Chapter 17
Evaporation

Dr. Hatem Alsyouri
IMPORTANT NOTES

- Review the use of steam tables
  (always bring them, to the class)
- Review the concepts of enthalpy, latent and sensible heats, and heat transfer coefficient
- Pay attention to units
- Familiarize your self with INTERPOLATION
- Always bring the steam tables to class (in different units).
Evaporation is a unit operation used to increase concentrations of process solutions. This is accomplished by evaporation of the solvent in an evaporator.

Evaporator design involves determination of:
- flow rates of products (vapor and thick solution)
- Amount and conditions of heating steam
- area of heat transfer needed
- Type of evaporator

Evaporation normally accompanies other operations like crystallization.
Double-effect evaporator system

Feed
10 wt% MgSO₄
1 atm
70°F

Vapor

Condensate

Centrifugal filter

65 wt% crystals

Recycle filtrate

50 wt% crystals

Underflow

Overflow recycle

Hydroclone

Magma
105°F
7,810 lb/h mother liquor

Overflow

2,311 lb/h H₂O Vapor

Combined feed
14,326 lb/h
31 wt% MgSO₄
120°F

Crystallizer

0.867 psia

Concentrated solution

Recycle

7,810 lb/h mother liquor

4,205 lb/h crystals

Air

Rotary dryer

Dried crystals
1.5 wt% moisture
**Continuous-flow, steady state Evaporator Model**

**Assumptions:**

1. One volatile component in feed
2. Steam is saturated (latent heat vaporizes the solution)
3. Boiling creates mixing $\Rightarrow$
   - $T_v = T_e$
   - $T_p = T_e$
4. $T_v = T_p = T_e$ corresponding to evaporator pressure $P$
5. Overall driving force for heat transfer is $\Delta T = T_s - T_p$
6. No heat loss
Mass and Energy Balance

Total and Solute mass balance

\[ m_f = m_p + m_v \]
\[ \omega_f m_f = \omega_p m_p + \omega_v m_v \]

Energy balance on Solution

\[ Q + m_f H_f = m_p H_p + m_v H_v \]

\[ Q = m_s \Delta H^{vap} \]

\[ Q = U A (T_s - T_p) \]

Latent heat for steam \((\lambda)\)
Enthalpy of Solutions
(NaOH-Water)

Figure 17.35 Enthalpy-concentration diagram for sodium hydroxide–water system.
Boiling Point Elevation (BPE) or Boiling Point Rise (BPR)

- Solutions have higher boiling points than pure water. The increase of boiling point over the pure water is called Boiling Point Elevation (BPE).

- BPE is high for concentrated solutions.

- BPE is calculated from empirical (experimental) relations like Duhring rule (e.g., charts are available for NaOH aqueous solution)

- Large liquid head also causes BPE.

- Neglecting the impact of BPE can yield wrong design of evaporator.
Calculation of Boiling Point Elevation (BPE)

Example:

35 wt% NaOH solution at 6 psia

From Steam Table at 6 psia
Boiling point of pure water ($T_w$) = 170 F

Duhring chart
$T_w$ and 35% $\Rightarrow$
Boiling point of solution ($T_{sol}$) = 210 F

BPE = 210 − 170 = 40 F
Example:
At 270°F a 22% CaCl₂ solution has a boiling-point rise of 9.7°F.

Note: Points shown are based mainly on atmospheric boiling point.

Figure 17.33 Nomograph for boiling-point elevation of aqueous solutions.
**Exercise (1)**

**S&H 17-39**

**Subject:** Evaporation of aqueous NaOH in a single-effect evaporator

**Given:** Feed of 50,000 lb/h of a 20 wt% aqueous solution of NaOH at 120°F. Concentration to 40 wt% NaOH at a pressure of 3.7 psia. Heating medium is saturated steam at a temperature 40°F higher than the solution temperature in the evaporator.

**Assumptions:** Perfect mixing in the evaporator. No heat losses.

**Find:**
(a) Boiling-point elevation of the solution
(b) Saturated heating steam temperature and pressure
(c) Evaporation rate
(d) Heat transfer rate
(e) Heating steam flow rate
(f) Economy
(g) Heat-transfer area if $U = 300$ Btu/h-ft$^2$-°F
**Heat Input Utilization**

\[
\text{Economy} = \frac{m_{\text{vapor}}}{m_{\text{steam}}} \quad \ldots \text{(1)}
\]

\[
Q_{\text{steam}} = Q_{\text{feed}} + Q_{\text{vaporization}} \quad \ldots \text{(2)}
\]

\[
m_s \lambda_s = m_f C_p f (T_v - T_f) + m_v \lambda_v \quad \ldots \text{(3)}
\]

Equation (3) is equivalent to the general energy balance equation on the model evaporator:

\[
m_f C_p f (T_f - T_{ref}) + Q_s = m_p C_p p (T_p - T_{ref}) + m_v H_v \quad \ldots \text{(4)}
\]
Exercise (2)  
 McCabe Problem 16.1

A solution of organic colloids in water is to be concentrated from 8 to 45% solids in a single-effect evaporator. Steam is available at 1.03 atm gauge (120.5°C). A pressure of 102 mmHg absolute is to be maintained in the vapor space. The feed rate to the evaporator is 20,000 kg/h. Overall heat transfer coefficient (U) is 2800 W/m².°C. The solution has a negligible BPE and negligible heat of dilution.

Calculate:

(1) the steam consumption ($m_s = 17782$ kg/h)
(2) the economy (0.925)
(3) heating surface area required (56.4 m²)

Conditions: The temperature of the feed is: a) 51.7 °C, b) 21.1 °C, and c) 93.3 °C.

Properties:
Specific heat of the feed solution is 3.77 J/g .°C
Latent heat of vaporization of the solution can ne taken as that of water.

Answers: slight variations from the ideal answers are ok

(b) 21.1 °C:  \( m_s = 18,831 \) kg/h  \( \text{Economy} = 0.873 \)  \( A = 59.7 \) m²
(a) 51.7 °C:  \( m_s = 17,782 \) kg/h  \( \text{Economy} = 0.925 \)  \( A = 56.4 \) m²
(c) 93.3 °C:  \( m_s = 16,356 \) kg/h  \( \text{Economy} = 1.005 \)  \( A = 51.9 \) m²
Enthalpy of feed/product solutions

1) From chart

\[
m_f H_f + Q_s = m_p H_p + m_v H_v
\]

2) Heat capacity values are provided.
A reference temperature (datum) is needed. You can assume 0°C, the reference temp of steam table, or any suitable reference.

\[
m_f C_{p_f} (T_f - T_{ref}) + Q_s = m_p C_{p_p} (T_p - T_{ref}) + m_v H_v
\]

3) Assume water
Use steam tables
Brain Storming Points

1. Factors leading to boiling point elevation and impact of ignoring BPE in calculations
2. The physical meaning of Economy in evaporation and ways to improve economy
3. Main resistances to heat transfer in evaporation and steps to calculate overall heat transfer coefficient
4. Heat of dilution effect
Heat of Dilution
Superheated or Sub-cooled Steam

- Superheated steam
- Sub-cooled steam

Latent heat

Sensible heat

Solid

Liquid

Gas

Supercritical fluid

Pressure (atm)

Temperature (°C)

Sub-cooled

Saturated

Superheated

T1_{SH}

T_{Sat}

T_{2SC}
A single effect evaporator is used to concentrate 7 kg/s of a solution from 10 to 50% solids. Steam is available at 205 kN/m$^2$ and evaporation takes place at 13.5 kN/m$^2$. The overall heat transfer coefficient of heat transfer is 3 kW/m$^2$.$^\circ$K. The feed enters to evaporator at 294 K and the condensate leaves the heating space at 352.7 K. The specific heats of the 10% and 50% solutions are 3.76 and 3.14 kJ/kg.$^\circ$ K respectively.

**Estimate:**

(a) Heating surface area required
(b) Amount of steam used
Multiple Effect Evaporators

1. During evaporation, steam generates vapor. Single effect evaporator can be wasteful of energy if the vapor’s heat content is not used.

2. The latent heat can be recovered and re-used by employing a multiple effect evaporators (MEE).

3. Types of MEE: a) forward, b) backward, and c) parallel feed.

4. How much will 1 kg steam evaporate from solution? (depends on the feed’s temp)

5. What is the driving force for evaporation? (T_{steam}-T_e)

6. Why pressure should successively reduce across evaporators?

7. What is the economy for a 3-effect evaporator if 1 kg steam is used and approximately 1 kg vapor is produced from each evaporator?
**Forward feed**

- **Uses:**
  - Feed is hot
  - Product is heat sensitive

**Backward feed**

- **Uses:**
  - Higher capacity ($m_v$)
  - Feed is cold
  - Lower economy than forward if feed is cold
  - Product is viscous

\[ P \downarrow \text{ and } T \downarrow \]

---

P

\( \downarrow \)

T

\( \downarrow \)
Parallel feed

Mixed feed

- Permits final evaporation to be done at the highest temperature
Cost savings by multiple effect

<table>
<thead>
<tr>
<th>Type</th>
<th>Approx. installed cost (£)</th>
<th>Cost of steam (£/year)</th>
<th>Net saving compared with single effect (£/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single effect</td>
<td>50,000</td>
<td>403,000</td>
<td>—</td>
</tr>
<tr>
<td>Double effect</td>
<td>70,000</td>
<td>214,000</td>
<td>189,000</td>
</tr>
<tr>
<td>Double effect with vapour compression</td>
<td>90,000</td>
<td>137,000</td>
<td>266,000</td>
</tr>
<tr>
<td>Triple effect</td>
<td>100,000</td>
<td>143,000</td>
<td>260,000</td>
</tr>
</tbody>
</table>

Table 14.3. Comparison of various systems for the concentration of a protein liquid
### Overall Heat Transfer Coefficient (U)

<table>
<thead>
<tr>
<th>Type Evaporator</th>
<th>U (Btu/h-ft$^2$-°F)</th>
<th>U (W/m$^2$-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal-tube</td>
<td>200–500</td>
<td>1,100–2,800</td>
</tr>
<tr>
<td>Short-tube vertical</td>
<td>200–500</td>
<td>1,100–2,800</td>
</tr>
<tr>
<td>Long-tube vertical</td>
<td>200–700</td>
<td>1,100–3,900</td>
</tr>
<tr>
<td>Forced circulation</td>
<td>400–2,000</td>
<td>2,300–11,300</td>
</tr>
</tbody>
</table>
Condensed milk is produced by evaporation of milk in a falling film evaporator containing stainless steel tubes 32 mm in diameter and 6 m long. Evaporation takes place at 60°C, which is the boiling point of milk at 2.7 lb/in² absolute, using steam at 70°C. The feed rate is 40 kg/h per tube at 60°C.

(a) Estimate the internal coefficient $h_i$ and the overall coefficient $U$
(b) What is the evaporation rate per tube?
(b) If the raw milk has 13.5% fat plus solids, what is the concentration of the condensed milk?
(c) Calculate the average residence time in the evaporator. The properties of milk at 60°C are:

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ (cP)</th>
<th>$\rho$ (kg/m³)</th>
<th>$k$ (W/m.K)</th>
<th>$\lambda$ (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw milk</td>
<td>0.94</td>
<td>1010</td>
<td>0.62</td>
<td>2357</td>
</tr>
<tr>
<td>25% solids</td>
<td>1.6</td>
<td>1030</td>
<td>0.55</td>
<td>2357</td>
</tr>
</tbody>
</table>
Types of Evaporators

- (a) Horizontal tube
- (b) Short vertical tube
- (c) Long vertical tube
- (d) Forced circulation

Product viscosity
Heat sensitivity
Scale formation and deposition
# Evaporator Selection

<table>
<thead>
<tr>
<th>Operational category</th>
<th>Evaporator type</th>
<th>Feed condition</th>
<th>Suitable for heat-sensitive products</th>
<th>Retention time (s)</th>
<th>Holding volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recirculating</td>
<td>Calandria&lt;sup&gt;d&lt;/sup&gt; (short vertical tube)</td>
<td></td>
<td>No</td>
<td>168</td>
<td>3.03</td>
</tr>
<tr>
<td></td>
<td>Forced circulation</td>
<td></td>
<td>Yes</td>
<td>41.6</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>Falling film</td>
<td></td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
<td>Not available</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Natural circulation (thermo-siphon)</td>
<td></td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
<td>16</td>
<td>10.1</td>
</tr>
<tr>
<td>Single pass</td>
<td>Agitated film (vertical or horizontal)</td>
<td></td>
<td>Yes</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Tubular (long tube)</td>
<td></td>
<td>Yes</td>
<td>Not available</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td>Falling film</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rising film</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single pass special type</td>
<td>Rising-Falling concentrator</td>
<td></td>
<td>Yes</td>
<td>0.45</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Plate (can be recirculating)</td>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Applicable to conditions noted
- Applicable over lower portion of range noted

---

a. Viscosities are at operating temperatures
b. Based on agitated film evaporator = 1.0
c. Based on agitated film evaporator = 1.0, proportioned to equal surface
d. Special disengagement arrangement required for foamy liquids
e. May be used in special cases