Combined Heat and Mass Transfer

Lec 4: Evaporation

Content

Introduction, Factors affecting evaporation, Types of evaporators, Heat Transfer in evaporators, Methods of operation, multiple-effect evaporators

Prof. Zayed Al-Hamamre

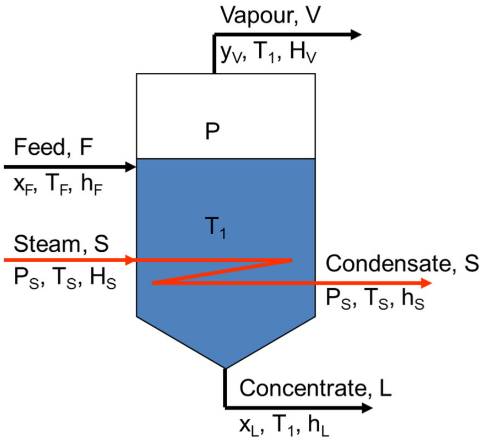
Content

- Introduction
- Factors affecting evaporation
- Types of evaporators
- Heat Transfer in evaporators
- Methods of operation.
- Single and multiple-effect evaporators

Principal reference: Chapter 7 in C.J. Geankoplis, Transport Processes and Separation Process principles., 4th Edition, Prentice-Hall.

Introduction

- Evaporation is the removal of solvent as vapor from a dilute solution consisting of non volatile solute and volatile solvent by boiling the liquor in a suitable vessel, an evaporator, and withdrawing the vapor



- **Objective:** “The aim is to concentrate a non-volatile solute, such as organic compounds, inorganic salts, acids or bases from a solvent.

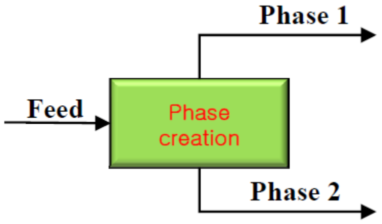
i.e. in evaporation the vapor from a boiling liquid solution is removed and a more concentrated solution remains

- Common solutes such as caustic soda, caustic potash, sodium sulfate, sodium chloride, phosphoric acid, and urea.
- Sugar, milk, orange juice

- The most common solvent in most of the evaporation systems is water.

Introduction

- Evaporation is achieved by adding heat to the solution to vaporize the solvent.
  - The heat is supplied principally to provide the latent heat of vaporization, and,
  - By adopting methods for recovery of heat from the vapor, it has been possible to achieve great economy in heat utilization.



- Compared with other processes

- Evaporation differs from drying in that the residue is a liquid-sometimes a highly viscous one-rather than a solid. Evaporation is normally stopped before the solute starts to precipitate in the operation of an evaporator.

Introduction

Evaporation	Drying
○ Removal of large amount of water from solution or mixture	○ Removal of small amount of water from solid material (moisture)
○ Commonly occurs at boiling point of water	○ Occur at temperature below boiling point and usually be affected by humidity

- It differs from distillation in that the vapor usually is a single component, and even when the vapor is a mixture, no attempt is made in the evaporation step to separate the vapor into fractions.

Processing Factors Affecting Evaporation

1. Concentration

- The density and viscosity increase with solid content until either the solution becomes saturated or the liquor becomes too viscous for adequate heat transfer.
- Continued boiling of a saturated solution causes crystals to form; these must be removed or the tubes clog.
- The boiling point of the solution may also rise considerably as the solid content increases, so that the boiling temperature of a concentrated solution may be much higher than that of water at the same pressure.

As the concentration increases: The viscosity and density increases
thereby the boiling point of solution increases

Processing Factors Affecting Evaporation

2. Solubility:

- As solution is heated, concentration of the solute in the solution increases.
- In case the solubility limit of the solute in solution is exceeded, then crystals may form.
- Solubility of the solute therefore determines the maximum concentration of the solute in the product stream.
- In most cases, the solubility of the solute increases with temperature. This means when a hot concentrated solution from an evaporator is cooled to room temperature, crystallization may occur.

- Evaporation normally accompanies other operations like crystallization.

Processing Factors Affecting Evaporation

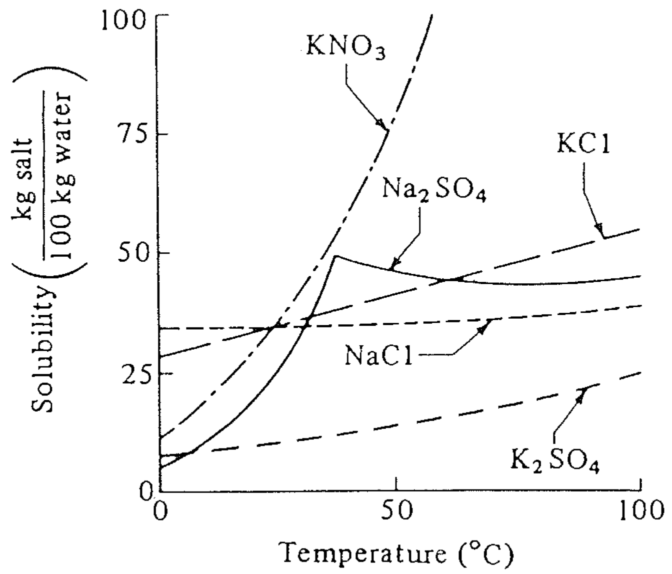


FIGURE 8.1-1. *Solubility curves for some typical salts in water.*

Processing Factors Affecting Evaporation

2. Foaming

- Solutions like organic compounds tend to foam and froth during vaporization.
- A stable foam accompanies the vapor out of the evaporator, causing heavy entrainment.
- In extreme cases the entire mass of liquid may boil over into the vapor outlet and be lost.

4. Scale deposition:

- Some solutions deposit solid materials (called **scaling** or **fouling**) on the heating surfaces.
- The result is that the **overall heat-transfer coefficient** (**U**) may drastically decrease, leading to shut down of the evaporators for **cleaning purposes**.

Processing Factors Affecting Evaporation

5. Temperature sensitivity of materials:

- Pharmaceuticals products, fine chemicals and foods are damaged when heated to moderate temperatures for relatively short times.
- So special techniques are employed to reduce temperature of the liquid and time of heating during evaporation.

6. Pressure and temperature:

- The boiling point of the solution is related to the pressure of the system.
- The higher the operating pressure of the evaporator, the higher the temperature at boiling.
- Also, as the concentration of the dissolved material in solution increases by evaporation, the temperature of boiling may rise (a phenomenon known as **boiling point rise/elevation**).
- To keep the temperatures low in heat-sensitive materials, it is often necessary to operate below atmospheric pressure (that is, under vacuum).

Processing Factors Affecting Evaporation

7. Materials of construction:

- Evaporators are made of some kind of stainless steel.
- However many solutions attack ferrous metals and are contaminated by them.
- Alloys of copper, nickel, and stainless steels can also be used.

6. Toxicity, explosion hazards and radioactivity

Industrial Evaporators

Industrial Evaporators

horizontal tube evaporator

thin-film evaporators

Classification Of Evaporators

(1) Natural circulation evaporators

(a) Long tube vertical falling film evaporator
(b) Long tube vertical climbing up evaporator

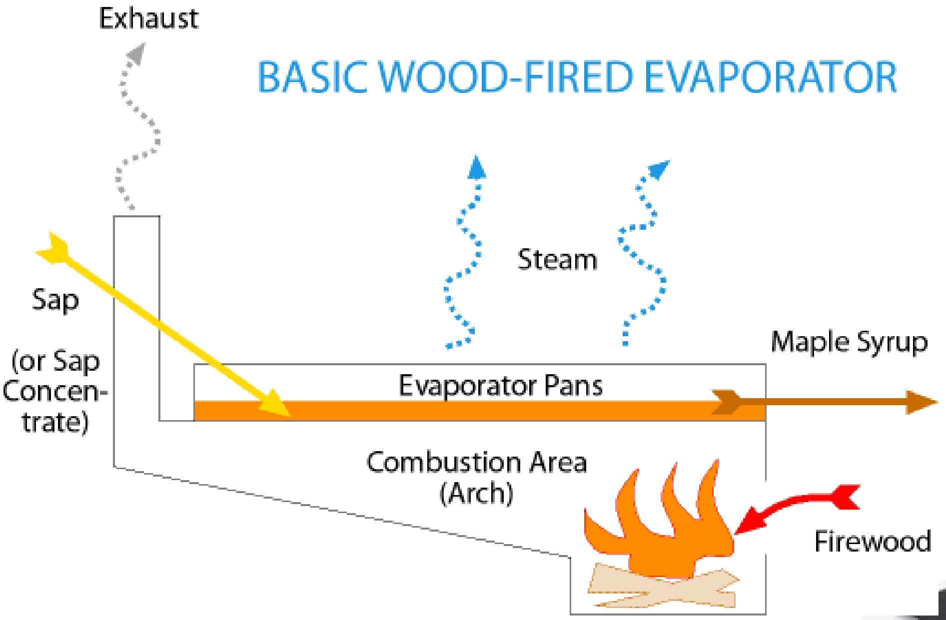
(2) Forced circulation evaporators
(a) Forced circulation evaporator with horizontal heating element
(b) Forced circulation evaporator with vertical heating element

(3) Agitated film evaporator

(4) Based on method of operation evaporators also can be classified as **single effect evaporators and multiple effect evaporators.**

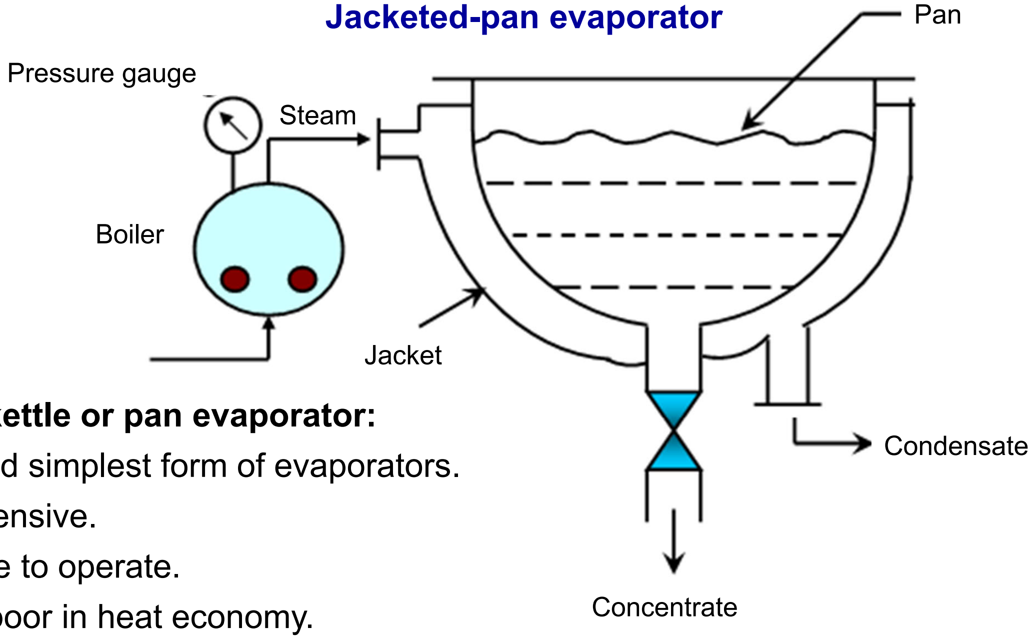
Types Of Evaporators

1. Open kettle or pan evaporator:



Types Of Evaporators

Jacketed-pan evaporator



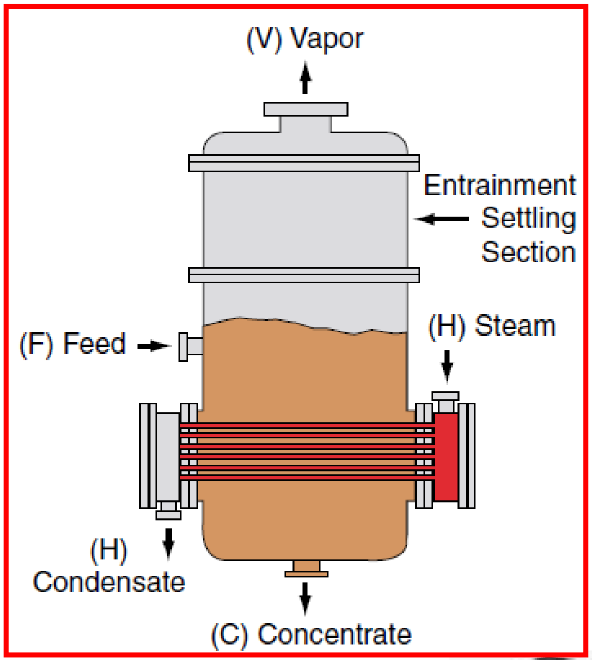
Open kettle or pan evaporator:

- old and simplest form of evaporators.
- Inexpensive.
- Simple to operate.
- Very poor in heat economy.
- In some cases paddles and scrapers for agitation are used.

Types Of Evaporators

2. Horizontal-tube evaporator:

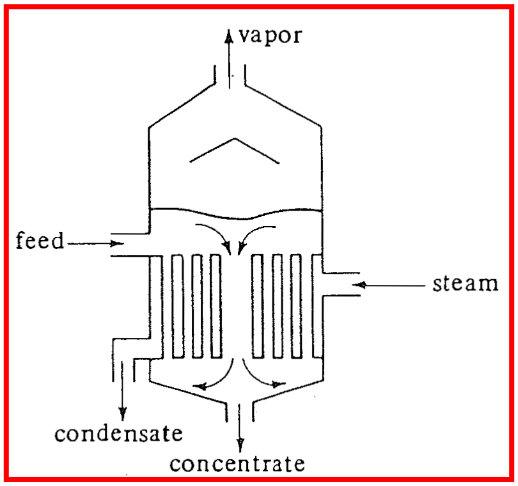
- Old and relatively cheap.
- Heating medium is inside the tubes.
- Used for non-viscous liquids having high heat-transfer coefficients and liquids that do not deposit scales.
- Poor liquid circulation; i.e. unsuitable for viscous liquids).



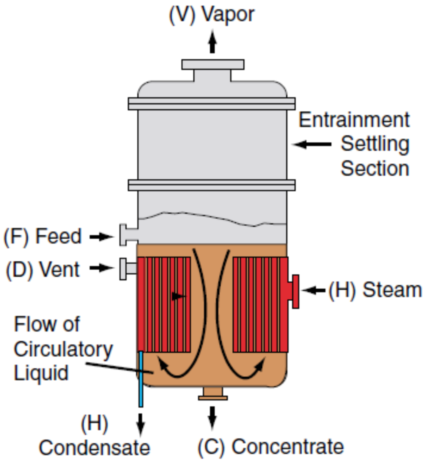
Types Of Evaporators

3. Vertical-type short-tube evaporator:

- Liquid solution is inside the tubes.
- Steam condenses outside the tubes.
- Tubes are around 1-2 m long.
- Used for non-viscous liquids having high heat-transfer coefficients and liquids that do not deposit scales.
- Widely used in sugar, salt, and caustic soda industries.
- it is not for use with temperature-sensitive materials, and it is unsuitable for crystalline products unless agitation is provided



Types Of Evaporators

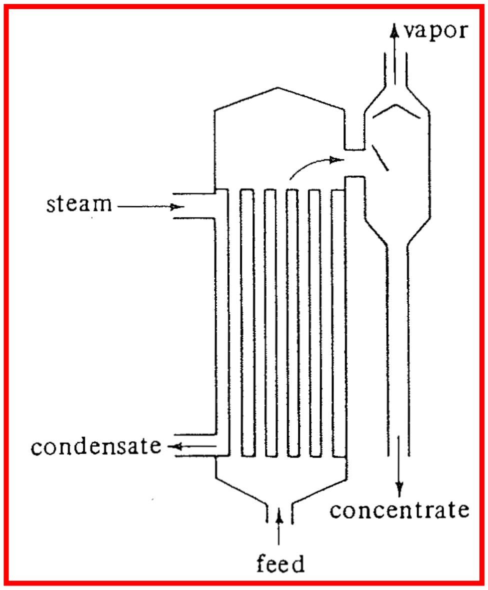


Vertical-type short-tube evaporator:

Types Of Evaporators

4. Vertical-type long-tube evaporator:

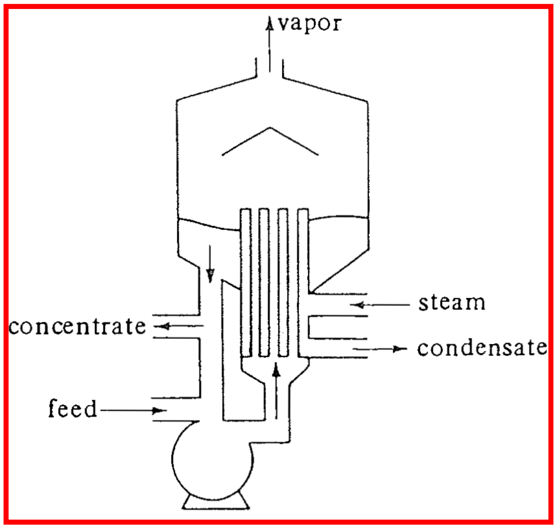
- Feed flows upward through the tubes and heating medium flows downward on the shell side of a long-tube vertical evaporator
- High heat-transfer coefficient on the steam side.
- Tubes are around 3-10 m long.
- Formation of vapor bubble inside tubes gives quite high liquid velocities.
- Some of the common uses are the concentration of cane sugar syrups, black liquor in paper plants, nitrates and electrolytic tinning liquors



Types Of Evaporators

5. Forced circulation evaporator:

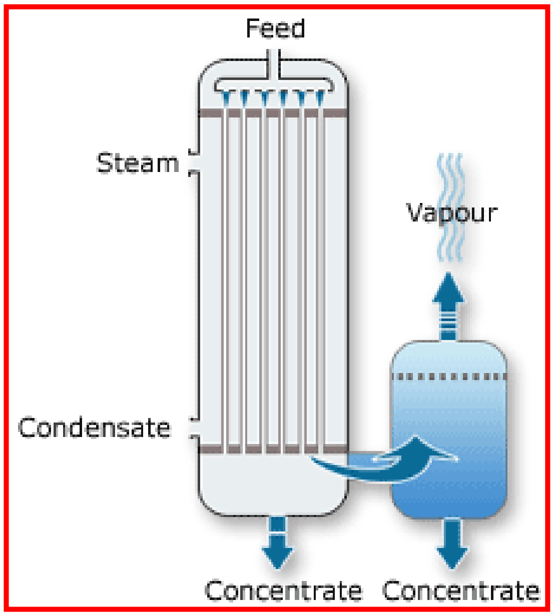
- Similar to vertical long-tube type but with shorter tubes.
- High liquid film hear transfer coefficient (pumping action).
- In some cases, external horizontal type.
- Useful for viscous liquids.



Types Of Evaporators

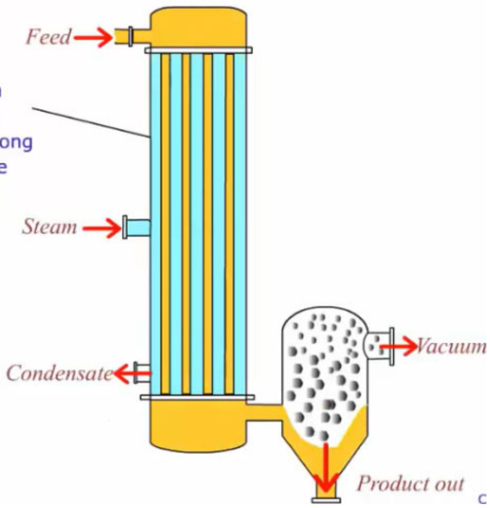
6. Falling-film evaporator:

- Upside down vertical long-tube evaporator.
- Liquid solution flows down (by gravity) near the walls as a thin film inside tubes.
- Vapor liquid separation occurs at the bottom.
- Small holdup time (5-10 s).
- High heat-transfer coefficient.
- Useful for heat–sensitive materials and viscous liquids.

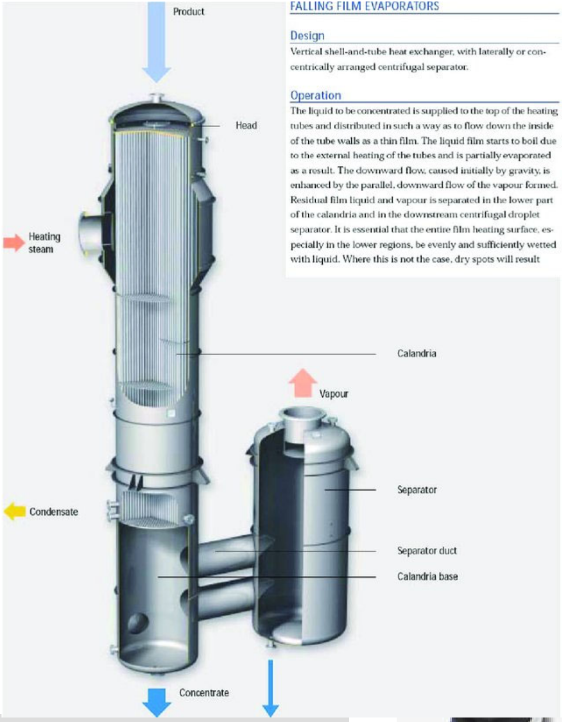


Types Of Evaporators

Falling-film evaporator:



In a falling film evaporator the product falls along the heated pipe surface in a thin film



FALLING FILM EVAPORATORS

Design

Vertical shell-and-tube heat exchanger, with laterally or concentrically arranged centrifugal separator.

Operation

The liquid to be concentrated is supplied to the top of the heating tubes and distributed in such a way as to flow down the inside of the tube walls as a thin film. The liquid film starts to boil due to the external heating of the tubes and is partially evaporated as a result. The downward flow, caused initially by gravity, is enhanced by the parallel, downward flow of the vapour formed. Residual film liquid and vapour is separated in the lower part of the calandria and in the downstream centrifugal droplet separator. It is essential that the entire film heating surface, especially in the lower regions, be evenly and sufficiently wetted with liquid. Where this is not the case, dry spots will result

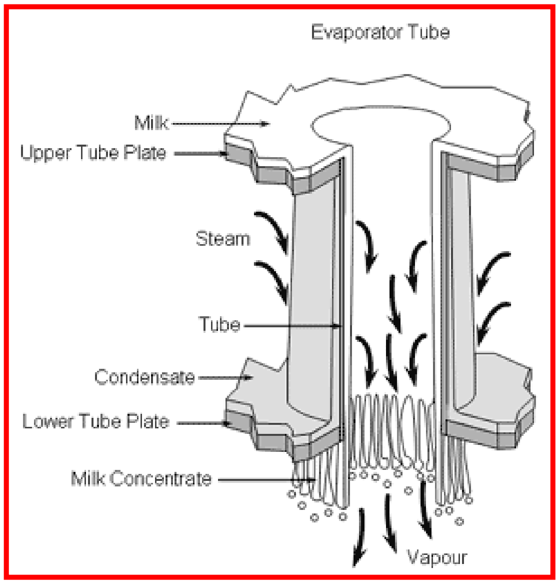
---

Types Of Evaporators

Falling-film evaporator:

- The falling-film evaporator is particularly useful in applications where the temperature driving force between the heating medium and the liquid is small, i.e. very low temperature differences between the heating media and the boiling liquid(less than 15 ^{o}C).

- It is today the most frequently used



Types Of Evaporators

Falling-film evaporator (cont.):

- Typical applications for falling-film evaporators are the concentration of dairy products (such as whey, milk protein, skim milk, cream and hydrolyzed milk), sugar solutions, urea, phosphoric acid and black liquor.
- However, falling film evaporators must be designed very carefully for each operating condition.
  - Sufficient wetting (film thickness) of the heating surface by liquid is extremely important for trouble-free operation of the plant.
  - If the heating surfaces are not wetted sufficiently, dry patches will occur.
  - The proper design of the feed distribution system in the head of the evaporator is critical to achieve full and even product wetting of the tubes.

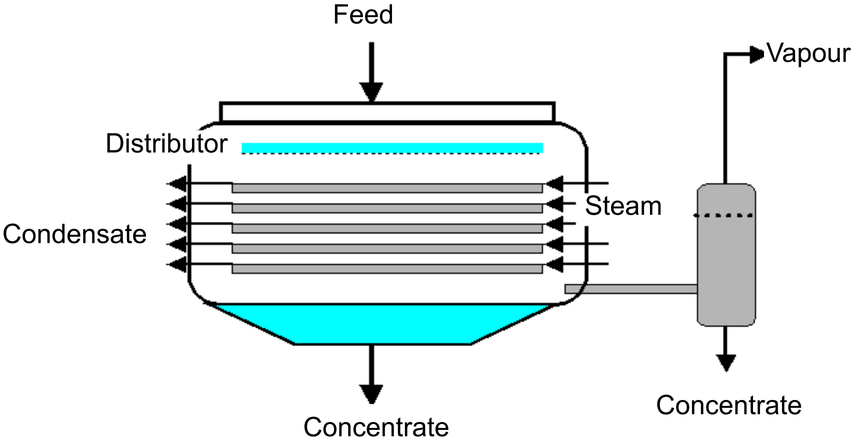
Types Of Evaporators

Falling-film evaporator (cont.):

- Because of the low liquid holding volume in this type of unit, the falling film evaporator can be started up quickly and changed to cleaning mode or another product easily.
- Falling film evaporators are highly responsive to alterations of parameters such as energy supply, vacuum, feed rate, concentrations, etc. When equipped with a well designed automatic control system they can produce a very consistent concentrated product.
- The tube length is typically 6 m to 11 m, but can be as short as 1.5 m to 3 m (for example, in deep vacuum applications).
- Diameters are typically 20 mm to 64 mm.

Types Of Evaporators

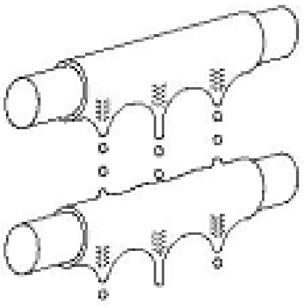
7. Horizontal falling-film evaporator:



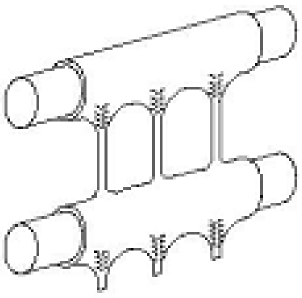
- Liquid solution is evaporated at the outside of the tubes.
- It flows from one tube to the other in form of droplets, jets or as a continuous sheet.

Types Of Evaporators

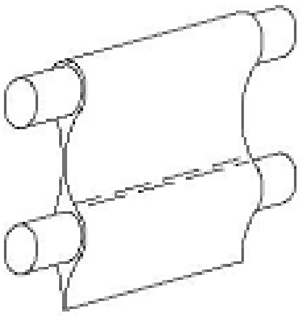
Horizontal falling-film evaporator:



Droplets form



Jets form



Sheet form

Types Of Evaporators

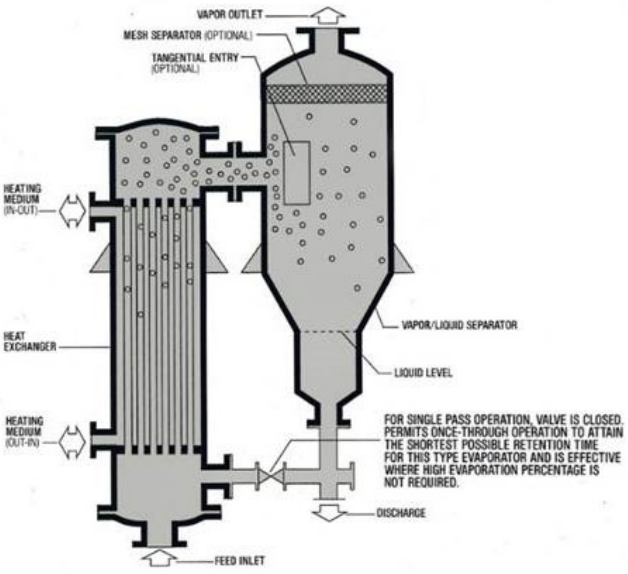
Horizontal falling-film evaporator (cont.:

- Due to the impinging effect when flowing from one tube to the other the heat transfer is higher compared to vertical falling film evaporators.
- In addition, this unit type can be operated with even lower pressure drops compared to the vertical design.
- It is also possible to design a higher heat transfer area for a given shell compared to the vertical units.
- Perforated plates or specially designed spray nozzles can be used in order to guarantee a even liquid distribution for each tube.
- Cleaning of the outside tubes can be difficult, therefore this type of evaporators is not used for processes with tendency to foul.
- Tube dimensions are typically 0.75 to 1".

Types Of Evaporators

Rısıng Fılm Evaporator

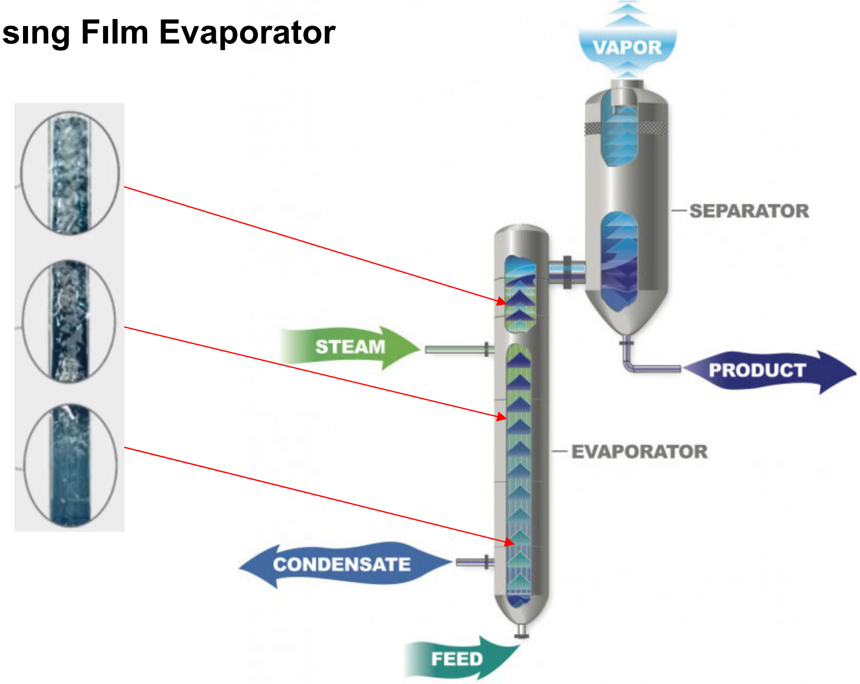
- The rising film evaporator provides a simple solution for concentration, volume reduction of liquids that have moderately heat sensitive products.
- Boiling in vertical tubes promotes vigorous circulation of remaining liquid.
- The liquid and vapor are separated in the cyclone separator.
- Multiple effect arrangement provides the steam economy.



FOR SINGLE PASS OPERATION, VALVE IS CLOSED. PERMITS ONCE-THROUGH OPERATION TO ATTAIN THE SHORTEST POSSIBLE RETENTION TIME FOR THIS TYPE EVAPORATOR AND IS EFFECTIVE WHERE HIGH EVAPORATION PERCENTAGE IS NOT REQUIRED.

Types Of Evaporators

Rising Film Evaporator



Types Of Evaporators

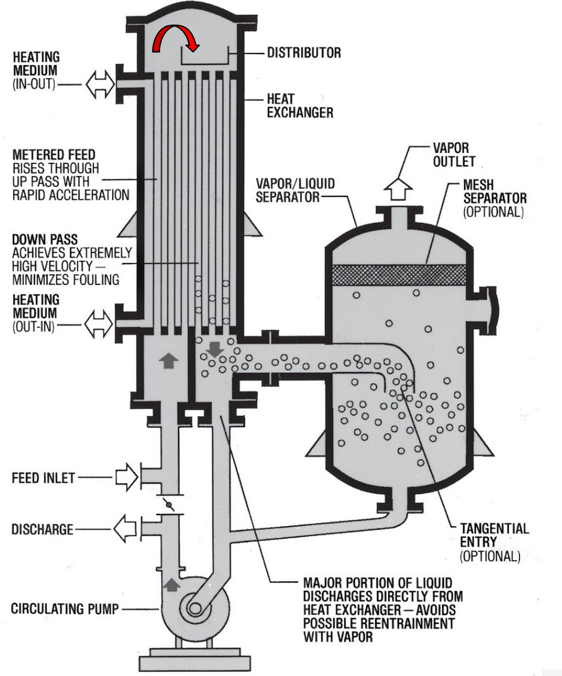
Rising Film Evaporator

- Concentration of dilute solutions containing water and organic solvents in applications such as
  - Contaminated solvents recovery
  - Waste water treatment
  - Plant extracts in water or organic solvents
  - As a reboiler to distillation column

Types Of Evaporators

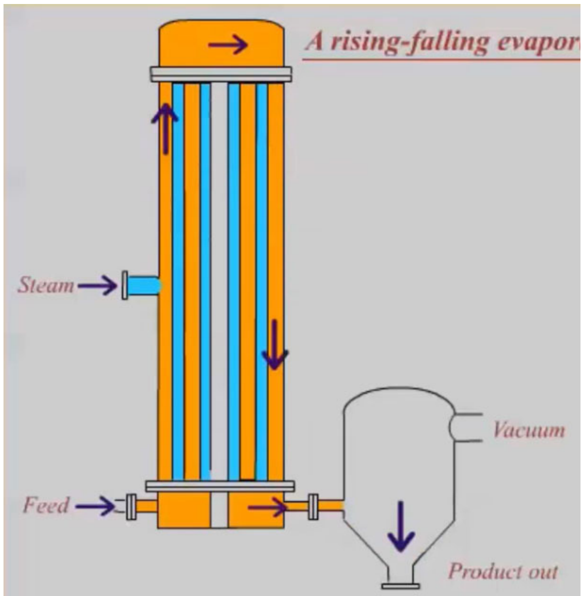
9. Rising/falling film evaporator:

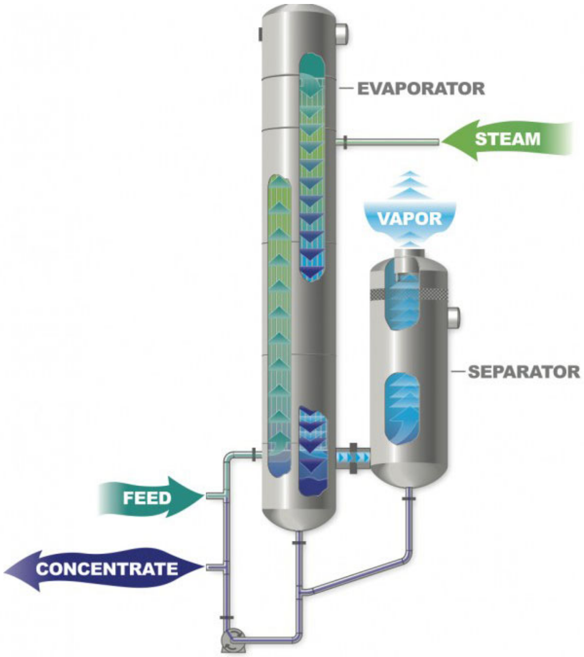
- When a high ratio of evaporation to feed is required and the concentrate may be viscous, a tube bundle can be divided into two sections, with the first functioning as a rising- film evaporator and the second as a falling-film evaporator.
- **Best applied :**
  - For foamy liquids.
  - When large evaporation load are required.



Types Of Evaporators

Rising/falling film evaporator:

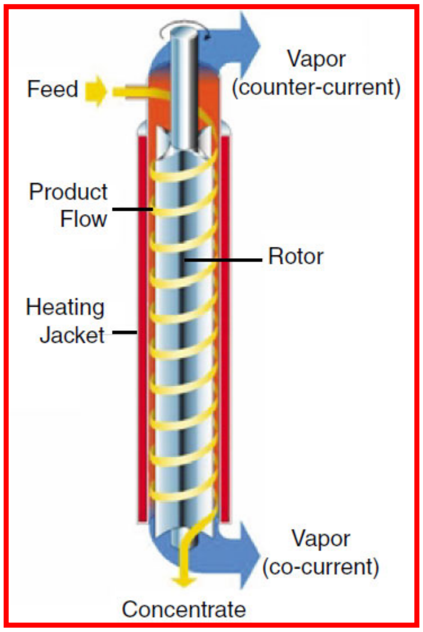




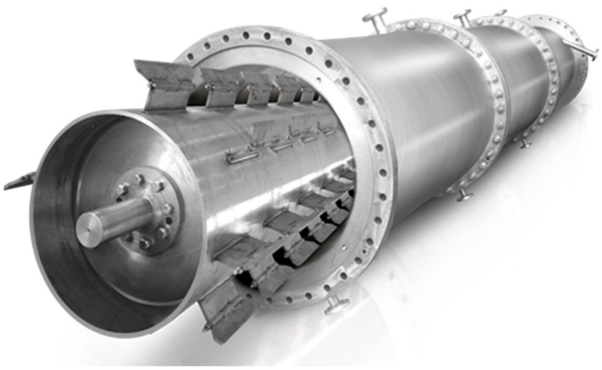
Types Of Evaporators

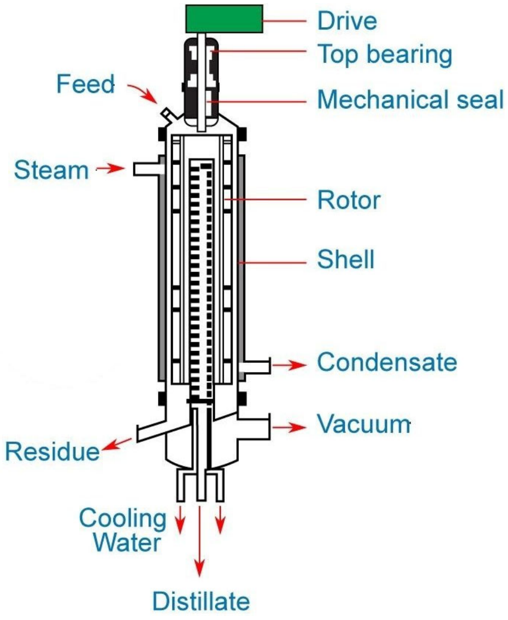
10. Agitated thin-film evaporator:

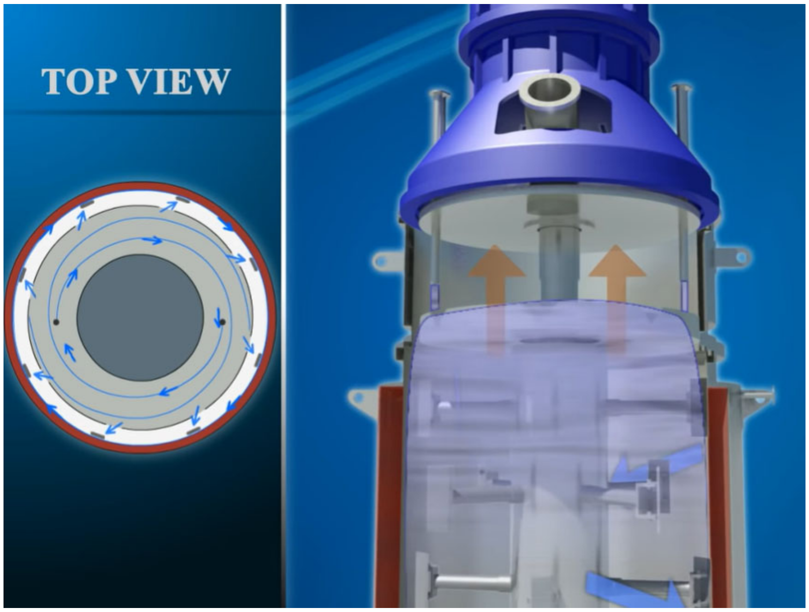
- Falling-film evaporator with only a single jacketed tube containing an internal agitator.
- Liquid solution spread downward into a turbulent film by vertical agitator blades.
- Higher heat transfer coefficient.
- Small residence time
- Widely used for heat sensitive viscous materials such as antibiotics, gelatin, rubber latex
- High cost and small capacity.



Types Of Evaporators






TOP VIEW

Types Of Evaporators

Agitated thin-film evaporator:

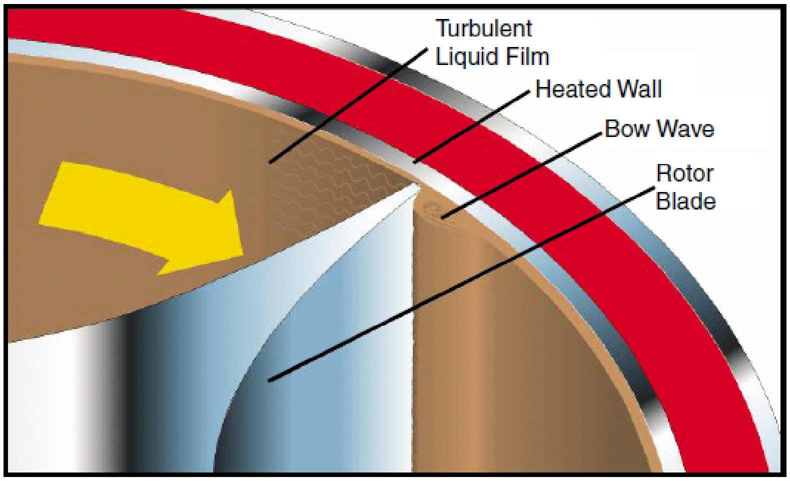


Figure 9. A rotor distributes the feed evenly over the inner circumference of the body of the wiped-film evaporator.

Flow Characteristics In Vertical Film Flow

- The liquid film can be observed in different hydrodynamic conditions.

- This conditions are characterized by **film Reynolds number**, defined as follows:

$$Re_{film} = \frac{4 \text{ x Mass flow rate / circumference}}{\text{Liquid viscosity}} = \frac{4\,(m/\pi D)}{\mu_L} = \frac{4m}{\pi D \mu_L}$$

m mass flow rate of concentrate solution in one tube(kg/s)
D tube diameter (m)
μ_L liquid viscosity (Pa.s)

Flow characteristics in vertical film flow

Pure laminar flow

- $Re_{film} < 30$

- This flow condition can hardly ever be encountered in technical processes.

- Only in very viscous flows this flow condition can be encountered. But even that in literature it is mentioned that wavy behavior was observed!.

$Re_{film} = 10$ (already wavy)

Flow characteristics in vertical film flow

Wavy laminar flow

- $Re_{film} < 1800$

- The thickness of a wavy laminar fluid film is reduced compared to a pure laminar film.

- Smaller average film thickness and increased partial turbulence yield a higher heat transfer compared to pure laminar flow conditions.

$Re_{film} = 500$

Flow characteristics in vertical film flow

Turbulent flow

$Re_{film} > 1800$

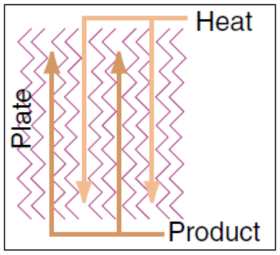
- Apart from the near to the wall laminar sub layer the flow is fully turbulent.

-In this region, heat transfer increases with increased turbulence which means with increased Reynolds number.

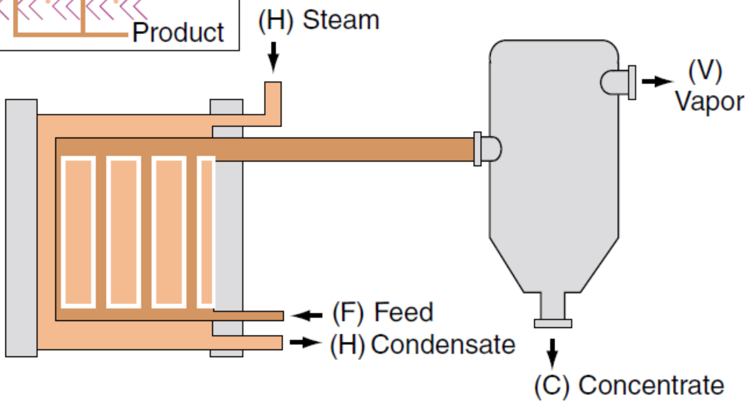
$Re_{film} = 5000$

Types Of Evaporators

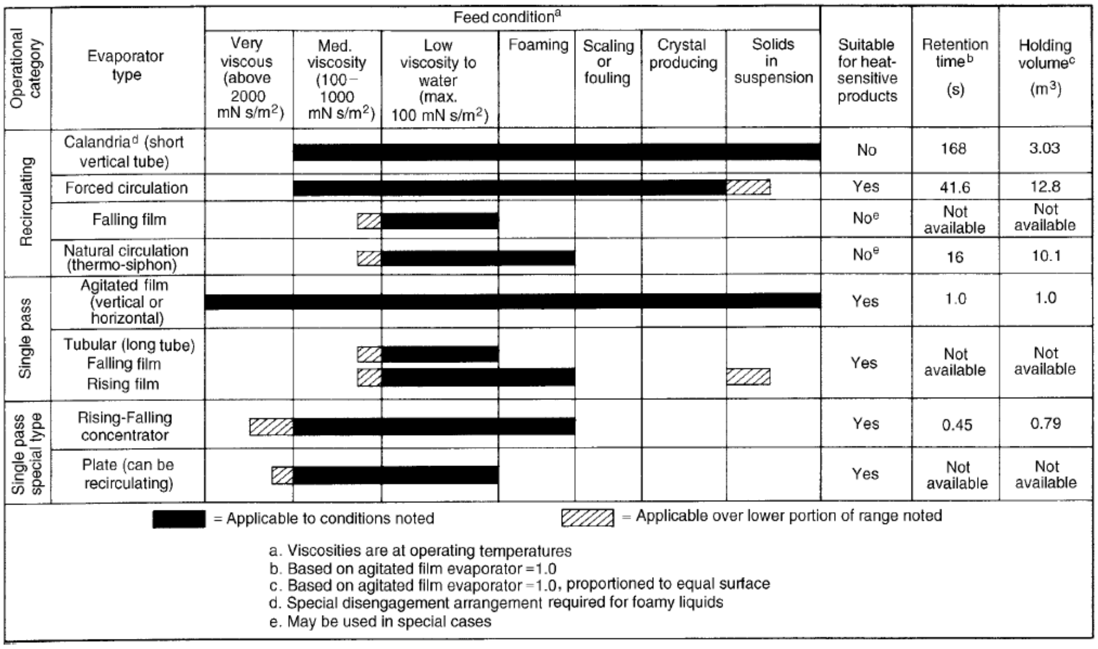
10. Gasket plate-and-frame evaporator:



Typical application: stripping applications, removing monomers from polymers and deodorization



Evaporator Selection



Operational category	Evaporator type	Very viscous (above 2000 mN s/m^2)	Med. viscosity (100–1000 mN s/m^2)	Low viscosity to water (max. 100 mN s/m^2)	Foaming	Scaling or fouling	Crystal producing	Solids in suspension	Suitable for heat-sensitive products	Retention time[b] (s)	Holding volume[c] (m^3)
Recirculating	Calandria[d] (short vertical tube)		■	■	■	■	■	■	No	168	3.03
	Forced circulation		■	■	■	■	■	▨	Yes	41.6	12.8
	Falling film		▨	■					No[e]	Not available	Not available
	Natural circulation (thermo-siphon)		▨	■	■				No[e]	16	10.1
Single pass	Agitated film (vertical or horizontal)	■	■	■	■	■	■	■	Yes	1.0	1.0
	Tubular (long tube) Falling film Rising film		▨ ▨	■ ■	 ■			 ▨	Yes	Not available	Not available
Single pass special type	Rising-Falling concentrator	▨	■	■	■				Yes	0.45	0.79
	Plate (can be recirculating)	▨	■	■					Yes	Not available	Not available

Feed condition[a]

■ = 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

Reference: Coulson & Richardson Vol. 2, Ch. 14

Evaporator Selection

	Short tube	Long tube		Vertical flow		Forced circulating		
		Natural flow	Forced flow	Natural flow	Forced flow	Vertical	Horizontal	Mixer film
Low viscosity fluid	A	A	A	A	A	A	A	X
High viscosity fluid	D	B	B	B	B	A	A	A
Sludge	D	B	B	D	D	A	A	A
Boiler cleaning or salting	C	D	E	D	E	B	B	A
Corrosive liquids	C, E	C, A	C, A	C, A	C, B	C, B	C, B	C, D
Crystal-formation fluids	D	B	B	E	E	B	B	A
Bubbling fluid	D	B	B	E	E	B	B	D
Heat-sensitive liquids	D	A	D	A	D	B	B	B
Conjoined, sticky fluid	X	X	X	X	X	E	B	B
High capacity	D	A	A	B	B	A	A	E
Using as a multiple-effective	A	A	B	A	B	A	A	E
Process feed	B	B	D	D	D	D	D	D
Limited vertical field	A	E	E	E	E	D	A	D
Small pressure difference	D	D	D	A	A	D	D	A
OTHER CRITERIA								
Resistance value	A	A	A	B	B	B	B	D
Power consumption	A	A	A	A	A	B	B	B
Easy cleaning	A	B	B	B	B	B	B	B
Heat transfer efficiency	D	B	B	B	B	A	A	A

Letters: A: Perfect or unlimited, B: Modest limits or problems, C: Minor problems in high value parts, D: limited, E: very limited, X: Not acceptable

Remember

In evaporation the vapor from a boiling liquid solution is removed and a more concentrated solution remains

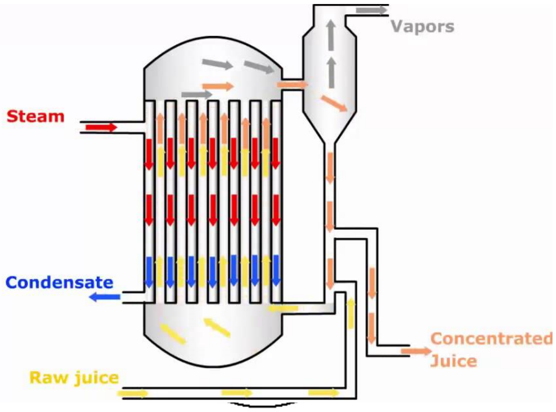
Evaporation is achieved by adding heat to the solution to vaporize the solvent.

- The heat is supplied principally **to provide the latent heat of vaporization**, and,
- By adopting methods for recovery of heat from the vapor, it has been possible to achieve **great economy in heat utilization**.

Method of Operation Of Evaporators

Single-effect evaporation:

- It is simple but utilizes steam ineffectively, the vapor from the boiling liquid is condensed and discarded. This is called single effect evaporation.
- The solution to be concentrated flows inside the tubes.
- The heating medium is steam condensing on metal tubes.

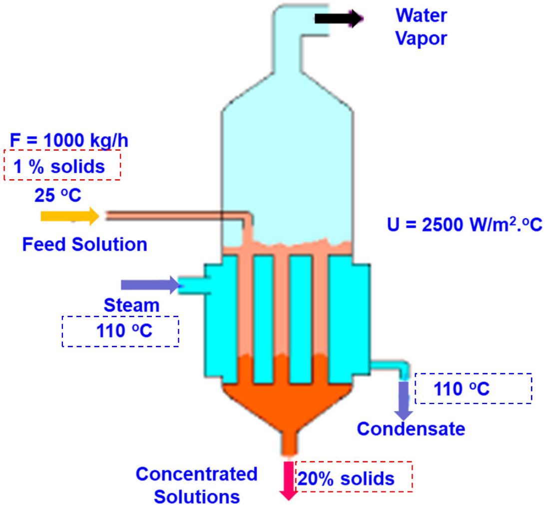


Method of Operation Of Evaporators

Single-effect evaporation:

- Usually the steam enters at 3 atm abs. and boiling liquid is under moderate vacuum.
- This increases the temperature difference between the steam and boiling liquid.

- To evaporate 1 kg of water from the solution we require 1-1.3 kg of steam.



Method of operation of evaporators

Multiple-effect evaporation:

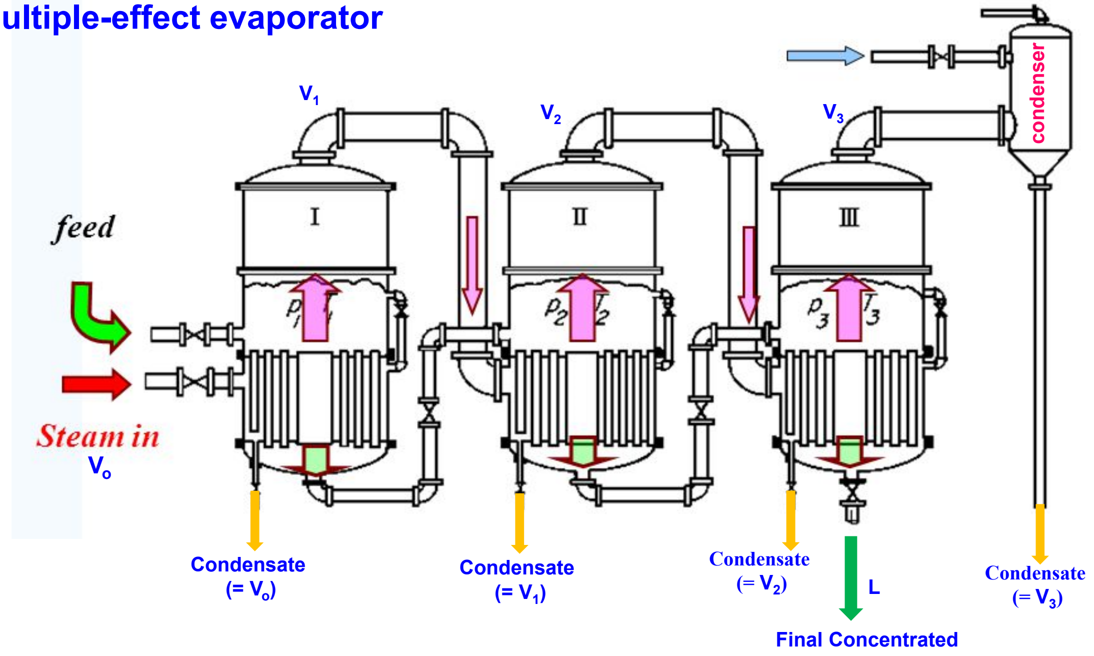
- The vapor produced in the 1st unit is passed to the to a similar unit, provided the boiling temperature in the second unit is reduced so that an adequate temperature difference is maintained.
- This can be effected by applying a vacuum to the second effect in order to reduce the boiling point of the solution.

- Increasing the evaporation per kg of steam by using a series of evaporators between the steam supply and condenser is called multiple effect evaporation
- Each individual effect will have a smaller temperature difference, thus high area of heating surfaces.

- Overall temperature drop for single effect is somewhat equal to multiple effect

Method of operation of evaporators

Multiple-effect evaporator

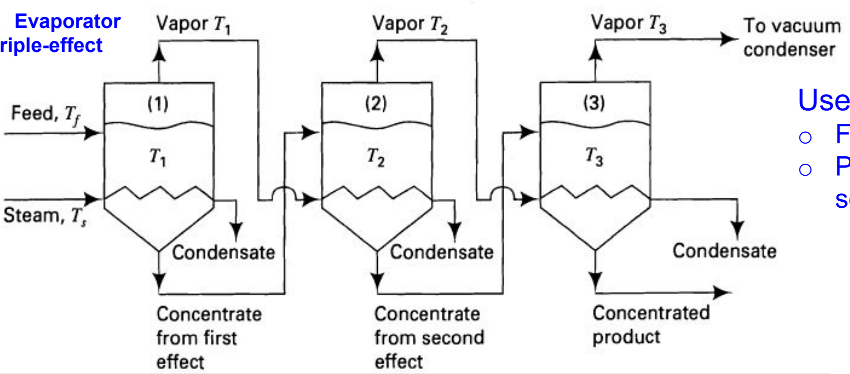


Method of operation of evaporators

Method of operation of evaporators

- **In Multiple Effect Evaporator Forward-feed multiple-effect evaporators**
  - If the feed to the first effect is near the boiling point at the pressure in the first effect, 1 kg 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.

Multiple Effect Evaporator Forward-feed, triple-effect



Uses:
- Feed is hot
- Product is heat sensitive

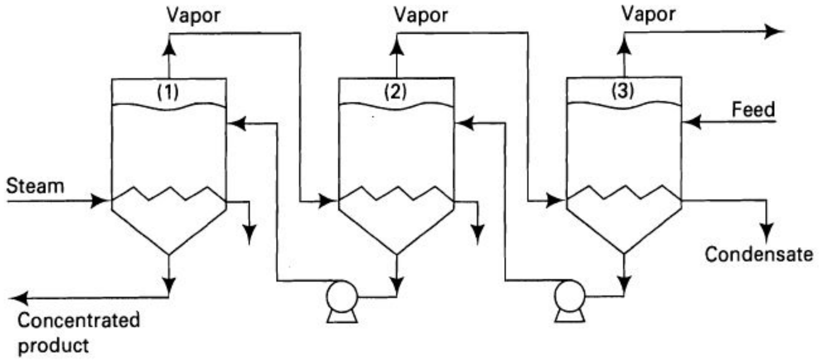
Method of operation of evaporators

- In the figure, 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 will be under vacuum at pressure P_3.
- As a very rough approximation, almost 3 kg of water will be evaporated for 1 kg of steam in a three effect three-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 (Capital cost more costly).

Method of operation of evaporators

Backward-feed multiple-effect evaporators

- The fresh feed enters the last and coldest effect and continues on until the concentrated product leaves the first effect
- This method of reverse feed is advantageous when the feed is cold since a smaller amount of fresh cold, liquid must be heated to the higher temperatures in the second and first effects.



Multiple Effect Evaporator Backward-feed , triple-effect

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

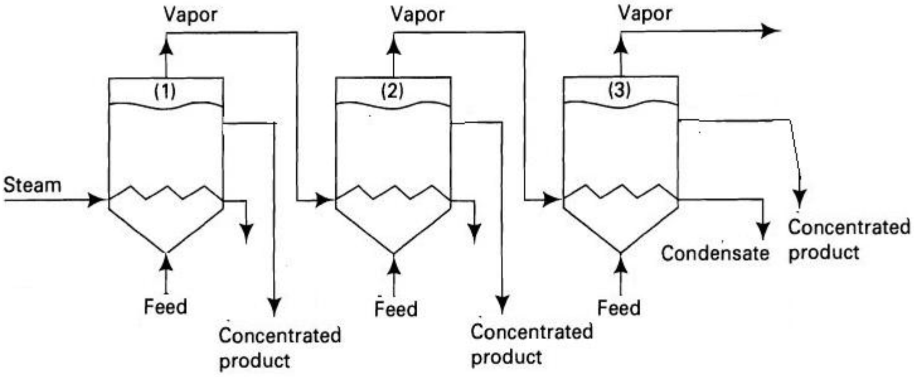
Method of operation of evaporators

- 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.

Method of operation of evaporators

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.



Cost savings by multiple effect

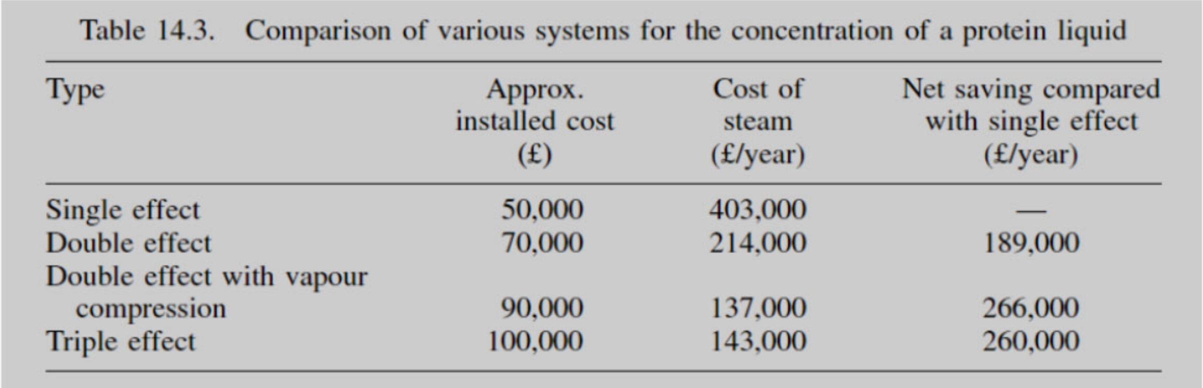
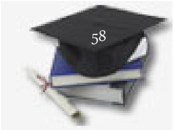


Table 14.3. Comparison of various systems for the concentration of a protein liquid

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



Performance of evaporators

- The basic factors that affect the rate of evaporation are the:
  - i. Rate at which heat can be transferred to the liquid,
  - ii. Quantity of heat required to evaporate each kg of water,
  - iii. Maximum allowable temperature of the liquid,
  - iv. Pressure at which the evaporation takes place,
  - v. Changes that may occur in the foodstuff during the course of the evaporation process

Performance of evaporators

- Capacity is defined as the number of kilograms of water vaporized per hour.

$$\text{Capacity} = \frac{\text{kg of vapor evaporated}}{\text{Time}} = m_V$$

- Economy is the number of kilograms vaporized per kilogram of steam fed to the unit.

$$\text{Economy} = \frac{\text{kg of vapor evaporated}}{\text{kg of steam used}} = \frac{m_V}{m_S}$$

- In a single-effect evaporator the economy is nearly always less than 1, but in multiple-effect equipment it may be considerably greater.

Performance of evaporators

- The steam consumption, in kilograms per hour, is also important. It equals the capacity divided by the economy.

$$\text{kg of steam used} = m_S = \frac{\text{Capacity}}{\text{Economy}}$$

- The rate of heat transfer q through the heating surface of an evaporator is the product of three factors: the area of the heat-transfer surface A, the overall heat-transfer coefficient U, and the overall temperature drop ΔT.

$$q = U \times A \times \Delta T$$

Performance of evaporators

Effect of the feed state on the capacity

- If the feed to the evaporator is at **the boiling temperature** corresponding to the absolute pressure in the vapor space, all the heat transferred through the heating surface is available for evaporation and the capacity is proportional to *q*.

- If the feed is cold, the heat required to **heat it to its boiling point may be quite large** and the capacity for a given value of *q is reduced accordingly, as heat used* to heat the feed is not available for evaporation.

- if the feed is at a temperature above the boiling point in the vapor space, a portion of the feed evaporates spontaneously by adiabatic equilibration with the vapor-space pressure and the capacity is greater than that corresponding to *q. This process is called* ***flash evaporation****.*

Evaporator Economy

Influencing factor

i. Number of effects

- By proper design the enthalpy of vaporization of the steam to the first effect can be used one or more times, depending on the number of effects.

ii. Temperature of the feed

- Feed temperature, T_f if cold, some of steam is used to heat up the feed to the boiling point. If feed is under pressure/vacuum and T_f is above the boiling point, additional vaporization is obtained, flash of hot feed.

iii. **Operating Pressure**: if in vacuum, high ΔT can be obtained, resulting large decrease in heating surface area, A.

iv. **Steam pressure**: increasing steam pressure will increase ΔT, resulting in low A and low capital cost. However the price for high-pressure steam is more costly.

Heat Transfer in evaporators

Design equation: $q = U\,A\,\Delta T = U\,A\,(T_S - T_1)$

Ts : Steam temperature
T_1 : Temperature in the evaporator
A: Surface area

- The overall heat transfer coefficient U consists of the following:
  - Steam-side condensation coefficient.
  - A metal wall with small resistance (depending on steam pressure, wall thickness)
  - Scale resistance on the process side.
  - A liquid film coefficient on the process side.

Heat Transfer in evaporators

- For flow ($Re_{film} < 1800$), the steam-side condensation coefficient for vertical surfaces can be calculated by the following equation:

$$Nu = \frac{h\,L}{k_L} = 1.13 \left[\frac{\rho_L(\rho_L - \rho_V)\, g\, \lambda\, L^3}{\mu_L\, k_L\, \Delta T} \right]^{0.25}$$

- For flow ($Re_{film} < 1800$), the steam-side condensation coefficient for horizontal surfaces can be calculated by the following equation:

$$Nu = \frac{h\,D}{k_L} = 0.725 \left[\frac{\rho_L(\rho_L - \rho_V)\, g\, \lambda\, D^3}{N\mu_L\, k_L\, \Delta T} \right]^{0.25}$$

Heat Transfer in evaporators

Nu	Nusselt number
h	heat transfer coefficient (W/m^2.K)
L	vertical height of tubes (m)
k_L	liquid thermal conductivity (W/m.K)
ρ_L	liquid density (kg/m^3)
ρ_V	vapour density (kg/m^3)
g	$= 9.8066$ m/s^2
λ	latent heat (J/kg)
μ_L	liquid viscosity (Pa.s)
ΔT	$= T_{sat} – T_{wall}$ (K)
D	outside tube diameter (m)
N	Number of horizontal tubes

Heat Transfer in evaporators

- All physical properties of the liquid are evaluated at the film temperature

  $T_{film} = (T_{sat} + T_{wall})/2.$

- λ (latent heat of condensation) is evaluated at T_{sat}.

- For turbulent flow ($Re_{film} > 1800$), the steam-side condensation coefficient for vertical surfaces can be calculated by the following equation:

$$Nu = \frac{h\,L}{k_L} = 0.0077\left[\frac{\rho_L^2\,g\,L^3}{\mu_L^2}\right]^{1/3} Re^{0.4}$$

Heat Transfer in evaporators

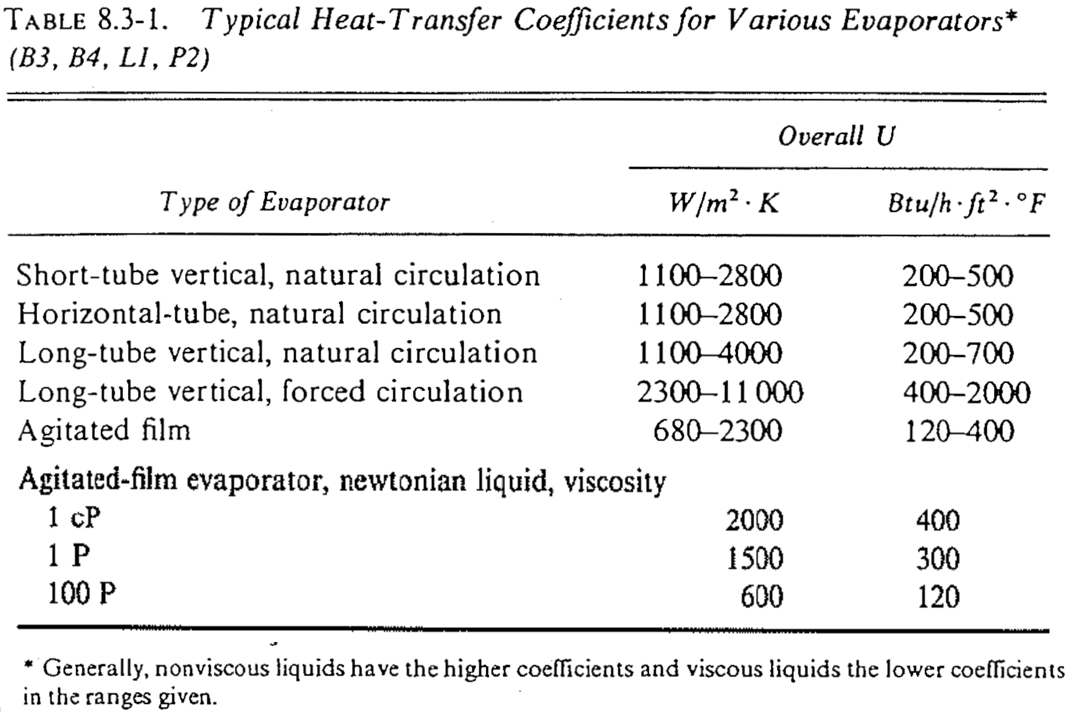
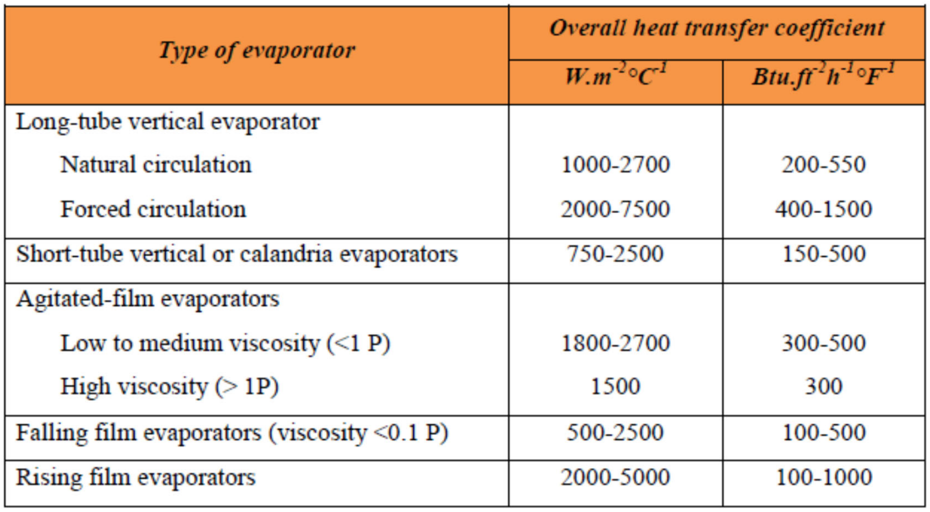


TABLE 8.3-1. *Typical Heat-Transfer Coefficients for Various Evaporators** *(B3, B4, L1, P2)*

Type of Evaporator	*Overall U* $W/m^2 \cdot K$	*Overall U* $Btu/h \cdot ft^2 \cdot °F$
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
Agitated-film evaporator, newtonian liquid, viscosity		
1 cP	2000	400
1 P	1500	300
100 P	600	120

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

Heat Transfer in evaporators



Type of evaporator	Overall heat transfer coefficient	
	$W.m^{-2}°C^{-1}$	$Btu.ft^{-2}h^{-1}°F^{-1}$
Long-tube vertical evaporator		
Natural circulation	1000-2700	200-550
Forced circulation	2000-7500	400-1500
Short-tube vertical or calandria evaporators	750-2500	150-500
Agitated-film evaporators		
Low to medium viscosity (<1 P)	1800-2700	300-500
High viscosity (> 1P)	1500	300
Falling film evaporators (viscosity <0.1 P)	500-2500	100-500
Rising film evaporators	2000-5000	100-1000

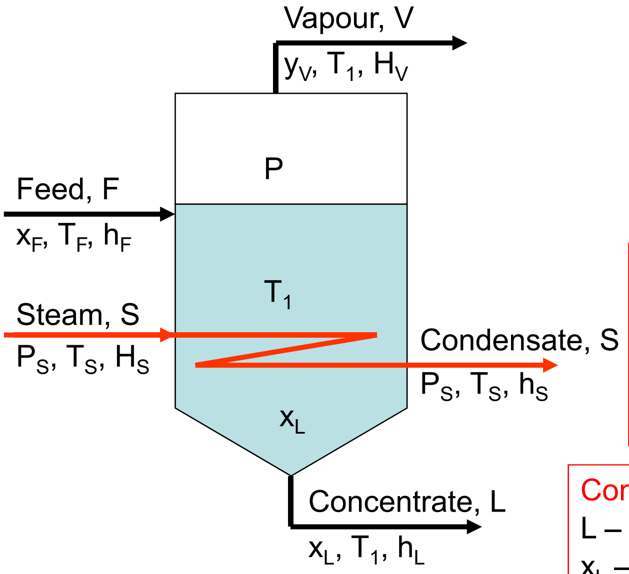
Calculations

- **Calculation for single-effect evaporators**

- **Calculation methods for multiple-effect evaporators**

- 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

Calculation methods for single-effect evaporators



Feed:

F – mass flow rate

x_F – mass fraction of solute in feed

T_F – temperature of feed

h_F – enthalpy of feed

Vapour leaving the evaporator:

V – mass flow rate

y_V – mass fraction of solute in vapour

T_1 – temperature of vapour

H_V – enthalpy of vapour

Concentrate leaving the evaporator:

L – mass flow rate

x_L – mass fraction of solute in concentrate

T_1 – temperature of concentrate

h_L – enthalpy of concentrate

Steam:

S – mass flow rate

P_S – steam pressure

T_S – steam temperature

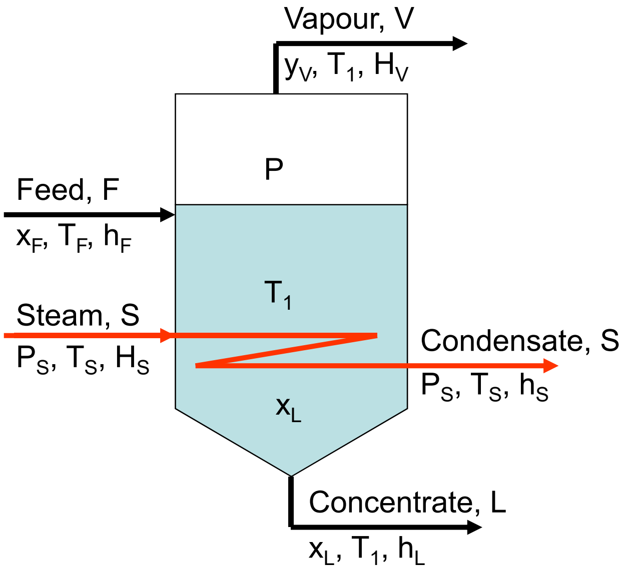
H_S – enthalpy of steam

h_S – enthalpy of condensate

P – pressure in the evaporator

T_1 – temperature in the evaporator

Calculation methods for single-effect evaporators



Overall material balance:

$$F = L + V$$

Solute balance:

$$F x_F = L x_L + V y_V$$

If the vapour is free of solute:

$$F x_F = L x_L$$

Heat balance:

$$F h_F + S H_S = L h_L + V H_V + S h_S$$

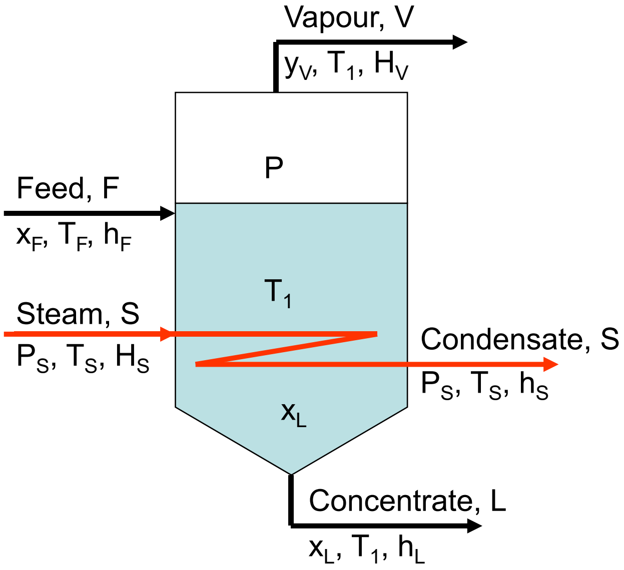
Rewriting:

$$F h_F + S (H_S - h_S) = L h_L + V H_V$$

$$F h_F + S \lambda = L h_L + V H_V$$

where $\lambda = H_S - h_S$

Calculation methods for single-effect evaporators



Energy lost by the steam

$$\boxed{q = S\,\lambda = S\,(H_S - h_S)}$$

In case of no energy loss to the environment, q amount of energy gets transferred from steam to the solution through the tube wall of area A and overall heat transfer coefficient U.

Therefore,

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

Example

A continuous single-effect evaporator concentrates 9072 kg/h of a 1.0 wt % salt solution entering at 38ºC to a final concentration of 1.5 wt %.

The vapor space of the evaporator is at 101.325 kPa (1.0 atm abs) and the steam supplied is saturated at 150 kPa. The overall coefficient U = 1704 W/m^2.K.

Calculate

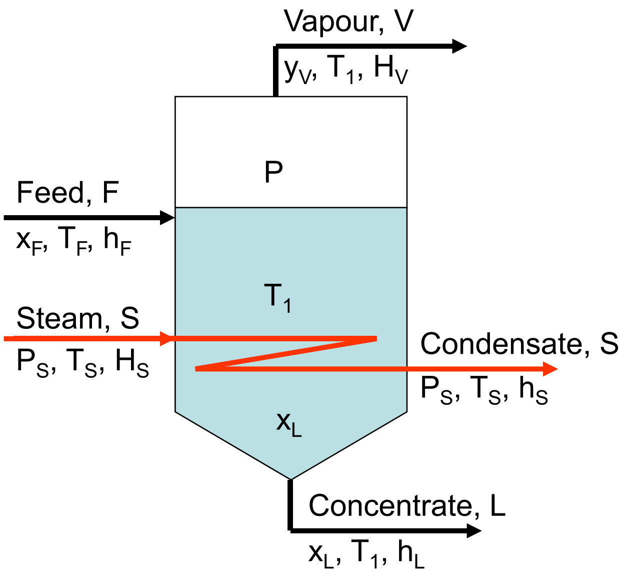
a. The amounts of vapor and liquid products and

b. The heat-transfer area required.

Assumption :

1. Since it its dilute, the solution has the same boiling point as water.
2. Well mixed (Concentration inside evaporator = exist concentration
3. Heat of mixing =0.0
4. BPR=0.0

Solution



Data provided:

$F = 9072$ kg/h

$x_F = 1$ wt % = 0.01 kg solute / kg feed

$T_F = 38$ºC

$x_L = 1.5$ wt %

= 0.015 kg solute / kg liquid product

P = 101.325 kPa (1.0 atm abs)

$P_S = 150$ kPa

U = 1704 W/m^2.K

T_1 = saturated temperature at P (= 101.325 kPa) = 100ºC

T_S = saturated temperature at 150 kPa = 111.4ºC

Solution Cont.d

Data provided:

$F = 9072$ kg/h

$x_F = 0.01$ kg solute / kg feed

$T_F = 38$ºC

$x_L = 0.015$ kg solute / kg liquid product

P = 101.325 kPa; T_1 = 100ºC

P_S = 150 kPa; T_S = 111.4ºC

U = 1704 W/m^2.K

Available equations:

Overall material balance:

$F = L + V$

Solute balance:

$F x_F = L x_L$ (no solute in the vapour)

Heat balance:

$F h_F + S \lambda = L h_L + V H_V$

where $\lambda = H_S - h_S$

$q = S \lambda = U A \Delta T = U A (T_S - T_1)$

Solution Cont.d

Overall material balance:

F = L + V (1)

Solute mass balance:

F x_F = L x_L (no solute in the vapor) (2)

F = 9072 kg/h

x_F = 1 wt % = 0.01 kg solute / kg feed

x_L = 1.5 wt % = 0.015 kg solute / kg liquid product

Solve Eqns. (1) and (2) to have :

L = 6048 kg/h

V = 3024 kg/h

Solution Cont.d

Data known:

F = 9072 kg/h; L = 6048 kg/h, V = 3024 kg/h

T_F = 38°C

P = 101.325 kPa; T_1 = 100°C

P_S = 150 kPa; T_S = 111.4°C

U = 1704 W/m^2.K

Available equations:

Heat balance:

$F\ h_F + S\ \lambda = L\ h_L + V\ H_V$

where $\lambda = H_S - h_S$

$q = S\ \lambda = U\ A\ \Delta T = U\ A\ (T_S - T_1)$

Heat transfer area $A = S\ \lambda / U\ (T_S - T_1)$ **= ?**

$$\begin{aligned} S\ \lambda &= L\ h_L + V\ H_V - F\ h_F \\ &= (F - V)\ h_L + V\ H_V - F\ h_F \\ &= F\ (h_L - h_F) + V\ (H_V - h_L) \\ &= F\ C_{pF}\ (T_1 - T_F) + V\ \text{(Latent heat of vapourization at 101.325 kPa)} \end{aligned}$$

Solution Cont.d

Heat transfer area $A = S\lambda / U(T_S - T_1)$ **= ?**

$S\lambda = F\,C_p\,(T_1 - T_F) + V$ (Latent heat of vapourization at 101.325 kPa)

F, T_1, T_F and V are already known.

$C_p = 4.14$ kJ/kg.K (assumed)

Latent heat of vapourization at 101.325 kPa = 2256.7 kJ/kg Steam table

Therefore,

$S\lambda = (9072)(4.14)(100 - 38) + (3024)(2256.7)$ kJ/h

$= 9152862$ kJ/h

Solution Cont.d

Note: you may assume that the feed is saturated liquid at 38 °C

h_F = enthalpy of saturated water at 38 °C =159.3 kJ/kg

Data known:

$F = 9072$ kg/h; $L = 6048$ kg/h, $V = 3024$ kg/h

$T_F = 38$°C

$P = 101.325$ kPa; $T_1 = 100$°C

h_F (saturated water at 38 °C) = 159.3 kJ/kg

h_L (saturated liquid at T_1 = 100°C) = 419 kJ/kg

H_V (saturated vapor at T_1 = 100°C) = 2676 kJ/kg

Heat balance:

$F\,h_F + S\lambda = L\,h_L + V\,H_V$

Rewriting:

$S\lambda = L\,h_L + V\,H_V - F\,h_F$

$S\lambda = (6048)(419) + (3024)(2676) - (9072)(159.3)$ kJ/h

$= 9181166.4$ kJ/h

Solution Cont.d

Heat transfer area $A = S\lambda / U\,(T_S - T_1)$ **= ?**

$S\lambda$ = 9152862 kJ/h = 9152862 / 3600 W = 2544.9 kW

T_1 and T_S are known

U = 1704 W/m^2.K

Therefore,

$A = S\lambda / U\,(T_S - T_1)$

= [9152862 * 1000 / 3600] / [1704 * (111.4 – 100)]

= **130. 9 m^2**

S =q/λ = 9161583/2230.2= 4108.0 kg/h

Steam economy = V / S = **0.736**

Effects of processing variables on evaporator operation

Effect of feed temperature:

- The inlet temperature of the feed has a large effect on the evaporator operation.
- When feed is not at its boiling point, steam is needed first to heat the feed to its boiling point and then to evaporate it.
- Preheating the feed can reduce the size of evaporator heat-transfer area.

Effect of steam pressure:

- High pressure provides high T_s values, and hence $T_S - T_1$ will increase.
- High pressure steam is however more costly.
- Therefore, overall cost analysis must be considered to determine the optimum steam pressure.

Effects of processing variables on evaporator operation

Effect of pressure:

- Pressure in the evaporator sets the boiling point of the solution (T_1).
- Steam pressure determines the steam temperature (T_s)
- Since $q = U\,A\,(T_S - T_1)$, larger values of $(T_S - T_1)$ will help reduce the heat-transfer area needed and hence the cost of evaporator.
- Vacuum can be maintained in the solution side using a vacuum pump.
- For example, if the pressure in the previous example is reduced to 47.4 kPa, boiling point of water reduces to 80 ºC and that would increase the $(T_S - T_1)$ from 10 ºC to 30 ºC. A large decrease in heat-transfer area would be obtained.

Boiling point rise (BPR) of solutions

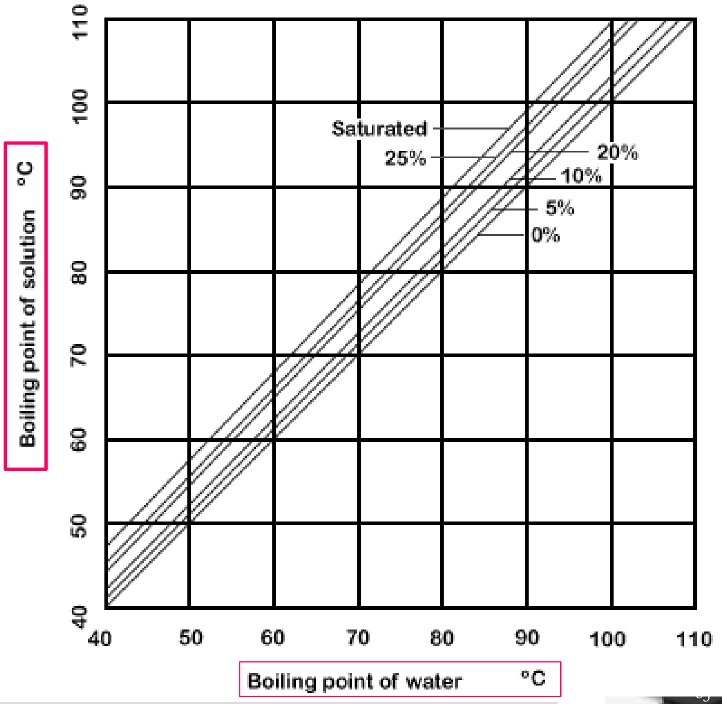
- **Boiling point elevation (BPE) or Boiling point rise of solutions**

$$\boxed{\text{BPE or BPR} = \text{BP}_{\text{solution}} - \text{BP}_{\text{solvent}}}$$

- In the previous Example (Ex. 8.4.1), the solution is assumed to be dilute enough to be considered to have the same thermal properties as water. **It is not true always.**
- For concentrated solutions, heat capacity and boiling point are quite different from that of water.
- **Duhring's rule** is an empirical law that relates the boiling point of a solution to the boiling point of the solvent at different pressures for a solution of given concentration.

Boiling point rise (BPR) of solutions

Duhring lines for boiling point of sodium chloride solutions



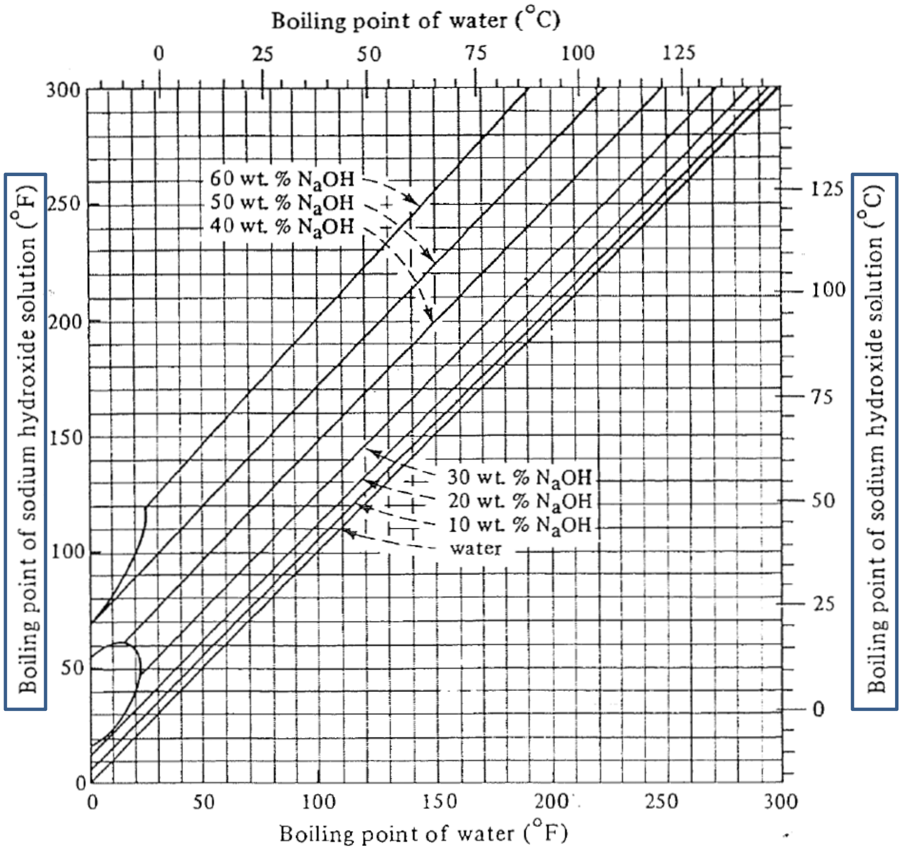


FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

Example

The pressure in an evaporator is given as 1 atm and a solution of 50 wt% NaOH is being boiled. Determine the boiling point temperature and subsequently the boiling proint rise of this solution.

As we know that at 1 atm the BP of water is 212°F

In this case the boiling point is 292°F and so the BPR is 292°F – 212°F = 80°F.

The latent heat of the vapour would be estimated as 1177 Btu/lbm from the saturated steam tables at 292°F or alternatively from the superheated steam tables at 292°F And 14.7 psia as 1189 Btu/lbm.

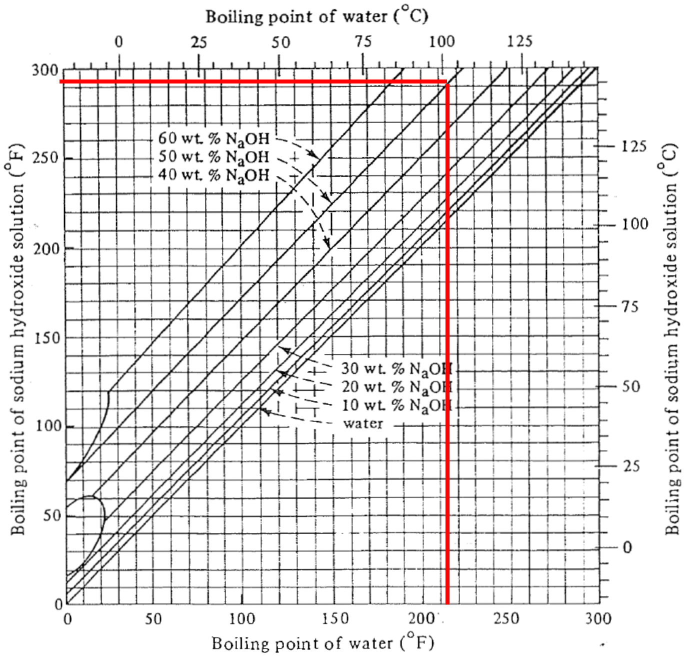


FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

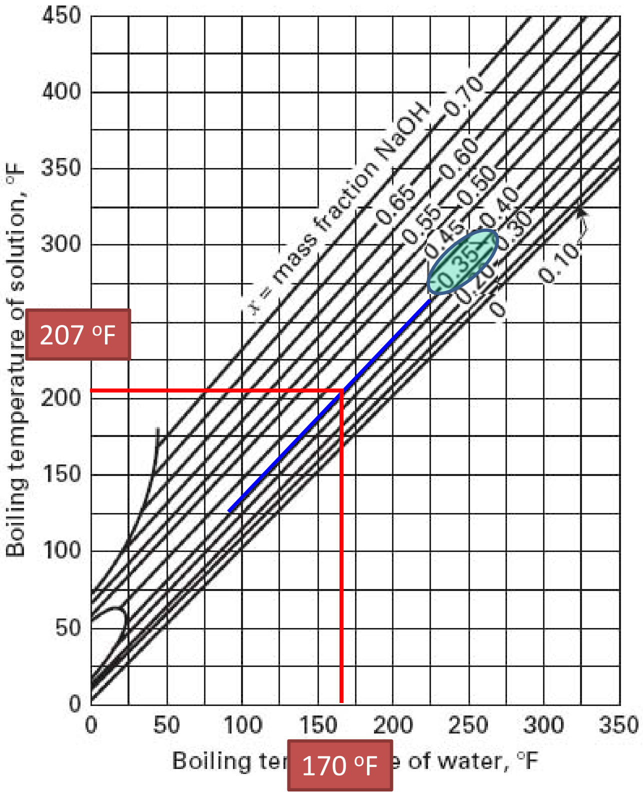
Boiling point rise (BPR) of solutions

Example: Approximate BPE for 35 wt% NaOH solution at 6 psia.

Using steam tables (Appendix A.2) at 6 psia:
Boiling point of pure water ; **BP_w = 170 °F**

Duhring chart at
BP_w = 170 °F and 35% ⇒
Boiling point of solution
BP_{sol} = 207 °F

BPE = 207 – 170 = **37 °F**



Enthalpy-concentration charts of solutions

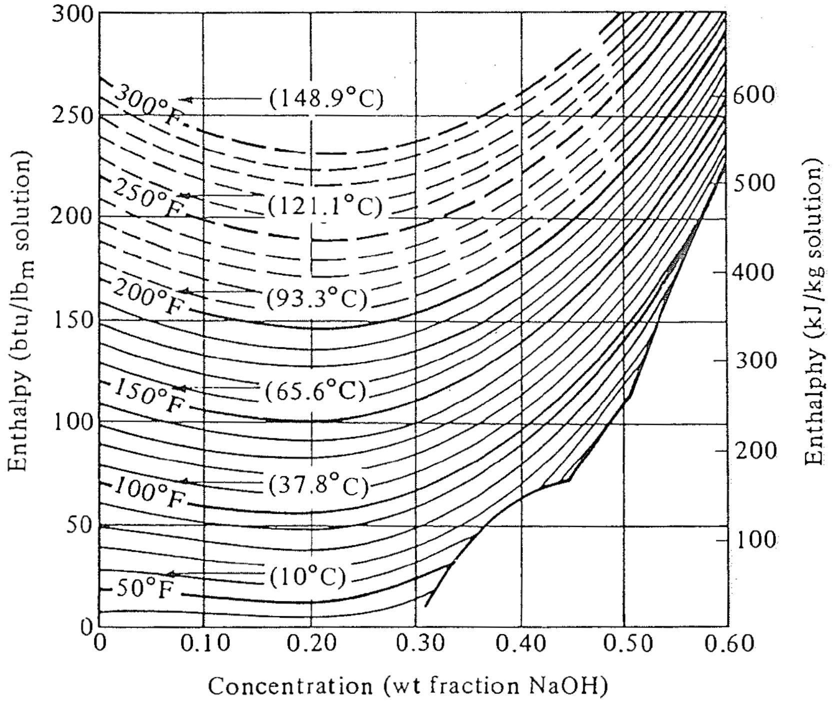
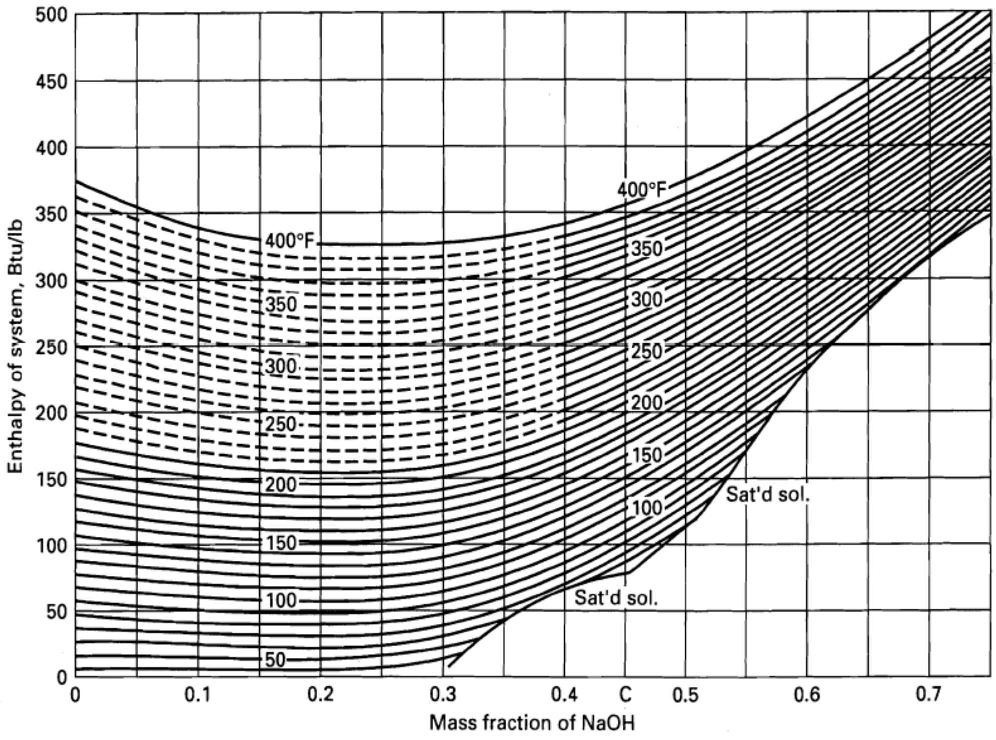


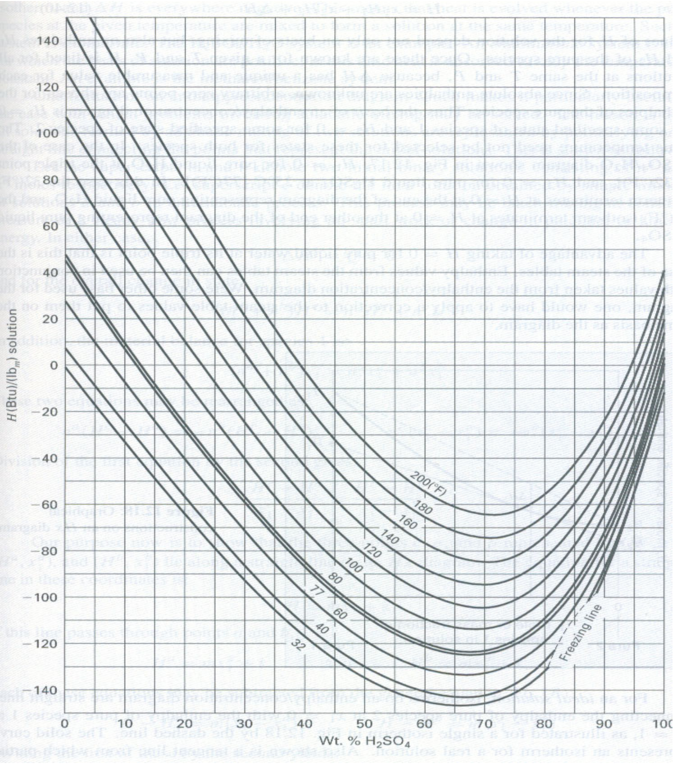
FIGURE 8.4-3. *Enthalpy–concentration chart for the system NaOH–water. [Reference state liquid water at 0°C (273 K) or 32°F.] [From W. L. McCabe, Trans. A.I.Ch.E.,* **31**, *129 (1935). With permission.]*

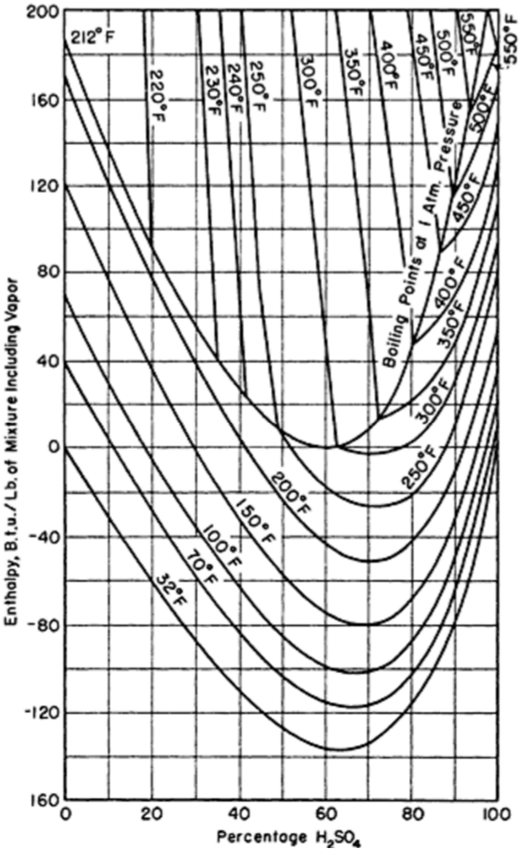


Enthalpy-concentration diagram for sodium hydroxide-water system.

Multiply the energy value Btu/lbm by 2.3263 to get kJ/kg

Enthalpy-concentration charts of solutions





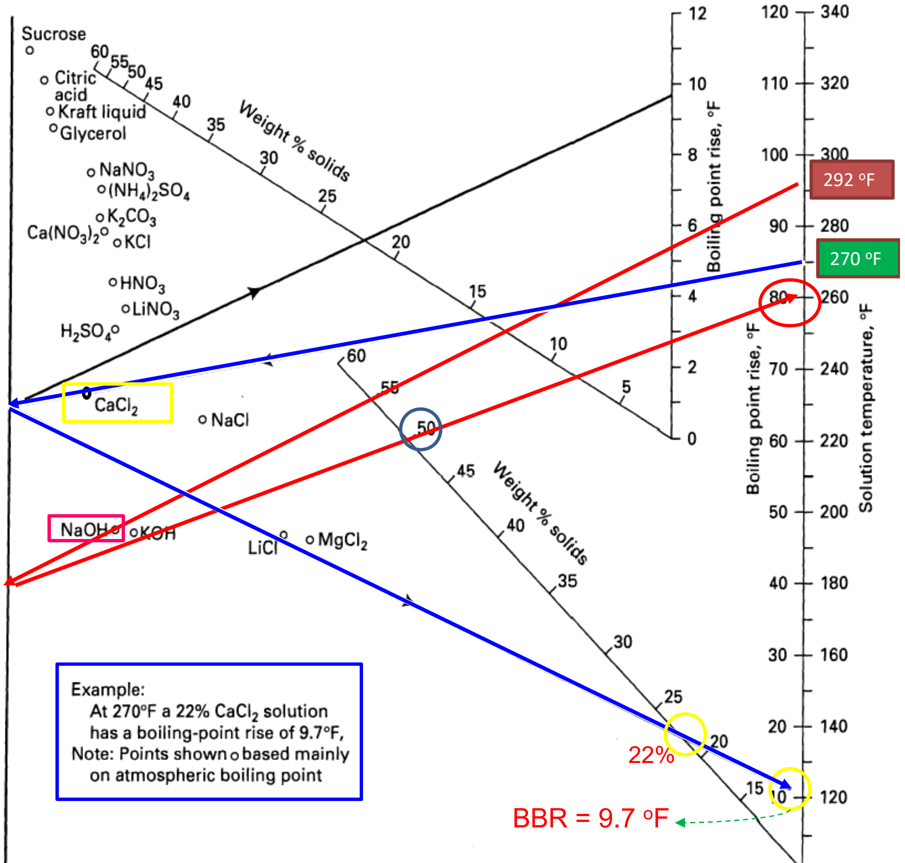
Multiply the energy value Btu/lbm by 2.3263 to get kJ/kg

For 50 % NaOH solution with BP 292 °F

BBR = 80 °F

The real useful aspect of this chart is determining solids contents from boiling point data.

As we know that at 1 atm the BP of water is 212°F and having measured a BP of the solution of 292°F, we can determine from this chart that the solids content is: 50 wt%.



Example:
At 270°F a 22% $CaCl_2$ solution has a boiling-point rise of 9.7°F,
Note: Points shown ○ based mainly on atmospheric boiling point

Nomograph for boiling-point elevation of aqueous solutions

Example

An evaporator is used to concentrate 4536 kg/h of a 20% NaOH solution entering at 60ºC to a product of 50% solids.

The pressure of the saturated steam used is 170 kPa and the vapor space pressure of the evaporator is at 12 kPa. The overall coefficient U is 1560 W/m^2.K.

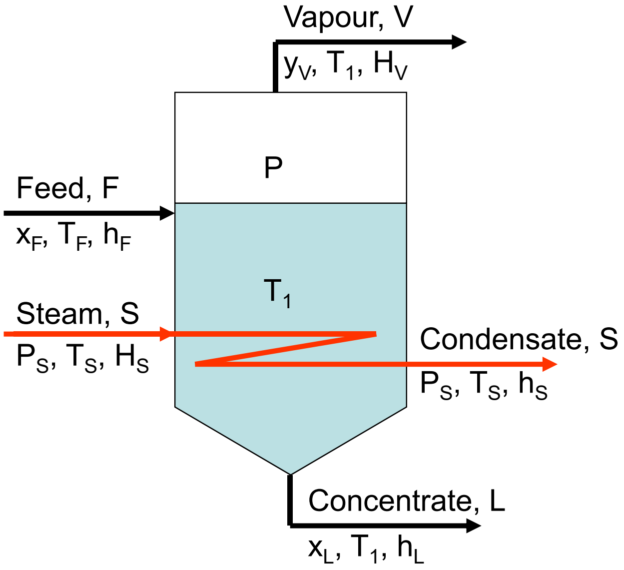
Calculate

a. the steam used

b. The steam economy (in kg vaporized / kg steam used) and

c. The heating surface area.

Solution



Data provided:

F = 4536 kg/h

x_F = 20 wt % = 0.2 kg solute / kg feed

T_F = 60ºC = 140 ºF

x_L = 50 wt %

= 0.5 kg solute / kg liquid product

P = 12 kPa = 0.12 bar

P_S = 170 kPa = 1.7 bar

U = 1560 W/m^2.K

From steam tables (Appendix A.2):

$T_1 \neq$ saturated temperature at P (= 0.12 bar) = 49.4^{o}C

T_S = saturated steam temperature at 1.7 bar = 115.2^{o}C

Solution Cont.d

Overall material balance:

$F = L + V$ (1)

Solute mass balance:

$F\ x_F = L\ x_L$ (2)

$F = 4536$ kg/h ; $x_F = 0.2$; $x_L = 0.5$

Solve Eqns. (1) and (2) to have

L = 1814 kg/h and **V = 2722** kg/h

Steam used = ?

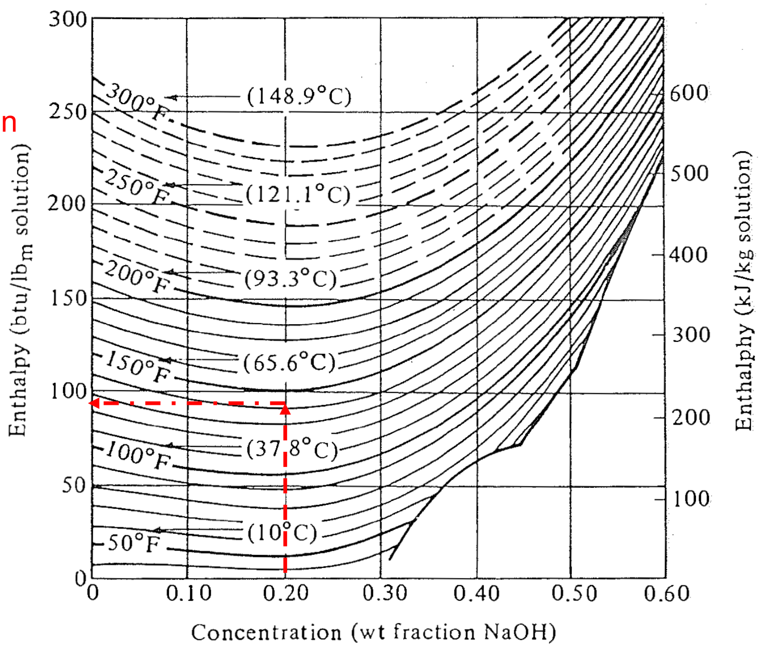
$S\ \lambda = L\ h_L + V\ H_V - F\ h_F$

Solution Cont.d

h_F = enthalpy of 20% solution at 60°C

(using the enthalpy–concentration chart)

h_F = 92 btu/Ib = 214 kJ/kg



Multiply the energy value Btu/Ibm by 2.3263 to get kJ/kg

Solution Cont.d

h_L = enthalpy of 50% solution at T_1 = ?

- (using the enthalpy–concentration and boiling-point rise charts)

- Saturated temperature at P (= 0.12 bar) = 49.4°C = 120 °F

Using the boiling-point rise chart

the boiling point of the solution.
T_1 =193 °F = 89.5°C

(read against 49.4°C and 50 wt%)

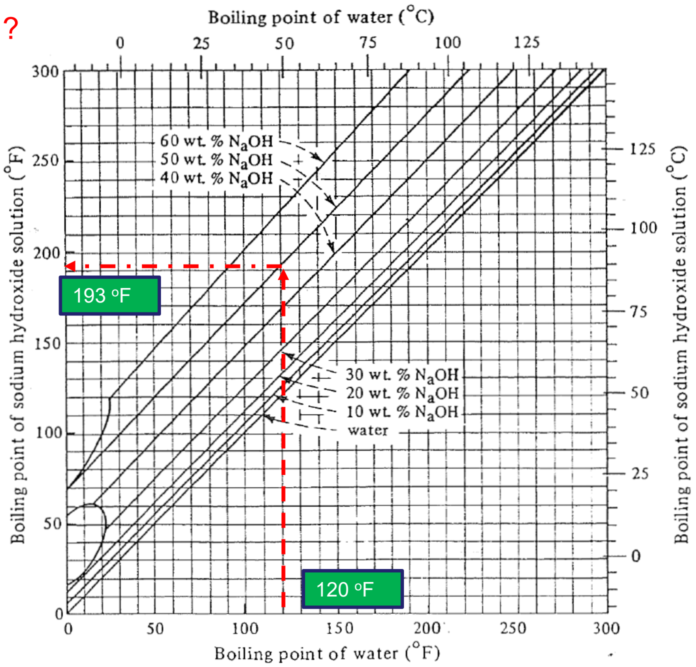


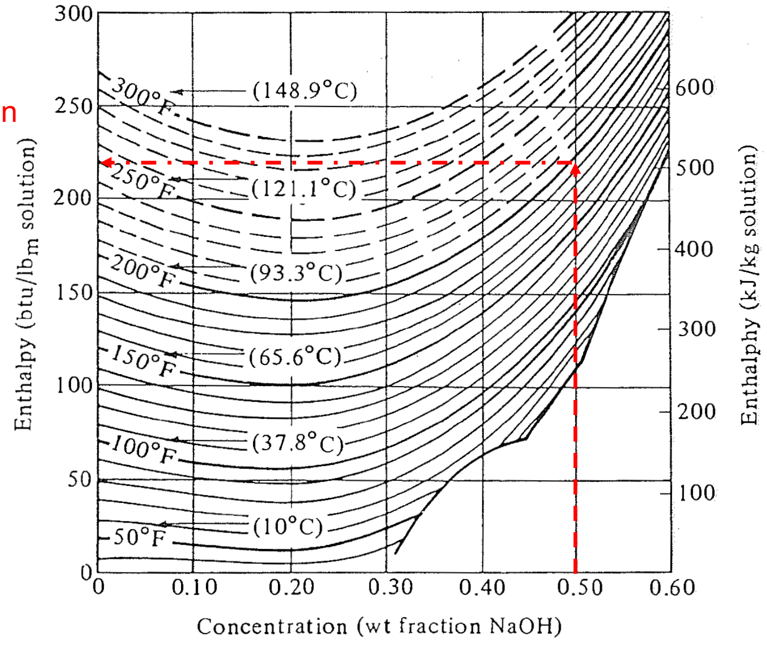
FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

Solution Cont.d

h_L = enthalpy of 50% solution at 89.5°C

(using the enthalpy–concentration chart)

Enthalpy of 50% solution at 89.5°C
h_L = 117 btu/lb = 505 kJ/kg



Multiply the energy value Btu/Ibm by 2.3263 to get kJ/kg

Solution Cont.d

In summary

Steam used = ?

$S\ \lambda = L\ h_L + V\ H_V - F\ h_F$

h_F = enthalpy of 20% solution at 60°C = 214 kJ/kg
(using the enthalpy–concentration chart)

h_L = enthalpy of 50% solution at T_1 = ?
(using the enthalpy–concentration and boiling-point rise charts)

Saturated temperature at P (= 0.12 bar) = 49.4°C, Using the boiling-point rise chart, we get 89.5°C (read against 49.4°C and 50 wt%) as the boiling point of the solution. That is T_1 = 89.5°C

h_L = enthalpy of 50% solution at 89.5°C = 505 kJ/kg
(using the enthalpy–concentration chart)

Solution Cont.d

H_V = enthalpy of superheated steam at 89.5°C and 0.12 bar = 2667 kJ/kg
(using the superheated steam table)

Steam used = S = ?

$F\ h_F + S\ \lambda = L\ h_L + V\ H_V$

$S\ \lambda = 1814 \times 505 + 2722 \times 2667 - 4536 \times 214 = 7204940$ kJ/h

Amounts of vapor and liquid products = ?

From steam tables (Appendix A.2):

For saturated steam at 172.4 kPa: → T_S = 115.6 °C

Solution Cont.d

λ = latent heat of vaporization of water at 1.7 bar and 115.2°C
= 2216 kJ/kg (using the steam table)

Therefore S = 7204940 / 2216 kg/h = 3251 kg/h

Steam economy = kg vapourized / kg steam used **= V / S = ?**
Steam economy = 2722 / 3251 = 0.837

$A = S\,\lambda / U\,(T_S - T_1)$ = [7204940 * 1000 / 3600] / [1560 * (115.2 – 89.5)]
= **49. 9 m^2**

Exercise

Repeat Example 8.4.3 assuming that the thermal properties of the liquid in the evaporator can be approximated by those of water.

Solution.

Amounts of vapor and liquid products = ?

F, x_F and x_L are known, and therefore L = 1814 kg/h and V = 2722 kg/h

Steam used = ?

$S\,\lambda = L\,h_L + V\,H_V - F\,h_F = (F - V)\,h_L + V\,H_V - F\,h_F = F\,(h_L - h_F) + V\,(H_V - h_L)$

$= F\,C_p\,(T_1 - T_F) + V$ (Latent heat of vapourization at 0.12 bar)

$= (4536)\,(4.14)\,(49.4 - 60) + (2722)\,(2383)$ kJ/h (C$_p$ = 4.14 kJ/kg.K is assumed)

= 6301078 kJ/h

λ = latent heat of vapourization of water at 1.7 bar = 2216 kJ/kg

Therefore S = 6301078 / 2216 kg/h = 2843.5 kg/h

Steam economy = kg vapourized / kg steam used **= V / S = ?**

Steam economy = 2722 / 2843.5 = 0.957

$A = S\,\lambda / U\,(T_S - T_1) = [6301078 * 1000 / 3600] / [1560 * (115.2 - 49.4)]$

$= 17\ m^2$

Summary: 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.

$$m_f Cp_f (T_f - T_{ref}) + Q_s = m_p Cp_p (T_p - T_{ref}) + m_v H_v$$

3) Assume water

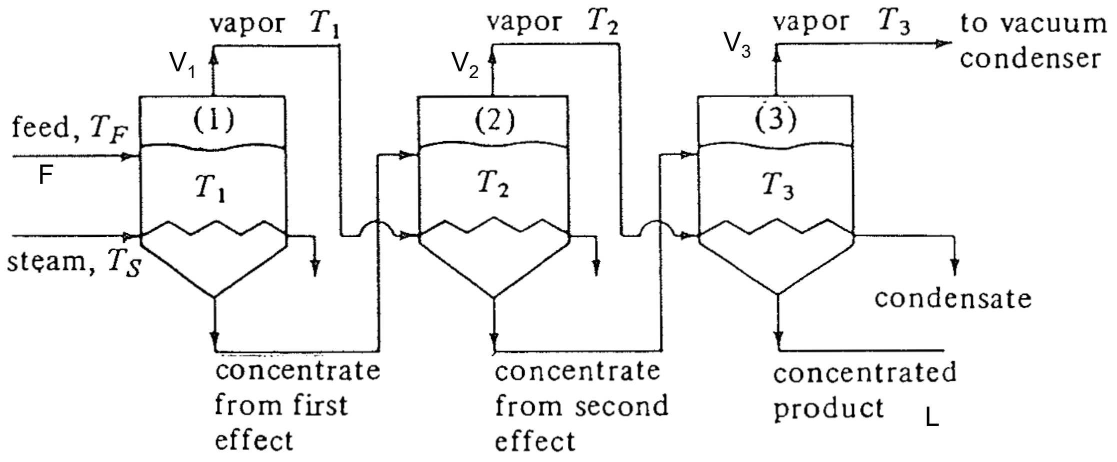
Use steam tables

Exercises

In order to concentrate 4536 kg/h of an NaOH solution containing 10 wt% NaOH to a 20 wt% solution, a single-effect evaporator is being used, with an area of 37.6 m2. The feed enters at 21.1 °C (294.3 K). Saturated steam at 110 °C (383.2 K) is used for heating and the pressure in the vapor space of the evaporator is 51.7 kPa. Calculate the kg/h of steam used and the overall heat-transfer coefficient.

A single-effect evaporator is concentrating a feed solution of organic colloids from 5 to 50 wt %. The solution has a negligible boiling-point elevation. The heat capacity of the feed is c_p=4.06 kJ/kg.K and the feed enters at 15.6 °C. Saturated steam at 101.32 kPa is available for heating, and the pressure in the vapor space of the evaporator is 15.3 kPa. A total of 4536 kg/h of water is to be evaporated. The overall heat transfer coefficient is 1988 W/m^2.K. What is the required surface area in m^2 and the steam consumption?

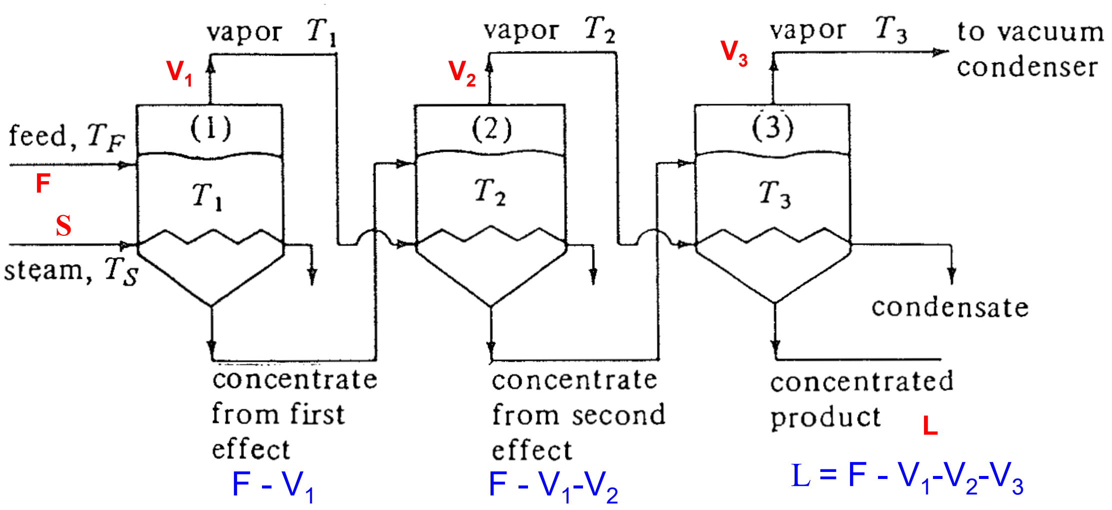
Calculation methods for multiple-effect evaporators



- Remember that mass/heat balances must be satisfied over each evaporator and over the whole process. **For example**, overall mass balance over the whole process is:

$$F = V_1+V_2+V_3+L$$

Calculation methods for multiple-effect evaporators



$$x_1 = \frac{x_F F}{F - V_1} \qquad x_2 = \frac{x_F F}{F - V_1 - V_2} \qquad x_3 = \frac{x_F F}{F - V_1 - V_2 - V_3}$$

Calculation methods for multiple-effect evaporators

- The heat transmitted per unit time across each effect is:

○ Heat balance for the first evaporator:

$$q_1 = S\,\lambda_s = U_1 A_1 \Delta T_1 = U_1 A_1 (T_S - T_1)$$

○ Similarly, in the second evaporator, remembering that the "steam" in the second is the vapor from the first evaporator and that this will condense at approximately the same temperature as it boiled, since pressure changes are small,

$$q_2 = V_1\,\lambda_{s1} = U_2 A_2 \Delta T_2 = U_2 A_2 (T_1 - T_2)$$

○ Heat balance for the third evaporator:

$$q_3 = V_2\,\lambda_{s2} = U_3 A_3 \Delta T_3 = U_3 A_3 (T_2 - T_3)$$

and so on.

Calculation methods for multiple-effect evaporators

Also, for the 1st effect

$$F\,h_F + S\,H_S = L\,h_L + V\,H_V + S\,h_S$$

$$\boxed{S_o\,\lambda_{so} = L\,h_L + V\,H_V - F\,h_F \quad \rightarrow \quad S\,\lambda_o = F\,C_{pF}\,(T_1 - T_F) + V_1\,\lambda_1}$$

In similar manner for the 2nd and 3rd effects, respectively

$$\boxed{V_1\,\lambda_{s1} = (F - V_1)\,C_{p1}\,(T_2 - T_1) + V_2\,\lambda_{s2}}$$

$$\boxed{V_2\,\lambda_{s2} = (F - V_1 - V_2)\,C_{p2}\,(T_3 - T_2) + V_3\,\lambda_{s3}}$$

For **Neglect sensible heat effects**

$$\boxed{S_o\,\lambda_{so} = V_1\,\lambda_{s1} = V_2\,\lambda_{s2} = V_3\,\lambda_{s3}}$$

Calculation methods for multiple-effect evaporators

- Assuming that heat losses, boiling-point elevation of solution, and heat of solution are negligible, the feed is supplied at its boiling point (i.e. neglecting the heat required to heat the feed from T_F to T_1,) to have approximately:

$$q_1 = q_2 = q_3 = \ldots\ldots$$

That is, $$U_1\,A_1\,\Delta T_1 = U_2\,A_2\,\Delta T_2 = U_3\,A_3\,\Delta T_3 = \ldots.$$

- Further, if the evaporators are constructed so that $A_1 = A_2 = A_3$ (to reduces the cost of equipment):

$$q/A = U_1\;\Delta T_1 = U_2\,\Delta T_2 = U_3\,\Delta T_3 = \ldots.$$

That is, the temperature differences are inversely proportional to the overall heat transfer coefficients.

Calculation methods for multiple-effect evaporators

- Further, $\sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = T_s - T_3$

$$\rightarrow \sum \Delta T = \Delta T_1 + \frac{U_1}{U_2}\Delta T_1 + \frac{U_1}{U_3}\Delta T_1$$

Hence, $$\Delta T_1 = \frac{\sum \Delta T}{1 + \frac{U_1}{U_2} + \frac{U_1}{U_3}}$$

$$\Delta T_2 = \frac{U_1}{U_2}\Delta T_1 \qquad \text{and} \qquad \Delta T_3 = \frac{U_1}{U_3}\Delta T_1$$

Calculation methods for multiple-effect evaporators

This represents a simplification, however, since:

i. The heat required to heat the feed from T_F to T_1 has been neglected, and

ii. The liquor (concentrate) passing from stages 1 to 2 carries heat into the second effect, and this is responsible for some evaporation. This is also the case in the third effect.

- **Capacity of multiple-effect evaporator**:

$$q = q_1 + q_2 + q_3 + \ldots\ldots$$

- **Vapor from all effects:**

$$V = V_1 + V_2 + V_3$$

Calculation methods for multiple-effect evaporators

- In a typical multiple effect evaporator homework problem the feed conditions and flow rate (F) are given.
- The overall heat transfer coefficients (U_i) are assumed to be known.
- The desired final concentration (x_1) is specified as well as the pressure (or equivalently, the temperature) of the saturated steam used as the heat source (P_s).
- Additionally, the pressure in one effect (usually the last) is specified (P_3).
- The task of the students is **to find** the amount of steam that must be fed to the first effect (S), the unknown liquid and vapor flow rates (V_1, V_2, V_3, L_1, L_2, L_3), the pressures in the other effects (P_1, P_2), and heat transfer area of each effect (A).
- Generally the heat transfer areas for all effects are assumed equal.
- H (h) is the enthalpy of the vapor (liquid) phase with corresponding temperature T_i and latent heat λ_i.

Calculation methods for multiple-effect evaporators

- For a three effect evaporator, there are 9 unknowns (S, A, P_1, P_2, V_1, V_2, V_3, L_2, L_3).
- In general for N effects there will be 3N unknowns and 3N equations – namely a mass balance, energy balance, and heat transfer rate equation for each effect; the solute balance having been used already to calculate the x_i's.
- The overall strategy is to estimate intermediate temperatures, solve the material balances for the solvent vapor flow rates, use these to determine the heat transferred in each effect, and from that information find the heat transfer area.

Example

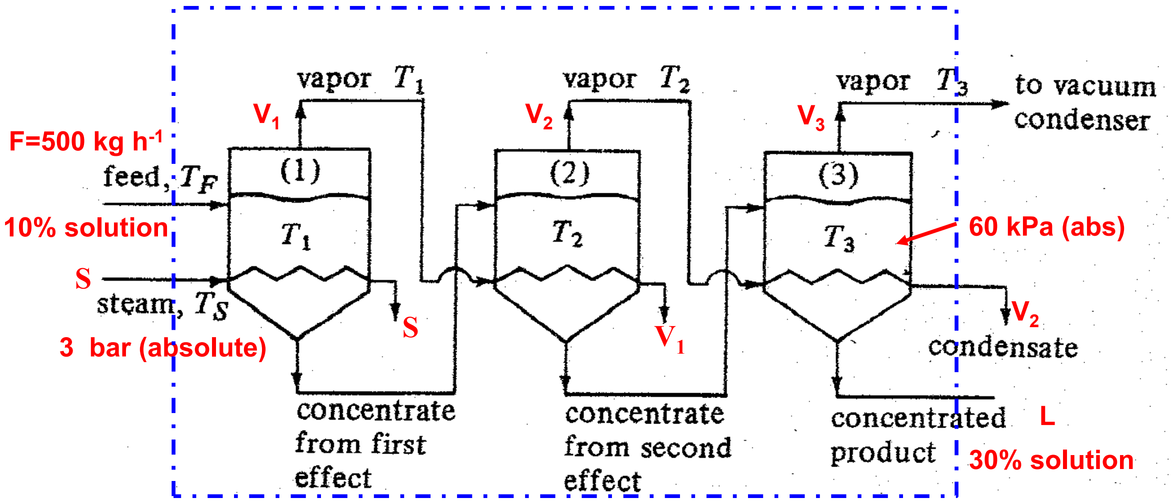
Estimate the requirements of steam and heat transfer surface, and the evaporating temperatures in each effect, for a triple effect evaporator evaporating 500 kg h^{-1} of a 10 wt% solution up to a 30 wt% solution.

Steam is available at 3 bar (absolute) and the pressure in the evaporation space in the final effect is 60 kPa absolute.

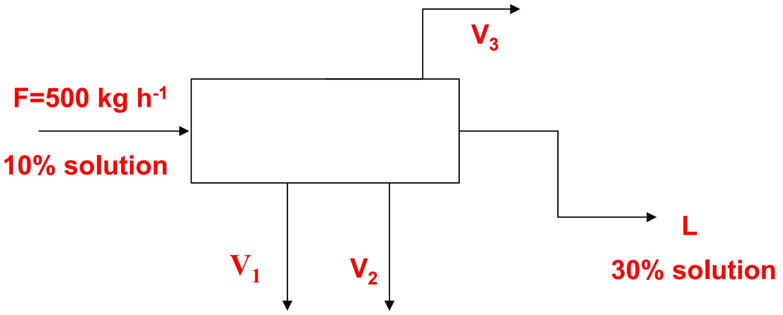
Assume that the overall heat transfer coefficients are 2270, 2000 and 1420 J m^{-2} s^{-1} $°C^{-1}$ in the first, second and third effects, respectively.

Neglect sensible heat effects and assume no boiling-point elevation, and assume equal heat transfer in each effect.

Solution



Solution Cont.d



- **Solute mass balance over the whole process:**

$F\ x_F = L\ x_L \rightarrow (500)(0.1)=(0.3)(L) \rightarrow$ **$L = 166.7$ kg/h**

- **Overall material balance over the whole process:**

$F = L + V \rightarrow 500 = 166.7 + V \rightarrow$ **$V = 333.3$ kg/h**

Solution Cont.d

Stream	Solute	Solvent	Solution
Feed	50 kg/h	450 kg/h	500 kg/h
Concentrated product	50 kg/h	116.7 kg/h	166.7 kg/h
Vapor from all effects	0	333.3 kg/h	333.3 kg/h

Steam properties:
Data: Steam is available at 3 bar (absolute) and the pressure in the evaporation space in the final effect is 60 kPa absolute. (Neglect sensible heat effects and assume no boiling-point elevation). From steam tables:

Steam pressure	Saturation temperature	Latent heat of vaporization
3 bar (abs)	T_s=133.5°C	λ_1 =2164 kJ/kg
60 kPa (abs)	**T_3 = 86.0 °C**	2293 kJ/kg

Solution Cont.d

Evaporator layout:

	First effect	Second effect	Third effect
Steam temperature	T_s=133.5°C	T_1°C	T_2°C
Solution temperature	T_1°C	T_2°C	86.0°C
Temperature driving force	$\Delta T_1 = 133.5 - T_1$	$\Delta T_2 = T_1 - T_2$	$\Delta T_3 = T_2 - 86.0$

Solution Cont.d

Heat balances:

Data: U_1=2270, U_2=2000 and U_3 = 1420 J m^{-2} s^{-1} $°C^{-1}$.

Assume equal heat transfer in each effect, $q_1 = q_2 = q_3$ which gives:

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = U_3 A_3 \Delta T_3$$

U_1, U_2 and U_3 are given. A_1, A_2 and A_3 can be found if ΔT_1, ΔT_2 and ΔT_3 are known.
Let us assume that the evaporators are so constructed that $A_1 = A_2 = A_3$, then we have

$$U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3$$

$$2270\ (133.5 - T_1) = 2000\ (T_1 - T_2) = 1420\ (T_2 - 86.0)$$

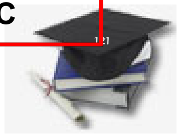
There are two equations and two unknowns in the above expression. The equations can be solved to give the following:

$\mathbf{T_1 = 120.8\ °C}$ and $\mathbf{T_2 = 106.3\ °C}$

Solution Cont.d

Properties in all effects:

	First effect	Second effect	Third effect
Steam temperature	133.5 °C	T_1 = 120.8 °C	T_2 = 106.3 °C
Solution temperature	T_1 = 120.8°C	T_2 = 106.3 °C	86.0 °C
Temperature driving force	ΔT_1 = 12.7 °C	ΔT_2 = 14.4 °C	ΔT_3 = 20.3 °C
Heat transfer coefficient	U_1 = 2270 J m^{-2} s^{-1} °C^{-1}	U_2 = 2000 J m^{-2} s^{-1} °C^{-1}	U_3 = 1420 J m^{-2} s^{-1} °C^{-1}
Latent heat of vapourization of steam	λ_1 = 2164kJ/kg at 133.5 °C	λ_2 = 2200 kJ/kg at 120.8°C	λ_3 = 2240 kJ/kg at 106.3 °C
Latent heat of vaporization of solution	2200 kJ/kg at 120.8 °C	2240 kJ/kg at 106.3 °C	2293 kJ/kg at 86.0 °C



Solution Cont.d

Consider the first effect:

	First effect
Steam temperature	133.5°C
Solution temperature	T_1 = 120.8°C
Temperature driving force	ΔT_1 = 12.7°C
Heat transfer coefficient	U_1 = 2270 J m^{-2} s^{-1} °C^{-1}
Latent heat of vaporization of steam	λ_1 = 2164 kJ/kg
Latent heat of vaporization of solution	2200 kJ/kg

Steam used = ?

$S_o (\lambda_o) = F\, C_p (T_1 - T_F) + V_1$ (Latent heat of vaporization of solution)

Assuming feed enters at the boiling point ($T_F = T_1$) then

$S_o (\lambda_o) = V_1$ (Latent heat of vaporization of solution)

S_1 is the flow rate of steam used in the first effect and V_1 is the flow rate of vapor leaving the first effect. Therefore,

S_1 (2164) = V_1 (2200)

Solution Cont.d

Consider the second effect:

	Second effect
Steam temperature	**$T_1 = 120.8\ ^oC$**
Solution temperature	**$T_2 = 106.3\ ^oC$**
Temperature driving force	**$\Delta T_2 = 14.4\ ^oC$**
Heat transfer coefficient	**$U_2 = 2000\ J\ m^{-2}\ s^{-1}\ ^oC^{-1}$**
Latent heat of vaporization of steam	**$\lambda_2 = 2200$ kJ/kg**
Latent heat of vaporization of solution	**2240 kJ/kg**

Steam used = ?

- Feed enters at the boiling point

- steam used in the second effect is the vapor leaving the first effect .Therefore,

V_1 (λ_2) = V_2 (Latent heat of vaporization of solution)

where

V_2 is the flow rate of vapor leaving the second effect. Therefore,

V_1 (2200) = V_2 (2240)

Solution Cont.d

Consider the third effect:

	Third effect
Steam temperature	**$T_2 = 106.3\ ^oC$**
Solution temperature	**86.0 ^oC**
Temperature driving force	**$\Delta T_3 = 20.3\ ^oC$**
Heat transfer coefficient	**$U_3 = 1420\ J\ m^{-2}\ s^{-1}\ ^oC^{-1}$**
Latent heat of vapourization of steam	**$\lambda_3 = 2240$ kJ/kg**
Latent heat of vaporization of solution	**2293 kJ/kg**

Steam used = ?

- Feed enters at the boiling point

- steam used in the third effect is the vapor leaving the second effect. Therefore,

V_2 (λ_3) = V_3 (Latent heat of vaporization of solution)

where

V_3 is the flow rate of vapor leaving the third effect.

Therefore,

V_2 (2240) = V_3 (2293)

Solution Cont.d

S_1 (2164) = V_1 (2200) = V_2 (2240) = V_3 (2293)

$V_1 + V_2 + V_3$ = 333 kg/h (from the mass balance).

4 Equations by 4 unknowns

Solve

S_1 (2164/2200) + S_1 (2164/2240) + S_1 (2164/2293) = 333 kg/h

2164 S_1 (1/2200 + 1/2240 + 1/2293) = 333 kg/h

2164 S_1 (1/2200 + 1/2240 + 1/2293) = 333 kg/h

→ S_1 = 115 kg/h

We could calculate the vapor flow rate as

V_1 = 113.2 kg/h; **V_2 = 111.2 kg/h**; **V_3 = 108.6 kg/h**

Steam economy:

Steam economy = kg vaporized / kg steam used = 333 / 115 = **2.9**

Solution Cont.d

	First effect
Steam temperature	**133.5 °C**
Solution temperature	**T_1 = 120.8°C**
Temperature driving force	**ΔT_1 = 12.7°C**
Heat transfer coefficient	**U_1 = 2270 J m^{-2} s^{-1} °C^{-1}**
Latent heat of vapourization of steam	**λ_1 = 2164 kJ/kg**
Latent heat of vaporization of solution	**2200 kJ/kg**

$$A_1 = S_1 \lambda_1 / U_1 \Delta T_1$$

$$= (115 \text{ kg/h}) (2164 \text{ kJ/kg}) / [2270 \text{ J m}^{-2} \text{ s}^{-1} \text{ °C}^{-1} \times (12.7)\text{°C}]$$

$$= (115 \times 2164 \times 1000 / 3600 \text{ J/s}) / [2270 \times 12.7 \text{ J m}^{-2} \text{ s}^{-1}]$$

= **2.4 m^2**

Overall heat transfer area required

$$= A_1 + A_2 + A_3 = 3 \times A_1$$

= **7.2 m^2**

Exercise

Repeat the previous example taking boiling point elevation into considerations and assuming equal vapor evaporation rate from the three effects **with NaOH as solute and the feed temperature is 30 ^oC**.

Solution

- **Solute mass balance over the whole process:**

$F x_F = L x_L \rightarrow (500)(0.1)=(0.3)(L) \rightarrow$ **$L = 166.7$ kg/h**

- **Overall material balance over the whole process:**

$F = L + V \rightarrow 500 = 166.7 + V \rightarrow$ **$V = 333.3$ kg/h**

Stream	Solute	Solvent	Solution
Feed	50 kg/h	450 kg/h	500 kg/h
Concentrated product	50 kg/h	116.7 kg/h	166.7 kg/h
Vapor from all effects	0	333.3 kg/h	333.3 kg/h

Solution Cont.d

Steam properties:
Data: Steam is available at 3 bar (absolute)

Steam pressure	Saturation temperature	Latent heat of vaporization
3 bar (abs)	T_s=133.5°C	λ_1 =2164 kJ/kg

and the pressure in the evaporation space in the final effect is 60 kPa absolute and x_L = 0.3

60 kPa (abs)	$T_{sat\ 3}$=86.0 °C	????

Solution Cont.d

- Saturated temperature at P (= 60 kPa) = 86 °C = 120 °F

Using the boiling-point rise chart

the boiling point of the solution. T_3 = 105°C

BPR = 19 °C

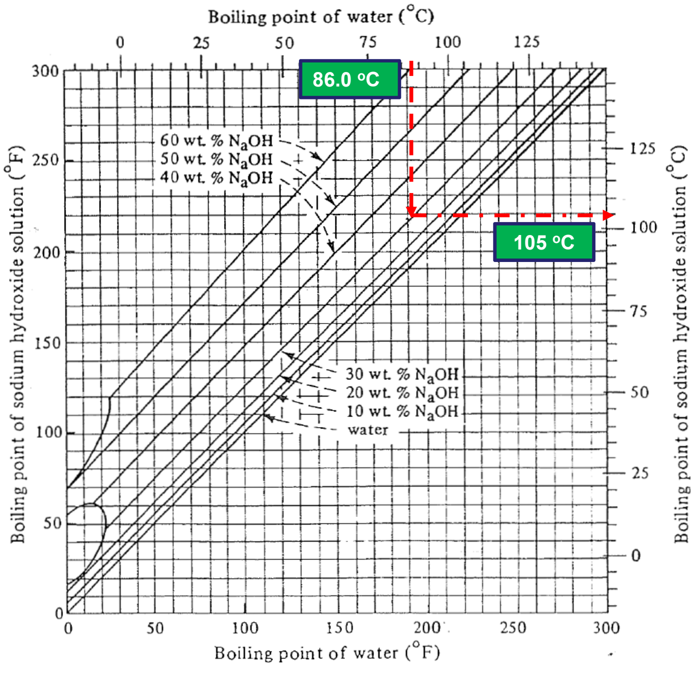


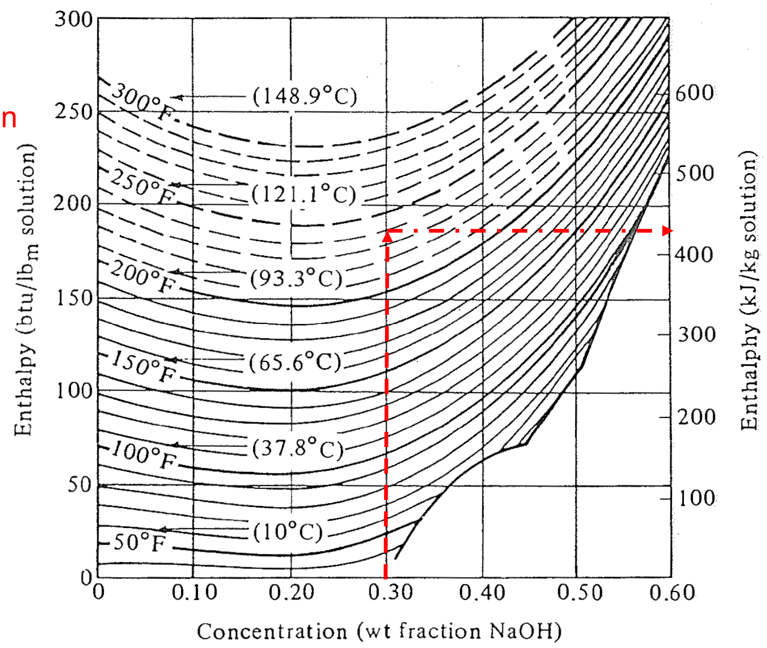
FIGURE 8.4-2. *Dühring lines for aqueous solutions of sodium hydroxide.*

Solution Cont.d

h_L = enthalpy of 30% solution at 105°C

(using the enthalpy–concentration chart)

Enthalpy of 30% solution at 105°C
h_L = 425 kJ/kg



Solution Cont.d

H_V = enthalpy of superheated steam at 105°C and 60 kPa = 2691 kJ/kg
(using the superheated steam table)

Evaporator layout:

	First effect	Second effect	Third effect
Steam temperature	T_s=133.5°C	T_1°C	T_2°C
Solution temperature	T_1°C	T_2°C	**105°C**
Temperature driving force	$\Delta T_1 = 133.5 - T_1$	$\Delta T_2 = T_1 - T_2$	$\Delta T_3 = T_2 - 105.0$

Assuming equal amount vaporized in each effect,

$\mathbf{V_1 = V_2 = V_3}$ = 111.11 kg/h

$$x_1 = \frac{x_F F}{F - V_1} \qquad x_2 = \frac{x_F F}{F - V_1 - V_2} \qquad x_3 = \frac{x_F F}{F - V_1 - V_2 - V_3}$$

x_1 = 0.13 **x_2 = 0.18** **x_3 = 0.3**

BPR ≅ 1 °C **BPR ≅ 6 °C** **BPR = 19 °C**

Solution Cont.d

$U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3$

$2270\ (133.5 - T_1) = 2000\ (T_1 - T_2) = 1420\ (T_2 - 105.0)$

$$\sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 - (BPR_1 + BPR_2 + BPR_3) = T_s - T_3 - (BPR_1 + BPR_2)$$

$= 133.5 - 105 - (6+1) = 21.5$

$$\Delta T_1 = \frac{\sum \Delta T}{1 + \frac{U_1}{U_2} + \frac{U_1}{U_3}} = \frac{21.5}{1 + \frac{2270}{2000} + \frac{2270}{1420}} = 5.76\,^{o}\mathrm{C}$$

$\rightarrow T_1 = 133.5 - 5.76 = 127.7\ ^{o}\mathrm{C}$

Solution Cont.d

$$\Delta T_2 = \frac{U_1}{U_2}\Delta T_1 = 6.435\ ^{o}C \qquad \rightarrow T_2 = T_1 - BPR_1 - \Delta T_2$$

$$= 127.7 - 1 - 6.435 = 120.3\ ^{o}C$$

$$\Delta T_3 = \frac{U_1}{U_3}\Delta T_1 = 9.06\ ^{o}C \qquad \rightarrow T_3 = T_2 - BPR_2 - \Delta T_3 = 105.24\ ^{o}C$$

$$S_o \lambda_o = L_1 h_{L1} + V_1 H_{V1} - F h_F \qquad L_1 = F - V_1$$

$$V_1 \lambda_1 = L_2 h_{L2} + V_2 H_{V2} - L_1 h_{L1} \qquad L_2 = F - V_1 - V_2$$

$$V_2 \lambda_2 = L_3 h_{L3} + V_3 H_{V3} - L_2 h_{L2} \qquad L_3 = F - V_1 - V_2 - V_3$$

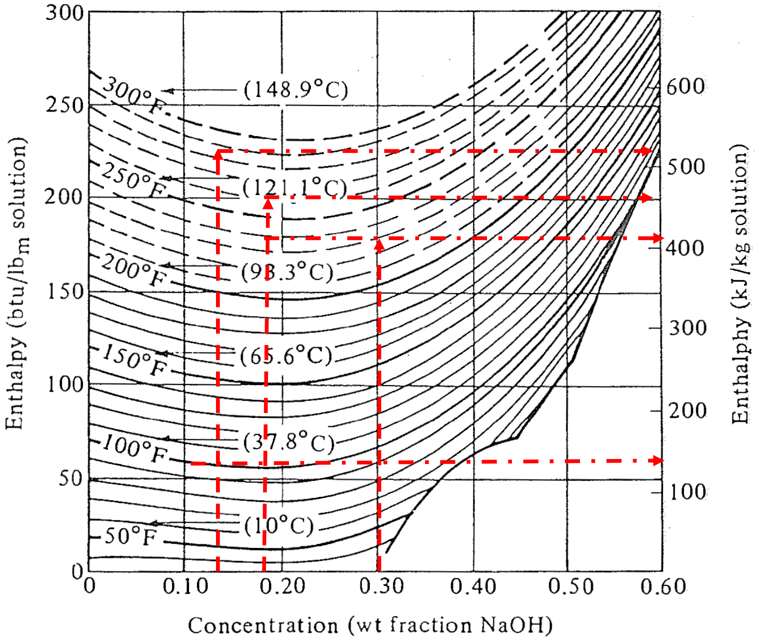
Solution Cont.d

h_F = 125 kJ/kg

h_{L1} = 525 kJ/kg

h_{L2} = 450 kJ/kg

h_{L3} = 405 kJ/kg



Solution Cont.d: Properties in all effects

	First effect	Second effect	Third effect
Steam temperature	133.5 °C	T_1 = 127.7 °C	T_2 = 120.3 °C
Solution temperature	T_1 = 127.7 °C	T_2 = 120.3 °C	105.0 °C
ΔT	ΔT_1 = 5.76 °C	ΔT_2 = 6.435 °C	ΔT_3 = 9.06 °C
U J m^{-2} s^{-1} $°C^{-1}$	U_1 = 2270	U_2 = 2000	U_3 = 1420
λ of inlet steam, kJ/kg	λ_1 = 2164 At 133.5 °C	λ_2 = 2180.5 At 127.7 °C	λ_3 = 2202 At 120.3 °C
λ_v kJ/kg, outlet	2180.5 At 127.7 °C	2202 At 120.3 °C	2243.9 At 105.0 °C
h_L kJ/kg	525 at 127.7 °C	450 At 120.3 °C	405 At 105.0 °C
H_v kJ/kg	2716 At 127.7 °C	2706 At 120.3 °C	2684 At 105.0 °C

Solution Cont.d

$S_o\ 2164 = L_1\ (525) + V_1\ (2716) - (500)\ 125$ $\quad L_1 = 500 - V_1$

$V_1\ (2180.5) = L_2\ 405 + V_2\ 2706 - L_1\ 525$ $\quad L_2 = 500 - V_1 - V_2$

$V_2\ (2202) = 166.7\ (450) + V_3\ 2684 - L_2\ 450$ $\quad L_3 = 166.7 = 500 - V_1 - V_2 - V_3$

$\rightarrow 333.3 = V_1 + V_2 + V_3$

Solve the above equations to get:

V_1= 101.33 kg/h	L_1 = 398.66 kg/h		x_1= 0.125
V_2 = 116.8 kg/h	L_2 = 281.48 kg/h	➡	x_2 = 0.177
V_3 = 115.14 kg/h	S_o =195.02 kg/h		x_3 = 0.30

Solution Cont.d

Compare, check and repeat your steps

If necessary…

Steps in the Procedure

- The steps in the procedure can be summarized as

  i. From the known outlet concentration and pressure in the last effect, determine the boiling point in the last effect

  ii. Determine the total amount of vapor produced using an overall mass balance. For an initial guess, make the vapor produced in each effect equal.

  iii. Use component and material balance to get estimates for the remaining flowrates within the system and the compositions of the intermediate streams. These are initial guesses.

  iv. Use the guessed pressures and/or solids fractions to calculate boiling point rise.

  v. Determine the overall temperature drops between the steam and the saturation temperature of the last effect.

  vi. Estimate ΔT_1, ΔT_2 and ΔT_3. Then calculate the boiling point in each effect

Steps in the Procedure

vii. Determine the saturation temperatures, solution temperatures and liquid enthalpies

viii. Using heat and material balances in each effect, calculate the amount vaporized and the flows of liquid in each effect.

ix. If the amounts vaporized differ appreciably from those assumed in step 2, then steps 3, to 8 can be repeated using the amounts of evaporation just calculated. (In step 2 only the solids balance is repeated.)

Exercise

4 kg/s (14.4 tonne/hour) of a liquor containing 10 per cent solids is fed at 294 K to the first effect of a triple-effect unit. Liquor with 50 per cent solids is to be withdrawn from the third effect, which is at a pressure of 13 kN/m^2 (∼0.13 bar). The liquor may be assumed to have a specific heat of 4.18 kJ/kg K and to have no boiling point rise. Saturated dry steam at 205 kN/m^2 is fed to the heating element of the first effect, and the condensate is removed at the steam temperature in each effect as shown

If the three units are to have equal areas, estimate the area, the temperature differences and the steam consumption. Heat transfer coefficients of 3.1, 2.0 and 1.1 kW/m^2 K for the first, second, and third effects respectively, may be assumed.

Exercise

For a total heat transfer area of $A = 104$ m^{2,} taking about 10% excess area to provide a reasonable overdesign. Design the required evaporator