Topic 4.1. Drying

This lecture

- ✓ Overview and definitions
- ✓ Drying applications

Definitions

Drying: is a mass transfer process consisting of the removal of water or another solvent by evaporation from a solid, semi-solid, or liquid.

- It is a physical change that occurs when moisture is lost from a substance.
- A gas stream such as air applies the heat by convection and carries away the vapor as humidity
- Other possibilities are vacuum drying, where heat is supplied by conduction or radiation (or microwaves)

Classification of drying

1. Natural drying

- Natural drying occurs when a solid-solvent system is exposed to the sun leading to the transport of solvent from solid to ambient.

Utah's Great Salt Lake is drying out

2. Artificial drying

- Solvent is removed from the solid by means of mechanical, Infrared or dielectric, or Chemical drying methods.

Drying of ceramic

Advantage and disadvantage of drying

1. Natural drying

- **Advantage**
  - No cost
  - Natural method
- **Disadvantage**
  - Uncontrolled method
  - The process takes a long time
  - This method requires a large area

2. Artificial drying

- **Advantage**
  - Controlled process and can be done whenever it needs
  - It takes a short time and small area
- **Disadvantage**
  - Costly and need a large amount of initial investment

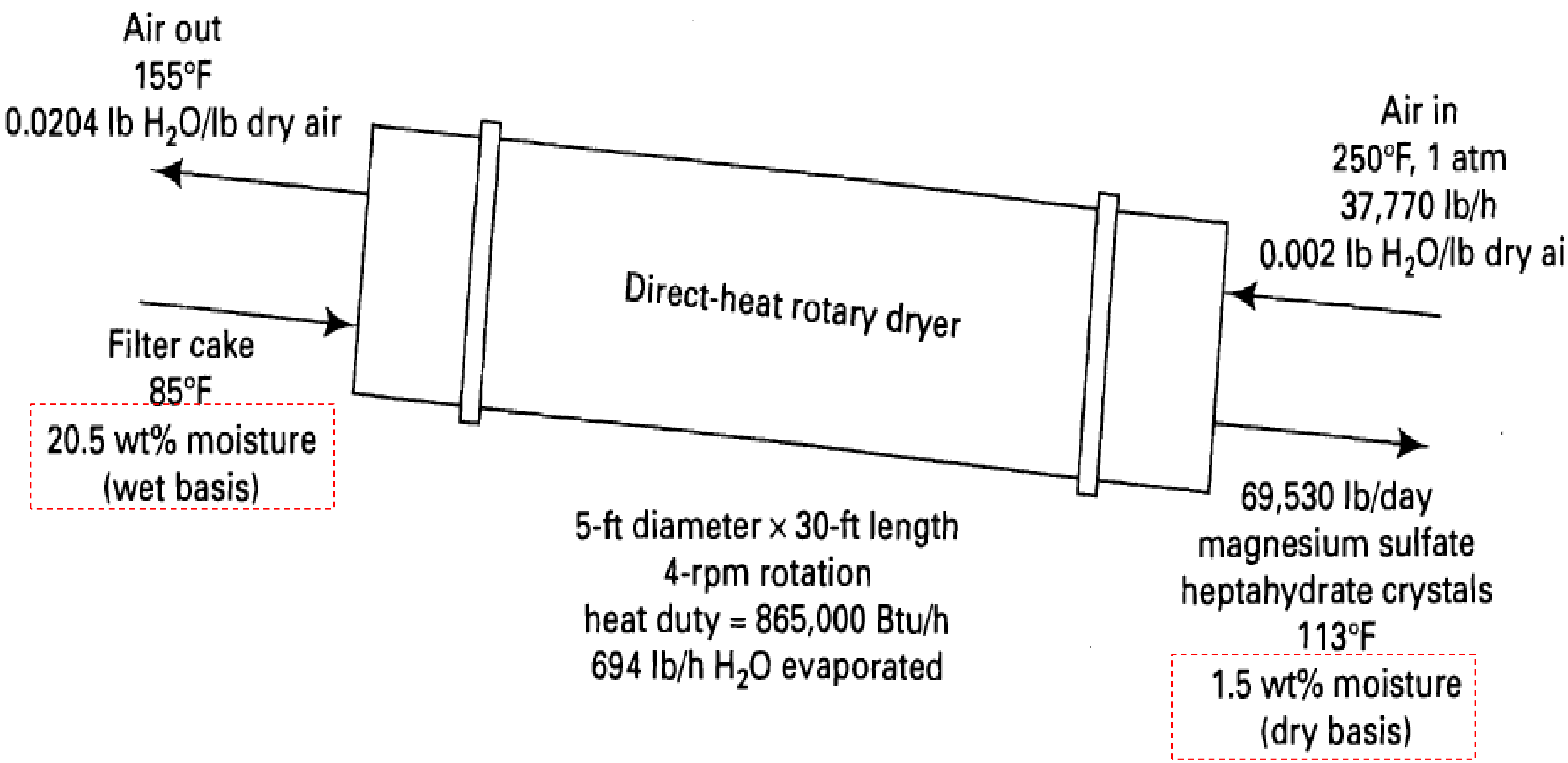
Application of drying

1. **Pharmaceutical**
2. **Biological materials, including foods and milk**
3. **Crops, grains, and cereal products**
4. **Lumber, pulp, and paper products**
5. **Catalysts**
6. **Detergents**

- **Drying can be expensive**, especially **when large amounts of water**, must be evaporated.

- Therefore, it is important, before drying, to remove as much moisture as possible by **mechanical means** such as **filtration**; **settling**; and **centrifugation**.

Industrial example: Drying of magnesium sulfate heptahydrate filter cake



Difference between drying and evaporation

Drying

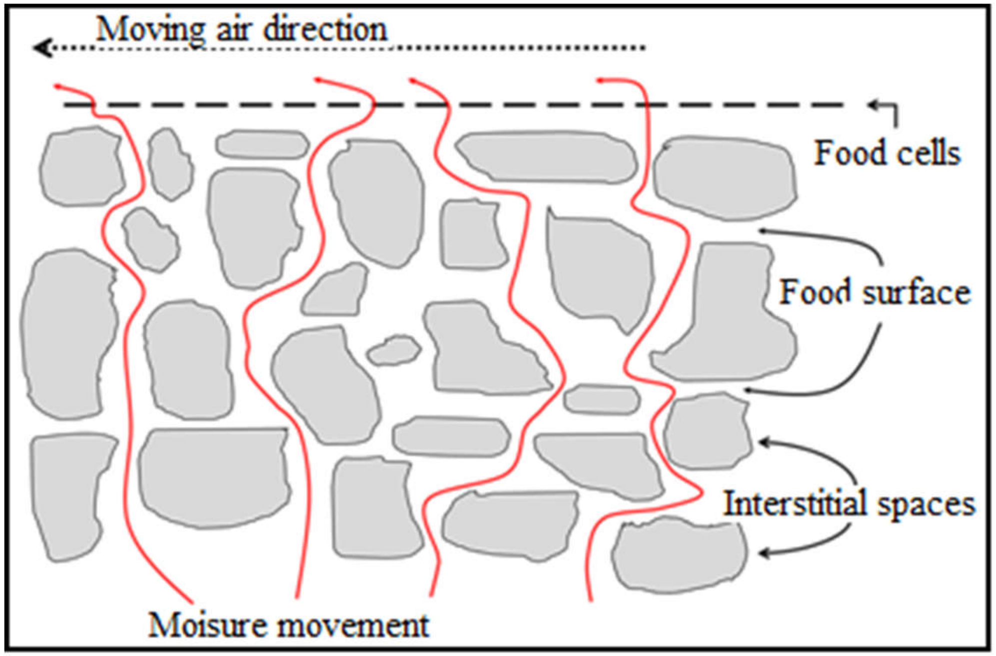
- Removal of relatively small amounts of water from solids
- In most cases, involves the removal of water at temperatures below its boiling point
- Water is usually removed by circulating air over the material in order to carry away the water

Evaporation

- Removal of large amounts of water from solutions.
- The removal of water by boiling a solution.
- Water is removed from the material as pure water vapor mixed with other gases.

Drying mechanism

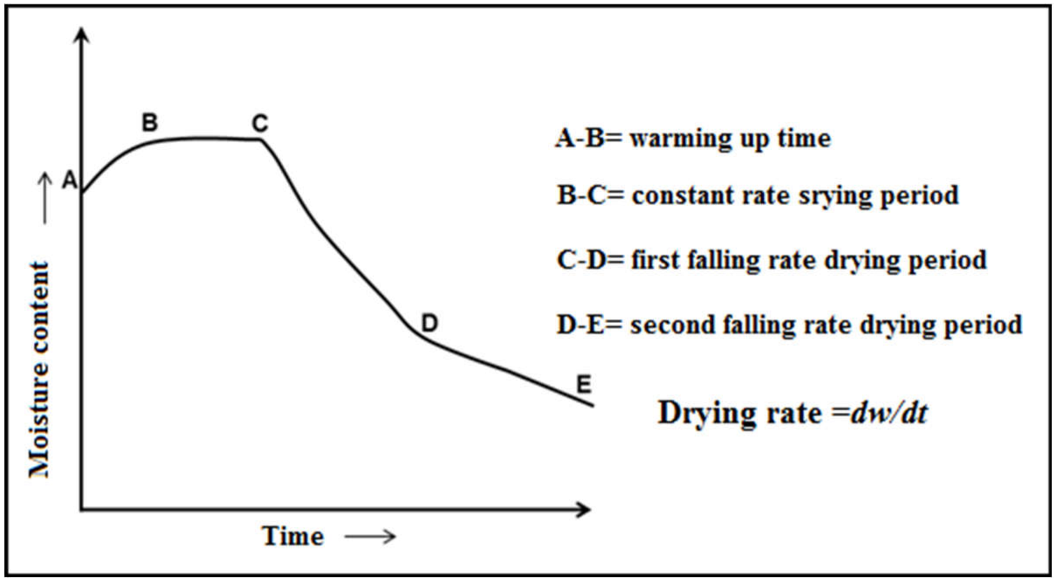
The mechanisms of water transfer in the product during the drying process can be summarized as follows:



1. Liquid movement by capillary force.
2. Diffusion of liquids, caused by a concentration gradient.
3. Diffusion of liquids, which are absorbed in layers at the surfaces of solid components of the solid.
4. Water vapor diffusion in air spaces within the solid is caused by vapor pressure gradients.

Phases of drying

1. The initial warm-up period
2. Constant drying rate period
3. Falling drying rate period

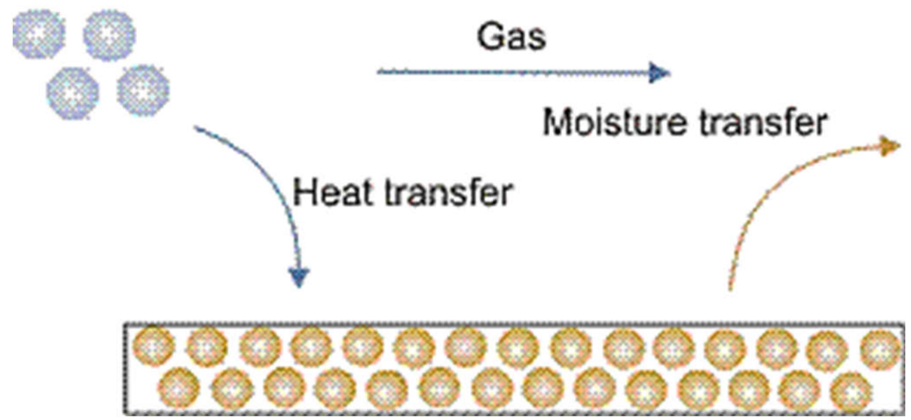


There are 4 resistances to heat transfer in drying:

1. Resistance to external heat transfer
2. Resistance to internal heat transfer
3. Resistance to external mass transfer
4. Resistance to internal mass transfer

Equilibrium Moisture Content (EMC) of Materials

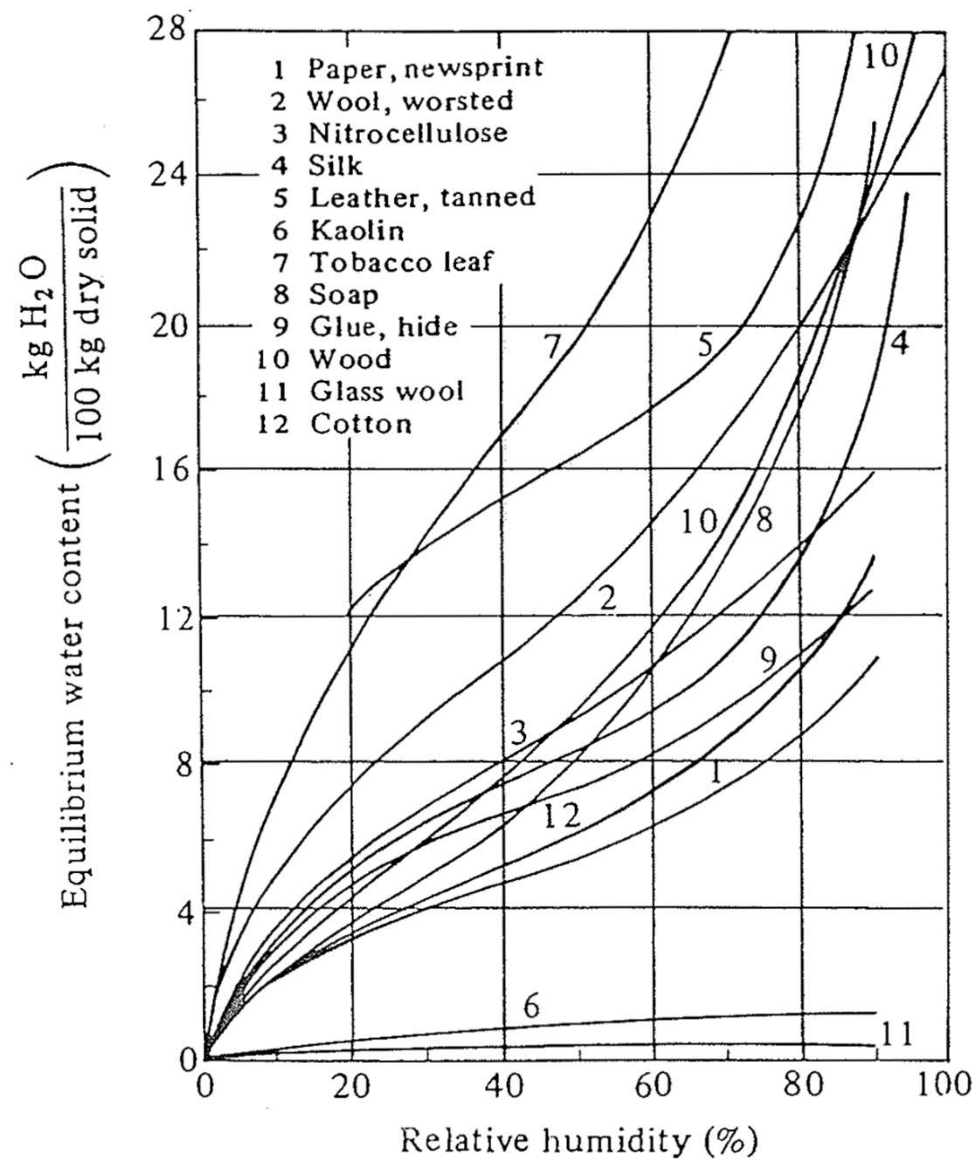
- When the air gets into contact with a moist surface, moisture is transferred from the solid to the gas phase based on concentration driving force.
- If contacting air is more humid than the solid, the solid absorbs moisture from the air until equilibrium is attained.



- When a wet solid containing moisture is brought into contact with a stream of air having a constant humidity H and temperature, and for sufficiently long exposure, the solid will attain a definite ***equilibrium moisture content (EMC)***.

$$(P_A^{sat} = p_A)$$

- **Equilibrium moisture content** is the lowest moisture content obtainable by a solid at equilibrium under the drying conditions.
- Expressed on a dry basis **(kg of water per kg dry solid) i.e. kg W/kg dry solid.**
- The lowest moisture content depends on
  - Structure of the solid
  - Temperature of the gas
  - Moisture content of the gas.
- Varies greatly with the type of material for any given % relative humidity.
- Decreases with an increase in temperature
- It may change with temperature.



The nature of water in solid material

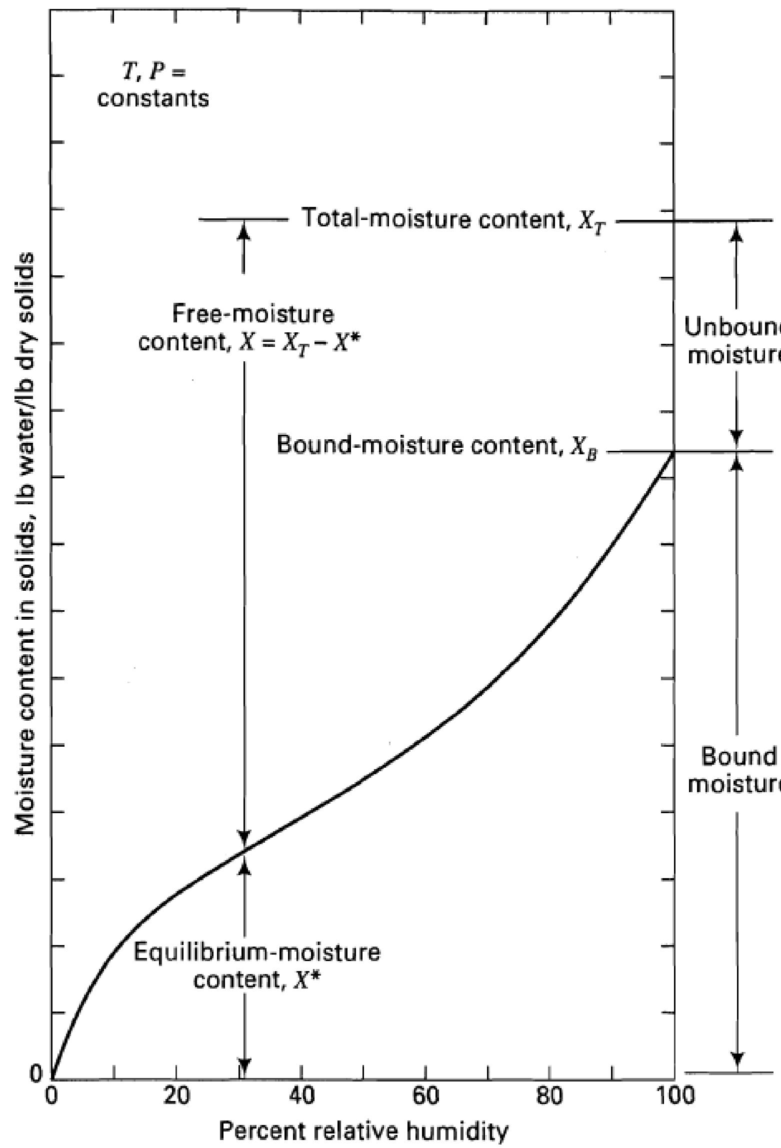
- **Bound moisture (XB)**

  - If the EMC curve for a given material is continued to intersect with 100% relative humidity line, this equilibrium moisture is called bound water with moisture content XB

  - It is the part of the *moisture present in a wet solid that is adsorbed on the surfaces* of the solid

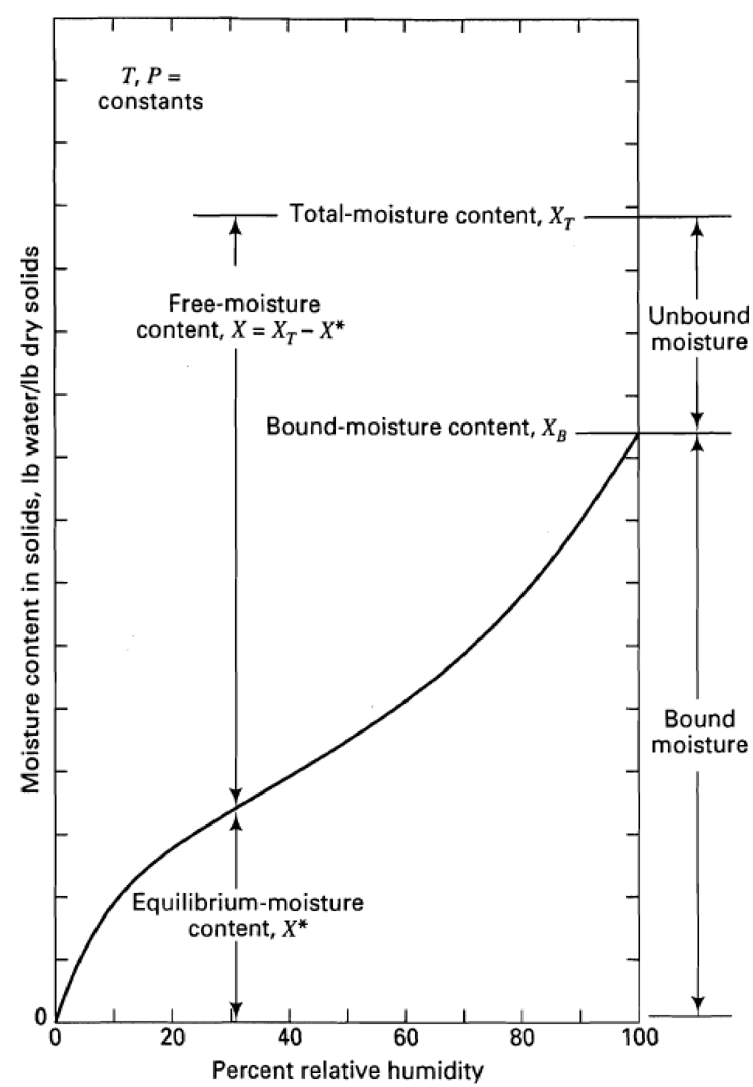
  - The vapor pressure of moisture over this moist solid becomes less than the vapor pressure of pure water at that temperature

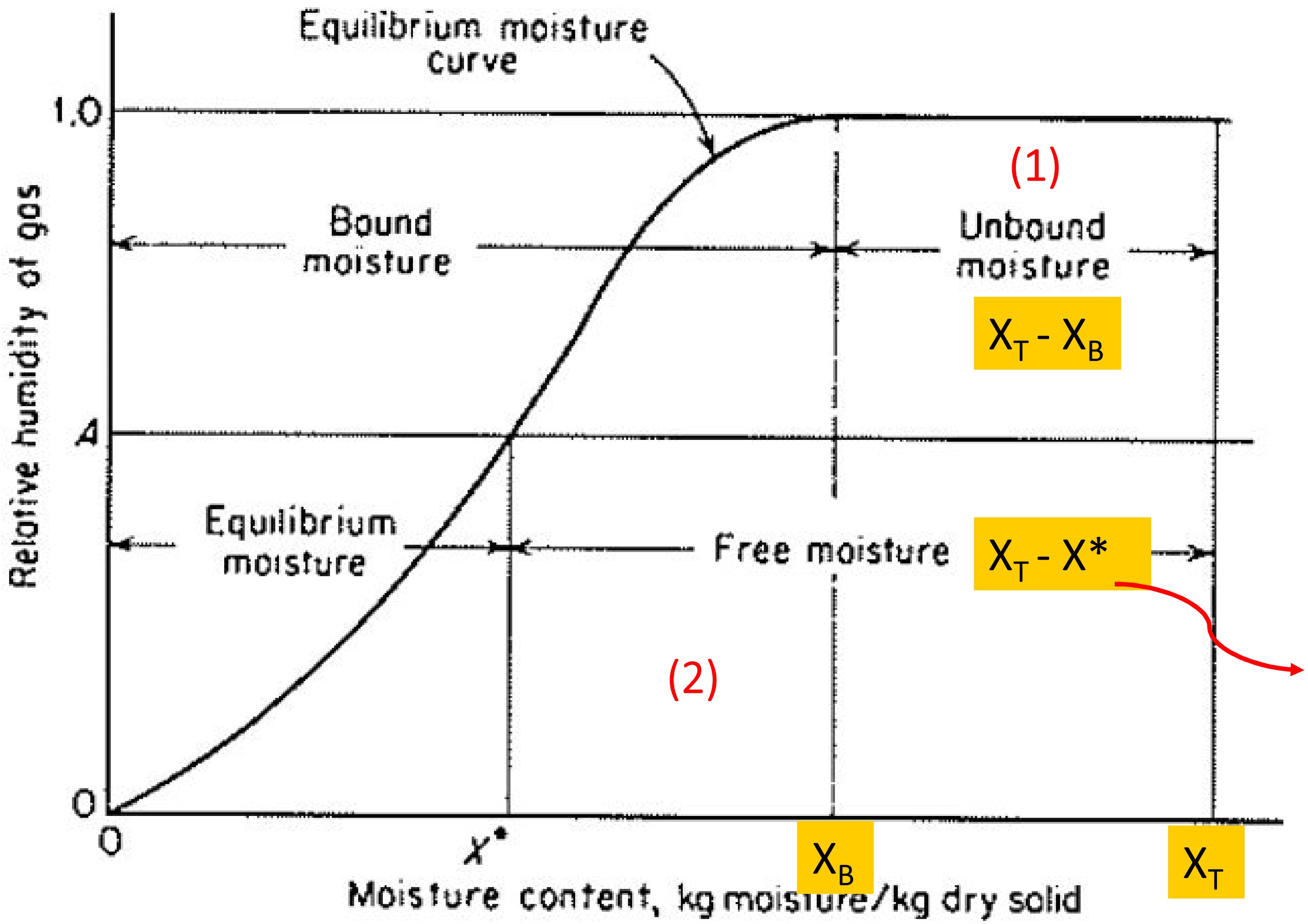
  - It is more difficult to remove than unbound water.



- ○ **Unbound moisture**
  - When the solid material contains more water than indicated by the intersection with the line HR=100%.
  - The moisture in the solid exerts a vapor pressure equivalent to that of the free liquid.
- ○ **Free moisture (X)**
  - The moisture above the equilibrium moisture content. This is the moisture that can be removed by drying under given percent relative humidity.

The nature of water in solid material





1. The moisture in a solid exerts a vapor pressure equivalent to that of the free liquid

2. the vapor pressure of moisture over a moist solid is less than the vapor pressure of pure water

- Only free moisture can be removed by drying under a given set of conditions (T, H) of gas.

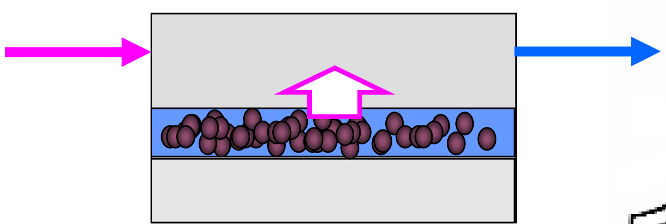
Characteristics of Drying Air

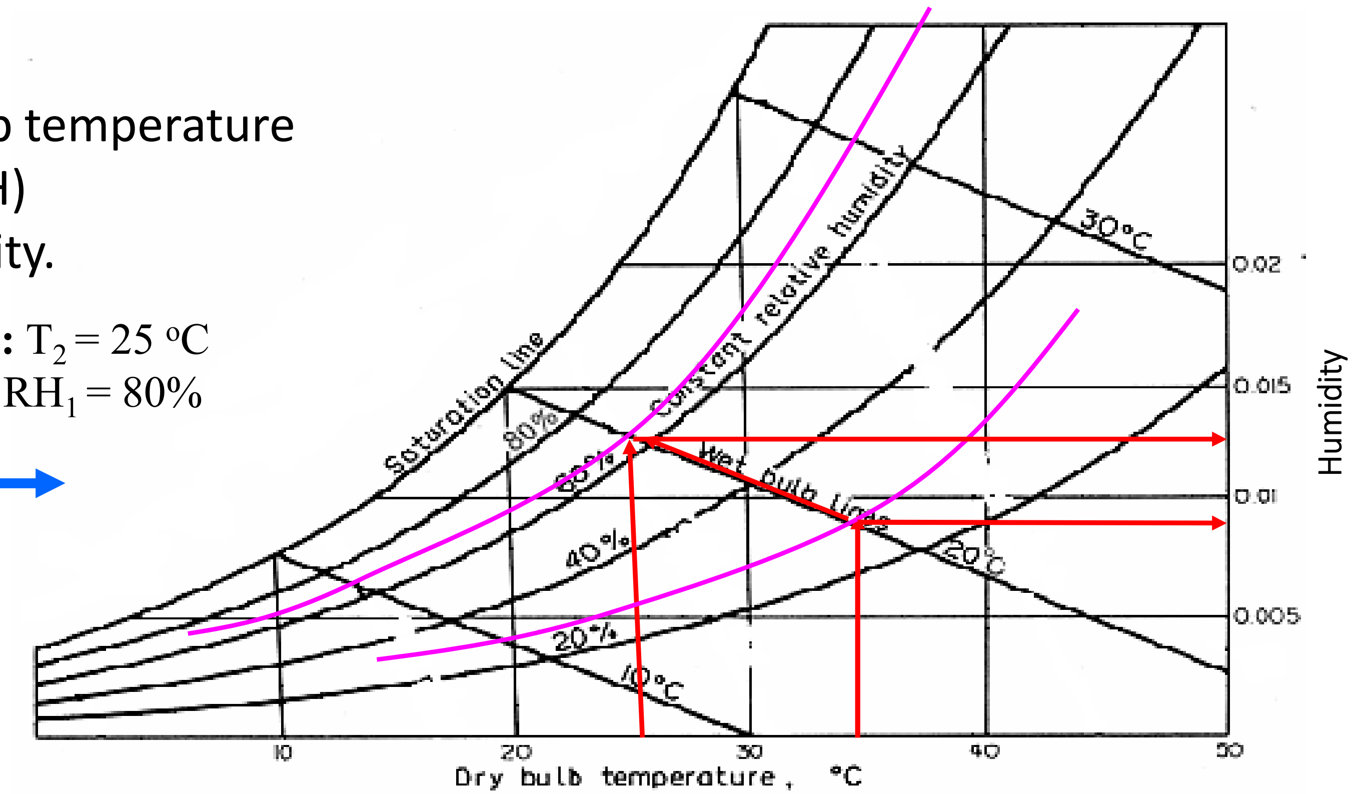
The air that is capable of carrying moist from solid for drying should have the following characteristics:

- A moderately high dry-bulb temperature
- A low relative humidity (RH)
- A high convective air velocity.

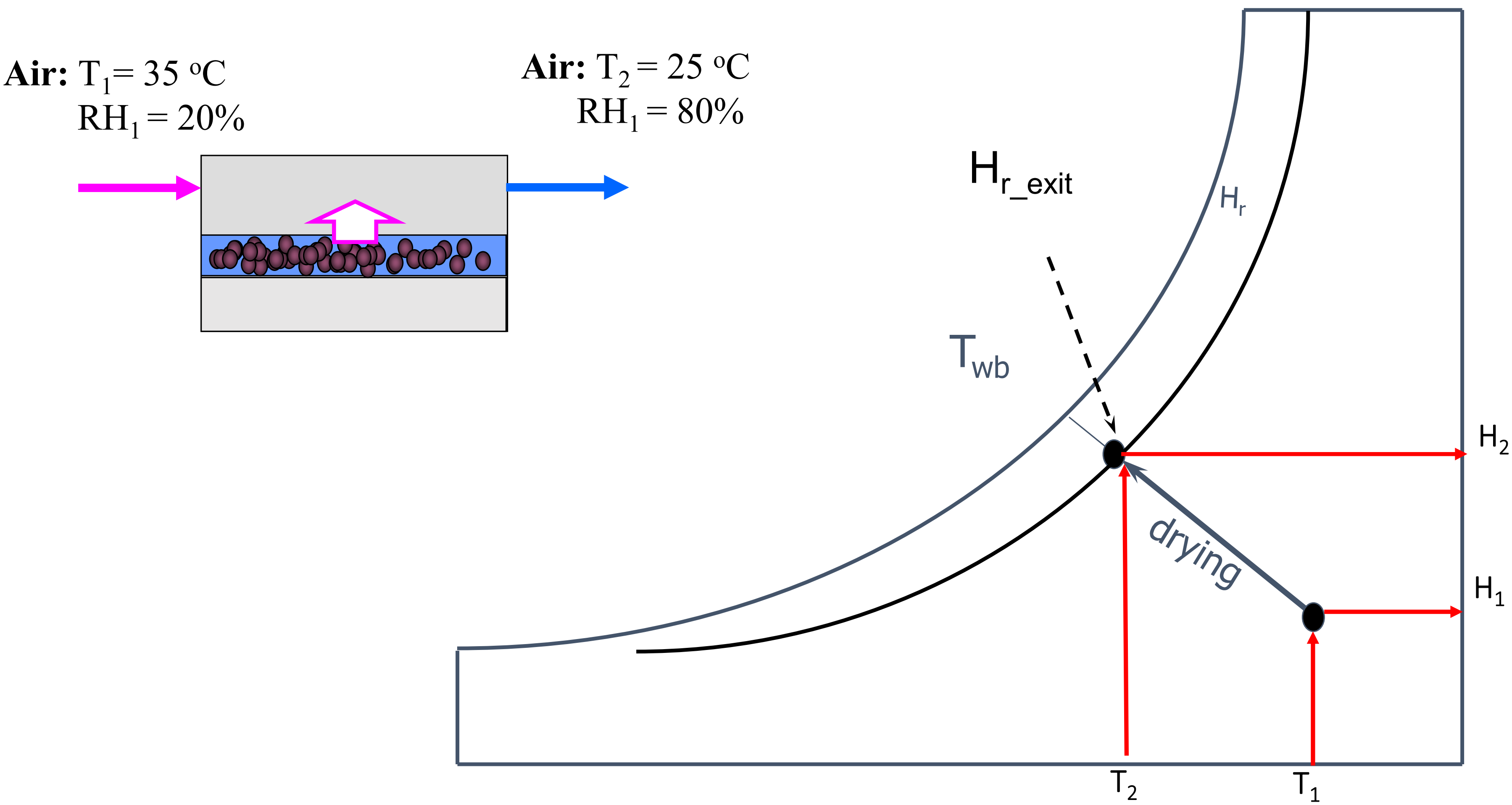
Air: $T_1 = 35\ ^oC$
$RH_1 = 20\%$

Air: $T_2 = 25\ ^oC$
$RH_1 = 80\%$

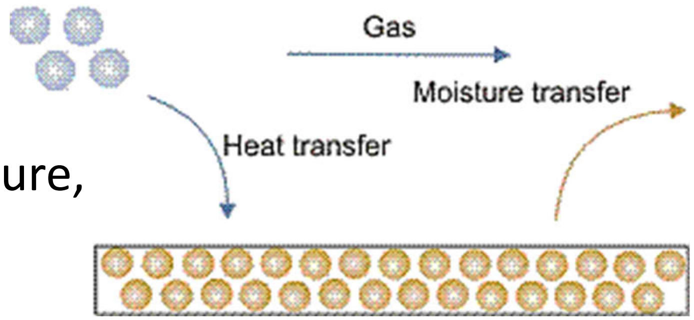




Assumption:
Evaporation surface is a liquid film
Constant wet-bulb temperature process


Air: T1= 35 oC
RH1 = 20%
Air: T2 = 25 oC
RH1 = 80%
Hr_exit
Hr
Twb
H2
H1
drying
T2
T1

Drying Fundamentals



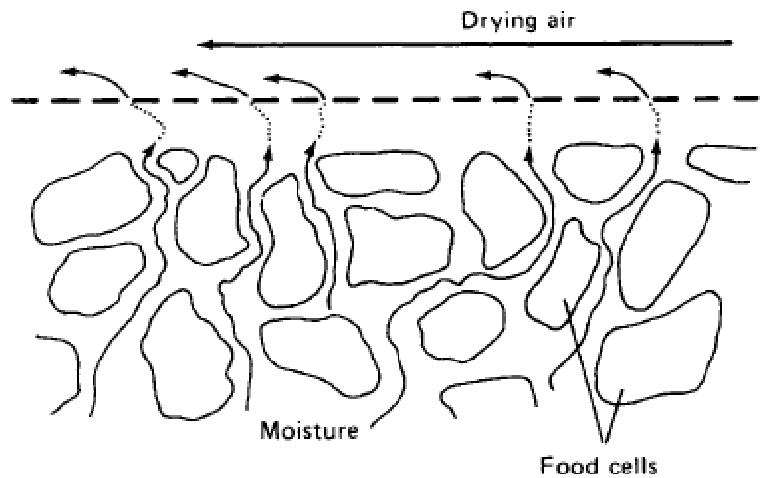
- The rate of drying is controlled by air temperature, humidity, & air velocity.
- Drying involves both heat and mass transfer.
- **Heat transfer:**

  When hot air is blown over a wet solid: Heat transfers to the surface of the material in order to provide the latent heat of evaporation for the moisture to evaporate.

- **Mass transfer:**
  - A water vapor pressure gradient is established from the moist interior of the wet surface to the dry air.
  - This gradient provides the "**driving force**" for water removal from the material
  - Diffusion of water through a boundary film of air surrounding the solid and is carried away by the moving air.

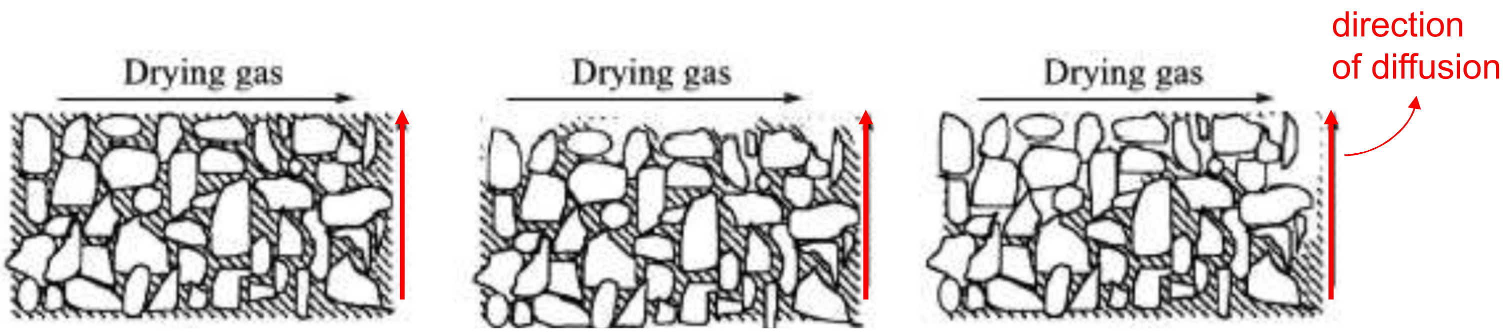
- The boundary film acts as a barrier to both **heat transfer** and **water vapor removal** (mass transfer) during drying.
- The **thickness** of the film is determined primarily by the **air velocity**; if the velocity is **low**, the boundary film is **thicker.**

Movement of moisture during drying.



- This reduces the **heat transfer coefficient** and consequently the **rate of removal** of water vapor.
- Water vapor leaves the surface of the solid and increases the humidity of the surrounding air, causing a reduction in the water vapor pressure gradient and hence the rate of drying.
- The faster the air, the thinner the boundary film, hence the faster the rate of drying.

Stages of drying of moist solid



a) The solid is uniformly wet

b) The upper region is partly dry

c) The upper region of the solid is dry

- The resistance to moisture diffusion increases from (a) to (b) to (c) and the drying rate decreases

Transport of moisture within the solid may occur by any one or more of the following mechanisms of mass transfer:

- **Liquid diffusion**, if the wet solid is at a temperature below the boiling point of the liquid
- **Vapor diffusion**, if the liquid vaporizes within the material
- **Knudsen diffusion**, if drying takes place at very low temperatures and pressures, e.g., in freeze drying
- **Surface diffusion** (possible although not proven)
- **Hydrostatic pressure differences**, when internal vaporization rates exceed the rate of vapor transport through the solid to the surroundings
- **Combinations of the above** mechanisms

Drying mechanisms

Mass transfer

- Bring liquid from interior of product to surface
- Vapourization of liquid at/near the surface
- Transport of vapour into the bulk gas phase

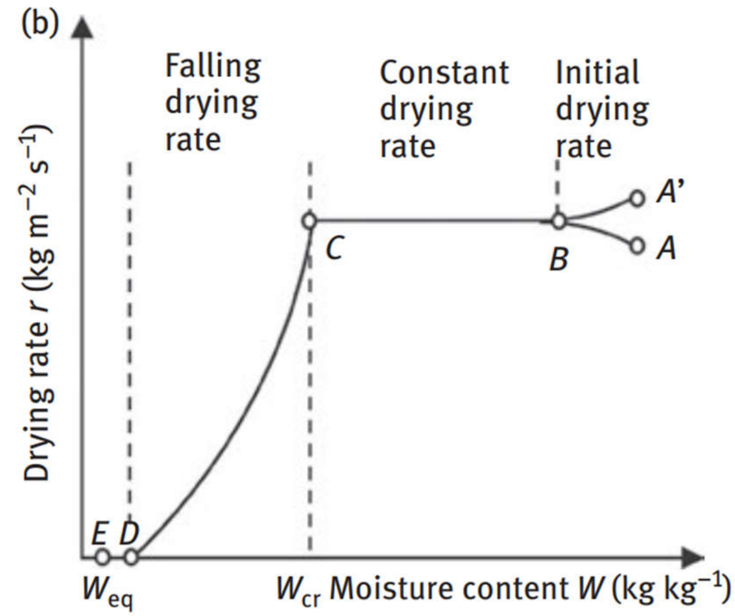
Heat transfer from bulk gas phase to solid phase:

- portion of it used to vapourize the liquid (latent heat)
- portion remains in the solid as (sensible heat)

- Key point: heat to vapourize the liquid is adiabatically provided by the air stream. Air is cooled as a result of this evaporation
- The ΔH_{vap} is a function of the temperature at which it occurs:
  - 2501 kJ/kg at 0°C
  - 2260 kJ/kg at 100°C
  - Linearly interpolate over this range (small error though)

Three regions can be observed:

1. ***Initial drying period* AB**
   - The liquid in the solid has a lower temperature and it needs some time to get its stationary drying state
   - The mass transfer rate adjusts to the heat transfer rate and the wet surface reaches the wet bulb temperature T_{wb}



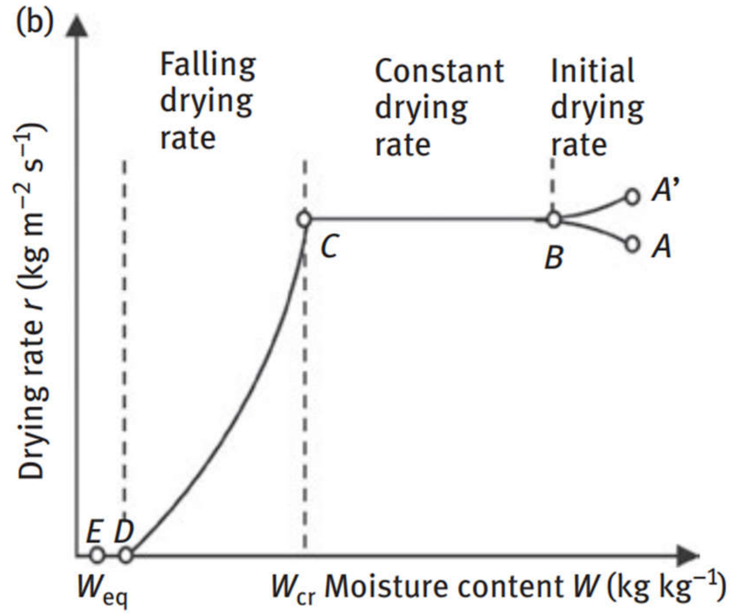
2. ***Constant drying period* BC**

The surface of the solid is initially very wet and a continuous film of water exists on the drying surface.

This water is entirely unbound and acts as if the solid were not present. The evaporation rate is controlled by the heat transfer rate to the wet surface

3. *Falling drying period* ***CD***

Three regions can be observed:



- Occurs when the moisture content is reduced below a critical value, W_{cr}
- The surface of the solid dries out and a further decrease of the free moisture content starts taking place in the interior of the porous solid
- In this period, the velocity of the carrier gas is less important because the transport of the moisture from within the solid to the outer surface
- The drying rate is controlled by the internal material moisture transport and decreases with decreasing moisture content

Classification of drying operations

- **Batch drying:**

  The material is inserted into the drying equipment and drying proceeds for a given period of time

  - It is best suited for small lots and for use in single-product

- **Continuous drying:**

  The material is continuously added to the dryer and the dried material is continuously removed.

  - Optimum operation of most continuous dryers is at design rate and steady state
  - Continuous dryers are unsuitable for short operating runs in multiproduct plants

Classification of drying operations

Drying processes can also be classified to the physical conditions used to add heat and remove water vapor

- **Convection drying:**

  The heat of hot gas is supplied to the material surface by convection

  (**Batch dryer, Belt dryer, Rotary dryer, Flash dryer, Fluidized bed dryer, Spray dryer**)

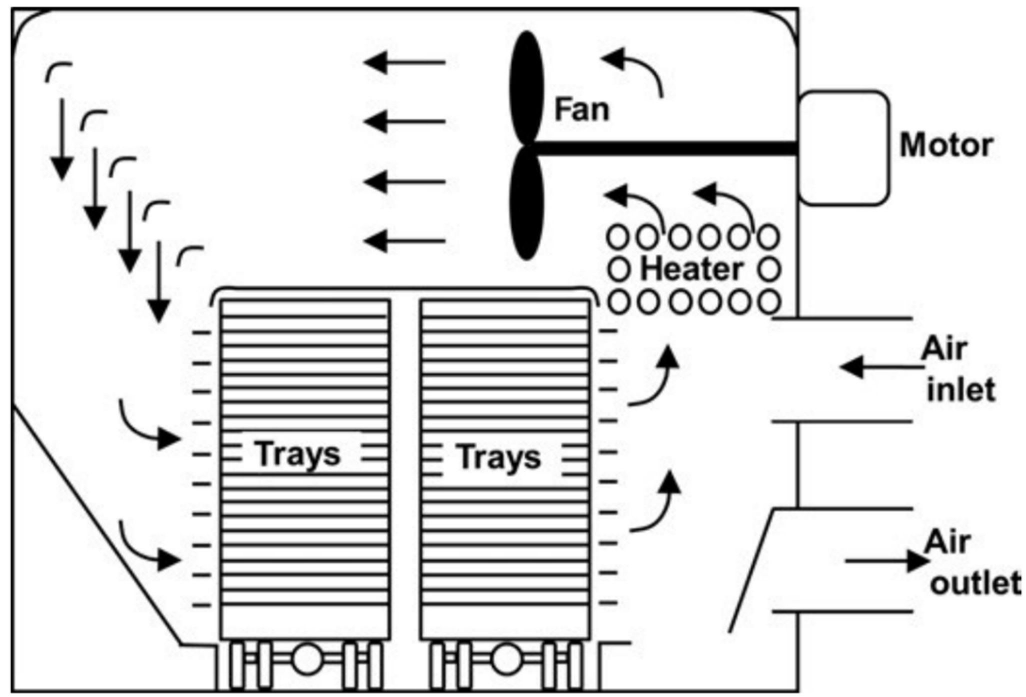
- **Contact drying:**

  The heat is supplied to the wet material by conduction from the heated surface as bands, plates, cylinders, or the dryer wall

  (**Rotary and agitator dryers, Vacuum dryers, Fluid bed dryers**)

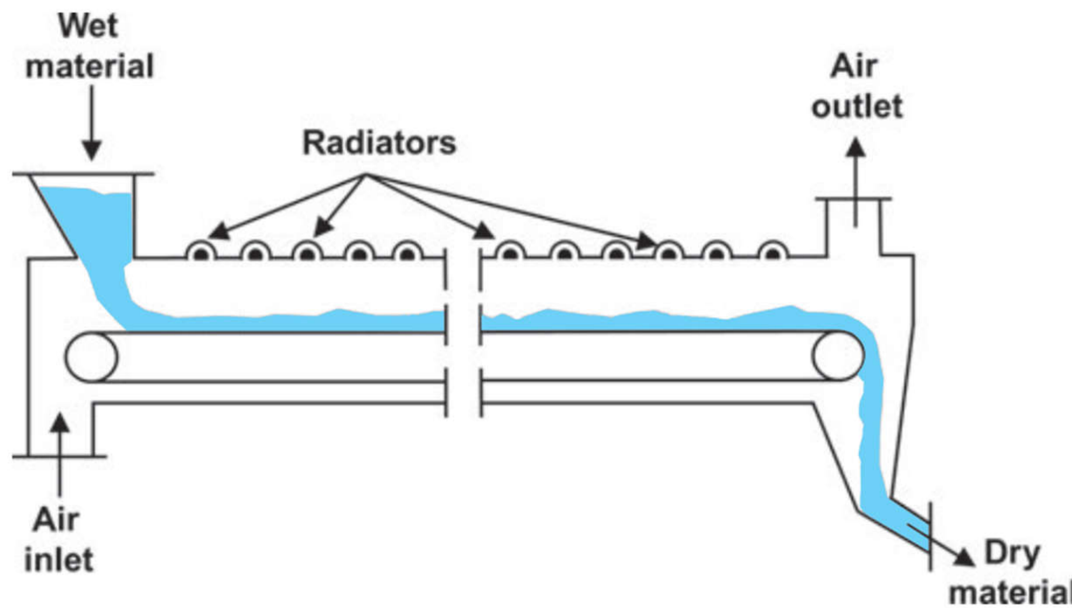
Convective dryers: **Batch dryers**

- Large objects are placed on shelves or stacked in piles
- Unless the material is dusty, gas is recirculated through an internal heater
- These dryers are economical only for single-product rates of less than 500 tons/year.



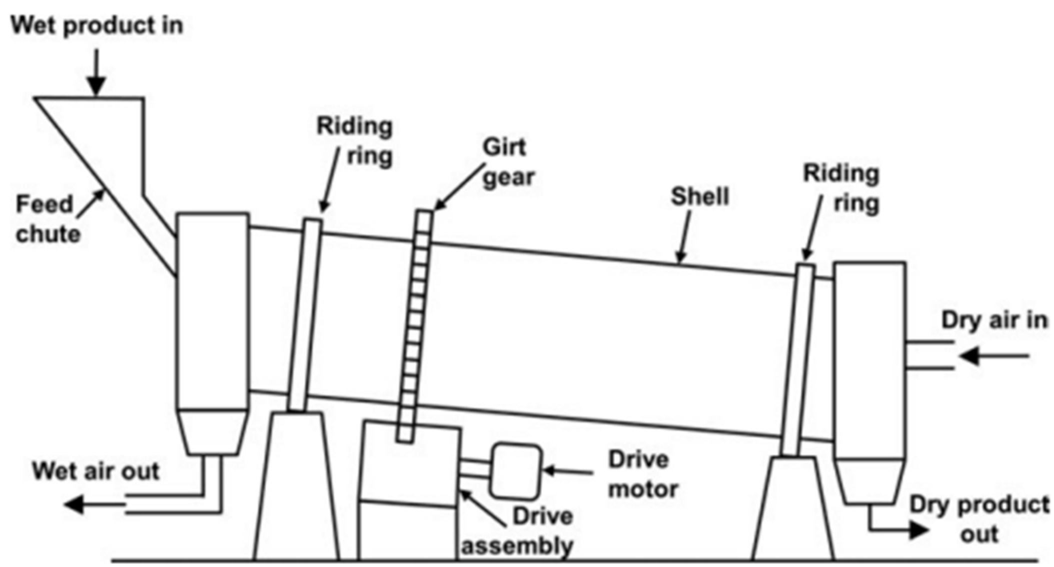
Convective dryers: **Belt dryers**

- A moist solid is placed on the belt through the opening of the dryer. At the end of this chamber, the material falls from the belt into a chute for further processing.
- It can be co-current or counter-current.
- Centrifugal or axial flow blowers are used to aerate the moist materials



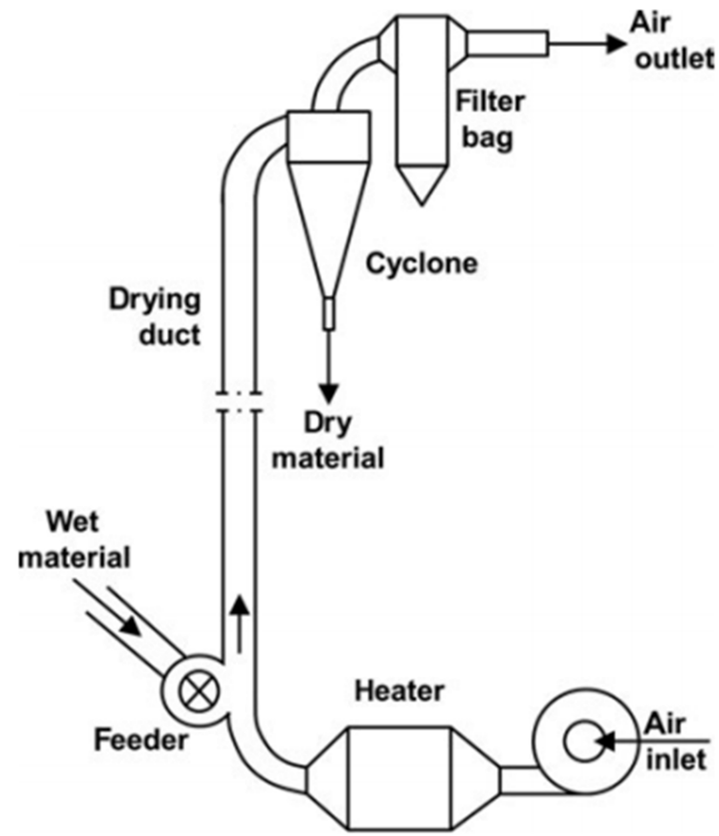
Convective dryers: **Rotary dryers**

- Shell diameters are 0.5–6 m.
- The length of the batch rotary dryer will be similar to the diameter or double the diameter.
- Continuous dryers are at least 4-10 times the diameter long
- Material filling in a continuous dryer is 10–18% of cylinder volume



Contact dryers: **Flash dryers**

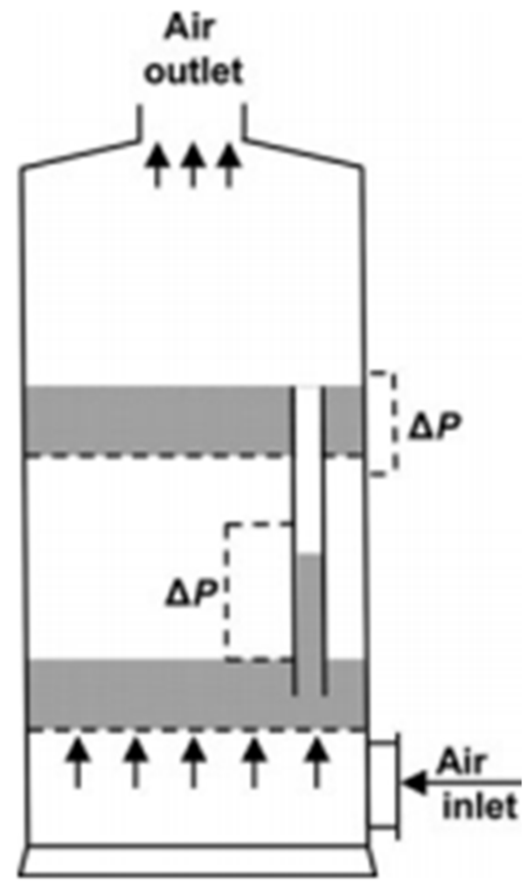
- A vertical tube in which granular or pulverized materials are dried while suspended in a gas or air stream
- The available drying time is only a few seconds
- Only fine materials with high rates of heat and mass transfer or coarser products with only surface moisture to be removed are used in such dryers



- Flash dryers are well suited for drying thermally sensitive materials and are widely used for drying organic and inorganic salts, plastic powders, granules, foodstuffs

Convective dryers: **Fluidized bed dryers**

- Fluidized bed dryers have a high drying efficiency
- The solid moves horizontally in a chute and the drying agent flows vertically through a perforated floor to fluidize the solid
- These machines can operate continuously because the solid is transported while suspended in the drying agent

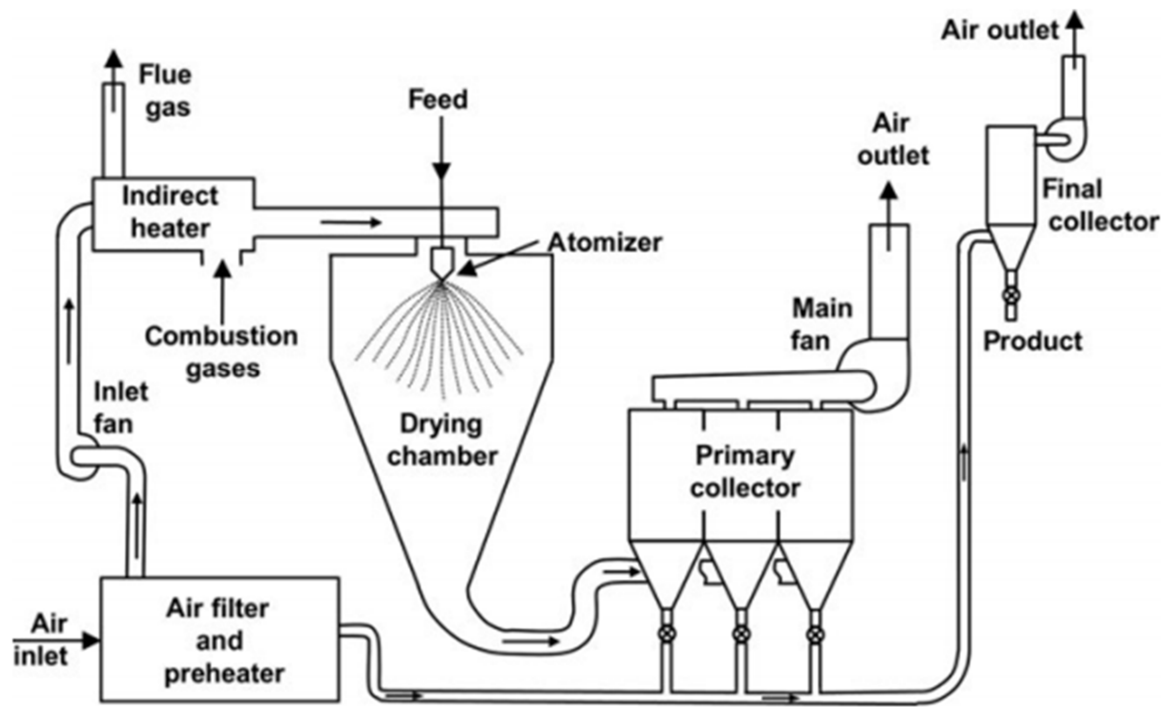


Convective dryers

Spray dryers

- Spray drying is used for the drying of pastes, suspensions or solutions

- The moist material is sprayed into the drying agent and converted into a powder that is entrained by the gas stream



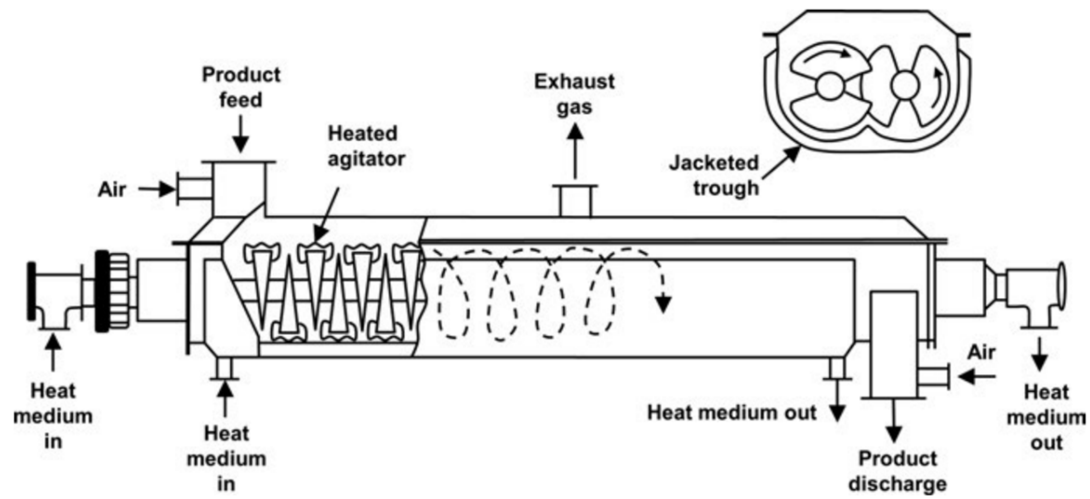
- The largest spray-dried particle is about 1 mm, the smallest about 5 µm.

- Nozzle chambers are tall towers, usually having height/diameter ratios of 4–5

Contact dryers

Rotary and agitator dryers

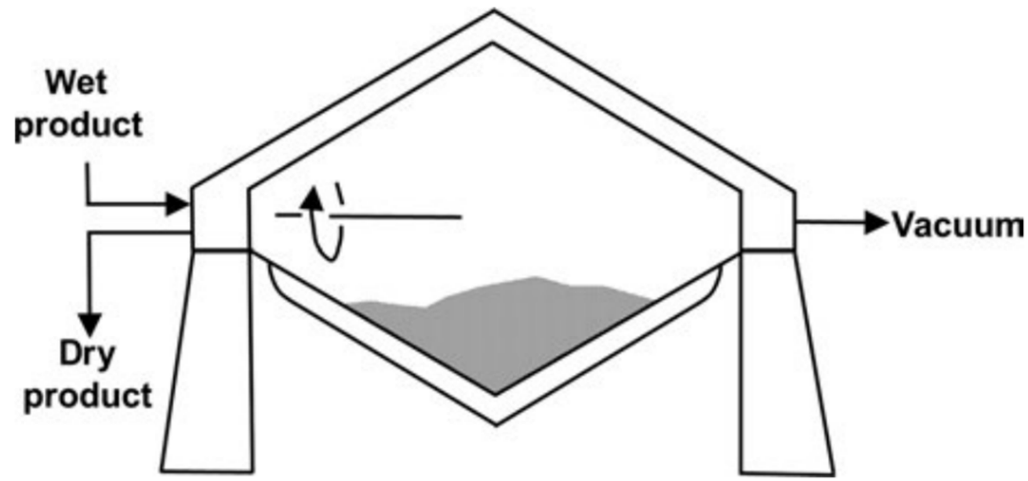
- the heat is transferred by conduction
- The heat necessary for drying is transferred through the peripheral walls of these dryers in contact drying



- Only a small amount of air is necessary to carry the moisture that is taken from the solid. Low air velocity minimize generation dust during drying

Contact dryers

Vacuum dryers

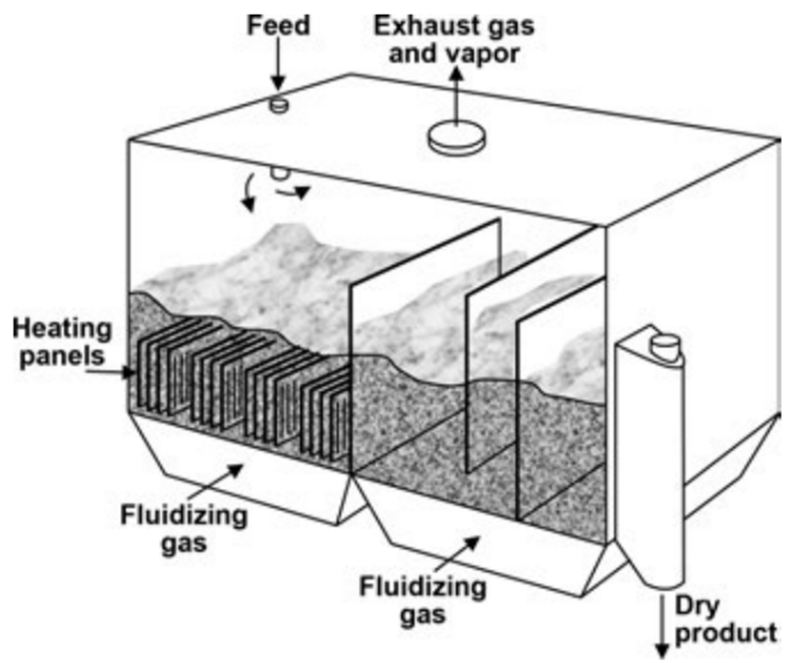


- the heat is transferred by conduction
- Drying under reduced pressure is advantageous for materials that are temperature sensitive
- They are most often used to dry pharmaceutical products and foodstuffs

Contact dryers

Fluid bed dryers

- the heat is transferred by conduction
- Indirect-heat fluid bed dryers are usually rectangular vessels in which vertical pipe or plate coils are installed



- Indirect-heat fluid bed is an ideal vessel for vapor recovery and drying in special atmospheres

Thermodynamic and transport properties of the air-water system

Property	Expression
P_v	$P_v = 100\exp[27.0214 - (6887 / T_{abs}) - 5.32\ln(T_{abs} / 273.16)]$
Y	$Y = 0.622 RH\, P_v / (P - RH\, P_v)$
c_{pg}	$c_{pg} = 1.00926\times10^3 - 4.0403\times10^{-2}T + 6.1759\times10^{-4}T^2 - 4.097\times10^{-7}T^3$
k_g	$k_g = 2.425\times10^{-2} - 7.889\times10^{-5}T - 1.790\times10^{-8}T^2 - 8.570\times10^{-12}T^3$
ρ_g	$\rho_g = PM_g / (RT_{abs})$
μ_g	$\mu_g = 1.691\times10^{-5} + 4.984\times10^{-8}T - 3.187\times10^{-11}T^2 + 1.319\times10^{-14}T^3$
c_{pv}	$c_{pv} = 1.883 - 1.6737\times10^{-4}T + 8.4386\times10^{-7}T^2 - 2.6966\times10^{-10}T^3$
c_{pw}	$c_{pw} = 2.8223 + 1.1828\times10^{-2}T - 3.5043\times10^{-5}T^2 + 3.601\times10^{-8}T^3$

P_v vapor pressure of pure water, Pa

Y absolute air humidity, kg water vapor/kg dry air

c_p specific heat, J kg^{-1} K^{-1}

k_g thermal conductivity, W m^{-1} K^{-1}

T_{abs} absolute temperature, K

g gas

v vapor

w water

ρ_g density, kg m^{-3}

μ_g dynamic viscosity, kg m^{-1} s^{-1}