

CHAPTER TWO

Drying of Solids

2019-2020

1.1 Introduction.

Drying refers to the removal of water, or another solute "liquid", to reduce the content of residual liquid to an acceptably low value. The drying of materials is often the final operation in a manufacturing process, carried out immediately prior to packaging or dispatch. Drying is the operation often follows evaporation, filtration, or crystallization.

1.2 Drying is carried out for one or more of the following reasons:

- (a) To reduce the cost of transport.
- (b) To make a material more suitable for handling as, for example, with soap powders, dyestuffs and fertilizers.
- (c) To provide definite properties, such as, for example, maintaining the free-flowing nature of salt.
- (d) To remove moisture which may otherwise lead to corrosion.

1.3 General Principles.

The moisture content of a material is usually expressed in terms of its water "liquid" content as a percentage of the mass of the dry material, though moisture content is sometimes expressed on a wet basis. If a material is exposed to air at a given temperature and humidity, the material will either lose water "if the air have lower humidity than that the moisture content of the solid" or gain water "if air has more humid than the solid" until an equilibrium condition is established.

1.4 Moisture may be present in the following forms:

❖ □ *Bound Moisture:*

This is water retained so that it exerts a vapour pressure less than that of free water at the same temperature. Such water may be retained in small capillaries, adsorbed on surfaces, or as a solution in cell walls.

❖ **Unbound Moisture.**

This is the moisture "water" contained by a substance which exerts a vapor pressure as high as that of free water at the same temperature and is largely held in the voids of solid.

❖ **Equilibrium Moisture Content w_e .** Is the portion of the water in the wet solid which cannot be removed by the inlet air.

❖ **Free Moisture.** This is water which is in excess of the equilibrium moisture content. Where free moisture = $w - w_e$, w is the total moisture content.

1.5 Terminology and Definitions:

For the air–water system, the following definitions are of importance:

- **Humidity H ,** mass of vapor "water" per unit mass of dry air.

$$H = M_A P_A / (M_B (P - P_A))$$

P_A : Partial pressure of water vapor.

P : Total pressure.

M_A : Molecular weight of water vapor.

M_B : Molecular weight of dry air.

- **Humidity of saturated air H^0 ,** this is the humidity of air when it is saturated with water vapor. The air then is in equilibrium with water at the given temperature and pressure.

$$H = M_A P_A^0 / (M_B (P - P_A^0))$$

P_A^0 : partial pressure of vapor in saturated gas.

- **Percentage Relative Humidity RH %**

$$= \frac{\text{Partial pressure of water vapour in air}}{\text{Vapour pressure of water at the same temperature}} * 100 = \frac{P_A}{P_A^0} * 100$$

100% humidity means saturated gas, and 0% humidity means vapor free gas.

- **Percentage humidity:**

$$= \frac{\text{Humidity of air}}{\text{Humidity of saturated air}} * 100 = \frac{P - P_A^0}{P - P_A} * \text{RH \%}$$

- **Humid volume V_H ,** Is the volume of unit mass of dry air with accompanying water vapor at a given temperature and pressure.

$$V_H = \frac{22.4}{273} \left(\frac{1}{M_B} + \frac{H}{M_B} \right) * T \quad \text{Where T: temperature in K}$$

- **Humid heat S .** is the energy required to raise the temperature of unit mass of dry air and its associated water vapor through 1 degree K at constant pressure.

$$S = C_a + C_w H, \text{ kJ/kg.K}$$

Where C_a and C_w is the specific heat of gas and vapor respectively.

- **Dry Bubble Temperature:** This is the temperature of air measured by a thermometer whose bulb is dry, i.e. not in touch with water or any other liquid. This is the true temperature of the air.

- **Wet-bulb temperature:** when stream of unsaturated gas is passed over the surface of a liquid, the humidity of the gas is increased due to evaporation of the liquid and heat is transferred from the gas to the liquid. At equilibrium the rate of heat transfer from the gas just balances that required to vaporize the liquid and the liquid is said to be the *wet-bubble temperature*.

The rate of transfer of heat from the gas to the liquid can be written as:

$$Q = hA(T - T_w) \dots\dots\dots(1)$$

Where Q: heat transfer rate.

A: the area for transfer.

h: heat transfer coefficient.

T: dry bulb temperature

T_w : wet bulb temperature.

The liquid evaporating into the gas is transferred by diffusion from the interface to the gas stream as a result of a concentration difference (C_o-C) C_o and C mass per unit volume. The rate of evaporation is then given by:

$$W = h_D A (C_o - C)$$

Where:

C_o : concentration of the vapor at the surface.

C : concentration in the gas stream.

h_D : coefficient of mass transfer.

$$W = h_D A \frac{M_w}{RT} (P_A^0 - P_A)$$

$P_A^0 - P_A$ can be expressed in terms of the corresponding humidities H and H_w .

If P_A and P_A^0 are small compared with P , $(P-P_A)$ and $(P-P_A^0)$, can be replaced by a mean partial pressure of the gas.

$$W = h_D A \rho_A (H - H_w)$$

Where: H_w : is the humidity of saturated gas at wet-bulb temperature.

ρ_A : density of the gas at partial pressure.

The heat transfer required to maintain this rate of evaporation is:

$$Q = h_D A \rho_A (H - H_w) \lambda \dots\dots\dots(2)$$

Where λ is the latent heat of vaporization of the liquid.

Thus, equating equation (1) and (2):

$$(H - H_w) = \frac{h}{h_D \rho_A \lambda} (T - T_w)$$

Where $\frac{h}{h_D \rho_A \lambda} = S$ (humid heat).

- **Adiabatic saturation temperature.** If the gas is passed over the liquid at such a rate that the time of contact is sufficient for equilibrium to be

established, the gas will become saturated and both phases will be brought to the same temperature. In a thermally insulated system, the total sensible heat falls by an amount equal to the latent heat of the liquid evaporated. As a result of continued passage of the gas the temperature of the liquid gradually approaches an equilibrium value which is known as adiabatic saturation temperature.

1.5 Rate of drying:

The time required for drying of a moist solid to final moisture content can be determined from knowledge of the rate of drying under a given set of conditions. The drying rate of a solid is a function of temperature, humidity, flow rate and transport properties (in terms of Reynolds number and Schmidt number) of the drying gas. 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.

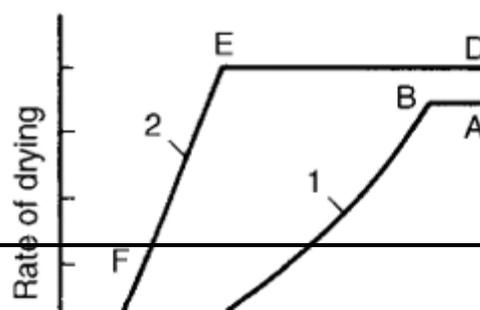


Fig. (1) Rate of drying of a granular material

- ***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 vapor through a stationary air film into the air stream.

- ***First falling-rate period***

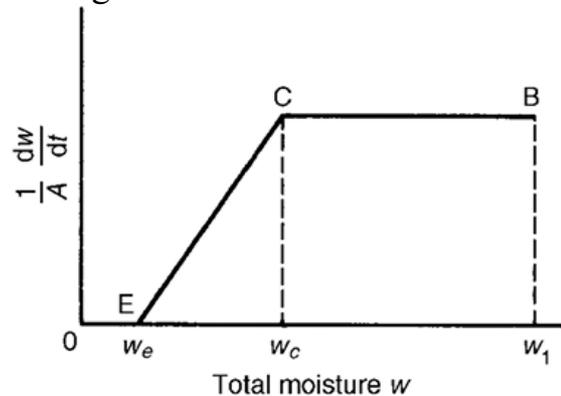
The points B and E in Figure (1) represent conditions where the surface is no longer capable of supplying sufficient free moisture to saturate the air in contact with it. Under these conditions, the rate of drying depends very much on the mechanism by which the moisture from inside the material is transferred 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 vapor reaches the surface by molecular diffusion through the material. The forces controlling the vapor diffusion determine the final rate of drying, and these are largely independent of the conditions outside the material.

1.6 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.



Fig(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.

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:

$$t_c = \frac{w_1 - w_c}{R_c A}$$

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:

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

$$-\left(\frac{1}{mA}\right) \int_{w_e}^w \frac{dw}{(w - w_e)} = \int_0^{t_f} dt$$

$$t_f = \frac{1}{mA} \ln \frac{f_c}{f} \quad \text{where } f = (w - w_e), f_c = (w_c - w_e).$$

1.7 Calculation methods for constant rate drying period:

In the constant rate period of drying, the surfaces of grains of solid in contact with drying air flow remain completely wetted. Drying of material occurs by mass transfer vapor from the saturated surface of the material through the air film to the bulk gas phase. The rate of moisture movement within the solid is sufficient to keep the surface saturated. The rate removal of water vapor (drying) is controlled by the rate of heat transfer to the evaporating surface which furnishes the latent heat of evaporation for the liquid. At steady state the rate of mass transfer balances the rate of heat transfer. Assuming only heat transfer to the solid surface by convection from the hot gas to the surface of the solid and mass transfer from the surface to the hot gas.

- No heat transfer by conduction from metal surface, neglect heat transfer by radiation.

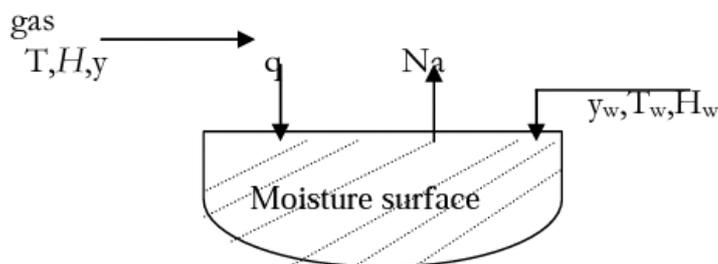


Fig. (3) Heat and mass transfer in constant rate drying

The rate of heat transfer by convection (q) from the gas at T to the surface of the solid at T_w is:

$$q = hA (T - T_w) \dots\dots\dots (1)$$

Where h is heat transfer coefficient.

A is surface area.

The flux of water vapor from the surface is:

$$N_A = k_y \left(\frac{M_B}{M_A} \right) (H_w - H) \dots\dots\dots (2)$$

Where k_y is mass transfer coefficient.

M_A, M_B are molecular weight of water and air respectively.

The amount of heat needed $q = m \cdot \lambda_w$

$$q = N_A M_A A \lambda_w \dots \dots \dots (3)$$

Where λ_w latent heat of vaporization at T_w .

Equating equation (1) and (3) and sub into (2)

$$R_C = \frac{q}{A \lambda_w} = \frac{h (T - T_w)}{\lambda_w} = k_y M_B (H_w - H)$$

• **To predict R_C , the heat transfer coefficient h must be known**

1) *If air flowing parallel to the drying surface.*

$$h = 0.0204 G^{0.8} \quad (\text{SI})$$

$$h = 0.0128 G^{0.8} \quad (\text{English})$$

2) *If air flowing perpendicular to the drying surface.*

$$h = 1.17 G^{0.37} \quad (\text{SI})$$

$$h = 0.37 G^{0.37} \quad (\text{English})$$

Where gas mass velocity $G = \rho_{\text{air}} \cdot v$

v is air velocity.

1.8 Material and Heat Balance for Continuous Dryers.

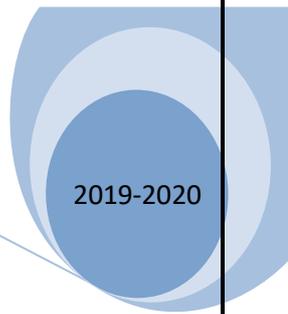
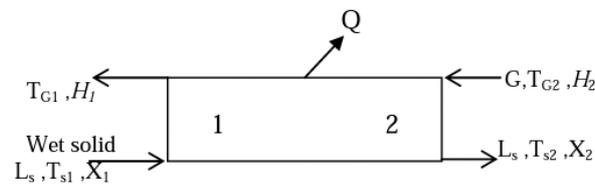


Figure below show a flow diagram for a continuous type dryer where the drying gas flows counter currently to the solids flow.



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The solid enters at a rate of L_s kg dry solid/h, having a free moisture content w_1 and a temperature T_{s1} . It leaves at w_2 and T_{s2} . The gas enters at a rate G kg dry air/h, having a humidity H_2 kg water vapor/ kg dry air and a temperature of T_{G2} . The gas leaves at T_{G1} and H_1 . For material balance on the moisture:

$$G H_2 + L_s w_1 = G H_1 + L_s w_2$$

For heat balance a datum of T_0 is selected. The enthalpy of wet solid is composed of the enthalpy of the dry solid plus that of free liquid as free moisture. The heat of wetting is usually neglected.

A heat balance on dryer is

$$G H_{G2} + L_s H_{s1} = G H_{G1} + L_s H_{s2} + Q$$

Where:

H_{G2} , H_{G1} are enthalpy of gas inlet and outlet dryer respectively.

H_{s1} , H_{s2} are enthalpy of wet solid inlet and outlet dryer respectively.

Q is heat loss in the dryer in kJ/h. for an adiabatic process $Q=0$, and if the heat is added, Q is negative.