DRYING

Part A

1.Write about the drying and its importance of drying?

Drying is the final removal of water, or another solute, by applying heat. The importance of drying is

(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.

(e) In some cases, drying is an essential part of the manufacturing process, as for instance in paper making or in the seasoning of timber, although, in the majority of processing industries, drying is carried out for one or more of the following reasons:

---

2. Define moisture content wet and dry basis.

Moisture content, wet basis. The moisture content of a solid or solution is usually described in terms of weight percent moisture, and unless otherwise mentioned this is ordinarily understood to be expressed on the wet basis, i.e., as (kg moisture/kg wet solid)100 = [kg moisture/(kg dry solid + kg moisture)] 100 = 100X/(1 + X).

Moisture content, dry basis. This is expressed as lb moisture/lb dry solid = X.

Percentage moisture, dry basis = 100X.

---

3. Define Equilibrium moisture content.

Equilibrium moisture X*. This is the moisture content of a substance when at equilibrium with a given partial pressure of the vapor.

---

4. Define the term bound and unbound moisture content.

Bound moisture: This refers to the moisture contained by a substance which exerts an equilibrium vapor pressure less than that of the pure liquid 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 refers to the moisture contained by a substance which exerts an equilibrium vapor pressure equal to that of the pure liquid at the same temperature.

---

5. Define free moisture.

Free moisture is that moisture contained by a substance in excess of the equilibrium moisture: X - X*. Only free moisture. can be evaporated,

---

6. Draw a diagram to explain the different types of moisture.

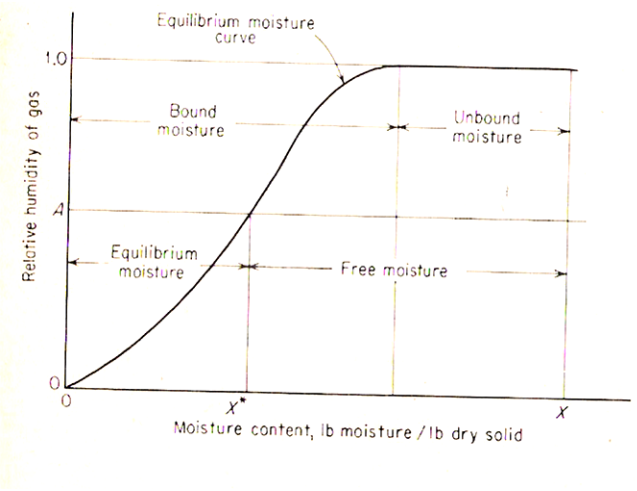


Fig . Types of Moisture

---

8. Explain the effect of air temperature and mass flow rate of air on the constant rate of drying, Nc.

Effect of Gas Velocity: If radiation and conduction through the solid are negligible, *Nc* is proportional to $G^{O.8}$ for parallel flow of gas and to $G^{O.37}$ for perpendicular flow. If radiation and conduction are present, the effect of gas rate will be less important.

Effect of Gas Temperature: Increased air temperature increases the quantity $t_G - t_s$. and hence increases N_c. In the absence of radiation effects, and neglecting the variation of λ. over moderate temperature ranges, N_c is directly proportional to $t_G - t_s$.

Effect of Gas Humidity: *Nc* varies directly as $Y_s - Y$, and consequently increasing the humidity lowers the rate of drying. Usually, changes in Y and t_G involve simultaneous changes in t_s. and Y_s.

Effect of Thickness of Drying Solid: If heat conduction through the solid occurs, the lowered values of N_c with increased solid thickness. However, conduction of heat through edge surfaces of pans and trays may be an important source of heat which can result in increased rate of drying if the edge surface is large. If nondrying surfaces are heat-insulated, or if drying occurs from all surfaces of the solid, .*Nc* is independent of thickness. The *time* for drying between fixed moisture contents within the constant-rate period will then be directly proportional to thickness.

---

9. What is meant by hold up in a rotary drier?

In a continuous operation of a rotary drier the total weight of the material at any given point of time is known as the hold up of the drier

---

10. Discuss briefly the term unsaturated surface drying.

During unsaturated surface drying the rate of drying will usually vary linearly with moisture content since the mechanism of evaporation during this period is the same as that in

constant rate period the effect of such variable as temperature, humidity and the velocity of the gas and the thickness of the solid are the same as for the constant rater drying.

---

11. Write about the major classification of driers.

1.Dryers in which the solid is directly exposed to a hot gas (usually air)

2.Dryers in which heat is transferred to the solid from an external medium such as condensing steam

3. Dryers that are heated by dielectric, radiant, or microwave energy.

Dryers that expose the solids to a hot gas are called **adiabatic or direct dryers;** those in which heat is transferred from an external medium are known as **non-adiabatic or indirect dryers;** units which combine both are called **direct-indirect dryers**.

(a) Temperature and pressure in the dryer,
(b) The method of heating,
(c) The means by which moist material is transported through the dryer,
(d) Any mechanical aids aimed at improving drying,
(e) The method by which the air is circulated,
(f) The way in which the moist material is supported,
(g) The heating medium, and
(h) The nature of the wet feed and the way it is introduced into the dryer.

In selecting a dryer for a particular application,two steps are of primary importance:

(a) A listing of the dryers which are capable of handling the material to be dried,
(b) Eliminating the more costly alternatives on the basis of annual costs, capital charges + operating costs.

---

12. What do you mean by constant drying conditions?

The exposure of the sample to air of constant temperature, humidity, and velocity constitutes drying under constant drying conditions.

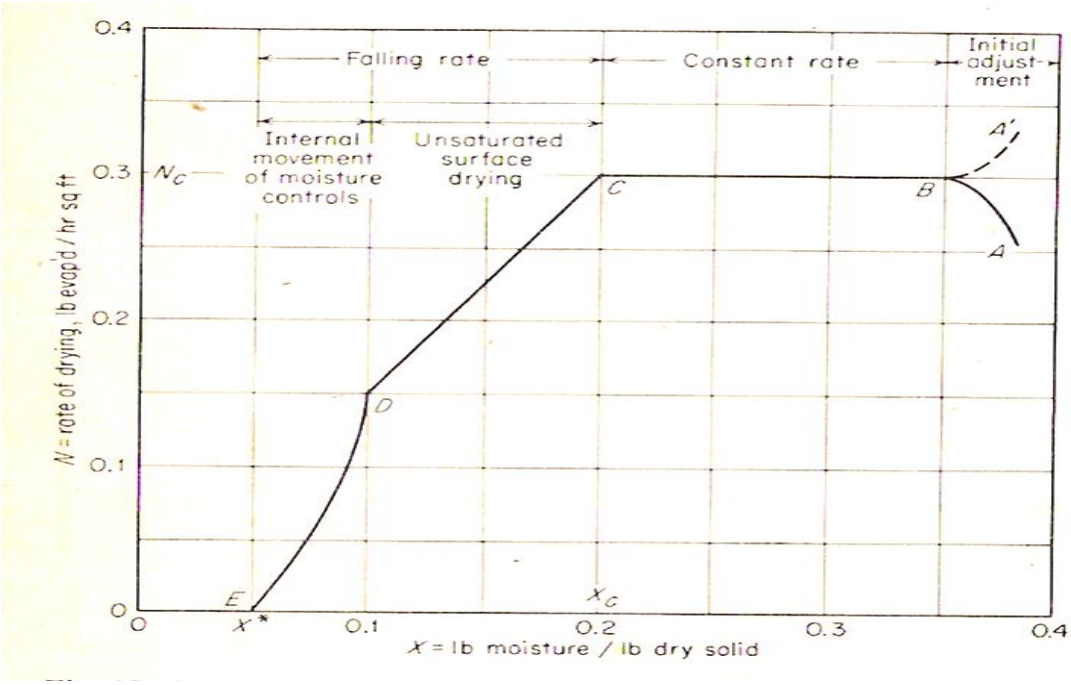
---

13. What is drying test

The rate of drying may be determined for a sample of a substance by suspending it in a cabinet or duct, in a stream of air, from a balance. The weight of the drying sample may then be measured as a function of time. Certain precautions must be observed if the data are to be of maximum utility. The sample should not be too small. Further, the following conditions should resemble as closely as possible those expected to prevail in contemplated large-scale operation: (1) The sample should be similarly supported in a tray or frame. (2) It should have the same ratio of drying to nondrying surface. (3) It should be subjected to similar conditions of radiant-heat transfer. (4) The air should have the same temperature, humidity, and velocity (both speed and direction with respect to the sample). If possible, several tests should be made on samples of different thicknesses. The dry weight of the sample should also be obtained.

---

14. Draw a typical rate of drying curve.



15. Define critical moisture content.

Critical moisture content of a substance is the moisture content at which the rate of drying just changes from constant rate period to falling rate period.

---

16. Define rate of drying.

In order to set up drying schedules and to determine the size of equipment, it is necessary to know the time which will be required to dry a substance from one moisture content to another under specified conditions. We shall also wish to estimate the influence that different drying conditions will have upon the time for drying. Our knowledge of the mechanism of drying is so incomplete that it is necessary with few exceptions to rely upon at least some experimental measurements for these purposes. Measurements of the rate of batch drying are relatively simple to make and provide much information not only for batch but also for continuous operation.

$$N = -Ls\ \Delta X / A\ \Delta\theta.$$

Here Ls is the weight of dry solid, and A is the wet surface over which the gas blows and through which evaporation takes place in the case of cross-air circulation drying. In the case of through-circulation drying, A is the cross section of the bed measured at right angles to the direction of gas flow.

---

17. What do you mean by freeze drying?

Substances which may not be heated even to moderate temperatures, such as foodstuffs and certain pharmaceuticals may be dried by this method. The substance to be dried is customarily frozen by exposure to very cold air and placed in a vacuum chamber, where the moisture sublimes and is pumped off by steam-jet ejectors or mechanical vacuum pumps. An alternative method of freezing is by flash vaporization of part of the moisture under vacuum, although foodstuffs which are not rigid in the unfrozen state may be damaged by this procedure.

Some foods, beef for example, evidently contain capillary channels, and the water vapor diffuses from the receding ice surface through these channels as drying proceeds. In other cases diffusion through cell walls must occur. In any event, one of the major problems is to supply the heat necessary for sublimation: as the plane of sublimation recedes, heat must be driven through larger thicknesses of dried matter of poor thermal conductivity, requiring increasing temperature differences which may damage the product. Radiant heat is used, and dielectric heat is a possibility although an expensive one. Still an additional method, useful for granular products, is through circulation drying with air instead of pumping off the water by vacuum pump.

---

18. What is the difference between constant rate and falling rate period?

Other condition being the same, at constant rate period the rate of drying remains constant but the moisture content varies. In falling rate period the rate of drying varies with the moisture content.

---

19. Give examples for batch driers and continuous driers.

Batch driers: Tray driers, vacuum shelf driers,

Continuous driers: Rotary driers, tunnel drier, drum drier, spray driers and fluidized bed driers

---

20. A wet solid is to be dried from 80 to 5 % moisture, wet basis. Compute the moisture to be evaporated, per 1,000 Ib of dried product.

Solution

Initial moisture content = 0.80 / (1 - 0.80) = 4.00 lb water / lb dry solid

Final moisture content = 0.05 / (1 + 0.80) = 0.0527 lb water / lb dry solid

Lb dry solid in product = 1,000(0.95) = 950 Ib

Moisture to be evapd = 950(4 - 0.0527) = 3,750 Ib

Part –B

1. Explain rotary drier with a neat diagram.

Rotary Dryers

For the continuous drying of materials on a large scale, 0.3 kg/s (1 tonne/h) or greater, a rotary dryer, which consists of a relatively long cylindrical shell mounted on rollers and driven at a low speed, up to 0.4 Hz is suitable. The shell is supported at a small angle to the horizontal so that material fed in at the higher end will travel through the dryer under gravity, and hot gases or air used as the drying medium are fed in either at the upper end of the dryer to give co-current flow or at the discharge end of the machine to give countercurrent flow. One of two methods of heating is used: (a) Direct heating, where the hot gases or air pass through the material in the dryer. (b) Indirect heating, where the material is in an inner shell, heated externally by hot gases. Alternatively, steam may be fed to a series of tubes inside the shell of the dryer.

The shell of a rotary dryer is usually constructed by welding rolled plate, thick enough for the transmission of the torque required to cause rotation, and to support its own weight and the weight of material in the dryer. The shell is usually supported on large tyres which run on wide rollers, as shown in Figure 1, and although mild steel is the usual material of construction, alloy steels are used, and if necessary the shell may be coated with a plastics material to avoid contamination of the product.

With countercurrent operation, since the gases are often exhausted by a fan, there is a slight vacuum in the dryer, and dust-laden gases are in this way prevented from escaping.

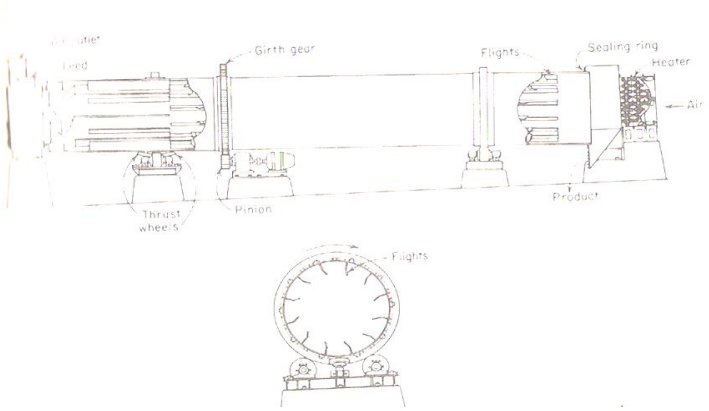


Figure 1. Rotary dryer, 0.75 m diameter × 4.5 m long

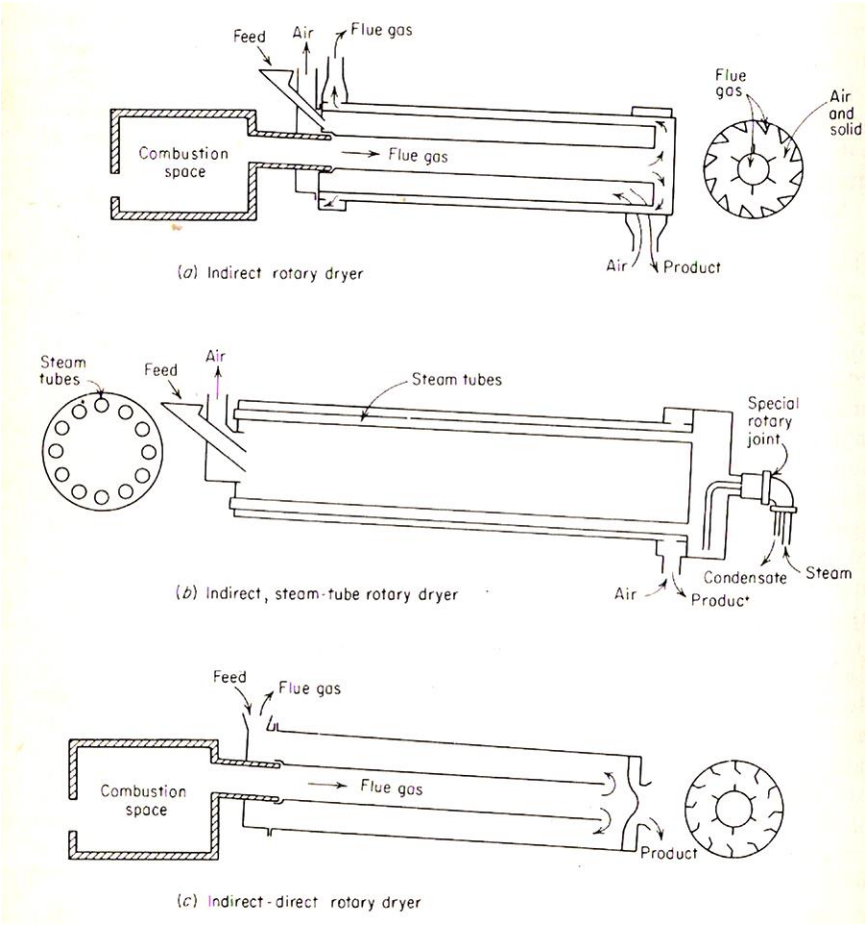


Figure 2: Some types of rotary driers

This arrangement is suitable for sand, salt, ammonium nitrate and other inorganic salts, and is particularly convenient when the product is discharged at a high temperature. In this case, gas or oil firing is used and, where air is used as a drying medium, this may be filtered before heating, in order to minimize contamination of the product. As the gases leaving the dryer generally carry away very fine material, some form of cyclone or scrubber is usually fitted. Since the hot gases come into immediate contact with the dried material, the moisture content may be reduced to a minimum, though the charge may become excessively heated. Further, since the rate of heat transfer is a minimum at the feed end, a great deal of space is taken up with heating the material.

With co-current flow, the rate of passage of the material through the dryer tends to be greater since the gas is travelling in the same direction. Contact between the wet material and the inlet gases gives rise to rapid surface drying, and this is an advantage if the material tends to stick to the walls. This rapid surface drying is also helpful with materials containing water of crystallisation. The dried product leaves at a lower temperature than with countercurrent systems, and this may also be an advantage. The rapid lowering of the gas temperature as a result of immediate contact with the wet material also enables heat sensitive materials to be handled rather more satisfactorily.

Since the drying action arises mainly from direct contact with hot gases, some form of lifter is essential to distribute the material in the gas stream. This may take the form of flights, as shown in Figure2 or of louvres. In the former case, the flights lift the material and then shower it across the gas stream, whilst in the latter the gas stream enters the shell along the louvres. In Figure 2 it may be seen that, in the rotary louvre dryer, the hot air enters through the louvres, and carries away the moisture at the end of the dryer. This is not strictly a co-current flow unit, but rather a through circulation unit, since the material continually meets fresh streams of air. The rotation of the shell, at about 0.05 Hz (3 rpm), maintains the material in agitation and conveys it through the dryer. Rotary dryers are 0.75–3.5 m in diameter and up to 9 m in length.

The thermal efficiency of rotary dryers is a function of the temperature levels, and ranges from 30 per cent in the handling of crystalline foodstuffs to 60–80 per cent in the case of inert materials. Evaporative capacities of 0.0015–0.0080 kg/m3 s may be achieved and these are increased by up to 50 per cent in louvre dryers.

In one form of indirectly heated dryer, shown in Figure , hot gases pass through the innermost cylinder, and then return through the annular space between the outer cylinders. This form of dryer can be arranged to give direct contact with the wet material during the return passage of the gases. Flights on the outer surface of the inner cylinder, and the inner surface of the outer cylinder, assist in moving the material along the dryer. This form of unit gives a better heat recovery than the single flow direct dryer, though it is more expensive. In a simpler arrangement, a single shell is mounted inside a brickwork chamber, through which the hot gases are introduced.

The steam-tube dryer, incorporates a series of steam tubes, fitted along the shell in concentric circles and rotating with the shell. These tubes may be fitted with fins to increase the heat transfer surface although material may then stick to the tubes. The solids pass along the inclined shell, and leave through suitable ports at the other end. A small current of air is passed through the dryer to carry away the moisture, and the air leaves almost saturated. In this arrangement, the wet material comes in contact with very humid air, and surface drying is therefore minimised. This type of unit has a high thermal efficiency, and can be made from corrosion resisting materials without difficulty.

---

2. Write the calculation procedure for time of drying for constant and falling rate period.

3. Calculation of drying time under constant drying conditions

For drying under constant drying conditions, the time of drying can be determined from the rate-of-drying curve if it can be constructed. Often the only source of this curve is an experiment on the material to be dried, and this gives the drying time directly. During rate curves for one set of conditions often may be modified to other conditions, and then working back from the drying rate curve to drying time is useful.

By definition

$$R = -\frac{dmv}{(Adt)} = -\frac{ms\,dX}{(Adt)}$$

Integrating between X1 and X2, the initial and final free-moisture contents, respectively, gives

$$tT = \frac{ms}{A}\int_{X2}^{X1} \frac{dX}{R}$$

Where tT is the total drying time. Equation may be integrated numerically from the rate-of-drying curve or analytically if equations are available giving R as a function of X.

In the constant-rate period R = Rc and the drying time is simply

$$tc = \frac{ms(x1 - x2)}{(ARc)}$$

If R is linear in X, as with many porous solids, during the falling – rate period,

$$R = ax + b$$

Where a and b are constants, and dR = adX. Substitutions for dX gives, for the time required in the falling-rate period,

$$tT = \frac{ms}{(aA)}\int_{R2}^{R1} \frac{dR}{R} = \left(\frac{ms}{aA}\right) \ln\left(\frac{R1}{R2}\right)$$

where R1 and R2 are the drying rates corresponding to the initial and final moisture contents. The constants a is the slope of the drying rate curve. If there are two falling- rate periods, a may be written as

$$a = \frac{Rc - R}{Xc - X}$$

Where Rc = rate at first critical point

R = rate at second critical point

Xc = free-moisture content at first Critical point

X = free-moisture content at second Critical point

Substitution of a gives

$$tf = \frac{ms\,(Xc - X)}{A\,(Rc - R)} \ln \frac{R1}{R2}$$

When the drying process covers both a constant – rate period and a falling-rate period, X2 of eauals Xc, and R1 equals Rc. The toal time of the drying tT is then

$$tT = tc + tf = \frac{ms}{A}\left[\frac{X1 - Xc}{Rc} + \frac{l}{a}\right] \ln \frac{Rc}{R2}$$

Here X1 is the moisture content at the start of the entire process, and R2 is the drying rate at the end of the process.

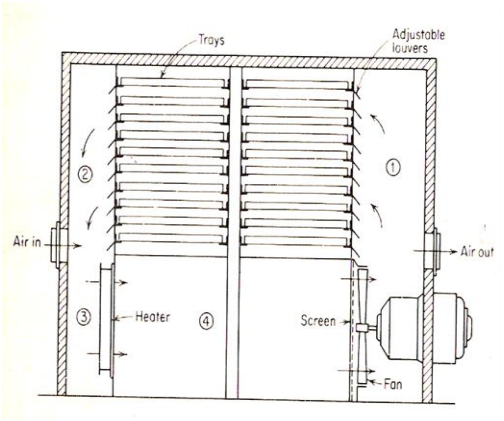
In some situations, a single straight line passing through the origin adequately represents the entire falling-rate period. The point (Xc,Rc)lies on the line. When this approximation may be made, equation may be simplified by noting that a = Rc/Xc and that Rc/R2 = Xc/X2. Equation then becomes

$$tT = \frac{ms}{ARc}\left[X1 - Xc + Xc \ln \frac{Xc}{X2}\right]$$

Here X2 is the moisture content at the end of the entire process.

---

4. Explain batch tray drier with a neat diagram.



I. BATCH DRYING

Drying in batches is a relatively expensive operation and is consequently limited to small-scale operations, to pilot-plant and development work, and to drying valuable materials whose total cost will be little influenced by added expense in the drying operation.

Direct driers: The construction of such driers depends greatly upon the nature of the substance being dried. Tray driers, also called cabinet, compartment, or shelf driers, are used for drying solids which must be supported on trays. This may include pasty materials such as wet filter cakes from filter presses, lumpy solids which must be spread upon trays, and similar materials. A

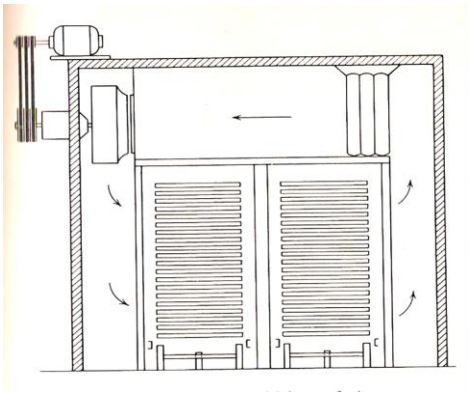


Fig 1. **Typical Tray Drier**

typical device, shown schematically in Fig, consists of a cabinet containing removable trays on which the solid to be dried is spread. After loading, the cabinet is closed, and steam-heated air is blown across and between the trays to evaporate the moisture (cross-circulation drying). Inert gas, even superheated steam, rather than air may be used if the liquid to be evaporated is combustible. When the solid has reached the desired degree of dryness, the cabinet is opened and the trays replaced with a new batch. Figure

Fig.2. Two Truck Drier

shows a simple modification, a truck drier, where the trays are racked upon trucks which may be rolled into and out of the cabinet. Since the trucks may be loaded and unloaded outside the drier, considerable time may be saved between drying cycles. Other obvious modifications of the design are also used, depending upon the nature of the drying substance. Thus, skeins of fibers such as rayon may be hung from poles, and wood or board like materials may be stacked in piles, the layers separated from each other by spacer blocks.

In the case of granular materials, the solid may be arranged in thin beds supported on screens so that air or other gas may be passed through the beds. This results in very much more rapid drying. A typical device for this purpose, a batch *through circulation drier*, is shown schematically in Fig.3. Crystalline solids and materials which are naturally granular such as silica gel may be dried in this manner directly. In the case of others, some sort of preliminary treatment to put them into satisfactory form, performing, is necessary. Pastes, for example, those resulting from precipitation of pigments or other solids, may be preformed by extrusion into short, spaghetti like rods, granulation, i.e., forcing them through screens, or by briquetting.

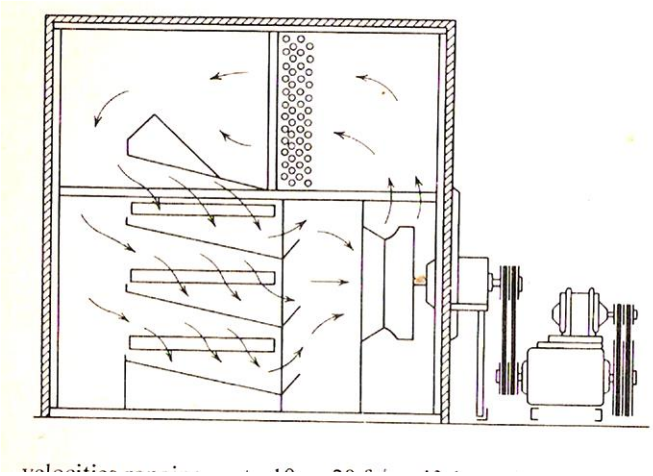


Fig.3.**Throughcirculation Tray drier**

One of the most important difficulties in the use of driers of the type described is the Non uniformity of moisture content found in the finished product taken from various parts of the drier. This is largely the result of inadequate and non uniform air movement inside the drier. It is important to eliminate stagnant air pockets and to maintain reasonably uniform air humidity and temperature throughout the drier. In order to do this, large volumes of air must be blown over the

trays, if possible at velocities ranging up to 10 or 20 ft/sec if the solid will not blow from the trays at these air rates. This may be accomplished by blowing large quantities of heated fresh air only once through the drier, but the loss of heat in the discharged air will then usually be prohibitive in cost. Instead, it is the practice to admit only relatively small quantities of fresh air and to recirculate the bulk of it, sometimes as much as 80 to 95 percent.44 this may be done inside the drier, as shown, for example, in Fig.1, with dampers in the inlet and outlet pipes to regulate the extent of recirculation. The louvers at each tray level may then be adjusted so as to ensure as nearly uniform air velocity over each tray as possible. Alternatively, the heaters and fans may be installed outside the drier, with ductwork and dampers to permit more careful control of the relative amounts of fresh and recirculated air admitted to the drier itself. It is important also that the trays in such driers be filled level to the brim but not overloaded, so that uniform free space for air movement is available between trays.

The recirculation of large quantities of air necessarily raises the humidity of the air in the drier considerably above that of the fresh air. Low percentage humidity and consequently reasonably rapid drying rates are then obtained by using as high a temperature as practicable. The drier must then be thoroughly insulated, not only to conserve heat but also to maintain the inside walls at temperatures above the dew point of the air to prevent condensation of moisture upon the walls. Specially conditioned, low-humidity air is not used except where 10w-temperature drying is necessary to avoid damage to the product.

---

5. Explain spray drier with a diagram.

Principle:

- In a spray dryer, a slurry or liquid solution is dispersed into a stream of hot gas in the form of fine droplets.
- Moisture is rapidly vaporized from the droplets, leaving residual particles of dry solid.
- The solid is then separated from the gas stream.
- The flow of liquid and gas may be concurrent, countercurrent or a combination of both in the same unit.
- I n the drying chamber, droplets may be formed by pressure nozzles or high-speed spray disks.
- Hence, drying chambers are large (2.5 to 9 m diameter) to prevent the droplets from striking solid surfaces.

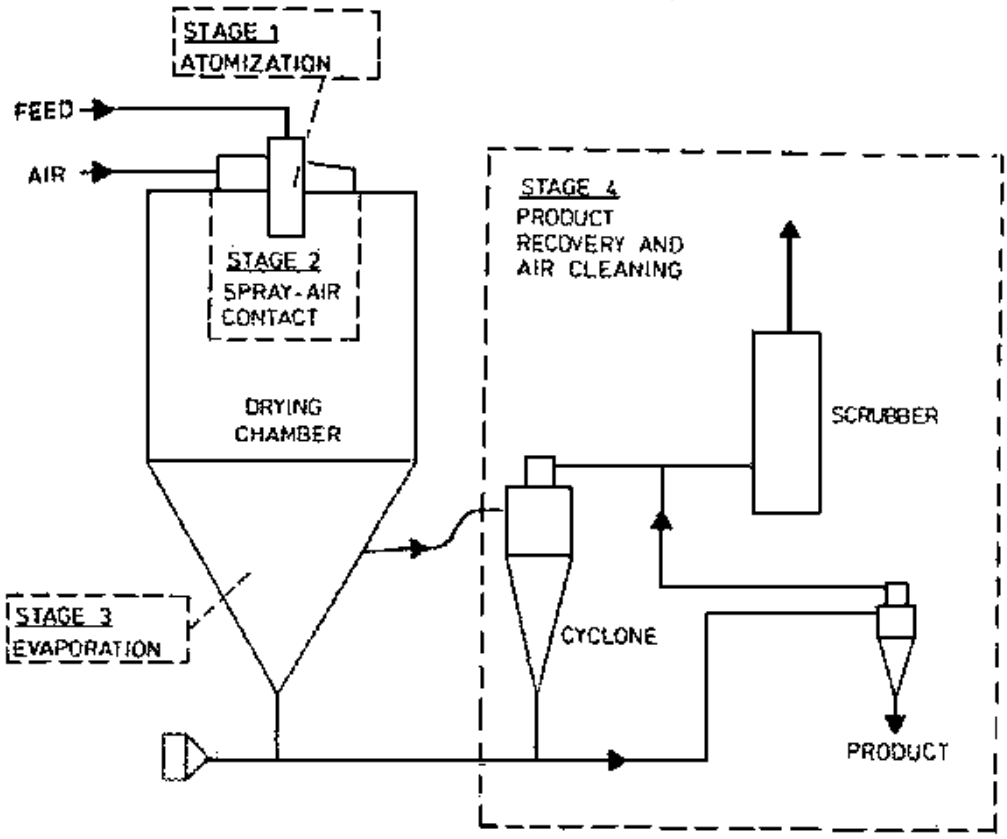
Construction and working:

- The spray dryer consists of a cylindrical chamber with a short conical bottom.
- The roof contains a spray-disk atomizer set, used to pump in the liquid feed.
- It atomizes the liquid into tiny droplets, thrown radially into a stream of hot gas, entering near the top of the chamber.
- There is an exhaust fan attached to a horizontal discharge line set in the side of the chamber, at the bottom of the cylindrical section. Cooled gas is drawn through this.
- The gas passes through a cyclone separator, where any entrained solid particles are removed.
- Much of the dry solid settles out of the gas into the bottom of the drying chamber.
  From here, it is removed by a rotary valve and screw conveyor and then combined with any solid collected in the cyclone.

Equation for the volume-surface mean diameter D_s of the drops from a disk atomizer is:

$$\mathbf{D_s/r = 0.4\,(\Gamma/\rho_L n r^2)^{0.6}\,(\mu/\Gamma)^{0.2}\,(\sigma\rho_L L_p/\Gamma^2)^{0.1}}$$

D_s = average drop diameter
r = disk radius
Γ = spray mass rate per unit length of disk periphery
σ = surface tension of liquid
ρ_L = density of liquid
n = disk speed
μ = viscosity of liquid
L_p = disk periphery



- The heat transfer coefficient for the individual drops can be estimated from the equation.
- The time required to dry a drop depends on the height and mixing pattern of the dryer.
- In dryers with low ratio of height: diameter, there is considerable mixing near the top.
- To calculate the drying times, it is assumed that the diameter of the largest drop is twice the value of D_s.
- Average drop diameters range from 20 μm and 180 μm in case of disk atomizer and coarse spray nozzle respectively.

- Residence times vary from 3 – 6 s in concurrent dryers to 25 – 30 s in countercurrent dryers.

Advantages:

- Very short drying time.
- Drying of highly heat-sensitive materials.
- Production of solid or hollow spherical particles.
- Easily adjustable to desired consistency, bulk density, appearance and flow properties etc.
- They yield dry products from a solution, slurry or thin paste in a single step, ready for package.
- It can combine the functions of an evaporator, a crystallizer, a size reduction unit, a dryer and a classifier, all in a single unit.

Disadvantages:

- Not very efficient.
- Much loss of heat in the discharge gases.
- Very bulky and large and inconvenient to operate.
- It is difficult to keep the bulk density constant.

Note:

The evaporation from the surface of the drops causes initial deposition of solute at the surface. This happens before the interior of the drop saturation. The rate of diffusion of the solute back into the drop is slower than the flow of water from the interior to the surface. So the entire solute content accumulates at the surface. The final particles are often hollow, and the product from the spray dryer is generally porous.

---

6).A certain material was dried under constant drying conditions and it was found that 2 hrs are required to reduce the free moisture content from 20% to 10%. How much longer would be required to reduce the free moisture to 4%. Assume that no constant rate period is encountered.

Solution :

Formulae to be used

For Constant rate period X_1 and X_2 are > Xc and N = Nc Where

X_1 = Initial moisture content (dry basis)

X_2 = Final moisture content (dry basis)

Nc = Critical moisture content

A = drying surface area

θc = Time of drying for constant rate period

$\theta c = Ls (X_1 – X_2)/ A Nc$

For Falling rate period :

If X_1 and X_2 are < Xc

θ_f = Time of drying in falling rate period

$\theta_f = Ls (Xc – X^*) \ln[(X_1 – X^*)/ (X_2 – X^*)/ A Nc$

X^* = Equilibrium moisture content

Ls = weight of a dry solid in a batch

$\theta t = \theta c + \theta f$
$\theta t = Ls[(X_1 – X_2)/ + (Xc – X^*) \ln[(X_1 – X^*)/ (X_2 – X^*)]/ A Nc$
θt = Total time required to dry both in constant and falling rate period
$X_1 = 0.2/(1-0.2) = 0.2/0.8 = 0.25$ kg of moisture/kg of dry product
$X_2 = 0.1/(1-0.1) = 0,1/0.9 = 0.11$ kg of moisture/kg of dry product
θ_f = Time of drying in falling rate period
$\theta_f = Ls (Xc – X^*) \ln[(X_1 – X^*)/ (X_2 – X^*)/ A Nc$
Assume $X^* = 0$

$2 = Ls (Xc – 0) \ln[(0.25 – 0)/ (0.11 – 0)/ A Nc$
$2 = Ls (Xc) \ln[(0.25)/ (0.11)/ A Nc$
$2.44 = Ls (Xc) / A Nc$
To reduce to 4% under the same conditions
$X_3 = 0.04/0.96 = 0.042$
$Ls (Xc) \ln[(0.25)/ (0.042)/ A Nc = \theta_f$
$2.44 (\ln[(0.25)/ (0.042) = 4.35$ hrs
We require (4.35 – 2.00) = 2.35 hrs to dry from 10% to 4%

---

7). A 50 Kg batch of granular solids containing 25% of moisture is to be dried in a tray to 12% moisture by a stream of air at 92 degree Celsius tangentially across its surface at a velocity of 1.8 m/s. If the constant rate of drying under these conditions is 0.008 kg moisture/m^2 .s and the critical moisture content is 10%, Calculate the drying time. The surface area available is 1.0 m^2

For Constant rate period X_1 and X_2 are > Xc and N = Nc Where
X_1 = Initial moisture content (dry basis)
X_2 = Final moisture content (dry basis)
Nc = Critical moisture content
A = drying surface area
θc = Time of drying for constant rate period
$\theta c = Ls (X_1 – X_2)/ A Nc$
X_1 = Initial moisture content (dry basis) = 0.25/0.75
= 0.33 kg of moisture/kg of dry product
X_2 = Final moisture content (dry basis) = 0.12/(1-0.12)
= 0.0.136kg of moisture/kg of dry product
Nc = 0.008 kg moisture/m^2 .s
$\theta c = 50x0.75 (0.33 – 0.0136)/ 0.008 = 923.44$ sec = 0.2565 hrs.

---

8). A wet solid is to be dried from 35% to 10% moisture in 5hrs. the critical and equilibrium moisture contents are 14% and 4% respectively. How long will it take to dry the materials to 6% moisture under the same conditions? All moisture contents are on wet basis.

Formulae to be used
For Constant rate period X_1 and X_2 are > Xc and N = Nc Where
X_1 = Initial moisture content (dry basis)

X_2 = Final moisture content (dry basis)
Nc = Critical moisture content
A = drying surface area
θc = Time of drying for constant rate period
θc = Ls ($X_1 – X_2$)/ A Nc
For Falling rate period:
If X_1 and X_2 are < Xc
θ_f = Time of drying in falling rate period
θ_f = Ls (Xc – X*) ln[(X_1 – X*)/ (X_2 – X*)/ A Nc
X* = Equilibrium moisture content
Ls = weight of a dry solid in a batch
θt = θc + θf
θt = Ls[($X_1 – X_2$)/ + (Xc – X*) ln[(X_1 – X*)/ (X_2 – X*)]/ A Nc
θt = Total time required to dry both in constant and falling rate period

X_1 = Initial moisture content (dry basis) = 0.35/0.65
= 0.538 kg of moisture/kg of dry product
X_2 = Final moisture content (dry basis) = 0.1/0.9
= 0.111kg of moisture/kg of dry product
Xc = Critical moisture content(dry basis) = 0.14/0.86
= 0.163kg of moisture/kg of dry product
X* = Equilibrium moisture content(dry basis) = 0.04/0.96
= 0.042kg of moisture/kg of dry product
5 = Ls[(0.538 –0.163) + (0.163 – 0.042) ln[(0.538 – 0.042)/ (0.111 – 0.042)]/ A Nc
Ls/A Nc = 12.5
X_3 = 0.06/0.94 = 0.064kg of moisture/kg of dry product
Θt = 12.15(0.375 + 0.121 ln (0.538-0.042)/(0.064-0.042))
Θt = 6.13 hrs

---

9). A wet solid is dried from 25 to 10 per cent moisture under constant drying conditions in 15 ks (4.17 h). If the critical and the equilibrium moisture contents are 15 and 5 per cent respectively, how long will it take to dry the solid from 30 to 8 per cent moisture under the same conditions?

Solution
For the first drying operation:
w1 = 0.25 kg/kg,w = 0.10 kg/kg,wc = 0.15 kg/kg and we = 0.05 kg/kg
Thus: f1 = (w1 - we) = (0.25 - 0.05) = 0.20 kg/kg
fc = (wc - we) = (0.15 - 0.05) = 0.10 kg/kg
f = (w - we) = (0.10 - 0.05) = 0.05 kg/kg
From equation the total drying time is:
t = (1/mA)[(f1 - fc)/fc + ln(fc/f)]
or: 15 = (1/mA)[(0.20 - 0.10)/0.10 + ln(0.10/0.05)]
and: mA = 0.0667(1.0 + 0.*693*) = 0.113 kg/s
For the second drying operation:
w1 = 0.30 kg/kg,w = 0.08 kg/kg,wc = 0.15 kg/kg and we = 0.05 kg/kg

Thus: f1 = (w1 - we) = (0.30 - 0.05) = 0.25 kg/kg
fc = (wc - we) = (0.15 - 0.05) = 0.10 kg/kg
f = (w - we) = (0.08 - 0.05) = 0.03 kg/kg
The total drying time is then:
t = (1/0.113)[(0.25 - 0.10)/0.10 + ln(0.10/0.03)]
= 8.856(1.5 + 1.204)
= 23.9ks (6.65 h)

---

10). A 100 kg batch of granular solids containing 30 per cent moisture is to be dried in a tray drier to 15.5 per cent of 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 0.0007 kg/s m2 and the critical moisture content is 15 per cent, calculate the approximate drying time. Assume the drying surface to be 0.03 m2/kg dry mass.

Solution
In 100 kg feed, mass of water = (100 × 30/100) = 30 kg
and: mass of dry solids = (100 - 30) = 70 kg
For b kg water in the dried solids: 100b/(b + 70) = 15.5
and the water in the product, b = 12.8kg
Thus: initial moisture content, w1 = (30/70) = 0.429 kg/kg dry solids
final moisture content, w2 = (12.8/70) = 0.183 kg/kg dry solids
and water to be removed = (30 - 12.8) = 17.2kg
The surface area available for drying = (0.03 × 70) = 2.1m2 and hence the rate of drying during the constant period = (0.0007 × 2.1) = 0.00147 kg/s.
As the final moisture content is above the critical value, all the drying is at this constant rate and the time of drying is:
t = (17.2/0.00147) = 11,700sor 11.7ks (3.25 h)

In a drying experiment, a tray dryer containing a single tray of 1 sq. metre area is used to dry crystalline solids. The following data has been collected.

S.No	Time, hr	Wt.of material, kg	S.No	Time, hr	Wt.of material, kg
1	0	5.314	9	3.0	4.743
2	0.4	5.238	10	3.4	4.667
3	0.8	5.162	11	4.2	4.524
4	1.0	5.124	12	4.6	4.468
5	1.4	5.048	13	5.0	4.426
6	1.8	4.972	14	6.0	4.340
7	2.2	4.875	15	∞	4.120

8	2.6	4.819			

a) Calculate and plot drying rates. Find the critical moisture content.

b) If dry air is available at 40oC with an absolute humidity of 0.01 kg per kg dry air and the drier is maintained at 90oC, calculate the amount of air required in first two hours.

Assume that the air is heated up to 90oC and the dry air leaves the drier at 90oC with 5% saturation.

c) Test the consistency of the falling rate period (choose critical moisture content and anyone point in the falling rate period).

Solution :

Assumptions : $X^* = 0$

Wt.of the material at ∞ = Ls = 4.12 kg.

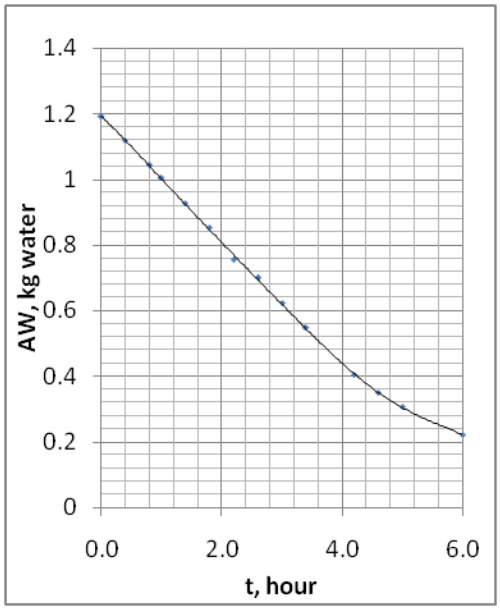
A = 1 m^2

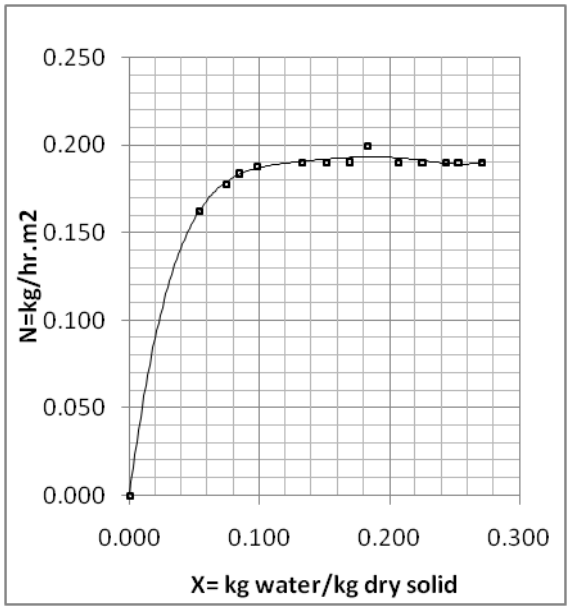
Ls/A = 4.12/1 = 4.12 kg/m^2

Amount of moisture = W – Ls

X = (W – Ls)/Ls Kg of water/kg of dry solid.

S.no	t hr	W	W-Ls	AW	X	N=Aw/At	t	W-Ls
1	0.0	5.314	1.194	0.000	0.290	0.000	0.0	1.194
2	0.4	5.238	1.118	0.076	0.271	0.190	0.4	1.118
3	0.8	5.162	1.042	0.152	0.253	0.190	0.8	1.042
4	1.0	5.124	1.004	0.190	0.244	0.190	1.0	1.004
5	1.4	5.048	0.928	0.266	0.225	0.190	1.4	0.928
6	1.8	4.972	0.852	0.342	0.207	0.190	1.8	0.852
7	2.2	4.875	0.755	0.439	0.183	0.200	2.2	0.755
8	2.6	4.819	0.699	0.495	0.170	0.190	2.6	0.699
9	3.0	4.743	0.623	0.571	0.151	0.190	3.0	0.623
10	3.4	4.667	0.547	0.647	0.133	0.190	3.4	0.547
11	4.2	4.524	0.404	0.790	0.098	0.188	4.2	0.404
12	4.6	4.468	0.348	0.846	0.084	0.184	4.6	0.348
13	5.0	4.426	0.306	0.888	0.074	0.178	5.0	0.306
14	6.0	4.34	0.22	0.974	0.053	0.162	6.0	0.22
15	∞	4.12	0	1.194	0.000	0.000		





From fig X vs N, Xc = 0.098 kg water/ kg dry solid

b) From fig t vs Δw, Water removed from first 2 hrs = 1.194 – 0.81 = 0.384 kg.
Humidity of inlet air = 0.01 kg water/ kg dry air
Humidity of exit air (90 ^{o}C and 5% saturation) = 0.068 kg water/kg dry air
Water removed = 0.068 – 0.01 = 0.058 kg / kg dry air
Dry air required in first 2 hours = 0.384/0.058 = 6.62 kg.
Amount of inlet air (40^{o}C, H = 0.01) required = 6.62x 1.01 = 6.69 kg.

c)Let us assume a value of X in the falling rate period from the plot and check for the drying time. X = 0.074 (corresponding to t = 5 hrs).
For drying of the material from X =0.29 to 0.074, let the time required = t_T

$t_T = t_c + t_f$,
$t_c = L_s (X_1 – X_c) / A N_c = 4.12(0.29 – 0.098) / 0.19 = 4.16$ hr.
$t_f = L_s (X_c – X^*) \ln [(X_c – X^*)/(X_2 – X^*)] / AN_c = 4.12 \times 0.098 \ln(0.098/0.074) = 0.6$ hr. since $X^* = 0$
$t_T = 4.16 + 0.6 = 4.76$ hr.
Time of drying from experimental data = 5 hrs.
Since both the timings are nearly equal, hence the falling rate period is consistent.

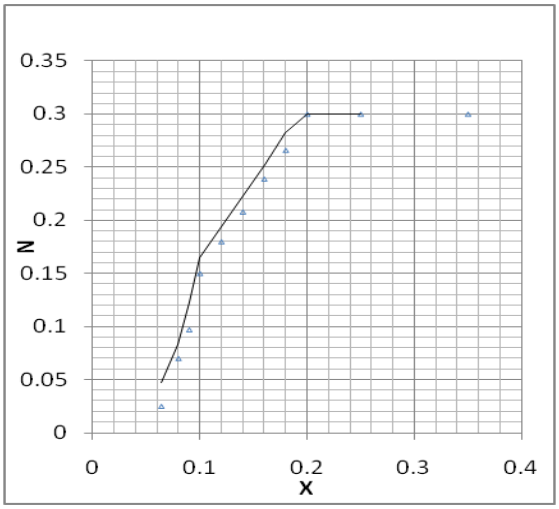
A batch of solid for which the following table of data applies is to be dried from 25% to 6% moisture under conditions identical to those for which the data were tabulated. The initial weight of the wet solid is 300kg and the drying surface is 1m^2/8kg dry weight. Determine the time for drying.

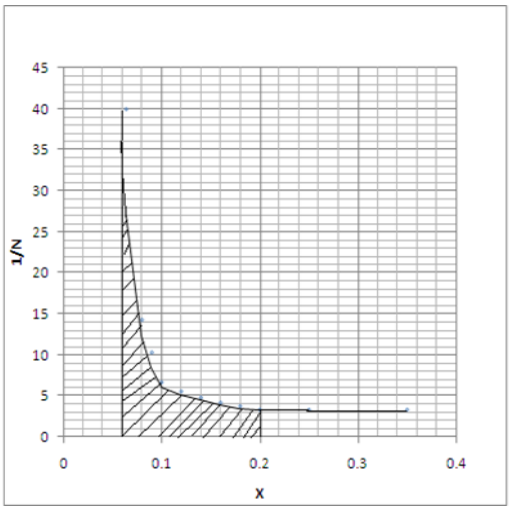
X	**0.35**	**0.25**	**0.20**	**0.18**	**0.16**	**0.14**	**0.12**	**0.10**	**0.09**	**0.08**	**0.064**
N	**0.30**	**0.30**	**0.30**	**0.266**	**0.239**	**0.208**	**0.180**	**0.150**	**0.097**	**0.070**	**0.025**

Where X = Kg moisture / kg dry solid, N = kg moisture evaporated / hr m^2

Solution :

$X_1 = 25/75 = 0.333$, $X_2 = 6/94 = 0.064$, $Ls / A = 8$





The rate of drying curve is plotted in fig. The values of Xc and Nc are obtained from it

$Nc = 0.3$ kg/hr m^2, $Xc = 0.2$ kg moisture / kg dry solid.

The drying from X1 = 0.333 to X2 = 0.064 covers both the constant and the falling rate periods.

Constant rate period $X_1 = 0.333$, $X_2 = 0.20$,

$Tc = Ls (X_1 – Xc) / A\ Nc = 8 (0.333 – 0.20) / 0.3 = 3.55$ hrs.

Falling rate period : $tf = Ls / A \int dX/N = 1.063 \times 8 = 8.5$ hrs.

Total drying time = 3.35 +8.5 = 12.05 hrs.

11).Write the calculation procedure for time of drying for constant and falling rate period?

Rate-or-drying curve. From the data obtained during drying test, a curve of moisture content as a function of time (Fig.1) may be plotted. This will be useful directly in determining the time required for drying larger batches under the same drying conditions. Much information can be obtained if the data are converted to rates of drying, expressed as lb moisture evaporated/(hr)(sq ft), and plotted against moisture content, as in Fig. This may be done by measuring the slopes of tangents drawn to the curve of Fig. or by determining from the curve small changes in moisture content ΔX for corresponding small changes in time and calculating the rate as

$N = -Ls\ \Delta X / A\ \Delta\theta$. Here *Ls* is the weight of dry solid, and *A* is the wet surface over which the gas blows and through which evaporation takes place in the case of cross-air circulation drying. In the case of through-circulation drying, *A* is the cross section of the bed measured at right angles to the direction of gas flow.

The rate-of-drying curve is sometimes plotted with the ordinate expressed as lb moisture evaporated/(hr)(lb dry solid), which in the present notation is $-dX/d\theta$.

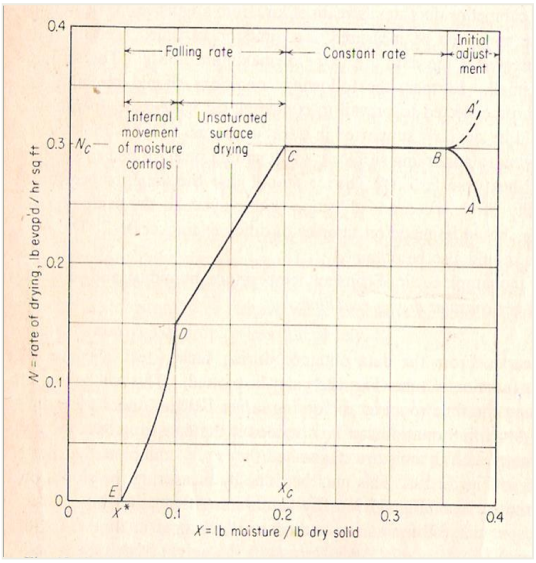
There are usually two major parts to the rate curve of Fig.2 , a period of constant rate and one of falling rate, as marked on the figure 2. While different solids and different conditions of drying will frequently give rise to curves of very different shape in the falling-rate period, the curve shown occurs frequently. Some of the differences which may arise will be considered later, but for the present let us briefly review the reasons generally advanced for the various parts of the curve shown.

If a solid is initially very wet, the surface will be covered with a thin film of liquid, which we

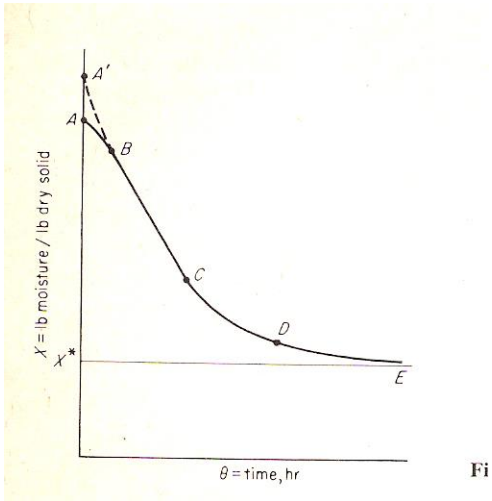
shall assume is entirely unbound moisture. When it is exposed to relatively dry air, evaporation will take place from the surface. The rate at which moisture evaporates can be described in terms of a gas mass-transfer coefficient *ky* and the difference in humidity of the gas at the liquid surface *Y.* and in the main stream *Y.* Thus, for cross-circulation drying

$$N_s = k_y(Y_s - Y) \qquad (1)$$

The coefficient *ky* may be expected to remain constant as long as the speed and direction of gas flow past the surface do not change. The humidity *Y.* is the saturated humidity at the liquid-surface temperature *t.* and will therefore depend upon this temperature. Since evaporation of moisture absorbs latent heat, the liquid surface will come to, and remain at, an equilibrium temperature such that the rate of heat flow from the surroundings to the surface exactly equals the rate of heat absorption.*Y.* Therefore remains constant. Since in addition *Y* remains unchanged under constant drying conditions, the rate of evaporation must remain constant at the value *N.*, as shown on Figs(1&2). and between points Band C. In the beginning, the solid and the liquid surface are usually colder than the ultimate surface temperature *t.*. and the evaporation rate will increase while the surface temperature rises to its ultimate value during the period *AB* on these curves. Alternatively the equilibrium temperature *t.* may be lower than the initial value, which will give rise to a curve *A'B* while the initial adjustment occurs. The initial period is usually so short that it is ordinarily ignored in subsequent analysis of the drying times.



When the average moisture content of the solid has reached a value X_c, the *critical* moisture content (Fig2.), the surface film of moisture has been so reduced by evaporation that further drying causes dry spots to appear upon the surface, and these occupy increasingly larger proportions of the exposed surface as drying proceeds. Since, however, the rate *N* is computed by means of the constant gross surface *A*, the value of *N* must fall even though the rate per unit of wet surface remains constant.



Fi

This gives rise to the first part of the falling-rate period, the period of *unsaturated surface drying*, from points C to *D* (Figs.2). Ultimately the original surface film of liquid will have entirely evaporated at an average moisture content for the solid corresponding to point *D.* This part of the curve may be missing entirely, or it may constitute the whole of the falling-rate period. In the case of some textiles, other explanations for the linear falling-rate period have been necessary. On further drying, the rate at which moisture may move through the solid, as a result of concentration gradients existing between the deeper parts and the surface, is the controlling Figure 2 Batch drying step. As the moisture concentration generally *is* lowered by the *drying*, the rate of internal movement of

moisture decreases. In some cases, evaporation may take place beneath the surface of the solid in a plane or zone which retreats.

Time of drying. If it is desired to determine the time of drying a solid under the same conditions for which a drying Curve such as Fig.2 has been completely determined, one need merely read the difference in the times corresponding to the initial and final moisture contents from the curve.

Within limits, it is sometimes possible to estimate the appearance of a rate-of drying curve such as Fig.2 for conditions different from those used in the experiments. In order to Figure 2 Typical rate of drying curve determine the time for drying for such a curve, we may proceed as follows: The rate of drying is, by definition,

$$N = (L_s dX / A d\theta) \qquad (2)$$

Rearranging and integrating over the time interval while the moisture content changes from its initial value X_l to its final value X_2,

$$\theta = \text{integral } (0, \theta)\, d\theta = [\, (L_s / A) \text{ integral } (x_2 , x_1)\, (dX / N)\,] \qquad (3)$$

1. The constant-rate period. If the drying takes place entirely within the constant rate period so that X_l and $X_2 > X_c$ and $N = N_c$, Eq. (3) becomes

$$\theta = \frac{L_S(X_I - X_2)}{AN_c} \qquad (4)$$

2. The falling-rate period. If X_l and X_2 are both less than X_c, so that drying occurs under conditions of changing *N,* we may. proceed as follows:

a. General case. For any shape of falling-rate curve whatsoever, Eq. (3) may be integrated graphically by determining the area under a curve of 1 / N as ordinate, X as abscissa, the data for which may be obtained from the rate of drying curve.

b. Special case. N is linear in X, as in the region BC of Fig. 2. In this case

$$N = mX + b \qquad (5)$$

where *m* is' the slope of the linear portion of the curve and *b* is a constant. Substitution in Eq. (3) *provides*

$$\theta = \int (L_s / A) \text{ integral } (x_2 , x_1)(dX / mX+b)] = [\, (Ls / mA)\ln(mX_1+b /mX_2+b)\,] \qquad (6)$$

But since $NI = mX_l + b$, $N_2 = mX_2 + b$, and $m = (N_I - N_2)/(X_I - X_2)$, Eq. (6) becomes

$$\theta = \frac{LS(X_I - X_2)}{A(N_I - N2)} \text{ In } \frac{NI}{N_2} = \frac{LS(X_I - X_2)}{ANm} \qquad (7)$$

where N_m is the logarithmic average of the rate N_l > at moisture content X_l, and N_2 at X_2.

Frequently the entire falling-rate curve may be taken as a straight *line* between points C and *E* (Fig. 2). It is often assumed to be so for lack of more detailed data.In this case

$$N= m(X - X^*) = \frac{Nc(X - X^*)}{Xc - X^*} \qquad (8)$$

And Eq.(12.7) becomes

$$\theta = \frac{Ls(Xc - X^*)}{NcA} \text{ In } \frac{Xl - X^*}{X2 - X^*} \qquad (9)$$

In any particular drying problem, either or both constant- and falling-rate periods may be involved, depending upon the relative values of Xl> X2, and Xc. The appropriate equations and limits must then be chosen.

CONTINUOUS DRYING

Continuous drying offers the advantages that usually the equipment necessary is small " relative to the quantity of product, the operation is readily integrated with continuous . chemical manufacture without intermediate storage, the product has a more uniform moisture content, and the cost of drying per unit of product is relatively small. As in the case of batch drying, the nature of the equipment used is greatly dependent upon the type of material to be dried. Either direct or indirect heating, and someti both, may be used.

In many of the direct driers to be described, the solid is moved through a d while in contact with a moving gas stream. The gas and solid may flow in parallel in countercurrent, or the gas may flow across the path of the solid. If heat is neitl
supplied within the drier nor lost to the surroundings, operation is adiabatic and! gas will lose sensible heat and cool down as the evaporated moisture absorbs latC heat of vaporization. By supplying heat within the drier, the gas may be maintain at constant temperature.

In *countercurrent* adiabatic operation, the hottest gas is in contact with the dry solid, and the discharged solid is therefore heated to a temperature which may approach to that of the entering gas. This provides the most rapid drying, since especially in the case of bound moisture the last traces are the most difficult to remove, this is done more rapidly at high temperatures. On the other hand, the dry solid will be damaged by being heated to high temperatures in this manner. In addition, the hot discharged solid will carry away considerable sensible heat, thus lowering the thermal efficiency of the drying operation.

In *parallel* adiabatic operation, the wet solid is contacted with the hot gas. As long as unbound surface moisture is present, the solid will be heated only to the wet-bulb temperature of the gas, and for this reason even heat-sensitive solids will, frequently be dried by fairly hot gas in parallel flow. For example, a typical flue gas resulting from combustion of a fuel, which may have a humidity of 0.03 lb water vapor per lb of dry gas at 800°F, has a wet-bulb temperature of only about 150°F. any event, the wet-bulb temperature can never exceed the boiling point of the liquid at the prevailing pressure. At the outlet of the drier, the gas will have been considerably cooled, and no damage will result to the dry solid. Parallel flow also permit greater control of the moisture content of the discharged solid, in cases where the solid must not be completely dried, through control of the quantity of gas passing through the drier and consequently its exit temperature and humidity.

Tunnel driers

These direct driers are essentially adaptations of the truck drier to continuous operation. They consist of relatively long tunnels through which trucks, loaded with trays filled with the drying solid, are moved in contact with a current of gas to evaporate the moisture. The trucks may be pulled continuously through the drier by a moving chain, to which they are attached. In a simpler arrangement, the loaded trucks arc introduced periodically at one end of the drier, each displacing a truck at the other end. The time of residence in the drier must be sufficiently great to reduce the moisture content of the solid to the desired value. For relatively low-temperature operation the gas is usually steam-heated air, while for higher temperatures and especially for products which need not be kept scrupulously clean, flue gas from the combustion of a fuel may be used. Parallel or countercurrent flow of gas and solid may be used, or in some cases fans placed along the sides of the tunnel blow the gas through the trucks in cross flow. Operation may be essentially adiabatic, or the gas may be heated by steam coils along its path through the drier, and operation may then be substantially at constant temperature. Part of the gas may be recycled, much as in the case of batch driers, for heat economy. Truck-type tunnel driers may be used for

any material which may be dried on trays: crystals, filter cakes, pastes, pottery, and the like

There are many modifications of the tunnel drier which are essentially the same in principle but different in detailed design owing to the nature of the material being dried.

For example, skeins of wet yarn may be suspended from poles or racks which move through the tunnel drier. Hides may be stretched on frames which hang from conveyor chains passing through the drier. Material in continuous sheets, such as cloth, may move through the drier under tension, as in a continuous belt over a series of rollers, or may be hung in festoons from moving racks if it is to be dried in the absence of tension.

12) Turbo-shelf dryers

The handling of sticky materials can present difficulties, and one type of dryer which is useful for this type of material is the turbo-dryer. Solids which ordinarily may be dried on trays, such as **powdery and granular materials, heavy sludge and pastes, beads and crystalline solids,** may be continuously dried in a turbo-type drier, a form of direct drier. As shown in Figure 1, wet solid is fed in a thin layer to the top member of a series of annular shelves each made of a number of segmental plates with slots between them. These shelves rotate and, by means of suitably placed arms, the material is pushed through a slot on to a shelf below. After repeated movements, the solid leaves at the bottom of the dryer. The shelves are heated by a row of steam pipes, and in the centre there are three or more fans which suck the hot air over the material and remove it at the top.

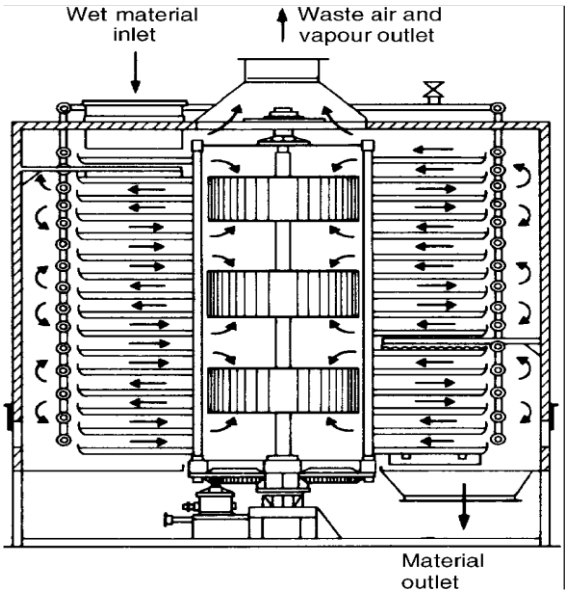


Figure 1. Turbo-shelf dryer

The accelerated drying induced by the raking of the material gives evaporative capacities of 0.0002–0.0014 kg/s m2 shelf area which are comparable with those obtained by through circulation on perforated belts. Shelf areas are 0.7–200 m2 in a single unit and the dryer may easily be converted to closed-circuit operation, either to prevent emission of fumes or in order to recover valuable solvents. Typical air velocities are 0.6–2.5 m/s, and the lower trays are often used to cool the dry solids. A turbo-dryer combines crosscirculation drying, as in a tray dryer, with drying by showering the particles through the hot air as they tumble from one tray to another.