-type air seal on an air-cooled tapered feed end. (*Allis-Chalmers Corp.*)

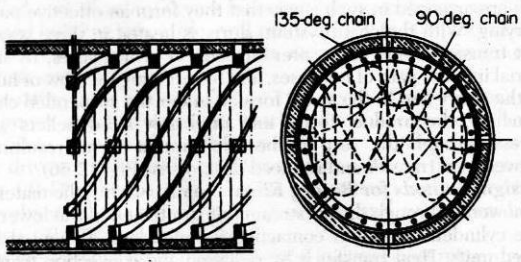



**FIG. 12-66** Kiln chain installation (patented). (*Allis-Chalmers Corp.*)

resistance to convection heat transfer from the gas to the brick is limiting and that at any point the bed temperature approaches the wall temperature. Hence, the effective heat-transfer area is the inner kiln surface. For kilns under these conditions, the following empirical relationship is recommended for the convection heat-transfer coefficient from gas to brick:

$$Us = 23.7G^{0.67} \qquad (12\text{-}57)$$

where $Us$ = heat-transfer coefficient, J/(m²·s·K) [(Btu/(h·ft² kiln surface·°F)]; and $G$ = gas mass flow rate, kg/(s·m² kiln cross section) [lb/(h·ft²)].

Equation (12-57) does not account for gas radiation at high temperature when the kiln charge can "see" the burner flame; hence, the method will yield a conservative design. When a kiln is fired internally, the major source of heat transfer is radiation from the flame and hot gases. This occurs directly to both the solids surface and the wall, and from the latter to the product by reradiation (with some conduction).

Generally, a dry-feed kiln will have three zones of heating, and a wet-feed kiln will have four:

1. Drying zone at feed end, when moisture is removed
2. Heating zone, where the charge is heated to the reaction temperature, i.e., the decomposition temperature for limestone or "burning" temperature for cement
3. Reaction zone, in which the charge is burned, decomposed, reduced, oxidized, etc.
4. Soaking zone, where the reacted charge is superheated or "soaked" at temperature or, if desired, cooled before discharge

The rates of heat transfer in each zone will be different.

Rotary kilns operate at various temperatures throughout their length. A graph of approximate gas and charge temperatures for wet-process cement is shown in Fig. 12-67. The maximum charge temperature is 1700 to 1800 K; for the gases, 1800 to 1925 K. Overall heat-transfer rates have been estimated to be in the range of 25 to 60 KJ/(s·m³) on the basis of total kiln volume.

Some commercial performance data for cement and lime kilns are shown in Table 12-20.

Some of the other major uses of direct rotary kilns are in the following processes:

*Roasting.* Rotary kilns are used for oxidizing and driving off sulfur and arsenic from various ores, including gold, silver, iron, etc. Temperatures employed will vary from 800 to 1600 K.

*Chloridizing.* Silver ores are chloridized successfully in rotary kilns. Temperatures must be closely controlled between 1030 and 1090 K.

*Black ash.* Barium sulfide (BaS) is produced by calcining a mixture of barite ($BaSO_4$) and carbon at a temperature of 1350 K in continuous rotary kilns.

*Spodumene.* A mixture of quartz, feldspar, and spodumene is being calcined in rotary kilns at 1475 K to produce lithium aluminum silicate.

*Vermiculite.* A micaceous mineral is roasted to cause exfoliation for use as an insulating material.

*Revivification.* Temperatures of 800 to 1030 K are used to revivify fuller's and diatomaceous earth, although for some earths lower temperatures are employed.

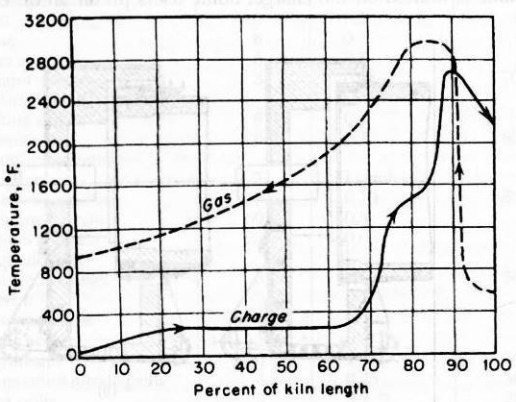



**FIG. 12-67** Temperatures in rotary kiln on wet-process cement.

**TABLE 12-20 Typical Rotary-Kiln Installations***

| Size, diam. × length | Usual No. of supports | Range of motor hp. to operate† | Nominal 24-hr. capacities‡ | | | |
|---|---|---|---|---|---|---|
| | | | Portland cement, 376-lb. bbl. | | Lime, net tons | |
| | | | Dry process | Wet process | Lime sludge | Limestone |
| 5 × 80 ft. | 2 | 5–7.5 | 140 | 100 | 10 | 16 |
| 6 × 70 ft. | 2 | 7.5–15 | 190 | 135 | 15 | 24 |
| 7 × 70 ft. | 2 | 15–20 | 275 | 200 | 20 | 35 |
| 5 ft. 6 in. × 180 ft. | 4 | 15–20 | 285 | 250 | 30 | 45 |
| 7 × 120 ft. | 2 | 15–25 | 475 | 340 | 35 | 55 |
| 7 ft. 6 in. × 125 ft. | 2 | 20–30 | 575 | 415 | 40 | 70 |
| 6 × 220 ft. | 4 | 20–30 | 420 | 375 | 45 | 65 |
| 8 × 140 ft. | 2 | 25–30 | 750 | 540 | 55 | 90 |
| 9 × 160 ft. | 2 | 30–50 | 1100 | 800 | 80 | 130 |
| 8 ft. 6 in. × 185 ft. | 4 | 30–50 | 1125 | 810 | 80 | 135 |
| 10 × 150 ft. | 2 | 40–75 | 1300 | 950 | — | 145 |
| 10 × 175 ft. | 2 | 50–75 | 1500 | 1100 | — | 155 |
| 8 × 300 ft. | 5 | 50–75 | 1150 | 1000 | 110 | 160 |
| 7 ft. 6 in. × 8 ft. 6 in. × 320 ft. | 5 | 50–75 | 1175 | 1020 | 115 | 165 |
| 7 ft. 6 in. × 10 ft. × 8 ft. 6 in. × 300 ft. | 5 | 50–75 | 1175 | 1020 | | |
| 10 × 11 × 175 ft. | 2 | 50–75 | 1650 | 1200 | 120 | 180 |
| 10 ft. 6 in. × 185 ft. | 2 | 50–75 | 1800 | 1300 | 130 | 190 |
| 11 × 175 ft. | 2 | 60–100 | 1850 | 1375 | — | 205 |
| 8 ft. 6 in. × 10 ft. × 8 ft. 6 in. × 300 ft. | 5 | 50–75 | 1400 | 1200 | | |
| 8 × 10 × 300 ft. | 5 | 50–75 | 1425 | 1225 | 140 | 200 |
| 9 ft. 6 in. × 265 ft. | 4 | 60–100 | 1500 | 1300 | 150 | 215 |
| 9 × 10 ft. 6 in. × 9 ft. × 325 ft. | 5 | 60–100 | 1700 | 1500 | | |
| 10 ft. 6 in. × 250 ft. | 4 | 60–100 | 1750 | 1525 | 175 | 240 |
| 9 ft. 6 in. × 11 ft. × 9 ft. 6 in. × 300 ft. | 5 | 60–100 | 1800 | 1550 | | |
| 10 × 300 ft. | 5 | 75–125 | 1900 | 1650 | 190 | 250 |
| 9 ft. 6 in. × 11 ft. × 9 ft. 6 in. × 375 ft. | 6 | 75–125 | 2025 | 1800 | | |
| 11 × 300 ft. | 5 | 75–125 | 2400 | 2100 | 225 | 300 |
| 11 ft. 6 in. × 300 ft. | 4 | 100–150 | 2600 | 2250 | 240 | 320 |
| 10 ft. 6 in. × 375 ft. | 5 | 100–150 | 2700 | 2400 | 250 | 325 |
| 11 ft. 3 in. × 360 ft. | 5 | 125–175 | 2900 | 2500 | 275 | 350 |
| 11 ft. 6 in. × 475 ft. | 7 | 150–250 | 4000 | 3500 | 375 | 450 |
| 12 × 500 ft. | 8 | 200–300 | 4600 | 4000 | 425 | 500 |

*Allis-Chalmers Manufacturing Co.

†Power requirements vary according to size of kiln, character of material handled, and method of operation.

‡Capacities indicated are conservative, and apply to normal operation at sea level. Corrections would apply at increased altitudes, and for differing methods of operation.

*Zinc.* Oxidized ores are calcined to drive off water of hydration and carbon dioxide. The sulfide ore is always roasted before smelting.

*Titanium oxide ($TiO_2$).* This is produced from ilmenite ore by mixing ore with carbon and heating in a rotary kiln. Also, the rotary kiln is used in the process of recovery of titanium oxide from hydrated titanium precipitate at about 1250 K.

*Roofing granules.* Crushed quartz or sand of definite size is treated with various minerals, borax, soda ash, etc., and calcined at temperatures ranging from 1250 to 1600 K. Glass of different colors forms on the surface of the granules at various temperatures. An oxidizing or reducing flame is used to influence the final coloring.

*Alumina ($Al_2O_3$).* Alumina is produced by calcining either bauxite or aluminum hydroxide in rotary kilns at temperatures from 1250 to 1600 K. In obtaining the highest-purity alumina, the bauxite is digested with alkali to remove impurities; the resultant aluminum hydroxide [$Al_2(OH)_3$], of approximately 200-mesh size, is then calcined in rotary kilns at 1350 K.

*Potassium salts.* In this operation, potassium chloride (KCl) is introduced to the rotary kiln at a fineness of minus 100 mesh and containing 9 percent water. The salt is brought to the fusion temperature of 1048 K.

*Magnesium oxide.* The natural minerals, i.e., magnesite ($MgCO_3$), brucite [$Mg(OH)_2$], etc., after being crushed to predetermined size, are calcined at temperatures varying from 1055 to 2000 K, depending upon whether a caustic or a dead-burned product (periclase) is being produced. Magnesium hydroxide, recovered from seawater or salt brine, is also being treated in a similar manner except that it is added in the form of a sludge.

*Sodium aluminum sulfate.* This product is now being successfully calcined in rotary kilns. In this process, the salt cake is broken up just before it enters the kiln. Calcination is for the purpose of driving off the combined water (45 percent) and sulfuric acid (3 percent). Temperatures employed are approximately 800 K.

*Phosphate rock.* In this application, the rotary kiln is used to nodulize the fines in the ore and prepare them for electric-furnace operation. Ore under 5 cm in size and containing 50 percent or more minus 100 mesh is calcined. Ore nodulizes at approximately 1475 to 1500 K.

*Mercury.* In recovering mercury from cinnabar ores, the ore is crushed to minus 1.5 cm and fed to rotary kilns, where it is calcined to over 800 K. Since the mercury exists as mercuric sulfide (HgS), the sulfur is oxidized to $SO_2$ and the mercury vaporized. The gases are passed through cooling chambers, where the mercury condenses and is collected. Mercury vaporizes at 625 K.

*Gypsum.* The rotary kiln is rapidly replacing the kettle in producing plaster of paris. Great care is required, as the temperatures for reaction are low and within narrow limits, 382 to 403 K. Gypsum ($CaSO_4 \cdot 2H_2O$) is heated to drive off three-fourths of the water of crystallization to produce plaster of paris [$(CaSO_2) \cdot H_2O$]. Any overheating drives off all the water, producing gypsite ($CaSO_4$), which is unsatisfactory.

*Clay.* To produce lightweight aggregate for concrete, clay is calcined in rotary kilns. Temperatures employed vary from 1350 to 1600 K. The apparent density of the clay is reduced by 50 to 75 percent.

*Iron ores.* Crushed iron ores are partially reduced in rotary kilns to obtain nodules which are used in blast-furnace charges.

*Manganese.* Manganese ore, rhodochrosite, or manganese carbonate ($MnCO_3$) is calcined at about 1525 K to produce the oxide ($Mn_3O_4$). When the oxide ore is available but is in a finely divided state, the rotary kiln is used only for nodulizing.

*Petroleum coke.* In order to eliminate excess volatile matter, petroleum coke is calcined at temperatures of 1475 to 1525 K. This is a sensitive material, and temperature control is difficult to maintain.

When it is desired to increase the capacity of an existing kiln installation, consideration should be given to the following changes:

1. Increase charge volume held in kiln.
2. Increase temperature and quantity of combustion gases.
3. Decrease quantity of air in excess of combustion needs.
4. Increase speed of rotation of kiln.
5. Install ring dams at intermediate and discharge points.
6. Increase capacity of feeding and discharge mechanisms.
7. Decrease moisture content of feed material.
8. Increase temperature of feed material.
9. Install chains or flights, etc., in feed end.
10. Preheat all combustion air.
11. Reduce leakage of cold air into kiln at hot end.
12. Increase stack draft by increasing height or by use of jets.
13. Install instrumentation to control the kiln at maximum-capacity conditions.

The time of passage in rotary kilns (from which holdup can be calculated) can be estimated by the following formula (U.S. Bur. Mines Tech. Pap. 384, 1927):

$$\theta = 0.19L/NDS \qquad (12\text{-}58)$$

where $\theta$ = time of passage in the kiln, min; $L$ = kiln length, ft; $N$ = rotational speed, r/min; $S$ = slope of kiln, ft/ft; and $D$ = diameter inside brick, ft. Other equations for estimating the time of passage employing internal dams and a discharge dam are given by Bayard [*Chem. Metall. Eng.*, **52**(3), 100–102 (1945)].

The total power required to drive a rotary kiln or a dryer with lifters can be calculated by the following formulas (courtesy of ABB Raymond). For a rotary kiln or calciner without lifters,

$$\text{bhp} = \frac{N\,[18.85y\,(\sin B)w + 0.1925DW + 0.33W]}{100{,}000} \qquad (12\text{-}59)$$

For a rotary dryer or section of a kiln with lifters,

$$\text{bhp} = \frac{N\,(4.75dw + 0.1925DW + 0.33W)}{100{,}000} \qquad (12\text{-}60)$$

where bhp = brake horsepower required (1 bhp = 0.75 kW); $N$ = rotational speed, r/min; $y$ = distance between centerline of kiln and the center of gravity of material bed, ft; $B$ = angle of repose of material; $W$ = total rotating load (equipment plus material), lb; $w$ = live load (material), lb; $D$ = riding-ring diameter, ft; and $d$ = shell diameter, ft. For estimating purposes, let $D = (d + 2)$.

**Drive motors** should be of the high-starting-torque type and selected for 1.33 times maximum rotational speed. For two- or three-diameter kilns, the brake horsepower for the several diameters should be calculated separately and summed. Auxiliary drives should be provided to maintain shell rotation in the event of power failure. These are usually gasoline or diesel engines.

***Thermal Efficiency of Rotary Kilns*** Kiln length is a major factor in determining thermal efficiency, and kilns with a high ratio of length to diameter have a greater thermal efficiency than those with a low ratio. The use of chains inside the kiln and of heat-recovery equipment on the gases and product leaving the kiln can increase substantially the thermal efficiency of a kiln installation. Efficiencies ranging from 45 to more than 80 percent have been reported. A reasonably satisfactory range based on present fuel prices and construction costs would be 65 to 75 percent utilization and recovery of the heat content of the fuel plus any heat of reaction of the charge. No distinction is made from an efficiency-calculation standpoint between the heat utilized in the kiln and that recovered (or utilized) outside the kiln. With countercurrent flow of the combustion gases and the charge material, an exceptionally long kiln will give high efficiencies within itself. However, good economics may dictate that a shorter kiln be installed with a waste-heat boiler on the hot gases to obtain an equivalent thermal efficiency at a lower investment. The heat in the hot product usually is recovered as preheat in the combustion air.

***Size Segregation in Kilns*** When an assemblage of solid particles, not very closely screened, is rotated within a cylinder, the solids assume a lunar shape, as shown in Fig. 12-68. This causes serious size segregation. The finest sizes remain at the bottom, in contact with the hot brick. The coarser particles form the upper layer of the agitated mass. As the kiln completes a revolution, the exposed brick, in an upper position, absorbs sensible heat from the gas mass. As the heated brick completes its circuit, it passes under and is in conductive contact with the fine particles. These fines are thus effectively heated by direct solid-to-solid transfer. The larger particles are heated by direct radiation from gas and brick, and become adequately calcined. The particles of size intermediate between the fine and coarse remain, throughout a complete revolution, "sandwiched" between the coarse and fine layers and are protected from heat by the excellent insulation properties of these layers, thus perhaps escaping complete calcination. This factor of segregation is offset by some kiln operators who classify or screen the kiln feed so that only a narrow range of particle size is fed at one time. Also, faster kiln speeds which give a better agitation of the charge are used.

Rotary kilns are usually operated with between 3 and 12 percent of their volume filled with material; 7 percent is considered normal.

***Cost Data for Kilns*** Purchase prices, weights, and horsepower requirements of typical units are given in Table 12-21. Installed costs will run to from 300 to 500 percent of purchase cost. Maintenance will average 5 to 10 percent of the total installed cost per year but is dependent largely on the life of the refractory lining.

For estimating purposes refractory lining for a 2.7- to 3.4-m-diameter kiln costs \$6000 to \$15,000 per meter of kiln length installed (50 percent material, 50 percent labor).

A discussion of retention time in rotary kilns is given in *Brit. Chem. Eng.*, 27–29 (January 1966). Rotary-kiln heat control is discussed in detail by Bauer [*Chem. Eng.*, 193–200 (May 1954)] and Zubrzycki [*Chem. Can.*, 33–37 (February 1957)]. Reduction of iron ore in rotary kilns is described by Stewart [*Min. Congr. J.*, 34–38 (December 1958)]. The use of balls to improve solids flow is discussed in [*Chem. Eng.*, 120–222 (March 1956)]. Brisbane examined problems of shell deformation [(*Min. Eng.*, 210–212 (February 1956)]. Instrumentation is discussed by Dixon [*Ind. Eng. Chem. Process Des. Dev.*, 1436–1441 (July 1954)], and a mathematical simulation of a rotary kiln was developed by Sass [*Ind. Eng. Chem. Process Des. Dev.*, 532–535 (October 1967)]. This last paper employed the empirical convection heat-transfer coefficient given previously, and its use is discussed in later correspondence [ibid., 318–319 (April 1968)].

**Indirect-Heat Rotary Steam-Tube Dryers** Probably the most common type of indirect-heat rotary dryer is the steam-tube dryer (Fig. 12-69). Steam-heated tubes running the full length of the cylinder are fastened symmetrically in one, two, or three concentric rows inside the cylinder and rotate with it. Tubes may be simple pipe with condensate draining by gravity into the discharge manifold or bayonet-type. Bayonet-type tubes are also employed when units are used

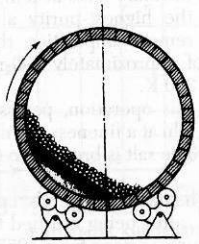


**FIG. 12-68** Size segregation of solids in a rotary kiln.

**TABLE 12-21 Approximate Purchase Costs and Weight of Rotary Kilns***

| Kiln size, diameter × length | Total purchase price includes drive, burner, and controls (not including brick)† |
|---|---|
| 8′0″ × 80′0″ | $ 448,000 |
| 8′0″ × 140′0″ | 600,000 |
| 8′0″ × 200′0″ | 960,000 |
| 8′0″ × 300′0″ | 1,240,000 |
| 9′0″ × 250′0″ | 1,373,000 |
| 9′0″ × 300′0″ | 1,545,000 |
| 10′0″ × 100′0″ | 682,000 |
| 10′0″ × 150′0″ | 965,000 |
| 10′0″ × 250′0″ | 1,502,000 |
| 10′0″ × 300′0″ | 1,682,000 |
| 10′0″ × 350′0″ | 1,779,000 |
| 10′6″ × 175′0″ | 1,182,000 |
| 10′6″ × 250′0″ | 1,677,000 |
| 10′6″ × 350′0″ | 1,942,000 |
| 11′0″ × 160′0″ | 1,213,000 |
| 11′0″ × 250′0″ | 1,670,000 |
| 11′0″ × 300′0″ | 1,858,000 |
| 11′0″ × 350′0″ | 2,344,000 |
| 11′0″ × 400′0″ | 2,544,000 |
| 11′6″ × 160′0″ | 1,251,000 |
| 11′6″ × 250′0″ | 1,768,000 |
| 11′6″ × 350′0″ | 2,393,000 |
| 11′6″ × 425′0″ | 2,676,000 |
| 12′0″ × 250′0″ | 1,837,000 |
| 12′0″ × 325′0″ | 2,598,000 |
| 12′0″ × 400′0″ | 2,645,000 |
| 12′0″ × 450′0″ | 3,570,000 |
| 13′0″ × 500′0″ | 4,388,000 |
| 14′0″ × 400′0″ | 4,155,000 |
| 16′6″ × 600′0″ | 8,190,000 |

*Courtesy of Fuller Co.
†Prices for January 1982

as water-tube coolers. When handling sticky materials, one row of tubes is preferred. These are occasionally shielded at the feed end of the dryer to prevent buildup of solids behind them. Lifting flights are usually inserted behind the tubes to promote solids agitation.

Wet feed enters the dryer through a chute or screw feeder. The product discharges through peripheral openings in the shell in ordinary dryers. These openings also serve to admit purge air to sweep moisture or other evolved gases from the shell. In practically all cases, gas flow is countercurrent to solids flow. To retain a deep bed of material within the dryer, normally 10 to 20 percent fillage, the discharge openings are supplied with removable chutes extending radially into the dryer. These, on removal, permit complete emptying of the dryer.

Steam is admitted to the tubes through a revolving steam joint into the steam side of the manifold (Fig. 12-70). Condensate is removed continuously, by gravity through the steam joint to a condensate receiver and my means of lifters in the condensate side of the manifold. By employing simple tubes, noncondensables are continuously vented at the other ends of the tubes through Sarco-type vent valves mounted on an auxiliary manifold ring, also revolving with the cylinder.

Vapors (from drying) are removed at the feed end of the dryer to the atmosphere through a natural-draft stack and settling chamber or wet scrubber. When employed in simple drying operations with $3.5 \times 10^5$ to $10 \times 10^5$ Pa steam, draft is controlled by a damper to admit only sufficient outside air to sweep moisture from the cylinder, discharging the air at 340 to 365 K and 80 to 90 percent saturation. In this way, shell gas velocities and dusting are minimized. When used for solvent recovery or other processes requiring a sealed system, sweep gas is recirculated through a scrubber-gas cooler and blower.

Steam manifolds for pressures up to $10 \times 10^5$ Pa are of cast iron. For higher pressures, the manifold is fabricated from plate steel, staybolted, and welded. The tubes are fastened rigidly to the manifold face plate and are supported in a close-fitting annular plate at the other end to permit expansion. Packing on the steam neck is normally graphite-asbestos. Ordinary rotating seals are similar in design to those depicted in Fig. 12-61, with allowance for the admission of small quantities of outside air when the dryer is operated under a slight negative internal pressure.

Steam-tube dryers are used for the continuous drying, heating, or cooling of granular or powdery solids which cannot be exposed to ordinary atmospheric or combustion gases. They are especially suitable for fine dusty particles because of the low gas velocities required for purging of the cylinder. Tube sticking is avoided or reduced by employing recycle, shell knockers, etc., as previously described; tube scaling by sticky solids is one of the major hazards to efficient operation. The dryers are suitable for drying, solvent recovery, and chemical reactions. Steam-tube units have found effective employment in

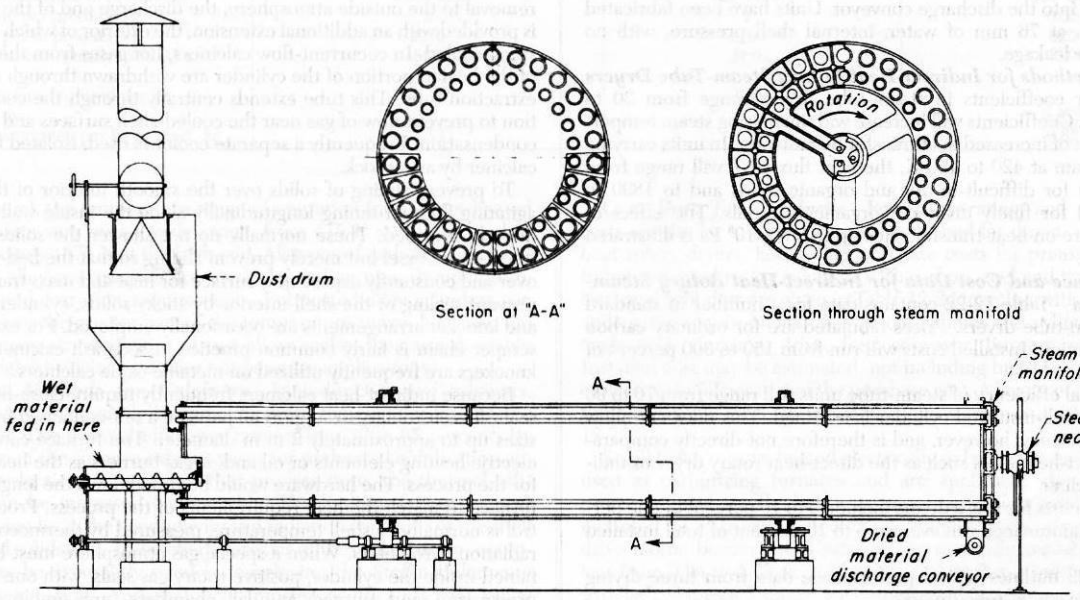



**FIG. 12-69** Steam-tube rotary dryer.

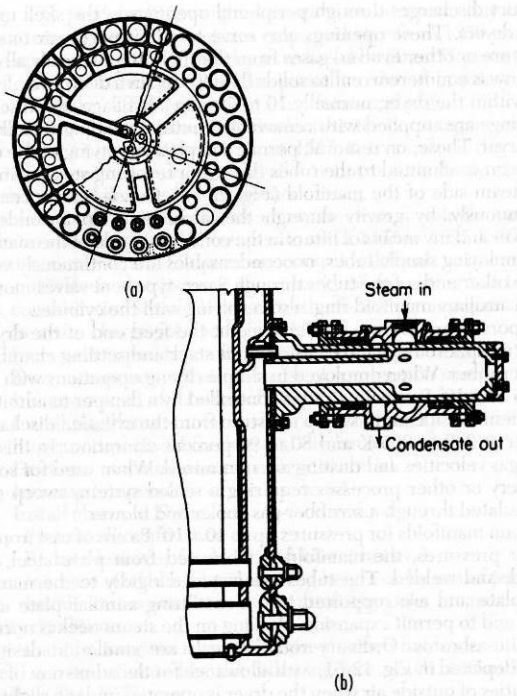



**FIG. 12-70** Rotary steam joint for a standard steam-tube dryer. *(a)* Section of cast-steam manifold. *(b)* Section of manifold and steam joint.

soda-ash production, replacing more expensive indirect-heat rotary calciners.

Special types of steam-tube dryers employ packed and purged seals on all rotating joints, with a central solids-discharge manifold through the steam neck to reduce the seal diameter. This manifold contains the product discharge conveyor and a passage for the admission of sweep gas. Solids are removed from the shell by special volute lifters and dropped into the discharge conveyor. Units have been fabricated for operation at 76 mm of water, internal shell pressure, with no detectable air leakage.

***Design Methods for Indirect-Heat Rotary Steam-Tube Dryers*** Heat-transfer coefficients in steam-tube dryers range from 30 to 85 J/(m²·s·K). Coefficients will increase with increasing steam temperature because of increased heat transfer by radiation. In units carrying saturated steam at 420 to 450 K, the heat flux $U\Delta T$ will range from 6300 J/(m²·s) for difficult-to-dry and organic solids and to 1890 to 3790 J/(m²·s) for finely divided inorganic materials. The effect of steam pressure on heat-transfer rates up to $8.6 \times 10^5$ Pa is illustrated in Fig. 12-71.

***Performance and Cost Data for Indirect-Heat Rotary Steam-Tube Dryers*** Table 12-22 contains data for a number of standard sizes of steam-tube dryers. Prices tabulated are for ordinary carbon steel construction. Installed costs will run from 150 to 300 percent of purchase cost.

The thermal efficiency of steam-tube units will range from 70 to 90 percent, if a well-insulated cylinder is assumed. This does not allow for boiler efficiency, however, and is therefore not directly comparable with direct-heat units such as the direct-heat rotary dryer or indirect-heat calciner.

Operating costs for these dryers include 5 to 10 percent of one person's time. Maintenance will average 5 to 10 percent of total installed cost per year.

Table 12-23 outlines typical performance data from three drying applications in steam-tube dryers.

**Indirect-Heat Calciners** Indirect-heat rotary calciners, either batch or continuous, are employed for heat treating and drying at higher

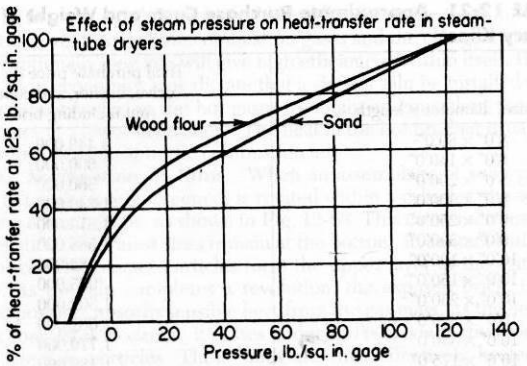



**FIG. 12-71** Effect of steam pressure on the heat-transfer rate in steam-tube dryers.

temperatures than can be obtained in steam-heated rotating equipment. They generally require a minimum flow of gas to purge the cylinder, to reduce dusting and are suitable for gas-sealed operation with oxidizing, inert, or reducing atmospheres. Indirect calciners are widely utilized and some examples of specific applications are as follows:

1. Activating charcoal
2. Reducing mineral high oxides to low oxides
3. Drying and devolatilizing contaminated soils and sludges
4. Calcination of alumina oxide-based catalysts
5. Drying and removal of sulfur from cobalt, copper, and nickel
6. Reduction of metal oxides in a hydrogen atmosphere
7. Oxidizing and "burning off" of organic impurities
8. Calcination of ferrites

This unit consists essentially of a cylindrical retort, rotating within a stationary insulation lined furnace. The latter is arranged so that fuel combustion occurs within the annular ring between the retort and the furnace. The retort cylinder extends beyond both ends of the furnace. These end extensions carry the riding rings and drive gear. Material may be fed continuously at one end and discharged continuously at the other. Feeding and solids discharging are usually accomplished with screw feeders or other positive feeders to prevent leakage of gases into or out of the calciner.

In some cases in which it is desirable to cool the product before removal to the outside atmosphere, the discharge end of the cylinder is provided with an additional extension, the exterior of which is water-spray-cooled. In cocurrent-flow calciners, hot gases from the interior of the heated portion of the cylinder are withdrawn through a special extraction tube. This tube extends centrally through the cooled section to prevent flow of gas near the cooled-shell surfaces and possible condensation. Frequently a separate cooler is used, isolated from the calciner by an air lock.

To prevent sliding of solids over the smooth interior of the shell, agitating flights running longitudinally along the inside wall are frequently provided. These normally do not shower the solids as in a direct-heat vessel but merely prevent sliding so that the bed will turn over and constantly expose new surface for heat and mass transfer. To prevent scaling of the shell interior by sticky solids, cylinder scraper and knocker arrangements are occasionally employed. For example, a scraper chain is fairly common practice in soda-ash calciners, while knockers are frequently utilized on metallic-oxide calciners.

Because indirect-heat calciners frequently require close-fitting gas seals, it is customary to support all parts on a self-contained frame, for sizes up to approximately 2 m in diameter. The furnace can employ electric heating elements or oil and/or gas burners as the heat source for the process. The hardware would be zoned down the length of the furnace to match the heat requirements of the process. Process control is normally by shell temperature, measured by thermocouples or radiation pyrometers. When a special gas atmosphere must be maintained inside the cylinder, positive rotary gas seals, with one or more pressurized and purged annular chambers, are employed. The diaphragm-type seal ABB Raymond (Bartlett-Snow TM) is suitable for pressures up to 5 cm of water, with no detectable leakage.

**TABLE 12-22 Standard Steam-Tube Dryers***

| Size, diameter × length, m | Tubes | | $m^2$ of free area | Dryer speed, r/min | Motor size, hp | Shipping weight, kg | Estimated price |
|---|---|---|---|---|---|---|---|
| | No. OD (mm) | No. OD (mm) | | | | | |
| 0.965 × 4.572 | 14 (114) | | 21.4 | 6 | 2.2 | 5,500 | $152,400 |
| 0.965 × 6.096 | 14 (114) | | 29.3 | 6 | 2.2 | 5,900 | 165,100 |
| 0.965 × 7.620 | 14 (114) | | 36.7 | 6 | 3.7 | 6,500 | 175,260 |
| 0.965 × 9.144 | 14 (114) | | 44.6 | 6 | 3.7 | 6,900 | 184,150 |
| 0.965 × 10.668 | 14 (114) | | 52.0 | 6 | 3.7 | 7,500 | 196,850 |
| 1.372 × 6.096 | 18 (114) | 18 (63.5) | 58.1 | 4.4 | 3.7 | 10,200 | 203,200 |
| 1.372 × 7.620 | 18 (114) | 18 (63.5) | 73.4 | 4.4 | 3.7 | 11,100 | 215,900 |
| 1.372 × 9.144 | 18 (114) | 18 (63.5) | 88.7 | 5 | 5.6 | 12,100 | 228,600 |
| 1.372 × 10.668 | 18 (114) | 18 (63.5) | 104 | 5 | 5.6 | 13,100 | 243,840 |
| 1.372 × 12.192 | 18 (114) | 18 (63.5) | 119 | 5 | 5.6 | 14,200 | 260,350 |
| 1.372 × 13.716 | 18 (114) | 18 (63.5) | 135 | 5.5 | 7.5 | 15,000 | 273,050 |
| 1.829 × 7.62 | 27 (114) | 27 (76.2) | 118 | 4 | 5.6 | 19,300 | 241,300 |
| 1.829 × 9.144 | 27 (114) | 27 (76.2) | 143 | 4 | 5.6 | 20,600 | 254,000 |
| 1.829 × 10.668 | 27 (114) | 27 (76.2) | 167 | 4 | 7.5 | 22,100 | 266,700 |
| 1.829 × 12.192 | 27 (114) | 27 (76.2) | 192 | 4 | 7.5 | 23,800 | 278,400 |
| 1.829 × 13.716 | 27 (114) | 27 (76.2) | 217 | 4 | 11.2 | 25,700 | 292,100 |
| 1.829 × 15.240 | 27 (114) | 27 (76.2) | 242 | 4 | 11.2 | 27,500 | 304,800 |
| 1.829 × 16.764 | 27 (114) | 27 (76.2) | 266 | 4 | 14.9 | 29,300 | 317,500 |
| 1.829 × 18.288 | 27 (114) | 27 (76.2) | 291 | 4 | 14.9 | 30,700 | 330,200 |
| 2.438 × 12.192 | 90 (114) | | 394 | 3 | 11.2 | 49,900 | 546,100 |
| 2.438 × 15.240 | 90 (114) | | 492 | 3 | 14.9 | 56,300 | 647,700 |
| 2.438 × 18.288 | 90 (114) | | 590 | 3 | 14.9 | 63,500 | 736,600 |
| 2.438 × 21.336 | 90 (114) | | 689 | 3 | 22.4 | 69,900 | 838,200 |
| 2.438 × 24.387 | 90 (114) | | 786 | 3 | 29.8 | 75,300 | 927,100 |

*Courtesy of Swenson Process Equipment Inc. (prices from November, 1994). Carbon steel fabrication; multiply by 1.75 for 304 stainless steel.

**TABLE 12-23 Steam-Tube Dryer Performance Data**

| | Class 1 | Class 2 | Class 3 |
|---|---|---|---|
| Class of materials handled | High-moisture organic, distillers' grains, brewers' grains, citrus pulp | Pigment filter cakes, blanc fixe, barium carbonate, precipitated chalk | Finely divided inorganic solids, water-ground mica, water-ground silica, flotation concentrates |
| Description of class | Wet feed is granular and damp but not sticky or muddy and dries to granular meal | Wet feed is pasty, muddy, or sloppy; product is mostly hard pellets | Wet feed is crumbly and friable; product is powder with very few lumps |
| Normal moisture content of wet feed, % dry basis | 233 | 100 | 54 |
| Normal moisture content of product, % dry basis | 11 | 0.15 | 0.5 |
| Normal temperature of wet feed, K | 310–320 | 280–290 | 280–290 |
| Normal temperature of product, K | 350–355 | 380–410 | 365–375 |
| Evaporation per product, kg | 2 | 1 | 0.53 |
| Heat load per lb product, kJ | 2250 | 1190 | 625 |
| Steam pressure normally used, kPa gauge | 860 | 860 | 860 |
| Heating surface required per kg product, $m^2$ | 0.34 | 0.4 | 0.072 |
| Steam consumption per kg product, kg | 3.33 | 1.72 | 0.85 |

In general, the temperature range of operation for indirect-heated calciners can vary over a wide range, from 475 K at the low end to approximately 1475 K at the high end. All types of carbon steel, stainless, and alloy construction are used, depending upon temperature, process, and corrosion requirements. Fabricated-alloy cylinders can be used over the greater part of the temperature range; however, the greater creep-stress abilities of cast alloys makes their use desirable for the highest calciner-cylinder temperature applications.

***Design Methods for Calciners*** In indirect-heated calciners, heat transfer is primarily by radiation from the cylinder wall to the solids bed. The thermal efficiency ranges from 30 to 65 percent. By utilization of the furnace exhaust gases for preheated combustion air, steam production, or heat for other process steps, the thermal efficiency can be increased considerably. The limiting factors in heat transmission lie in the conductivity and radiation constants of the shell metal and solids bed. If the characteristics of these are known, equipment may be accurately sized by employing the Stefan-Boltzmann radiation equation. Apparent heat-transfer coefficients will range from 17 $J/(m^2 \cdot s \cdot K)$ in low-temperature operations to 85 $J/(m^2 \cdot s \cdot K)$ in high-temperature processes.

***Cost Data for Calciners*** Power, operating, and maintenance costs are similar to those previously outlined for direct- and indirect-heat rotary dryers. Estimating purchase costs for preassembled and frame-mounted rotary calciners with carbon steel and type 316 stainless-steel cylinders are given in Table 12-24 together with size, weight, and motor requirements. Sale price includes the cylinder, ordinary angle seals, furnace, drive, feed conveyor, burners, and controls. Installed cost may be estimated, not including building or foundation costs at up to 50 percent of the purchase cost. A layout of a typical continuous calciner with an extended cooler section is illustrated in Fig. 12-72.

Small batch retorts, heated electrically or by combustion, are widely used as carburizing furnaces and are applicable also to chemical processes involving the heat treating of particulate solids. These are mounted on a structural-steel base, complete with cylinder, furnace, drive motor, burner, etc. Units are commercially available in diameters from 0.24 to 1.25 m and lengths of 1 to 2 m. Continuous retorts with helical internal spirals are employed for metal-heat-treating purposes. Precise retention control is maintained in these operations. Standard diameters are 0.33, 0.5, and 0.67 m with effective lengths up

**TABLE 12-24 Indirect-Heat Rotary Calciners: Sizes and Purchase Costs***

| Diameter, ft | Overall cylinder length | Heated cylinder length | Cylinder drive motor hp | Approximate Shipping weight, lb | Approximate sale price in carbon steel construction† | Approximate sale price in No. 316 stainless construction |
|---|---|---|---|---|---|---|
| 4 | 40 ft | 30 ft | 7.5 | 50,000 | $275,000 | $325,000 |
| 5 | 45 ft | 35 ft | 10 | 60,000 | 375,000 | 425,000 |
| 6 | 50 ft | 40 ft | 20 | 75,000 | 475,000 | 550,000 |
| 7 | 60 ft | 50 ft | 30 | 90,000 | 550,000 | 675,000 |

* ABB Raymond (Bartlett-Snow™).
† Prices for November, 1994.

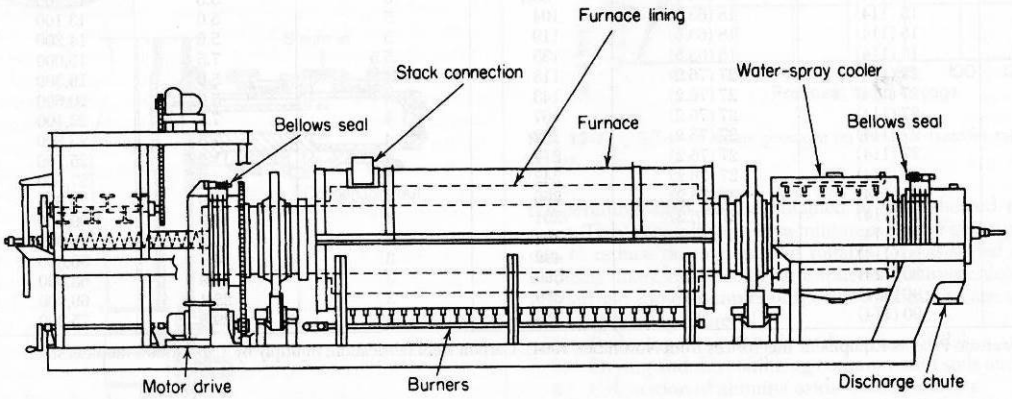



**FIG. 12-72** Gas-fired indirect-heat rotary calciner with a water-spray extended cooler and feeder assembly. (*ABB Raymond/Bartlett-Snow™.*)

to 3 m. These vessels are employed in many small-scale chemical-process operations which require accurate control of retention. Their operating characteristics and applications are identical to those of the larger indirect-heat calciners.

**Direct-Heat Roto-Louvre Dryer** One of the more important special types of rotating equipment is the Roto-Louvre dryer. As illustrated in Fig. 12-73, hot air (or cooling air) is blown through louvers in a double-wall rotating cylinder and up through the bed of solids. The latter moves continuously through the cylinder as it rotates. Constant turnover of the bed ensures uniform gas contacting for heat and mass transfer. The annular gas passage behind the louvers is partitioned so that contacting air enters the cylinder only beneath the solids bed. The number of louvers covered at any one time is roughly 30 percent. Because air circulates through the bed, fillages of 13 to 15 percent or greater are employed.

Roto-Louvre dryers range in size from 0.8 to 3.6 m in diameter and from 2.5 to 11 m long. The largest unit is reported capable of evaporating 5500 kg/h of water. Hot gases from 400 to 865 K may be employed. Because gas flow is through the bed of solids, high pressure drop, from 7 to 50 cm of water, may be encountered within the shell. For this reason, both a pressure inlet fan and an exhaust fan are provided in most applications to maintain the static pressure within the equipment as closely as possible to atmospheric. This prevents excessive in-leakage or blowing of hot gas and dust to the outside. For pressure control, one fan is usually operated under fixed conditions, with an automatic damper control on the other, regulated by a pressure detector-controller.

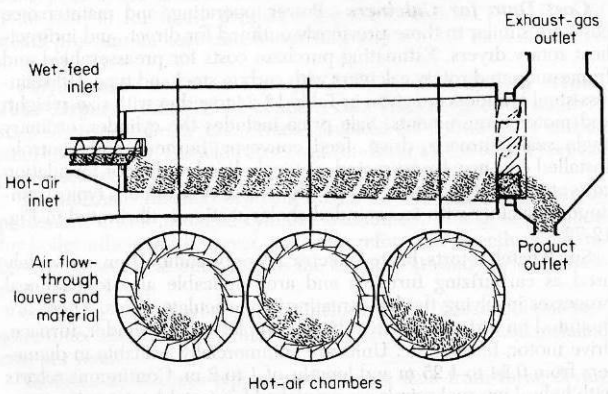



**FIG. 12-73** Link-Belt Roto-Louvre dryer. (*Material Handling Systems Division, FMC Corp.*)

In heating or drying applications, when cooling of the product is desired before discharge to the atmosphere, cool air is blown through a second annular space, outside the inlet hot-air annulus, and released through the louvers at the solids-discharge end of the shell.

Roto-Louvre dryers are suitable for processing coarse granular solids which do not offer high resistance to air flow, require intimate gas contacting, and do not contain significant quantities of dust.

Heat and mass transfer from the gas to the surface of the solids is extremely efficient; hence the equipment size required for a given duty is frequently less than required when an ordinary direct-heat rotary vessel with lifting flights is used. Purchase-price savings are partially balanced, however, by the more complex construction of the Roto-Louvre unit. A Roto-Louvre dryer will have a capacity roughly 1.5 times that of a single-shell rotary dryer of the same size under equivalent operating conditions. Because of the cross-flow method of heat exchange, the average $\Delta t$ is not a simple function of inlet and outlet $\Delta t$'s. There are currently no published data which permit the sizing of equipment without pilot tests as recommended by the manufacturer. Three applications of Roto-Louvre dryers are outlined in Table 12-25. Installation, operating, power, and maintenance costs will be similar to those experienced with ordinary direct-heat rotary dryers. *Thermal efficiency* will range from 30 to 70 percent.

## AGITATED DRYERS

**Description** An agitated dryer is defined as one on which the housing enclosing the process is stationary while solids movement is accomplished by an internal mechanical agitator. Many forms are in use, including batch and continuous versions.

**Field of Application** Agitated dryers are applicable to process-

**TABLE 12-25 Manufacturer's Performance Data for FMC Link-Belt Roto-Louvre Dryers***

| Material dried | Ammonium sulfate | Foundry sand | Metallurgical coke |
|---|---|---|---|
| Dryer diameter | 2 ft 7 in | 6 ft 4 in | 10 ft 3 in |
| Dryer length | 10 ft | 24 ft | 30 ft |
| Moisture in feed, % wet basis | 2.0 | 6.0 | 18.0 |
| Moisture in product, % wet basis | 0.1 | 0.5 | 0.5 |
| Production rate, lb/h | 2500 | 32,000 | 38,000 |
| Evaporation rate, lb/h | 50 | 2130 | 8110 |
| Type of fuel | Steam | Gas | Oil |
| Fuel consumption | 255 lb/h | 4630 ft³/h | 115 gal/h |
| Calorific value of fuel | 837 Btu/lb | 1000 Btu/ft³ | 150,000 Btu/gal |
| Efficiency, Btu, supplied per lb evaporation | 4370 | 2170 | 2135 |
| Total power required, hp | 4 | 41 | 78 |

*Material Handling Systems Division, FMC Corp. To convert British thermal units to kilojoules, multiply by 1.06; to convert horsepower to kilowatts, multiply by 0.746.

ing solids which are relatively free-flowing and granular when discharged as product. Materials which are not free-flowing in their feed condition can be treated by recycle methods as described in the subsection "Rotary Dryers." In general, agitated dryers have applications similar to those of rotating vessels. Their chief advantages compared with the latter lie in the fact that (1) large-diameter rotary seals are not required at the solids and gas feed and exit points because the housing is stationary, and for this reason gas-leakage problems are minimized. Rotary seals are required only at the points of entrance of the mechanical agitator shaft. (2) Use of a mechanical agitator for solids mixing introduces shear forces which are helpful for breaking up lumps and agglomerates. Balling and pelleting of sticky solids, an occasional occurrence in rotating vessels, can be prevented by special agitator design. The problems concerning dusting of fine particles in direct-heat units are identical to those discussed under "Rotary Dryers."

**Batch Vacuum Rotary Dryers** The more common type of vacuum rotary dryer consists of a stationary cylindrical shell, mounted horizontally, in which a set of agitator blades mounted on a revolving central shaft stirs the solids being treated. Heat is supplied by circulation of hot water, steam, or Dowtherm through a jacket surrounding the shell and, in larger units, through the hollow central shaft. The agitator is either a single discontinuous spiral or a double continuous spiral. The outer blades are set as closely as possible to the wall without touching, usually leaving a gap of 0.3 to 0.6 cm. Modern units occasionally employ spring-loaded shell scrapers mounted on the blades. The dryer is charged through a port at the top and emptied through one or more discharge nozzles at the bottom. Vacuum is applied and maintained by any of the conventional methods, i.e., steam jets, vacuum pumps, etc.

Another type of vacuum rotary dryer consists of a rotating horizontal cylindrical shell, suitably jacketed. Vacuum is applied to this unit through hollow trunnions with suitable packing glands. Rotary glands must be used also for admitting and removing the heating medium from the jacket. The inside of the shell may have lifting bars, welded longitudinally, to assist agitation of the solids.

The double-cone rotating vacuum dryer is a more common design. Although it is identical in operating design, the sloping walls of the cones permit more rapid emptying of solids when the dryer is in a stationary position. The older cylinder shape required continuous rotation during emptying to convey product to the discharge nozzles. As a result, a circular dust hood was frequently necessary to enclose the discharge-nozzle turning circle and prevent serious dust losses to the atmosphere during unloading. Several new designs of the double-cone type employ internal tubes or plate coils to provide additional heating surface.

On all rotating dryers, the vapor-outlet tube is stationary; it enters the shell through a rotating gland and is fitted with an elbow and an upward extension so that the vapor inlet, usually protected by a felt dust filter, will be at all times near the top of the shell.

A typical vacuum rotary dryer is illustrated in Fig. 12-74 and a double-cone vacuum dryer in Fig. 12-75.

Vacuum is used in conjunction with drying or other chemical oper-

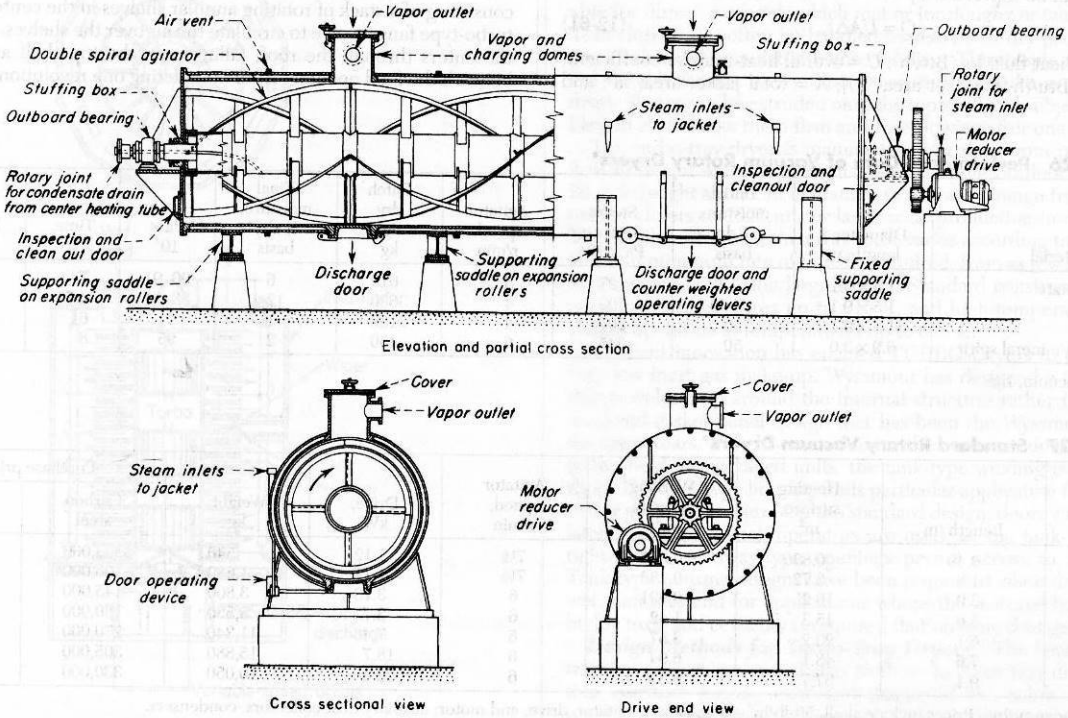



**FIG. 12-74** A typical vacuum dryer. (*Blaw-Knox Food & Chemical Equipment, Inc.*)