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Subject: Mass Transfer-II (CM-601)

Unit: III (Lecture-2)

Topic: Rate of Drying and Time for Drying

1. DRYING PERIODS

In drying, it is necessary to remove free moisture from the surface and also moisture from the interior of the material. If the change in moisture content for a material is determined as a function of time, a smooth curve is obtained from which the rate of drying at any given moisture content may be evaluated. The form of the drying rate curve varies with the structure and type of material, and two typical curves are shown in Figure 1. In curve 1, there are two well-defined zones: AB, where the rate of drying is constant and BC, where there is a steady fall in the rate of drying as the moisture content is reduced. The moisture content at the end of the constant rate period is represented by point B, and this is known as the *critical moisture content*. Curve 2 shows three stages, DE, EF and FC. The stage DE represents a constant rate period, and EF and FC are falling rate periods. In this case, the Section EF is a straight line, however, and only the portion FC is curved. Section EF is known as the first falling rate period and the final stage, shown as FC, as the second falling rate period. The drying of soap gives rise to a curve of type 1, and sand to a curve of type 2.

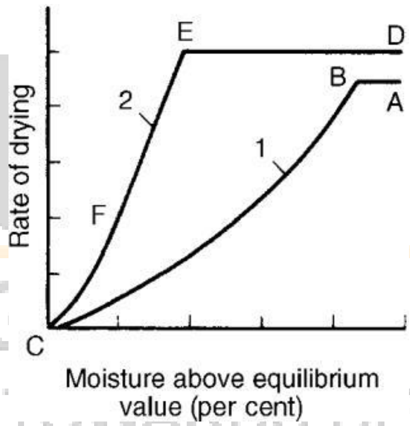

Figure 1.Rate of drying of a granular material

Constant rate period

During the constant rate period, it is assumed that drying takes place from a saturated surface of the material by diffusion of the water vapour through a stationary air film into the air stream. The rates of drying of a variety of materials in this stage are substantially the same as shown in Table 1.

In order to calculate the rate of drying under these conditions, the relationships obtained in Volume 1 for diffusion of a vapour from a liquid surface into a gas may be used. The simplest equation of this type is:

$$W = k_G A(P_s - P_w) \quad (1)$$

where k_G is the mass transfer coefficient.

Table 1.Evaporation rates for various materials under constant conditions

Material	Rate of evaporation	
	(Kg/m^2h)	(Kg/m^2s)
Water	2.7	0.00075
Whiting pigment	2.1	0.00058
Brass filings	2.4	0.00067
Brass turnings	2.4	0.00067
Sand (fine)	2.0–2.4	0.00055– 0.00067
Clays	2.3–2.7	0.00064– 0.00075

Since the rate of transfer depends on the velocity *u* of the air stream, raised to a power of about 0.8, then the mass rate of evaporation is:

$$W = k_G A(P_s - P_w)u^{0.8} \qquad (2)$$

where: A is the surface area,

P_s is the vapour pressure of the water, and

P_w is the partial pressure of water vapour in the air stream

This type of equation, used in Volume 1 for the rate of vaporisation into an air stream, simply states that the rate of transfer is equal to the transfer coefficient multiplied by the driving force. It may be noted, however, that $(P_s - P_w)$ is not only a driving force, but it is also related to the capacity of the air stream to absorb moisture.

These equations suggest that the rate of drying is independent of the geometrical shape of the surface. However, that the ratio of the length to the width of the surface is of some importance, and that the evaporation rate is given more accurately as:

(a) For values of $u = 1 - 3$ m/s:

$$W = 5.53 \times 10^{-9} L^{0.77} B(P_s - P_w)(1 + 61u^{0.85}) \text{ kg/s} \qquad (3)$$

(b) For values of $u < 1$ m/s:

$$W = 3.72 \times 10^{-9} L^{0.73} B^{0.8}(P_s - P_w)(1 + 61u^{0.85}) \text{ kg/s} \qquad (4)$$

where: P_s , the saturation pressure at the temperature of the surface (N/m^2),

P_w, the vapour pressure in the air stream (N/m^2), and

L and *B* are the length and width of the surface, respectively (m).

For most design purposes, it may be assumed that the rate of drying is proportional to the transfer coefficient multiplied by $(P_s - P_w)$. If the temperature of the surface is greater than that of the air stream, then P_w may easily reach a value corresponding to saturation of the air. Under these conditions, the capacity of the air to take up moisture is zero, while the force causing evaporation is $(P_s - P_w)$. As a result, a mist will form and water may be redeposit on the surface. In all drying equipment, care must therefore be taken to ensure that the air or gas used does not become saturated with moisture at any stage.

The rate of drying in the constant rate period is given by:

$$W = \frac{dw}{dt} = \frac{hA}{\lambda} = = k_G A(P_s - P_w) \quad (5)$$

where: W is the rate of loss of water,

h is the heat transfer coefficient from air to the wet surface,
dt is the temperature difference between the air and the surface,

λ is the latent heat of vaporisation per unit mass,
k_G is the mass transfer coefficient for diffusion from the wet surface through the gas film,

A is the area of interface for heat and mass transfer, and
$(P_s - P_w)$ is the difference between the vapour pressure of water at the surface and the partial pressure in the air.

If the gas temperature is high, then a considerable proportion of the heat will pass to the solid by radiation, and the heat transfer coefficient will increase. This may result in the temperature of the solid rising above the wet bulb temperature.

First falling-rate period

The points B and E in Figure 1 represent conditions where the surface is no longer capable of supplying sufficient free moisture to saturate the air in contact with it. Under these conditions, the rate of drying depends very much on the mechanism by which the moisture from inside the material is transferred to the surface. In general, the curves in Figure 1 will apply, although for a type 1 solid, a simplified expression for the rate of drying in this period may be obtained.

Second falling-rate period

At the conclusion of the first falling rate period it may be assumed that the surface is dry and that the plane of separation has moved into the solid. In this case, evaporation takes place from within the solid and the vapour reaches the surface by molecular diffusion through the material. The forces controlling the vapour diffusion determine the final rate of drying, and these are largely independent of the conditions outside the material.

1. TIME FOR DRYING

If a material is dried by passing hot air over a surface which is initially wet, the rate of drying curve in its simplest form is represented by BCE, shown in Figure 2.

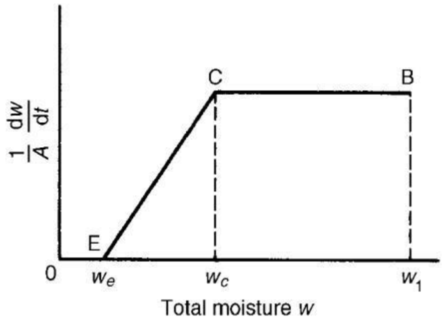

Figure 2. The use of a rate of drying curve in estimating the time for drying.

where: w is the total moisture,

w_e is the equilibrium moisture content (point E),

$w - w_e$ is the free moisture content, and

w_c is the critical moisture content (point C).

Constant-rate period

During the period of drying from the initial moisture content w_1 to the critical moisture content w_c, the rate of drying is constant, and the time of drying t_c is given by:

$$t_c = \frac{w1 - wc}{RcA} \qquad (6)$$

where: R_c is the rate of drying per unit area in the constant rate period, and

A is the area of exposed surface.

Falling-rate period

During this period the rate of drying is, approximately, directly proportional to the free moisture content ($w - w_e$), or:

$$-\left(\frac{1}{A}\right)\frac{dw}{dt} = m(w\text{-}w_e) = mf \qquad (7)$$

Thus:
$$-\frac{1}{mA}\int_{we}^{w}\frac{dw}{(w-we)} = \int_0^{tf} dt$$

Or:
$$\frac{1}{mA}\ln\left[\frac{wc-we}{w-we}\right] = t_f \qquad (8)$$

And:
$$t_f = \frac{1}{mA}\ln\left[\frac{fc}{f}\right] \qquad (9)$$

Total time of drying

The total time t of drying from w_1 to w is given by $t = (t_c + t_f)$.

The rate of drying R_c over the constant rate period is equal to the initial rate of drying in the falling rate period, so that $Rc = mf_c$

Thus: $t_c = \frac{(w1 - wc)}{mAfc}$ (10)

and the total drying time, $t = \frac{(w1 - wc)}{mAfc} + \frac{1}{mA} \ln[\frac{fc}{f}]$

$$t = \frac{1}{mA}[\frac{(f1 - fc)}{fc} + \ln[\frac{fc}{f}]] \quad (11)$$

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