Chapter No. 02

Drying

Lecture 1: Generalities on Drying

Duration: 1 h 15 min
Level: Master 1 – Chemical Engineering

Lecture Objectives –

At the end of this lecture, students should be able to:

- Define drying as a unit operation.
- Classify wet solids and types of moisture.
- Express and convert moisture content (wet and dry basis).
- Interpret equilibrium moisture content.
- Understand sorption isotherms.
- Identify key industrial applications.

1. Introduction

Def–Drying is a unit operation that consists of removing a liquid—most commonly water (moisture)—from a wet solid by vaporization, in order to obtain a relatively liquid-free solid product.

It is important to emphasize that drying does not necessarily imply complete removal of moisture.
In many industrial situations, residual moisture content is intentionally maintained to:

- Preserve mechanical properties,
- Avoid structural damage (cracking, shrinkage),
- Maintain product functionality,
- Ensure storage stability.

Therefore, drying is **a controlled moisture reduction process**, not an absolute dehydration process.

1.1. Position of Drying Among Separation Processes

Before drying, water is often partially removed using **mechanical separation techniques**, such as:

- Filtration,
- Settling (sedimentation),
- Centrifugation.

These operations are **based on mechanical forces** and allow removal of *unbound* or *free liquid*.
However, mechanical processes cannot remove:

- Capillary-held moisture
- Adsorbed moisture

- Bound moisture

Consequently, drying is usually **required as a final step** to remove the remaining liquid that cannot be eliminated mechanically.

1.2. Physical Principles Governing Drying

Drying is fundamentally governed by **heat and mass transfer principles**.It is a **coupled transport process** involving:

- Heat transfer to supply the latent heat of vaporization;
- Mass transfer to remove the generated vapor.

The process can be summarized as follows:

1. A wet solid is heated to an appropriate temperature;
2. Moisture vaporizes at or near the solid surface;
3. The required heat is generally supplied by a hot gas (commonly air);
4. As surface moisture evaporates, internal moisture migrates toward the surface.

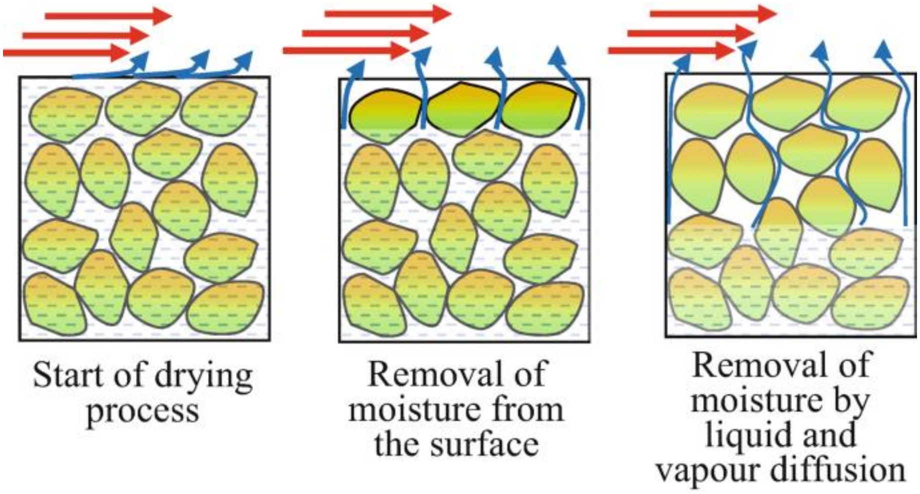


Figure 1 –Drying process.

Thus, drying simultaneously involves:

- External heat transfer (gas → solid surface);
- Internal heat conduction within the solid;
- Internal moisture diffusion;
- External mass transfer (vapor → bulk gas stream).

Mechanistic Description of the Process –

When a wet solid is exposed to a hot gas:

- Heat is transferred **from the gas to the solid surface**.
- The **surface temperature rises**.

- When sufficient energy is supplied, **liquid moisture vaporizes**.

As moisture leaves the surface:

- A **moisture concentration gradient** develops inside the solid.
- This gradient drives **internal moisture transport** toward the surface.

The internal transport mechanisms may include: liquid diffusion, vapor diffusion, and capillary flow.

Drying therefore continues as long as:

- Heat is supplied, and
- Moisture remains available inside the solid.

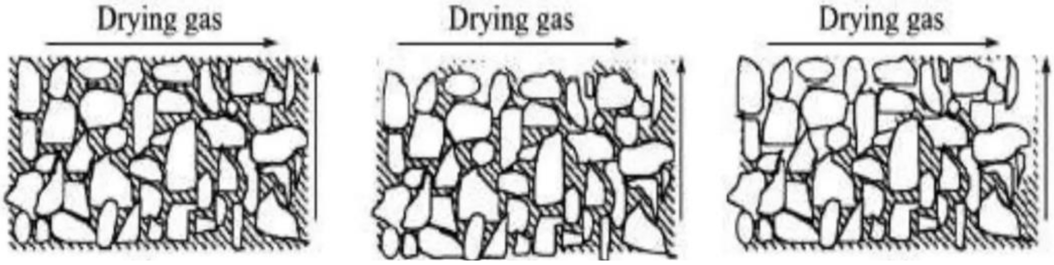


Figure 2 –Stages if drying of moisture solid.

Vertical arrows indicate the direction of diffusion.

2. Nature of Wet Solids

The behavior during drying depends on the **structure** of the solid.

- **Porous and non-porous solids:**

Porous materials have small openings or **pores** that allow water and air to pass through (**Moisture inside capillaries**), e.g. metal plates. Non-porous materials, on the other hand, have tightly compacted surfaces that prevent water penetration (**Moisture located at the surface**), e.g. ceramics.

Figure 1 – Porous and non-porous solids.

According to IUPAC definitions three groups of pores are distinguished:

- Macro pores (above 50 nm diameter).
- Mesopores (2-50 nm diameters).
- Micro pores (under 2 nm diameter).

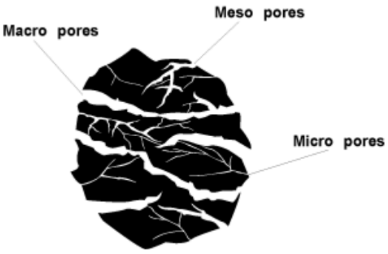


Figure 2 – Pores in porous solids.

- **Hygroscopic solids:**

Hygroscopic means capable of attracting and holding water from environment (**hydrophilic**, "**water-loving**"), either through absorption or adsorption. Typically, this process occurs near ambient or room temperature.

Many salts, fibers, and porous materials are hygroscopic. Examples of hygroscopic substances include: table salt (sodium chloride), brown sugar, paper, cotton, etc.

2. Types of Moisture

3.1. Moisture content of wet solids: is defined as kilograms of moisture associate with one kilogram of wet solid. Total moisture content is the total amount of moisture associated with a wet solid.

Moisture content is designated by two methods,

- Wet basis (wb), and
- Dry basis (db).

Wet basis (wb): the moisture content in this method is represented by the following expression:

$$\boldsymbol{moisture\ content}\ (\%) = \frac{\boldsymbol{weight\ of\ water\ in\ product}}{\boldsymbol{weight\ of\ product\ sample}} \times \mathbf{100}$$

Dry basis (db): the moisture content in this method is represented by the following expression:

$$\boldsymbol{moisture\ content}\ (\%) = \frac{\boldsymbol{weight\ of\ water\ in\ product}}{\boldsymbol{weight\ of\ dry\ matter\ product\ sample}} \times \mathbf{100}$$

The value of dry basis moisture content is more than the wet basis moisture content.

The relation between dry-basis (M) and wet-basis (m) moisture content is given by the following expression:

$$\boldsymbol{moisture\ content, dry - basis}(\%) = \frac{\boldsymbol{Moisture\ content, wet - basis, in\ decimal}}{\mathbf{1} - \boldsymbol{Moisture\ content, wet - basis, in\ decimal}} \times \mathbf{100}$$

$$\boldsymbol{m_{db}}(\%) = \frac{\boldsymbol{W_m}}{\boldsymbol{W_d}} \times \mathbf{100} = \frac{\boldsymbol{m_{wb}}}{\mathbf{100} - \boldsymbol{m_{wb}}} \times \mathbf{100}$$

On wet-basis:

$$\boldsymbol{m_{wb}}(\%) = \frac{\boldsymbol{W_m}}{\boldsymbol{W_m} + \boldsymbol{W_d}} \times \mathbf{100}$$

Where:

W_m: weight of moisture;

W_d: weight of bone dry material.

Example 1 –

Two tons of paddy with 22% moisture content on wet basis is to be dried to 13% moisture content on (db). Calculate the weight of bone dry products and water evaporated.

Response 1 –

1. **Calculate the Weight of Bone Dry Products (W_d):**

The weight of the bone dry product (solid matter) remains constant during the drying process. In wet basis moisture content:

$$W_{total} = W_{water} + W_{dry\ matter}$$

The formula for the dry matter is:

$$W_{dry\ matter} = W_{total} - W_{water}$$
$$W_{dry\ matter} = 2000 - (2000 \times 0.22)$$
$$W_{dry\ matter} = 1560\ kg$$

2. **Calculate the Weight of Water Evaporated:**

To find the water evaporated, we first determine the weight of water initially present and the weight of water remaining after drying.

- **Initial Weight of Water ($W_{w,i}$):**

$$W_{w,i} = W_i + W_d$$
$$W_{w,i} = 2000 + 1560$$
$$W_{w,i} = 440\ kg$$

- **Final Weight of Water ($W_{w,f}$):**

The final moisture content is given on a **dry basis** (MC_{db}), where:

$$MC_{db} = \frac{W_w}{W_d}$$
$$W_{w,f} = MC_{db} \times W_d$$
$$W_{w,f} = 0.13 \times 1560$$
$$W_{w,f} = 202.8\ \text{kg}$$

- **Weight of Water Evaporated (W_{evap}):**

$$W_{evap} = W_{w,i} - W_{w,f}$$
$$W_{evap} = 440 - 202.8$$
$$W_{evap} = 237.2\ kg$$

Example 2 –

Determine the quantity of parboiled paddy with 40% moisture content on a wet basis required to produce 1 ton of product with 12% moisture content on a wet basis. Work out the problem on wet basis and check the answer using dry basis.

Response 2 –

1. Calculation on Wet Basis:

From mass balance:

$$(\boldsymbol{Dry\ mater})_{\boldsymbol{initial\ state}} = (\boldsymbol{Dry\ mater})_{\boldsymbol{final\ state}}$$

$$W_1 \times (1 - MC_i) = W_2 \times \left(1 - MC_f\right)$$

$$W_1 \times (1 - 0{,}4) = 1000 \times (1 - 0{,}12)$$

$$\boldsymbol{W_1 = 1466{,}67\ kg}$$

2. Check using Dry Basis:

Step A: Determine the mass of dry matter (M_{dm})

$$M_{dm} = W_2 \times \left(1 - MC_f\right)$$

$$M_{dm} = 1000 \times (1 - 0{,}12)$$

$$\boldsymbol{M_{dm} = 880\ kg}$$

Step B: Convert initial moisture content to Dry Basis (m_{db})

$$m_{db}(\%) = \frac{m_{wb}}{100 - m_{wb}} \times 100$$

$$m_{db}(\%) = \frac{40}{100 - 40} \times 100$$

$$\boldsymbol{m_{db}}(\%) = \boldsymbol{66{,}67}\%$$

Step C: Calculate initial total mass (W_1) using Dry Basis

$$\boldsymbol{mass_{total} = Dry\ matter + Moisture\ content}$$

$$W_1 = M_{dm} + M_{dm} \times m_{db}(\%)$$

$$W_1 = 880 + 880 \times 66{,}67\%$$

$$\boldsymbol{W_1 \approx 1466{,}67\ kg}$$

Example 3 –

500 kg of paddy at 22% moisture content (wb) is dried to 14% moisture content (wb) for milling. Calculate the amount of moisture removed in drying.

3.2. Free Moisture: refers to water present on the surface or in the pores of a solid material that flows easily by gravity.

3.3. **Bound Moisture:** is water retained in small spaces like capillaries or absorbed on surfaces where it exerts less vapor pressure.

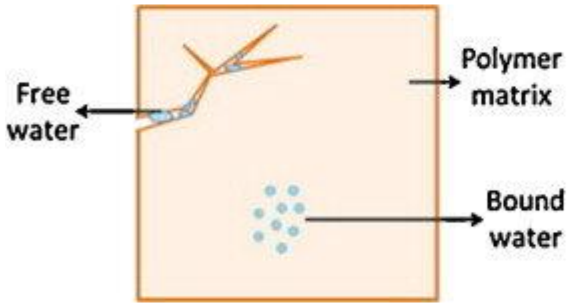


Figure 3 – Free water and bound water in polymer matrix.

3.4. **Unbound Moisture:** amount of moisture in a wet solid in excess of the bound moisture.
It exerts a vapor pressure equal to water vapor pressure at that temperature.

3.5. Equilibrium Moisture Content (EMC):

Equilibrium Moisture Content (EMC) is the moisture level at which a hygroscopic material (like wood, grain, or paper) neither gains nor loses moisture since it is at equilibrium with the relative humidity and temperature of the surrounding environment.

Lecture 2: Modes of Drying

Duration: 1 h 10 min
Level: Master 1 – Chemical Engineering

Lecture Objectives –

At the end of this lecture, students should be able to:

- Identify the main operating modes of drying ;
- Distinguish between batch and continuous drying ;
- Understand co-current and counter-current flow configurations ;
- Differentiate direct and indirect drying methods ;
- Recognize the main industrial drying techniques ;
- Select an appropriate drying mode based on process constraints.

1. Introduction to Drying Modes

Drying can be classified according to several criteria:

a) Operation mode:

- Batch (discontinuous) ;
- Continuous

b) Relative movement of gas and solid:

- Co-current ;
- Counter-current

c) Heat transfer mechanism:

- Convection ;
- Conduction ;
- Radiation ;
- Dielectric heating.

Each drying mode influences:

→ Energy consumption ;
→ Product quality ;
→ Process efficiency ;
→ Equipment design.

1. Operating Modes: Batch vs. Continuous:

- **Batch (Discontinuous) Drying:**

In **batch drying**, a fixed quantity of wet solid is loaded into the dryer, dried for a given period, and then discharged. It is simple and flexible, but has lower productivity and is mainly used for small-scale or sensitive products.

- **Continuous Drying:**

In **continuous drying**, wet material is continuously fed into the dryer while dried product is simultaneously removed. This mode allows steady-state operation, higher production capacity, and better energy efficiency, making it suitable for large-scale industrial processes.

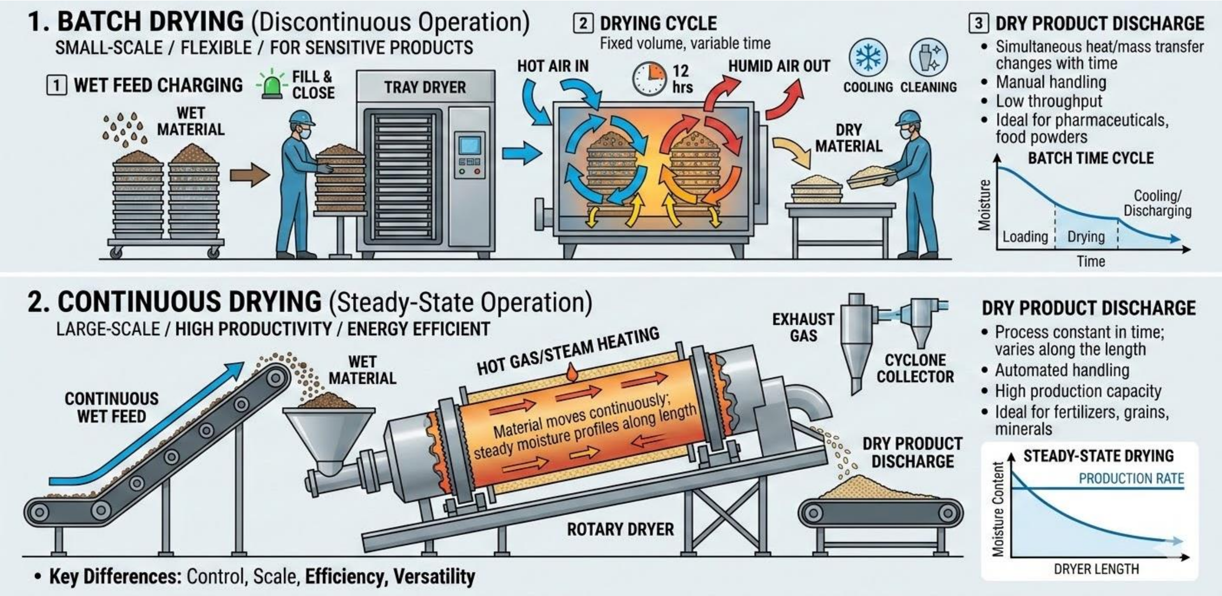


Figure 2.1 – Operating modes of drying: batch vs. continuous.

3. Gas–Solid Flow Configurations:

In convective dryers, the relative movement between the drying gas and the solid strongly influences heat and mass transfer efficiency. The main configurations are **co-current flow**, where gas and solid move in the same direction (suitable for heat-sensitive materials), and **counter-current flow**, where they move in opposite directions (providing higher thermal efficiency). A third configuration is **cross-flow**, where the gas flows perpendicular to the solid movement. The choice of configuration affects drying rate, energy consumption, and final product temperature.

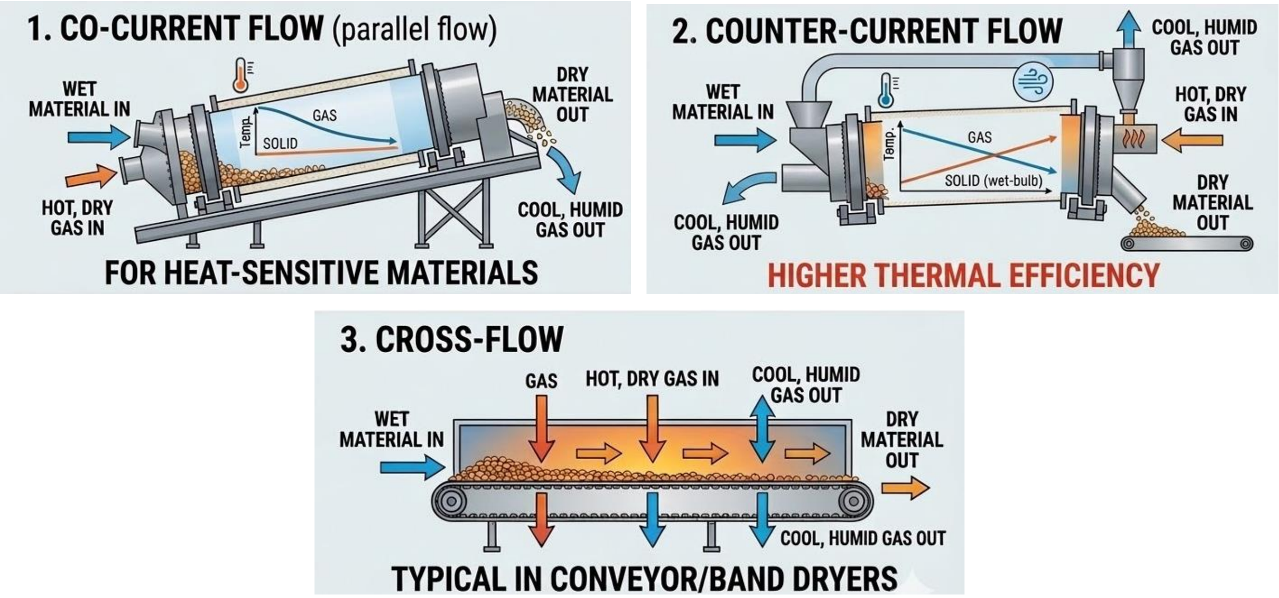


Figure 2.2 – Gas–Solid flow configurations.

4. Direct vs. Indirect Drying:

Another important classification depends on **how heat is transferred to the material**.

In **direct drying (convective drying)**, the wet solid is in direct contact with a hot gas (usually air), which supplies the heat required for moisture evaporation. This is the most common industrial drying method due to its high heat transfer rate and simplicity. In **indirect drying (conductive drying)**, heat is transferred to the material through a heated surface without direct contact with the drying gas. This method is preferred for sensitive, toxic, or easily oxidized materials where contamination must be avoided.

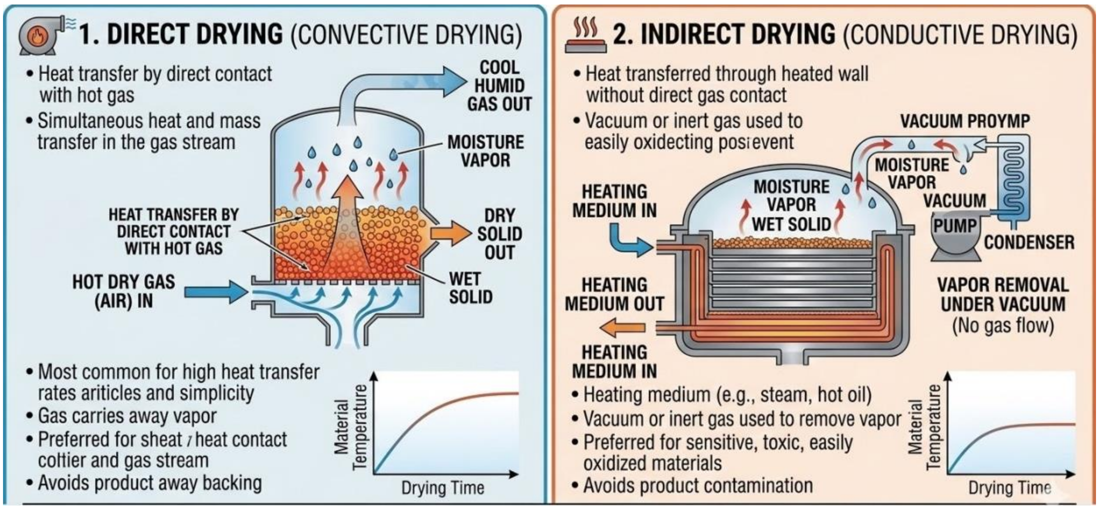


Figure 2.3 – Direct vs. indirect drying.

5. Other Drying Techniques:

In addition to conventional drying methods, several specialized techniques are used for specific applications. **Radiation drying** uses infrared energy to heat the material surface. **Microwave drying** generates internal heating by electromagnetic waves, resulting in rapid moisture removal. **Freeze drying (lyophilization)** removes water by sublimation under vacuum and low temperature, preserving the structure and quality of sensitive products such as pharmaceuticals and biological materials. These methods are generally used for high-value or heat-sensitive products.

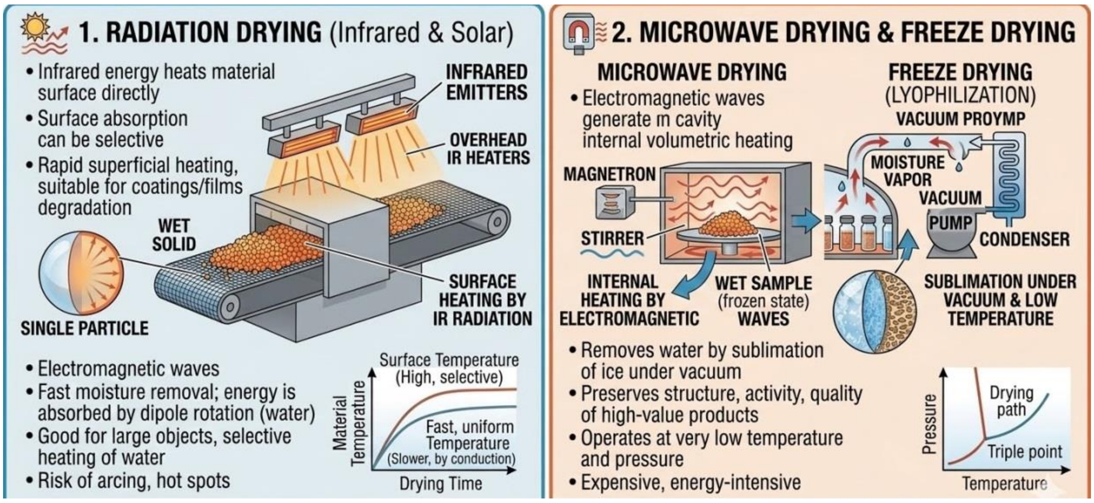


Figure 2.3 – Radiation, microwave and freeze drying.

2. Industrial Applications and Major Types of Dryers:

2.1. Spray Dryer: (convert liquid feed into dry powder)

In a spray dryer, a liquid solution or suspension is first **pumped to an atomizer**, which breaks the liquid into **very fine droplets**, forming a spray. These droplets are then introduced into **a chamber containing a stream of hot drying gas (usually air)**. Because of their small size and large surface area, the moisture in the droplets **evaporates rapidly**, producing dry solid particles. Finally, the **dried particles are separated from the air**, typically using a cyclone or similar device, and **collected in a container**.

Operation: Continuous
Heat transfer: Direct convective drying
Flow configuration: Co-current
Used for: milk powder production, detergents, and chemicals

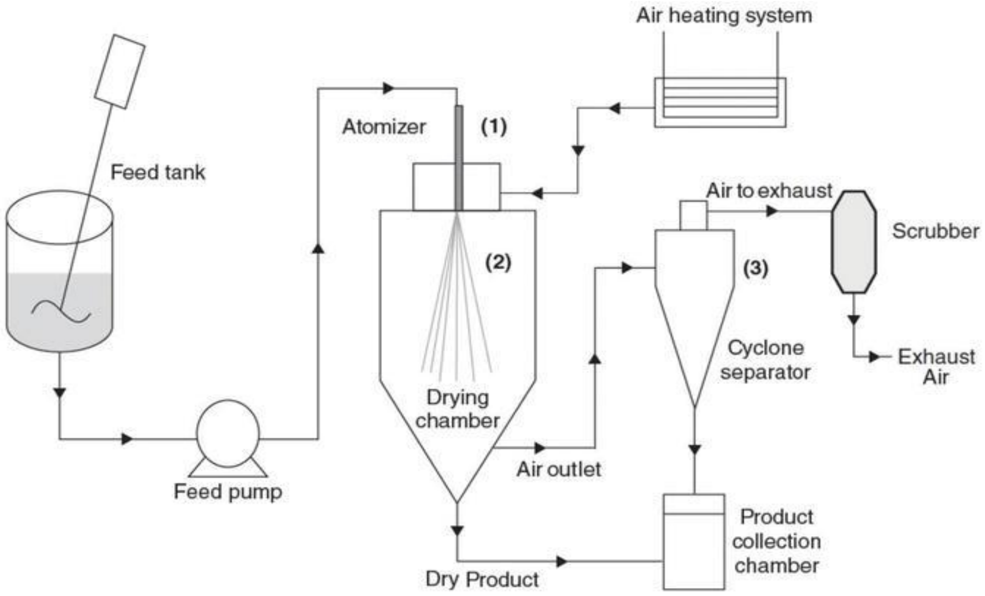


Figure 2.4 – Spray dryer.

2.2. Rotary Dryer:

In a rotary dryer, wet solid material is **fed into a slightly inclined rotating cylindrical drum**. As the drum rotates, the material moves gradually along its length while being **lifted and cascaded by internal flights**, increasing contact with the **hot drying gas**. Moisture evaporates during this contact, and **the dried solid is discharged at the outlet of the drum**, while the humid gas exits separately.

Operation: Continuous
Heat transfer: Direct convective drying
Flow configuration: Co-current or counter-current
Typical applications: drying sand, minerals, fertilizers, and other bulk solids.

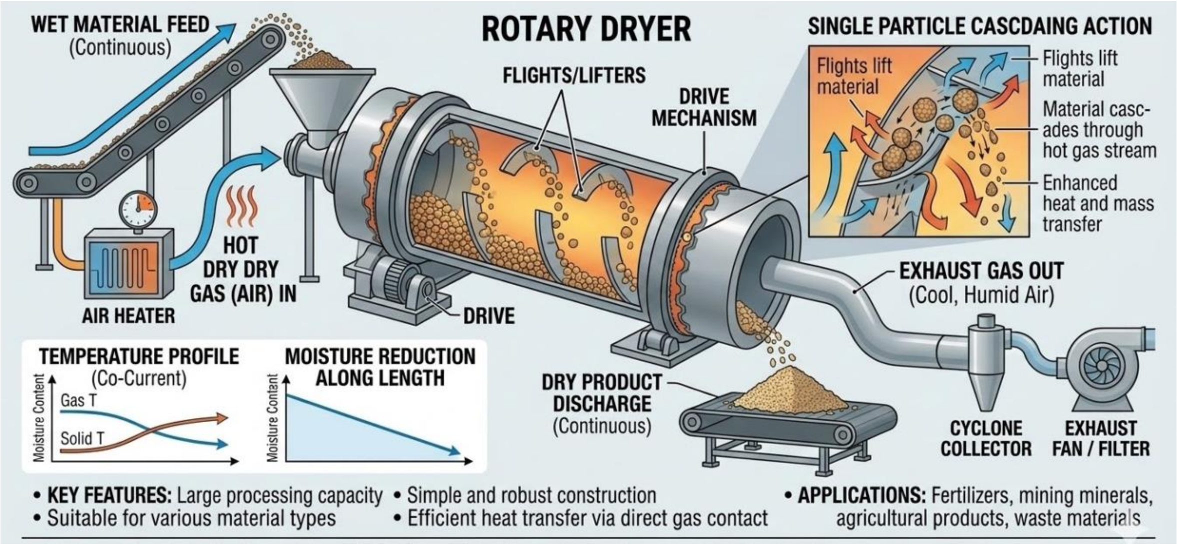


Figure 2.5 – Industrial rotary dryer: co-current operation.

2.3. Drum Dryer:

In a drum dryer, a liquid or paste is **fed onto the surface of a rotating heated drum**. A thin film of the material spreads over the drum surface, where **heat is transferred through the metal wall**, causing rapid evaporation of moisture. As the drum rotates, the dried material forms **a thin solid layer that is scraped off by a blade** and collected as dry flakes or powder.

Operation: Continuous
Heat transfer: Indirect conductive drying
Flow configuration: No direct gas–solid contact
Typical applications: drying starch, food pastes, cereals, and viscous products.

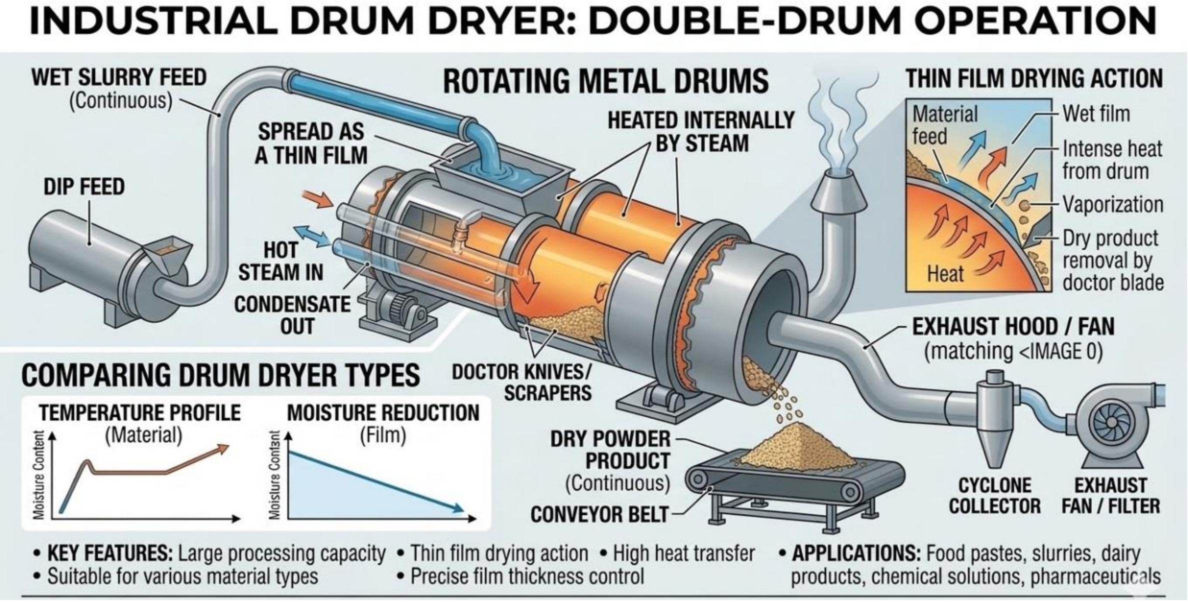


Figure 2.6 – Industrial drum dryer: double-drum operation.

2.4. Tray Dryer:

In a tray dryer, the wet material is **spread in thin layers on trays** placed inside an enclosed drying chamber. **Hot air is circulated over the trays**, transferring heat to the material and causing moisture to evaporate. The humid air is removed from the chamber, while the **dried material is taken out after the drying period**.

Operation: Batch

Heat transfer: Direct convective drying

Flow configuration: Cross-flow

Typical applications: drying pharmaceutical powders, chemicals, food products, and laboratory-scale materials.

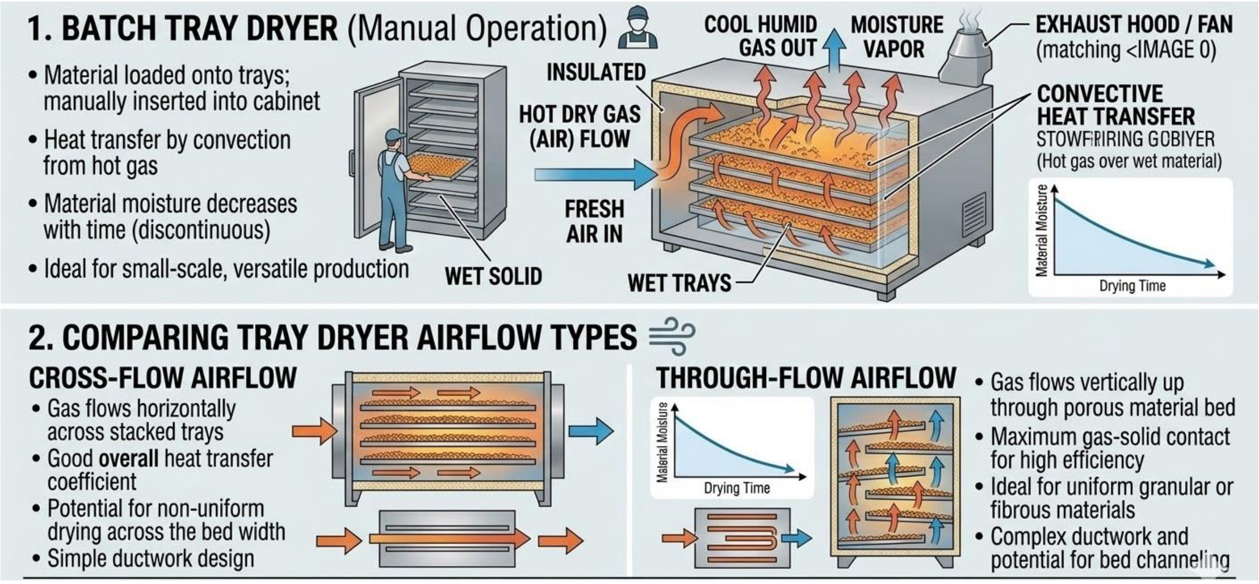


Figure 2.6 – Industrial tray dryer: batch operation.

Lecture 3 – Drying Mechanisms

Learning Objectives

At the end of this lecture, students should be able to:

- Explain the physical mechanisms governing moisture removal ;
- Distinguish between external and internal transport phenomena ;
- Identify the main moisture migration mechanisms inside solids ;
- Understand the coupling between heat and mass transfer ;
- Relate drying mechanisms to drying rate behavior.

1. Introduction to Drying Mechanisms

Drying is a **combined heat and mass transfer process** involving several simultaneous phenomena.

During drying:

- Heat is transferred from the drying medium (usually hot air) to the solid.
- This heat provides the **latent heat of vaporization** required to evaporate moisture.
- Water vapor is transported away from the surface into the gas stream.
- Moisture inside the solid migrates toward the surface.

Thus, drying involves **two main transport processes**:

- **External transport** (between gas and surface);
- **Internal transport** (inside the solid).

The slowest of these processes generally **controls the drying rate**.

2. External Heat and Mass Transfer

At the solid surface, two simultaneous transfers occur.

2.1. Heat Transfer

Heat is transferred from the hot gas to the solid surface mainly by **convection**:

$$q = h(T_g - T_s)$$

Where:

h: convective heat transfer coefficient

T_g: gas temperature

T_s: solid surface temperature

This heat supplies the **latent heat of evaporation**.

2.2. Mass Transfer

Once moisture vaporizes at the surface, water vapor must diffuse into the gas stream.

$$\boldsymbol{N_A = k(C_g - C_s)}$$

Where:

$\boldsymbol{k}$: mass transfer coefficient

$\mathbf{C_s}$: vapor concentration at surface

$\mathbf{C_g}$: vapor concentration in bulk gas

Efficient drying requires:

- high gas velocity ;
- low gas humidity ;
- high temperature difference.

Lecture 4 – Fundamentals of Drying: Mass & Energy Balances, Drying Rate, and Drying Time

Duration: ~80 minutes
Level: Master 1 – Chemical Engineering

Learning Objectives

At the end of this lecture, students should be able to:

- Apply overall mass balances to a drying process
- Establish the enthalpy (energy) balance of a dryer
- Interpret and construct the drying rate curve
- Distinguish between constant-rate and falling-rate periods
- Estimate the drying time for practical operations

3. Introduction

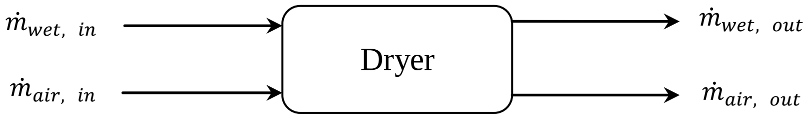
Drying is a fundamental unit operation in which moisture is removed from wet solids by evaporation through simultaneous heat and mass transfer. It is widely used in many industries such as food processing, pharmaceuticals, and materials engineering to improve product stability, reduce weight and volume, and facilitate storage and transportation. Understanding drying principles is essential for the design and operation of efficient industrial dryers.

4. Mass Balance of a Dryer

Goal: To quantify how much air is needed to remove a specific amount of water.

4.1. Overall Material Balance

For steady operation: **Input = Output**



Total mass balance:

$$\dot{m}_{wet,\ in} + \dot{m}_{air,\ in} = \dot{m}_{wet,\ out} + \dot{m}_{air,\ out}$$

4.2. Moisture Balance on the Solid

Let:

$\dot{m}_s$: The dry solid flow rate (constant);

MC : Solid moisture content (kg water/kg dry solid).

Moisture removed:

$$\dot{m}_{evap} = \dot{m}_s(MC_{in} - MC_{out})$$

4.3. Moisture Balance on the Air

Let:

$\dot{m}_{da}$: The dry air flow rate (constant);

H : Air absolute humidity (kg water/kg dry air).

Moisture removed:

$$\dot{m}_{evap} = \dot{m}_{da}(H_{in} - H_{out})$$

Example —

A wet solid containing **40%** moisture (wet basis) is dried to **10%** moisture (wet basis). Feed rate: **100 kg/h** wet solid.

Determine water removed per hour.

Solution —

Step 1 — Initial composition

Feed rate: 100 kg/h

Moisture 40% (wet basis) ⇒ Water = 40 kg/h

Dry solid = 60% ⇒ Dry solid = 60 kg/h

⇒ Dry solid **does not change** during drying.

Step 2 — Final product composition

Final moisture = 10% (wet basis) ⇒ Dry solid = 90%

Since dry solid = 60 kg/h:

Final product mass = 60/0.90 = 66.67 kg/h

Step 3 — Water remaining in dried product

Water final = 66.67 kg/h – 60 kg/h = 6.67 kg/h

Step 4 — Water removed

Initial water = 40 kg/h

Final water = 6.67 kg/h

Evaporated water = 40 kg/h – 6.67 kg/h = 33.33 kg/h

5. Enthalpy (Energy) Balance of a Dryer

5.1. Sources of Energy Demand

Energy is required for:

- Heating the solid / the moisture / the drying air;
- Evaporation of water (dominant term) ;
- Heat losses.

5.2. General Energy Balance

For steady-state operation:

Heat supplied = Heat for evaporation + Sensible heats + Losses

For practical calculations, the following assumptions are commonly adopted:

- The dryer is well insulated → **heat losses are negligible ;**
- Sensible heating of the solid and moisture is **small compared to latent heat ;**
- Most of the supplied heat is used to **evaporate water ;**
- Water evaporates at an approximately constant temperature ;
- No chemical reaction or phase change occurs in the solid ;
- Changes in kinetic and potential energies are negligible.

Under these assumptions, the heat required for drying is approximated by:

$$\boldsymbol{Q \approx \dot{m}_{evap}\lambda}$$

This expression is widely used for preliminary design and engineering calculations because evaporation is the dominant energy demand in most drying operations.

5.3. Air Enthalpy Approach (Psychrometric Method)

For convective dryers:

$$\boldsymbol{Q = \dot{m}_{da}(h_{out} - h_{in})}$$

Where ***h*** is humid air enthalpy. (Drying could appear as a process on a psychrometric chart.)

6. Drying Rate Concepts

6.1. Drying Rate Curve

Drying doesn't happen at a constant speed. The graph below shows how the **drying rate** (**kg·h^{-1}·m^{-2}**) varies with **the moisture content of a wet solid** (**kg H_2O/kg dry solid**).

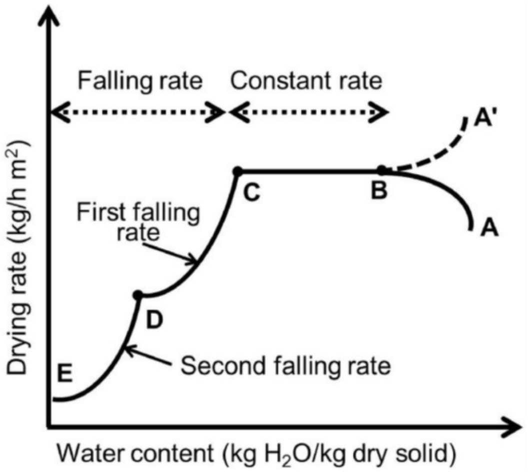


Figure 1 – Drying rate curve as a function of moisture content.

Drying proceeds from right to left as moisture content decreases.

- **A → B → C : Constant-Rate Period (R_c : constant drying rate)**

The solid surface is saturated with water. The rate depends only on external conditions (air temperature, humidity, velocity).

Critical moisture content (X_c): The point C where the surface starts to dry out.

- **C → E : Falling-Rate Period**

Two periods of falling-rate is shown. The rate is limited by internal diffusion of water within the solid where moisture must migrate from the interior to the surface.

- **Point E : Equilibrium Moisture Content (X_e)**

Solid is in equilibrium with surrounding air.

The moisture inside the solid and the moisture in the air are balanced, so no net evaporation occurs.

The air can no longer "absorb" more moisture from the solid.

Example:

Wet clothes in a humid room:

- In dry air → clothes continue drying.
- In very humid air → clothes remain damp.

6.2. Rate of Drying (R)

The rate of drying represents the amount of moisture removed from the solid per unit time and per unit drying surface area.

Expressed as: kg of water evaporated per hour per square meter of exposed surface: $(\frac{kg\ water\ evaporated}{h \times m^2})$.

Physically, it indicates how fast moisture leaves the material during drying.

During drying, the **moisture content** of the solid decreases with time. The moisture that can be removed under given air conditions is called **free moisture** (moisture above equilibrium).

The **equilibrium moisture** remains in the solid and cannot be removed unless air conditions change.

- **Experimental Determination of Drying Rate:**

The drying rate is obtained experimentally as follows:

- A wet sample is placed on a tray;
- Only one surface is exposed to the drying air;
- The tray is suspended from a balance;
- The loss of mass is recorded with time;

– Dry solid mass is determined at the end.

This procedure reproduces industrial drying conditions (air velocity, temperature, humidity, bed depth, etc.).

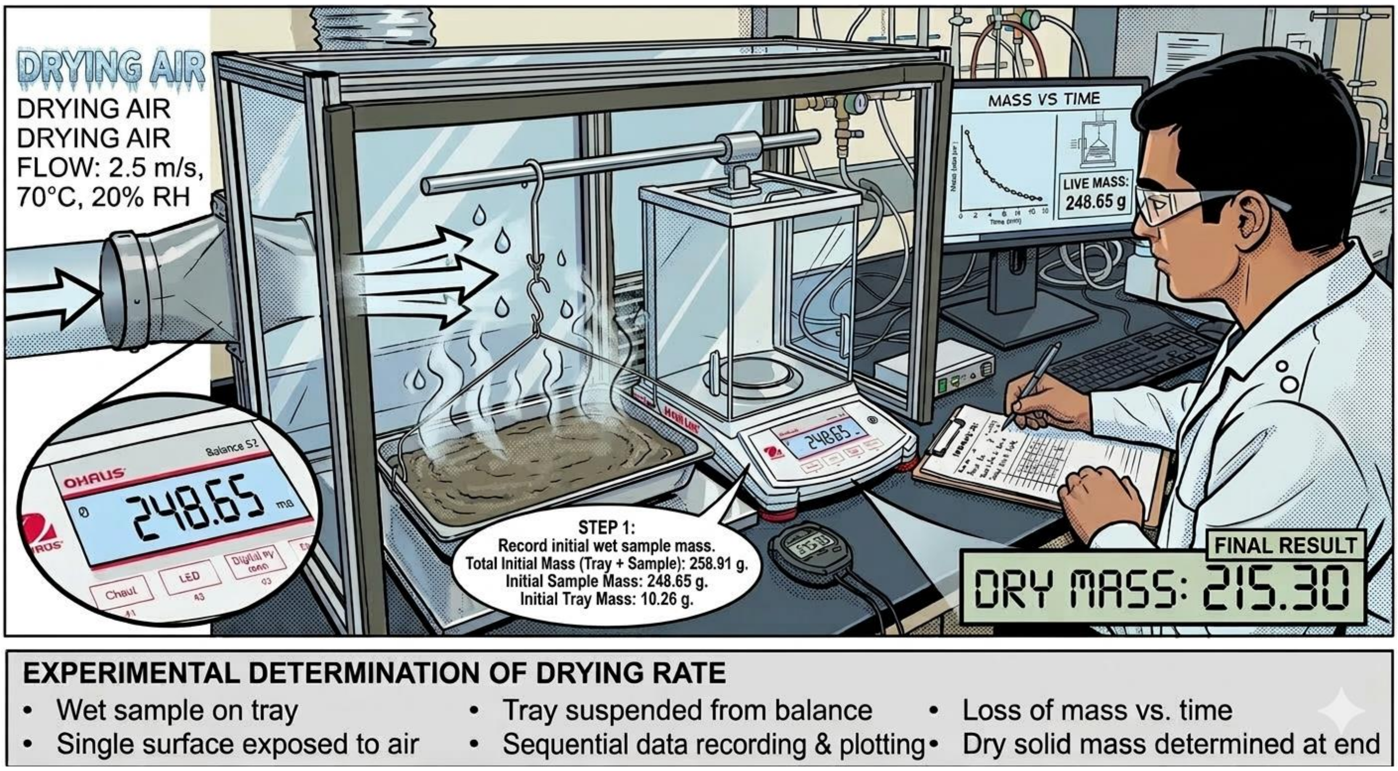


Figure 2 – Experimental determination method of drying rate (*image generated using Ai tools*).

Calculation of Drying Rate from Experimental Data:

From the measured mass–time data, the drying rate is obtained using the following relations.

a) Compute moisture content at different times:

At each recorded time, calculate the moisture content on a dry basis (X_t):

$$\boldsymbol{X_t = \frac{W_t - W_s}{W_s}}$$

Where:

$\boldsymbol{W_t}$: Mass of wet solid at time t.

$\boldsymbol{W_s}$: Mass of dry solid (constant, obtained after complete drying).

b) Free Moisture Content:

Compute the removable moisture (above equilibrium):

$$\boldsymbol{X = X_t - X_e}$$

Where:

$\boldsymbol{X_e}$**:** Equilibrium moisture content under the drying conditions.

c) Plot moisture content versus time:

Draw the curve of:

- Free moisture content X (vertical axis)
- Time *t* (horizontal axis)

This curve decreases as drying proceeds.

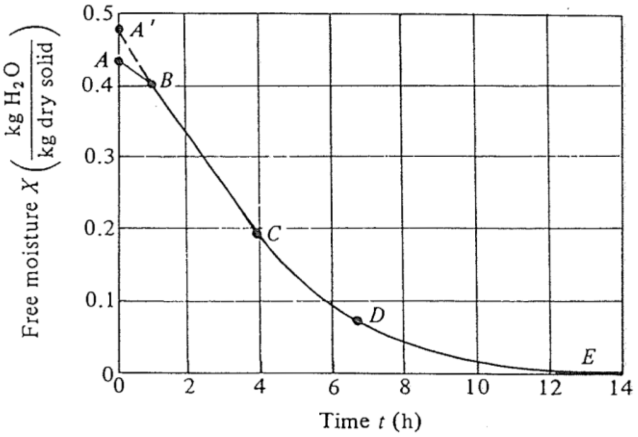


Figure 3 – Free Moisture Content vs Time.

d) Determine the slope of the curve at each point:

At selected moisture contents, draw tangents to the curve and determine the slope:

$$\frac{dX}{dt}$$

This slope represents the rate of change of moisture content with time.

e) Calculate the drying rate:

Convert the slope into drying rate per unit area using:

$$R = -\frac{L_s}{A}\frac{dX}{dt}$$

Where:

R**:** Drying rate ($kg \cdot h^{-1} \cdot m^{-2}$)

L_s**:** Mass of dry solid used (kg)

A**:** Exposed drying surface area (m^2)

The negative sign indicates that moisture content decreases with time.

Example —

A wet solid is dried in a laboratory tray dryer. Only the upper surface is exposed to the drying air. The mass of the sample is recorded at different times. After complete drying, the mass of dry solid is found to be **0.80 kg**. The exposed drying area is **0.25 m²**. The equilibrium moisture content under the operating conditions is **X_e = 0.02 kg H_2O/kg dry solid**.

The experimental data are given below:

Time (min)	**Mass of sample (kg)**
0	1.28
10	1.18
20	1.10
30	1.03
45	0.95
60	0.90
90	0.85

✦ **Questions**

- Calculate the moisture content $\mathbf{X_t}$ (dry basis) at each time.
- Determine the free moisture content **X** at each time.
- Plot the curve of free moisture content versus time.
- Using the graphical method, estimate the drying rate at **t = 20** min and **t = 60 min**.
- Plot the drying rate versus free moisture content and identify the drying regimes (constant-rate and falling-rate periods).

7. Drying Time Calculation

The total time is the sum of the two periods: $t = t_{constant} + t_{falling}$.

For **Constant-Rate Period**:

$$t_c = \frac{\dot{m}_s}{A.R_c}(X_0 - X_c)$$

Where:

A: Drying surface area;

X_0: Initial moisture content, previously designed MC;

For **Falling-Rate Period (Linear assumption)**:

General form:

$$t_c = \frac{\dot{m}_s}{A}\int_{X_c}^{X_f} \frac{dX}{R(X)}$$

In the falling-rate period, the drying rate depends on internal moisture transport mechanisms specific to the material; therefore, **the function N(X) is obtained experimentally**, and the drying time must be calculated using measured drying-rate data.

If drying rate decreases linearly:

$$t_c = \frac{\dot{m}_s}{A.R_c}\ln\left(\frac{X_c - X_e}{X_f - X_e}\right)$$

Where:

$\boldsymbol{X_e}$**:** Equilibrium moisture content;

$\boldsymbol{X_f}$**:** Final moisture content;

Example —

A wet porous solid is dried in a tray dryer under constant operating conditions. The drying process exhibits a constant-rate period followed by a falling-rate period. During the falling-rate period, the drying rate is assumed to decrease linearly with the moisture content.

The following data are available:

- Mass of dry solid: **80 kg (dry basis)**
- Effective drying surface area: **16 m²**
- Initial moisture content: **0.60 kg H_2O/kg dry solid**
- Critical moisture content: **0.25 kg H_2O/kg dry solid**
- Final moisture content: **0.08 kg H_2O/kg dry solid**
- Equilibrium moisture content: **0.03 kg H_2O/kg dry solid**
- Constant drying rate: **1.0 kg·h^{-1}·m^{-2}**

✦ **Questions:** Assume steady operating conditions and neglect heat losses.

– Calculate the time required for drying during the constant-rate period.

– Calculate the time required for drying during the falling-rate period.

– Determine the total drying time.

– Calculate the percentage of the total drying time that occurs in the falling-rate period.

Solution —

1) Constant-rate period time:

$t_c = [80 \times (0.60 - 0.25)] / (16 \times 1.0)$ → $t_c = 28 / 16$ → $\mathbf{t_c = 1.75\ h}$

2) Falling-rate period time (linear assumption):

$t_f = [80 / (16 \times 1.0)] \times \ln[(0.25 - 0.03) / (0.08 - 0.03)]$ → $t_f = 5 \times \ln(4.4) \approx 5 \times 1.482$ → $\mathbf{t_f = 7.41\ h}$

3) Total drying time:

$t_{total} = 1.75 + 7.41$ → $\mathbf{t_{total} = 9.16\ h}$

4) Percentage in falling-rate period:

(7.41 / 9.16) × 100 ≈ **81%**