Evaporation
Outline

• Difference between evaporation and boiling
• Purposes of evaporation
• Boiling point and factors that affect it
• Determination of boiling point of a solution
• Types of evaporators
• Capacity and economy of evaporator
• Energy conservation techniques
  – Multiple effects
  – Vapor recompression (Thermal or mechanical)
What is Evaporation?

- **Evaporation**
  - Occurs at any temperature above melting point
  - Occurs at surface of liquid
  - Heat is generally added from top
  - Only molecules with high kinetic energy participate
  - Slow process
  - Does not involve formation of bubbles

- **Boiling**
  - Occurs at boiling point
  - Occurs throughout liquid
  - Heat is generally added from bottom
  - Rapid process
  - Involves formation of bubbles
Purposes of Evaporation

• Concentrate liquid foods
• Energy savings in subsequent operations (e.g. spray drying)
• Reduces weight (and volume)
  – Energy savings in storage and transportation
• Reduces water activity (preservation)
• Changes flavor and/or color (caramelized syrups in baking)

Products: Salt, sugar, milk, juices, tomato paste, hard candies, purees
Vapor Pressure

• Consider a liquid in a beaker at atmospheric pressure
• The molecules at the surface are bound by only the molecules below it
  – All other layers have binding forces from the layers above and below it
• Thus, some molecules (having higher kinetic energy), leave the bulk of the liquid in vapor form and exert a pressure back on the liquid surface
  – This is the vapor pressure of the liquid at that temperature
• Vapor pressure increases non-linearly with temperature
• Volatile liquids have a high vapor pressure at ambient temperature
Boiling Point

• Boiling point is the temperature at which vapor pressure of liquid equals surrounding pressure
• Boiling point of water at sea level at atmospheric pressure is 100 °C
  – Boiling point in Denver is ~94 °C
  – Boiling point at top of Mt. Everest is ~71 °C
  – Boiling point decreases ~1 °C for every 285 ft elevation
Factors Affecting Boiling Point (BP)

- External pressure
  - Low pressure => low B.P.

- Dissolved solute
  - More solute => high B.P.

- Hydrostatic head
  - B.P. of solution increases with depth
    - Average B.P. of solution based on liquid level halfway up the evaporator is used in design calculations
Elevation in Boiling Point

- When a solute is added to pure water, the boiling point of the resulting solution rises

\[ \ln(X_w) = \frac{\lambda_{\text{vap}}}{R_g} \left[ \frac{1}{T'} - \frac{1}{T} \right] \]

- with

\[ X_w = \frac{m_w / M_w}{m_w / M_w + m_s / M_s} \]

- \( m = \) Mass of solute or water
- \( M = \) Molecular weight of solute or water
- \( X_w = \) Mole fraction of water in the solution
- \( T = \) Boiling point of pure water (in Kelvin)
- \( T' = \) Boiling point of solution after addition of solids (in Kelvin)
- \( R_g = \) Universal gas constant = 8.314 J/mol K
- \( \lambda_{\text{vap}} = \) Latent heat of vap. of water (\( \lambda_{\text{vap}} \) of water at atm. pr. = 2,257.06 kJ/kg = 40,627.08 J/mol)
- \( \Delta T_b = \) Elevation in boiling point = \( T' - T \)

Subscripts: ‘s’ for solute and ‘w’ for water
Elevation in Boiling Point  
(For Dilute Solutions)

\[ \Delta T_b = k_b \ (m) \]

\( k_b \): Molal boiling point constant of solvent  
(\( k_b \) for water = 0.51 °C/mol)

\( m \): Molality (no. of moles of solute per kg of water)
What happens during Evaporation?

- Boiling point of solution rises
  - Due to increase in solid content
- $\Delta T$ between steam and product decreases
  - Due to steam temperature remaining constant and product temperature (boiling temperature) increasing
- Rate of heat transfer decreases
  - Due to $\Delta T$ between steam and product decreasing
Equipment Involved

• Indirect contact heat exchanger (steam)
  – Supplies sensible and latent heat

• Vacuum pump (reduces B.P. & hence product damage)
  – Hence $\Delta T$ between steam & product increases

• Vapor-liquid separator
  – Separate vapor (undesirable) from product (desirable)

• Condenser
  – To condense vapor and remove it from system

• Pre-heater (optional)
  – Increases efficiency of operation
Types of Evaporators

- Batch-type pan
- Natural circulation
- Rising-film
- Falling-film
- Rising/falling-film
- Forced circulation
- Agitated (or mechanical) thin-film
Types of Evaporators (contd.)

Egg Shaped Batch

Calandria Type

Short Tube vertical
Types of Evaporators (contd.)

Natural Circulation   Forced Circulation Long Tube Vertical   Forced Circulation with Plate HX
Types of Evaporators (contd.)

Rising Film

Falling Film

Falling Film

Steam

Condensate

Vapor

Pump
Types of Evaporators (contd.)

Swept Surface
Capacity and Steam Economy

- **Capacity** ($\dot{m}_v$)
  - Amount of water vaporized per unit time (kg/hr)

- **Steam Economy** (SE)
  - Ratio of mass of water vapor produced to mass of steam used

\[
SE = \frac{\dot{m}_v}{\dot{m}_s} \sim 1.0 \quad \text{for a single effect evaporator}
\]
Mechanisms of Increasing Steam Economy

- Pre-heating the feed
  - Using vapors generated in evaporator
  - Using a non-steam source
    - Steam generation is an expensive operation
- Use of multiple-effects
- Vapor recompression
  - Thermal (steam jet booster)
  - Mechanical (compressor)

Note: The above techniques increase steam economy, but NOT capacity (throughput)
Multiple Effect Evaporator

- Principle
  - Vapor produced in one effect (evaporator) is used as heating medium in next effect (evaporator)
  - This reduces total energy requirement
  - Required ΔT between steam/vapor and product is created by progressively decreasing boiling point of the solution in each effect (by lowering pressure)

- Capacity of a triple-effect evaporator is generally less than one-third that of 3 single-effect evaporators with the same exit temperatures

- Optimum number of effects is determined by factoring extra cost in adding more effects and the corresponding decrease in steam requirement

- Configurations/arrangements
  - Forward feed, backward feed, mixed feed, and parallel feed
Single Effect Evaporator
Multiple Effect Evaporator (Double Effect)
Multiple Effect Evaporator
(Triple Effect)
Multiple Effect Evaporator (Forward Feed)
Multiple Effect Evaporator
(Different Arrangements)

Forward Feed

Backward Feed

Parallel Feed
Vapor Recompression

• Principle
  – Driving force for heat transfer to product is increased by pressurizing vapor exiting evaporator (which is then used as the heating medium), and consequently increasing the condensing temperature of the vapor/steam

• Categories of vapor recompression
  – Thermal
  – Mechanical
Thermal Recompression

• Principle
  – Compression of vapors using steam-jet booster (also referred to as jet ejector)
  – Yields more steam (at high temperature & pressure) than required for boiling; hence excess steam must be vented or condensed
  – Ratio of motive steam to vapor from the solution depends on the evaporation pressure
    • For many low temperature operations, with steam at 8-10 atm, ratio of steam required to mass of water evaporated is ~ 0.5. This system is used in a single-effect evaporator or in the first stage of a multiple-effect evaporator. The use of this system requires that steam be available at high pressure, and low-pressure steam is required for the evaporation process.
Thermal Recompression (Forced Circulation)

1. Steam jet
2. Venturi tube
3. Circulation pump
F. Feed
P. Concentrated product
S. Steam
C. Condensate
V. Vapor
V₁. Vapor that is not recompressed (goes to condenser or another stage)
Mechanical Recompression

- Principle
  - Involves compression of vapor leaving evaporator using mechanical means (compressor driven by an electric motor, a steam turbine or a gas engine)
  - Cold feed is preheated to almost its boiling point by exchange of heat with hot thick liquor and is pumped through a heater
  - Vapor evolved is compressed to a high pressure by a compressor; this serves as “steam” and is fed into the heater
  - Since the saturation temperature of compressed vapor is higher than the boiling point of feed, heat flows from the vapor to the solution, generating more vapor; a small amount of make-up steam may be necessary
  - Mechanical recompression systems can reduce energy requirements by the same amount as adding 15 effects
Mechanical Recompression
(Natural Circulation)
Mechanical Recompression (Forced Circulation)
Thermal versus Mechanical Recompression

• Thermal (steam jet)
  – Advantages
    • Can handle large volumes of low-density vapor
      – Hence, it is preferred over mechanical recompression for vacuum operation
    • Cheaper and easier to maintain than compressors
  – Disadvantages
    • Mechanical efficiency is low
    • Lacks the flexibility towards change in operating conditions

• Mechanical
  – Applications
    • Concentration of very dilute radioactive solutions
    • Production of distilled water
Design of an Evaporation System

• For each effect, determine steam requirement ($m_s$) by performing
  – Mass balance
  – Solids balance
  – Energy balance

• Use $Q = UA(\Delta T)$ to determine area required for heat transfer
Factors Affecting Rate and Economics of Evaporation

• Fouling
  – Burn-on of product components on heat transfer surface

• Heat transfer coefficient on the product & steam sides \( (h_i \& h_o) \)

• Thermal resistance of the wall \( (\Delta x/kA) \)

• Viscosity of product \( (\mu) \)

• Entrainment (air) and foaming

• Corrosion

• \( \Delta T \) between steam and the boiling product
Summary

• Factors affecting boiling point
  – External pressure (higher the pressure, greater the boiling point)
  – Added solute (adding solute increases boiling point)
    • Mole fraction of solvent ($X_w$) determines boiling point of solution

• Types of evaporators
  – Batch-type pan, natural circulation, rising-film, falling-film, rising/falling-film, forced circulation, agitated (or mechanical) thin-film

• Capacity of evaporator
  – Mass of vapor produced ($\dot{m}_v$)

• Steam economy
  – Ratio of vapor produced to steam utilized ($\dot{m}_v/\dot{m}_s$)

• Energy conservation techniques
  – Multiple effects
  – Vapor recompression (thermal or mechanical)