DRYING

Drying of materials is often the final operation in a manufacturing process, carried out immediately prior to packaging or dispatch. Drying refers to the final removal of water, or another solute, and the operation often follows evaporation, filtration, or crystallization.

Purposes of Drying

1- Removal of water from process material and other substances.
2- Removal of other organic liquids/solvents from solids
3- Removal of small amounts of water from material
(note: evaporation – removal of large amounts of water.)
4- Water usually removed as vapor by air
5- Usually the final processing step before packaging
6- As a preservation technique especially for food
7- Freeze-dried for biological & pharmaceuticals materials

General Methods of Drying

Batch
Material is inserted into the drying equipment and drying proceeds for given period of time.

Continuous
Material is continuously added to the dryer and dried material continuously removed.

Drying - categorized according to the physical conditions used to add heat and remove water vapor;
1.Direct contact with heated air at atmospheric pressure, and water vapor removed by the air.
2.Vacuum drying – heated indirectly by contact with a metal wall or by radiation.
3.Freeze drying – water is sublimed from the frozen material.

VAPOR PRESSURE OF WATER & HUMIDITY

- calculation involve properties and concentration of mixtures of water vapor and air.

Humidification
- transfer of water from the liquid phase into a gaseous mixture of air and water vapor.

Dehumidification
- reverse transfer where the water vapor is transferred from the vapor state to the liquid state.

Humidity

1. Humidity, $\mathscr{H}$ – the kg of water vapor contained in 1 kg of dry air. Mass of water per unit mass of dry air.

$$\frac{\text{moles of water vapour}}{\text{moles of dry air}} = \frac{P_w}{(P-P_w)}$$

Then: $$\mathscr{H} = \frac{18P_w}{29(P-P_w)}$$

where,

Pw = partial pressure of water vapor in the air.

P = Total pressure

Saturated air – water vapor in equilibrium with liquid water.

Pw = Pws

where, *Pws* = saturated vapor pressure.

Saturated humidity, $\mathscr{H}o$

$$\mathscr{H}o = \frac{18P_{ws}}{29(P-P_{ws})}$$

Percentage humidity, $\mathscr{H}p$

$$\mathscr{H}p = \frac{\text{Humidity of air}}{\text{Humidity of saturated air}} \times 100 = (\mathscr{H} / \mathscr{H}o) \times 100$$

Percentage relative humidity, $\mathscr{R}_o$

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

Note: $\mathscr{H}p \neq \mathscr{R}_o$

Where, $$\mathscr{H}p = \frac{P_w}{P_{ws}} \frac{P-P_{ws}}{P-P_w}(100)$$

Dew point

Dew point is the temperature at which condensation will first occur when air is cooled.

- or temperature at which vapor begins to condense when the gas phase is cooled at constant pressure.

Humid heat

- amount of heat required to raise the temperature of 1 kg of dry air plus the water vapor present by 1 K.

Cs (*kJ/kg* dry air.K) = **1.00 + 1.88H**

where,

Cp water* (v) = 1.88 *kJ/kg water vapor. K

Cp air* = 1.00 *kJ/kg dry air. K

Humid volume

Humid volume, is the volume of unit mass of dry air its associated vapour.

Humid volume **$V_H = (2.83 \times 10^{-3} + 4.56 \times 10^{-3}\ \mathscr{H}) \times T$**

Wet bulb temperature

Wet bulb temperature. If a stream of air is passed rapidly over a water surface, vaporization occurs, provided the temperature of the water is above the dew point of the air. The temperature of the waterfalls and heat flows from the air to the water. If the surface is sufficiently small for the condition of the air to change inappreciably and if the velocity is in excess of about **5 m/s**, the water reaches the wet bulb temperature θw at equilibrium. The rate of heat transfer from gas to liquid is given by:

$$Q = hA(\theta - \theta w) \qquad (1)$$

The mass rate of vaporisation is given by:

$$G_v = \frac{h_D A M_w}{RT}(P_{wo} - P_w) \qquad (2)$$

$$= \frac{h_D A M_A}{RT}[(P - P_w)_{mean}(\mathscr{H}_w - \mathscr{H})]$$

$$= h_D A \rho_A (\mathscr{H}_w - \mathscr{H})$$

The rate of heat transfer required to effect vaporisation at this rate is given by:

$$G_v = h_D A \rho_A (\mathscr{H}_w - \mathscr{H})\lambda \qquad (3)$$

At equilibrium, the rates of heat transfer given by equations (1) and (3) must be equal, and hence:

$$(\mathscr{H} - \mathscr{H}_w) = -\frac{h}{h_D \rho_A \lambda}(\theta - \theta_w) \qquad (4)$$

wet bulb temperature θw depends only on the temperature and humidity of the drying air.

h is the heat transfer coefficient,
h_D is the mass transfer coefficient,
A is the surface area,
θ is the temperature of the air stream,
θ_w is the wet bulb temperature,
P_{wo} is the vapour pressure of water at temperature θ_w,
M_A is the molecular weight of air,
M_w is the molecular weight of water,
R is the universal gas constant,
T is the absolute temperature,
$\mathscr{H}$ is the humidity of the gas stream,
$\mathscr{H}_w$ is the humidity of saturated air at temperature θw,
ρ_A is the density of air at its mean partial pressure, and
λ is the latent heat of vaporisation of unit mass of water.

RATE OF DRYING

Drying periods:

In drying, it is necessary to remove free moisture from the surface and also moisture from the interior of the material. If the change in moisture content for a material is determined as a function of time, a smooth curve is obtained from which the rate of drying at any given moisture content may be evaluated. The form of the drying rate curve varies with the structure and type of material, and two typical curves are shown in Figure (1).

In curve 1, there are two well-defined zones:

- AB, where the rate of drying is constant .
- BC, where there is a steady fall in the rate of drying as the moisture content is reduced.
- The moisture content at the end of the constant rate period is represented by point B, and this is known as the *critical moisture content*.

Curve 2 shows three stages, DE, EF and FC.

- The stage DE represents a constant rate period.
- EF and FC are falling rate periods. In this case, the Section EF is a straight line, however, and only the portion FC is curved. Section EF is known as the first falling rate period and the final stage, shown as FC, as the second falling rate period.

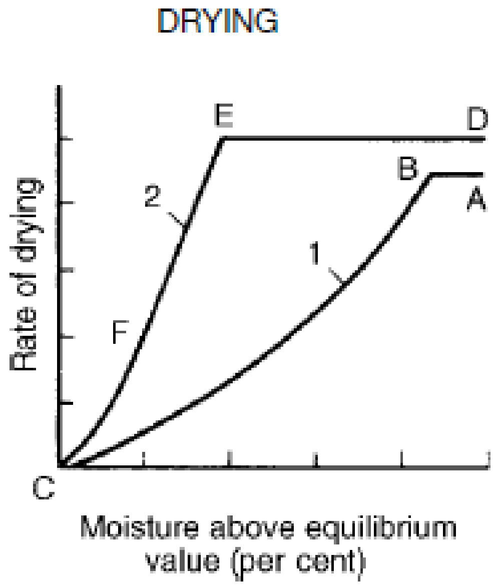


Figure (1). Rate of drying of a granular material.

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

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

where:

W is the rate of loss of water,
h is the heat transfer coefficient from air to the wet surface,
ΔT is the temperature difference between the air and the surface,
λ is the latent heat of vaporisation per unit mass,
k_G is the mass transfer coefficient for diffusion from the wet surface through the gas film,
A is the area of interface for heat and mass transfer, and
$(P_s - P_w)$ is the difference between the vapour pressure of water at the surface and the partial pressure in the air.

Time for drying

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

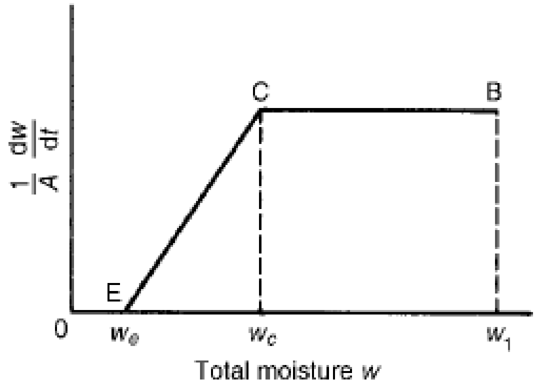


Figure (2). The use of a rate of drying curve in estimating the time for drying.

where:

w is the total moisture,
w_e is the equilibrium moisture content (point E),
$w - we$ is the free moisture content, and
w_c is the critical moisture content (point C).

Constant-rate period

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

$$t_c = \frac{w_1 - w_c}{R_c\,A} \qquad (6)$$

where: R_c is the rate of drying per unit area in the constant rate period.
A is the area of exposed surface.

Falling-rate period

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

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

Thus:
$$-\left(\frac{1}{m\,A}\right)\int_{w_e}^{w}\frac{dw}{(w - w_e)} = \int_0^{t_f} dt$$

Or:
$$\frac{1}{m\,A}\ln\left[\frac{w_c - w_e}{w - w_e}\right] = t_f$$

and:
$$t_f = \frac{1}{m\,A}\ln\left(\frac{f_c}{f}\right) \qquad (8)$$

Total time of drying

The total time t of drying from w_1 to w is given by $t = (t_c + t_f)$.
The rate of drying R_c over the constant rate period is equal to the initial rate of drying in the falling rate period, so that $R_c = mf_c$.

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

and the total drying time, $$t = \frac{w_1 - w_c}{R_c\,A} + \frac{1}{m\,A}\ln\left(\frac{f_c}{f}\right)$$

$$= \frac{1}{m\,A}\left[\frac{(f_1 - f_c)}{f_c} + \ln\left(\frac{f_c}{f}\right)\right] \qquad (9)$$

Example (1):

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:

$w_1 = 0.25$ *kg/kg*, $w = 0.10$ *kg/kg*, $wc = 0.15$ *kg/kg* and $w_e = 0.05$ *kg/kg*

Thus: $f_1 = (w_1 - w_e) = (0.25 - 0.05) = 0.20$ *kg/kg*

$f_c = (w_c - w_e) = (0.15 - 0.05) = 0.10$ *kg/kg*

$f = (w - w_e) = (0.10 - 0.05) = 0.05$ *kg/kg*

the total drying time is:

$$t = \frac{1}{m\,A}\left[\frac{(f_1 - f_c)}{f_c} + \ln\left(\frac{f_c}{f}\right)\right]$$

$$15 = \frac{1}{m\,A}\left[\frac{(0.2 - 0.1)}{0.1} + \ln\left(\frac{0.1}{0.05}\right)\right]$$

$$mA = 0.0667(1.0 + 0.693) = 0.113\ kg/s$$

For the second drying operation:

$w_1 = 0.30$ *kg/kg*, $w = 0.08$ *kg/kg*, $w_c = 0.15$ *kg/kg* and $w_e = 0.05$ *kg/kg*

Thus: $f_1 = (w_1 - w_e) = (0.30 - 0.05) = 0.25$ *kg/kg*

$f_c = (w_c - w_e) = (0.15 - 0.05) = 0.10$ *kg/kg*

$f = (w - w_e) = (0.08 - 0.05) = 0.03$ *kg/kg*

The total drying time is then:

$t = (1/0.113)[(0.25 - 0.10)/0.10 + \ln(0.10/0.03)]$

$= 8.856(1.5 + 1.204)$

= 23.9 *ks* (6.65 *h*)

Example (2):

Strips of material 10 mm thick are dried under constant drying conditions from 28 to 13 per cent moisture in 25 ks (7 h). If the equilibrium moisture content is 7 per cent, what is the time taken to dry 60 mm planks from 22 to 10 per cent moisture under the same conditions assuming no loss from the edges? All moistures are given on a wet basis. The relation between E, the ratio of the average free moisture content at time t to the initial free moisture content, and the parameter J is given by:

E	**1**	**0.64**	**0.49**	**0.38**	**0.295**	**0.22**	**0.14**
J	**0**	**0.1**	**0.2**	**0.3**	**0.5**	**0.6**	**0.7**

It may be noted that $J = kt/l^2$, where k is a constant, t the time in *ks* and $2l$ the thickness of the sheet of material in millimeters.

Solution:

For the 10 mm strips

Initial free moisture content = (0.28 − 0.07) = 0.21 *kg/kg*.

Final free moisture content = (0.13 − 0.07) = 0.06 *kg/kg*.

Thus: when t = 25 *ks*, E = (0.06/0.21) = 0.286

and from Figure (3), a plot of the given data, J = 0.52

Thus: $0.52 = (k \times 25)/(10/2)^2$

and: k = 0.52

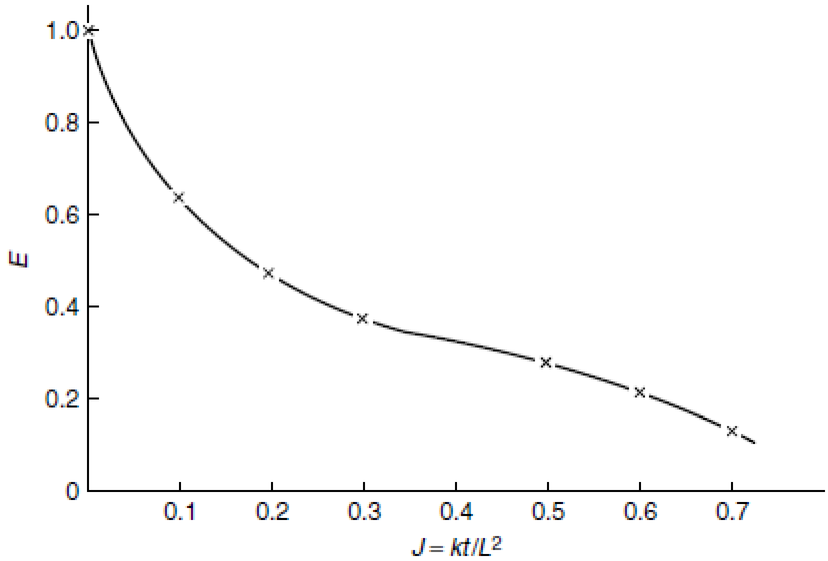


Figure (3). Drying data for Example (2).

For the 60 mm planks

Initial free moisture content = (0.22 − 0.07) = 0.15 *kg/kg*.

Final free moisture content = (0.10 − 0.07) = 0.03 *kg/kg*.

E = (0.03/0.15) = 0.20

From Figure (3) : J = 0.63

and hence: $\boldsymbol{t = J\, l^2/k}$

$= 0.63(60/2)^2/0.52 =$ **1090 *ks* (12.6 *days*)**

Example(3):

A granular material containing 40 per cent moisture is fed to a countercurrent rotary dryer at a temperature of 295 K and is withdrawn at 305 K, containing 5 per cent moisture. The air supplied, which contains 0.006 kg water vapour/kg dry air, enters at 385 K and leaves at 310 K. The dryer handles 0.125 kg/s wet stock. Assuming that radiation losses amount to 20 kJ/kg dry air used, determine the mass flow rate of dry air supplied to the dryer and the humidity of the exit air. The latent heat of water vapour at 295 K = 2449 kJ/kg, specific heat capacity of dried material = 0.88 kJ/kg K, the specific heat capacity of dry air = 1.00 kJ/kg K, and the specific heat capacity of water vapour = 2.01 kJ/kg K.

Solution:

This example involves a heat balance over the system. 273 K will be chosen as the datum temperature, and it will be assumed that the flow rate of dry air = *G kg/s*.

Heat in:

(a) *Air*

G kg/s dry air enter with 0.006*G kg/s* water vapour and hence the heat content of this stream = [(1.00G) + (0.006G × 2.01)](385 − 273) = 113.35*G kW*

(b) *Wet solid*

0.125 kg/s enter containing 0.40 kg water/kg wet solid, assuming the moisture is expressed on a wet basis.

Thus: mass flow rate of water = (0.125 × 0.40) = 0.050 *kg/s*

and: mass flow rate of dry solid = (0.125 − 0.050) = 0.075 *kg/s*

Hence:

the heat content of this stream = [(0.050 × 4.18) + (0.075 × 0.88)](295 − 273) = 6.05 *Kw*

Heat out:

(a) ***Air***

Heat in exit air = [(1.00 G) + (0.006 G × 2.01)](310 − 273) = 37.45*G kW*.

Mass flow rate of dry solids = 0.075 kg/s containing 0.05 kg water/kg wet solids.

Hence:

water in the dried solids leaving = (0.05 × 0.075)/(1 + 0.05) = 0.0036 *kg/s*

and:

the water evaporated into gas steam = (0.050 − 0.0036) = 0.0464 *kg/s*.

Assuming evaporation takes place at 295 K, then:

heat in the water vapour = 0.0464[2.01(310 − 295) + 2449 + 4.18(295 − 273)]

= 119.3 *kw*

and:

the total heat in this stream = (119.30 + 37.45G) *kW*.

(b) ***Dried solids***

The dried solids contain 0.0036 *kg/s* water and hence heat content of this stream is:

= [(0.075 × 0.88) + (0.0036 × 4.18)/(305 − 273)] = 2.59 *kW*

(c) ***Losses***

These amount to **20 *kJ/kg* dry air or 20 *mkW***.

Heat balance

(113.35 *G* + 6.05) = (119.30 + 37.45 *G* + 2.59 + 20 *G*)

and: ***G* = 2.07 *kg/s***

Water in the outlet air stream = **(0.006 × 2.07) + 0.0464 = 0.0588 *kg/s***

and: the humidity $\mathscr{H}$ **= (0.0588/2.07) = 0.0284 *kg/kg dry air***

Example (4):

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 $kg/s\ m^2$**

and the critical moisture content is **15 per cent**, calculate the approximate drying time. Assume the drying surface to be **0.03 m^2/kg** dry mass.

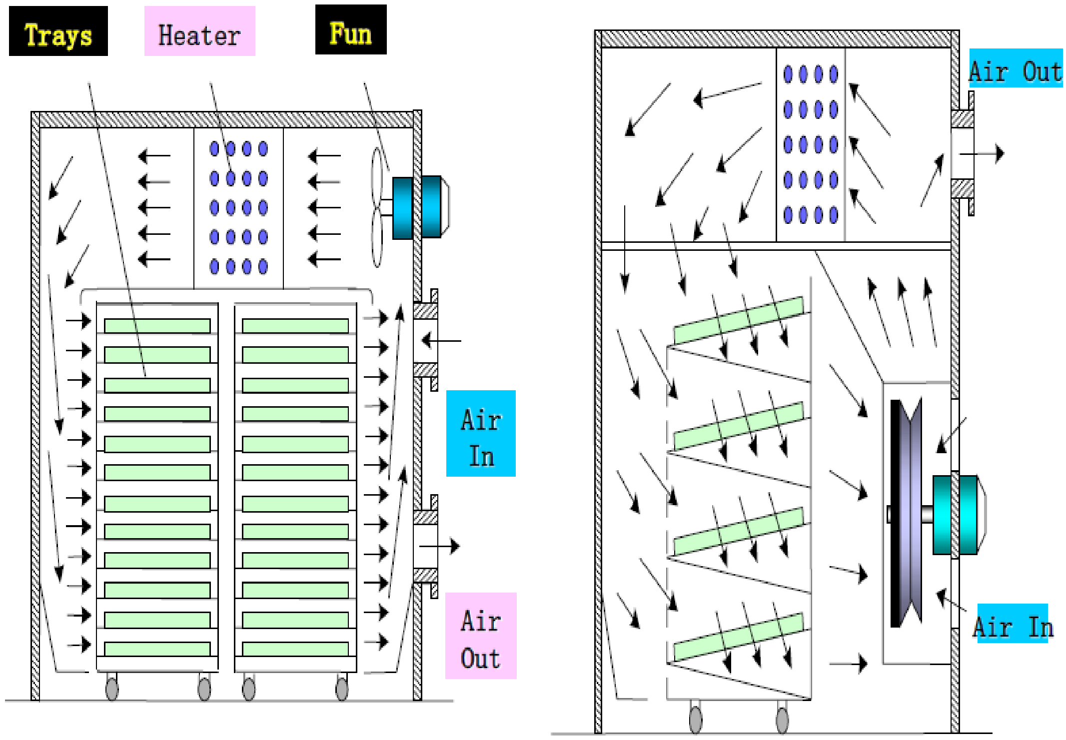
Solution:

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: 100*b*/(*b* + 70) = 15.5**
and the water in the product, b = 12.8 *kg*
Thus: initial moisture content, w_1 = (30/70) = 0.429 *kg/kg* dry solids
final moisture content, w_2 = (12.8/70) = 0.183 *kg/kg* dry solids
and water to be removed = (30 − 12.8) = 17.2 *kg*
The surface area available for drying = **(0.03 × 70) = 2.1 m^2** 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) = 11,700 s or 11.7 *ks* (3.25 *h*)**

EQUIPMENT FOR DRYING

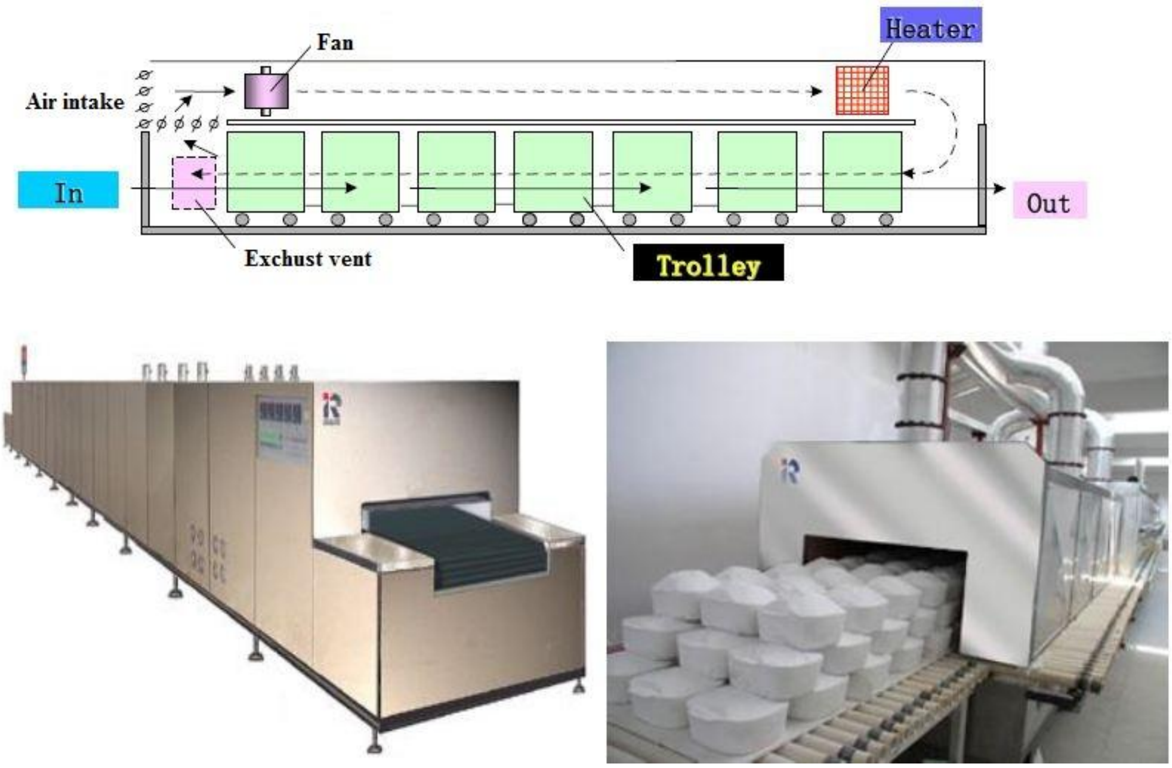
- **Tray dryer.**
- **Vacuum-shelf indirect dryers.**
- **Continuous tunnel dryers.**
  - ☒ **through-circulation screen conveyor dryer.**
  - ☒ **tunnel dryer trucks with countercurrent air flow.**
- **Rotary dryers.**
- **Drum dryers.**
- **Spray dryers.**

Tray Dryers:



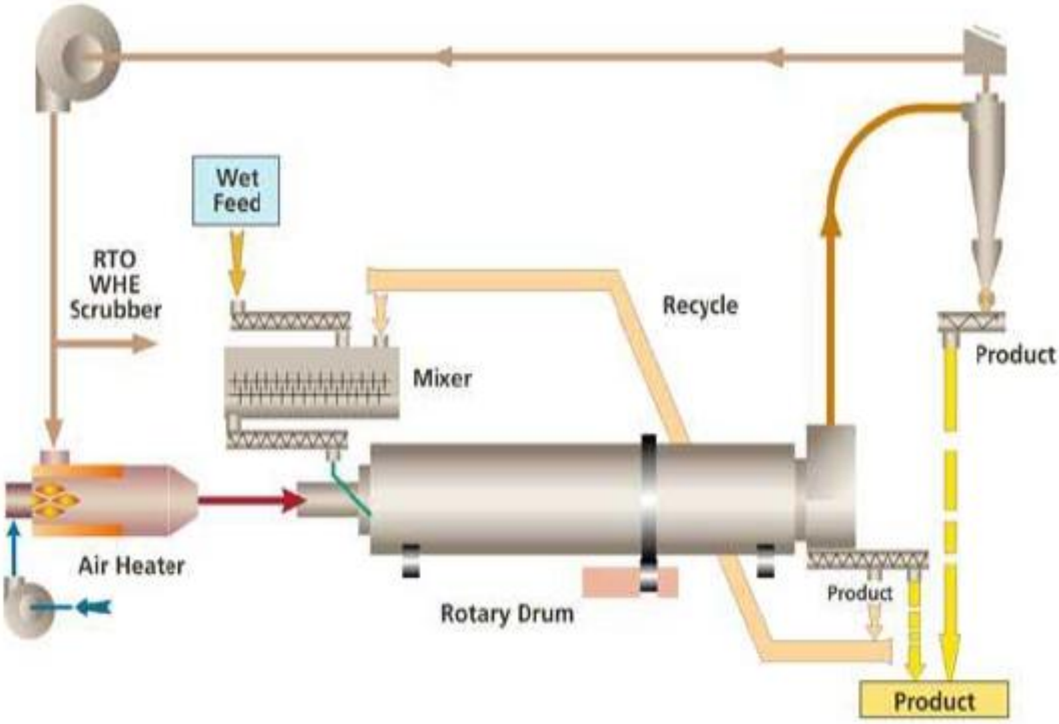
Figure(3): Tray Dryer.

Continuous Tunnel Dryers:



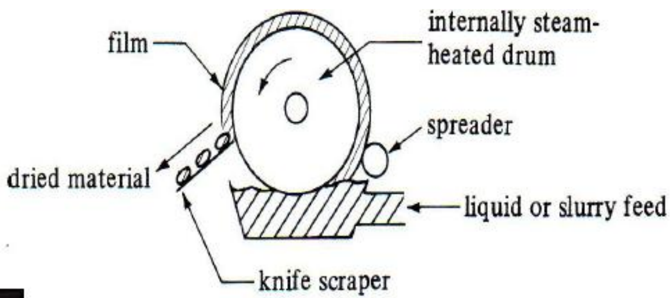
Figure(4): Continuous Tunnel Dryer.

Rotary Dryers:



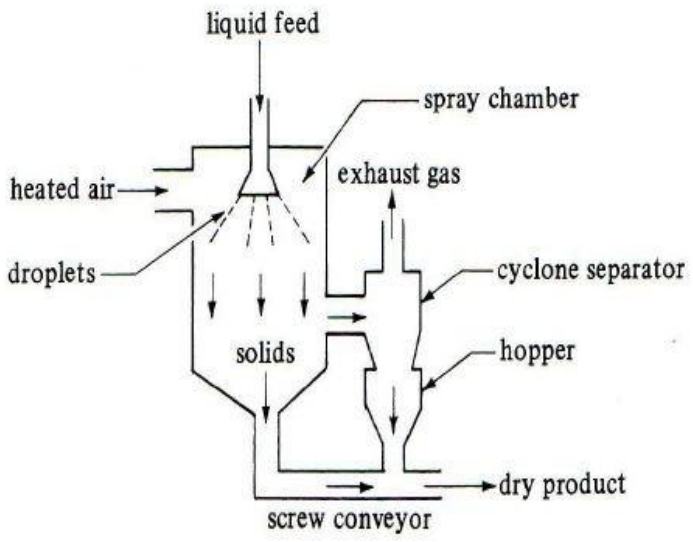
Figure(5): Rotary Dryer.

Drum Dryers:



Figure(6): Drum Dryer.

Spray Dryers :



Figure(7): Spray Dryer.

Selection of dryers

The following factors for selection of 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.