Equation 2 is applicable when the Reynolds number for liquid drops is less than 10. Drop diameters are almost always less than 500 microns, and are usually in the range of 20 to 150 microns.

The rate of evaporation of drops may be expressed in terms of heat transfer or mass transfer. In terms of heat transfer, the evaporation rate is given by the equation:

$$\frac{dw}{d\theta} = \frac{2\pi k_f D_p}{H}(t_a - t_s) \qquad (3)$$

where

$\frac{dw}{d\theta}$ = evaporation rate, pounds per hour.

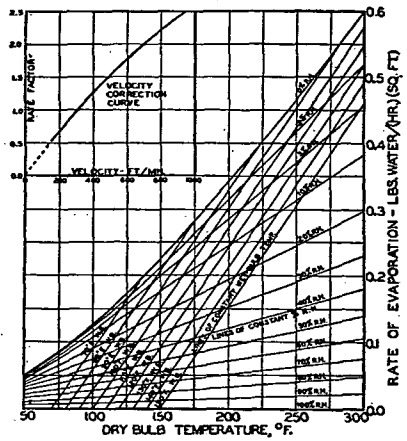

Fig. 3 .... Rate of Evaporation Chart[3]

Drying at Air Temperatures above the Boiling Point of the Liquid. When the temperature of the drying air is maintained above the boiling point of the liquid being evaporated, or when superheated vapors are used for drying, the usual equations for mass transfer, expressing rate of evaporation as a function of the vapor-pressure difference, lose significance, since large errors are introduced in the expression for vapor-pressure driving force due to its apparently small value. Such cases can be treated conveniently on a basis of heat transfer, since a temperature difference must always exist in order that drying may proceed.

Constant-Rate Period When Heat Transfer Depends on Conduction and Radiation. In indirect drying, where heat transfer and drying do not depend on the flow of heated gases, the drying rate depends either on heat 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 sheet 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 $(w - w_e)/(w_o - w_e) < 0.6$

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

where

w = moisture content on dry basis, at any time θ, pounds of water per pound.
w_e = moisture content at equilibrium with external conditions, pounds of water per pound of dry material.
w_o = 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 with the thickness. When this occurs the falling

Table 2 .... Approximate Classification of Materials Most Likely to Obey Equations 4 and 5

Materials Obeying Equation 4

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.

Materials Obeying Equation 5

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.

rate can be expressed with *fair* accuracy by the following equation:

$$\left(\frac{dw}{d\theta}\right)_f = -\frac{(dw/d\theta)_c}{(w_c - w_e)}(w - w_e) \qquad (5)$$

where

$(dw/d\theta)_c$ = the constant drying rate, pounds per (hour) (pound dry material).
$\left(\frac{dw}{d\theta}\right)_f$ = falling rate, pounds of water per (hour) (pound of dry material).
w_c = the critical moisture content, pounds per pound dry material.

The appropriate expression for $\left(\frac{dw}{d\theta}\right)_c$ obtained from Table 1, may then be substituted in Equation 5.

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

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. 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.

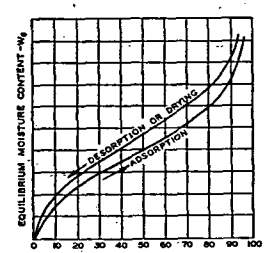

Fig. 4 .... Typical Equilibrium Moisture Content Curves[1]

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).

APPLICATION OF HYGROMETRY TO DRYING

In analyzing any particular drying problem it is sometimes advisable to consider the thermodynamic changes involving the drying medium, since in most cases the drying medium is an air-water-vapor mixture. The thermodynamic process can be traced on a psychrometric chart.

The psychrometric chart, Fig. 5, suggested by Grosvenor,[5] is suitable for most drying calculations. The adiabatic cooling lines on the chart indicate the paths along which the changes in the thermodynamic properties of the air occur in an adiabatic dryer.

The theoretical ability of air to pick up moisture corresponds to the difference between the final saturation content at the wet-bulb temperature (approximately the adiabatic cooling temperature or thermodynamic wet-bulb temperature) and the initial moisture content at the supply air dew point. The maximum possible pickup is never achieved in practical dryers because on the basis of good design, this would be undesirable. Experience has shown that there is an optimum pickup which is a function of the independent drying variables and is less than the maximum theoretical value as obtained from the psychrometric chart.

It should be noted that in practice the process will not necessarily follow exactly the adiabatic cooling line since there may be a transfer of heat to the tray or conveyor itself.

Use of the psychrometric chart for analysing drying problems is illustrated by *Example 1.*

Example 1: Assume a dryer having a capacity of 100 lb of gelatin per hour at 11.1 percent bone-dry basis. The initial moisture content is 228 percent bone-dry basis and the final moisture content is to be 32 percent bone-dry basis. The rate of production of bone-dry gelatin is 90.5 lb per hr. Supply air is available at 120 F dry-bulb, 85 F wet-bulb, with make-up air at 80 F dry-bulb and 65 F wet-bulb. Air is exhausted from the dryer at 100 F dry-bulb and 84.5 F wet-bulb.

Find (1) the required amount of make-up and exhaust air, and (2) the percentage of recirculated air.

Solution: Refer to psychrometric chart, Fig. 5, and obtain the humidity ratio of the make-up air and of the exhaust air. In order to maintain a steady-state condition in the dryer the water which is evaporated from the material must be carried away by the exhaust air. Therefore, the difference between the humidity ratio of the exhaust air and that of the make-up air (known as pickup) is equal to the water evaporated from the material divided by the pounds per hour of dry air in the exhaust.

Step 1: The moisture in exhaust air at 100 F dry-bulb and 84.5 F wet-bulb is found to be 0.022 lb per pound of dry air. The moisture in make-up air at 80 F dry-bulb and 65 F wet-