LECTURE 6
MASS TRANSFER FOR BIOLOGICAL SYSTEMS

EVAPORATION

Purpose of Evaporation

- To concentrate solution by removing the vapor from a boiling liquid solution
- In the majority of cases, evaporation refers to the removal of water from an aqueous solution.
- Example: concentration of aqueous solutions of sugar, sodium chloride, sodium hydroxide, glycerol, glue, milk, and orange juice.
- In these cases the concentrated solution is the desired product and the evaporated water is normally discarded.
- In a few cases, water, which contains a small amount of minerals, is evaporated to give a solids-free water to be used as boiler feed, for special chemical processes.
- Evaporation processes to evaporate seawater to provide drinking water have been developed and used.

Processing Factors

1. Concentration in the liquid

   - low viscosity: high mass transfer coefficient

   - high viscosity: low mass transfer coefficient

-adequate circulation and/or turbulence must be present to keep the coeffeicient from becoming too low

2. Solubility

   - solubility increases with temperature

   - crystallization may occur when a hot concentrated solution is cooled to room temperature

3. Temperature sensitivity of materials

   - food and biological materials may be temperature sensitive and degrade at higher temperature or after prolonged heating

4. Foaming or frothing

- food solution such as skim milk and some fatty-acid solution form a foam or froth during boiling.

5. Pressure and temperature

- high operating pressure: high boiling point

6. Scale deposition and materials of construction

- Some solutions deposit solid materials called *scale* on the heating surfaces.

- results in the overall heat-transfer coefficient decreases and evaporator must be cleaned

TYPES OF EVAPORATION EQUIPMENT

1. Open kettle or pan
2. Horizontal-tube natural circulation evaporator
3. Vertical-type natural circulation evaporator
4. Long-tube vertical-type evaporator
5. Falling-film-type evaporator
6. Forced-circulation-type evaporator
7. Agitated-film evaporator
8. Open-pan solar evaporator

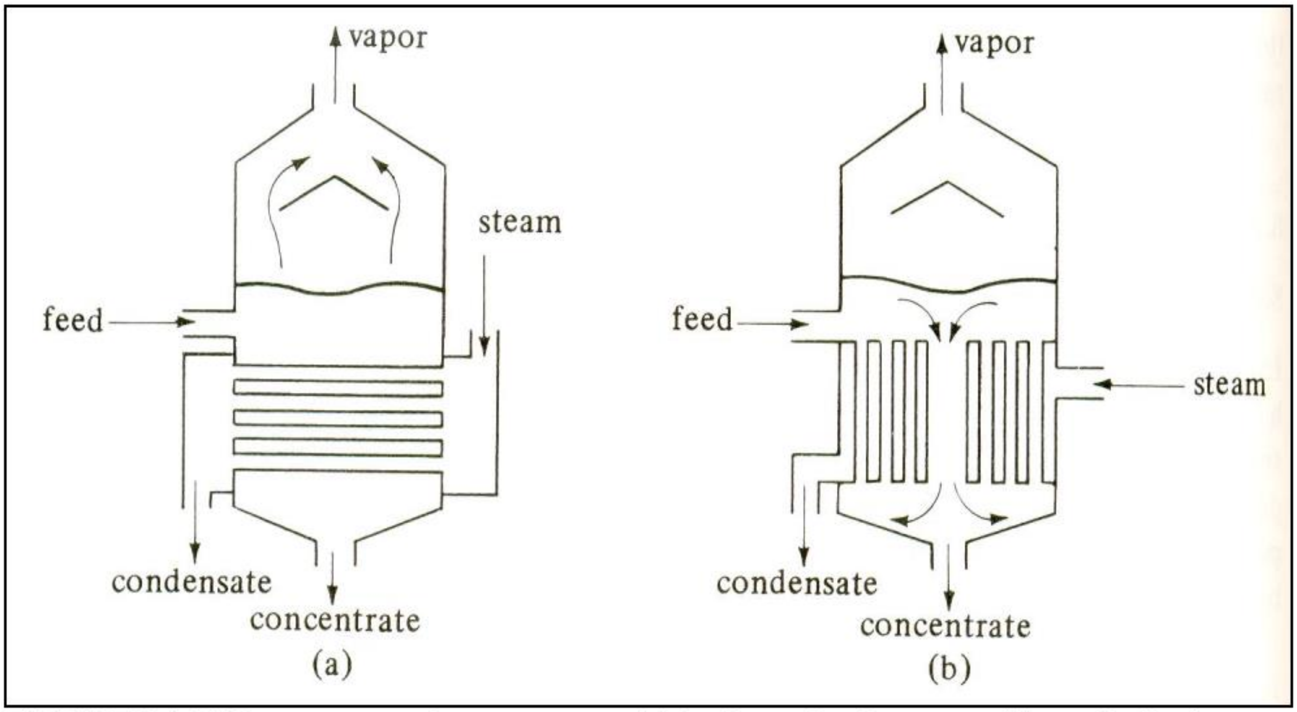

FIGURE 3.1 Different types of evaporators: (a) horizontal-tube type, (b) vertical-tube type

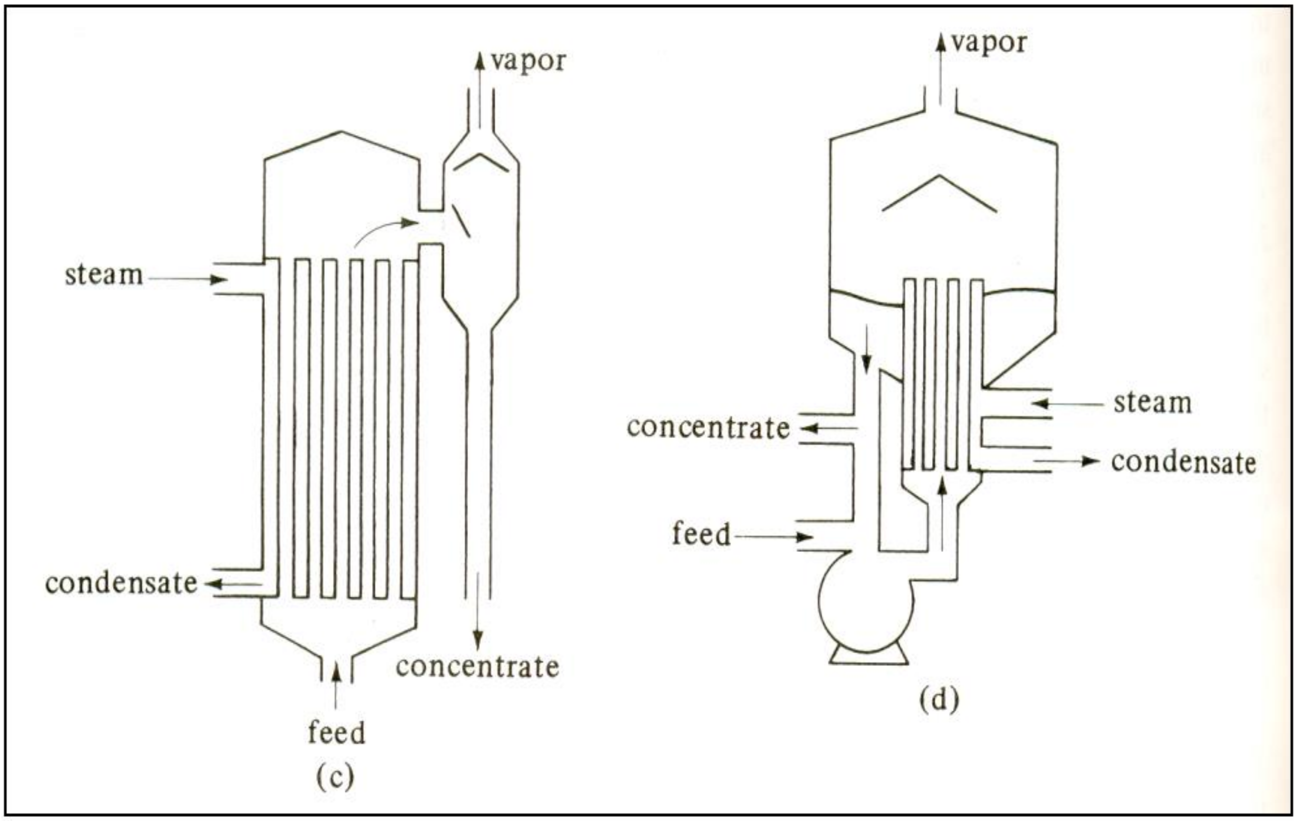

FIGURE 3.2 Different types of evaporators: (c) long-tube vertical type, (d) forced-circulation type

Methods of Operation of Evaporators

1. Single-effect evaporators
2. Forward-feed multiple-effect evaporators
3. Backward-feed multiple-effect evaporators
4. Parallel-feed multiple-effect evaporators

Single-effect evaporators

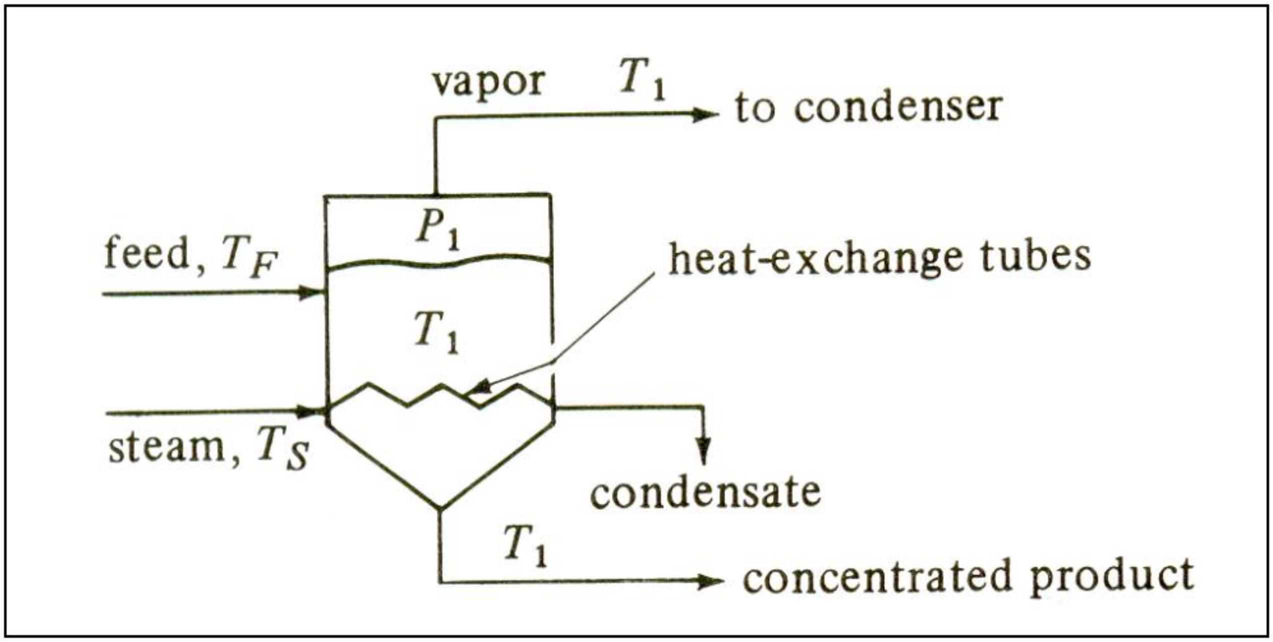

FIGURE 3.3 Simplified diagram of single-effect evaporator

- ✓ The feed enters at T_F
- ✓ Saturated steam at T_S enters the heat- exchange section.
- ✓ Condensed steam leaves as condensate or drips.
- ✓ The solution in the evaporator is assumed to be completely mixed
- ✓ Hence, the concentrated product and the solution in the evaporator have the same composition.
- ✓ Temperature T_1 is the boiling point of the solution.

  - The temperature of the vapor is also T_1, since it is in equilibrium with the boiling solution.
- The pressure is P_1, which is the vapor pressure of the solution at T_1.
- If the solution to be evaporated is assumed to be dilute and like water, then 1 kg of steam condensing will evaporate approximately 1 kg of vapor (if the feed entering has T_F near the boiling point)
- The concept of an overall heat-transfer coefficient is used in the calculation of the rate of heat transfer in an evaporator

  The general equation can be written

$$\boxed{q = UA\,\Delta T = UA(T_S - T_1)}$$

- Where:
- q is the rate of heat transfer in W (btu/h),
- U is the overall heat-transfer coefficient in W/m^2. K (btu/h ft. °F),
- A is the heat-transfer area in m^2 (ft^2),
- T_S is the temperature of the condensing steam in K (°F),
- T_1 is the boiling point of the liquid in K (°F).
- Single-effect evaporators are often used when the required capacity of operation is relatively small and/or the cost of steam is relatively cheap compared to the evaporator cost.

  However, for large-capacity operation, using more than one effect will markedly reduce steam costs

Forward-feed multiple-effect evaporators

- A single-effect evaporator as shown in Fig. 8.2-2 is wasteful of energy.
- The latent heat of the vapor leaving is not used but is discarded.
- Much of this latent heat, however, can be recovered and reused by employing a multiple - effect evaporator.

- A simplified diagram of a forward-feed triple-effect evaporation system is shown in Fig.3. 4

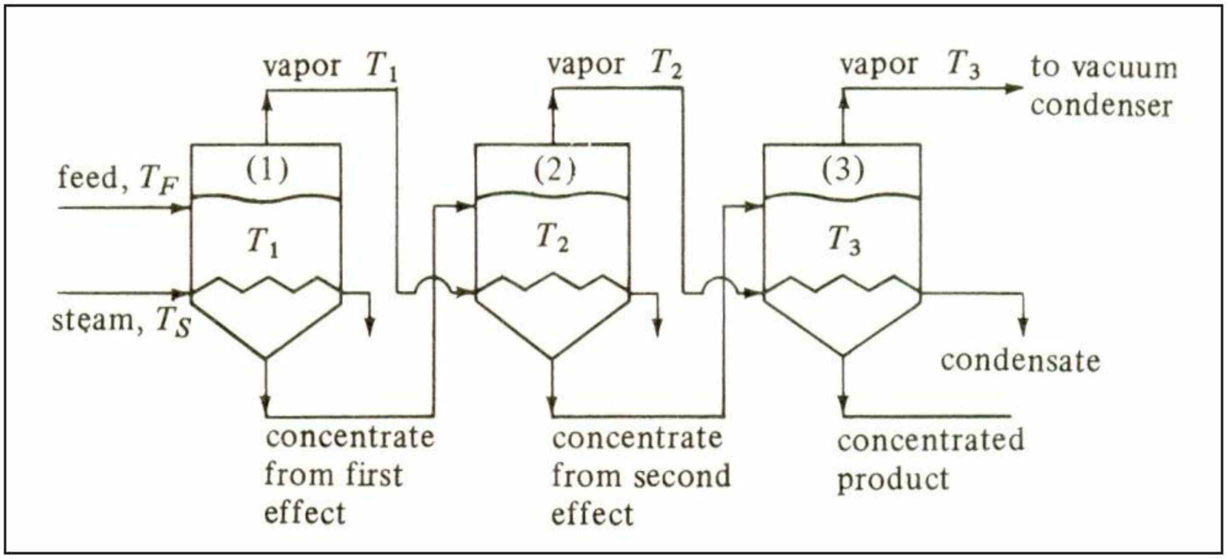

FIGURE 3.4 Simplified diagram of forward -feed triple-effect evaporator

- **If the feed to the first effect is near the boiling point at the pressure in the first effect, 1kg of steam will evaporate almost 1 kg of water.**

- The first effect operates at a temperature that is high enough that the evaporated water serves as the heating medium to the second effect.

- Here, again, almost another kg of water is evaporated, which can then be used as the heating medium to the third effect.

- As a very rough approximation, almost 3 kg of water will be evaporated for 1 kg of steam in a three-effect evaporator.

- Hence, the steam economy, which is kg vapor evaporated/kg steam used, is increased.

- This also holds approximately for more than three effects.

- However, the increased steam economy of a multiple-effect evaporator is gained at the expense of the original first cost of these evaporators

- In forward-feed operation as shown in Fig. 8.2-3, the fresh feed is added to the first effect and flows to the next in the same direction as the vapor flow.

- This method of operation is used when the feed is hot or when the final concentrated product might be damaged at high temperatures.

- The boiling temperatures decrease from effect to effect. This means that if the first effect is at $P_1 = 1$ atm abs pressure, the last effect wilt be under vacuum at a pressure P_3.

Backward-feed multiple-effect evaporators

- In the backward-feed operation shown in Fig. 8.2-4 for a triple-effect evaporator, the fresh feed enters the last and coldest effect and continues on until the concentrated product leaves the first effect.

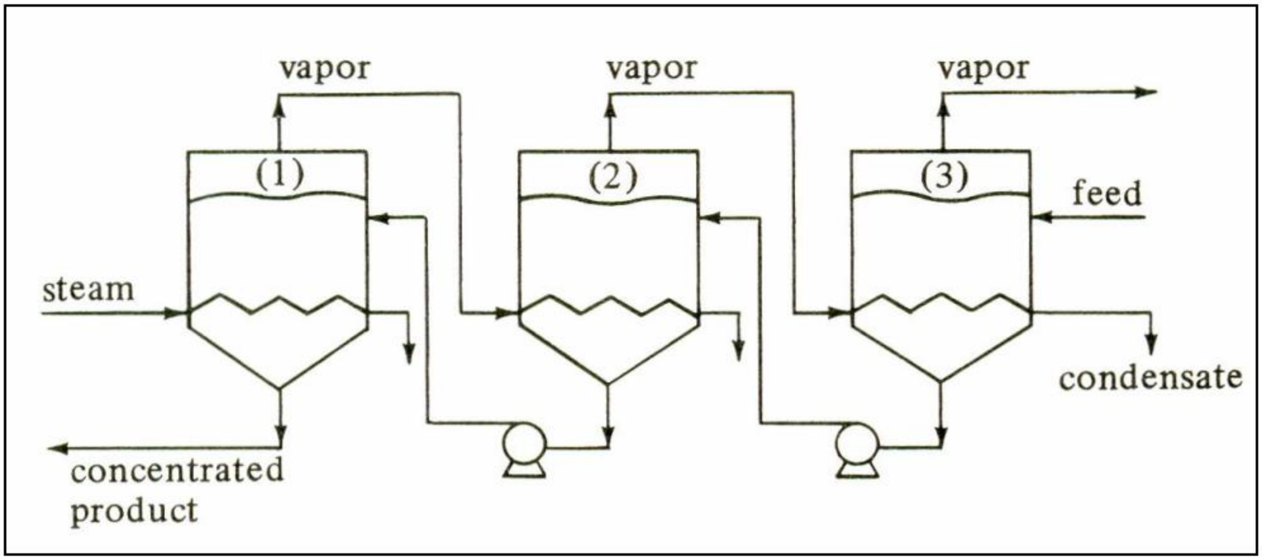

FIGURE 3.5 Simplified diagram backward-feed triple-effect evaporator

- This method of reverse feed is advantageous when the fresh feed is cold, since a smaller amount of liquid must be heated to the higher temperatures in the second and first effects.
- However, liquid pumps must be used in each effect, since the flow is from low to high pressure.
- This reverse-feed method is also used when the concentrated product is highly viscous.
- The high temperatures in the early effects reduce the viscosity and give reasonable heat-transfer coefficients.

Parallel-feed multiple-effect evaporators

- Parallel-feed in multiple-effect evaporators involves the adding of fresh feed and withdrawal of concentrated product from each effect.
- The vapor from each effect is still used to heat the next effect.

- This method of operation is mainly used when the feed is almost saturated and solid crystals are the product, as in the evaporation of brine to make salt.

Overall Heat Transfer Coefficient in Evaporators

The overall heat-transfer coefficient *U* in an evaporator is composed of:

1. The steam-side condensing coefficient, which has a value of about 5700 W/m^2.K (1000 btu/h ft^2.°F);

- The steam-side condensing coefficient outside the tubes can be estimated using Eqs. (4.8-20) through (4.8-26).

1. The metal wall, which has a high thermal conductivity and usually a negligible resistance;

3. The resistance of the scale on the liquid side; and the liquid film coefficient, which is usually inside the tubes

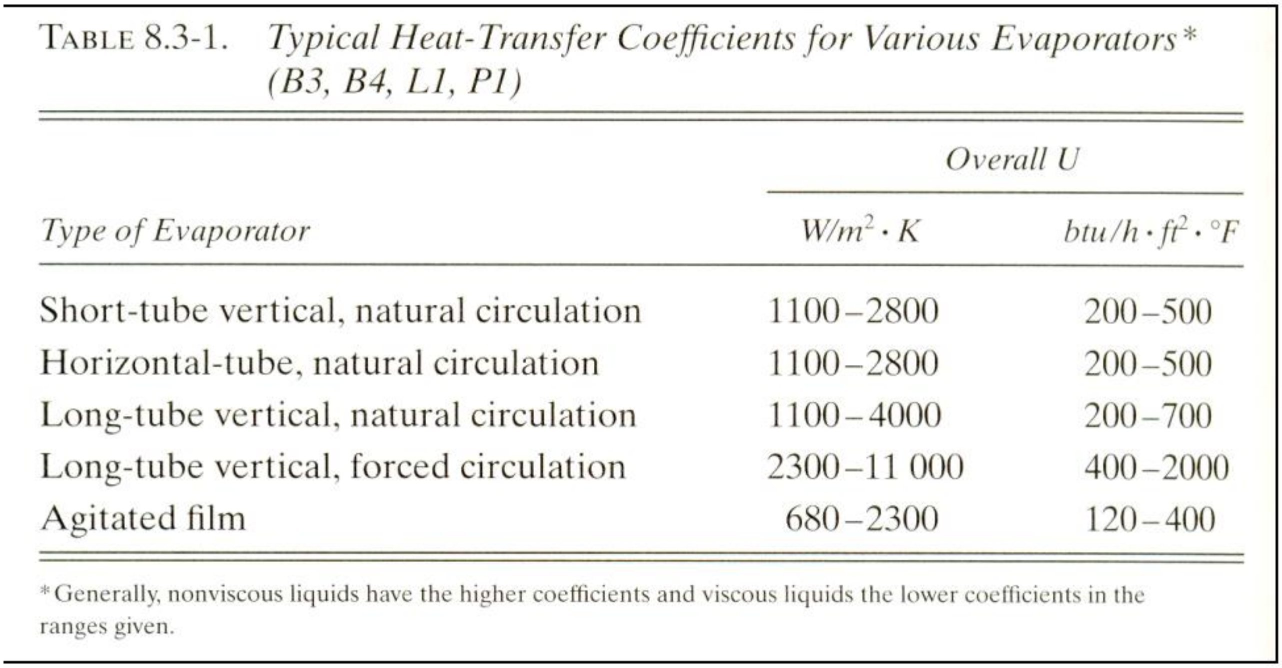

TABLE 8.3-1. *Typical Heat-Transfer Coefficients for Various Evaporators* (B3, B4, L1, P1)*

	Overall U	
Type of Evaporator	*W/m^2 · K*	*btu/h · ft^2 · °F*
Short-tube vertical, natural circulation	1100–2800	200–500
Horizontal-tube, natural circulation	1100–2800	200–500
Long-tube vertical, natural circulation	1100–4000	200–700
Long-tube vertical, forced circulation	2300–11 000	400–2000
Agitated film	680–2300	120–400

*Generally, nonviscous liquids have the higher coefficients and viscous liquids the lower coefficients in the ranges given.

Calculation Methods for Single-Effect Evaporator

- Heat and Material Balances for Evaporators
- Effects of Processing Variables on Evaporator Operation
- Boiling-Point Rise of Solutions
- Enthalpy - Concentration Charts of Solutions