Lecture 1: Fundamentals and Process Analysis of Evaporation

Duration: 80 min
Level: Master 1 – Chemical Engineering

I. INTRODUCTION: Industrial Context and Motivation

Evaporation is a thermal separation operation used to **concentrate liquid solutions by removing a volatile solvent** (generally water) through vaporization.

Typical Industrial Applications:

- Food industry: Concentration of fruit juices (orange juice concentration), vegetable juices (tomato juice and purees), and dairy products (condensed milk).
- Chemical industry: NaOH concentration
- Environmental engineering: desalination

> **Remark –** Concentration of liquid foods is a vital operation in many food processes. Concentration is different from dehydration. Generally, foods that are concentrated remain in the liquid state, whereas drying produces solid or semisolid foods with significantly lower water content. Evaporation is the most common technology used for liquid concentration process.

Example: Vertical Tube Falling Film Evaporator

A vertical tube falling-film evaporator operates by introducing the liquid feed at the top of vertical tubes, where it forms a thin liquid film flowing downward by gravity along the inner tube surface.

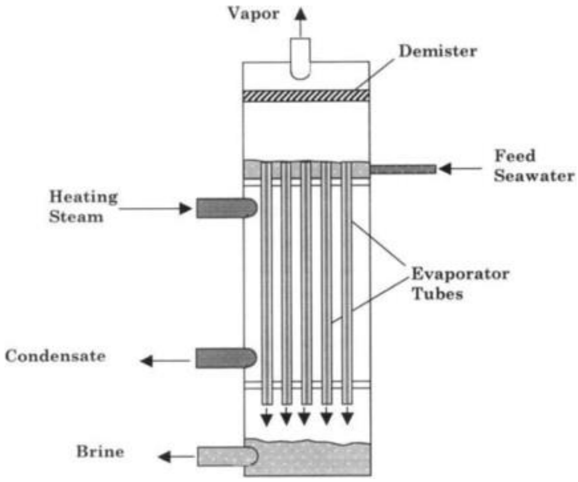
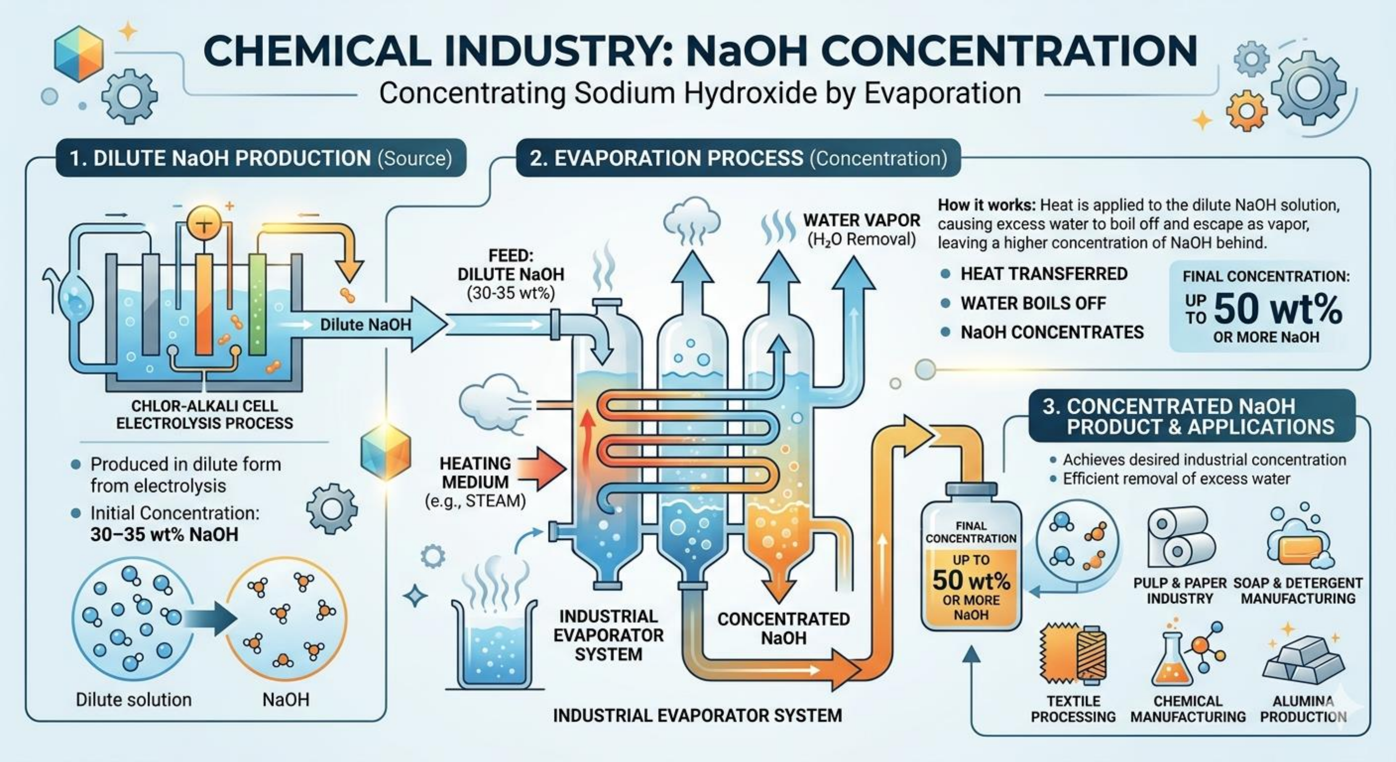
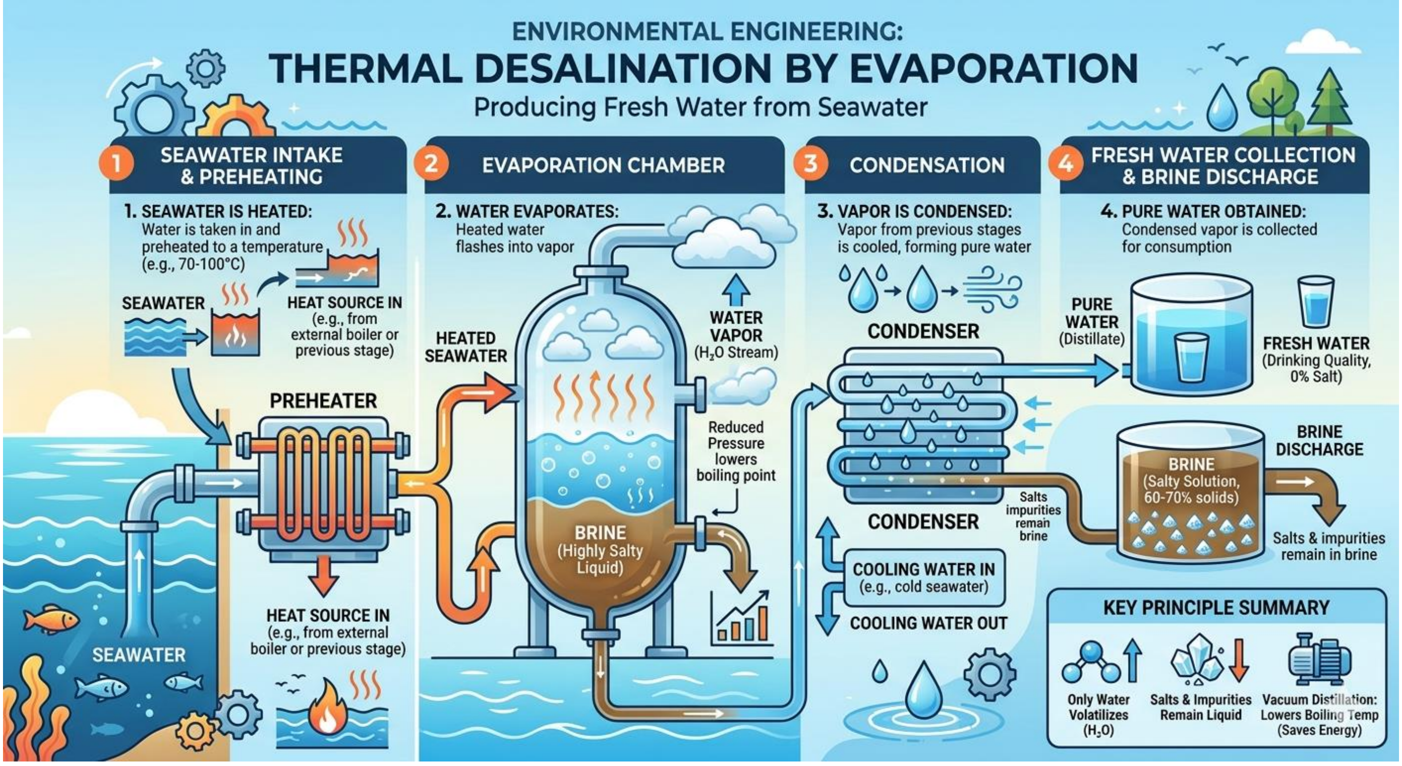


Figure 1 – Vertical tube falling-film evaporator

Simultaneously, heating steam flows on the shell side (outside the tubes) and condenses, releasing its latent heat. This heat is transferred through the tube wall to the falling liquid film, causing partial evaporation of the solvent as the film descends.

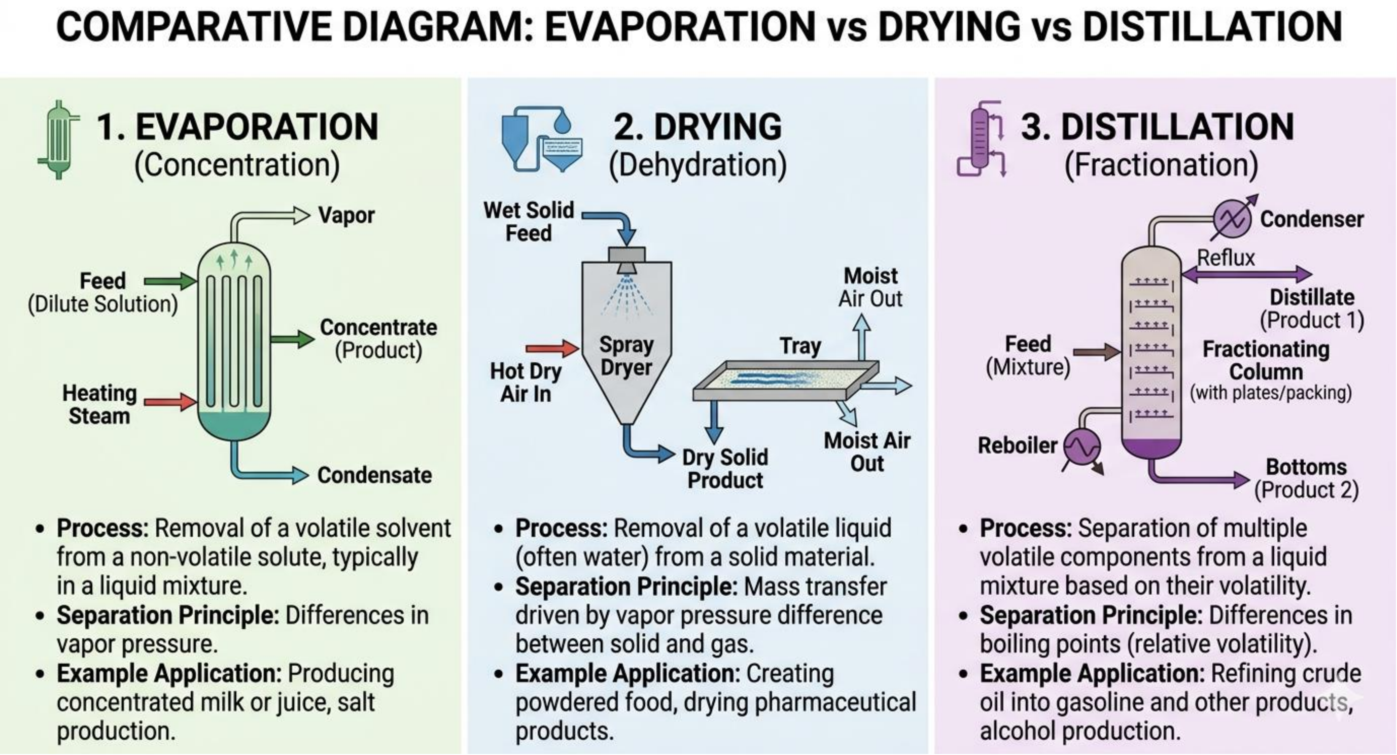
- **Illustrations:**





In both applications, evaporation serves to:

- Separate solvent from solute.
- Increase product value (NaOH) or recover pure water (desalination).
- But requires careful management of energy consumption and fouling phenomena.



COMPARATIVE DIAGRAM: EVAPORATION vs DRYING vs DISTILLATION

1. EVAPORATION (Concentration)

- **Process:** Removal of a volatile solvent from a non-volatile solute, typically in a liquid mixture.
- **Separation Principle:** Differences in vapor pressure.
- **Example Application:** Producing concentrated milk or juice, salt production.

2. DRYING (Dehydration)

- **Process:** Removal of a volatile liquid (often water) from a solid material.
- **Separation Principle:** Mass transfer driven by vapor pressure difference between solid and gas.
- **Example Application:** Creating powdered food, drying pharmaceutical products.

3. DISTILLATION (Fractionation)

- **Process:** Separation of multiple volatile components from a liquid mixture based on their volatility.
- **Separation Principle:** Differences in boiling points (relative volatility).
- **Example Application:** Refining crude oil into gasoline and other products, alcohol production.

Guiding Engineering Question:

How can a large quantity of solvent be removed efficiently while minimizing energy consumption and fouling phenomena and preserving product quality?

II. FUNDAMENTAL PRINCIPLES OF EVAPORATION

Def. – Evaporation is a thermal separation process involving:

- **Heat supply :**
  - External energy (usually steam) is provided to the system.
  - This heat raises the liquid temperature to its boiling point.
- **Phase change (liquid → vapor) :**
  - Once boiling is reached, the solvent undergoes vaporization requiring latent heat of vaporization.
  - Only the volatile component (solvent) evaporates, while solutes remain.
- **Concentration of solute:**
  - As solvent is removed, the solute concentration increases.
  - The remaining liquid becomes progressively more concentrated.

2.1. Thermodynamic Considerations

2.1.1. Boiling Condition and Pressure Effect:

At boiling:

$$P_{vapor} = P_{system}$$

Lower pressure → lower boiling temperature

Water as example –

Water evaporates when molecules at the surface gain enough energy to escape into the space above as vapor. In a closed container, these molecules accumulate until the system reaches **dynamic equilibrium**, a state where the rate of molecules escaping (**evaporating**) perfectly matches the rate of those returning to the liquid (**condensing**).

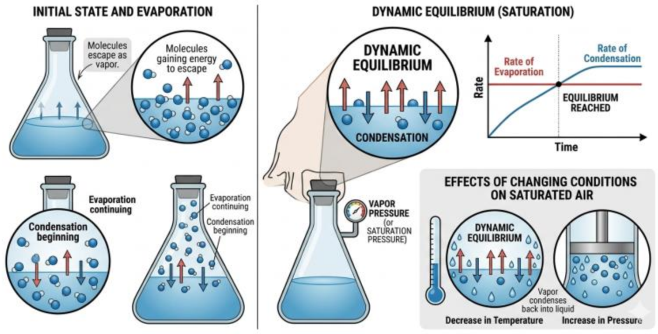


Figure 2 – Water evaporation and dynamic equilibrium in a closed container.

The pressure exerted by the vapor at this balanced point is known as **the vapor pressure** or **saturation pressure**. At this stage, the air is fully saturated; meaning any further increase in pressure or decrease in temperature will force the vapor to condense back into its liquid state.

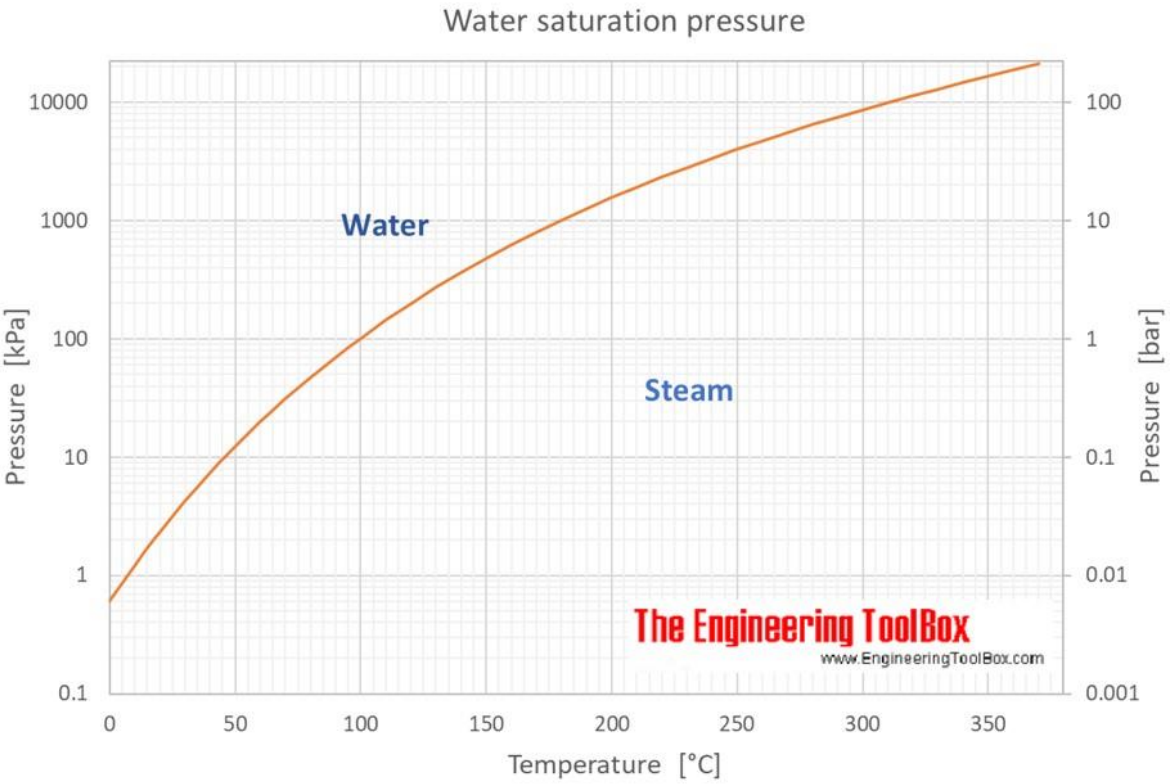


Figure 3 – Water boiling point at higher pressures.

2.1.2. Boiling Point Elevation:

When a **non-volatile solute** (e.g., salt, NaOH) is dissolved in a **solvent**:

- The solute particles **interact with solvent molecules** ;
- They **reduce the number of free solvent molecules** at the surface ;
- As a result, it becomes **more difficult for molecules to escape into vapor**.

Therefore, **more energy (higher temperature)** is required to reach boiling.

Example –

- Pure water boils at 100°C
- Saltwater boils at >100°C

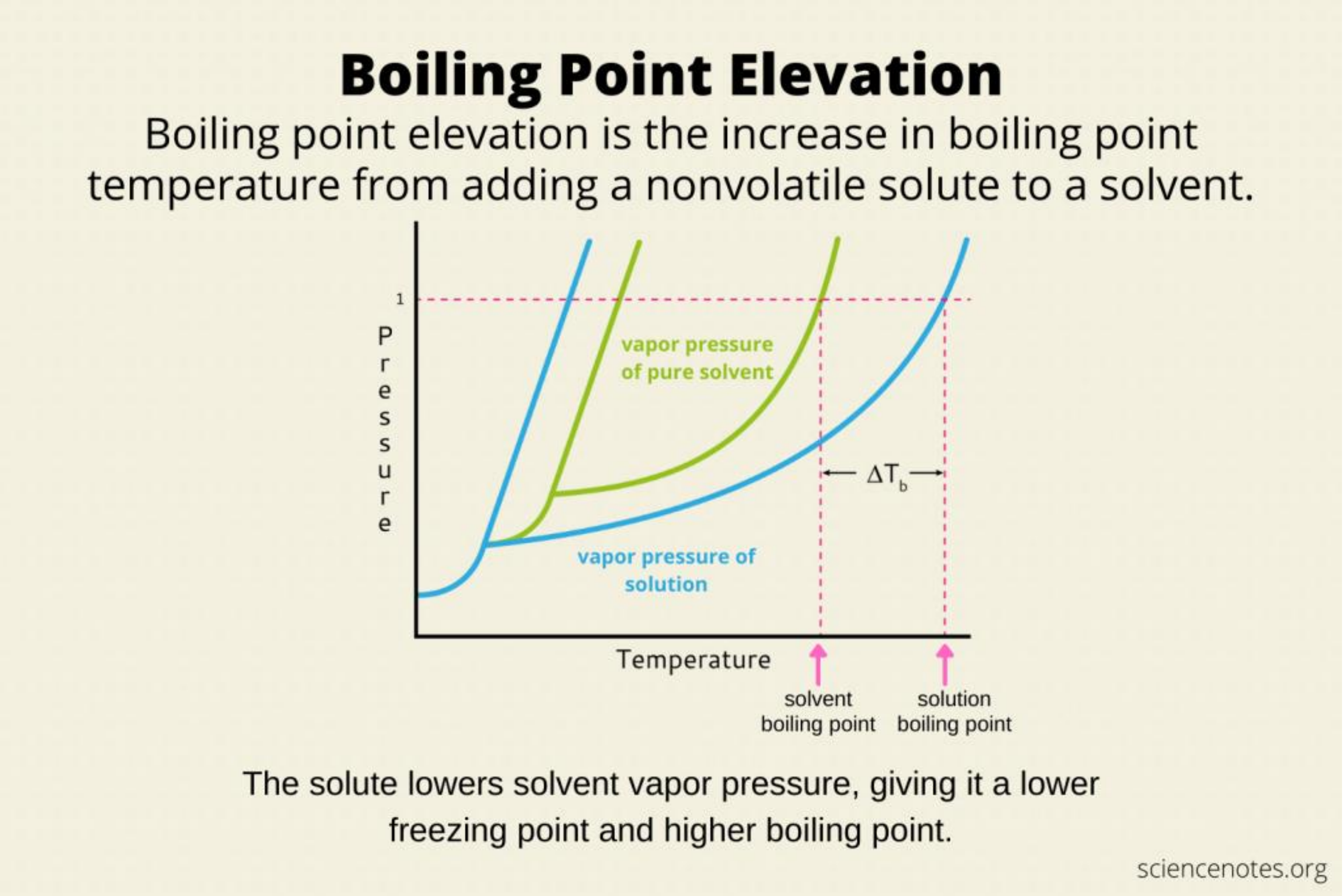
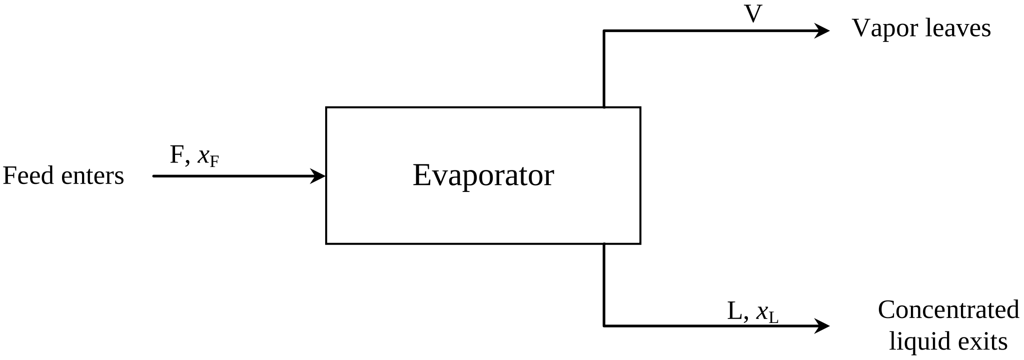


Figure 4 – Boiling point elevation is the increasing in the temperature of the boiling point of a solvent from adding a solute.

3. Mass Balance in Evaporation

3.1. System representation:



3.2. Governing Equations:

Total balance:

$$\mathbf{F = V + L}$$

Solute balance:

$$x_F.\mathbf{F} = \mathbf{V} + x_L.\mathbf{L}$$

Example 1 –

A feed of 1000 kg/h at 10% solids is concentrated to 30% solids.

Solution:

$$1000 \times 0.10 = L \times 0.30 \Rightarrow L = 333.3\text{kg/h}$$

$$V = 1000 - 333.3 = 666.7\text{kg/h}$$

4. Energy Balance

4.1. Heat requirement:

In an evaporator, the total heat supplied is used for two main purposes:

a) **Sensible Heating:** Heat required **to raise** the feed from its initial temperature to the boiling temperature. Depends on: flowrate, heat capacity, temperature difference.

b) **Latent Heat of Vaporization:** Heat required **to convert** liquid into vapor at boiling, this is the dominant energy term, depends on the amount of vapor produced

General Expression

$$Q = F.c_p(T_b - T_{in}) + V\lambda$$

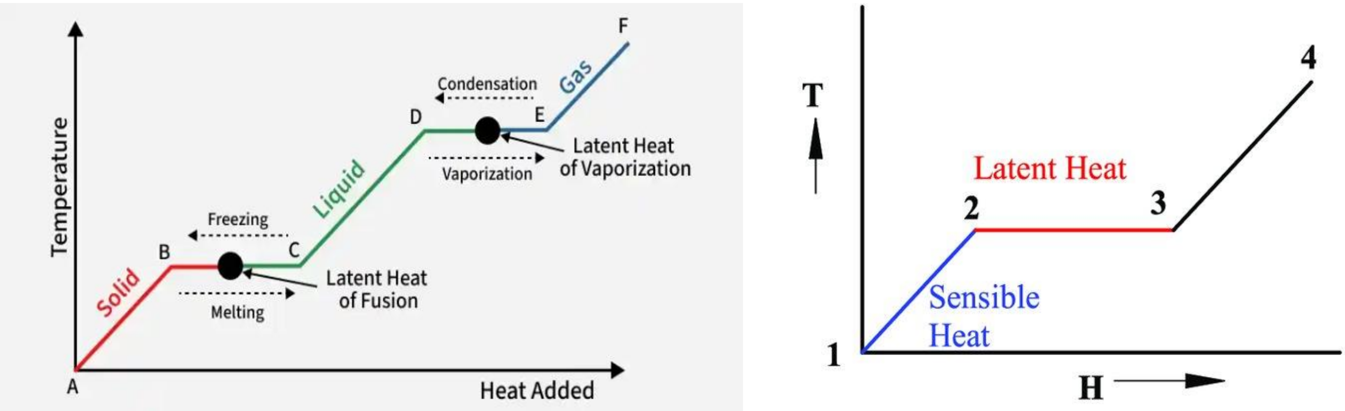


Figure 5 – change in various forms of matter and the heat related to each process.

APPLICATION EXERCISES –

Exercise 1 – Mass Balance

A solution is concentrated from **5%** to **20%** solids. Feed = **2000 kg/h**.

Calculate:

- Concentrated liquid flowrate.
- Vapor produced.

Exercise 2 – Energy Balance

Feed: Flowrate = **1500 kg/h**; Temperature = **25°C**; Boiling temperature = **90°C**

Data: C_p = **4.18 kJ/kg.K**; λ = **2300 kJ/kg**; Vapor produced = **800 kg/h**

Determine total heat requirement.

Lecture 2: Heat Transfer and Evaporator Design

Duration: 80 min

Level: Master 1 – Chemical Engineering

Recall that evaporation requires significant heat, mainly for vaporization. The key challenge is to **transfer this heat efficiently** to the liquid.

This lecture focuses on understanding **heat transfer mechanisms** and how they are used to **design and size evaporators**.

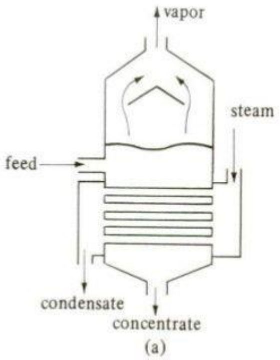


Figure 6 – A horizontal tube evaporator design.

1. Heat Transfer in Evaporators

Heat transfer in evaporators is a **coupled phenomenon** involving **conduction, convection, and phase change**, enabling the transfer of energy from a heating medium (usually steam) to a boiling liquid.

1.1. General Mechanism

In most evaporators:

- Steam condenses on one side of the heat transfer surface ;
- Heat passes through the **solid wall** (**conduction**) ;
- The liquid absorbs heat and **boils** (**convective + phase change heat transfer**).

This creates a continuous heat flow from **steam → wall → liquid**.

1.2. Overall Heat Transfer Coefficient (U)

***Def.* –**

$$\boldsymbol{Q = U.A.\Delta T}$$

Where:

U: overall heat transfer coefficient

A: heat transfer area

ΔT: temperature difference

With:

$$\frac{1}{U} = R_{steam} + R_{wall} + R_{liquid} + R_{fouling}$$

$R_{steam} = \frac{1}{h_s}$: Outside the tubes (steam side). How easily heat is released from condensing steam to the wall.

$R_{wall} = \frac{e}{k}$: Tube wall. Heat flows by **conduction through the metal wall**.

$R_{liquid} = \frac{1}{h_l}$: Inside the tubes (liquid side). How efficiently heat is transferred from the wall to the liquid.

$R_{fouling}$: Deposits on surfaces (both sides, mainly liquid side). Additional resistance caused by **unwanted deposits.**

Fouling resistance accounts for the accumulation of unwanted materials on heat transfer surfaces, which act as an insulating layer and reduce heat transfer efficiency.

2. Boiling Heat Transfer Mechanisms

Boiling heat transfer is a key phenomenon in evaporators, governing the rate at which heat is transferred from the heating surface to the liquid and converted into vapor.

2.1. General Description

Boiling occurs when a liquid is heated to **its saturation temperature**, and additional heat causes **phase change** (**liquid → vapor**).

In evaporators, boiling typically takes place at the **heated surface**, where vapor bubbles are generated and released into the bulk liquid.

2.2. Boiling Regimes and Circulation in Evaporators

Boiling in evaporators occurs mainly in **two regimes**:

- **Nucleate boiling (desirable):** vapor bubbles form at the surface, enhancing mixing and heat transfer → high heat transfer coefficient.
- **Film boiling (undesirable):** a vapor layer covers the surface, acting as insulation → low heat transfer efficiency.

Efficient operation requires maintaining nucleate boiling, typically ensured by a sufficient temperature difference:

$$q = h\Delta T$$

Circulation affects boiling performance:

- **Natural circulation:** driven by density differences → simple but limited heat transfer.
- **Forced circulation:** pump-driven flow → higher velocity, better heat transfer, reduced fouling.

Increasing liquid circulation improves heat transfer and helps maintain stable boiling conditions.

For more: **Nukiyama’s boiling curve**.

Lecture 3: Heat Transfer Area Calculation & Multiple-Effect Evaporation

Duration: 90 min

Level: Master 1 – Chemical Engineering

Evaporation is highly energy-intensive. The engineer must:

- Size the heat exchange surface (A)
- Optimize energy consumption using multiple-effect systems

Key Questions:

How do we calculate the required heat transfer area?

How does multiple-effect configuration improve efficiency?

1. HEAT TRANSFER AREA CALCULATION

1.1. Fundamental design equation

The evaporator design is based on:

$$\boldsymbol{Q = U.A.\Delta T \quad \Rightarrow \quad A = \frac{Q}{U.\Delta T}}$$

Where:

Q: heat duty (W)

U: overall heat transfer coefficient (W/m².K)

A: heat transfer area (m²)

ΔT: effective temperature difference (°C or K)

1.2. Single-Effect Evaporator Design

In a single-effect evaporator problem, you usually have:

Feed Conditions	Thermal Data	Heat Transfer Data
Feed flowrate, **F (kg/h)** Initial concentration, $\boldsymbol{x_F}$ Final concentration, $\boldsymbol{x_L}$	Feed temperature, $\mathbf{T_{in}}$ Boiling temperature, $\mathbf{T_b}$ Latent heat, **λ** Heat capacity, $\mathbf{c_p}$	Overall heat transfer coefficient, U Steam temperature (or directly **ΔT**)

We are looking for: Heat transfer area, **A (m²)**

Intermediate variables to determine:

- Vapor flowrate, **V**
- Heat duty, **Q**

1.2.1. Methodology (Step-by-Step Procedure)

Step 1 - Mass Balance: Determine vapor and liquid flowrates:

$$F = V + L \quad ; \quad x_F F = x_L L$$

Solve for:

- L (concentrate)
- V (evaporated solvent)

Step 2 - Energy Balance: Calculate heat duty, Q

$$Q = F.c_p(T_b - T_{in}) + V\lambda$$

- First term: sensible heat
- Second term: latent heat (dominant)

Step 3 - Temperature Driving Force

$$\Delta T = T_{steam} - T_b$$

Include boiling point elevation if needed.

Step 4 - Heat Transfer Area

$$A = \frac{Q}{U.\Delta T}$$

The calculation always follows this logic: **Mass → Energy → Heat Transfer → Area**

Designing an evaporator is essentially determining how much surface is needed to transfer the required heat for evaporation.

Exercise 1 – Single-Effect Evaporator Design

A solution is concentrated in a single-effect evaporator from **8 wt%** to **32 wt%** solids. The feed flowrate is **4000 kg/h**, entering at **25°C**. The boiling temperature is **95°C**.

Data:

C_p = 4.18 kJ/kg; λ = 2300 kJ/kg; U = 1400 W/m^2·K; ΔT = 30°C

Determine:

- Determine the required heat transfer area **A**;

If fouling reduces U to **800 W/m²·K**:

- Recalculate the required area
- Comment on the impact

1.2.2. Steam Economy

Steam economy is defined as:

$$\boldsymbol{steam\ economy = \frac{Mass\ of\ vapor\ produced}{Mass\ of\ steam\ consumed}}$$

Typical values are close to:

$$\boldsymbol{Steam\ economy\ \approx 1}$$

This means one kilogram of steam evaporates approximately one kilogram of water.

1.2.3. Limitations

- High energy consumption ;
- Poor efficiency ;
- Not suitable for large-scale operations.

1.3. Multiple-Effect Evaporators (MEE)

A **multiple-effect evaporator** consists of several evaporators (**effects**) arranged in series, where the **vapor produced in one effect is reused as the heating medium for the next**.

1.3.1. Fundamental Concept

The key principle behind MEE systems is **energy reuse**:

- First effect uses live steam ;
- Subsequent effects use vapor from previous stages ;
- Pressure and temperature decrease across effects.

This allows multiple uses of the same heat input.

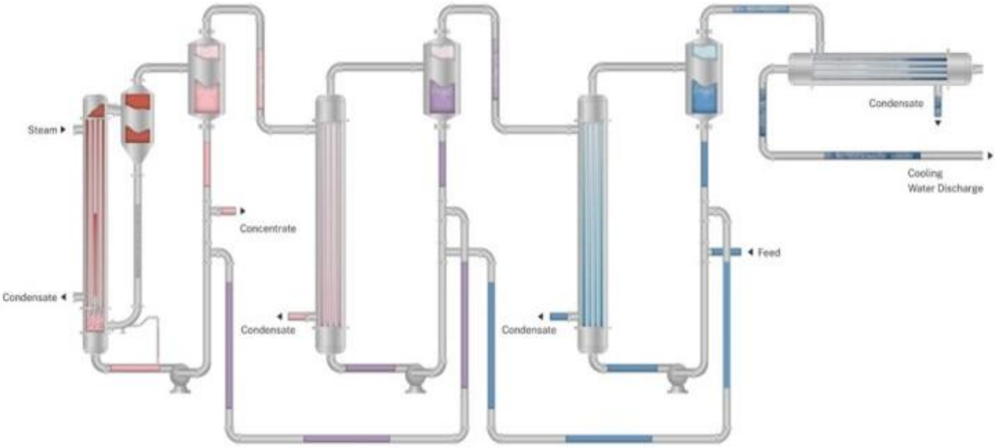


Figure 7 – Multiple-effect evaporator (MEE).

A **Multiple Effect Evaporator (MEE)** is a system of heat exchangers and vapor-liquid separators used in industry to concentrate solutions by evaporating water efficiently using steam or hot water.

The process typically stops before solutes begin to precipitate. Most evaporators use **tubular heating surfaces**, with variations in tube orientation and fluid placement.

In a **forward feed configuration**, the feed enters the first effect, where evaporation begins. The generated vapor is reused in subsequent effects to heat and concentrate the solution progressively. This arrangement ensures efficient energy utilization and enables high concentration levels.

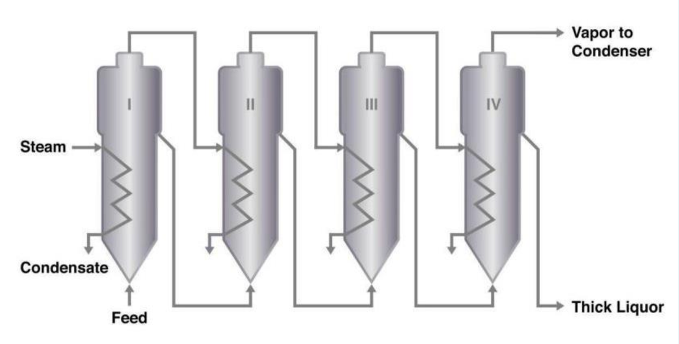


Figure 8 – Forward feed multi effect evaporator

In a **backward feed configuration**, the feed enters the last effect, where initial concentration occurs. The generated vapor is reused in preceding effects, enabling further evaporation and concentration. This arrangement enhances energy efficiency and allows for higher concentration levels, particularly suitable for viscous or concentrated solutions.

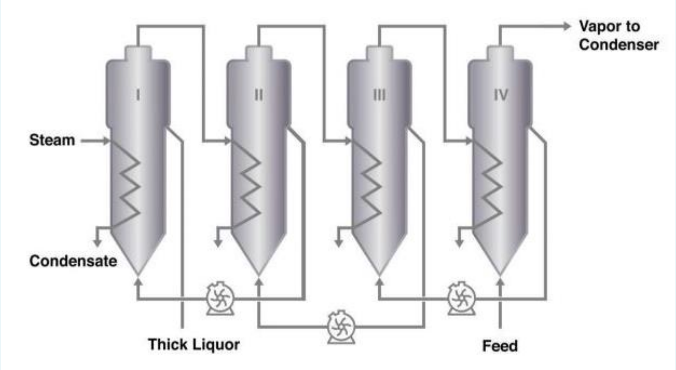


Figure 9 – Backward feed multi effect evaporator.

Design considerations for MEE systems include evaporator type, circulation method, feeding arrangement, boiling point elevation, heat transfer efficiency, fouling, and tube design.

Fouling—the buildup of unwanted deposits on heat transfer surfaces—is a major challenge. It reduces efficiency, increases pressure drop, and raises energy and maintenance costs. To address this, self-cleaning heat exchangers using fluidized solid particles can minimize or eliminate fouling. However, only selected effects in an MEE system may need such cleaning, depending on feed configuration and wastewater composition.

1.3.2. Pressure and temperature distribution

To enable heat transfer:

- Each subsequent effect operates at a **lower pressure**
- Correspondingly, the **boiling point decreases**

$$P_1 > P_2 > P_3 > \cdots > P_n$$

$$T_1 > T_2 > T_3 > \cdots > T_n$$

This gradient ensures that vapor from one effect can act as the heating medium for the next.

1.3.3. General Operation

- Feed enters the system ;
- Heating in the first effect generates vapor ;
- Vapor flows to the next effect as heating steam ;
- Liquid becomes progressively concentrated ;
- Final product exits the last effect.

1.3.4. Feed Arrangements

The way feed flows through the evaporator system significantly affects performance.

- **Forward Feed:** Feed enters the first effect and flows in the same direction as vapor.
- **Backward Feed:** Feed enters the last effect and flows opposite to vapor.
- **Mixed Feed:** Combination of forward and backward feed.
- **Parallel Feed:** Feed is distributed to all effects simultaneously.

1.3.5. Material balance

- **Overall Mass Balance: $F = P + V$**

Where:

F: Feed rate
P: Product rate
V: Vapor rate

- **Solute Balance: $F.x_F = P.x_P$**

Where:

x_F: Feed concentration
x_P: Product concentration

- **Effect-wise Balance:**

Each effect must satisfy: **$F_i = F_{i+1} + V_i$**

1.3.6. Energy Balances

- **General Energy Equation:**

In evaporation processes, the heat duty is often expressed in the simplified form:

$$Q = m.\,\lambda$$

Where:

Q: Heat supplied

m: vapor generation rate ($kg \cdot s^{-1}$)

λ: latent heat of vaporization ($J \cdot kg^{-1}$)

> This formulation assumes that the supplied heat is used exclusively for **phase change (latent heat of vaporization)**. However, this expression is **valid only under specific conditions**, notably when the feed enters the evaporator at or near its **boiling temperature**, or when the **sensible heat requirement is negligible** compared to the latent heat

In the general case, the complete energy balance should be considered:

$$Q = F.c_p(T_b - T_{in}) + V\lambda$$

where the first term represents the **sensible heat** required to raise the feed temperature to the boiling point. In industrial practice, especially in **multi-effect evaporators**, the latent heat term largely dominates the energy demand, which justifies the frequent use of the simplified expression for preliminary calculations. Nevertheless, for **rigorous design and accurate energy evaluation**, the sensible heat contribution should not be neglected.