Al-Mustaqbal University
Chemical Engineering and Petroleum Industries Department
4th Class
Subject: Operation units
Lecturer: Abbas K. Al-Gburi
1st/2nd term- Lect. 1 (Drying of solids)

Drying of solids

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. In some cases, drying is an essential part of the manufacturing process, as for instance in paper making or in the seasoning of timber.

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. One example is the drying of gaseous fuels or benzene prior to chlorination.

1.2 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 corresponding to the moisture content of the solid " or gain water "if air has more humid than the solid in equilibrium with it, the solid absorbs moisture from the air" until an equilibrium condition is established.

Moisture may be present in the following forms:

   1- Bound moisture.

This is the moisture "water" "contained by a substance that it exerts a vapor pressure less than that of free water at the same temperature. Bound water may be exist in several conditions such as water retained in small

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capillaries, on surfaces, or as a solution in cell walls and in organic substance in the physical and chemical combination.

2- 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.

3- Equilibrium Moisture Content X*.

Is the portion of the water in the wet solid which can not be removed by the inlet air.

Free Moisture X.

This is water which is in excess of the equilibrium moisture content. Where X = Xt - X*, Xt is the total moisture content.
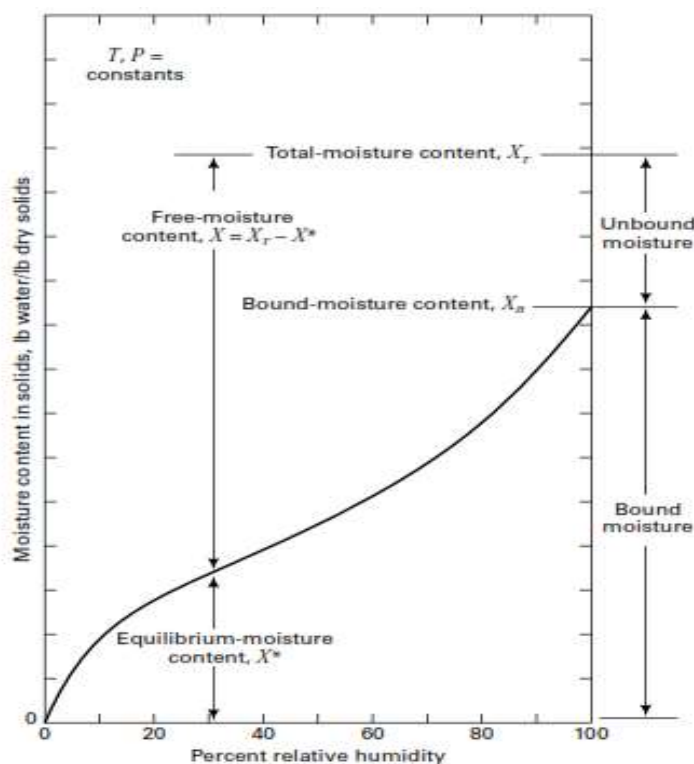

Figure (1) moisture content vs. Percentage relative humidity.

Abbas.Khaleel.Ibrahim@uomus.edu.iq

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1.3 Wet solid groups.

Wet solids classified into two categories according to their drying behavior:

1. **Granular or crystalline solids** that hold moisture in open pores between particles. These are mainly inorganic materials, examples of which are crushed rocks, sand, catalysts, titanium dioxide, zinc sulfate, and sodium phosphates. During drying, the solid is unaffected by moisture removal, so selection of drying conditions and drying rate is not critical to the properties and appearance of the dried product. Materials in this category can be dried rapidly to very low moisture contents.

2. **Fibrous, amorphous, and gel-like materials** that dissolve moisture or trap moisture in fibers or very fine pores. These are mainly organic solids, including tree, plant, vegetable, and animal materials such as wood, leather, soap, eggs, glues, cereals, starch, cotton, and wool. These materials are affected by moisture removal, often shrinking when dried and swelling when wetted. With these materials, drying in the later stages can be slow. If the surface is dried too rapidly, moisture and temperature gradients can cause checking, warping, case hardening, and/or cracking. Therefore, selection of drying conditions is a critical factor. Drying to low moisture contents is possible only when using a gas of low humidity.

In a direct-heat drying process, the extent to which moisture can be removed from a solid is limited, particularly for the second category, by the equilibrium-moisture content of the solid, which depends on factors that include temperature, pressure, and moisture content of the gas. Even if the drying conditions produce a completely dry solid, subsequent exposure of the solid to a different humidity can result in an increase in moisture content.

The water removed by vaporization is generally carried away by air or hot gases, and the ability of these gases to pick up the water is determined by their temperature and humidity. In designing dryers using air, the properties of the air– water system are essential.

A non-porous insoluble solid, such as sand or china clay, has an equilibrium moisture content approaching zero for all humidities and temperatures, although many organic materials, such as wood, textiles, and leather, show wide variations of equilibrium moisture content.

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1.4 Terminology and definition.

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

• *Humidity $\mathcal{H}$*, mass of vapor "water" per unit mass of dry air

$$\mathcal{H} = \frac{M_A P_A}{M_B(P - P_A)}$$

where

P_A = Partial pressure of water vapor.

P = Total pressure.

M_A = Molecular weight of water vapor.

• *Humidity of saturated air $\mathcal{H}_0$.* 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.

$$\mathcal{H}_\circ = \frac{M_A P_A^\circ}{M_B(P - P_A^\circ)}$$

where

P_A^o = Water vapor pressure.

M_B = Molecular weight of air.

• *Percentage relative humidity $R\mathcal{H}\%$*

$$= \frac{partial\ pressure\ of\ water\ vapour\ in\ air}{vapour\ pressure\ of\ water\ at\ the\ same\ temperature} \times 100$$

$$R\mathcal{H}\% = \frac{P_A}{P_A^\circ} * 100$$

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

• *Percentage humidity $\mathcal{H}_P$*

$$= \frac{humidity\ of\ air}{humidity\ of\ saturated\ air} \times 100 = \frac{\mathcal{H}}{\mathcal{H}_\circ} \times 100$$

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$$= \frac{M_A P_A / M_B (P - P_A)}{M_A P_A^{\circ} / M_B} \times 100$$

$$= \frac{P_A (P - P_A^{\circ})}{P_A^{\circ} (P - P_A)} * 100 = RH * \frac{(P - P_A^{\circ})}{(P - P_A)}$$

• **Humid volume** v_H. Is the volume of unit mass of dry air with accompanying water vapor at a given temperature and pressure. (assume ideal gas where volume of 1 kmole of a gas at 1 atm and 0 ˚C= 22.4 m³).

$$v_H = \frac{22.4}{273} \left(\frac{1}{M_B} + \frac{H}{M_A} \right) * T \quad \text{where T in ˚k}$$

For vapor–free gas $H = 0$, v_H is the specific volume of the fixed gas. For saturated gas $H = H_0$, v_H becomes the saturated volume.

• **Humid heat S.** is the energy required to rise the temperature of unit mass of dry air and its associated water vapor through unit temperature difference at constant pressure.

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

Where: C_a and C_w is the specific heat of gas and vapor kJ/kg.K

• **Dry-Bulb 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:** This is the temperature attained by a small amount of evaporating water in a manner such that the sensible heat transferred from the air to the liquid is equal to the latent heat required for the evaporation. The wet bulb temperature is measured by passing air over the bulb of a thermometer which is covered with a cloth – wick saturated water.

The rate of which this temperature is reached depends on the initial temperatures and the rate of flow of gas past the liquid surface with a small area of contact between the gas stream remain virtually unchanged.
The rate of transfer of heat from the gas to the liquid is:-

$$Q = h\,A(T_G - T_w) \dots \dots \dots \dots .1$$

Where

Q is the heat transfer rate.

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h is the heat transfer coefficient.

T_G is the dry bulb temperature.

T_W is the 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).

Where

C_o is the concentration of the vapor at surface.

C is the concentration in the gas stream. C_o and C mass per unit volume

The rate of evaporation is: $m = h_D A (C_o - C) \ldots \ldots \ldots \ldots 2a$

$$m = h_D A \frac{M_A}{RT} \left(P_A^\circ - P_A \right) \ldots \ldots \ldots \ldots \ldots 2b$$

Where h_D is the mass transfer coefficient.

P_A and P_A° partial pressure of air and vapor pressure of water vapor, and can be expressed in terms of the corresponding humilities $\mathcal{H}$ and $\mathcal{H}_w$.

• If P_A and P_A° are small compared with P, $(P-P_A)$ and $(P-P_A^\circ)$, can be replaced by a main partial pressure of the gas P_B.

$$\mathcal{H} = \frac{M_A P_A}{M_B (P - P_A)} \ldots \ldots. \, humidity \ at \ dry \ bulb \ temperature$$

$$\mathcal{H}_w = \frac{M_A P_A^o}{M_B (P - P_A^o)} \ldots \ldots. \, humidity \ at \ wet \ bulb \ temperature$$

$$\mathcal{H}_w - \mathcal{H} = \frac{M_A P_A}{M_B (P - P_A)} - \frac{M_A P_A}{M_B (P - P_A)} = \left[\frac{P_A^o}{(P - P_A^o)} - \frac{P_A}{(P - P_A)} \right] \frac{M_A}{M_B}$$

$$= \left[\frac{P_A^o - P_A}{P_B} \right] \frac{M_A}{M_B}$$

$$(P_A^o - P_A) = (\mathcal{H}_w - \mathcal{H}) P_B \frac{M_B}{M_A} \ldots \ldots \ldots \text{sub. in to eq. 2b}$$

$$m = h_D A \frac{M_A}{RT} (\mathcal{H}_w - \mathcal{H}) P_B \frac{M_B}{M_A}$$

$$\rho_A = \frac{P_B M_B}{RT}$$

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Therefore equations (2a) and (2b) become:-

$$m = h_D A \rho_A (\mathcal{H}_w - \mathcal{H}) \dots \dots \dots \dots .3$$

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

$$Q = m \, \lambda \dots \dots \dots \dots 4a$$

$$\therefore \quad Q = h_D A \rho_B (\mathcal{H}_w - \mathcal{H}) \lambda \dots \dots \dots \dots .4b$$

Where λ is the latent heat of vaporization of liquid.

Equating equations (1) and (4b):-

$$Q = hA(T_G - T_W) = h_D A \rho_B (\mathcal{H}_w - \mathcal{H}) \lambda$$

$$(\mathcal{H}_w - \mathcal{H}) = \frac{h}{h_D \rho \lambda}$$

Where $\left(\frac{h}{h_D \rho}\right) = S$ (humid heat) at moderate humilities.

The above equation is known Lewis relation.

Heat and mass transport through the air film on the moist wick are illustrated in figure (2).
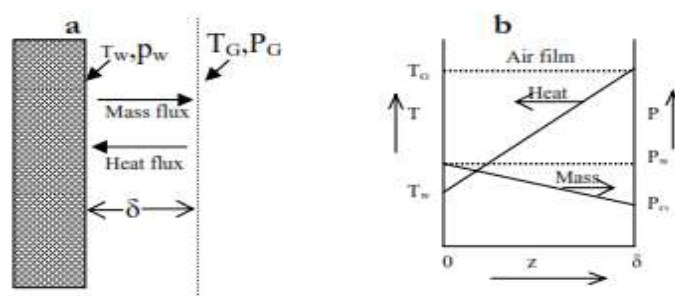

Figure 2: (a) schematic of the wick and air film; (b) temperature and partial pressure of water vapor profile in air film.

• **Dew point**. If the vapor-gas mixture is gradually cooled at a constant pressure, the temperature at which it just becomes saturated is called its dew point. The partial pressure at water vapor in air is the same as the vapor pressure of water at this temperature. If the temperature is reduced even slightly, condensation occurs and droplets (dew) of water appear.

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

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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 adiabatic saturation temperature.

Make heat balance over the column,

Enthalpy of the inlet air $= S(T_G - T_s) + \mathcal{H}\lambda$

Enthalpy of exit air $= S(T_s - T_s) + \mathcal{H}_s\lambda_s$

$$= \mathcal{H}_s\lambda_s$$

Where λs latent heat of vaporization of water at adiabatic saturation temperature.

-Because water temperature does not change, its enthalpy remain constant.

At steady state:

$$S(T_G - T_s) + \mathcal{H}\lambda_s = \mathcal{H}_s\lambda_s \dots \dots \dots \dots 6$$

$$(T_G - T_s) = (\mathcal{H} - \mathcal{H}_s)\frac{\lambda_s}{S} \dots \dots \dots \dots 7$$