DRYING

1. Introduction

The separation operation of thermal drying converts a solid, semisolid, or liquid feedstock into a solid product by evaporation of the liquid into the vapor phase via application of heat. In the special case of freeze drying, which takes place below the triple point of the liquid being removed, drying occurs by sublimation of the solid phase directly into vapor phase. This definition excludes conversion of a liquid phase into a concentrated liquid phase (evaporation), mechanical dewatering by filtration, centrifugation, sedimentation, supercritical extraction of water, and so-called drying of liquids or gases using molecular seives (adsorption). Thermally induced phase change and production of a solid phase as end product are essential features of thermal drying (often also termed dehydration). It is an essential operation in chemical, agricultural, biotechnology, food, polymer, ceramics, pharmaceuticals, pulp and paper, textiles, mineral processing as well as wood processing industries. Over 500 types of dryers have been reported in the literature while ~100 distinct types are commercially available. It is the most energy-intensive unit operation and competes with distillation as one of the major energy-consuming industrial operations.

It is interesting to note some of the significant and unique features of industrial drying:

- Dryer operating temperatures and pressures range from below triple point to supercritical condition.
- Product size may range from submicron to tens of centimeters in thickness.
- Product porosity may range from near zero to 99.9%.
- Drying times for the various products may range from 0.25 s to 5 months.
- Production capacities may range from a fraction of a kilogram per hour to 100 t/h.
- Product speed in dryer may range from zero (stationary) to 2000 m/min.
- Heat for drying may be supplied continuously or intermittently by convection, conduction, radiation or by electromagnetic fields (microwave, radio frequency)

Gas drying is the separation of condensable vapors from noncondensable gases by cooling, adsorption (qv), or absorption (qv) (see ADSORPTION, GAS SEPARATION). Evaporation (qv) differs from drying in that feed and product are both pumpable fluids.

Reasons for drying include user convenience, shipping cost reduction, product stabilization, removal of noxious or toxic volatiles, and waste recycling (qv), and disposal. Environmental factors, such as emission control and energy efficiency, increasingly influence equipment choices. Drying operations involving toxic, noxious, or flammable vapors employ gas-tight equipment combined with recirculating inert gas systems having integral dust collectors, vapor condensers, and gas reheaters (see EXHAUST CONTROL, INDUSTRIAL).

Drying is a combination of material science and transient transport phenomena. Although we are typically concerned with heat and mass transfer rates to allow proper sizing of drying equipment, note that several rate processes, such as physical or chemical transformations that can also occur during dehydration. These processes are important since they determine the ultimate quality of the finished dry product as well as the mechanisms of the heat and mass transfer during drying. Physical transformations that can occur include shrinkage, puffing, crystallization, glass transition, etc.

Drying is an applied science; ie, drying theory is based on the laws of physics, physical chemistry, and the principles underlying the transfer processes of chemical and mechanical engineering: heat (see HEAT EXCHANGE TECHNOLOGY, HEAT TRANSFER), mass and momentum transfer, vaporization, sublimation, crystallization (qv), fluid mechanics, mixing (see MIXING AND BLENDING), and material handling. Drying is one of several unit operations involving simultaneous heat and mass transfer. However, drying is complicated by the presence of solids that interfere with heat, liquid, and vapor flow and retard the transfer processes, at least during the final drying stages or when a solids phase is continuous.

Because all drying operations involve processing of solids, equipment material handling capability is of primary importance. In fact, most industrial dryers are derived from material handling equipment designed to accommodate specific forms of solids. If possible, liquid separation from solids as liquid, by dewatering (qv) in a mechanical separation operation, should precede drying. Solids handling is made easier and liquid separation without vaporization is less costly (see FILTRATION; SEDIMENTATION; SEPARATION, CENTRIFUGAL). Evaporators, which have lower investment and operating costs than dryers, are also used to minimize dryer loads.

Industrial dryers can be classified according to numerous criteria. The following list is one such classification scheme:

- Mode of operation (batch, continuous, or semicontinuous).
- Heat input mechanism (convection, conduction, radiation, electromagnetic fields, combination of heat transfer modes) or adiabatic/nonadiabatic.
- State of material in dryer (stationary, moving, agitated, dispersed).
- Operating pressure (vacuum, atmospheric).
- Drying medium (air, superheated steam, flue gases).
- Drying temperature (below boiling point, above boiling point, below freezing point).
- Relative motion between drying medium and drying solids (cocurrent, countercurrent, mixed flow).
- Number of stages (single, multistage).

The above classification is rather coarse since each dryer type (eg, fluidized bed or spray dryer) can be subclassified into numerous varients.

Considering mode of heat transfer as the criterion for the classification, the heat transfer mechanisms used in drying are (*1*) convection from a hot gas that contacts the material, used in direct-heat or convection dryers; (*2*) conduction from a hot surface that contacts the material, used in indirect-heat or contact dryers; (*3*) radiation from a hot gas or hot surface that contacts or is within sight of the material, used in radiant-heat dryers; and (*4*) dielectric and microwave heating in high frequency electric fields that generate heat inside the wet material by molecular friction, used in dielectric, or radio frequency, and microwave dryers (1–3). In the last group, high internal vapor pressures develop and the temperature inside the material may be higher than at the surface (see MICROWAVE TECHNOLOGY). Many dryers effect more than one heat-transfer mechanism, but most dryers can be identified by the one that predominates.

Some of the improtant factors that govern the selection of industrial dryers are (*1*) personnel and environmental safety; (*2*) product moisture and quality attainment; (*3*) material handling capability; (*4*) versatility for accommodating process upsets; (*5*) heat- and mass-transfer efficiency; and (*6*) capital, labor, and energy costs. In general, much more qualitative and quantitative information is necessary to arrive at the most appropriate dryer type (or types) for a given application. Some of the additional information is listed below:

- Dryer throughput; mode of feedstock production (batch/continuous).
- Physical, chemical, and biochemical properties of the wet feed as well as desired product specifications.
- Upstream and downstream processing operations.

- Moisture content of the feed and product.
- Drying kinetics; moist solid sorption isotherms.
- Quality parameters (physical, chemical, biochemical).
- Safety aspects, eg, fire hazard and explosion hazards, toxicity.
- Value of the product.
- Need for automatic control.
- Toxicological properties of the product.
- Turndown ratio, flexibility in capacity requirements.
- Type and cost of fuel, cost of electricity.
- Environmental regulations.
- Floor space or head room in plant, etc.

Additionally there may be a need for information on material of construction, corrosion characteristics, toxicity, flammability, fire and explosion hazards, color/ texture/aroma requirements if any. Note that in some cases quality specifications on the finished product may govern the ultimate selection of the dryer. It is noteworthy that one must consider selection and design of a drying system (which includes predrying and postdrying stages as well as the drying stage) rather than just the dryer itself, although this article deals only with the dryer.

It is not uncommon to arrive at several different dryer types for the same application. For example, nickel ore concentrate is dried industrially using rotary, fluid-bed, flash, as well as spray dryers. Dryer selection is also affected by the availability of fuel as well as the relative cost of electricity and fossil fuel. For each new installation it is important to make the selection based on local conditions.

Costs are determined by energy, labor, capacity, and equipment materials of construction. Continuous dryers are less expensive than batch dryers and drying costs rise significantly if plant size is <500 t/year. Vacuum batch dryers are four times as expensive as atmospheric pressure batch dryers and freeze dryers are five times as costly as vacuum batch dryers. Once-through air dryers are half as costly as recirculating inert-gas dryers. Per unit of liquid vaporization, freeze, and microwave dryers are the most expensive. The cost difference between direct- and indirect-heat dryers is minimal because of the former's large dust recovery requirement. Drying costs for particulate solids at rates of 1×10^3–50×10^3t/year are about the same for rotary, fluid-bed, and pneumatic conveyor dryers, although few applications are equally suitable for all three (4,5).

2. Terminology

Adiabatic saturation temperature is the equilibrium gas temperature reached by unsaturated gas and vaporizing liquid under adiabatic conditions. (Note: Only for an air–water system, it is equal to the wet-bulb temperature defined below).

Bound moisture is liquid held by a material that exerts a vapor pressure less than that of the pure liquid at the same temperature. Liquid can be bound by solution in cell or fiber walls, by homogeneous solution throughout the material, and by chemical or physical adsorption on solid surfaces.

Capillary flow is liquid flow through the pores, interstices, and over the surfaces of solids that is caused by liquid–solid molecular attraction and liquid surface tension.

Constant rate period is the drying period during which the liquid vaporization rate remains constant per unit of drying surface.

Critical moisture content is that obtained when the constant rate period ends and the falling rate periods begin. Second critical moisture content specifies that remaining in a porous material when capillary flow dominance is replaced by vapor diffusion.

Dew point is the temperature at which a given unsaturated air–vapor mixture becomes saturated.

Dry basis describes material moisture content as weight of moisture per unit weight of dry material.

Dryer efficiency is the fraction of total energy consumed that is used to heat and vaporize the liquid.

Equilibrium moisture content is that which a material retains after prolonged exposure to a specific ambient temperature and humidity.

Evaporative efficiency in a direct-heat dryer compares vaporization obtained to that which would be obtained if the drying gas were saturated adiabatically.

Falling rate period is a drying period during which the liquid vaporization rate per unit surface or weight of dry material continuously decreases.

Fiber saturation point is the bound moisture content of cellular materials such as wood.

Free moisture content is the liquid content that is removable at a specific temperature and humidity. Free moisture may include bound and unbound moisture, and is equal to the total average moisture content minus the equilibrium moisture content for the specific drying conditions.

Humid heat is the heat required to raise the temperature of unit mass of dry air and its associated vapor through one degree [J/(kg · K) or Btu/(lb °F)].

Humidity, absolute is the mass of water vapor per unit mass of dry gas (kg/kg or lb/lb).

Humidity, relative is the ratio of partial pressure of water vapor in a gas-vapor mixture to equilibrium vapor pressure at the same temperature.

Internal diffusion occurs during drying when liquid or vapor flow obeys the fundamental diffusion laws.

Moisture is a word used commonly to describe any volatile liquid or vapor involved in drying; ie, it is not used selectively to mean only water.

Moisture gradient is the moisture profile in a material at a specific moment during drying, which usually reveals the mechanisms of moisture movement in the material up to the moment of measurement.

Percent saturation is the ratio of the partial pressure of a condensable vapor in a gas to the vapor pressure of the liquid at the same temperature, expressed as a percentage. For water vapor in air this is called percent relative humidity.

Unaccomplished moisture change is the ratio of free moisture present in a material at any moment during drying to that present initially.

Unbound moisture in a hygroscopic material is moisture that exerts the same vapor pressure as the pure liquid at the same temperature. Unbound

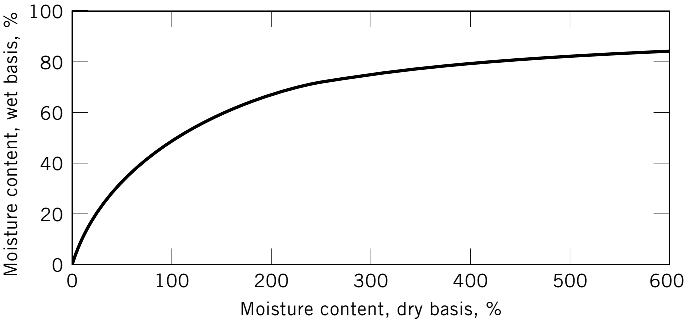


Fig. 1. Relationship between dry and wet weight bases, where dry basis = weight moisture per weight of dry material; wet basis = weight moisture per weight of moisture + dry material.

moisture behaves as if the material were not present. All moisture in a nonhygroscopic material is unbound.

Water activity is the ratio of vapor pressure exerted by water in a solid to that of pure water at the same temperature.

Wet bulb temperature is the liquid temperature attained when a large amount of air–vapor mixture is contacted with the surface. In purely convective drying, the drying surface reaches T_{wb} during the constant rate period.

Wet basis is a material's moisture content expressed as a percentage of the total weight of wet material. Although commonly employed, this basis is less satisfactory for drying calculations than the dry basis for which the percentage change of moisture per unit weight of dry material is constant at all moisture contents.

Figure 1 shows the relationship between dry and wet bases. When the wet basis is used to state moisture content, a 2–3% change at moisture contents >50% may represent a 10–30% change in evaporative load per unit weight of dry material.

3. Psychrometry

Before drying can begin, a wet material must be heated to such a temperature that the vapor pressure of the contained liquid exceeds the partial pressure of vapor already present in the surrounding atmosphere. The effect of a dryer's atmospheric vapor content and temperature on performance can be studied by construction of a psychrometric chart for the particular gas and vapor. Figure 2 is a standard chart for water vapor in air (6).

The wet bulb or saturation temperature curve indicates the maximum weight of vapor that can be carried by a unit weight of dry gas. For any temperature on the abscissa, saturation humidity is found by reading up to the saturation temperature curve, then across to the ordinate, kg/kg dry air. At saturation, the partial pressure of vapor in the gas is the vapor pressure of the

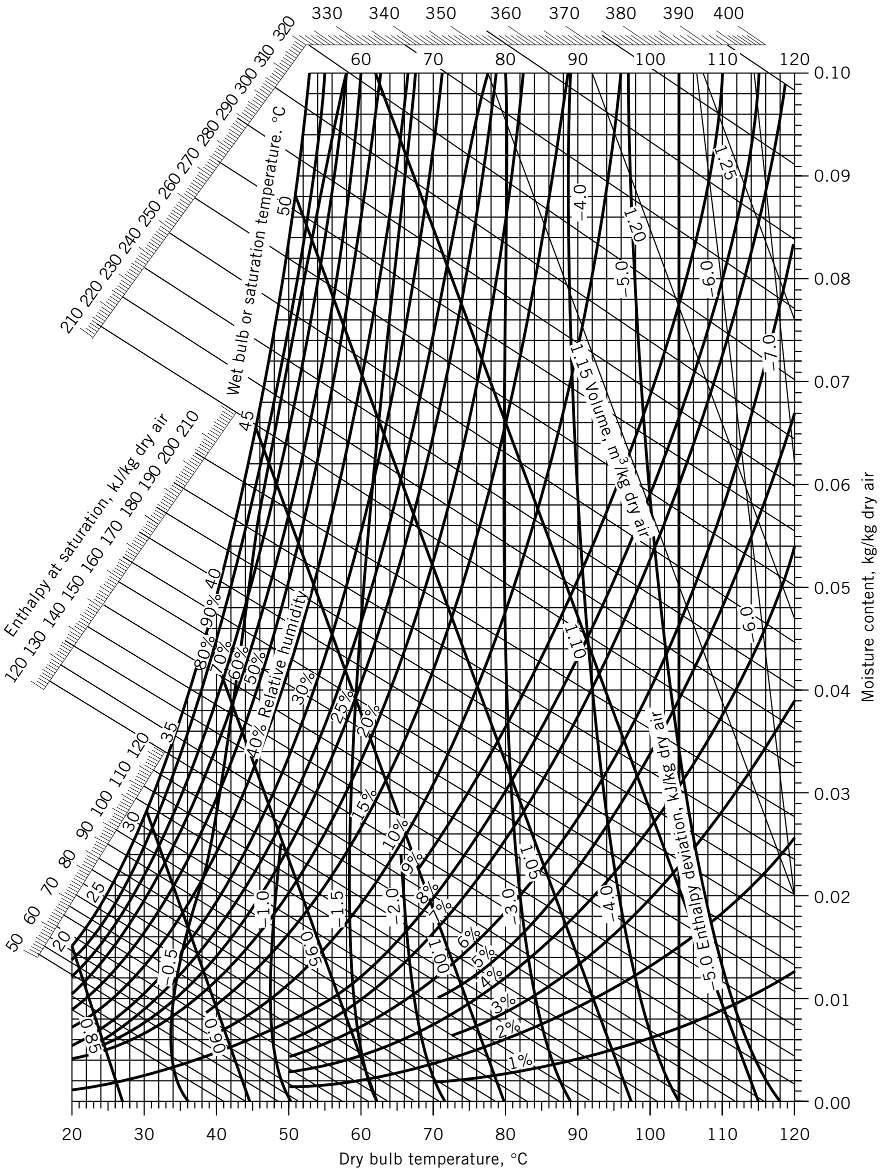


Fig. 2. Carrier psychrometric chart for air and water vapor at 101.325-kPa (1-atm) total pressure. Courtesy of Carrier Corp. (6).

liquid at the specific temperature:

$$H_s = \frac{p_s}{(P - p_s)} \frac{M_v}{M_g} \tag{1}$$

where H_s = saturation humidity, the weight ratio of moisture/kg dry gas; P = system total pressure; p_s = liquid vapor pressure at the gas temperature;

and M_v/M_g = molecular weight ratio of vapor to dry gas. Pressure is in units of kPa. At any condition less than saturation, humidity, H, is expressed similarly:

$$H = \frac{p}{(P - p)}\frac{M_v}{M_g} \tag{2}$$

where p = partial pressure of the vapor in the gas in kPa. Percent relative humidity, % rh, curves indicate percent saturation and are related to vapor pressure:

$$\%(\text{rh}) = 100\,\frac{p}{p_s} \tag{3}$$

In Figure 2, the lines, volume, m^3/kg dry air, indicate humid volume, which includes the volume of 1.0 kg of dry gas plus the volume of vapor it carries. Enthalpy at saturation data are accurate only at the saturation temperature and humidity; however, for air–water vapor mixtures, the diagonal wet bulb temperature lines are approximately the same as constant-enthalpy adiabatic cooling lines. The latter are based on the relationship:

$$(H - H_s) = -\frac{C_s}{L_s}\,(t - t_s) \tag{4}$$

where H_s and t_s are adiabatic saturation humidity, kg/kg, and temperature, K, respectively, corresponding to gas conditions represented by H and t; C_s = humid heat for humidity H in units of kJ/(kg · K); and L_s = latent heat of vaporization at t_s in kJ/kg. The slope of the constant-enthalpy adiabatic cooling line is $-C_s/L_s$, which is the relationship between temperature and humidity of gas passing through a totally adiabatic direct-heat dryer. The humid heat of a gas–vapor mixture per unit weight of dry gas includes the specific heat of the vapor

$$C_s = c_{pg} + c_{pv}H \tag{5}$$

where, c_{pg} = specific heat of the dry gas(air) and c_{pv} = specific heat of the vapor (water); both are in units of kJ/(kg · K). The wet bulb temperature is established by a steady-state, nonequilibrium relationship between heat and mass transfer when liquid evaporates from a small mass; eg, the wet bulb of a thermometer, into a sufficiently large mass of flowing gas, so that the latter undergoes no temperature or humidity change. Provided radiant heat transfer is insignificant, steady-state conditions are expressed by the relationship:

$$h_c(t - t_w) = -k'L_w(H - H_w) \tag{6}$$

where h_c = heat transfer by convection only in units of kW/(m^2 · K); k' = mass-transfer coefficient in kg/(s · m^2)(kg/kg); t = gas dry bulb temperature, K; t_w = gas wet bulb temperature, K; H = humidity at t; H_w = saturation humidity at t_w; and L_w = latent heat of vaporization at t_w, kJ/kg. For air–water vapor mixtures, it happens that $h_c/k \simeq C_s$. Therefore, because the ratio $(H-H_w)/(t-t_w) = -h_c/k'L_w$, the slope of the wet bulb temperature line in equation 6 is also approximately equal to $-C_s/L_s$, the slope of the constant enthalpy adiabatic cooling line in equation 4, and t_w is approximately the same as t_s. Enthalpy deviation curves in Figure 2 permit enthalpy corrections for humidities less than saturation and reveal the extent to which the wet bulb temperature lines do not coincide with constant enthalpy adiabatic cooling lines. For thorough treatment of wet-bulb thermometry, see Refs. 7–9. If system pressure is different from 101.3 kPa (1 atm), the humidity at measured dry-bulb and wet-bulb temperatures can be corrected (4). A separate chart is preferably constructed for the pressure of interest.

It is a coincidence that for water vapor in air, $h_c/k'C_s$ has a value of ~1. For most organic vapors encountered in drying, wet bulb temperatures are considerably higher than the adiabatic saturation temperatures, because of the higher molecular weights. Larger molecules do not diffuse as easily through air or through most inert gases. For example, values of $h_c/k'C_s$ at 101.3 kPa and 0°C for carbon tetrachloride, benzene, and toluene are 2.17, 1.87, and 1.98, respectively. Psychrometric charts for these vapors in air have been prepared (10). It is necessary to employ such charts for evaluating humidities and particularly material temperatures when vaporizing organic liquids in direct-heat dryers.

To illustrate changes in temperatures and humidities as gas passes through a direct-heat (convection) dryer, such as a pneumatic conveyor (see CONVEYING), rotary, or fluid-bed, several temperature profiles are drawn on Figure 3. Line AB is an adiabatic saturation line. Gas that enters the dryer at H_1 and t_1 cools and humidifies along line *a*. Assuming ideal adiabatic operation, the gas could leave at H_2 and t_2. The maximum humidity gain, were the gas cooled to saturation adiabatically, would be $(H_s - H_1)$ at t_s. The ratio, $(H_2 - H_1)/(H_s - H_1)$, is the ideal evaporative efficiency of this direct-heat dryer; however, as there are usually heat losses through the dryer enclosure and sensible heat absorbed by the solids, the gas temperature change is rarely accounted for completely by humidity gain; the outlet humidity, H_2, is less than the adiabatic saturation humidity at t_2, and the drying profile traces the path of line *b*. In dryers that employ internal

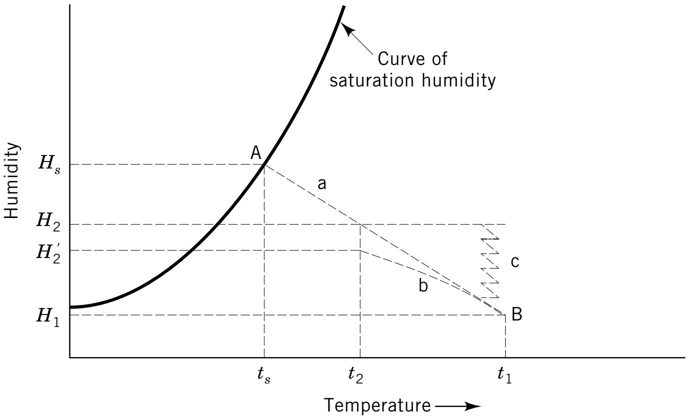


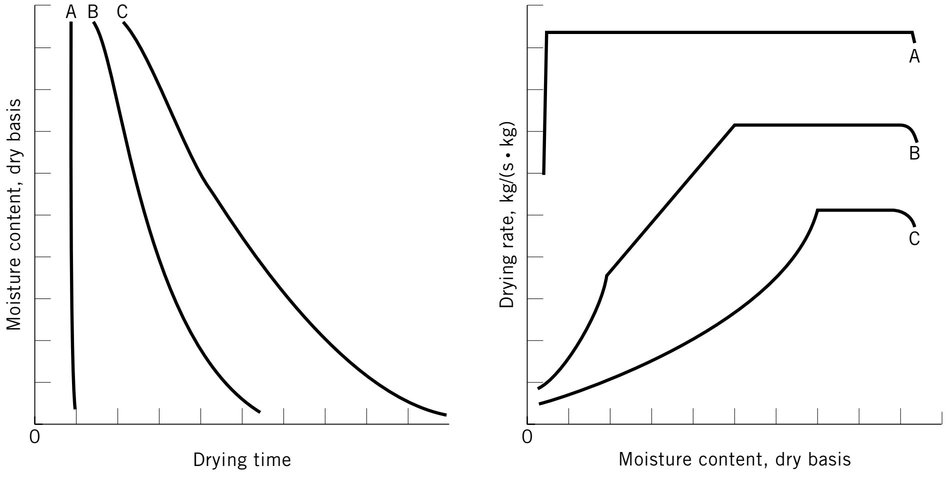
Fig. 3. Humidity chart illustrating changes in air temperature and humidity in adiabatic direct-heat (convection) dryers. AB is an adiabatic saturation line. Terms are defined in text.

steam coil gas reheaters, gas may pass several times through the material and heaters. Line *c* is a characteristic temperature–humidity profile.

4. Drying Mechanisms

4.1. Drying Periods. The goal of most drying operations is not only to separate a volatile liquid, but also to produce a dry solid of a desirable size, shape, porosity, density, texture, color, or flavor. An understanding of liquid and vapor mass-transfer mechanisms is essential for quality control. Mass-transfer mechanisms are best understood by measuring drying behavior under controlled conditions in a prototypic, pilot-plant dryer. No two materials behave alike and a change in material handling method or any operating variable, such as temperature or gas humidity, also affects mass transfer. For example, a layer of sand on a belt conveyor exhibits a different drying profile than sand dried on a vibrating (fluid-bed) conveyor.

Figure 4**a** shows drying time profiles for one material dried under three conditions. Corresponding rate profiles are in Figure 4**b**. Three products having



(a) (b)

Fig. 4. (**a**) Profiles of moisture content versus drying time; and (**b**) drying rate versus moisture content for a slightly soluble, water-wet organic powder centrifuge cake at 4.0-kPa (0.58 psi) absolute pressure using 120°C indirect heat. Profile A was produced in a continuous, high speed agitator dryer provided with scrapers to maintain a clean heating surface. Drying time was 45 s and at an almost entirely constant rate because of high solids surface exposure to the heating surface; the product particle size was 100% <150 μm. Profile B was produced in a paddle-agitated batch dryer also having scrapers. Drying time was 70 min, including periods of constant rate, capillary, and diffusion drying. Because of the much slower agitator, the product was a porous, 100–500-μm powder having some dust. Profile C was produced in a double-cone batch dryer using some dry recycle. Drying time was 120 min, and was almost entirely liquid and vapor diffusion-controlled because turning of the double-cone pelletized the wet material early in the cycle; the product was composed of rather dense (200–800 μm) spheres, having negligible dust.

uniquely different characteristics were produced by three different kinds of agitation. Other controllable drying conditions were constant. These profiles show that during drying several distinct periods may occur, which depend on how the material is handled. These are (*1*) an induction period during which wet material is heated to drying temperature; (*2*) a constant rate drying period indicated by the horizontal portions of the profiles in Figure 4**b**; (*3*) a period of decreasing rate shown by the sloping portions of two rate profiles during which the drying rate appears proportional to moisture content; and (*4*) a period of decreasing rate shown by the curved portions of two rate profiles during which the drying rate is evidently a more complex function of moisture content than simple proportionality.

The moisture content at the end of constant rate drying is the critical moisture content. Drying periods that follow are falling rate periods. The curved portion of profile B in Figure 4**b** is a second falling rate period; moisture content at the second break is the second critical moisture content. Profile C shows that drying may occur almost entirely in a falling rate period; a slight change in specified product moisture content can have a significant effect on drying time.

4.2. Constant Rate Drying.

During constant rate drying, vaporization occurs from a liquid surface of constant composition and vapor pressure. Material structure has no influence except moisture movement from within the material must be fast enough to maintain the wet surface. The vaporization rate is controlled by the heat-transfer rate to the surface. The mass-transfer rate adjusts to the heat-transfer rate and the wet surface reaches a steady-state temperature. The drying rate remains constant, therefore, as long as external conditions are constant. If heat is supplied solely by convection, the steady-state temperature is the gas wet-bulb temperature. When conduction and radiation contribute, eg, the material contacts and/or receives radiation from a warm surface, a liquid surface temperature between the wet-bulb temperature and the liquid's boiling point is obtained. In indirect-heat and radiant-heat dryers, where conduction and radiation predominate, surface liquid may boil regardless of ambient humidity and temperature. During constant rate drying, material temperature is controlled more easily in a direct-heat dryer than in an indirect-heat dryer because in the former the material temperature does not exceed the gas wet-bulb temperature as long as all surfaces are wet. For convection, all principles relating to simultaneous heat and mass transfer between gases and liquids apply. The steady-state relationship between heat and mass transfer at the liquid surface is

$$-\frac{dw}{d\theta} = \frac{h_t A}{L'_s}\left(t - t'_s\right) = k'_a A\left(p'_s - p\right) \tag{7}$$

where $dw/d\theta$ = moisture loss in kg/s; h_t = sum of all convection, conduction, and radiation components of heat transfer in kW/(m$^2 \cdot$K); A = effective surface area for heat and mass transfer in m^2; L'_s = latent heat of vaporization at t'_s in kJ/kg; k'_a = mass-transfer coefficient in kg/($s \cdot$ m^{2}kPa); t = mean source temperature for all components of heat transfer in K; t'_s = liquid surface temperature in K; p'_s = liquid vapor pressure at t'_s in kPa; p = partial pressure of vapor in the gas environment in kPa. It is often useful to express this relationship in terms of dry basis moisture change. For vaporization from a layer of material:

$$-\frac{dW}{d\theta} = \frac{h_t}{\rho_m d_m L'_s} \left(t - t'_s\right) \tag{8}$$

where $dW/d\theta$ = dry basis drying rate in units of kg/(s · kg); ρ_m = dry material bulk density in kg/m^3; and d_m = layer depth in m. A similar equation describes through-circulation drying in which gas flows through a bed of particles:

$$-\frac{dW}{d\theta} = \frac{h_t a}{\rho_m L'_s} \left(t - t'_s\right) \tag{9}$$

where a = the effective heat-transfer area per unit of bed volume in units of m^2/m^3. For a static bed, ρ_m can be measured, but the effective area of a particle bed is difficult to estimate except for uniform shapes such as cylinders and spheres (4). The practice is to conduct drying tests from which a value of the quantity $h_t a$ can be calculated by inserting property and drying data into equation 9. A modification of equation 9 is used to describe dryers in which gas flows among dispersed particles; eg, direct-heat rotary dryers. In dispersed-particle dryers, particle concentration per unit volume of dryer changes continuously and varies from place to place. For these, tests are conducted in a prototype of the commercial dryer and scale-up is based on average dispersion. The designer's concern is that the quality of particle dispersion in the gas in the scaled-up dryer duplicates that in the prototype or that a proper allowance is made for differences. From this procedure comes the concept of the volumetric heat-transfer coefficient:

$$U_a = h_t a \tag{10}$$

where U_a = an average volumetric heat-transfer coefficient having units of kW/(m^3 · K). For constant rate drying in dispersed-particle dryers, the general relationship is

$$-\frac{dw}{d\theta} = \frac{U_a V \Delta t_m}{L'_s} \tag{11}$$

where V = effective dryer volume in units of m^3; Δt_m = log mean temperature difference between all convection, conduction, and radiation heat sources and the material in K; and L'_s = latent heat of vaporization at the material surface temperature in kJ/kg. For estimating effective areas for various heat-transfer components, methods have been developed for tray dryers that may serve as a guide for other arrangements (11,12).

Convection heat transfer is dependent largely on the relative velocity between the warm gas and the drying surface. Interest in pulse combustion heat sources anticipates that high frequency reversals of gas flow direction relative to wet material in dispersed-particle dryers can maintain higher gas velocities around the particles for longer periods than possible in simple cocurrent dryers. This technique is thus expected to enhance heat- and mass-transfer performance. This is apart from the concept that mechanical stresses induced in material by rapid directional reversals of gas flow promote particle deagglomeration, dispersion, and liquid stream breakup into fine droplets. Commercial applications are needed to confirm the economic value of pulse combustion for drying.

Gas impingement from slots, orifices, and nozzles at 10–100-m/s velocities is used for drying sheets, films, coatings (qv), and thin slabs, and as a secondary heat source on drum dryers and paper (qv) machine cans. The general relationship for convection heat transfer is (13,14):

$$h_c = \alpha G^{0.78} \tag{12}$$

where α is a factor dependent on orifice-plate open area, hole, or slot size, and spacing between the plate, slots, or nozzles, and the heat-transfer surface; and G = hole, slot, or nozzle gas velocity in mass flow terms having units of kg/(s · m^2). Convection heat- and mass-transfer performance is enhanced by thinning of the laminar gas film immediately above the wet surface caused by direct gas impact on the surface. In a float dryer, cloth, sheet, or film is supported and conveyed on layers of gas which impinge on both sides of the material. This noncontact dryer is an impingement dryer modification.

4.3. Contact Drying. Contact drying occurs when wet material contacts a warm surface in an indirect-heat dryer (15–18). A sphere resting on a flat heated surface is a simple model. The heat-transfer mechanisms across the gap between the surface and the sphere are conduction and radiation. Conduction heat transfer is calculated, approximately, by recognizing that the effective conductivity of a gas approaches 0, as the gap width approaches 0. The gas is no longer a continuum and the rarified gas effect is accounted for in a formula that also defines the conduction heat-transfer coefficient:

$$\gamma = \frac{\gamma_g}{[1 + (p/s)]} \quad \text{or} \quad \frac{\gamma}{s} = h_d = \frac{\gamma_g}{(s + p)} \tag{13}$$

where γ_g = the continuum gas heat conductivity; γ = the rarified gas heat conductivity; s = local width of the gas gap; p = the product of the mean-free path of the gas molecules and a function of the accommodation coefficient (19); and h_d = the conduction heat-transfer coefficient based on heating surface. At the contact point, the gap goes to 0, and the coefficient reaches its maximum:

$$h_d(0) = \frac{\gamma_g}{p} \tag{14}$$

Figure 5 shows conduction heat transfer as a function of the projected radius of a 6-mm diameter sphere. Assuming an accommodation coefficient of 0.8, $h_d(0) = 3370$ W/(m^2 · K); the average coefficient for the entire sphere is 72 W/(m^2 · K). This variation in heat transfer over the spherical surface causes extreme nonuniformities in local vaporization rates and if contact time is too long, wet spherical surface near the contact point dries. The temperature profile penetrates the sphere and it becomes a continuum to which Fourier's law of nonsteady-state conduction applies.

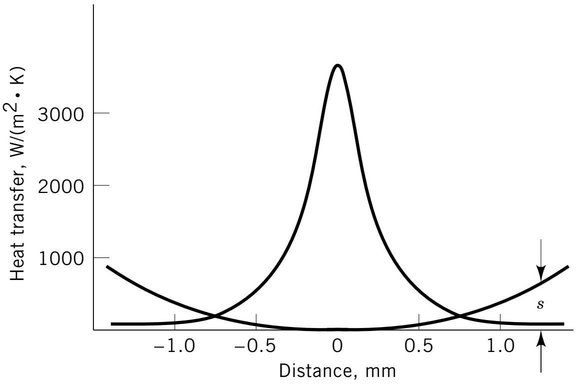


Fig. 5. Profile of conduction heat transfer across the gap between a sphere and a flat plate versus projected radius, $R = 3$ mm, of the sphere at 40°C and 2.1 kPa (0.30 psi); s is the width of the gas gap (17).

If the sphere is one of a mass of wet spherical particles, fastest drying occurs when the specific contact time of each particle approaches 0 in an ideally mixed bed. In general, gas thermal conductivity is independent of pressure between 150 Pa (0.022 psi) and 10^6 Pa (145 psi); <15 Pa (0.11 mmHg), conductivity is almost proportional to absolute pressure (20). The mean-free paths of gas molecules are inversely proportional to pressure. Equations 13 and 14 state that conduction heat transfer must decrease as pressure decreases. At very low pressures, conduction heat transfer approaches 0 and radiation alone is effective. Conduction heat transfer is also influenced by particle shape, surface roughness, and probably specific gravity. In agitator-stirred dryers, agitator speed, mixing efficiency, and heating surface clearance are important variables.

Between 1-s and 1-min specific contact time, conduction heat-transfer performance decreases theoretically as the 0.29 power of contact time. This is consistent with empirical data from several forms of indirect-heat dryers that show performance variation as the 0.4 power of rotational speed (21). In agitator-stirred and rotating indirect-heat dryers, specific contact time can be related to rotational speed provided that speed does not affect the physical properties of the material. To describe the mixing efficiency of various devices, the concept of a mixing parameter is employed. An ideal mixer has a parameter of 1.

$$N_{\mathrm{mech}} = \theta_s N \tag{15}$$

where N_{mech} is the mixing parameter, independent of thermal conditions; θ_s = specific particle contact time in seconds; N = agitator or dryer vessel rotational speed in units of 1/s. Values of N_{mech} reported for various dryers lie between 2 and 25. The principle applies to materials other than particulate solids. In the case of drum dryers used for solutions and slurries, capacity often can be increased by increasing drum speed, reducing specific contact time, and laying a thinner film on the drum surface. In the situations of cloth, paper, film, and fiber tow dried on heated cans, an additional resistance to drying is the inability of vapors and entrained gas to escape from between the moving material and the can surface, which also encourages shorter specific contact times.

4.4. Critical Moisture Content. Critical moisture content, which is the average material moisture content at the end of constant rate drying, is a function of material properties, the constant drying rate, particle size, or bed depth. Critical moisture content cannot be determined except by a prototypic drying test. For example, while a bed of material is drying during the constant rate period, assume that the drying rate is increased by increasing gas velocity over the material surface. The moisture gradient below the surface that causes liquid flow to replenish the surface becomes steeper and as the surface approaches dryness, the internal moisture content of the material is greater than it would have been had the gas velocity and drying rate not been increased. Critical moisture data are misleading, therefore, unless the exact conditions of drying are known (22,23).

Particle size distribution determines surface/mass ratios and the distance internal moisture must travel to reach the surface. Large pieces thus have higher critical moisture contents than fine particles of the same material dried under the same conditions. Pneumatic-conveyor flash dryers work because very fine particles are produced during initial dispersion and these have low critical moisture contents.

Case hardening refers to a circumstance in which a mass of nonporous, soluble, or colloidal material is dried at such a high rate during initial constant rate drying that the surface overheats and shrinks. Because liquid diffusivity decreases with moisture content, the barrier formed by the overdried surface prevents moisture flow from the interior of the mass to the surface. Case hardening of nonporous materials can be minimized by initially maintaining a high relative humidity environment and consequently a high surface equilibrium moisture content until internal moisture has time to escape.

4.5. Equilibrium Moisture Content. Equilibrium moisture content is the steady-state equilibrium reached by the gain or loss of moisture when material is exposed to an environment of specific temperature and humidity for a sufficient time. The equilibrium state is independent of drying method or rate. It is a material property. Only hygroscopic materials have equilibrium moisture contents. Clean beach sand is nonhygroscopic and has an equilibrium moisture content of 0. The same rules apply to organic vapors. Hygroscopic material retains a constant fraction of moisture under specific ambient humidity and temperature conditions. At constant temperature, if ambient humidity increases or decreases, an increase or decrease in moisture content follows, which is called equilibrium moisture because it is held in vapor pressure equilibrium with the partial pressure of vapor in the atmosphere. The reason it is retained even when the atmosphere is quite dry is that the retention mechanism reduces effective liquid vapor pressure. It is bound moisture because it is bound to material in solution or by adsorption and bound moisture behaves as if the atmosphere were saturated even when the atmosphere is not saturated relative to the unbound liquid's normal vapor pressure. Chemically combined liquid may behave like bound moisture depending on the nature of the chemical bond. Because equilibrium is influenced by partial vapor pressure in the atmosphere and the effective vapor pressure of the bound liquid, temperature and humidity are both important.

For many materials in the 15–50°C temperature range, equilibrium moisture content can be plotted versus relative humidity as an essentially straight line. Equilibrium moisture content appears independent of temperature and relates to Henry's law:

$$p = \mathrm{H}(x) \tag{16}$$

where p = partial vapor pressure in the atmosphere in kPa; H = Henry's constant; and x = dry basis moisture content. Henry's constant is a function of the unbound liquid's vapor pressure:

$$\mathrm{H} = f(p_s) \tag{17}$$

where p_s = the unbound liquid's vapor pressure; therefore, $p = f(p_s)\,(x)$, and since relative humidity = $100(p/p_s)$:

$$100(p/p_s) = 100f(x) \tag{18}$$

At any given relative humidity, x is constant. In a typical silica gel–air–water vapor system at 5–50°C, $p/p_s = 1.79(x)$, where p = partial pressure of vapor in the air; p_s = water-vapor pressure at the adsorption temperature; x = gel moisture content, kg/kg (24). For many materials, as the temperature increases >50°C, equilibrium moisture content decreases at constant relative humidity. Above 100°C at atmospheric pressure, saturation humidity for water vapor goes to infinity and the concept of relative humidity becomes meaningless; in fact, hygroscopic materials often can be dried in 100% superheated vapor atmospheres.

A profile of equilibrium moisture content versus percent relative humidity (Fig. 6) often is not linear because at high humidities a porous material may

Fig. 6. Equilibrium moisture content profiles versus relative humidity for a hygroscopic material.

retain condensed capillary moisture, whereas at low humidities moisture may be adsorbed in a single-molecular layer on capillary surfaces. The maximum bound moisture a material can hold is identified by the intersection of the equilibrium profile with the 100% relative humidity ordinate. A difference between adsorption and desorption profiles may have several causes. When material initially dries, shrinkage often closes many small capillaries that do not reabsorb moisture when the material is rewet. Also, some capillaries may be cul-desacs that resist vapor reentry once filled with gas. One reason for freeze drying solid foods is to minimize shrinkage and capillary closing so the dry residue can be reconstituted to its original moisture content more easily. On the other hand, for laboratory and pilot-plant studies, a once-dried material must never be rewet and reused for a drying test. In fact, once-dried material can never be returned, physically, to its original wet condition.

4.6. Falling Rate Drying. Heat transfer is limited by material conductivity, but the drying rate usually is controlled by internal liquid and vapor mass transfer. The principal mass-transfer mechanisms are (*1*) liquid diffusion in continuous, homogeneous materials; (*2*) vapor diffusion in porous and granular materials; (*3*) capillarity in porous and fine granular materials; (*4*) gravity flow in granular materials; (*5*) flow caused by shrinkage-induced pressure gradients; and (*6*) pressure flow of liquid and vapor when porous material is heated on one side, but vapor must escape from the other. It is possible to have multiple mass transfer mechanisms during a single drying operation. Note that mechanisms (*1)* and *(3)* from the above list are most common; most mathematical models assume these mechanisms to be applicable for simplicity.

Liquid flows by diffusion through materials in which the liquid is soluble, eg, single-phase systems like soap and gelatin. Movement of other bound moisture by liquid diffusion may occur, but the mechanisms probably are more complicated. Vapor flows by diffusion through the gas phase when liquid vaporizes below the surfaces of porous and granular materials. Wood and other cellular materials at moisture contents less than fiber saturation and the final drying stages of paper, textiles, and hydrophilic solids are examples. Vapor diffusion also occurs in the laminar sublayer of the gas film adjacent to the material surface during all drying periods. Diffusion-controlled (qv) is assumed in drying when liquid or vapor flow conforms to Fick's second law of diffusion, which applies to nonsteady-state systems (see DIFFUSION SEPARATION METHODS):

$$\frac{\delta c_{\mathrm{A}}}{\delta\theta} = D_{\mathrm{AB}}\,\frac{\delta^2 c_{\mathrm{A}}}{\delta z^2} \tag{19}$$

where c_{A} = concentration of one component in a two-component phase A and B; θ = diffusion time; z = distance in the direction of diffusion; and D_{AB} = binary diffusivity of the two components. This equation applies to one-dimensional diffusion in solids, liquids, and gases. The analogous Fourier laws apply to heat conduction. The units of the diffusion coefficient, $D_{\mathrm{AB}} = [\mathrm{mol/(s \cdot m^2)}]$ $(\mathrm{m^3/mol})(\mathrm{m}) = \mathrm{m^2/s}$, is the abbreviation usually employed both for this coefficient and the quantity thermal diffusivity in Fourier's heat conduction equations. The diffusion equation can be applied in two- and three-dimensions depending on the size and shape of the drying object. For nonisotropic materials, the diffusivities for both heat and mass may differ in different directions. For example, for paper, moisture diffusivity across the sheet is about one-tenth that in the fiber direction (in-plane). Effective diffusivities can also change with shrinkage or puffing of the product. For low temperature drying, it is often adequate to assume a liquid diffusion model since there is no evaporation of the liquid within the product; evaporation of the liquid occurs only at the product interface with the ambient.

In porous and granular materials, liquid movement occurs by capillarity and gravity, provided passages are continuous. Capillary flow depends on the liquid material's wetting property and surface tension. Capillarity applies to liquids that are not adsorbed on capillary walls, moisture content greater than fiber saturation in cellular materials, saturated liquids in soluble materials, and all moisture in nonhygroscopic materials.

When clay or similar material is dried, often a pressure gradient is developed by the forces of repulsion between particles as shrinkage brings the particles close together (25). This gradient forces liquid toward the surface and the resulting moisture profile resembles that characteristic of liquid diffusion.

When a layer of material pervious to gas flow is dried by through-circulation, a drying front usually moves through the layer in the direction of gas flow. In circumstances when material moisture content is sufficiently high, incoming gas is sufficiently hot and the material is of sufficient depth, the gas may cool adiabatically to saturation before it passes fully through the layer. The gas may then be subcooled by material contact with consequent liquid condensation within the layer. Condensed liquid fills the flow passages and is forced through the layer as liquid by the pressure of the blocked gas stream. This phenomenon is known as a vaporization-condensation sequence. It is an ingenious drying process usable most commonly on stationary or moving combination filter-dryers. Thermal efficiency exceeds 100%.

Usually, only one mass transfer mechanism predominates at any given time during drying, although several may occur together. In most materials, the mechanisms of internal liquid and vapor flow during falling rate drying are complex. Simultaneous heat transfer is a factor and falling rate drying rarely can be described with mathematical precision. Computer models for some materials are published (26), but most employ data from actual drying tests. In the absence of tests, the falling rate drying periods usually are studied on the assumption that internal mass transfer is controlled either by diffusion or capillarity depending on whether the material is porous or nonporous, soluble or not.

4.7. Diffusion.

Characteristic drying time and rate profiles for liquid diffusion appear as profile C in Figure 4. Figure 7 contains a diffusion drying curve for corn kernels and introduces the complicating factor in solids drying that liquid diffusivity is affected by material moisture content. The diffusion coefficient is not constant, but decreases as material moisture content decreases. Nonetheless, for evaluation of falling rate drying by liquid diffusion an integration of equation 19 is employed using four simplifying assumptions: (*1*) liquid diffusivity is independent of moisture content; (*2*) initial moisture distribution is uniform; (*3*) material size, shape, and density are unchanging; and (*4*) the material's equilibrium moisture content is constant. For material

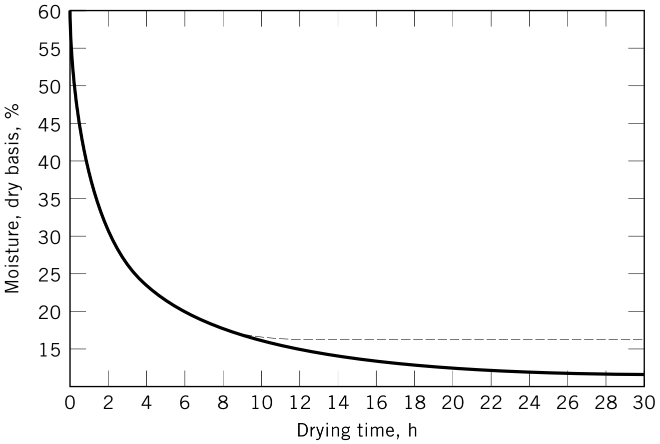


Fig. 7. Drying of corn kernels by liquid diffusion. The dashed line is that predicted by theory based on constant diffusivity. The solid curve shows actual performance at 38°C in air.

in the form of a slab:

$$\frac{W_\theta - W_e}{W_c - W_e} = \frac{8}{\pi^2}\left[\sum_{n=0}^{n=\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 D\theta(\pi/2d)^2\right]\right] \tag{20}$$

where W_θ, W_c, W_e are the moisture content at time θ, the first critical moisture content, and the equilibrium moisture content, respectively, so that the term on the left-hand side is the unaccomplished moisture change as defined; D = liquid diffusivity in units of m^2/s; θ = drying time in s; d = one-half the slab thickness for drying from both sides or total thickness for one-side drying in m. For long drying times, when $D\theta/d^2$ exceeds ~0.1,

$$\frac{W_\theta - W_e}{W_c - W_e} = \frac{8}{\pi^2} \exp\left[-D\theta(\pi/2d)^2\right] \tag{21}$$

from which a drying rate expression can be derived

$$-\frac{dW}{d\theta} = \frac{\pi^2 D}{4d^2}(W_\theta - W_e) \tag{22}$$

where $dW/d\theta$ = dry basis, drying rate in units of kg/(s · kg). When internal diffusion controls the drying rate, the rate is proportional to the free moisture content and diffusivity and inversely proportional to the square of material thickness. When equation 20 is plotted semilogarithmically with unaccomplished moisture change as the ordinate and the quantity, $D\theta/d^2$ as the abscissa, a straight line results for $(W_\theta - W_e)/(W_c - W_e)$ values <0.6. Equation 21 describes the straight line portion of this plot. An approximate relationship for falling rate drying by liquid diffusion is

$$\theta_f = \frac{4d^2}{\pi^2 D} \ln\left[\frac{8(W_c - W_e)}{\pi^2(W_\theta - W_e)}\right] \tag{23}$$

where θ_f = falling rate drying time in s. For nonhygroscopic materials, where $W_e = 0$, the unaccomplished moisture change becomes simply W_θ/W_c. Equations 20–23 apply to materials in layers or slabs. equation 19 is solved for other shapes as well (27), and these equations also may be used to study vapor diffusion in porous and granular materials (28) (see Fig. 7).

An analogy exists between mass transfer by diffusion and heat transfer by conduction. Each involves collisions between molecules and a gradient as the driving force which causes flow. For diffusion, this is a concentration gradient; for conduction, the driving force is an energy gradient. Fourier's nonsteady-state conduction equation is analogous to equation 19, Fick's second law of diffusion,

$$\frac{\delta T}{\delta \theta} = \left(\frac{k}{\rho c_p}\right) \frac{\delta^2 T}{\delta z^2} \tag{24}$$

where T = material temperature in K; θ = conduction time in s; z = distance in the direction of conduction in m; k = material thermal conductivity in units of $\mathrm{kW \cdot m/(m^2 \cdot K)}$; ρ = material density in $\mathrm{kg/m^3}$; and c_p = material specific heat in $\mathrm{kJ/(kg \cdot K)}$. The quantity, $k/\rho c_p$ is the thermal diffusivity of the material. This term is needed because temperature is a scale and not a quantity. The units of thermal diffusivity are $\mathrm{m^2/s}$, the same as for the diffusion coefficient. Solutions for equation 24 are available for many material shapes (29–32). During falling rate drying, material conductivity is important because liquid in porous materials is vaporized below the surface and heat must be conducted to this liquid by the dry material.

4.8. Capillarity. The outer surface of porous material has pore entrances of various sizes. As surface liquid is evaporated during constant rate drying, a meniscus forms across each pore entrance and interfacial forces are set up between the liquid and material. These forces may draw liquid from the interior to the surface. The tendency of liquid to rise in porous material is caused partly by liquid surface tension. Surface tension is defined as the work needed to increase a liquid's surface area by one square meter and has the units $\mathrm{J/m^2}$. The pressure increase caused by surface tension is related to pore size:

$$\Delta p = s_t / r \tag{25}$$

where Δp = the meniscus pressure increment resulting from surface tension in Pa; s_t = surface tension in $\mathrm{J/m^2}$; and r = pore radius in m. The excess pressure resulting from surface tension is always directed from the concave toward the convex surface of the meniscus.

A second property important to capillarity is surface wetting ability, which depends on properties of both the liquid and material. Wetting ability is indicated by the contact angle formed at the liquid–material interface; eg, water and clean glass have a contact angle of 0° and water rises in glass capillaries; mercury has a contact angle with glass of 132° and does not rise. When the contact angle is <90°, the force of surface adhesion exceeds liquid cohesive strength. Liquid molecules climb the capillary wall and surface tension causes a liquid column to follow. Liquids rise higher in fine capillaries because adhesive force is a wall effect. In very fine capillaries, meniscus radii become so small that the pressure increase caused by surface tension suppresses liquid vapor pressure. The effect is described in the Kelvin equation

$$\ln(p/p_s) = -2s_tM_1\cos\phi/(r\rho RT) \tag{26}$$

where p = effective vapor pressure of the capillary liquid in kPa; p_s = normal liquid vapor pressure in kPa, at temperature T in K; M_1 = liquid molecular weight in kg/mol; ρ = liquid density in kg/m^3; ϕ = liquid contact angle; $R = 8314$ J/(mol · K), the ideal gas constant; and r = pore radius in m. Calculated effects for water at 50°C and an s_t of 0.06791 J/m^2 give the following:

p/p_s	$r(\mu m)$
0.999	0.910
0.990	0.091
0.960	0.022
0.920	0.011
0.900	0.009
0.800	0.004
0.700	0.003
0.500	0.001

This is the capillary condensation phenomenon, which partly accounts for the hysteresis observed in adsorption profiles of porous materials.

At the critical moisture content, at the end of constant rate drying, dry areas begin to appear on the material surface. Menisci in the larger pores begin to withdraw below the surface. As drying continues, the surface becomes completely dry and liquid withdraws in even the smallest pores. This completes the first falling rate drying period that is represented by the straight line, decreasing rate portions of profiles A and B in Figure 4**b**. Final drying during the second falling rate period is accomplished by heat conduction to the liquid pockets and vapor diffusion through the pores to the material surface. In most porous materials during this period, the drying rate profile has the concave upward shape of diffusion control as appears in profile B, Figure 4**b**. In granular materials where pores are large and capillary forces are weak, gravity contributes to retreat of the liquid surface and both falling rate profiles may be straight lines (33). In other capillary porous materials dried from two sides, or in thin layers from one side, complete drying also may occur at a drying rate proportional to residual moisture content. Figure 8 is an example and falling rate drying often may be approximated by assuming the rate proceeds in this manner

$$-\frac{dW}{d\theta} = K\left(W_\phi - W_e\right) \tag{27}$$

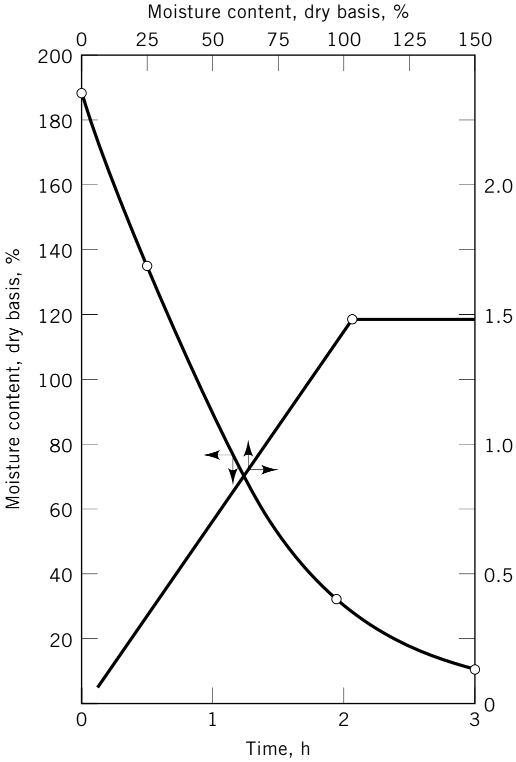


Fig. 8. Drying time and rate profiles for leather pasted on glass plates and dried in two temperature stages. Gas velocity = 5 m/s in parallel flow, 71°C in the first stage, 57°C in the second. The falling rate, drying rate is proportional to residual moisture content.

where K is a function of the constant rate, drying rate at the critical moisture content,

$$-\frac{dW}{d\theta_c} = K(W_c - W_e) \tag{28}$$

For a layer of wet material, using equation 8,

$$K = \frac{h_t}{\rho_m d_m L_s'}\left[\frac{(t - t_s')}{(W_c - W_e)}\right] \tag{29}$$

and

$$-\frac{dW}{d\theta} = \frac{h_t(t - t_s')}{\rho_m d_m L_s'}\left[\frac{(W_\theta - W_e)}{(W_c - W_e)}\right] \tag{30}$$

For materials that follow equation 30 the drying rate is inversely proportional to material thickness; falling rate drying time is estimated,

$$\theta_f = \frac{\rho_m d_m L_s'(W_c - W_e)}{h_t(t - t_s')} \ln\left[\frac{(W_c - W_e)}{(W_\theta - W_e)}\right] \tag{31}$$

A relationship for through-circulation drying analogous to equation 30 employs equation 9.

$$-\frac{dW}{d\theta} = \frac{h_t a(t - t_s')}{\rho_m L_s'} \left[\frac{(W_\theta - W_e)}{(W_c - W_e)}\right] \tag{32}$$

4.9. Drying Profiles. An application of diffusion principles to falling rate drying is exemplified in Figure 9 (34). Single drops of whole milk were dried by suspension in a warm air stream. Because of the rapid formation of surface films, drying was mostly by vapor diffusion. Drying times to an unaccomplished moisture change of 0.1 were 190 s and 300 s, respectively, for drops B and A. Based on Equations 22 and 23 and employing the square of the initial drop diameter for the d^2 dimension, drying time for the larger drop should have been 317 s. Neglecting the initially 8.0% greater moisture content of the larger

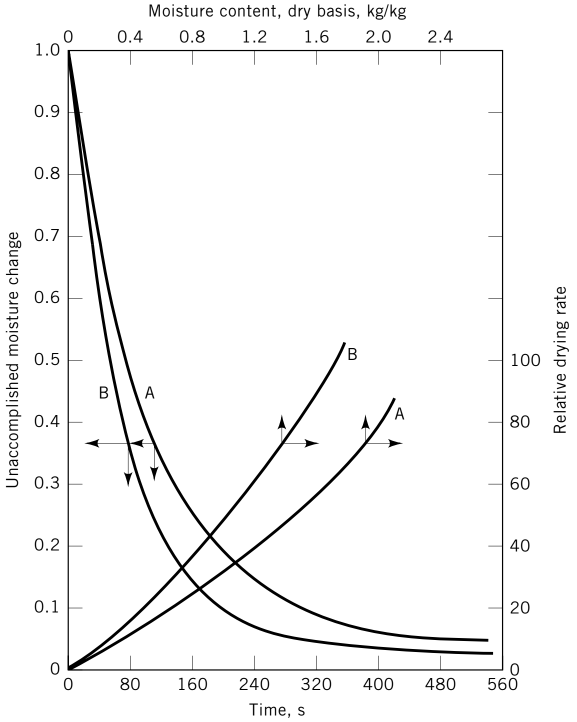


Fig. 9. Drying profiles for single drops of whole milk at 94°C and 0.6-m/s relative air flow. The initial diameter of drop A = 1900 μm, initial moisture content = 2.6 kg/kg, dry basis; drop B = 1470-μm initial diameter and 2.4-kg/kg moisture.

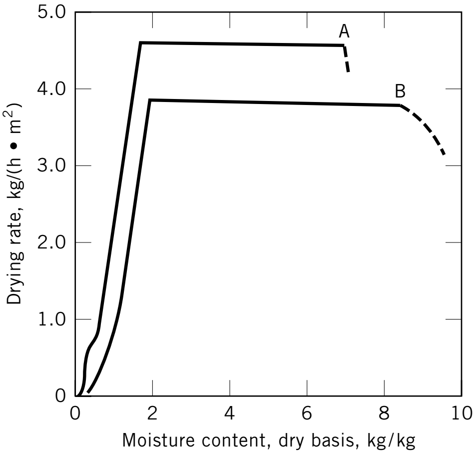


Fig. 10. Freeze drying profiles for A, whole milk, and B, nonfat milk. Heat was transmitted by radiation from heated wires above the frozen milk that rested in a transparent plastic tray. (---) is the induction period. Total pressure was 33 Pa (0.25 mmHg).

drop, drying time and rate varied with the 1.8 power of initial drop diameter. The error in predicting drying time for the larger drop is roughly 6%, which is probably attributable to material shrinkage during drying.

Figure 10 depicts freeze drying data for two milk products (35). Heat and mass transfer involved radiation to the material surface, conduction through the material to the retreating ice phase, and vapor diffusion through ice-free capillaries above the ice phase to the surface. Because both conduction heat transfer and vapor diffusion are distance dependent, a continuously falling rate drying profile would be expected. In freeze drying, however, it is necessary to control heat input to prevent temperature rise and melting of the ice. Also, it is necessary to limit vapor transport to condenser capacity so as to prevent drying chamber pressure rise. In this situation, dryer operation is controlled by external factors. The drying profile of necessity is mostly constant rate.

5. Dryers

Industrial dryers may be broadly classified by heat-transfer method as being either direct or indirect heat. Dryers evolved from material handling equipment and thus most types of industrial dryers are specially suited for certain forms of material. Dryers are also classified as being batch or continuous.

A batch dryer is best suited for small lots and for use in single-product plants. This dryer is one into which a charge is placed; the dryer runs through its cycle, and the charge is removed. In contrast, continuous dryers operate best under steady-state conditions drying continuous feed and product streams. Optimum operation of most continuous dryers is at design rate and steady state. Periods of low rate operation are energy inefficient; shutdowns and start-ups waste fuel and frequently include periods of offgrade production. Continuous dryers are unsuitable for short operating runs in multiproduct plants.

The material suitability of industrial dryers may be summarized as

Dryer	Material form
spray dryer	pumpable, heat-sensitive pastes, slurries, and solutions; all pumpables at high capacities
indirect-heat drum dryer	pumpable, heat-insensitive pastes, slurries, and solutions
pneumatic conveyor dryer	materials instantly dispersible into discrete particles in the drying gas
fluid-bed dryer	fluidizable particulate materials
spouted-bed dryer	particulate materials too coarse or uniform in size to fluidize adequately
hopper dryer	preheated coarse or uniform materials and beds pervious to gas throughflow
direct-heat rotary dryer	particulate materials too coarse, sticky, or unpredictable to be fluidized or spouted
indirect-heat rotary dryer	fine, dusty materials
double-cone (vacuum) dryer	particulate materials that do not stick together, ball, or pelletize during drying
agitator (vacuum) dryer	particulate materials that may stick together, ball, or pelletize until almost dry
through-circulation or band dryer	materials that can be formed into static beds pervious to gas throughflow
continuous conveyors	continuous webs, paper, fabric, film, and fiber tow
batch, cabinet, and tray dryers	small lots, batch identification, and single-product plants <500 t/year

5.1. Direct Heat Dryers. In direct-heat dryers, steam-heated, extended-surface coils are used for gas heating up to ~200°C. Electric and hot oil or vapor heaters are added for higher temperatures. Diluted combustion products are used for all temperatures. An increasingly popular technique for producing inert gas is to recycle the dryer exit gas and vapor as secondary dilution gas for incoming combustion products. Thereby the oxygen level in the dryer gas stream is reduced to safe levels for organic materials. This is usually less than 10% oxygen, but always material dependent. These are called self-inerting heaters.

If material must be protected from combustion product contact, gas may be heated indirectly by passing it through tubes in a furnace. A clean, high temperature gas is obtained, but fuel efficiency is 50–70% of direct combustion gas heaters. Unless metal surfaces are protected by insulating or refractory lining (see REFRACTORY COATINGS), maximum usable gas temperature is ~1000°C. For low temperature operations, gas may be dehumidified. It usually is more economical to recirculate gas back through the dehumidifier after each dryer pass than to continuously dehumidify fresh gas. Polymers dried to very low moisture contents for extrusion or solid-state polymerization require very dry gas regardless of drying temperature. It is more economical to predry these materials as low as possible using ambient humidity gas before final drying in very dry or inert gas.

In most direct-heat dryers, more gas is needed to transport heat than to purge vapor. Larger dust recovery installations are needed than for

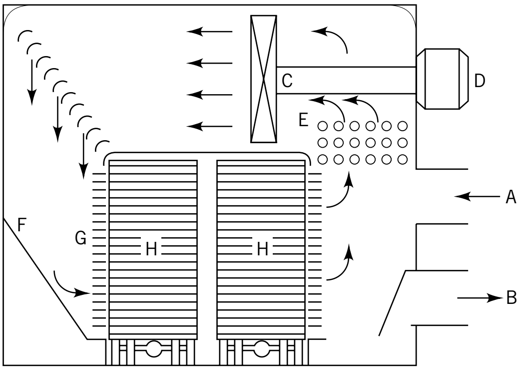


Fig. 11. Two-truck tray dryer. A, air inlet duct; B, air-exhaust duct with damper; C, axial flow fan; D, fan motor, 2–15 kW; E, air heaters; F, air-distribution plenum; G, distribution slots; and H, wheeled trucks and trays. The arrows indicate air and vapor flow pattern.

indirect-heat dryers handling the same vapor load. Strict environmental regulations have eliminated the capital cost advantage of direct-heat dryers, eg, dust recovery investment for a modern spray dryer often exceeds the dryer investment. The greater the gas velocity over, through, or impinging upon a material, the greater the convection heat-transfer coefficient. The more completely material is dispersed, ie, greater surface-to-mass exposure, the faster the drying rate. Gas and material flowing in the same direction in a continuous dryer is called cocurrent flow; gas flow opposing material flow is countercurrent flow. Gas flow across a material is parallel flow or crossflow. Gas flow normal to material flow is impingement flow or through-circulation.

Batch Compartment Dryers. Direct-heat batch compartment dryers are often called tray dryers because of frequent use for drying materials loaded in trays on trucks or shelves. Figure 11 illustrates a two-truck tray dryer. The compartment enclosure comprises insulated panels designed to limit exterior surface temperatures to $<50^\circ$C. Slurries, filter cakes, and particulate solids are placed in stacks of trays; large objects are placed on shelves or stacked in piles. An important design requirement is to assure gas flow uniformity, top-to-bottom of the compartment and back-to-front. This is essential but consumes fan power. Unless the material is dusty, gas is recirculated through an internal heater as shown. Only enough purge is exchanged so as to maintain needed internal humidity. For inert gas operation, purge gas is sent through an external dehumidifier and returned.

These dryers are economical only for a single-product rate <500 t/year, large objects on drying cycles >8 h, multiproduct operations, and batch identification. Tray loading depth and spacing must be uniform throughout the compartment. Tray loading is usually 2–10 cm. Parallel flow gas velocity is 1–10 m/s. Two-speed or variable speed fans are employed to provide higher gas velocity over the material during early drying stages. To minimize dusting, the fans reduce velocity after constant rate drying when heat transfer at the material surface is no longer the limiting drying mechanism. Deep tray loading reduces labor, but reduces overall capacity because falling rate drying time usually varies with the square of the loading depth. Shallow loading yields faster drying, but care is needed to ensure depth uniformity and labor is increased. Metal trays enhance heat flow through the tray walls and bottom. Screen-bottom trays permit vapor escape through the bottom; ie, two-side drying. Dryer efficiency should be 50–70%. Based on exposed material surface, vaporization rates are 0.2–2.0 kg/(h · m^2).

Through-circulation compartments employ perforated or screen bottom trays and suitable flow baffles so gas is forced through the material. If material is not inherently pervious to gas flow, it may be mechanically shaped into noodles, pellets, or briquettes. These dryers are used in small-scale operations to dry explosives, foods, and pigments. Dryer efficiency is 50–70%. Based on tray area, water vaporization rates are 1–10 kg/(h · m^2).

Continuous Conveyors. Continuous conveyors are characterized by continuous material flow without mixing. Dryer residence time is uniform for all material increments. Tray and tunnel conveyors comprise long insulated compartments through which material is moved on trucks or trays fastened together. Gas flow is usually parallel to material surface and may be cocurrent, countercurrent, or crossflow through recirculation fans and reheaters installed on each side of the compartment. Conveyor movement may be continuous, but usually must be interrupted periodically for introduction to new work at the wet end. Performance is otherwise comparable to batch compartments. Figure 8 data were obtained from a continuous conveyor dryer in which the glass plates were suspended vertically from an overhead chain conveyor.

Turbotray Dryers. The turbotray dryer is a continuous tray dryer comprising a stack of circular trays rotating slowly inside a vertical, insulated, cylindrical housing. Each rotating tray has uniformly spaced radial slots through which material is discharged to the tray below by a stationary plough once per revolution. Material falling through a slot is leveled to a uniform depth on the tray below by a stationary rake. After another revolution the process repeats. Wet material fed onto the uppermost tray moves down the stack in this manner and exits at the bottom. Circulating fans are carried on the central rotating shaft. Gas reheaters are mounted on the housing walls and gas flows across the trays parallel to material surface. Free flowing, nonsticky, and nondusty materials are dried more rapidly than in static beds. Having a stationary housing, the dryer finds employment in inert gas, solvent recovery (qv), and sublimation processes.

Foam-mat drying is a process in which a suspension, slurry, or solution is transformed into a stable foam by inert gas injection. The foam structure provides porosity and the mat is dried in trays or on a belt in a tunnel compartment, either under vacuum or with circulating gas. A free-flowing powder capable of rapid rehydration results. Fruit juices (qv) are dried successfully in this manner.

Continuous Web Dryers. Web dryers are used for polymer films, paper (qv), cloth, nonwoven fabrics (qv), printed and coated films, and printed fabrics. Gas impinges on or flows parallel to the moving material, called a web, that is supported by various methods. Electric and gas-fired radiant heaters also are usable on some dryer types. On a festoon conveyor the web is draped over sticks that are carried on chains through a heated enclosure. The web is unrestrained and free to shrink or stretch. Gas flow must be comparatively gentle to avoid excessive material movement. On single or multipass roll conveyors web is conveyed either vertically or horizontally over a series of driven rolls while web tension is controlled by differential roll speeds. The rolls are crowned slightly to hold axial alignment, but there is no restriction to lateral shrinkage. Because the web is restrained axially, however, high velocity gas impingement slots or nozzles may be employed on one or both faces. Radiant heaters are used in these dryers. For one-side drying of printed or coated webs, roll conveyors often are installed in ceiling-hung housings to conserve floor space. Tenter frames restrain a web in two directions and are employed to control shrinkage or to stretch a web during drying. It is an ideal setup for two-side gas impingement heating because the nozzles or orifice plates can be mounted close to the stretched web. The closer the spacing between the nozzles and web, the more effective are the impinging jets for heat and mass transfer. Tenter frames are also ideal for electric and gas-fired radiant heaters. Float dryers have closely mounted nozzles both for heat and mass transfer and to support and convey with minimum web tension. For long drying times, festoon or multipass roll conveyors are economical because a long length of web can be contained in a tall enclosure that occupies little floor space.

Through-Circulation Dryers. In through-circulation dryers, permeable materials are conveyed through enclosures on perforated plate or screen conveyors. The enclosures comprise a series of independent compartments, each having its own fans and recirculating gas heaters. Humid gas is removed at the material feed end of the enclosure; fresh dry gas is introduced at the dry end. Conveyor widths are 0.5–5.0 m; length may be 50 m in single or multiple conveyor tiers. Textile fibers, elastomer crumbs, plastic pellets, vegetables, and centrifuge and filter cakes are dried in 1–20-cm deep layers. On a conveyor area basis, drying rates up to 50 $\mathrm{kg/(h \cdot m^2)}$ of water are obtained at gas temperatures up to 400°C. Dryer efficiency is 50–70%. Centrifuge and filter cakes are preformed by extrusion into small noodles or by granulation in knife mills. Thin pastes and slurries are predried on indirect-heat drum dryers to form short sticks. Shear-thinning materials are scored and cut in small pieces. Powders are briquetted or pelleted (see POWDERS, HANDLING). Pin elevator feeders open fibrous clumps and lay a uniform bed on the conveyor. Fiber tow is distributed by oscillating chutes. Materials that shrink during drying may be redistributed on a second conveyor to prevent gas bypassing by ensuring full conveyor coverage.

Perforated-drum dryers are through-circulation conveyors specially suited for fiber staple, tow, and nonwoven fabrics. Material is continuously supported and conveyed on a series of perforated screen-covered suction drums installed in compartments similar in form to horizontal conveyor compartments. Compared to the former, drying is more uniform because the material is turned over as it passes from one drum to the next. Drying rates are greater than on perforated plate and screen conveyors because greater pressure drop and higher gas velocities can be taken through the drums. Because material is retained by drum suction, edge sealing is less of a problem as well.

Dispersed-Particle Dryers. Through-circulation conveyors realize relatively high drying rates because gas flows through the material and contacts more material surface than do parallel flow, cross-flow, and impingement arrangements. Nonetheless, if layer depth or material porosity is not uniform, gas channels through thin areas or larger passages and drying is not uniform. For drying particulate material, a better arrangement is one in which particles are separated completely, so that gas can flow freely among them. The drying rate for all particles of a given size then should be uniform. This is the purpose of all dispersed-particle dryers. Each is intended to provide optimum conditions of particle separation and surface exposure for materials having specific material handling requirements. A disadvantage, compared to continuous conveyors, is the loss of material plug-flow. Particle residence time in dispersed-particle dryers varies around an average and only the average can be calculated from feed rate, dryer fillage, and material density. Variations may be narrowed by various devices, but never eliminated completely. Figure 12 depicts relative particle residence time distributions among four dryers.

Rotary Dryers. A direct-heat rotary dryer is a horizontal rotating cylinder through which gas is blown to dry material that is showered inside. Shell diameters are 0.5–6 m. Batch dryers are usually one or two diameters long. Continuous dryers are at least four and sometimes ten diameters long. At each end, a stationary hood is joined to the cylinder by a rotating seal. These hoods carry the inlet and exit gas connections and the feed and product conveyors. One hood also attaches to the inlet gas heater. For continuous drying, the cylinder may be slightly inclined to the horizontal to control material flow. An array of material showering flights of various shapes is attached to the inside of the cylinder, as shown in Figure 13. Knockers are use to dislodge wet material that sticks to metal surfaces. A flight circle is usually 0.5 diameters long and adjacent circles are offset to minimize gas bypassing. Dry product may be recycled for feed conditioning if material is too fluid or sticky initially for adequate showering. Slurries also may be sprayed into the shell in a manner that the feed strikes and mixes with a moving bed of dry particles. Material fillage in a continuous

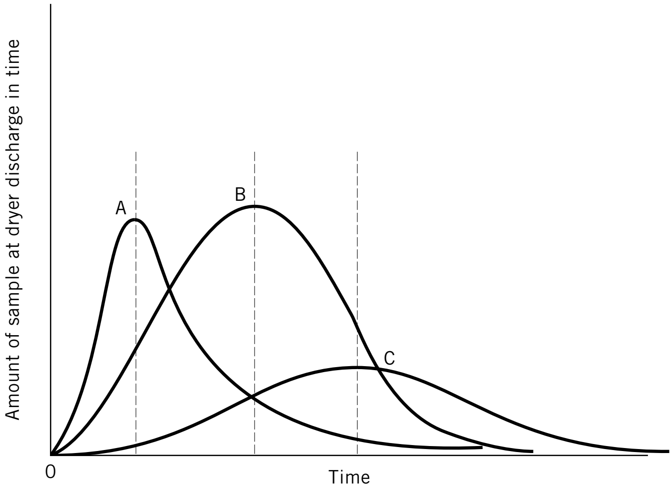


Fig. 12. Material residence time profiles in A, a pneumatic conveyor, B, a spray, and C, a rotary or fluid-bed dryer.

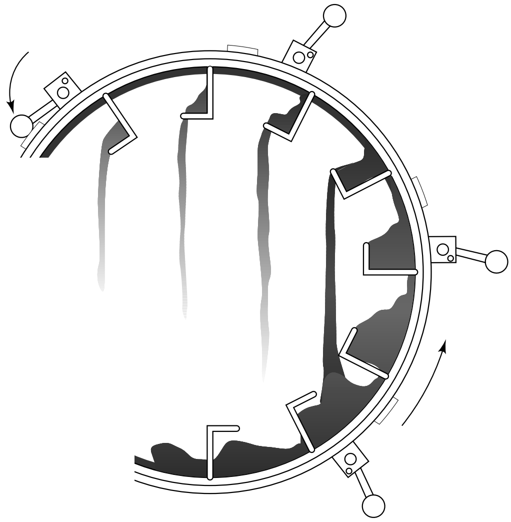


Fig. 13. Partial view through a direct-heat rotary dryer.

dryer is 10–18% of cylinder volume. Greater fillage is not showered properly and tends to flush toward the discharge end.

Gas flow in these rotary dryers may be cocurrent or countercurrent. Cocurrent operation is preferred for heat-sensitive materials because gas and product leave at the same temperature. Countercurrent operation allows a product temperature higher than the exit gas temperature and dryer efficiency may be as high as 70%. Some dryers have enlarged cylinder sections at the material exit end to increase material holdup, reduce gas velocity, and minimize dusting. Indirectly heated tubes are installed in some dryers for additional heating capacity. To prevent dust and vapor escape at the cylinder seals, most rotary dryers operate at a negative internal pressure of 50–100 Pa (0.5–1.0 cm of water).

Direct-heat rotary dryers are the workhorses of industry. Most particulate materials can somehow be processed through them. These dryers provide reasonably good gas contacting, positive material conveying without serious backmixing, good thermal efficiency in either cocurrent or countercurrent use, and good flexibility for control of gas velocity and material residence time. Usual drying rates are 10–50 kg water/($h \cdot m^3$) of cylinder volume.

Fluid and Spouted Beds. A fluid bed of particulate material is produced by introducing gas through a perforated plate, bubble caps, nozzles, or a ceramic grid beneath a static bed of material in such a manner that the solids are lifted uniformly and the particulate material and gas behave together like a boiling fluid (see FLUIDIZATION). For drying, the upward gas velocity is less than the terminal settling velocity of the particles, so few particles are conveyed out of the bed. At the same time, gas bubbles rise fast enough to lift particles directly above them. Particle motion is violent and a fluid bed exhibits intensive splashing at its surface. A substantial freeboard is included above the bed in the fluidizing vessel to allow particle disentrainment and full-back into the bed. Possibly because of a gas cushion that surrounds each particle as it circulates in the bed, particle attrition is usually moderate. For proper fluidization, it is essential that sufficient pressure drop be taken through the gas distributor so that the gas is distributed uniformly across the entire bed area independently of bed depth or bed behavior.

Spouted beds are used for coarse particles that do not fluidize well. A single, high velocity gas jet is introduced under the center of a static particulate bed. This jet entrains and conveys a stream of particles up through the bed into the vessel freeboard where the jet expands, loses velocity, and allows the particles to be disentrained. The particles fall back into the bed and gradually move downward with the peripheral mass until reentrained. Particle-gas mixing is less uniform than in a fluid bed.

Hopper Dryers. Gas-purged hopper dryers are used for granular materials that need holdup times measured in hours. Gas flow may be upflow or crossflow. Drying of pelleted and extruded animal feeds at <100°C are typical operations. Applications also include the continuous final drying of polymer pellets, such as nylon and polyester at temperatures of 150–200°C, prior to melt extrusion or solid-state polymerization. Gas flow is countercurrent to material flow and rarely exceeds 0.25 m/s. Because flow is insufficient to provide needed sensible heat, it is necessary to preheat the polymers to drying temperature before introduction into the hoppers. Drying usually starts at 0.1–0.5% moisture, so evaporative thermal loads are small. The hoppers serve essentially as holding vessels, at temperature, to permit release by diffusion of minute quantities of moisture. This prevents polymer degradation during later processing. A free-flowing character is the principal material requirement. Uniform material holdup is the principal hopper requirement, so all particles are retained the minimum required time. Average holdup usually is two to three times the minimum required.

Fluid and spouted beds offer ideal conditions for drying provided the feed material is consistently suitable for fluidization or spouting; however, if the drying operation is preceded by mechanical liquid separation, eg, centrifugation, use of these dryers should be considered with caution. Fluid and spouted beds do not tolerate sticky materials and oversize lumps. Successful applications are particulate and pelleted polymers, grain, sand, coal, and mineral ores, applications wherein the physical size and character of the feed material is known and controllable 100% of the time. Fluid and spouted beds are attractive for inert gas and organic liquid drying because the vessels are stationary. Superheated steam drying is carried out in fluid beds. This is an attractive alternative environmentally, but a process which was stalled for many years because of the lack of a suitable process vessel. The volumetric drying capacity of a fluid bed is many times that of a rotary dryer. The reason is that gas flowing through the latter moves between a series of parallel particle curtains in which the gas must be entrained and mixed to contact particle surfaces. In the former, small bubbles of gas enter through the distributor and immediately penetrate and mix with a cloud of particles. Figure 14 shows that whereas the dryer efficiency of a cocurrent rotary dryer and fluid bed may be comparable, because both are single-stage vessels, the vessel size requirements are quite different. To approach the dryer efficiency of a countercurrent rotary dryer, two or more fluid beds with countercurrent gas flow must be operated in series. Figure 15 shows one form of a two-stage fluid bed.

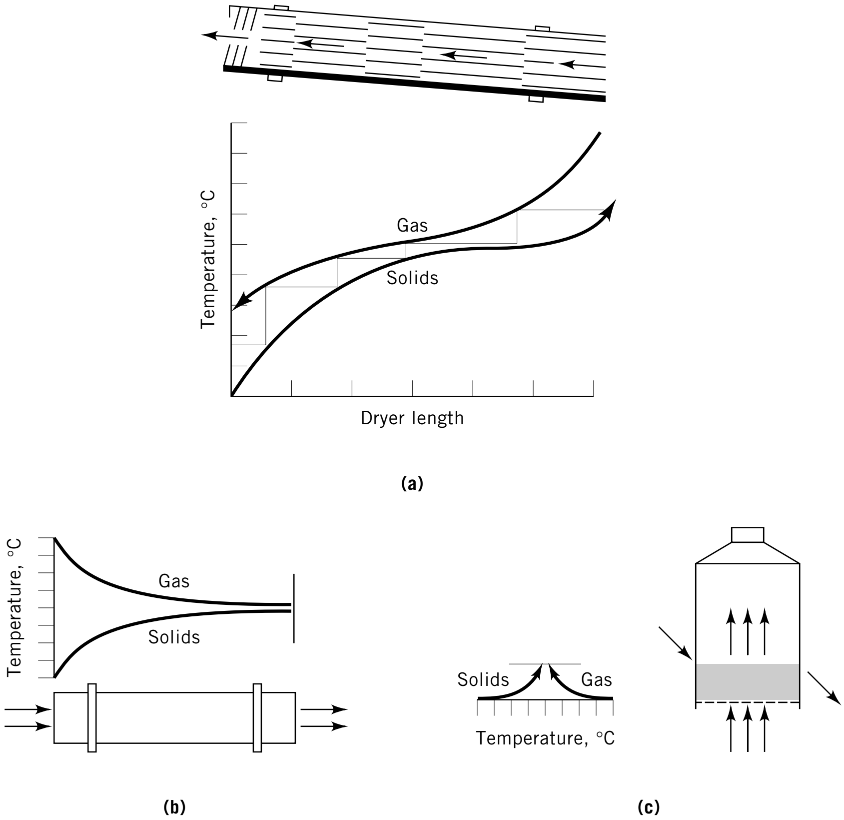


Fig. 14. Temperature profiles of gas and material in direct-heat dryers: (**a**) a countercurrent rotary dryer; (**b**) a cocurrent rotary dryer; and (**c**) a single-stage fluid bed.

A vibrating conveyor fluid bed dries while conveying particulate material on a screen-covered perforated deck. Gas is blown up through the material as it is conveyed mechanically and a particle dispersion much like that in a shallow fluid bed may be produced. Both mechanical and fluid energy contribute to fluidization. To minimize dusting, a lower fluidizing velocity is used than in a stationary fluid bed. Bed depth rarely exceeds 50 mm because mechanical energy is not transmitted through deeper beds effectively. Mechanical conveying encourages plug flow and several temperature stages may be incorporated in a single conveyor, but maximum material residence time is $\sim$5 min. As in stationary fluid beds, all feed material must be nonsticky and free-flowing.

Pneumatic Conveyors. Conveyors are adapted for drying by heating the conveying gas, although for drying, gas-to-material ratios must be greater than those sufficient for conveying (qv). Particle residence time is only a few seconds; in fact, most drying takes place near the feed point where the velocity difference between gas and material is the greatest. Conveying tubes rarely need to be $>$10 diameters long. For drying accompanied by deagglomeration, two or three pneumatic conveyors may be used in series and dry product may be recycled to the

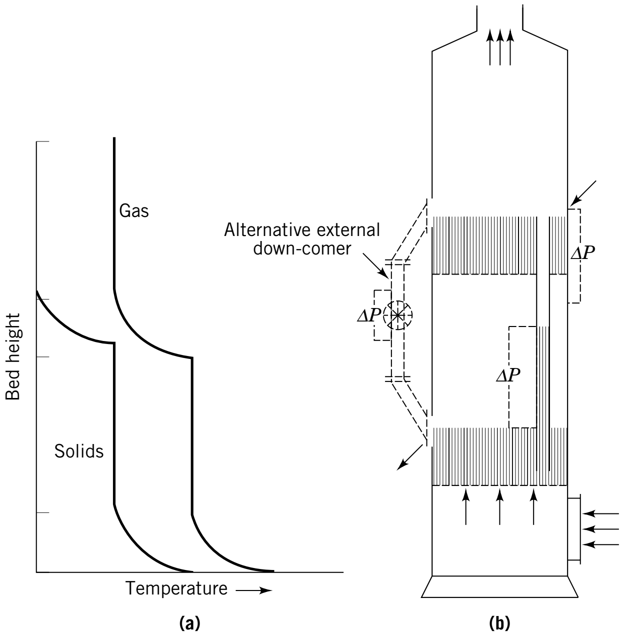


Fig. 15. A two-stage fluid bed dryer: (**a**) gas and material temperature profiles; (**b**) bed arrangements. ΔP = pressure drop through the upper stage distributor and bed.

first stage for feed conditioning. Figure 16 shows a simple dryer consisting of a venturi feeder, tube, and product collector. Knife, hammer, and roller mills are alternative feeding devices. A paddle conveyor, its paddles inclined to retard material flow, may be installed in place of the venturi to increase residence time and enhance dispersion. Conveying tube gas velocity is usually 25–35 m/s; venturi throat velocity is 100–140 m/s. The conveyor is a low power fluid energy mill and particle attrition may be severe. This dryer is single-stage and cocurrent,

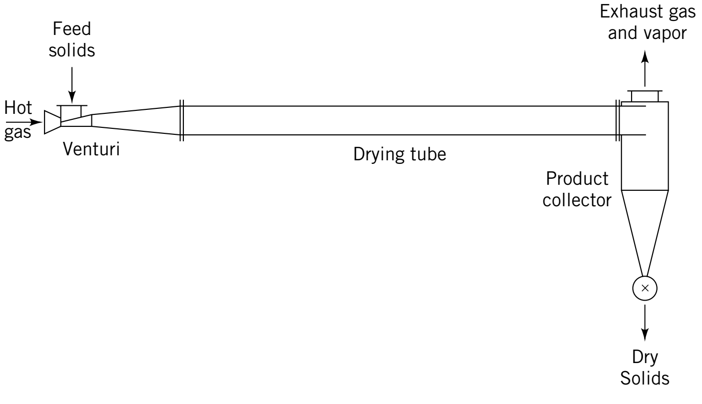


Fig. 16. Single-stage pneumatic conveyor dryer using a venturi for material acceleration and gas–solids mixing.

like the cocurrent rotary, but has much lower residence time. Indirect heat may be combined with direct heat by jacketing the conveying tube.

The principal applications of pneumatic conveyors are for materials that are nonsticky and readily dispersible in the gas stream as drying must be entirely constant rate. Many are employed as predryers ahead of longer residence time fluid-bed and rotary dryers in polymer drying operations.

Spray Dryers. A spray dryer is a large, usually vertical chamber through which hot gas is blown and into which a solution, slurry, or pumpable paste is sprayed by a suitable atomizer. Three atomizers are commonly used: (*1*) two-fluid pneumatic nozzles for very fine particles, between 10 and 100 μm, at rates <2 t/h; (*2*) single-fluid pressure nozzles for large particles, 125–500 μm, for dust-free products; and (*3*) centrifugal atomizers for various particle sizes at rates up to 150 t/h. The largest spray-dried particle is ∼1000 μm; the smallest is ∼5 μm. For large capacity dryers, the first two atomizers require multiple-nozzle setups, which may result in spray interference and particle agglomeration. In two-fluid nozzles, particle size is controlled by atomizing fluid pressure, usually compressed air or steam, and atomizing fluid/liquid ratio; therefore, very fine particles are obtainable with high fluid/liquid ratios and these nozzles are preferred for small, low capacity dryers. Pressure nozzles are limited by the fact that a change in feed rate or atomizing pressure causes a significant change in particle size distribution unless the nozzle orifice size is changed; high pressure feed pumps are required and, with abrasive materials, orifice wear may be rapid with a consequent increase in particle size distribution. Centrifugal atomizers are characterized by large capacity ranges, simple feed systems, narrow particle size distributions, and ease of particle size control by disk speed changes.

Because all drops must reach a nonsticky state before striking a chamber wall, the largest drop produced determines the size of the drying chamber. Chamber shape is determined by nozzle or disk spray pattern. Nozzle chambers are tall towers, usually having height/diameter ratios of 4–5. Disk chambers are large diameter and short, height being fixed by the fact that the discharge cone slope must be at least 60°, preferably 70° to discourage dry product accumulation on the sloping wall. For any evaporative load, chamber volume may be estimated by assuming a usable inlet gas temperature, exit gas and product at 100°C, and an average gas residence time of 15 s based on total chamber volume and exit gas humid volume, ie, from a simple dryer heat balance. This calculation does not obviate pilot-plant demonstrations, of course.

A spray dryer may be cocurrent, countercurrent, or mixed flow. Cocurrent dryers are used for heat-sensitive materials because relatively high inlet gas temperatures, up to 800°C, may be used while holding the exit gas and product near 100°C. Material temperature usually does not exceed the exit gas temperature provided chamber wall sticking is avoided. At any rate, a maximum dryer inlet gas temperature is ∼1100°C because of limits for materials of construction. Countercurrent spray dryers yield higher bulk density products and minimize hollow particle production. Figure 17 shows an open-cycle, cocurrent, disk atomizer chamber with a pneumatic conveyor following for product cooling. Alternative cocurrent chamber discharge arrangements, two of which accomplish particle classification, are shown in Figure 18. The scheme of a closed-cycle, gas recirculation dryer, the self-inerting system, is shown in Figure 19. Spray

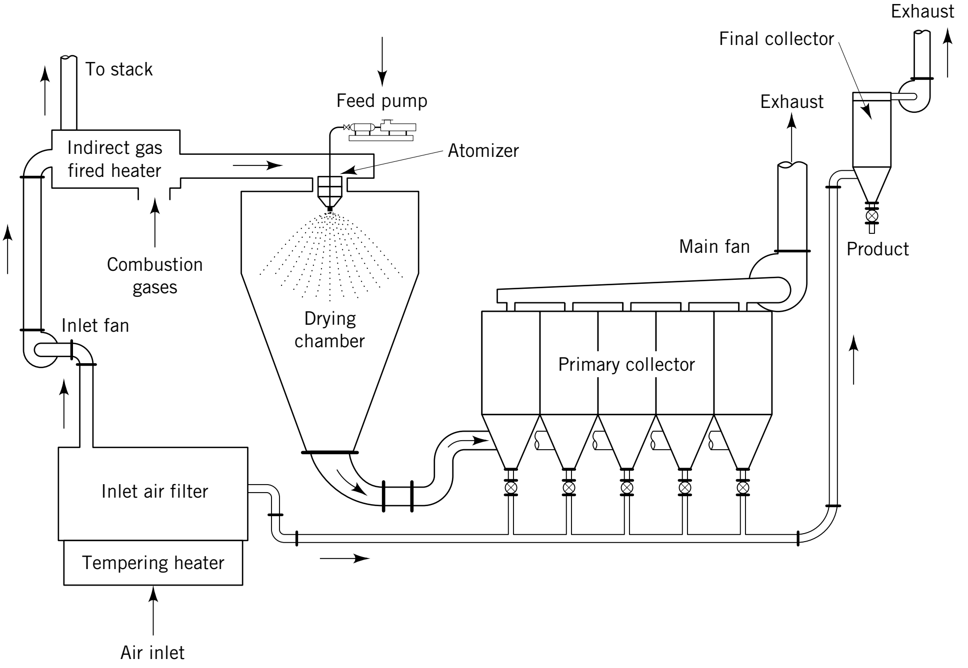


Fig. 17. Open-cycle, cocurrent, disk atomizer spray dryer. Courtesy of Niro Atomizer, Inc., Columbia, Md.

dryers are often followed by fluid beds for second-stage drying or fines agglomeration. Some two-stage dryers make the fluid bed the bottom of the spray chamber, in effect copying the method of slurry and solution drying obtained by spraying directly onto a fluid bed of dry particles (36). Overall, two-stage efficiency is improved. Spray dryer applications include coffee and milk powders, detergents, instant foods, pigments, dyes, and chemical reactions, eg, flue gas desulfurization.

Note that in recent years a horizontal chamber instead of a vertical one is also being studied and offered by a few vendors. It can be a single stage spray dryer or a two-stage one where the bottom floor of the spray chamber can accommodate a fluidized bed or through circulation dryer to remove internal moisture from surface-dry particles. Also, use of ultrasonic atomizer in a low pressure spray dryer has been proposed and marketed for heat sensitive, high value products.

5.2. Indirect-Heat Dryers. In indirect-heat dryers, heat is transferred mostly by conduction, but heat transfer by radiation is significant when conducting surface temperatures exceed 150°C. For jacketed vessels, steam is the common heating medium because the condensing-side film resistance is insignificant compared to material-side resistance. Hot water is circulated for low temperature heating. Heat-transfer oils or condensing organic vapors are used for high temperatures. Liquid film resistance to heat transfer is much greater than that of condensing vapor; therefore, liquids are better suited for simple heating jobs rather than for drying operations having high evaporative thermal loads.

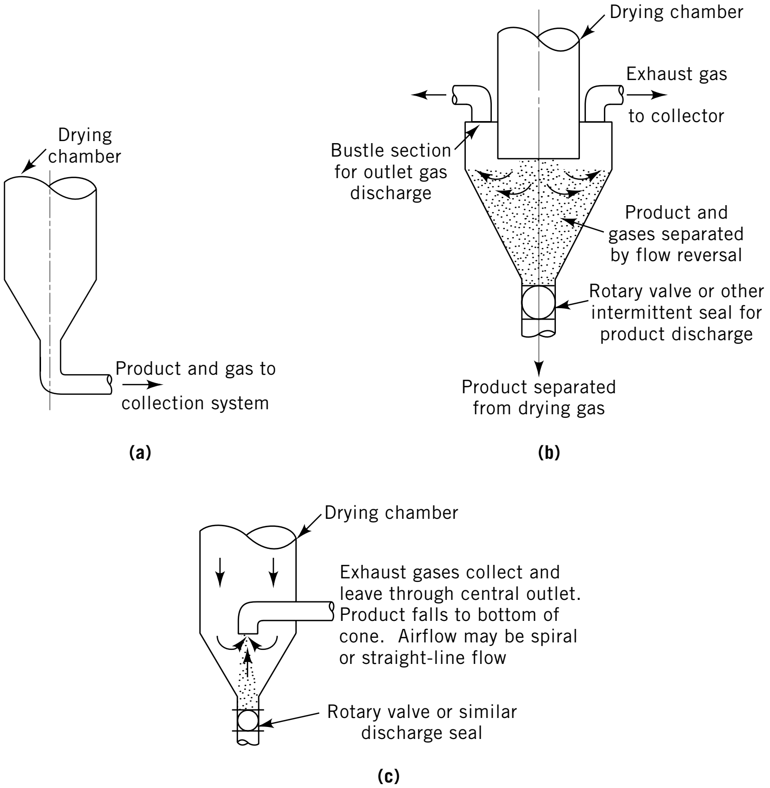


Fig. 18. Product removal arrangements for cocurrent spray dryers: (**a**) simple outlet; (**b**) product separation in an agglomeration chamber; and (**c**) classifying cone to reduce collector load.

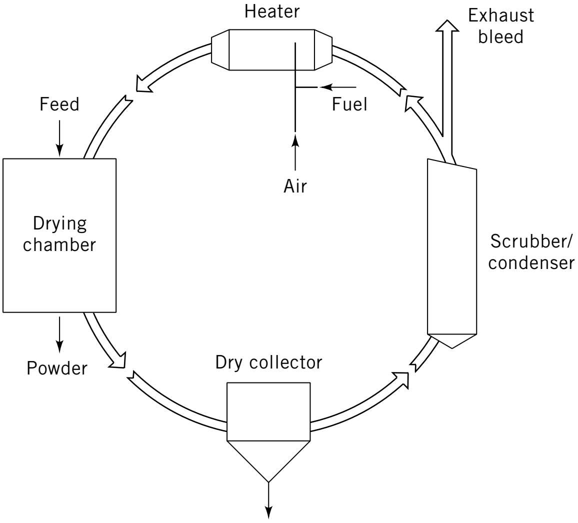


Fig. 19. Self-inerting spray dryer. Courtesy of Niro Atomizer, Inc., Columbia, Md.

Indirect-heat rotary dryers and calciners operating at temperatures exceeding 200°C usually are furnace enclosed. The cylinders are heated externally by electric or gas-fired radiant heaters and circulating combustion products. Regardless of heating medium or method, the primary heat-transfer resistance in indirect-heat drying is on the material side. The material-side heat-transfer coefficient is affected by the rapidity of material agitation, particle size, shape, porosity, density, and degree of wetness.

Based on dryer cost alone, indirect-heat dryers are more expensive to build and install than direct-heat dryers designed for the same duty. As environmental concerns and resulting restrictions on process emissions increase, however, indirect-heat dryers are more attractive because they employ purge gas only to remove vapor and not to transport heat as well. Dust and vapor recovery systems for indirect-heat dryers are smaller and less costly: to supply heat for drying, gas throughput in direct-heat dryers is 3–10 kg/kg of water evaporated; indirect-heat dryers require only 1–1.5 kg/kg of vapor removed. System costs vary directly with size, so whereas more money may be spent for the dryer, much more is saved in recovery costs. Wet scrubbers are employed for dust recovery on indirect-heat dryers because dryer exit gas usually is close to saturation. Where dry systems are employed, all external surfaces must be insulated and traced to prevent vapor condensation inside.

Atmospheric Dryers. The rotary steam-tube dryer is a horizontal rotating cylinder in which are installed one or more circumferential rows of steam-heated tubes. These tubes extend axially the length of the cylinder and are connected to a steam and condensate manifold at one end. Figure 20 is a dryer installation that incorporates a dry product recycle system for feed conditioning. An essential component of this system is the recycle storage hopper which must be sufficient for one dryer fillage and kept full at all times, so that an empty dryer can be started without immediately fouling tube surfaces with nonconditioned feed.

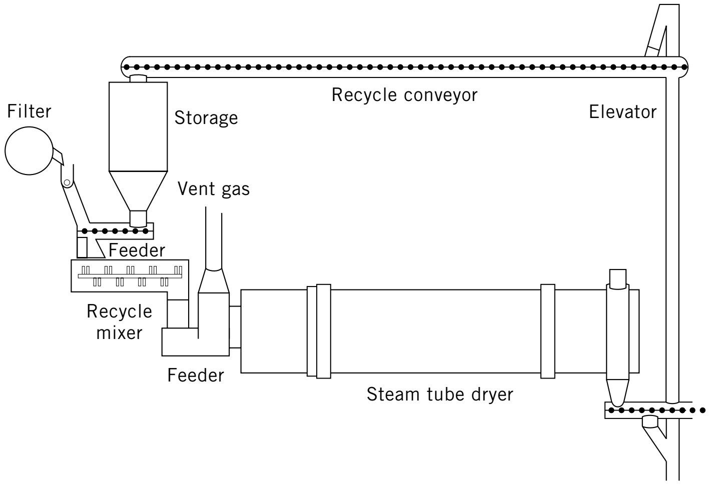


Fig. 20. Steam-tube rotary dryer using a dry product recycle and feed conditioning system.

Cylinder diameters are 0.5–4 m; length may be 40 m. A large dryer carrying 1500 m^2 of tube surface in three circumferential rows may evaporate 8-t/h water. A nominal water evaporation rate in a dryer operating with 1.0 MPa (150 psig) saturated steam is 5 kg/(h $\cdot$ m^2). Steam-tube dryers are built for steam-tube pressures up to 3.5 MPa (500 psig). Steam is introduced and condensate is removed through a rotary joint attached to the manifold at the product discharge end. The need for a rotary joint to introduce and remove the heating medium discourages the use of media other than steam and hot water. Feed is introduced and purge gas usually is removed through a stationary throat piece attached to the rotating cylinder by a sliding seal at the end opposite the manifold. The cylinder is slightly inclined to the horizontal to direct material flow and aid condensate drainage from the tubes. The diameter of the throat seal fixes maximum cylinder fillage, which rarely exceeds 20% of cylinder volume, but must be sufficient to ensure that the inner tube row is submerged in material.

To prevent dust and vapor escape at the cylinder seals, a negative internal pressure of 50–100 Pa (0.5–1.0 cm of water column) is maintained. Steam-tube dryers are suitable for any particulate material that can be conditioned so as not to stick to metal when dry. Because of relatively inexpensive heating surface and large capacities, these dryers are probably the most commonly used of the indirect-heat dryers. Gas- and vapor-tight seals sometimes are built for operations involving dangerous vapors and inert gas circulation, but these seals are expensive and high maintenance. Small installations excepted, stationary vessels are preferable.

Calciners. The indirect-heat rotary dryer or calciner resembles the direct-heat type except that the cylinder is enclosed in a furnace and showering flights are replaced by short turning bars attached to the inner cylinder wall, so that material rolls on itself but remains in contact with the wall. Heat is transferred by convection and radiation from the furnace heaters to the cylinder, then by conduction and radiation to the material. Cylinder volume fillage is limited to 5–8% to avoid formation of a core of unheated material in the center of the rolling bed. By choosing suitable metal alloys, cylinders can be fabricated for temperatures up to 1150°C, for drying operations that are too dusty for direct-heat dryers, at temperatures that are too high for steam-tube dryers. Evaporation rates for water are 5–15 kg/(h $\cdot$ m^2), based on total cylinder surface. Cylinders $<$1 m in diameter are employed commonly for calcining and heat-treating operations that require special atmospheres, including hydrogen. Gas-tight rotary seals work successfully on these vessels because cylinder and seal diameters are relatively small.

Fluid-Bed Dryers. Indirect-heat fluid-bed dryers are usually rectangular vessels in which are installed vertical pipe or plate coils. Figure 21 is a diagram of a two-stage, indirect-heat fluid-bed incorporating plate coil heaters. This dryer comprises a fully back-mixed section with a centrifugal feed distributor above, followed by a plug-flow section for final drying or cooling. The general design is used for drying several particulate polymers. Vertical plate coils provide heating surface up to 8 m^2/m^3 of bed volume. Excellent heat transfer is obtained in an environment of intense particle agitation and mixing. Water evaporation rates, based on panel surface, are 10–25 kg/(h $\cdot$ m^2). The fluidizing gas is also the vapor purge gas but contributes little heat to the operation, all of which is transferred

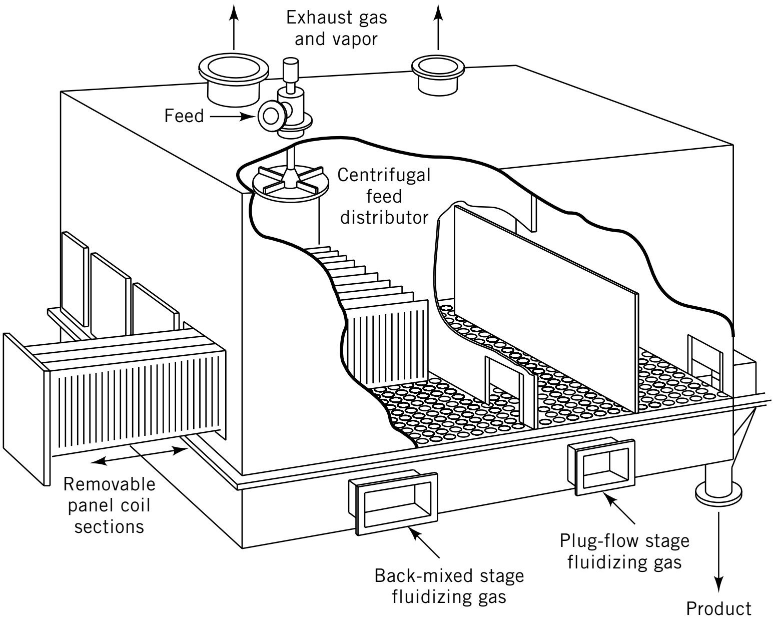


Fig. 21. Indirect-heat, two-stage, back mixed, and plug flow fluid-bed dryer. Courtesy of Niro Atomizer, Inc., Columbia, Md.

indirectly from the coils. Because of its favorable heat- and mass-transfer capabilities, flexibility for staging both temperatures and fluidizing gas velocities and the fact that the vessel is stationary, so rotary seals are not needed except for the feed distributor shaft, an indirect-heat fluid bed is an ideal vessel for vapor recovery and drying in special atmospheres.

Screw Conveyors. Indirect-heat screw conveyor dryers carry hollow, double-wall screws heated with saturated steam or hot oil. The conveyor trough may be jacketed as well, but the trough is only a small fraction of the total heating surface, and because there is a fairly wide clearance between the screw tips and the jacket, transfer coefficients are low. One trough may carry up to four parallel heated screws. A popular arrangement used for both batch and continuous drying consists of two screws that convey in opposite directions in a single trough. This internal recycle arrangement is used for drying slurries and solutions. A bed of dry particles is loaded, circulated, and heated. Feed material is sprayed onto the hot moving bed on one side of the dryer, mixed, and dried by contact with the circulating hot solids. Product is discharged through an overflow weir on the opposite side. Recycle rates as high as 2000 can be obtained. The feed rate is controlled so that the circulating dry solids contain enough sensible heat to fully dry the wet feed falling on and mixing with them before wet feed can contact heating surface. Purge gas is circulated through a vapor hood covering the screws.

Agitator Dryers. Increasing interest in indirect-heat drying has brought out a variety of relatively slow speed, batch, and continuous agitator dryers. These combine the advantages of low purge gas flow, characteristic of all

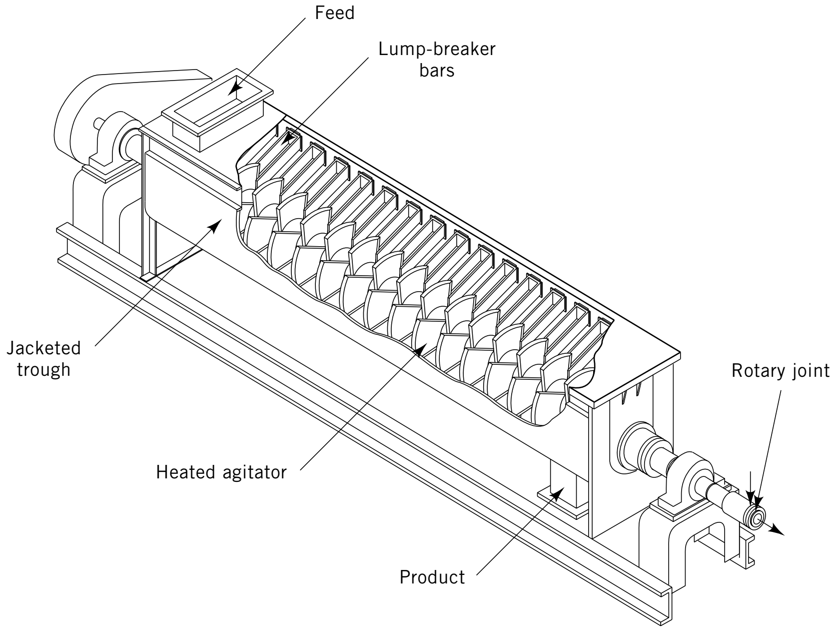


Fig. 22. Indirect-heat, paddle-type agitator dryer. Courtesy of the Bethlehem Corp., Easton, Pa.

indirect-heat dryers, with a material handling versatility lacking in fluid beds and an ease of gas-tight operation lacking in rotary dryers. Material holdup may be varied from a few minutes to several hours. Figure 22 is an example of this dryer type, called a porcupine dryer. It may have one or two parallel shafts and, as shown, can be provided with stationary, lump-breaker bars that intermesh with the moving paddles. Other types may provide scrapers for both jacket and agitator heating surfaces. Most can be operated under vacuum or well above atmospheric pressure and at temperatures up to 400°C using hot oil, steam, and water. The vessels are stationary and shaft seals are small to minimize leakage.

Paddle dryers are used for drying lumpy materials. Disk dryers contain a series of closely spaced, parallel, internally heated plates mounted on the rotating shaft. Disk dryers are suitable for granular, essentially free-flowing materials; these often include adjustable scrapers for continuous disk doctoring to maintain a clean heating surface. Water evaporation capacity of these dryers when operated using 1.0 MPa (145 psig) saturated steam is about 15 kg/$(h \cdot m^2)$. Dryer capacities vary with type, eg, a single, quad-screw conveyor dryer can provide 150 m^2 of heating surface, whereas one disk dryer can carry 400 m^2 of heating surface on a single shaft. Agitator dryers are ideally suited for vapor recovery and drying in special atmospheres.

Both theory and empirical data demonstrate that the faster the movement of particulate material in contact with heated surface, the greater the heat-transfer rate. Nonetheless, agitator speed of the agitator dryers discussed herein rarely exceeds 10 min^{-1}. Because these dryers usually run between 50 and 90% full, mechanical stresses and power demand would become intolerable

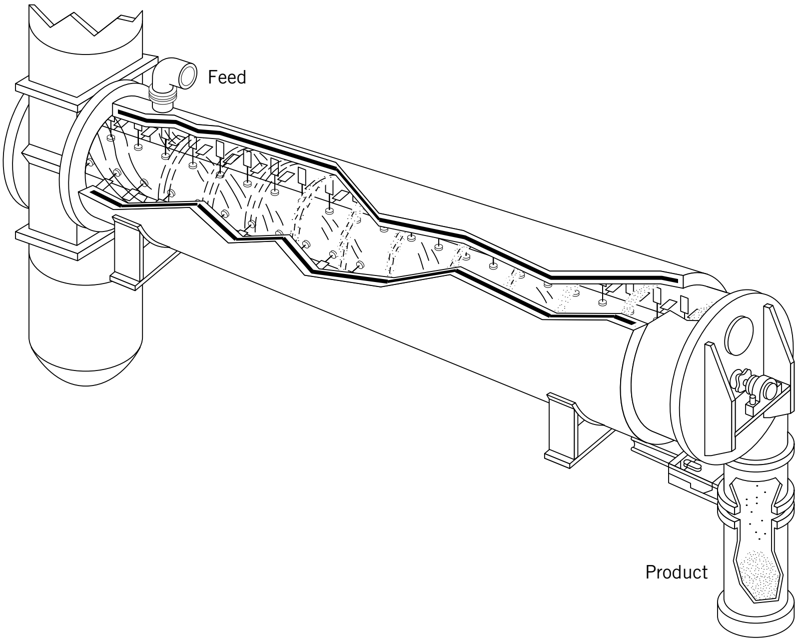


Fig. 23. Indirect-heat, high speed agitator dryer. Courtesy of B-pex Corp., Minneapolis, Minn.

at higher agitator speeds, especially when drying sticky or sluggish materials. The tradeoff is between heat-transfer efficiency and fillage, power, and mechanical construction being dependent variables. For high fillage, long holdup, and the need to accommodate pasty, sticky, and sluggish materials, the best choice is usually a low speed and as much heating surface as possible built into the agitator.

High speed agitator dryers operate at $\sim$10% fillage and are used for continuous evaporation of easily removable surface moisture. The example in Figure 23 consists of a stationary, horizontal, jacketed cylinder inside of which is carried an array of paddles mounted on a central shaft. Only the cylinder is heated. Paddle tip speed is $\sim$15 m/s. The largest dryer has 100 m^2 of jacket surface. Water evaporation rate when operating using 1.0 MPa (145 psig) saturated steam is 20–25 $kg/(h \cdot m^2)$. To handle fluidlike or sticky feed materials, some high speed agitators include jacket scrapers. These dryers are suitable, however, only for materials that do not stick to metal when dry.

Drum Dryers. Indirect-heat drum dryers, like spray dryers, are usable only for materials that are fluid initially and pumpable. Drying is effected by applying a thin film of material onto the outer surface of a rotating heated drum using applicator rolls, spray nozzles, or by dipping the drum into a reservoir. Usually, the drum is cast iron or steel and chrome-plated to provide a smooth surface for ease of product release by doctoring. Drum rotational speed is such that drying occurs in a few seconds. Little thermal damage is experienced and acceptable milk powders have been produced on drum dryers. Nonetheless, material surface directly in contact with the drum reaches drum temperature, so heat effects are less favorable than in spray dryers. Single-, twin-, and double-drum arrangements are used, depending on material properties and feed method.

Drum dryers are operated at atmospheric pressure and enclosed in vacuum housings for heat-sensitive materials. Twin drums are merely two single drums using a common feed system. On double-drum dryers, feed is retained and partially concentrated in a reservoir formed by the nip between two drums. Drum clearance is adjusted to fix film thickness. Material in the nip is drawn through the nip clearance, dried, and released from the back side of each drum by spring-loaded doctor knives. Single and twin drums may be provided with nip applicators by installing auxiliary feed rolls (see COATING PROCESSES). Water evaporation rates on drum dryers, based on total drum surface, are 50–80 kg/(h $\cdot$ m^2). Greater capacities usually follow higher rotational speeds and thinner films.

The fin-drum dryer is a preforming device for fluid and pastelike materials intended for through-circulation drying. Slurry or paste is forced by a feed roll into circumferential grooves machined in the outer drum surface, partially dried and released in the form of short sticks by finger scrapers. Total drying rarely is attempted. Thin films of solutions, slurries, and pastes also are dried on horizontal belt dryers which are heated by radiant heaters mounted above and below the belt and operate at atmospheric pressure or under vacuum. Thicker films are handled than on drums because residence time can be longer. Temperature staging is feasible.

Can dryers, also called cylinder dryers, are similar in construction to drum dryers and used to dry paper, fiber tow, cloth, and other continuous webs that are insufficiently self-supporting for accommodation by festoon, roll, or tenter-frame equipment. A can dryer may be one 3–5-m diameter can, eg, the Yankee dryer, or it may comprise a number of cans arranged so that material passes over them in series, eg, a paper machine. To enhance conduction heat transfer initially, the web may be forced against the cans by an endless fabric belt, or felt, that also absorbs liquid and is dried separately. Further along, gas impingement nozzles may be mounted close to the web surface to add convection heat transfer. Humid air is removed through hoods above the cans. Paper (qv) drying is the largest application.

Vacuum Dryers. The indirect-heat form of batch compartment dryer usually operates under vacuum and is called a vacuum shelf dryer. Wet material is spread on trays that rest on heated shelves in an insulated vacuum chamber. The shelves are heated by steam, hot oil, or water and vacuum is produced by steam jets or pumps (see VACUUM TECHNOLOGY). Heat is transferred by conduction and radiation from the supporting shelf and by radiation from the shelf above the material. Conduction heat-transfer rates are low, however, because contact between the tray bottom and its supporting shelf rarely is continuous or uniform. In chambers maintained at 1.5-kPa (0.22-psi) pressure, with shelves heated by 200-kPa (29-psig) saturated steam, water evaporation based on exposed tray area is 1–2 [kg/(h $\cdot$ m^2)]. Because of low drying rates, dust losses are negligible, and these dryers are suitable for small lot drying of valuable products. Batch identification is maintained, but if there are alternative choices, shelf dryers rarely are economical for production rates exceeding 200 t/year.

A rotating vacuum dryer is formed by equipping a double-cone mixer with a jacket and an internal vapor exit tube passing through a rotary joint in one trunnion. Volume capacity is 0.1–30 m^3. Fillage is 50–70% of total volume. Internal operating pressures are 1–10 kPa (0.15–1.5 psi). In dryers operated at 1.5 kPa, having jackets heated by 200-kPa saturated steam, water evaporation based on total heated surface is 4–5 $kg/(h \cdot m^2)$. Rotating vacuum dryers are suitable for materials that do not stick to metal when wet or dry and do not pelletize during drying. Feed conditioning is an option. The ratio of jacket surface to operating volume decreases as dryer size increases, so large dryers often include internal plate or pipe coils to compensate. These internal elements partially destroy a principal attraction of the dryers, however, which is ease of complete emptying and cleaning between batches.

The rotary vacuum dryer is a horizontal stationary jacketed cylinder having an internal rotating ribbon or paddle agitator. If material does not stick to metal when wet or dry, the rotating shaft, ribbon arms, and paddles also may be heated. For materials that are sticky, jacket scrapers can be included. Feed conditioning by wet/dry blending externally and inside the dryer are options. Volume capacity is 0.1–30 m^3. Fillage is 50–90% of total volume. In dryers operated at 1.5 kPa, using jackets and internals heated by 200-kPa saturated steam, water evaporation based on total heated surface is 5–7 $kg/(h \cdot m^2)$. Agitator speed is 2–8 min^{-1}, but dust carryover may be severe during initial drying. Vacuum bag-type dust collectors usually are provided to recover dust. Rotary dryers are more versatile than the rotating type, but are difficult to empty completely and are less attractive for multiproduct operations and batch identification.

The vacuum pan dryer, the workhorse of this vacuum group of batch dryers, is a vertical stationary jacketed cylinder having a jacketed dished or flat bottom and a vertical top-driven plough-type agitator to overcome torque loads presented by heavy, sticky, and doughlike materials that would overload or break the ribbons and paddles in rotary vacuum dryers. The agitator stirs these heavy materials at 1–4 min^{-1} until they are dry enough to break down into particulate form. Power usually peaks just before the material breaks apart. The largest pan is ~4-m diameter. Maximum fillage is ~10 m^3. In pans operated at 1.5-kPa pressure, using jackets heated by 200-kPa saturated steam, water evaporation based on total heated surface is 2–4 $kg/(h \cdot m^2)$. These dryers also operate at atmospheric pressure; a purge gas is employed for vapor removal.

Freeze Dryers. The original freeze dryer was a vacuum shelf dryer, operated at much lower pressure: 100 Pa (0.8 mmHg) for seafood, meat, and vegetables, 50 Pa (0.4 mmHg) for fruits, 20 Pa (150 μmHg) for concentrated beverages, and 10 Pa (80 μmHg) for pharmaceuticals (qv). The material is first frozen to effect separation of solutes and solvents by crystallization. Frozen material is placed in trays in a closed compartment that is evacuated and ice is caused to sublime by careful introduction of heat. The purpose is to protect heat-sensitive materials from thermal damage and prevent shrinkage of porous materials, so they can be instantly and fully rehydrated (see FOOD PROCESSING). The sublimation driving force is the difference between the vapor pressure of the ice and the condenser pressure. The drying rate is controlled by heat input and the conductivity of the material.

Most rapid drying and uniform product quality is obtained when all material surfaces are heated uniformly. Use of metal rib trays is helpful because metal conducts heat better than most organic materials and these trays distribute heat more effectively bottom to top. Channels for vapor escape are also opened; however, bottom material may still overheat. A suspended rib tray depends on heat transfer entirely by radiation. Higher shelf temperatures may be used without a danger of local material overheating and both top and bottom are heated uniformly. Typical food dryer shelf temperatures of the suspended tray type are 50–150°C, using a refrigeration system at −50°C. Many biological dryers contain movable shelves, so product vials can be stoppered after drying and before compartment venting. The vials are assembled in trays that rest directly on heated shelves. Typical shelf temperatures are −20–50°C, the condenser temperature is −60°C. Based on exposed material surface, the sublimation capacity of shelf-type food dryers is 0.2–2.0 kg/(h · m^2).

Freeze drying has also been carried out at atmospheric pressure in fluid beds using circulating refrigerated gas. Vacuum-type vibrating conveyors, rotating multishelf dryers and vacuum pans can be used as can dielectric and microwave heating.

5.3. Radiant-Heat Dryers. Heat transfer by radiation occurs in all dryers to some degree and is controlled by the temperature and emissivity of the source and the temperature and absorptivity of the receiver. For drying, sources may consist of a number of incandescent lamps, reflector-mounted quartz tubes, electrically heated ceramic surfaces, and ceramic-enclosed gas burners. Usual source temperatures are 800–2500 K. Radiant energy does not penetrate most material surfaces. Heat penetration below the surface is dependent on material conductivity. In situations wherein radiant-heat flow to a surface is high while material thermal conductivity is relatively low, the surface temperature may rise above the liquid boiling point at dryer operating pressure. When drying printed cloth, film, and coatings in continuous conveyor dryers, adjustments to source spacing and temperature often can prevent boiling, skin formation on films, and bubble formation in coatings. For thicker materials, radiant-heat sources are installed alternately with gas impingement and parallel flow zones of more moderate temperature to allow time for liquid diffusion to the material surface, evaporation, and vapor dispersion.

Radiant heaters are most suitable for the drying of thin films, eg, paint films. They are not suitable for large objects and deep material layers in which drying rates are controlled by material internal heat- and mass-transfer mechanisms. When drying heat-sensitive materials, low temperature sources should be used. In continuous dryers, banks of radiant sources are placed above, below, and on both sides of the material in an enclosed tunnel designed to minimize direct and reflection losses to the outside. When materials are dried that may degrade or burn if exposed too long, means are provided to shut off and shutter all radiating surfaces instantly when material flow is interrupted. Purge gas must be provided to remove vapors from atmospheric radiant-heat dryers. A common practice is to pass the incoming purge gas behind the source enclosures to cool the enclosures and preheat the gas. On roll conveyor and tenter frame dryers, water evaporation based on exposed material surface is 10–100 kg/(h · m^2).

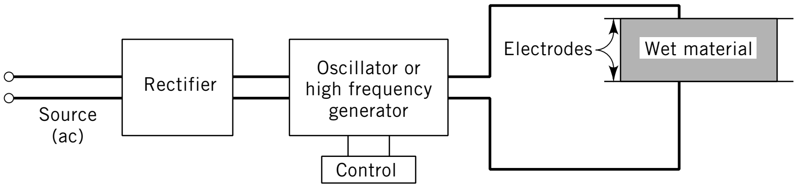


Fig. 24. Diagram of a dielectric (radio frequency) dryer.

5.4. Dielectric and Microwave Dryers. Dielectric, also called radio frequency, dryers operate in the frequency range of 1–100 MHz. Microwave dryers in the United States operate at 915 and 2450 MHz (see MICROWAVE TECHNOLOGY). As depicted in Figure 24, a dielectric dryer may consist of two flat metal plates between which material is placed or conveyed. The arrangement forms a capacitor, the plates of which are connected to a high frequency generator. During one-half of a cycle, one plate has a positive charge, the other a negative charge. One-half cycle later, the charges are reversed. Flat plate or platen electrodes are used for bulky objects. Parallel rods of alternating charge, called stray field electrodes, are employed for thin webs and are installed directly in line below or above the moving web. Parallel rods, called staggered-type electrodes, are used for thick webs and boards and are installed alternately above and below the material. The web moves between them.

Microwave applicators are single, like a microwave oven, or multimode cavities in which material is placed or through which it is conveyed, or rectangular waveguides, which in effect surround material as it is conveyed. Rapid reversal of electrode polarity generates heat in the material. In a mechanism called dipole rotation, dipoles, which normally are in random orientation, become ordered in the electrical field. As the field dies, they return to random orientation; as the field reverses, they again become ordered but in the opposite direction. Electrical energy is converted to potential energy, to random kinetic energy, and to heat. In ionic conduction, ions are accelerated by the electrical field. They collide with nonionized molecules in random billiard ball fashion. Electrical energy is converted to kinetic energy and to heat. These are two primary mechanisms of energy conversion.

Industrial applications of dielectric and microwave energy for drying are many; however, response to high frequency electromagnetic radiation depends on a material's dielectric constant and dissipation factor, the product of which is its loss factor. A material having a loss factor >0.05 is a potential drying candidate. Air, glass, some ceramics, and plastics transmit high frequency radiation. Metals may reflect radiation. Water, alcohols, aldehydes, ketones, unsymmetrical halogenated hydrocarbons, and ionic solutions absorb radiation. Hydrocarbons and symmetrical halogenated hydrocarbons do not. Depth of material penetration at which half the energy is absorbed is called a half power depth and is proportional to wave length. For dielectric heating, this may be measured in meters; for microwaves, in centimeters. If the material is large or wide, dielectric heating is preferred. If watt density is high because of a low loss factor, microwaves are preferred; however, if power requirement exceeds 50 kW, economics favor dielectric equipment.

The cost of microwave equipment per kilowatt output is about twice that of the dielectric. For irregular shapes, microwaves are preferable because to avoid hot spots during heating, dielectric electrodes are needed that conform to the material shape. Industrial dielectric dryers are employed for lumber drying, plywood bonding and drying, furniture parts drying, textile skeins and package drying, paper moisture leveling, tire cord drying, and many food products. Dielectric heating frequently is combined with radiant heat and hot air for print and coating drying. Microwave dryers are employed for drying cloth, lumber, and foods. Microwaves are used as an energy source in vacuum and freeze dryers.

Dielectric and microwave heating are generally more costly than alternative methods. Thus many applications involve material preheating and second-stage drying where energy demand is low and cycle times can be reduced significantly. Dielectric and microwave heating are chosen mostly when other methods will not work or are impractical. Material behavior in high frequency electromagnetic fields is frequency dependent and varies with moisture content, salt concentrations, and other factors. Laboratory testing is necessary. Water evaporation is ~1.0 kg/kWh, and overall power efficiency is ~60% (see FURNACES, ELECTRIC).

5.5. Superheated Steam Dryers. Although use of superheated steam as a drying medium in place of heated air or combustion gases was proposed >100 years ago in a German book, superheated steam drying (SSD) has emerged as a viable drying technology with major potential only in recent years. Essentially SSD involves use of superheated steam in a direct (convective dryer of any design, eg, fluidized bed, flash dryer, spray dryer, impingement dryer, tray dryer etc). Although simple in principle the fabrication and operation of steam dryers is more demanding since leakage of air into the dryer or steam from the dryer to the ambient are highly undesirable.

One of the obvious advantages of SSD is that the dryer exhaust is also superheated steam although of lower specific enthalpy. In air drying, the latent heat of water vapor in the exhaust is difficult and expensive to recover. On the other hand, if it is pure steam the exhaust heat can be recovered more cost effectively by partial recycle, compression or condensation. Some of the other key advantages of SSD are

- No oxidative or combustion reactions are possible hence there is no fire or explosion hazard.
- Higher drying rates are possible if the steam temperature can be increased.
- For products containing toxic or nonaqueous solvents SSD avoids danger of fire/explosion while allowing condensation of the exhaust stream in smaller condensers.
- SSD permits pasteurization, sterilization and/or deodorization of food products.
- SSD produces a more porous product which improves rehydration characteristics.

Following are some of the limitations of SSD systems:

- The system is more complex since no leakage in or out of the drying chamber is permissible.
- Start up and shut down of dryer is more complex and must be minimized.
- Since dryer feed typically enters the dryer at ambient temperature there is inevitable condensation in the SSD before drying begins.
- For heat-sensitive materials (eg, food products, like fruits and vegetables), a low pressure operation is feasible but hardware costs are increased.
- If steam produced by the SSD is not needed elsewhere in the plant then the energy related advantages of SSD cannot be exploited.

Among the current commercial application of steam drying are drying of coal, pulp, biomass, peat, waste sludges, wood, some meat products, etc. There is potential for application of SSD for numerous products. However, there is limited database currently available for design and scale-up of such equipment.

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