

conduction through retaining walls to wet material in contact with such surfaces, or on radiation, or both. This applies to drum dryers, agitated pan dryers, indirect continuous sheeting dryers, steam tube rotary dryers, vacuum rotary and vacuum tray dryers, and infra-red dryers.

A principal difference between indirect drying and direct drying is that, with the former, the material is usually at a higher temperature than the surrounding air, so that heat is actually transferred to the air instead of from the air.

The Falling-Rate Period. In the discussion of the periods of drying, it was shown that the drying process is discontinuous, consisting of a period of a constant rate of evaporation and a period in which the rate continuously decreases. (See Fig. 2). This latter period is usually designated as the falling-rate period. It begins when the constant-rate period ends at the critical moisture content. If the critical moisture content is less than the required final moisture content, the constant-rate period will constitute the whole of the drying process. On the other hand, if the initial moisture content is less than the critical moisture content, as in the case of some slow-drying materials, such as soap and wood, then no constant rate will appear, and the whole of the drying process will be in the falling-rate period. This period, in the most general case, can be divided into two zones which may be termed (1) the zone of unsaturated surface drying, and (2) the zone where internal liquid flow controls.

The zone of unsaturated surface drying follows immediately after the critical point and results from a progressively decreasing wetted surface. With the surface no longer completely wetted, dry portions of the solid protrude into the air film, so that the rate of evaporation per unit of total surface is reduced. The effective wetted surface in this zone is frequently a linear function of the water content, so that the curve representing rate of drying *vs.* water content of the solid is straight in this region, as shown by line AD in Fig. 2. The mechanism of drying is essentially the same as during the constant-rate period.

The zone where internal liquid flow is in control is usually the second zone of the falling-rate period. In this phase the rate of internal liquid movement by one or more of the controlling mechanisms considered previously, such as diffusion, capillarity, etc., will determine the drying rate.

When diffusion does control in the falling-rate period, it obeys the same fundamental laws of diffusion as those applying to the diffusion of heat. Thus for the case where the surface is dry or at the equilibrium moisture content and the solid has a uniform initial moisture distribution the following rate equation holds for relatively large values of time θ , and when $(w - w_e)/(w_o - w_e) < 0.6$

$$\frac{dw}{d\theta} = -\frac{\pi^2 d}{4L^2} (w - w_e) \quad (4)$$

where

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

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

w_o = initial moisture content at start of diffusional period, pounds of water per pound dry material.

d = the liquid diffusivity, square feet per hour.

L = one-half material thickness, feet.

Equation 4 is restricted to a slab-shaped solid, the length of which is large compared with the thickness.

For some materials the drying time in the falling-rate period varies directly as the thickness. When this occurs the falling-rate can be expressed with fair accuracy by the following equation:

$$\left(\frac{dw}{d\theta}\right)_t = -\frac{(dw/d\theta)_o}{(w_o - w_e)} (w - w_e) \quad (5)$$

where

$(dw/d\theta)_o$ = the constant drying rate, pounds per (hour) (pound dry material).

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

w_e = the critical moisture content, pounds per pound dry material.

The appropriate expression for $\left(\frac{dw}{d\theta}\right)_o$ obtained from Table 1, may then be substituted in the above equation.

Table 2 gives an approximate classification of materials which are most likely to obey Equations 4 and 5.

TABLE 2. APPROXIMATE CLASSIFICATION OF MATERIALS MOST LIKELY TO OBEY EQUATIONS 4 AND 5

MATERIALS OBEYING EQUATION 4	MATERIALS OBEYING EQUATION 5
1. Single-phase solid systems such as soap, gelatin, glue. 2. Wood and similar solids below the fiber saturation point. 3. Last stages of drying starches, textiles, paper, clay, hydrophilic solids, and other materials when bound water is being removed.	1. Coarse granular solids, such as sand, paint pigments, minerals, etc. 2. Materials in which moisture flow occurs at concentrations above the equilibrium moisture content at atmospheric saturation, or above the fiber saturation point.

Equilibrium Moisture Content

In the drying of solids it is important to distinguish between hygroscopic and non-hygroscopic materials. A hygroscopic material is one which retains a definite percentage of moisture under definite conditions of air humidity. This bound moisture is in a state of equilibrium with the water vapor in the surrounding air, and a decrease in the water vapor content will decrease the amount of equilibrium bound water. Water so retained by a solid in equilibrium with the humidity of the surrounding air, is designated as the *equilibrium moisture content*. Such moisture may be held as adsorbed surface films or condensed in fine capillary structures at reduced vapor pressure.

The equilibrium moisture content varies with the temperature and humidity of the surrounding air. Consequently, any correlation of equilibrium moisture content should take these two factors into account. However, at low temperatures, *e.g.*, 60 to 120 F, a plot of equilibrium moisture content *vs.* percent relative humidity, expressed as 100 (p/p_s), is essentially independent of temperature. Such a plot usually results in a curve of double curvature with a point of inflection (see Fig. 4).