DRYING

Drying refers to an operation in which the moisture of a substance (usually solid) is removed by thermal means (i.e., with the help of thermal energy).

Drying usually refers to the removal of relatively small amounts of water from a solid or nearly solid material. It involves the transfer of liquid from a wet solid into an unsaturated gas phase (drying medium).

During drying operation, mass and heat transfer occur simultaneously. Heat is transferred from the the bulk of the gas phase (drying medium) to the solid phase and mass is transferred from the solid phase to the gas phase in the form of liquid and vapour through various resistances. The material (liquid) that is transferred is the solute and transfer takes place as the gas phase is always unsaturated with respect to the solute material.

In drying, relatively small amounts of water or other liquid is removed from a solid or semi-solid material (using thermal energy), whereas in evaporation relatively large amount of water is removed from solutions. Drying involves the removal of water at a temperature below the boiling point, while evaporation involves the removal of water as vapour at its boiling point. Drying involves circulation of a hot air or other gas over a solid material for the removal of water, whereas evaporation involves use of steam heat for the removal of water. To obtain products almost in the dried form is the purpose of drying operation, while to obtain concentrated solutions is the main purpose of evaporation.

As the removal of moisture by thermal means is more costly than mechanical means (e.g., filtration), the moisture content of material must be reduced to the minimum possible level by the latter means before the material is fed to drying equipments.

In most of the drying operations, the heat (required to evaporate water) is provided by hot air or any other gas-drying medium.

Drying is frequently the last operation in manufacturing processes and is usually carried after evaporation, filtration, or crystallisation.

This operation is carried out in food, chemical, agricultural, pharmaceutical and textile industries.

Drying operation is carried out for the reasons given below :

(i) For reducing the transport cost.

(ii) For purifying a crystalline product so that the solvent adhering to the crystals is removed.

(iii) For making a material more suitable for handling and storage. Handling and storage of dry solids is easy.

(iv) To meet the market specifications of solid products set by the customers.

(v) For providing definite properties to materials.

(vi) In some cases for preventing corrosion arising due to the presence of moisture. Dry chlorine gas is not corrosive but traces of moisture make it very corrosive.

(vii) Sometimes it is an essential part of the process (e.g., drying of paper in paper making).

General Definitions :

The moisture content of a wet material may be expressed on the wet or dry basis.

Moisture content, wet basis :

The moisture content of a wet feed material, on wet basis, is defined as the *ratio of the weight of the moisture to the weight of the wet feed material.* If X is the kg moisture associated with one kg of dry solids, then

$$\text{Moisture content (wet basis)} = \frac{X}{1+X}$$

The weight percent moisture of a wet feed material, on wet basis, is defined as the weight of the moisture expressed as a percentage of the weight of the wet feed material (i.e., wet solid).

$$\text{Weight \% moisture content (wet basis)} = \frac{\text{kg moisture}}{\text{kg wet solid}} \times 100 = 100\left[\frac{X}{1+X}\right]$$

Moisture content, dry basis :

The moisture of a wet feed material, on dry basis, is defined as the *ratio of the weight of the moisture to the weight of the dry solids present in the wet feed material.* If the feed material contains X kg moisture and 1 kg of dry solids, then

$$\text{Moisture content (dry basis)} = \frac{\text{kg moisture}}{\text{kg dry solid}} = \frac{X}{1} = X$$

$$\text{Percentage moisture content on dry basis} = 100\,X$$

Equilibrium moisture content (X^*) :

It is the moisture content of a substance that is in equilibrium with its vapour in the gas phase under the specified humidity and temperature of the hot gas or air. It represents the limiting moisture content to which a given material can be dried under constant drying conditions.

It is the moisture content of a substance which is in equilibrium with a given partial pressure of the vapour.

Bound Moisture content :

It is the *moisture content in a material which exerts a vapour pressure less than that of the pure liquid at the same temperature.*

Unbound moisture content :

It is the *moisture held by a material in excess of the equilibrium moisture content corresponding to saturation humidity*. It is primarily held in the voids of solid.

It is the *moisture content in a material which exerts an equilibrium vapour pressure equal to that of the pure liquid at the same temperature.*

Free moisture content :

It is the *moisture contained by a material in excess of the equilibrium moisture content* $(X - X^*)$. At a given temperature and humidity, it is the moisture content of a material that can be removed by drying. It may include bound and unbound moisture.

Critical moisture content :

It is the moisture content of a material at which the constant rate period ends and the falling rate period starts. This moisture content is a function of constant drying rate, material properties and particle size.

Constant rate period :

It is that part of the *drying process during which the rate of drying expressed as the moisture evaporated per unit time per unit area of drying surface remains constant.*

Falling rate period :

It is that part of the *drying process during which the rate of drying varies with time and the instantaneous drying rate expressed as the amount of moisture evaporated per unit time per unit area of drying surface continuously decreases.*

Properties of air-water system :

The moisture removed (from a wet solid) during drying operation gets added in the hot gas or air which in turn depends upon the temperature and humidity of the gas or air. Usually, in drying operation the hot air is used as a drying medium, so it is essential to know some of the properties of the air-water vapour system.

Relative humidity (R.H.) :

It is a measure of the degree of saturation of air at the dry bulb temperature.

It is defined as the *ratio of the partial pressure of water vapour in the air water-vapour mixture to the vapour pressure of pure water at the temperature of the mixture, expressed on a percentage basis.*

$$\% \text{ R.H.} = (p_A/p_A^o) \times 100$$

where p_A = partial pressure of water vapour in the mixture

p_A^o = vapour pressure of pure water

when $p_A = p_A^o$, air is said to be saturated with water vapour.

The relative humidity is defined as the ratio of the actual water vapour content of air to the water vapour content of the fully saturated air at the same temperature, expressed on a percentage basis.

Humidity (H)/Absolute humidity :

It is the *ratio of the mass of water vapour to the mass of dry air present in the air-water vapour mixture under any given set of conditions.*

$$H = \frac{\text{kg of water vapour}}{\text{kg of dry air}} = \frac{18}{29}\left(\frac{p_A}{P - p_A}\right) = 0.62\ H_m$$

H_m is the molal humidity.

Dry bulb temperature :

The temperature of the air-water vapour mixture recorded by a thermometer whose bulb is kept dry is called dry bulb temperature.

Wet bulb temperature :

The temperature of the air-water vapour recorded by a thermometer whose bulb is kept wet by wrapping a wet cloth in the open air is called wet bulb temperature.

Since the latent heat of vaporisation required for natural evaporation of water from the cloth will be supplied from the bulb, the temperature of the bulb decreases. The evaporation is continued until the air surrounding the bulb becomes saturated. Some of the heat will flow from the surrounding air to the bulb by temperature difference, even then the temperature of bulb will not rise as that heat gets consumed in evaporation of water. At one particular point, the temperature becomes constant and is recorded as wet bulb temperature.

When the air is more unsaturated, then the difference between dry bulb temperature and wet bulb temperature is more and is less for a more humid air. The relative humidity of the air is found out from a psychrometric chart knowing wet bulb and dry bulb temperatures.

Saturation humidity :

It is the *humidity of air when it is fully saturated with water vapour.* It is denoted by the symbol H_S.

$$H_s = \frac{18}{29}\left(p_A^o / P - p_A^o\right)$$

Percentage humidity/Percentage saturation :

It is the *ratio of the actual humidity (H) to the saturation humidity (H_s).*

$$\text{Percentage humidity} = p_A (P - p_A^o) / p_A^o (P - p_A) \times 100$$

Dew point :

When the air-water vapour mixture is cooled, at some temperature it becomes saturated and further cooling results in the condensation of water vapour. The *temperature at which the condensation will first occur* is known as dew point *[i.e., it is temperature at which a given air-water vapour mixture is saturated.]* Dew point is lower or equal to the dry-bulb temperature. For saturated air, the dew point, wet bulb and dry bulb temperatures are identical.

Equilibrium :

The moisture of wet solids exerts a definite vapour pressure depending upon the temperature and the nature of solid and the moisture. Consider that the wet solids containing liquid which exerts a vapour pressure of p_m^o are exposed to a continuous supply of fresh gas (usually air) with a fixed partial pressure of the vapour (p_A). If p_m^o is greater than p_A, then the solids will lose moisture (reverse is true for $p_m^o < p_A$) by evaporation till the vapour pressure of the moisture of the solids equals the partial pressure of the vapour in the gas. The solid and the gas are then said to be in equilibrium with each other and the corresponding moisture content is referred to as equilibrium moisture content. The equilibrium data in case of drying operations are given as the *relationship between the moisture content of a solid (expressed on a dry basis) and the relative humidity of a gas in contact with the solid.*

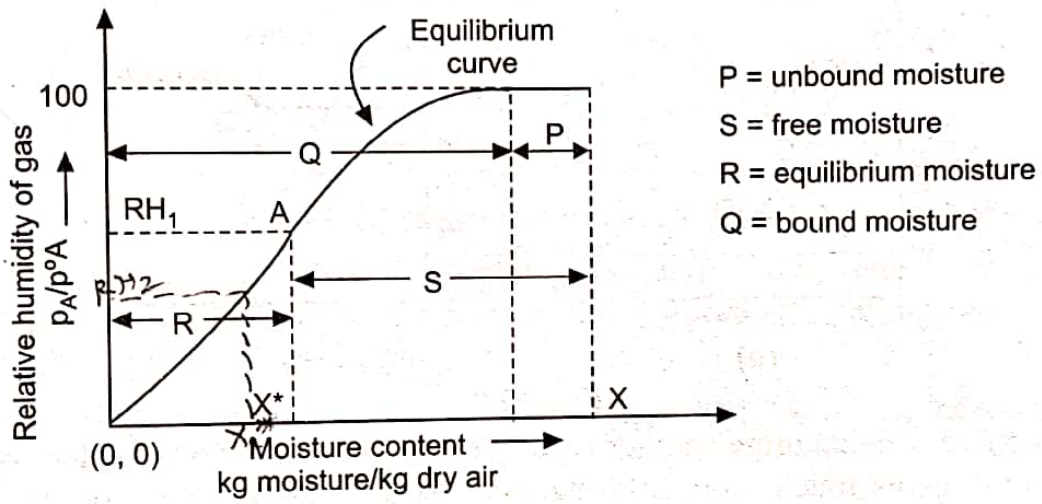


Fig. 12.1 : Equilibrium Moisture Curve

When the humidity of air is less as compared with the moisture content of the solids, then the solids will lose moisture by evaporation and dry to equilibrium and if the air is more humid than the solids, then they will gain moisture until the equilibrium is attained. A typical equilibrium curve for drying of a certain wet solid is shown in Fig. 12.1 where the ordinate is the relative humidity of the gas and the abscissa is the moisture content on dry basis. When solids having very high initial moisture content (X) are exposed to a continuous supply of air with relative humidity of (RH_1), the solids will lose moisture by evaporation and thus go on drying until the moisture content corresponding to the point A is reached (equilibrium moisture content X*).

Beyond this, no drying takes place even if the solids are exposed to this air for infinitely long periods. The moisture content of solids can be reduced below X* (below that corresponding to point A) only by exposing the solids to air of a lower humidity and to obtain bone-dry solids, we have to expose it to perfect dry air which corresponds to the origin of curve.

Constant drying conditions :

These conditions mean the *conditions under which the temperature, humidity, velocity and direction of flow of the hot air or gas across the drying surface are constant during drying operation.*

Rate-of-drying curve :

The drying characteristics of wet solids are generally described by the drying rate curves obtained under constant drying conditions. These curves : moisture content v/s time and drying rate v/s moisture content are shown in Figs. 12.2 and 12.3. Generally, the experimental evaluation of these curves is done before design calculations.

Consider that the wet solids with an initial moisture content (X_I) are exposed to air of constant temperature and humidity. If we then measure the moisture content as a function of time (i.e., moisture content of the material is measured at various values of time), then a curve as shown in Fig. 12.2 (a) is obtained from the collected data. The curve relates the moisture content on dry basis with time. It is clear from the curve that the moisture content of solids decreases with time and after sometime it remains constant at X^*, which is the equilibrium moisture content.

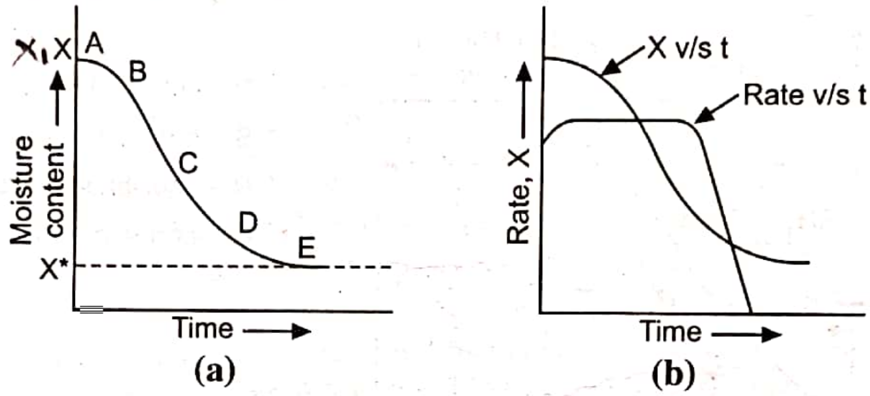


Fig. 12.2

From this curve, we can draw another type of curve which is known as the rate of drying curve. This curve gives much more information regarding the drying process. The rate of drying curve gives a relationship between the rate of drying, expressed as, the moisture evaporated per unit time per unit area of the drying surface and the moisture content on a dry basis. This curve can be constructed by measuring the slopes of tangents drawn to the curve of Fig. 12.2 (a) at various values of the moisture content and then calculating rate as $R = -W' \frac{dX}{dt} \times \frac{1}{A}$, where W' is the weight of dry solids and A is the drying area/surface.

Fig. 12.3 shows the **rate of drying curve**. The section AB of the curve represents the warming up period during which the temperature of the solid is becoming equal to the temperature of drying air. From B to C, the curve is a straight line parallel to X-axis representing the constant rate of drying, thus the section BC is called the **constant rate period** during which the layer of water on the surface of solid is being evaporated. The rate of drying is constant from B to C as the drying takes place from a saturated surface. The section (CE) of the curve represents the **falling rate period** composed of the first falling rate period (CD) and the second falling rate period (DE). From point 'C' onwards some dry patches starts forming on the surface of the solid. The rate of drying decreases for the unsaturated portion and hence the rate for total surface decreases. The section CD of the curve represents the period corresponding to the zone of unsaturated surface drying. The moisture content at which the constant rate period ends and the drying rate starts to fall (i.e. at which unsaturated surface drying starts) is known as the **critical moisture content.**

After point D, the surface of the solid is completely dry and now the internal moment of moisture starts coming to the surface and this is continued upto the point E, where the equilibrium is attained. The rate of drying over section DE is governed by the rate of internal moisture movement. The second falling rate period (DE) represents zone where the internal moisture movement controls.

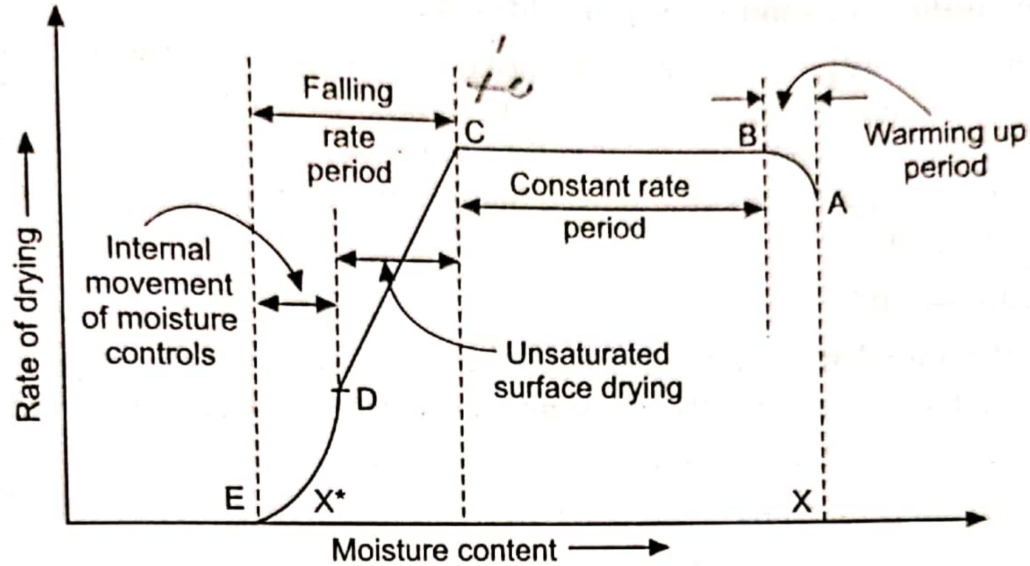


Fig. 12.3 : Typical rate of drying curve under constant drying conditions

The rate of drying curve consists of two parts : (i) a period of constant rate/a constant rate period, wherein the rate of drying is constant and (ii) a period of falling rate/a falling rate period, wherein the rate of drying is falling.

The rate of drying as a function of time is given in Fig. 12.4, which indicates how long each drying period lasts.

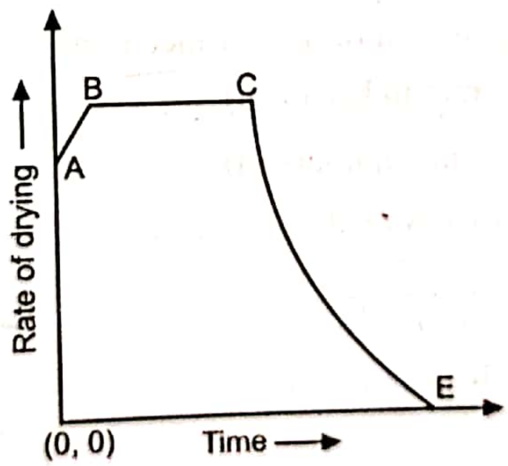


Fig. 12.4 : Drying rate v/s time

Factors on which the rate of drying depends :

(a) **Gas velocity :** When the velocity of the gas or air is high, the rate of drying will also be high.

(b) **Humidity of gas :** Lesser the relative humidity, the more will be the rate of drying.

(c) **Area of drying surface :** If the area of the wet surface exposed to the gas or air is more, the rate of drying will also be more.

(d) **Temperature :** If the temperature of the gas is increased, its relative humidity decreases (i.e., gas becomes more unsaturated) and thus increases a driving force (i.e., the concentration difference of moisture between the solid and gas) and so the rate of drying increases.

Time of drying under constant drying conditions :

Consider that the wet solids are to be dried by passing the hot air over them under constant drying conditions. The time of drying required to dry the material from the initial moisture to the final moisture content of solids, is the sum of the time required during the constant rate period and time required during the falling rate period (when the final moisture is less than the critical).

(a) Constant rate period :

Let X_1 be the initial moisture content of the wet solids and X_2 be the final moisture content of the wet solids during the constant rate period. Let X_c be the critical moisture content of the wet solids. $[X_1, X_2 > X_c]$

The rate of drying is given by

$$R = -\frac{W'}{A} \times \frac{dX}{dt} \quad \text{... (12.1 a)}$$

$R = R_c =$ rate during constant rate period

$$R_c = -\frac{W'}{A} \times \frac{dX}{dt} \quad \text{... (12.1 b)}$$

where W' = mass of dry solids in kg

A = area of drying surface in m^2

R_c = rate in $kg/(m^2 \cdot h)$

t = time in hours (h)

Rearranging Equation (12.1 b), we get

$$dt = \frac{-W'}{A \cdot R_c} dX \quad \text{... (12.2)}$$

Integrating Equation (12.2) between the limits :

$t = 0, \quad X = X_1$

and $t = t, \quad X = X_2$, we get

$$\int_0^t dt = \left[\frac{-W'}{AR_c}\right] \int_{X_1}^{X_2} dX \quad \text{... (12.3)}$$

$$t = \frac{-W'}{A \cdot R_c} [X_2 - X_1] \quad \text{... (12.4)}$$

$$t = \frac{W'}{A \cdot R_c} [X_1 - X_2] \quad \text{... (12.5)}$$

Equation (12.5) gives the time required for drying the material from X_1 to X_2 in the constant rate period.

If the material is to be dried to the moisture content of X_C, then the time required during the entire constant rate period is given by

$$t_C = \frac{W'}{A\,R_C}\,[X_1 - X_C] \qquad \dots (12.6)$$

(b) Falling rate period :

During this period, the rate of drying is proportional to the free moisture content.

$$\frac{-W'}{A} \times \frac{dX}{dt} = m\,[X - X^*] \qquad \dots (12.7)$$

where X^* is the equilibrium moisture content and X is the moisture content of wet solids less than critical moisture content.

Let X_1 be the initial moisture content and X_2 be the final moisture content such that $X_1, X_2 < X_C$.

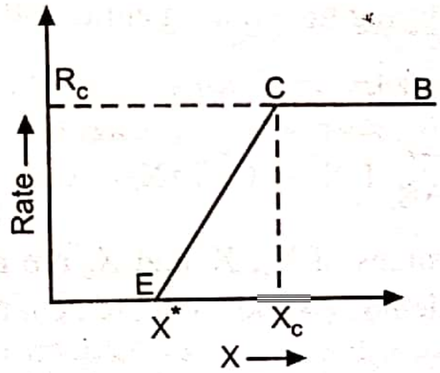


Fig. 12.5 : Rate v/s moisture content

Assume that the entire falling rate period is represented by a straight line CE, then

$$m = \frac{R_C}{[X_C - X^*]} \qquad \dots (12.8)$$

$$m = \text{slope of line CE}$$

Equation (12.1) then becomes :

$$\frac{-W'}{A}\,\frac{dX}{dt} = \frac{R_C}{[X_C - X^*]}\,[X - X^*] \qquad \dots (12.9)$$

$$\frac{-dX}{[X - X^*]} = \frac{R_C\,A}{[X_C - X^*]\;W'}\,dt \qquad \dots (12.10)$$

Integrating Equation (12.10) between the limits

$$X = X_1$$

$$X = X_2\ [X_1, X_2 < X_C], \text{ we get}$$

$$-\int_{X_1}^{X_2} \frac{dX}{[X - X^*]} = \frac{R_c A}{[X_c - X^*] W'} \int_0^t dt \quad \text{... (12.11)}$$

$$t = \frac{W' (X_c - X^*)}{R_c A} \ln \left[\frac{X_1 - X^*}{X_2 - X^*}\right] \quad \text{... (12.12)}$$

Equation (12.12) gives the time of drying during the falling rate period to dry the material from X_1 to X_2.

If the material is to be dried from the critical moisture content X_c to the final moisture content X_2 ($X_2 < X_c$), then the time required for drying during the entire falling rate period is given by t_f as :

$$t_f = \frac{W' (X_c - X^*)}{R_c \cdot A} \ln \left[\frac{X_c - X^*}{X_2 - X^*}\right] \quad \text{... (12.13)}$$

[As X_1 becomes X_c]

t_f = drying time during entire falling rate period.

Total time of drying = $t_c + t_f$

$$t = \frac{W'}{AR_c} [(X_1 - X_c) + (X_c - X^*)] \ln \left[\frac{X_c - X^*}{X_2 - X^*}\right] \quad \text{... (12.14)}$$

Appropriate equations and values of X_1, X_2 and X_c are to be used for the calculation of the time required during a particular period or for calculating the total time required for drying.

DRYING EQUIPMENTS :

Dryers used in industry may be classified on the basis of (a) mode of operation (b) physical properties and handling characteristics of the material and (c) the method of supplying heat to the material to be dried, i.e., method of heat transfer.

(i) Mode of operation :

On the basis of mode of operation that is based on the production schedule there are two types of drying equipments – (i) batch dryers and (ii) continuous dryers.

In case of batch dryer, a definite size of batch of the wet feed is charged to the dryer and drying is carried out over a given time period. These dryers operate under unsteady state conditions.

Drying in batches is relatively expensive operation and consequently batch dryers are preferred for small-scale production, pilot plant and for drying valuable materials.

In case of continuous dryer, the material flows in and out continuously and drying is carried out under steady state conditions continuously. These are generally used for large scale production.

Advantages of continuous drying include :

Equipment necessary is small relative to the quantity of product.

Product has more uniform moisture content.

Cost of drying per unit of product is relatively small.

(ii) Physical properties and handling characteristics of material :

The wet feed material may be a liquid solution, a slurry, a paste, a sludge, free flowing powder, granular, crystalline or fibrous solid. The design of a dryer depends upon the physical properties of the wet feed material and therefore dryers handling similar feed materials may have many common design features.

(iii) Method of heat transfer :

On the basis of method of heat transfer, dryers are classified as (a) direct dryers, and (b) indirect dryers.

Direct dryers :

In such dryers, heat transfer is accomplished by direct contact between the wet feed material and hot gases. The heat of evaporation is supplied by the sensible heat of the gas in contact with the material to be dried (adiabatic dryer). The moisture evaporated from the wet feed is carried by the hot gases.

Indirect dryers :

In such dryer, heat necessary for drying is transferred to the wet feed by conduction through a metal surface/wall in contact with the feed material to be dried (non-adiabatic dryer). The moisture evaporated from the wet feed is carried by the air or other gas independently of a heating medium.

Tray Dryer :

Construction : It is the simplest of batch dryers and also known as a cabinet or compartment dryer. The tray dryer shown in Fig. 12.6 is a batch operated direct dryer. It consists of an enclosed insulated cabinet or a large compartment into which the material to be dried is placed on a number of removable trays. The trays may either be fabricated from sheets or from screens. The trays may be stacked on racks or loaded on trucks. It is provided with inlet and outlet connections for air. A heating coil either electrical or steam-heating is incorporated in it. In these dryers, steam, gas or electrically heated air is used as the drying medium. The air is circulated in the dryer over the trays by means of a fan fitted at the top (on one of the sides, opposite to the coil).

Working : The material to be dried is spread over the trays and put into the cabinet and then it is closed. Steam is continuously passed through the coil and fan is started. Air is heated by heating coil, its relative humidity decreases (i.e., its capacity to evaporate the moisture is increased) and the hot air then passes over the trays.

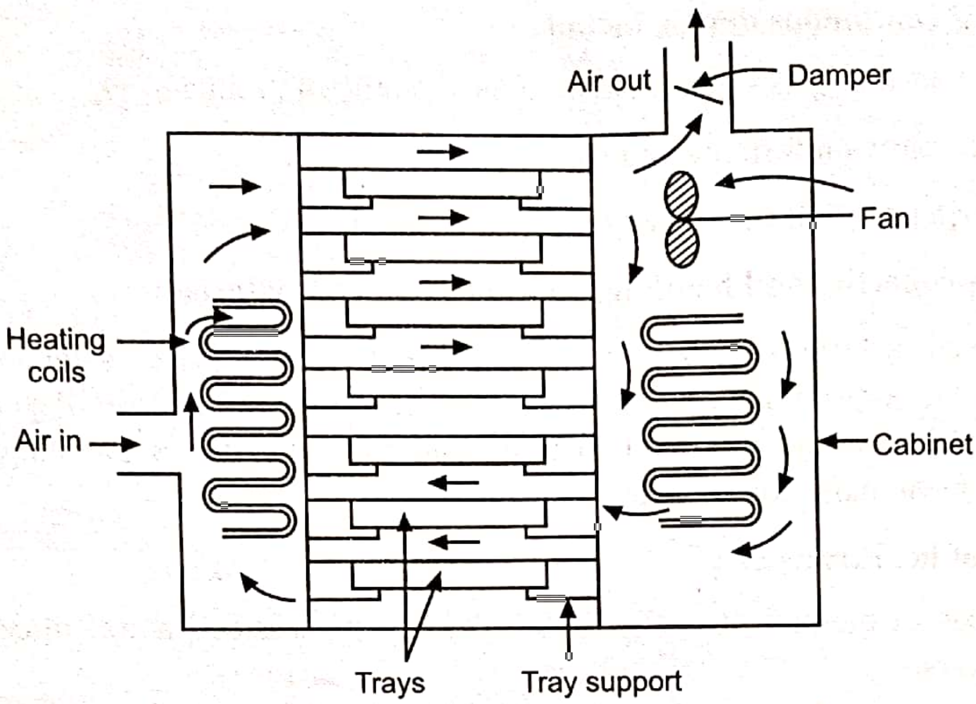


Fig. 12.6 : Tray Dryer

The moisture is evaporated from the wet feed, gets added in the air and finally the air leaves the dryer through the outlet. The process is continued until the solids are dried. The cabinet is opened and the dried material is removed from the trays and a fresh batch is charged.

For getting good drying, air after drying should be thrown out completely but by this way, a large portion of heat associated with the hot air will be lost and the operation will become costly. To avoid this heat loss (i.e., to conserve heat), about 80 – 95 % of the air is recirculated by adjusting a damper provided at the outlet, and the remaining portion is exhausted out, and the same amount of fresh air is taken in through the inlet.

The overall rate of drying of such a dryer is 0.2 to 2.0 kg water/($m^2 \cdot h$) and the thermal efficiency is of the order of 20 - 25 %.

The trays are generally 600 mm wide, 900 to 1500 mm long and 30 to 40 mm deep. They are made of mild steel, stainless steel, enamelled iron, etc. and are fabricated from sheets of 3 mm to 6 mm thick.

Advantages :

- Relatively cheap and easy to construct/build.
- Low space requirement.
- Ease in cleaning.
- Requires low maintenance (low maintenance cost).
- No loss of product during drying.

Disadvantages :

- Expensive to operate due to high labour requirements for loading and unloading (high labour costs and low heat economy).
- Long drying cycles (4 to 48 h per batch).
- Small quantities are handled.

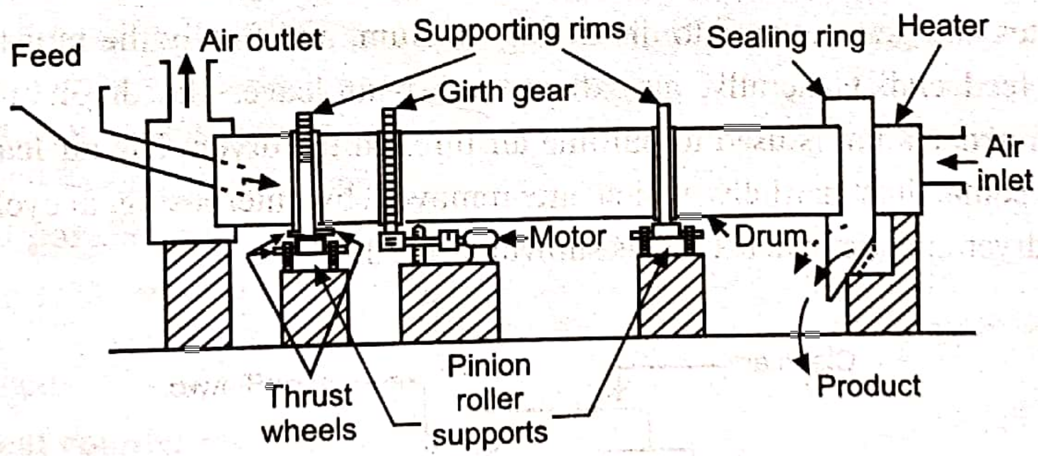
Applications :

Tray dryer is well suited for small scale production (i.e., for small production rate) and drying valuable materials like dyes and pharmaceuticals. It is especially useful for drying wet lumpy solids and wet filter cakes which must be spread over the trays.

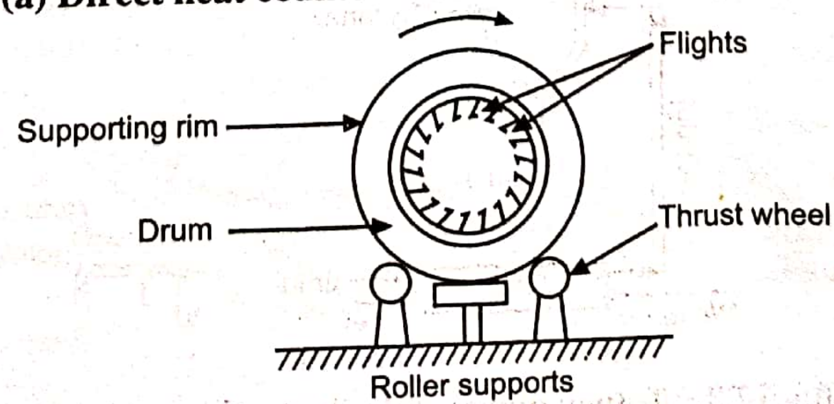
These dryers may be operated under vacuum, in many cases with indirect heating. In such dryers, all joints must be air-tight. The trays may rest on hollow metal plates supplied with steam vapour from the wet solid is removed by a vacuum pump. Vacuum tray dryers are suited for heat sensitive materials (i.e., thermally degradable materials).

Rotary Dryer :

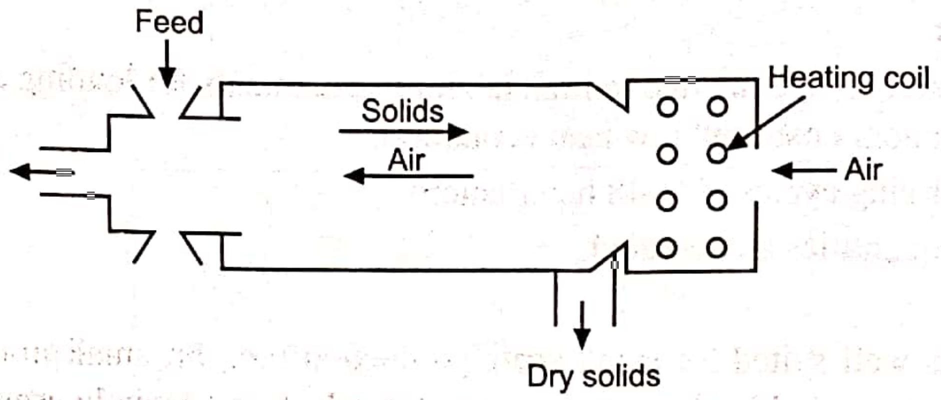
This type of dryer (that may be directly or indirectly heated) is adopted for continuous drying of free-flowing granular materials on a large scale. Fig. 12.7 shows one form of a rotary dryer. It consists of a relatively long cylindrical shell (having a diameter of 1 m to 3 m and length 3 m to 30 m). The cylindrical shell set with its axis at a slight angle to the horizontal (slightly inclined towards the outlet), so that the material fed is consequently advanced through the dryer (under gravity) from one end to the other end (from where it is discharged).



(a) Direct heat counter current flow, Rotary dryer



(b) Rotary dryer, side view



(c) Schematic view of Rotary dryer

Fig. 12.7

The shell is mounted on rollers so that it can be rotated. To avoid its slipping over the rollers, it is fitted with thrust wheels. It is fitted inside with flights which lift the material upward and shower it down from the top. A few spiral flights are fitted near the feed end which help in giving the initial forward motion to the material before principle flights are reached. The material to be dried (feed) is fed at the high end of the dryer by a hopper and the product is taken out from the lower end of the dryer. The material moves through the dryer by virtue of rotation, heat effect and slope (inclination) of the cylindrical shell.

The cylindrical shell is rotated by a gear mechanism at a speed of 2 to 25 r.p.m. Air is taken into the dryer from the product end, it is heated in a heater, and then moves through the dryer in a counter current fashion with respect to the material to be dried. The moisture of the feed evaporates and gets added into the drying medium, and finally the moist air leaves the dryer at the feed end. Generally, an exhaust moist air leaves the dryer at the feed end. Generally, an exhaust fan is used to pull the air through the dryer. The air leaving the dryer will contain some dust particles which are removed by interposing a cyclone separator between the dryer and the exhaust fan as shown in Fig. 12.8.

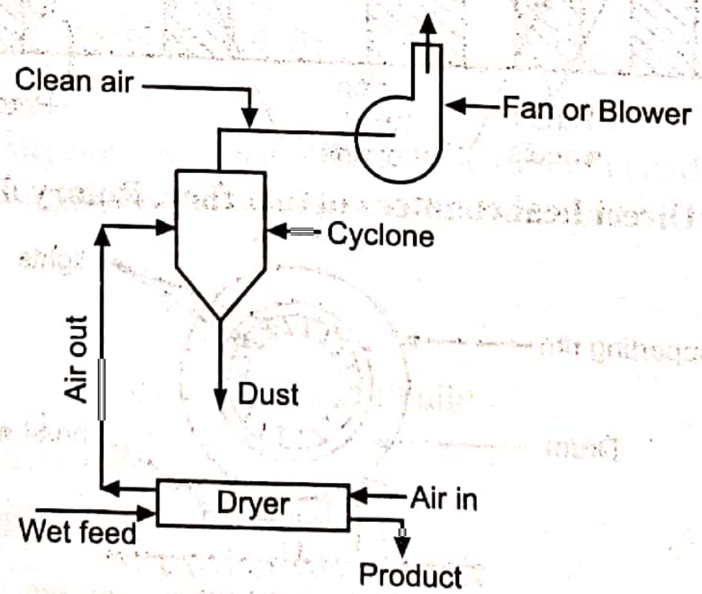


Fig. 12.8 : Rotary dryer with dust collcctor (cyclone)

The mode of operation is usually continuous. In case of direct contact, the hot gas is passed over the material in a counter-current fashion. In case of indirect contact, heat is transferred through the wall of the cylindrical shell.

The thermal efficiency of rotary dryers is about 50 - 80 % and the drying rate ranges between 10 - 50 kg/(h·m³ of shell volume).

Advantages :

- good gas contacting
- moderate drying time
- low capital cost
- drying and calcining in the same unit
- high thermal efficiency
- greater flexibility of control of the gas velocity.

Disadvantages :

- difficulty of sealing
- product build-up on interior walls
- high structural load
- non-uniform residence time.

Rotary dryers are grouped into four categories :

1. **Direct heat counter current flow :**

This type of dryer is shown in Fig. 12.7 and employed for the materials which may be heated to a high temperature like minerals, sand clays, etc. Hot flue gas is usually used as the drying medium. It is also used for products like ammonium sulphate and cane sugar wherein the hot air is used as a drying medium.

2. **Direct heat parallel flow :**

In this type both the material and hot gas/air move in the same direction through the dryer. It is used for drying materials like gypsum, iron pyrites, etc., which should not be heated to destructive temperatures.

3. **Indirect heat counter current flow :**

It is used for materials which can be heated to high temperatures out of contact with flue gas such as white pigments, etc. It is shown in Fig. 12.9.

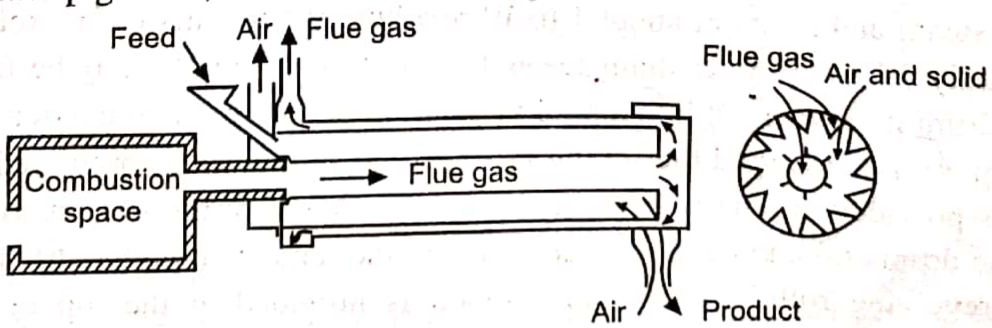


Fig. 12.9 : Indirect Counter flow Rotary dryer

4. Direct-indirect type dryer :

This type of dryer is used for solids, which may be heated to very high temperatures by flue gas, such as lignite, coal, and coke. It is shown in Fig. 12.10.

It contains an inner hollow tube through which the flue gas passes from a combustion chamber to the lower end of the dryer. At this end, the direction of flue gas is reversed and made to pass through hollow flights, through an annular space and leaves the dryer from the feed end. The central tube is provided with longitudinal fins to increase the outer area of heat

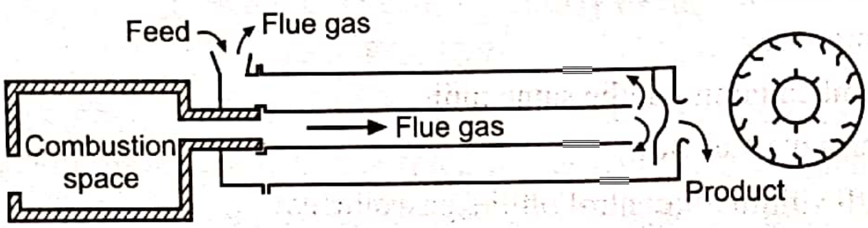


Fig. 12.10 : Direct - Indirect type dryer

transfer. The wet material is admitted at the high end of the dryer and travels down to the lower end and taken out as dried product. Air enters from the product end and travels over the solid in the reverse direction. The moisture gets added in the air and finally leaves the dryer from the feed end. The material is heated indirectly by flue gas by conduction and radiation and the moisture is taken out by air, flowing in a counter current fashion with respect to the feed. Another type of indirect dryer is the steam tube dryer employing a number of tubes and finds application where the material must not be heated to a high temperature, e.g., drying of cattle feed, etc.

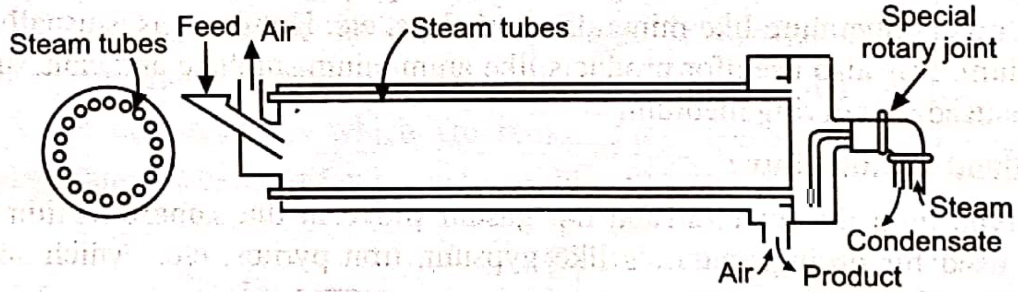


Fig. 12.11 : Indirect steam-tube dryer

Drum Dryer

Construction : A drum dryer consists of one or more metal rolls (drums) that are heated internally by steam and rotate at about 1 to 10 revolutions per minute. The rolls of the drum dryer are usually 0.6 to 3.5 m in diameter and 0.6 to 5 m in length (may be fabricated from plates). The drum is submerged into a pool of solution or slurry contained in a trough. For an agitation purpose, i.e., to avoid the setting of solids, an agitator is incorporated in the trough. A spreader is provided on one side to regulate the thickness of the film of substance on the outside of the drum and a knife is provided on the other end to scrap the dried material from the slowly revolving roll/drum. A vapour-hood is provided at the top of the drum for collection and removal of vaporised moisture. Fig. 12.12 shows such a dryer.

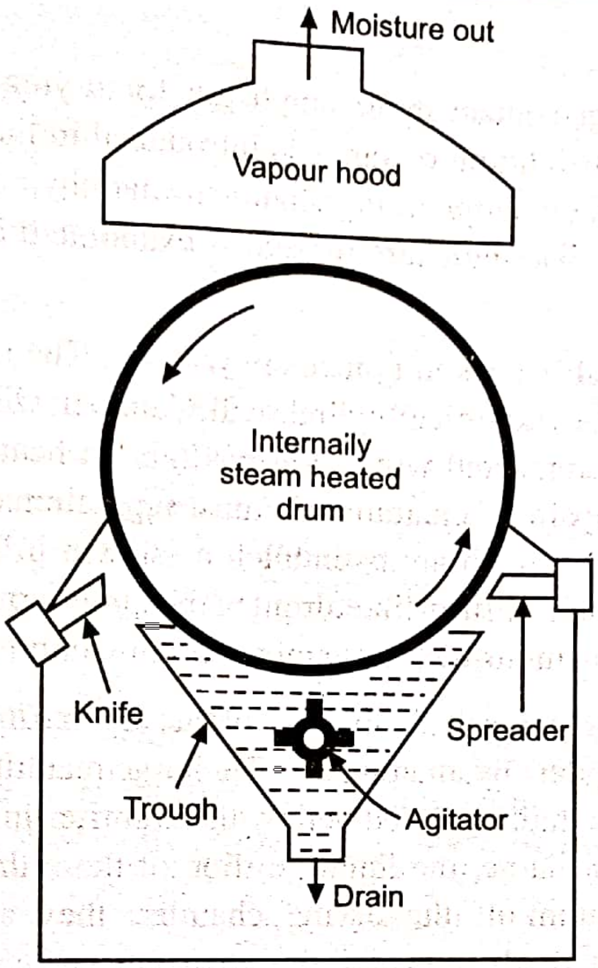


Fig. 12.12 : Single drum dryer

Working :

A slowly revolving internally steam heated drum continuously dips into a trough and picks up the feed which retains on the drum surface as a thin film. The thickness of this film of material is regulated by means of a spreader. During the course of revolution of the drum, the material is dried due to heat transfer from condensing steam through the metal wall of the drum and large surface area. As it reaches the other end, the dried product (in the form of flakes) of operation is scrapped by a knife. The moisture evaporated from the feed material is collected and removed through a vapour-hood provided above the drum(s).

Drum dryers are usually made of cast iron but where contamination of the product must be avoided, for example, in case of pharmaceuticals or food products, chromium plated steel or alloy steel is used as a material of construction. The capacity of the drum dryers is less as compared to the spray dryer but their operating cost is low.

Drum dryers are suitable for handling fluid and semifluid materials such as slurries, pastes of solids in fine suspension and dilute or concentrated solutions of highly soluble materials. These units are not suited for solution of salts with limited solubility and for slurries of abrasive solids that have the tendency to settle-out.

Cylindrical dryers are drum dryers which are commonly employed for handling material in the continuous sheet form, such as paper and cloth. The wet material is fed continuously over the revolving drum or a series of drums each heated internally by steam.

Spray Dryer :

It is a continuous direct contact dryer employed for drying of solutions, slurries, and pastes. In this dryer, a liquid solution or slurry is introduced in the form of very fine droplets into a stream of hot gas inside a large drying chamber, thereby a large contact area becomes available for perfect drying. The moisture of feed is evaporated and gets added into the hot gas.

Construction : Fig. 12.13 shows a typical spray dryer. The essential components of the dryer are : a drying chamber (a vertical cylindrical chamber with a short conical bottom), where the feed material is contacted with a hot gas (air), a heater for heating the fresh air sucked by a fan or blower, cyclone separators for dust separation and collection, a pneumatic conveying duct and blowers, which are assembled as shown in Fig. 12.13. The material is usually spread in the form of a mist of fine droplets by spray nozzles or high speed rotating spray discs into a hot gas stream inside the chamber as shown in Fig. 12.13.

Working : The feed is pumped to the top of the dryer (drying chamber) where it is disintegrated into small droplets by an atomiser. The large quantity of fresh air is taken in by a fan, it is heated in a heater and finally fed below the atomiser in the drying chamber. As the surface area of drops is very large, the liquid portion of these drops rapidly evaporates and before they touch the bottom of the drying chamber they are completely dried. This dried product (in the form of dry powder) is taken out and conveyed to a cyclone dust collector-2 by a stream of air. The major portion of the air is taken out through the air outlet duct which mostly contains dust and is sent to a cyclone-1. The solids collected by the cyclone-1 are fed to a pneumatic conveying duct. The air leaving the cyclone - 2 may contain some dust and therefore it is sent to the cyclone - 1, for further separation, by the fan. The air from the cyclone -1 is thrown out to the atmosphere by a blower. The dried product from the cyclone-2 is collected in a dry product collector.

An atomiser is a device which causes the liquid to be disintegrated into the fine drops. The atomisers commonly used are :

1. Pressure nozzles which make use of pressure energy for atomisation.
2. Two fluid nozzles wherein air or steam at a certain pressure is used to tear a liquid into droplets, i.e., they make use of gas energy and
3. Rotating discs make use of centrifugal energy for atomisation. Spray nozzles (type -1 and type - 2) are relatively inflexible in operation and also subject to erosion and tear. The rotating discs (may be plane, vaned or cup-shaped) rotate at a speed of about 3000 to 12000 r.p.m. The feed introduced at the centre of disc is centrifugally accelerated to the periphery and ultimately thrown in an umbrella-shaped spray. The rotating discs are very flexible in their operating characteristics and can handle thick slurries without danger of clogging.

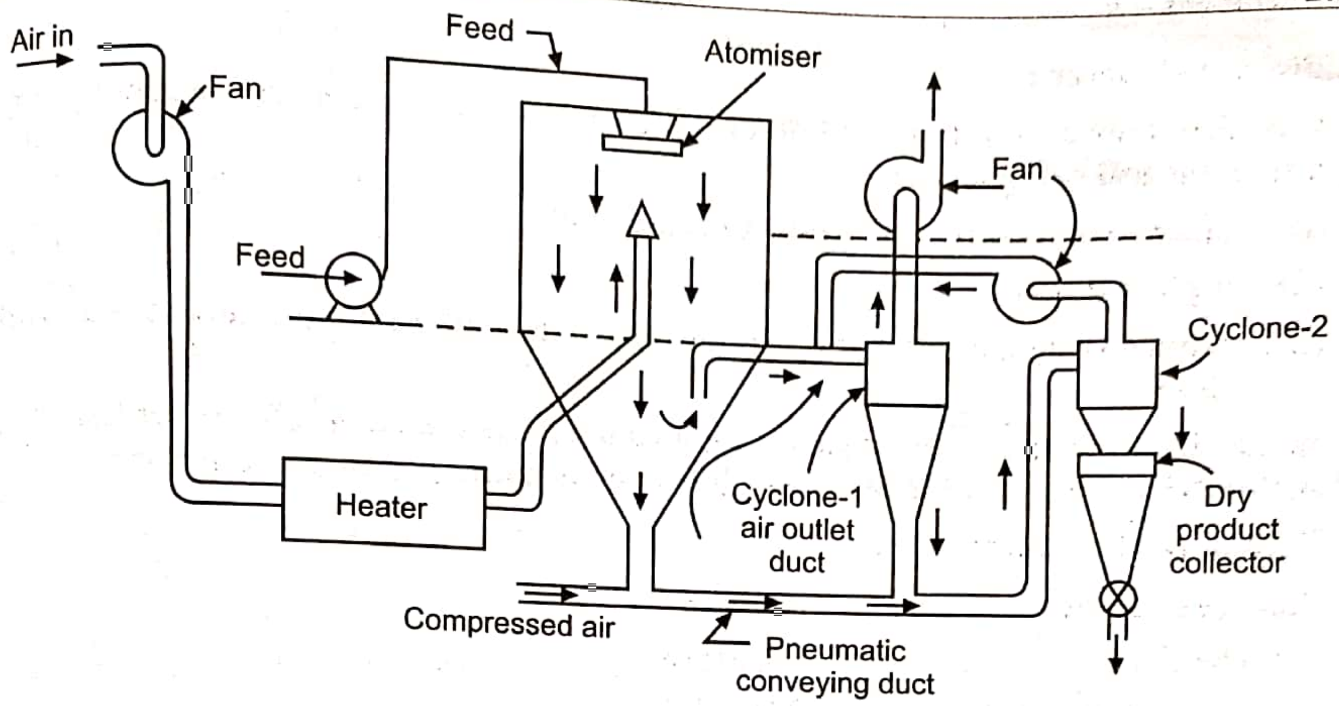


Fig. 12.13 : Spray Dryer

In this dryer, care must be taken to ensure that the droplets or wet particles of solids do not strike and stick to the solid surfaces before complete drying. So as to avoid this, large drying chambers are used.

Advantages :

- very short drying times (2 – 20 s)
- handle heat sensitive products
- control of a product particle size
- rapid dehydration.
- relatively low operating costs, particularly in large capacity units.

Disadvantages :

- low solids content
- relatively large units
- maintenance of atomiser
- inefficient in (its) energy use
- product built-up on interior walls.

Applications :

These dryers are common in dairy industry, food industry, detergent industry, chemical and dyes industry.

Spray dryers are widely used for products such as milk powder, detergents, dyes, coffee, pharmaceuticals, etc.

Fluidised Bed Dryer :

It is also known as a fluid bed dryer. Fluid bed drying systems are becoming popular because of the following reasons :

(i) absence of moving parts-results in ease of maintenance

(ii) high heat transfer rates

(iii) rapid mixing indicating more or less an isothermal operation leading to the uniform drying.

In this dryer, a hot gas / air is passed through a wet material at a velocity sufficiently high to fluidise the wet material but not too high enough to cause pneumatic conveying.

Typical gas/air velocities are :

Particle size (μm)	Velocity (m/s)
300 – 800	0.4 to 0.8
800 – 2000	0.8 to 1.2

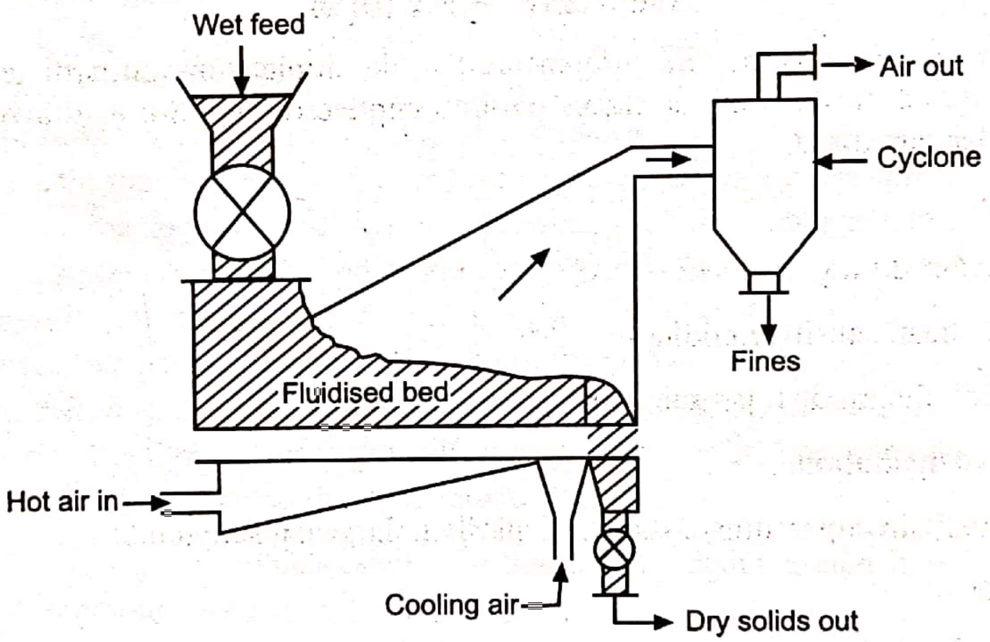


Fig. 12.14 : Fluidised Bed Dryer

A fluidised bed system in addition to a fluidising chamber also needs an air blower, a hot air generator, a feed conveyor, a cyclone separator and a product conveyor.

In this dryer, hot air is used to keep the wet feed in a fluidised state. In the dryer shown in Fig. 12.14 the wet material is dried and cooled in the same bed. Wet feed material is admitted to the top of the bed through a hopper via a rotary valve and hot air is distributed at the bottom of the bed through a diffuser plate and dry product is taken out from the side or near the bottom. Heat and mass transfer coefficients are high because of turbulence created in the bed. The material to be dried and hot air are in cross flow with respect to the direction of flow of each other. The residence time can be controlled from seconds to hours. The moist air from the dryer containing fines is admitted to a cyclone separator for the recovery of fines.

It is used for drying very fine size free flowing materials. It is well suited for temperature/heat sensitive materials.

These dryers may also be operated batchwise. A charge of wet feed material in a perforated container attached to the bottom of the fluidising chamber is fluidised, heated until dry and then discharged. Such units have replaced tray dryers in many processes.

Tunnel Dryer :

The continuously operated direct type tunnel dryer is shown in Fig. 12.15. This dryer is built in the form of a long tunnel. It is provided with inlet and outlet arrangements for air. Fan and heating coils are incorporated in the tunnel as shown in Fig. 12.15. The materials to be dried is filled in trays and trucks loaded with these trays move progressively through the tunnel in contact with a current hot gas to evaporate the moisture. Air flow in the tunnel dryer can be totally concurrent, counter current or a combination of both with respect to the material flow. The wet material enters at one end and dried product leaves at the other end. For relatively low temperature operation, steam heated air is used as a drying medium, while for high temperatures, flue gas is used as a drying medium (where contamination is permissible). These dryers are generally employed for drying of all forms of particulate solids and large solid objects, on a large scale.

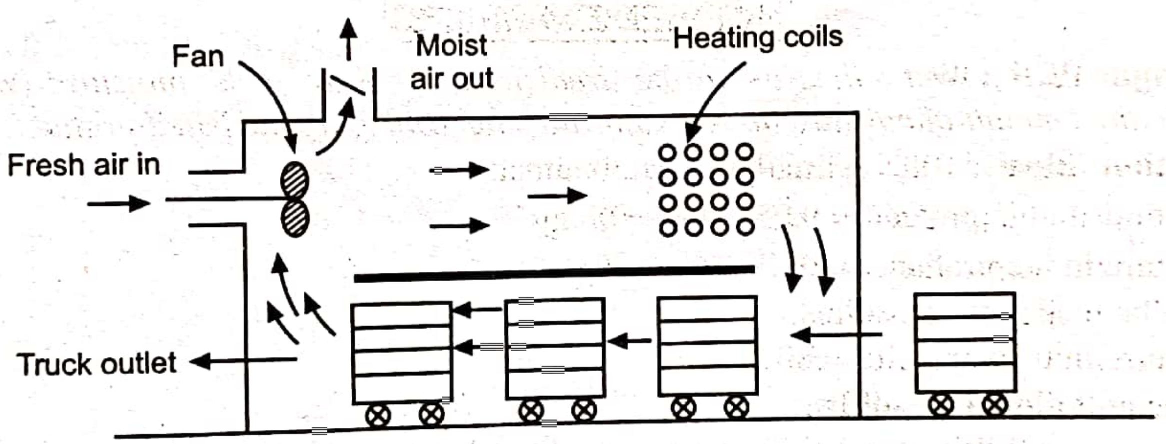


Fig. 12.15 : Tunnel Dryer

It is often used for drying of pottery, ceramic products, paraffin wax, etc. which require slow rate of drying.

Pneumatic (flash) Dryer :

In a flash dryer, drying is carried out in a very short span of time-0.5 to 3 seconds. Pneumatic conveying duct is the heart of the system wherein drying operation is carried out. Hot gas is the conveying medium which is flowing rapidly with a velocity of the order ~ 25 m/s and in which the granular free flowing solids are dispersed.

Finely powdered wet material is introduced into the hot gas (air stream) with the help of a screw conveyor. The material is pneumatically conveyed through the duct and during its conveyance moisture is removed. The dried material is separated from the air stream in a cyclone and a bag filter. The product from the bottom of the collecting equipments (cyclone and bag filter) is transported to a silo via screw conveyor (not shown).

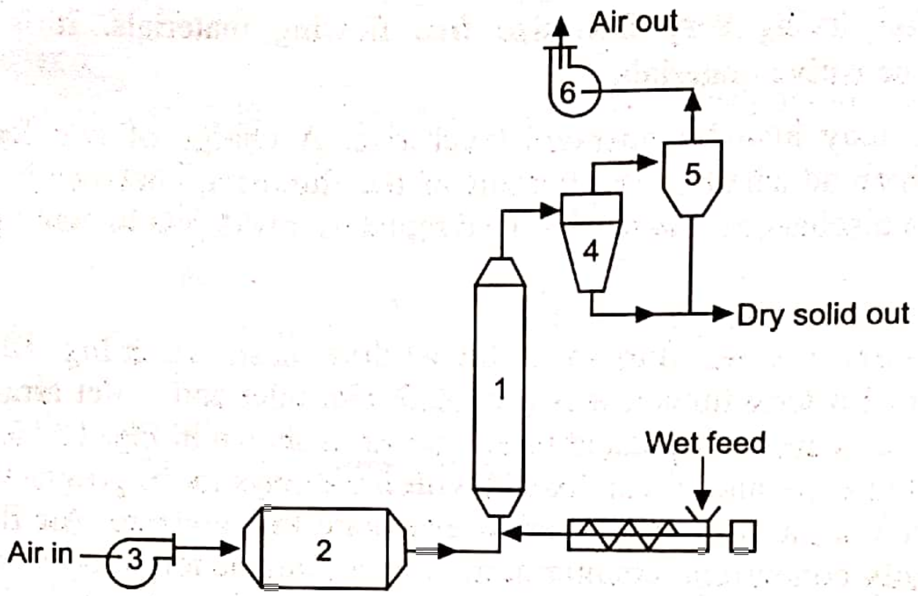


Fig. 12.16 : Pneumatic (Flash) dryer

1 : drying duct 2 : Heater 3; 6 : blower, 4 : cyclone and 5 : bag filter

Due to very short residence time these dryers are used for drying of heat sensitive materials.

SOLVED EXAMPLES

Example 12.1 : *Wet solids are to be dried from 80 % to 5 % moisture (wet basis). Calculate the amount of moisture to be evaporated per 100 kg of the dried product.*

Solution : Basis : 100 kg dried product obtained.

dry solids in the product = 0.95 × 100 = 95 kg

moisture in the product = 0.05 × 100 = 5 kg.

Let x be the kg of wet solids,

moisture in the wet solid = 80 %

Material balance of solids :

solids in wet solid feed = solids in dried product

$$0.20\,x = 95$$

$$x = 475 \text{ kg}$$

Moisture in the wet solid = 0.80 × 475 = 380 kg

Amount of moisture to be evaporated per 100 kg of the dried product is

= moisture in wet feed – moisture in dried product

= 380 – 5 = **375 kg** ... **Ans.**

Example 12.2 : *Find out the rate of drying and moisture content from the following data :*

Weight of wet saw dust	*Weight of saw dust after drying*	*Time (h)*
250 g	*230 g*	*0.5*
250 g	*215 g*	*0.75*

Dimension of tray = 10 cm × 10 cm

Weight of dry saw dust on tray = 150 g

Solution :

$$A = \text{Area of tray} = \text{Area of drying surface}$$

$$A = 0.1 \times 0.1 = 0.01 \text{ m}^2$$

$$W' = \text{weight of dry solids (saw dust)}$$

$$W' = 150 \text{ g} = \frac{150}{1000} = 0.15 \text{ kg}$$

Moisture in the saw dust initially = 250 – 150 = 100 g

$$X_1 = \text{Initial moisture content on dry basis}$$

$$X_1 = \frac{100}{150} = 0.666 \text{ kg/kg dry solid}$$

Moisture after 0.5 h in the wet saw dust = 230 – 150 = 80 g

$$X_2 = \text{Final moisture content (after 0.5 h) on dry basis}$$

$$X_2 = \frac{80}{150} = \mathbf{0.533}$$ **... Ans.**

$$\text{Time of drying} = t = \frac{W'}{A}\left[\frac{X_1 - X_2}{R}\right]$$

where R is rate of drying in kg/(m²·h)

Rearranging the above equation, we get

$$R = \frac{W'}{A \cdot t}[X_1 - X_2]$$

$$= \frac{0.15}{0.01 \times 0.5}[0.666 - 0.533]$$

$$= \mathbf{3.99 \ kg/(m^2 \cdot h)}$$ **... Ans. (1)**

Weight of the wet sample after 0.75 h = 215 g

Weight of moisture in the wet saw dust sample after 0.75 h

$$= 215 - 150 = 65 \text{ g}$$

$$X_3 = \text{Moisture content after 0.75 h on dry basis}$$

$$= \frac{65}{150} = \mathbf{0.433}$$ **... Ans. (2)**

$$\text{Rate of drying} = R = \frac{W'(X_1 - X_3)}{A \cdot t}$$

$$= \frac{0.15[0.666 - 0.433]}{0.01 \times 0.75}$$

$$= \mathbf{4.194 \ kg/(m^2 \cdot h)}$$ **... Ans. (3)**

Example 12.3 : *A batch of wet solids is to be dried from 35 % to 10 % moisture under constant drying conditions in five hours. If the equilibrium moisture content is 4 % and the critical moisture content is 14 %. Estimate the time required to dry the solids to 6 % moisture under the same drying conditions. All moisture content are on the wet basis.*

Solution : Case-I :

Initial moisture = 35 %

Final moisture = 10 %

Critical moisture = 14 %

and Equilibrium moisture = 4 %

Time required for drying the solids from 35 % to 10 % moisture = 5 h

It is clear from the values of the moisture content given above (final moisture and critical moisture) that the period of five hours will be the time required during the constant rate period plus the time required during the falling rate period.

Let x = wt. fraction of moisture in the solids = (wt. %)/100

X_1 = Initial moisture content on dry basis

$$= \frac{x_1}{1-x_1} = \frac{0.35}{1-0.35} = 0.5385$$

X_c = Critical moisture content on dry basis

$$= \frac{x_c}{1-x_c} = \frac{0.14}{1-0.14} = 0.1628$$

X^* = Equilibrium moisture content

$$= \frac{x^*}{1-x^*} = \frac{0.04}{1-0.04} = 0.0417$$

X_2 = Final moisture content (in the falling rate period)

$$= \frac{x_2}{1-x_2} = \frac{0.1}{1-0.1} = 0.111$$

t = Time of drying

$= t_c + t_f$

The time required for drying is given by

$$t = \frac{W'}{A \cdot R_c}[X_1 - X_c] + \frac{W'(X_c - X^*)}{R_c \cdot A} \ln\left[\frac{X_c - X^*}{X_2 - X^*}\right]$$

where R_c = rate of drying in constant rate period

W' = kg of dry solids

A = area of drying surface.

The above equation can be written as

$$t = \frac{W'}{A \cdot R_c}\left[(X_1 - X_c) + (X_c - X^*) \ln\left(\frac{X_c - X^*}{X_2 - X^*}\right)\right] \quad \ldots (1)$$

Substituting the values of t, X_1, X_2, X_c and X^*, we get

$$5 = \frac{W'}{R_c \cdot A}\left[(0.5385 - 0.1628) + (0.1628 - 0.0417)\ln\left(\frac{0.1628 - 0.0417}{0.111 - 0.0417}\right)\right]$$

$$\therefore \quad \frac{W'}{R_c \cdot A} = 11.28$$

Case-II : The final moisture in this case is given as 6 %

$$\therefore \quad X_2 = \text{Final moisture content on dry basis}$$

$$= \frac{0.06}{1 - 0.06} = 0.0638$$

Using Equation (1) and substituting the values of the various terms involved, the time for drying the solids from 35 % to 6 % moisture is

$$t = \frac{W'}{R_c \cdot A}\left[(X_1 - X_c) + (X_c - X^*)\ln\left(\frac{X_c - X^*}{X_2 - X^*}\right)\right]$$

$$t = (11.28)\left[(0.5385 - 0.1628) + (0.1628 - 0.0417)\ln\left(\frac{0.1628 - 0.0417}{0.0638 - 0.0417}\right)\right]$$

$$t = \mathbf{6.56\ h}$$ ... **Ans.**

Example 12.4 : *A 100 kg bath of granular solids containing 30 % moisture is to be dried in a tray dryer to 16 % moisture by passing a current of air at 350 K tangentially across its surface at a velocity of 1.8 m/s. If the constant rate of drying under these conditions is 0.7×10^{-3} kg/(m²·s) and the critical moisture content is 15 %, calculate the time required for drying the solids.*

Drying surface = 0.03 m²/kg dry weight.

Solution : Moisture content data for the constant rate period is

Initial moisture = 30 % ... on wet basis

Final moisture = 16 %

Critical moisture = 15 %

As the final moisture is greater than the critical moisture, we are in the constant rate period. The equation for calculating the time of drying during the constant rate period is

$$t = \frac{W'}{A}\left[\frac{X_1 - X_2}{R_c}\right]$$

where W' = weight of dry solids

A = Area of drying surface (surface area available for drying)

and X_1 and X_2 are the initial and final moisture contents (dry basis), respectively.

$$X_1 = \text{Initial moisture content (dry basis)}$$

$$= \frac{0.3}{1 - 0.3} = 0.428$$

X_2 = Final moisture content

$$= \frac{0.16}{1-0.16}$$

$$= 0.19 \frac{\text{kg moisture}}{\text{kg dry solid}}$$

Surface of drying is given as :

0.03 m² per kg dry solid weight. Therefore,

$$\frac{A}{W'} = 0.03$$

$$\frac{W'}{A} = \frac{1}{0.03} = 33.33$$

R_c = Rate of drying during the constant rate period

$$= 0.7 \times 10^{-3} \text{ kg/(m}^2\cdot\text{s)}$$

$$= 0.7 \times 10^{-3} \times 3600 \text{ kg/(m}^2\cdot\text{h)}$$

$$= 2.52 \text{ kg/(m}^2\cdot\text{h)}$$

The time required for drying the solids is given by

$$t = \frac{W'}{A} \times \left[\frac{X_1 - X_2}{R_c}\right]$$

Substituting the values of X_1, X_2, R_c and $\frac{W'}{A}$ in the above equation, we get

$$t = 33.33 \times \left[\frac{0.428 - 0.19}{2.52}\right] = 3.15 \text{ h}$$

$$= \mathbf{3.15\ h}$$ ... **Ans.**

Example 12.5 : *A 50 kg batch of granular solids containing 25 % moisture is to be dried in a tray dryer to 12 % moisture by passing a stream of air at 360 K (87 °C) tangentially across its surface at a velocity of 2 m/s. The constant rate of drying under these conditions is 0.0008 kg moisture/(m²·s) and the critical moisture content is 10 %. Estimate the drying time. The surface area available for drying is 1.0 m².*

All moisture contents are on the wet basis.

Solution : Basis : 50 kg batch of granular solids.

Moisture content data for the constant rate period is

Initial moisture (wet basis) = 25 %

Final moisture = 12 %

Critical moisture = 10 %

As the final moisture is greater than the critical moisture, we are in the constant rate period. Equation for calculating the time of drying during the constant rate period is

$$t = \frac{W'}{A}\left[\frac{X_1 - X_2}{R_c}\right]$$

where, W' = Weight of dry solids

A = Area of drying surface

X_1 and X_2 are the initial and final moisture contents (dry basis), respectively.

X_1 = Initial moisture content (dry basis)

$$= \frac{0.25}{1-0.25} = 0.333$$

X_2 = Final moisture content

$$= \frac{0.12}{1-0.12} = 0.1364 \text{ kg moisture/kg dry solid}$$

$A = 1 \text{ m}^2$

Quantity of dry solids in the batch = $0.75 \times 50 = 37.5$ kg

$\therefore$ $W' = 37.5$ kg

R_c = rate of drying during constant rate period

$= 0.0008 \text{ kg/(m}^2\cdot\text{s)}$

$= 0.0008 \times 3600$

$R_c = 2.88 \text{ kg/(m}^2\cdot\text{h)}$

The time required for drying is

$$t = \frac{W'}{A}\left[\frac{X_1 - X_2}{R_c}\right]$$

$$= \frac{37.5}{1.0}\left[\frac{0.333 - 0.1364}{2.88}\right] = \mathbf{2.56\ h}$$ ... **Ans.**

Example 12.6 : *1400 kg (bone dry) of granular solid is to be dried under constant drying conditions from a moisture content of 0.2 kg/kg dry solid to a final moisture content of 0.02 kg/kg dry solid. The drying surface is given as 0.0615 m²/(kg). Under the same drying conditions, the following drying rates were previously known. Estimate the time required for drying.*

Moisture content :

X, kg/kg dry solid	*0.3*	*0.2*	*0.14*	*0.096*	*0.056*	*0.046*	*0.026*	*0.016*
Rate, R, kg/(m²·h)	*1.71*	*1.71*	*1.71*	*1.46*	*1.29*	*0.88*	*0.54*	*0.376*

Solution : Construct a plot of rate v/s X [Fig. Ex. 12.6]. It is evident from the plot that the falling rate period is not a straight line. Hence, the time for it is to be calculated by graphical integration.

W' = kg dry solid = 1400 kg

X_1 = Initial moisture content = 0.2 kg/kg dry solid

X_2 = Final moisture content = 0.02 kg/kg dry solid

Drying surface = $A = 0.0615 \times 1400 = 86.1\ m^2$

Constant drying rate = R_c = 1.71 kg/(m^2·h)

Drying time = $t = t_c + t_f$

For constant rate period :

$$t_c = \frac{W'}{A R_c} [X_1 - X_c]$$

where W' = 1400 kg

$A = 86.1\ m^2$

R_c = 1.71 kg/(m^2·h)

$X_c = 0.14$

$$t_c = \frac{1400}{86.1 \times 1.71} [0.20 - 0.14] = 0.57\ h$$

For falling rate period : $t_f = \frac{-W'}{A} \int_{X_c}^{X_2} \frac{dX}{R} = \frac{W'}{A} \int_{X_2}^{X_c} \frac{dX}{R}$

X	0.140	0.096	0.056	0.046	0.026	0.02	0.016
R	1.71	1.46	1.29	0.88	0.54	0.50	0.376
1/R	0.585	0.685	0.775	1.136	1.852	2.0	2.66

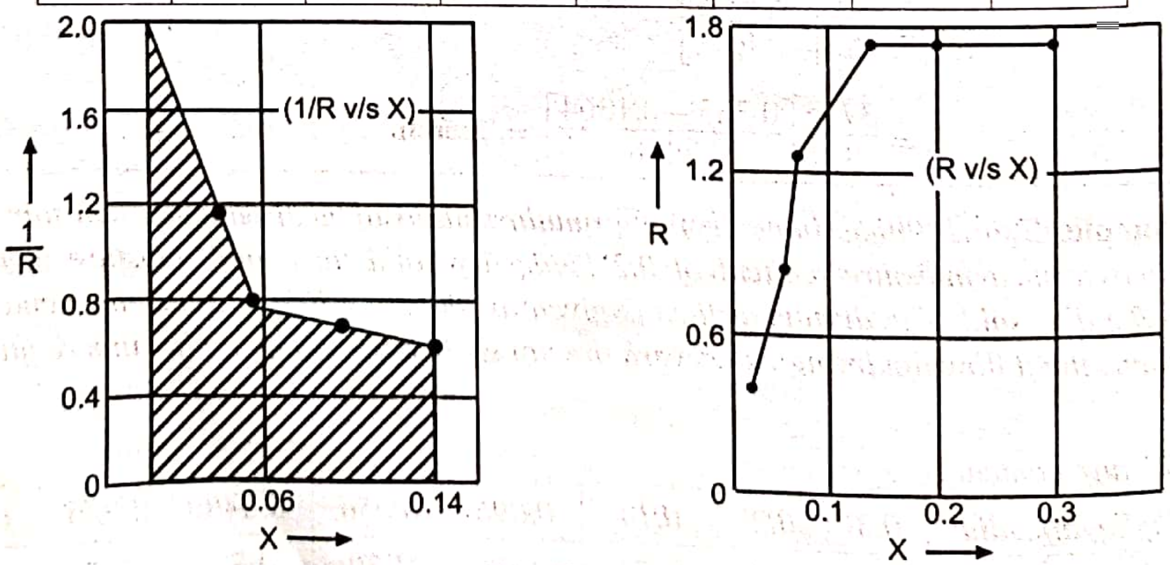


Fig. Ex. 12.6

Plot 1/R v/s X and measure the area under the curve. The area under the curve between $X_c = 0.14$ and $X_2 = 0.02$ will give the value of the integration.

$$\int_{X_2}^{X_c} \frac{dX}{R} = \text{Area under curve} \times \text{Scale of x-axis} \times \text{Scale of y-axis}$$

$$= 0.104$$

$$t_f = \frac{W'}{A} \int_{X_2}^{X_c} \frac{dX}{R}$$

$$= \frac{1400}{86.1} \times 0.104 = 1.69 \text{ h}$$

Time required for drying is

$$t = t_c + t_f$$

$$= 0.57 + 1.69 = \mathbf{2.26\ h}$$ ... **Ans.**

Example 12.7 : *Solids are to dried under constant drying conditions from 67 % to 25 % moisture. The value of equilibrium moisture for the material is 1 %. If the critical moisture content is 40 % and rate of drying in the constant rate period is 1.5 kg/(m²·h), calculate the drying time*

Drying surface = 0.5 m²/kg dry solid

Solution : X_1 = Initial moisture content on dry basis.

$$= \frac{0.67}{1-0.67} = 2.03, \quad \left[= \frac{x_1}{1-x_1}, \quad x_1 = 67/100 = 0.67 \right]$$

X_2 = Final moisture content on dry basis

$$= \frac{0.25}{1-0.25}, \quad \left[= \frac{x_2}{1-x_2}, \quad x_2 = 25/100 = 0.25 \right]$$

$$= 0.333$$

X^* = Equilibrium moisture content

$$X^* = \frac{0.01}{1-0.01} = 0.0101, \quad \left[= \frac{x^*}{1-x^*}, \quad x^* = 1/100 = 0.01 \right]$$

X_c = Critical moisture content

$$= \frac{0.40}{1-0.40} = 0.67$$

Rate of drying in the constant rate period =

$$R_c = 1.5 \text{ kg/(m}^2\cdot\text{h)}$$

Drying surface = 0.5 m² per kg dry solid. Therefore,

$$\frac{A}{W'} = 0.5$$

$$\therefore \quad \frac{W'}{A} = 2.0$$

The time required for drying is given by

$$t = \frac{W'}{A \cdot R_c}\left[(X_1 - X_c) + (X_c - X^*) \ln \frac{X_c - X^*}{X_2 - X^*}\right]$$

$$t = \frac{2}{1.5}\left[(2.03 - 0.67) + (0.67 - 0.0101) \ln \left[\frac{0.67 - 0.0101}{0.333 - 0.0101}\right]\right]$$

$$t = \mathbf{2.44\ h}$$ ... **Ans.**

Example 12.8 : *Slabs of paper pulp 100 cm × 100 cm × 1.5 cm is to be dried under constant drying conditions from 67 % to 30 % moisture. The equilibrium moisture for the material is 0.5 %. If the critical moisture content is 60 % and rate of drying at the critical point is 1.5 kg/(m²·h), calculate the drying time. The dry weight of each slab is 2.5 kg. All moisture contents are on the weight basis.*

Solution : Consider drying from the two big faces of slab. Therefore,

$$A = 100 \times 100 \times 2 = 2 \times 10^4\ cm^2 = 2\ m^2$$

$$W' = \text{dry weight of slab} = 2.5\ kg$$

$$x = \text{wt. fraction of moisture in the slab on wet basis.}$$

Initial moisture content (dry basis) of the slab

$$= X_1 = \frac{0.67}{1 - 0.67}, \left[= \frac{x_1}{1 - x_1} \text{ with } x_1 = \frac{67}{100} = 0.67\right]$$

$$= 2.03 \frac{\text{kg moisture}}{\text{kg dry solid}}$$

Final moisture content (dry basis) of the slab

$$= X_2 = \frac{0.30}{1 - 0.30} = 0.428, \left[= \frac{x_2}{1 - x_2} \text{ with } x_2 = \frac{30}{100} = 0.30\right]$$

Similarly, equilibrium moisture content

$$= X^* = \frac{0.005}{1 - 0.005} = 0.005025$$

Critical moisture content (dry basis) of the slab

$$= X_c = \frac{0.60}{1 - 0.60} = 1.5$$

$$R_c = \text{Constant rate of drying} = 1.5\ kg/(m^2 \cdot h)$$

Here X_2 is less than X_c. Therefore, the time required for drying is given by

$$t = t_c + t_f$$

$$t = \frac{W'}{A \cdot R_c}\left[(X_1 - X_c) + (X_c - X^*) \ln \left(\frac{X_c - X^*}{X_2 - X^*}\right)\right]$$

$$= \frac{2.5}{2 \times 1.5}\left[(2.03 - 1.5) + (1.5 - 0.005025) \ln \frac{(1.5 - 0.005025)}{(0.428 - 0.005025)}\right] = 2.01\ h$$

$$= \mathbf{2.01\ h}$$ ... **Ans.**