[7] P. Drinker and T. Hatch: *Industrial Dusts* (McGraw-Hill Book Co., New York, 1936).

[8] J. L. Alden: *Design of Industrial Exhaust Systems* (Industrial Press, New York, 1948).

[9] W. N. Witheridge: Ventilation (*Industrial Hygiene and Toxicology*, Vol. 1, Chapter 10, ed. F. A. Patty, Interscience Publishers, New York, 1948).

[10] A. C. Stern et al: Transport velocities for industrial dusts (*American Industrial Hygiene Association Quarterly*, December 1948).

[11] A. D. Brandt: *Industrial Health Engineering* (John Wiley and Sons, New York, 1947).

[12] L. Silverman: Velocity characteristics of narrow exhaust slots (*Journal of Industrial Hygiene and Toxicology*, November 1942, p. 267).

[13] W. C. L. Hemeon: *Plant and Process Ventilation* (The Industrial Press, New York, 1955).

[14] *Code of Recommended Good Practice for Metal Cleaning Sanitation* (American Foundrymen's Association).

[15] *Industrial Ventilation Manual* (American Conference of Governmental Industrial Hygienists, 1958, 5th ed.).

[16] W. C. Dressen et al: *A Study of Asbestosis in the Asbestos Textile Industry* (*U. S. Public Health Service Bulletin* No. 241, 1938).

[17] R. T. Page and J. J. Bloomfield: *A Study of Dust Control Methods in an Asbestos Fabricating Plant* (*U. S. Public Health Reports*, Reprint No. 1883, November 1937).

[18] *Rules Relating to the Control of Silica Dust in Stone Crushing Operations* (New York State Department of Labor, *Industrial Code Rule* No. 34, July 1942).

[19] J. M. Kane: Design of exhaust systems (*Heating and Ventilating*, November 1945, p. 68).

[20] J. M. Kane: Foundry ventilation (*The Foundry*, February, March 1946).

[21] W. M. Oddie: Pottery dusts: their collection and removal (*Pottery Gazette*, Vol. 53, 1928, p. 1280).

[22] J. M. Kane: Scrapbook of exhaust hood design (*Heating and Ventilating*, July, August, November 1950 and February, March, April, June 1951).

[23] R. T. Pring et al: Design of exhaust ventilation for solid material handling (*Industrial and Engineering Chemistry*, November 1949).

[24] *Hartzell Blowers: Engineering Data & Installation* (*Hartzell Propeller Fan Company Bulletin* 1001).

[25] J. M. Kane: The application of local exhaust ventilation to electric melting furnaces (*American Foundrymen's Association Transactions*, Vol. 52, 1945, p. 1351).

[26] T. Hatch et al: Control of silicosis hazard in the hard rock industries. II. An investigation of the Kelley dust trap for use with pneumatic rock drills of the jackhammer type (*Journal of Industrial Hygiene*, February 1932, p. 69).

[27] P. S. Hay: Modified design of Hay dust trap (*Journal of Industrial Hygiene*, January 1930, p. 28).

[28] *American Standard for Grinding, Polishing and Buffing Equipment Sanitation* (American Standards Association Z 43-1941).

[29] J. M. Kane: Swing frame grinder dust control (*The Foundry*, August 1944).

[30] J. M. DallaValle: Design of kitchen range hoods (*Heating and Ventilating*, August 1953, p. 95).

[31] *What We Make* (*B. F. Sturtevant Co. Catalog* No. 500).

[32] P. Drinker and J. R. Snell: Ventilation of motion picture booths (*Journal of Industrial Hygiene and Toxicology*, April 1938, p. 321).

[33] P. J. Marschall: How to justify an industrial air conditioning investment (*Heating, Piping and Air Conditioning*, February 1952, p. 71).

[34] E. C. Riley et al: How to design exhaust hoods for quartz-fusing operations (*Heating and Ventilating*, April 1940, p. 23).

[35] E. C. Riley and J. M. DallaValle: A study of quartz-fusing operations with reference to measurement and control of silica fumes (*U. S. Public Health Reports*, 1939, Vol. 54, p. 532).

[36] A. C. Stern: Ventilation of open tanks (*Industrial Hygiene Quarterly*, September 1950).

[37] I. Kingsley: Tabulation of atmospheric contaminants released by open surface tanks (New York State Department of Labor, Division of Industrial Hygiene, *Engineering Unit Plates* 161, 162, 163).

[38] K. M. Morse and L. Goldberg: Chlorinated solvent exposures at degreasing operations (*Industrial Medicine*, October 1943, p. 706).

[39] W. N. Witheridge and H. T. Walworth: Ventilation of a trichlorethylene degreaser (*Journal of Industrial Hygiene and Toxicology*, May 1940, p. 175).

[40] *American Standard for Safety in Electric and Gas Welding and Cutting Operations* (American Standards Association, A 49.1).

[41] *Rules Relating to the Removal of Dust, Gases, and Fumes* (New York State Department of Labor, *Industrial Code Rule* No. 12, January 1931).

[42] T. F. Hatch and D. Barron-Oorrazco: Air flow in free convection over heated bodies (ASHAE TRANSACTIONS, Vol. 63, 1957, p. 275).

[43] A. D. Brandt and R. J. Steffy: Energy losses at suction hoods (ASHVE TRANSACTIONS, Vol. 52, 1946, p. 205).

[44] A. Nutting: Resistance test on pipe (*Mechanical Engineering*, May 1938).

[45] G. E. McElroy: *Design of Injector for Low Pressure Air Flow* (*U. S. Bureau of Mines Technical Paper* 678).

[46] *American Standard Safety Code for Ventilation and Operation of Open Surface Tanks* (American Standards Association, Z 9.1-1951).

CHAPTER 53

INDUSTRIAL DRYING SYSTEMS

Drying Terminology, Mechanism of Drying, Internal and External Conditions, Periods of Drying, Equilibrium Moisture Content, Application of Hygrometry to Drying, Determination of Drying Time, Commercial Drying Time, Dryer Calculations, Drying Methods and Equipment; Radiant, Conduction, and Convection Drying; Agricultural Drying, Solution of Drying Problem

THE term *drying*, in a broad sense, encompasses the removal of water, and occasionally other liquids, from gases, liquids, or solids. However, the common usage of the word confines the meaning principally to the removal of water or solvent from solids by thermal means. *Dehumidification* is the term that is commonly assigned to the drying of gases. This is usually accomplished by condensation or adsorption by various drying agents, and is treated in Chapter 42. *Distillation*, and more particularly *fractional distillation*, is associated with the drying of liquids.

It is usually more economical to employ, whenever possible, mechanical means of separating as much water as is practicable from the solid materials before undertaking drying or dehydration steps. These mechanical methods such as filtration, screening, pressing, centrifuging, or settling usually require much less power, and frequently less capital outlay, thereby making the operation cheaper in terms of cost per pound of water removed.

DRYING TERMINOLOGY[1]

The generally accepted definitions of terms used in drying technology follow:

Adiabatic drying occurs in a dryer when all of the sensible heat given up by the air in cooling is used to evaporate water from the wet stock.

Batch drying is that type of drying operation in which the material is fed to and discharged from the drying chamber in batches at definite intervals of time.

Bone-dry basis indicates the moisture content of a wet solid as pounds of water per pound of bone-dry solid. The advantage of using this basis is that the absolute amount of moisture loss is obtained simply by subtracting the moisture contents before and after drying. (See definition of *Wet Basis*.)

Bound moisture refers to liquid (held by a solid) which exerts a vapor pressure less than that of the pure liquid at the same temperature. Liquid may become *bound* by retention in small capillaries, by solution in cell or fiber walls, by homogeneous solution throughout the solid, and by chemical or physical adsorption on solid surfaces. Bound moisture can be removed from a solid only under specific conditions of humidity in the external surroundings.

Capillary flow refers to the flow of liquid through the interstices and over the surface of a solid. It is caused by liquid-solid molecular attraction.

Commercial dry basis expresses the moisture content of a product as pounds of water per pound of solid as it leaves the dryer, i.e., per pound of commercially dry solid.

Commercial drying time is the residence time of the material being dried in a commercial dryer.

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

Continuous drying is that type of drying operation in which the material to be dried is fed and discharged continuously to and from the dryer. The operating conditions are independent of time.

Critical moisture content is that obtaining when the constant-rate period ends and the falling-rate period begins.

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

Evaporative load is the total amount of water evaporated per hour in the dryer.

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

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

Final moisture content is the percentage by weight of moisture remaining in the solid at the end of the drying operation.

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

Fuel economy is the number of units of fuel (cubic feet of gas, pounds of steam, gallons of oil, etc.) required to remove 1 lb of water from the solid being dried.

Humidity denotes the amount of water vapor actually present in a gas, and is generally expressed as weight of vapor per unit weight of any gas.

Hygroscopic material is material that may contain bound moisture.

Initial moisture content is the percentage by weight of moisture in the solid at the start of the drying operation.

Initial moisture distribution refers to the moisture distribution throughout a solid when drying begins.

Moisture gradient refers to the internal distribution of water in a solid at a given moment in the drying process, the nature of which depends on the characteristics of the solid involved.

Non-hygroscopic material is material that can contain no bound moisture.

Test drying time is the drying time of a relatively small and representative sample of the material which is dried in a laboratory dryer under conditions simulating commercial operation.

Through-circulation drying is that method of drying in which the air flow is directed through a permeable bed of solids.

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

Wet basis expresses the moisture in a material as a percentage of the weight of the *wet* solid. This basis is less satisfactory than the dry-weight basis on which the percentage change of moisture is constant for all moisture contents.

MECHANISM OF DRYING[1]

When a solid dries, two fundamental processes are involved: (1) the transfer of heat to evaporate the liquid, and (2) the