particle size, bulk density, and dustiness, are determined to a great extent by the characteristics of atomization and by the temperature and direction of flow of the drying gas. The final moisture content of the product is controlled by the humidity and temperature of the exhaust gas stream.

*Spray Dryer Theory and Design.* Unfortunately, the extent of the theory is such that the design of spray dryers is an art rather than a science. At present, pilot-plant or full-scale production operating data are required for design purposes.

The design of the drying chamber is determined by the spray characteristics as well as heat and mass transfer rates. Many investigations have been conducted of the capacity and spray distribution of spinning disks and nozzles. Friedman et al[9] found that the mean drop diameter for a spinning-disk atomizer was correlated by the following dimensionless equation:

$$\frac{D_M}{r} = 0.4\left(\frac{G_d}{\rho_L N r}\right)^{0.6}\left(\frac{\mu}{G_d}\right)^{0.2}\left(\frac{\sigma\rho_L L_p}{2}\right)^{0.1} \quad (8)$$

*where*

$D_m$ = mean particle diameter (diameter of a particle having the average volume per unit of surface area), feet.
$r$ = disk radius, feet.
$G_d$ = mass velocity of the drying medium, pounds per (hour) (square foot).
$\rho_L$ = density of feed, pounds per cubic foot.
$N$ = disk speed, revolutions per hour.
$\mu$ = viscosity of feed, pounds per (hour)(foot).
$\sigma$ = surface tension of feed, pounds force per foot.
$L_p$ = wetted periphery of disk, feet.

The distribution of drop diameters was represented by a straight line on log-normal probability paper, with the maximum diameter three times as large as the mean diameter. It is essential from the standpoint of product uniformity and length of drying time that the spray distribution be as uniform as possible. Probably the greatest effect on the time is particle size, which affects the drying time as the square of the particle diameter.

For drops ranging in mean diameter from 11.5 to 38.5 microns, the rate of evaporation can be calculated by assuming that vaporization occurs in stagnant air. The resulting expression for the drying time of a pure liquid drop is then,[9]

$$\theta = \frac{H w_{\rho_s} D_m^2}{12 k_f (t_a - t_s)} \quad (9)$$

*where*

$\theta$ = time, hours.
$H$ = enthalpy of evaporation, Btu per pound.
$w_{\rho_s}$ = initial moisture content, dry basis, pounds of water per pound.
$\rho_s$ = density of dry particle, pounds per cubic foot.
$k_f$ = thermal conductivity of drying medium, Btu per (hour) (square foot) (Fahrenheit degree per foot).
$t_a$ = air temperature, Fahrenheit.
$t_s$ = temperature of drop, Fahrenheit.

In order to determine the size of the drying chamber required for the specified production rate, the drying time and trajectory of the particles, and the flow pattern of the drying medium must be known. For preliminary estimates, however, the required residence time of the particles may be obtained from the following expressions.[10]

$$\theta_r = 50\sqrt{w_f/S} \quad (10)$$

$$\theta_r = 17(w_f/S) \quad (11)$$

*where*

$\theta_r$ = residence time, seconds.
$w_f$ = weight of water in feed, pounds per pound of feed.
$S$ = weight of solids in feed, pounds per pound of feed.

The chamber volume can then be estimated from the following:

$$V = \theta_r Q \quad (12)$$

*where*

$V$ = volume of chamber, cubic feet.
$Q$ = average volumetric gas rate, cubic feet per second.

From the specified production rate, and inlet and outlet gas temperatures, $Q$ can be calculated. Thus,

$$Q = 4000\ Ev/(t_i - t_o) \quad (13)$$

*where*

$E$ = evaporation rate, pounds of water per minute.
$v$ = average specific volume of gas, cubic feet per pound.
$t_i$ = inlet temperature, Fahrenheit.
$t_o$ = outlet temperature, Fahrenheit.

It must be emphasized that the above method for determining the chamber size is very approximate, and should not be used for design purposes.

## Tobacco Curing[11]

Considerable progress has been made recently in developing improved tobacco curing systems, through the application of heating equipment for maintaining uniform temperatures. Controlled heat and air circulation shortens the curing period and improves the quality of tobacco.

Suitable barn ventilation effected by bottom and ridge venting reduces the time and cost of curing. Orientation of barn with respect to the prevailing wind is helpful.

## Tobacco Re-drying

In modern plants, tobacco is re-dried in continuous, conveyor type machines under controlled temperature and humidity conditions. One type of machine re-dries leaf tobacco in hands. This machine consists of a drying section, cooling section, and ordering section. As the hands are carried through the drying section on sticks, a high velocity of air is directed down through the heads, and a low velocity of air passes over the body of the tobacco resulting in fast and uniform re-drying.

In the cooling section, the tobacco is quickly cooled and conveyed through the ordering section, where a controlled amount of moisture is added in this section which is maintained at almost saturated humidity ratio, so that the leaves can be packed for storage without the danger of breakage.

## Agricultural Drying

Information on drying of agricultural products, such as milk, apples, flowers, tung nut, lumber, fruit juices, broom corn, grain, hay, peanuts, tobacco, and other farm crops, may be found in current issues of the *Agricultural Index*.[12]

# SOLUTION OF TYPICAL DRYING PROBLEM

Since there are so many types of dryers that may be used, and so many special conditions surrounding each particular problem, it is usually recommended that those having experience with the dryer to be used be consulted. The following example, however, will serve as a guide for typical dryer calculations.

*Example 2:* Magnesium hydroxide is to be dried from 82 percent moisture on the bone-dry basis to 4 percent moisture content on bone-dry basis. The production rate is to be 3000 lb per hr on 4 percent bone-dry basis. Previous experience indicates that a continuous single-conveyor through-circulation dryer with a fin-drum feed as illustrated in Fig. 10 should be used. The dryer is to be heated with steam at 50 psig. The optimum circulating air temperature is 160 F which is not limited by the existing steam pressure.

*Step 1:* Laboratory tests or previous experience indicate that the material enters the dryer at a temperature of 60 F with an initial moisture content of 82 percent bone-dry basis. The test drying time is 25 min and the final moisture content is 4 percent bone-dry basis. The temperature of make-up air is 70 F dry-bulb and 60 F wet-bulb. The temperature of circulating air is 160 F dry-bulb and 100 F wet-bulb. The air velocity down through the preformed bed is 250 fpm, and the static pressure drop through the bed is 0.4 in. of water. The dryer bed is to be loaded with 6.820 lb per sq ft of bone-dry material. Depth of the bed is to be 4 in.

*Step 2:* Previous experience indicates that the commercial drying time is 70 percent greater than the test time obtained in the particular laboratory setup used.

Therefore, the commercial drying time = $1.7 \times 25 = 42.5$ min.

*Step 3:* In order to dry the desired 3000 lb per hr of material the holding capacity of the dryer is $3000 \times \frac{42.5}{60} = 2125$ lb at 4 percent bone-dry basis.

The required conveyor area is $\frac{2125}{6.820} = 312$ sq ft. Assuming that a perforated plate conveyor with an 8 foot effective width is used, the length of the drying zone is $\frac{312}{8} = 39$ ft.

*Step 4:* The amount of water entering the dryer is $\frac{3000}{1.04} \times \frac{82}{100} = 2370$ lb per hr, while the amount of water leaving the dryer is $\frac{3000}{1.04} \times \frac{4}{100} = 115$ lb per hr. Thus, the evaporation rate in the dryer is $2370 - 115 = 2255$ lb per hr.

*Step 5:* Since the air circulation is perpendicular to the perforated plate conveyor, the total quantity of air that must be circulated equals the air velocity (based on the face area) multiplied by the conveyor area. Thus,

$$\text{Supply air} = 250 \times 312 = 78{,}000 \text{ cfm}$$

From Fig. 5 the humidity ratio of the supply air at 160 F dry-bulb, 100 F wet-bulb is 0.0235 lb per lb dry air. The specific volume of the supply air is 16.33 cu ft of moist air per lb of dry air, from Table 2 and Equation 21 of Chapter 3 in the 1961 Guide And Data Book.

The quantity of dry air circulated is

$$\frac{78{,}000 \times 60}{16.33} = 286{,}500 \text{ lb per hr.}$$

*Step 6:* The amount of moisture pickup is $\frac{2255}{286{,}500} = 0.0079$ lb per lb of dry air. The humidity ratio of the exhaust air is $0.0079 + 0.0285 = 0.0364$ lb per lb dry air.

Substitute in Equation 6 and solve for $G_T$, the required quantity of make-up air. The humidity ratio of the make-up air is 0.0086 lb per lb dry air, from Fig. 5.

$$G_T\ (0.0364 - 0.0086) = \left(\frac{3000}{1.04}\right)\left(\frac{82 - 4}{100}\right)$$

$$G_T = 81{,}000 \text{ lb dry air per hr.}$$

Therefore,

$$\text{Make-up air} = \frac{81{,}000}{286{,}500} = 28.2 \text{ percent.}$$

$$\text{Recirculated air} = 71.8 \text{ percent.}$$

*Step 7:* Heat Balance

Sensible heat of material $= M(t_{m2} - t_{m1})c_m$
$= \frac{3000}{1.04}(100 - 60)\ 0.3$
$= 34{,}600$ Btu per hr



Sensible heat of water $= M w_1 (t_a - t_{m1}) c_w$
$= 2370\ (100 - 60)\ 1.0$
$= 94{,}800$ Btu per hr

Latent heat of evaporation $= M(w_1 - w_2)H$
$= 2255 \times 1037$
$= 2{,}338{,}400$ Btu per hr

Sensible heat of vapor $= M(w_1 - w_2)\ (t_2 - t_a)c_v$
$= 2255\ (160 - 100)\ 0.45$
$= 60{,}900$ Btu per hr

Required heat for material = 2,528,700 Btu per hr

The temperature drop $(t_i - t_2)$ through the bed is

$$\frac{\text{Required heat}}{\text{Supply air, lb per hr} \times c_a} = \frac{2{,}528{,}700}{286{,}500 \times 0.24} = 37 \text{ deg}$$

Therefore, the exhaust air temperature is $160 - 37 = 123$ F

Required heat for make-up air $= G_T(t_2 - t_1)c_a$
$= 81{,}000\ (123 - 70)\ 0.24$
$= 1{,}030{,}300$ Btu per hr.

The total heat required for material and make-up air is

$$2{,}528{,}700 + 1{,}030{,}300 = 3{,}559{,}000 \text{ Btu per hr.}$$

Additional heat must be provided for the radiation and convection losses, which may be calculated from the known construction of the dryer surfaces.

# LETTER SYMBOLS USED IN CHAPTER 22

$A$ = area of heat transfer and evaporation, square feet per pound of material.
$a$ = drying area, square feet per cubic foot of bed volume.
$c_a$ = specific heat of air, Btu per (pound) (Fahrenheit degree).
$c_m$ = specific heat of material, Btu per (pound) (Fahrenheit degree).
$c_s$ = humid heat, Btu per (pound of dry air) (Fahrenheit degree).
$c_v$ = specific heat of water vapor, Btu per (pound) (Fahrenheit degree).
$c_w$ = specific heat of water, Btu per (pound) (Fahrenheit degree).
$d$ = diffusivity of the liquid or vapor, square feet per hour.
$D_m$ = mean particle diameter (diameter of a particle having the average volume per unit of surface area), feet.
$D_p$ = average diameter of particle, feet.
$E$ = evaporation rate, pounds of water per minute.
$G$ = mass velocity of dry air, pounds per (hour) (square foot).
$G_d$ = mass velocity of the drying medium, pounds per (hour) (square feet).
$G_T$ = dry air supplied as make-up air to the dryer, pounds per hour.
$H$ = enthalpy of evaporation of water at wet-bulb temperature, Btu per pound.
$h$ = film heat transfer coefficient, Btu per (hour) (square foot) (Fahrenheit degree).
$h_c$ = coefficient of heat transfer by convection, Btu per (hour) (square foot) (Fahrenheit degree).
$h_r$ = coefficient of heat transfer by radiation, Btu per (hour) (square foot) (Fahrenheit degree).
$h_t$ = total gas film heat transfer coefficient, Btu per (hour) (square foot) (Fahrenheit degree).
$k_f$ = gas film thermal conductivity, Btu per (hour) (square foot) (Fahrenheit degree per foot).
$k_g$ = mass transfer coefficient, pounds per (hour) (square foot) (atmosphere).
$L$ = one-half material thickness, feet.
$L_p$ = wetted periphery of the disk, feet.
$M$ = weight of stock dried in a continuous dryer, pounds per hour.
$M_1$ = weight of stock charged in a discontinuous dryer, pounds per batch.