

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 27 of Chapter 3.

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 $0.0079 + 0.0235 = 0.0364$ lb per lb dry air.

Substitute in Equation 6 and solve for G_r , 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.

$$G_r (0.0364 - 0.0086) = \frac{(3000)(82 - 4)}{1.04} \left(\frac{1}{100} \right)$$

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

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 = $M(t_m - t_m)c_m$
= $\frac{3000}{1.04} (100 - 60) 0.3$
= 34,600 Btu per hr

Sensible heat of water = $M_w(t_w - t_m)c_w$
= $\frac{2370}{1.04} (100 - 60) 1.0$
= 94,800 Btu per hr

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

Sensible heat of vapor = $M(w_2 - w_1)(t_2 - t_m)c_w$
= $2255 (160 - 100) 0.45$
= 60,900 Btu per hr

Required heat for material = 2,528,700 Btu per hr
The temperature drop ($t_1 - t_2$) 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 = $G_r(t_1 - t_2)c_a$
= $81,000 (123 - 70) 0.24$
= 1,030,300 Btu per hr.

The total heat required for material and make-up air is
 $2,528,700 + 1,030,300 = 3,559,000$ 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 53

- 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_p = average diameter of particle, feet.
- G = mass velocity of dry air, pounds per (hour) (square foot).
- G_r = 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_p = mass transfer coefficient, pounds per (hour) (square foot) (atmosphere).
- L = one-half material thickness, feet.
- M = weight of stock dried in a continuous dryer, pounds per hour.
- M_t = weight of stock charged in a discontinuous dryer, pounds per batch.
- Δp = $p_1 - p_2$ = vapor-pressure difference, atmospheres.
- p_a = partial pressure of water vapor in air, atmospheres.
- p_s = vapor pressure of water at t_s , atmospheres.
- t_a = air or gas temperature, Fahrenheit.
- t_s = temperature of particle, solid, or surface of evaporation, Fahrenheit.
- t_w = wet-bulb temperature of drying air, Fahrenheit.
- t_1 = make-up air temperature, Fahrenheit.
- t_2 = temperature of air entering stock, Fahrenheit.
- t_m = exhaust air temperature, Fahrenheit.
- t_{m1} = entering stock temperature, Fahrenheit.
- t_{m2} = leaving stock temperature, Fahrenheit.
- Δt = $(t_1 - t_2)$ = temperature difference between air and surface of evaporation, Fahrenheit.
- Δt_m = logarithmic mean between air temperature entering and

Industrial Drying Systems

leaving the bed, and the wet-bulb temperature, Fahrenheit.

W_1 = humidity ratio of entering air, pounds of water vapor per pound of dry air.

W_2 = humidity ratio of leaving air, pounds of water vapor per pound of dry air.

w = moisture content on dry basis at any time θ , pounds of water per pound.

w_c = critical moisture content, pounds water per pound dry material.

w_d = water content, dry basis, of the drop as it enters the drying chamber, pounds per pound of dry solid.

w_e = moisture content at equilibrium with external conditions, pounds per pound dry material.

w_s = moisture content at start of diffusional period, pounds per pound dry material.

$\frac{dw}{d\theta}$ = drying rate, pounds of water per (hour) (pound dry material).

$\left(\frac{dw}{d\theta}\right)_c$ = constant drying rate, pounds per (hour) (pound dry material).

$\left(\frac{dw}{d\theta}\right)_f$ = falling rate, pounds water per (hour) (pound of dry stock).

θ = time, hours.

ρ_s = bulk density of dry granular bed, density of dry particle, pounds per cubic foot.

REFERENCES

- ¹ W. R. Marshall, Jr. and S. J. Friedman: Drying (*Perry's Chemical Engineers' Handbook*, McGraw-Hill Co., New York, 1950, 3rd ed.). Indicated material supplied by W. R. Marshall, Jr. and S. J. Friedman, authors of the Section on Drying in the Third Edition of the *Chemical Engineers' Handbook*. Permission to use this material has been kindly granted to THE GUIDE by the Editor, John H. Perry, and by McGraw-Hill Book Company, publishers of the *Chemical Engineers' Handbook*.
- ² W. R. Marshall, Jr.: The drying of foods (*Heating, Piping and Air Conditioning*, September to December 1942, also November and December 1943).
- ³ C. B. Shepherd, C. Hadlock, and R. C. Brewer: Drying materials in trays (*Industrial and Engineering Chemistry*, April 1938).
- ⁴ B. W. Gamson, G. Thodos, and O. A. Hougen: Heat, mass and momentum transfer in the flow of gases through granular solids (*American Institute of Chemical Engineers Transactions*, 1943).
- ⁵ W. M. Grosvenor: Calculations for dryer design (*American Institute of Chemical Engineers Transactions*, Vol. 1, 1908, p. 184).
- ⁶ S. J. Friedman: Steps in the selection of drying equipment (*Heating and Ventilating*, February 1951, p. 95).
- ⁷ What the air conditioning engineer should know about drying (*Heating and Ventilating*, December 1942).
- ⁸ B. B. Fogler and R. V. Kleinschmidt: Spray drying (*Industrial and Engineering Chemistry*, December 1938).
- ⁹ Tobacco Curing (*Virginia Agricultural Experiment Station Technical Bulletin* 116, January 1951).
- ¹⁰ *Agricultural Index* (H. W. Wilson Co., New York).
- J. A. Goff and S. Gratch: Thermodynamic properties of moist air (*ASHVE TRANSACTIONS*, Vol. 51, 1945, p. 125).
- C. F. Prutton and C. O. Miller: Factors influencing the performance of rotary dryers (*American Institute of Chemical Engineers Transactions*, February, August 1942).
- W. R. Marshall and O. A. Hougen: Drying of solids by through circulation (*American Institute of Chemical Engineers Transactions*, 1942).
- A. Weissberg: Factors that influence dryer performance (*Chemical and Metallurgical Engineering*, August 1932).
- O. A. Hougen: Typical dryer calculations (*Chemical and Metallurgical Engineering*, January, March 1940).
- W. K. Lewis, W. H. Carrier, A. E. Stacey, Jr., R. S. Fleming, R. G. Metz, G. B. Ridley, C. O. Lavett, and D. J. Van Marle: Symposium on drying (*Industrial and Engineering Chemistry*, May 1921, p. 427).
- S. J. Friedman and W. R. Marshall, Jr.: Studies in rotary drying, I and II (*Chemical Engineering Progress*, 1949).
- Symposium on drying (*Industrial and Engineering Chemistry*, 1938).
- H. D. Tiemann: Principles of Drying Lumber and Humidity Diagram (*Forest Service Bulletin* 104, 1912).
- T. K. Sherwood: The Drying of Solids (*Massachusetts Institute of Technology Bulletin* Nos. 237, 247, 258).
- T. P. Brown: Radiant energy drying with heat lamps (*Metal Industry*, December 1939, p. 607).
- E. W. Floedorf: Drying by sublimation (*Food Industry*, January 1945, p. 607).
- F. H. Slade: Evaporative drying system (*Food Manufacturing*, March 1943, p. 70).
- I. R. Berkness: High frequency methods in gluing and drying wood (*Wood Products*, Vol. 45, 1940, p. 12).
- T. K. Sherwood: Development of the unit operations of chemical engineering: drying (*Chemical and Metallurgical Engineering*, Vol. 42, p. 214).
- D. W. Biocheno: The spray dryer—its possibilities in industry (*Food Manufacturing*, June 1944, p. 195).
- L. E. Stout, K. J. Caplan, and W. G. Baird: Mechanism and rate of drying by near-infrared radiation (*American Institute of Chemical Engineers Transactions*, Vol. 41, 1945, p. 283).
- W. B. Van Arsdell: Some engineering problems of the new vegetable dehydration industry (*ASHVE TRANSACTIONS*, Vol. 49, 1943, p. 49).
- V. W. Sherman: Electronic dehydration of foods (*Electronics*, Vol. 17, 1944, p. 94).
- Air Conditioning and Engineering* (American Blower Co., 1935).
- Drying in Industrial Plants* (J. O. Ross Company).
- Badger and McCabe: *Elements of Chemical Engineering* (McGraw-Hill Co., New York, 1931).
- Fan Engineering (Buffalo Forge Co.).
- M. Hirsch: *Die Trockentechnik* (Julius Springer, Berlin, 1932).
- Drying (Kent's Mechanical Engineers Handbook)*.
- W. H. Carrier: Drying (*Mark's Mechanical Engineers Handbook*).
- A. Koehler and R. Thelen: *Kiln Drying of Lumber* (McGraw-Hill Co., New York, 1926).
- H. D. Tiemann: *Kiln Drying of Lumber* (J. B. Lippincott, New York, 1920).
- O. A. Hougen, H. J. McCauley, and W. R. Marshall: Limitations of diffusion equations in drying (*American Institute of Chemical Engineers Transactions*, Vol. 1, 1940, p. 183).
- V. P. Victor: An introduction to convection drying and drying calculations (*Heating and Ventilating*, December 1944, p. 67).

BIBLIOGRAPHY

W. H. Carrier: The temperature of evaporation (*ASHVE TRANSACTIONS*, Vol. 24, 1918, p. 25).