transfer of mass as vapor and internal liquid. These two processes occur simultaneously, and the factors governing the rate of each process determine the rate of drying.

In any commercial drying problem, a principal objective is to supply the required heat in the most efficient manner. Consequently, heat transfer may occur by convection, conduction, or radiation, or by any combination of these mechanisms. The various types of industrial dryers may be shown to differ fundamentally with respect to the method used for transferring heat to the solid. In general, heat must flow first to the outer surface of the solid and then into the interior. An important exception is drying with high frequency electrical currents where heat is *generated within the solid*, producing a higher temperature at the interior than at the surface, and consequently, causing heat to flow from inside the solid to the outer surfaces.

Mass transfer in drying occurs as liquid or vapor flow, or both, within the solid, and as vapor flow from the external wet surfaces. The nature of liquid-concentration gradients in solids during drying depends on the mechanism of internal liquid flow, and this mechanism, in turn, depends to a large extent upon the physical and chemical characteristics of the solid being dried.

Internal and External Conditions

A study of how a solid dries may be based on the *internal* mechanism of liquid flow, or on the effect of the *external conditions* of temperature, humidity, air flow, state of subdivision, etc., on the drying rate of the solid. The former procedure involves a fundamental study of the liquid flow conditions within a solid during drying. The latter procedure, although less fundamental, is more generally used because the effects are easier to establish and the results have greater immediate application in dryer design and operation.

Internal Mechanism of Liquid Flow. Internal liquid flow may occur by several mechanisms, depending on the structure of the solid. Several mechanisms of flow are as follows:

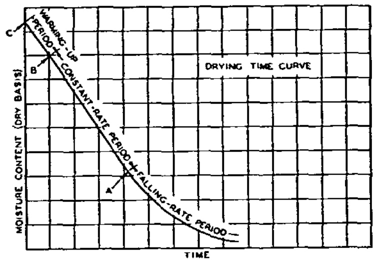
1. *Diffusion* in continuous, homogeneous solids.
2. *Capillary flow* in granular and porous solids.
3. Flow caused by *shrinkage* and *pressure* gradients.
4. Flow caused by a *vaporization-condensation* sequence.
5. Flow caused by *gravity*.
6. Flow caused by an electrical potential, *electro-osmosis*.
7. Flow caused by temperature gradients, *thermal diffusion*.

Although more than one of these mechanisms of flow may be effective at one time, only one predominates as a rule at a given time in a solid during drying. However, a different mechanism may predominate at a different time in the cycle. The mechanism of moisture flow is usually established experimentally from a study of moisture gradients.

External Variables. The principal external variables involved in any drying problem are: *temperature, humidity, air flow, state of subdivision* of the solid, *agitation* of the solid, *method of supporting the solid*, and the *contact* between hot surfaces and wet solid. All these variables do not necessarily occur simultaneously in one problem.

Periods of Drying[1]

A typical drying time curve for a wet solid is shown in Fig. 1. This curve is a plot of the moisture content at any time in a solid undergoing drying. It is the usual method of presenting experimental drying data. Although Fig. 1 shows that the moisture content is subject to a continuous variation with time, a more precise illustration of the nature of this variation can be obtained by differentiating the curve and plotting the drying rate in pounds of water per (hour) (pound of dry material) against the moisture content in pounds of water per pound of dry material as shown in Fig. 2. The *rate curve* shows that the drying process is not a smooth, continuous one in which a single mechanism controls throughout.



From Reference 2

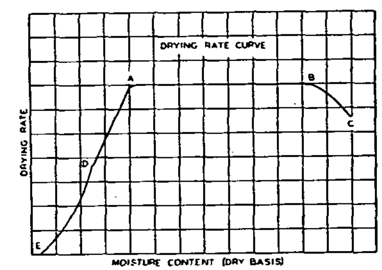
Fig. 1 .... Moisture Content w vs. Drying Time θ

Section *BA* on each curve represents a *constant-rate period*. In Fig. 1, it is shown by a straight line of constant slope $dw/d\theta$, which becomes a horizontal line on the rate curve in Fig. 2.

The curved portion of Fig. 1 is termed the falling-rate period, and, as shown in Fig. 2, it is typified by a continuously changing rate. Point *A*, where the constant rate ends and the drying rate begins to decrease, is termed the *critical moisture content*.

The portion of the curve designated by *CB* in Figs. 1 and 2 represents a warming-up period, and it may, or may not, be a significant item depending on the total time involved.

Constant-Rate Period. Drying during the constant-rate period is equivalent to evaporation from a free-water surface on the surface of the solid. The rate of drying in this period is determined by the rate of diffusion of water vapor through an air film at the wet surface of the solid. A constant rate of evaporation on the surface of the solid maintains the surface at a



From Reference 2

Fig. 2 .... Rate of Drying $\frac{dw}{d\theta}$ vs. Moisture Content w

constant temperature, which, in the absence of other heat effects, is very nearly the wet-bulb temperature of the air. If heat flows to the surface of evaporation by radiation and conduction, or both, in addition to convection, the surface temperature will be constant at some value between the air temperature and the wet-bulb temperature. This higher temperature in turn produces a higher constant rate of evaporation.

In those dryers in which heat is transferred to a wet solid by conduction through hot surfaces, and heat transfer by convection is not a factor, the wet surfaces approach the boiling point temperature rather than a wet-bulb temperature.

When all the heat for evaporation in the constant-rate period is supplied by a hot gas, a dynamic equilibrium is established between the rate of heat transfer to the material and the rate of vapor removal from the surface. This equilibrium between heat and mass transfer rates can be expressed as follows:

$$\frac{dw}{d\theta} = \frac{h_t A \Delta t}{H} = k_g A \Delta p \qquad (1)$$

where

- $\frac{dw}{d\theta}$ = drying rate, pounds of water per (hour) (pound of bone-dry material).
- h_t = total heat transfer coefficient, Btu per (hour) (square foot) (Fahrenheit degree).
- A = area of heat transfer and evaporation, square feet per pound of bone-dry material.
- H = enthalpy of evaporation at t_s, Btu per pound.
- k_g = mass transfer coefficient, pounds per (hour) (square foot) (atmosphere).
- Δt = $(t_a - t_s)$ = temperature difference between air and surface of evaporation, Fahrenheit degrees.
- t_a = air temperature, Fahrenheit.
- t_s = temperature of surface of evaporation, Fahrenheit.
- Δp = $(p_s - p_a)$ = vapor-pressure difference, atmospheres.
- p_s = vapor pressure of water at t_s, atmospheres.
- p_a = partial pressure of water vapor in air, atmospheres.

When $h_t = h_c$, the coefficient of heat transfer by convection only, then t_s under equilibrium conditions becomes t_w, the wet-bulb temperature of the air, and p_s is the vapor pressure at this temperature. If heat is also supplied by radiation, then h_t is the sum $(h_c + h_r)$ where h_r is the radiation coefficient and h_c is the convection coefficient, and t_s becomes higher than the wet-bulb temperature. A similar result occurs when heat reaches the surface of evaporation by convection and conduction.

Effect of Air Velocity. The principal effect of air velocity is on h_c and k_g, since the rate of transfer of heat and mass in the constant-rate period depends mainly on the rate of diffusion of heat and vapor through the air film at the surface of the solid, and air velocity is the chief factor affecting the thickness of this film. The influence of direction of air flow on the heat transfer coefficient h_c and on the corresponding drying rate $\frac{dw}{d\theta}$ is shown in Table 1.

Effect of Temperature or Humidity. Temperature or humidity enters the drying rate equation as a driving force across the air film. The wet-bulb depression, which is the difference between the dry-bulb temperature and the wet-bulb temperature, is directly proportional to the drying rate in this period.

Table 1 .... Convection Heat Transfer (h_c) and Rates of Drying $\left(\frac{dw}{d\theta}\right)$ Coefficients for Constant-Rate Period

Direction of Air Flow	h_c	$\frac{dw}{d\theta}$
Parallel to plane surfaces[3]	$0.0128G^{0.8}$	$\frac{0.0128G^{0.8}A}{H}(t_a - t_w)$
Perpendicular to plane surfaces[1]	$0.37G^{0.37}$	$\frac{0.37G^{0.37}A}{H}(t_a - t_w)$
Through circulation[4] (for Reynolds number > 300)	$\frac{0.37G^{0.59}c_s}{D_p^{0.41}}$	$\frac{0.37c_s a G^{0.59}\Delta t_m}{\rho_s H D_p^{0.41}}$

Letter Symbols for Table 1

(not previously defined)

- h_c = convection heat transfer coefficient, Btu per (hour) (square foot) (Fahrenheit degree).
- G = mass velocity of dry air, pounds per (hour) (square foot).
- t_w = wet-bulb temperature of drying air, Fahrenheit.
- a = drying area, square feet per cubic foot of bed volume.
- ρ_s = bulk density of dry granular bed, pounds per cubic foot.
- D_p = average diameter of particle, feet.
- Δt_m = logarithmic mean difference between air temperature entering and leaving the bed and the wet-bulb temperature, Fahrenheit.
- c_s = humid heat, Btu per (pound of dry air) (Fahrenheit degree).

When dealing with heat transfer coefficients the wet-bulb depression is the driving force, whereas with mass transfer coefficients the driving force is expressed in terms of humidity or vapor-pressure differential.

Fig. 3 permits a ready estimate of the constant drying rate for various air temperatures and humidities. The chart is based on the difference between the dry-bulb and wet-bulb temperatures of the entering stream of air, and on an air velocity of 300 fpm. It may be assumed satisfactory for tray drying of any material in the constant-rate drying period. It does not apply to rotary or through-circulation drying. A curve for correcting the air velocity is incorporated in Fig. 3. This curve is based on the variation of drying rate with the 0.8 power of the velocity.

Evaporation from Liquid Drops. For the important problem of spray drying, evaporation rates of liquid drops must be estimated. Below a value of Reynolds number $(D_p G/\mu)$ of 10 for spherical particles, the heat transfer coefficient across the gas film surrounding the drop is given by

$$h = \frac{2k_f}{D_p} \qquad (2)$$

where

- h = film heat transfer coefficient, Btu per hour) (square foot) (Fahrenheit degree).
- k_f = thermal conductivity of gas film, Btu per (hour) (square foot) (Fahrenheit degree per foot).