LECTUERE NOTES

SUB: HEAT TRANSFER

4th Semester,

Diploma in chemical engineering

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CHAPTER-1
Evaporation

The objective of evaporation is to concentrate a solution consisting of a non-volatile solute and a volatile solvent.
Generally the solvent is water

Evaporation:

It is a process of vaporising a portion of the solvent to produce a concentrated solution of thick liquor.

- For conducting evaporation we use evaporators.

Evaporator:

It is a device which is used to Concentrate a solution consisting of a non-volatile solute and a volatile solvent by removing a portion of solvent by supplying heat.

Single effect evaporator:

- Evaporation is a special case of heat transfer to a boiling liquid. This particular heat transfer application is so common and important that it is treated as a separate unit operation.

- Here the intention is to concentrate the non-volatile solute from a volatile solvent, usually water. This is done by evaporating the solvent by boiling. Concentration by evaporation is normally done until the solute begins to precipitate; otherwise the operation will be considered as crystallisation.
- Evaporation is usually treated as the separation of a liquid mixture into a liquid product (concentrate or thick liquor) and a vapour byproduct.
- An evaporator consists of a heat exchanger for boiling the solution and a way to separate the vapour from the boiling liquid.
- Different types evaporators are categorised on the basis of length and alignment (horizontal or vertical) of the evaporator tubes. The evaporation tubes may be located inside or outside of the main vessel where the vapour is driven off.
- Here we condense the vapour coming out of

the evaporator and reject. As we don’t use the latent heat of the vapour properly, it usually has an economy less than one.

Design of single effect evaporator:

Material balance:

Let F be the mass flow rate of feed.
L be the mass flow rate of product. V be the mass flow rate of vapour.
x_F is the mass fraction of solute in the feed.
x_L is the mass fraction of solute in the product. and y_V is the mass fraction of solute in the vapour.

Applying overall mass balance:

Total mass input = total mass output

i.e. $F \quad V \quad L$

Here we have neglected the steam as the amount of steam entering the steam chest is equal to the amount of condensate leaving the steam chest.

Solute balance:

$$Fx_F = L\,x_L + Vy_V$$

If no solute is transferred into vapour, then $y_V = 0$,

that means $Fx_F = L\,x_L$

Energy balance:

If h_F is the specific enthalpy of the feed.
h_V is the specific enthalpy of the vapour. h_L is the specific enthalpy of the product.
h_S and h_S' are the specific enthalpy of saturated vapour (steam) and saturated liquid (condensate) respectively.
P is the pressure in vapour space.
T_F is the feed temperature.

T is the boiling point of the feed/solution corresponding to the pressure in vapour space.
T_S is the saturation temperature of the steam. C_P is the specific heat of the feed.

Applying total energy balance:

Total energy input = total energy output

$$Fh_F + Sh_S = Vh_V + Lh_L + Sh'$$

$$S(h_S - h') = Vh_V + Lh_L - Fh_F$$

$$S\lambda_S = Vh_V + (F - V)h_L - Fh_F$$

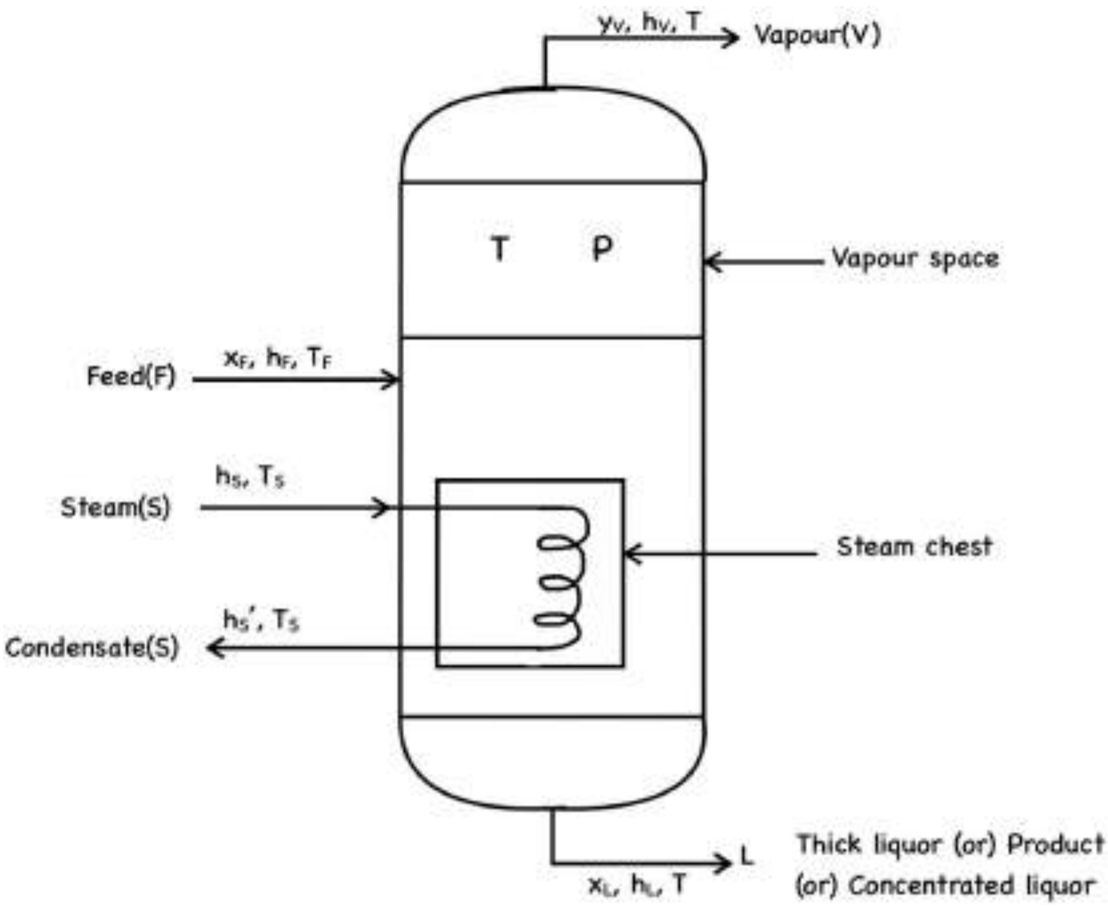
[Put $h_S - h' = \lambda_S$ = Latent heat of condensation]

$$S\lambda_S = V(h_V - h_L) + F(h_L - h_F)$$

$$S\lambda_S = V\lambda_V + F\left[C_P(T - T_{ref}) - C_P(T_F - T_{ref})\right]$$

Here we have taken T_{ref} as some reference temperature.

$$S\lambda_S = V\lambda_V + FC_P(T - T_F)$$



SINGLE EFFECT EVAPORATOR

The rate of heat transfer (Q) in the evaporator is then given by,

$$Q = S\lambda_S = UA\Delta T$$

Where,

$\Delta T = (T_S - T)$ = Temperature drop

U = Overall heat transfer coefficient

A = Heat transfer area

Performance of a an evaporator:

Capacity(V):

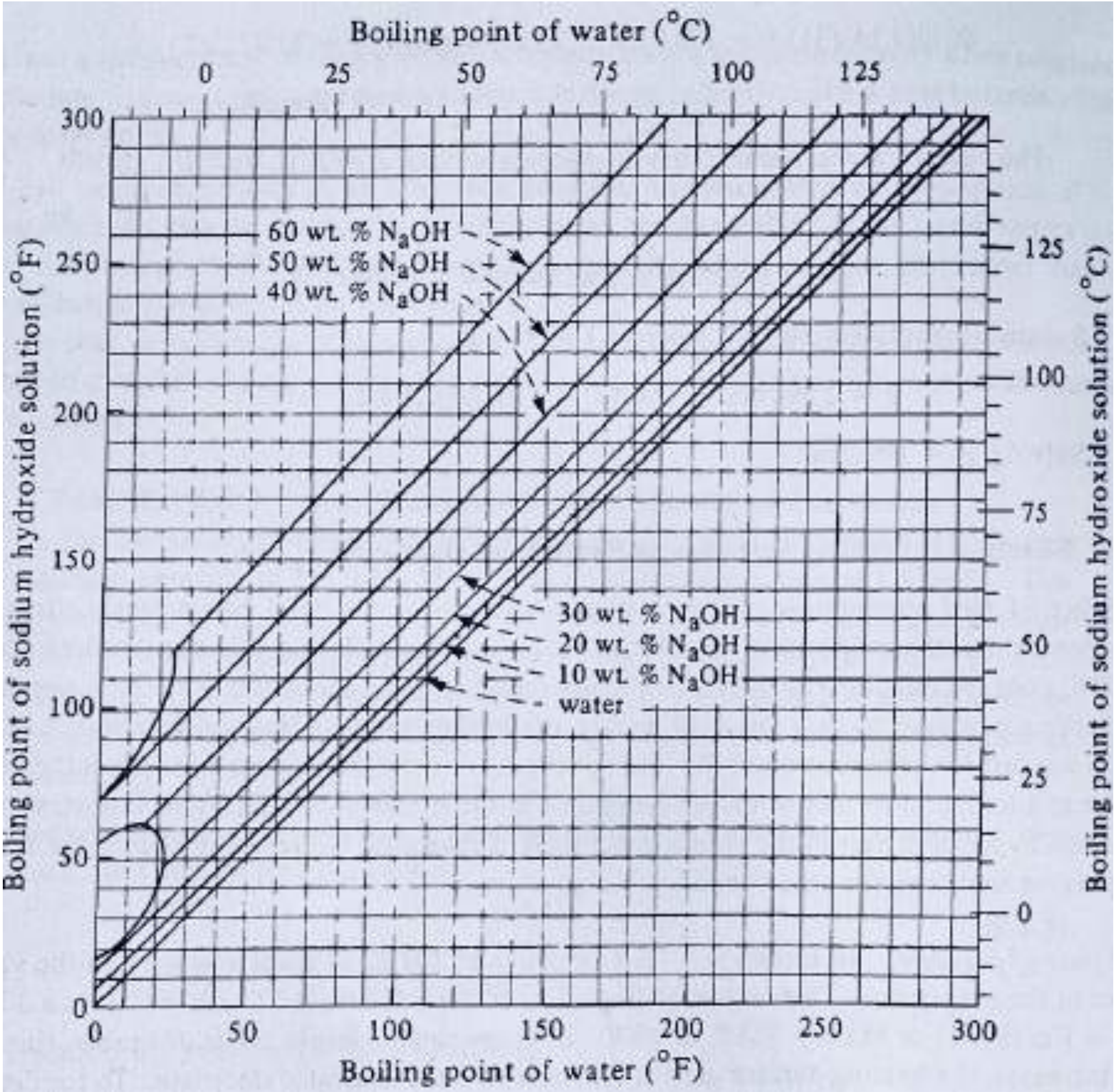
Capacity is defined as the amount of water vaporised per unit time.

Economy(V/S):

Economy is defined as the amount of water vaporised per kg of steam used.

Steam consumption(S):

Steam consumption is the amount of steam used per unit time.



DÜHRING LINES FOR SOLUTIONS OF SODIUM HYDROXIDE

It is the ratio of capacity and economy.

Concept of boiling point elevation:

Boiling point rise or elevation is the difference between the boiling point of solution and boiling point of pure water at a given pressure.

-When any solute is added in a pure solvent, then vapour pressure of solution get decreased and consequently the boiling point get increases.

Dühring plot:

This plot is used to find out the boiling point of solution.

According to Dühring rule , boiling point of a solution is a linear function of boiling point of pure water at a given concentration.

To determine/obtain a line for a solution of given concentration, it is necessary to know the boiling point of the given solution and water at minimum two different pressures.

Effect of boiling point rise on capacity and economy of evaporator:

$$Q = S\lambda_S = FC_P(T - T_F) + V\lambda_V$$

If T_0 is the boiling point of pure water corresponding to pressure in vapour space, then
Boiling point rise = $T - T_0$

- If solution is very dilute, then the boiling point rise is negligible. It means boiling point of solution is equal to boiling point of pure water.
- If solution is highly concentrated, then boiling point rise can not be neglected.

When $T = T_F$, $Q = S\lambda_S = UA(T_S - T) = V\lambda_V$

Due to boiling point rise, T increases, that means (T_S - T) decreases.
So, for a given heat transfer coefficient(U) and heat transfer area(A), rate of heat transfer(Q) decreases.
Also we can say that for a given latent heat of vaporisation, V decreases. That means capacity

decreases.

As $\uparrow$ T $\Rightarrow$ $(T_S - T)\downarrow$ $\downarrow$ $\Longrightarrow$ V $\downarrow$ Capacity

- Due to boiling point rise, capacity will decrease.
- But, boiling point rise does not affect the economy of the evaporator.

(As we can see clearly, whenever capacity(V) decreases, steam consumption(S) also decreases)

Effect of variables:

Effect of feed temperature (T_F):

$$Q = S\lambda_S = FC_P(T - T_F) + V\lambda_V$$

(a) If $T_F > T$, then $FC_P(T - T_F) < 0$

Here energy will be supplied by the feed also.

(b) If $T_F = T$, then heat load term is zero.

Here energy transferred by condensing steam is totally utilised in vaporising the feed or solution.

(c) If $T_F < T$, then $FC_P(T - T_F) > 0$

Here some part of energy supplied by condensing steam is utilised in increasing the temperature of the feed to its boiling point corresponding to pressure in vapour space.

Effect of vapour space pressure (P):

$$Q = UA(T_S - T)$$

As the pressure in vapour space decreases, corresponding boiling point of the solution also decreases. That means $(T_S - T)$ increases.

As $\downarrow P \Longrightarrow T \downarrow \Longrightarrow \uparrow (T_S - T) \uparrow Q$

So for a constant rate of heat transfer (Q), area required(A) for heat transfer will be lesser (or) for a constant heating surface area(A), the rate of heat transfer(Q) will increase.

Effect of steam pressure(P_S):

As the pressure of steam increases, then its saturation temperature also get increases. Hence the driving force(T_S - T) also increases.

As $\uparrow P_S \Longrightarrow \uparrow T_S \Longrightarrow (T_S - T) \uparrow \Longrightarrow$

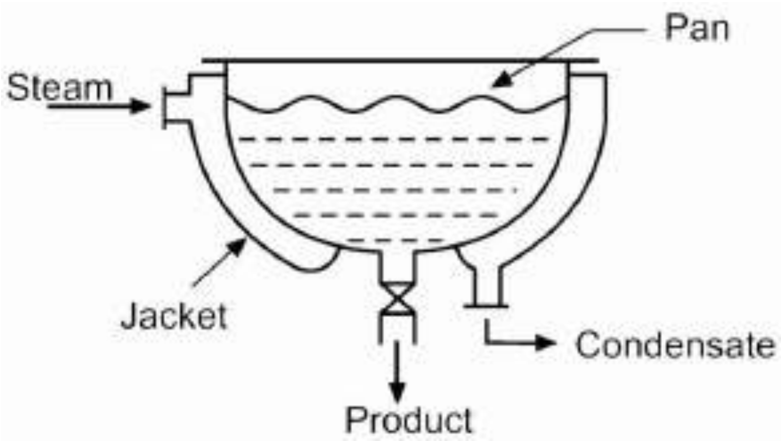
Q

That means for constant heat transfer rate(Q), area(A) required for heat transfer will decrease (or) for a constant heating surface area(A), rate of heat transfer(Q) will decrease.

Different types of evaporators: Open pan evaporator/ Jacketed pan evaporator:

The simplest method of concentrating a solution makes use of jacketed pans. Such a type of evaporator is particularly suitable when small quantities are to be handled. In an open/ jackete d pan evaporator, condensing steam is fed to a jacket for evaporating a part of the solvent. Pan is made of a single sheet of metal (for small sizes) or several sheets joined by welding/ brazing. A

JACKETED PAN EVAPORATOR

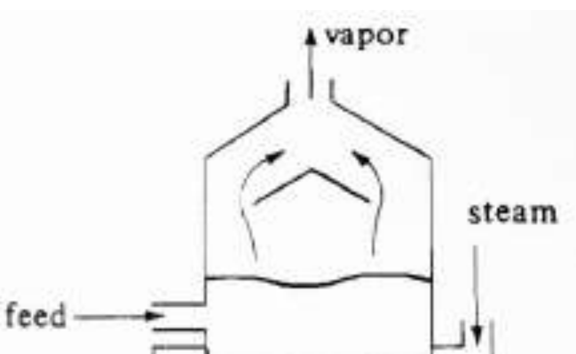


jacket is welded to the pan. The jacket is provided with a steam inlet at the top, while a condensate drain is provided at its bottom. The pan is provided with an outlet at the bottom for draining its contents. The jacket is usually constructed out of mild steel, while the pan is constructed out of mild steel, stainless steel, copper or aluminium as per process requirements.

The solution to be concentrated is taken into the pan and steam is admitted in the jacket. Evaporation is carried out for a predetermined time to achieve a desired concentration level. The thick liquor is then drained from the outlet.

Horizontal-tube natural circulation evaporator:

It consists of a vertical cylindrical shell incorporating a horizontal square tube



bundle at the lower portion of the shell. The horizontal bundle of heating tubes is similar to the bundle of tubes in a heat exchanger. A vapour outlet is provided on the top cover and a thick liquor outlet is provided at the bottom. Feed point is located at the left.

The steam enters the tubes, where it condenses. The steam condensate leaves at the other end of the tubes. The boiling liquid solution covers the tubes. Heat given out by the condensing steam will be gained by the solution in the evaporator and the solution boils. Vapours formed are removed from the top, while the thick liquor is removed from the bottom.

This type of evaporator is relatively cheap and is used for non viscous liquids with high heat transfer coefficients and liquids that do not deposit scale. Since liquid circulation is poor, they are unsuitable for viscous liquids. In almost all cases, evaporators are operated continuously, that is, the feed enters at a constant rate and the concentrate leaves at a constant rate.

Standard basket/Calandria type/Vertical tube/Short tube evaporator:

(Natural circulation type)

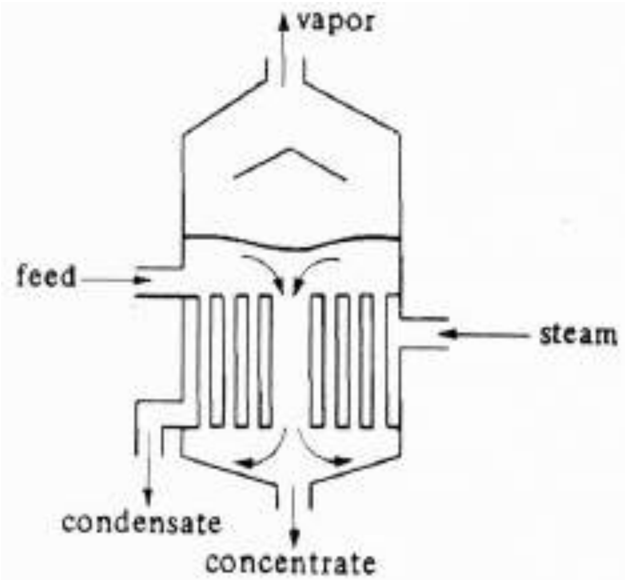
Construction:

It consists of a vertical cylindrical shell incorporating a short vertical tube bundle at the lower portion. In this type of evaporator, vertical tubes are used, rather than horizontal. Vapour outlet is provided at the top cover while a thick liquor discharge is provided at the bottom. The liquid is inside the tubes and the steam condenses outside the tubes in a steam chest. Baffles are incorporated in the steam chest to promote uniform distribution of steam.

- In Calandria type/Short tube/Vertical natural circulation evaporator, there is a central space as the downcomer.
- In case of basket type, the heating element(steam chest) is held suspended in the body so there is an annular open space as the downcomer instead of a central space.

Working:

Thin liquor is introduced at a convenient point and it travels through the tubes.



Heat transfer to the

boiling liquid inside the tubes takes place from condensing steam on the outside of the tubes. Because of boiling and decreases in density, the liquid rises in the tubes by natural circulation and flows downward through a large, central open space or downcomer, where it is removed as a thick liquor. This natural circulation increases the heat transfer coefficient. The type of evaporator is not used with viscous liquids.

Advantages:

(i) Relatively inexpensive.

(ii) As scaling occurs inside the tubes, it can be easily removed by mechanical or chemical means.

(iii) Provides moderately good heat transfer at a reasonable cost.

(iv) Can be put into more rigorous services than horizontal tube evaporators.

(v) High heat transfer coefficients.

(vi) Requires low head room.

Disadvantages:

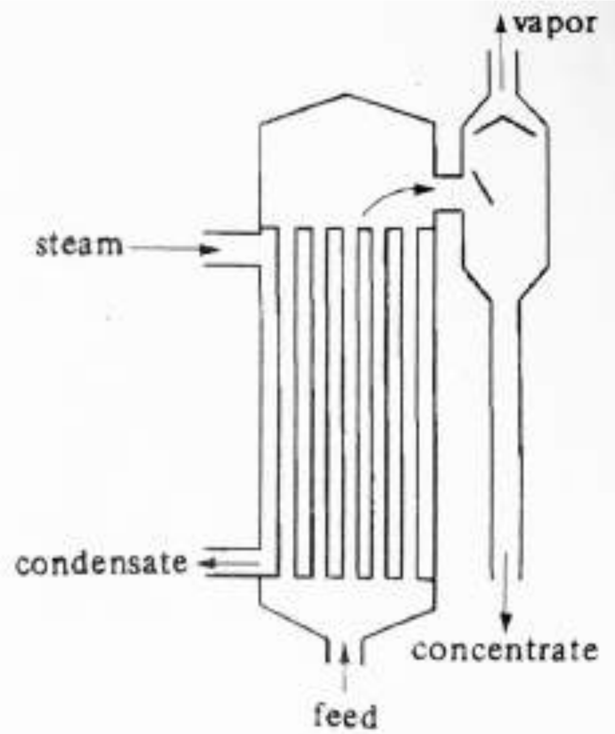
(i) Floor space required is large.

(ii) Amount of liquid hold up in the evaporator is large.

(iii) Since there is no circulation, these units are not suitable for viscous liquid.

Long tube vertical evaporator:

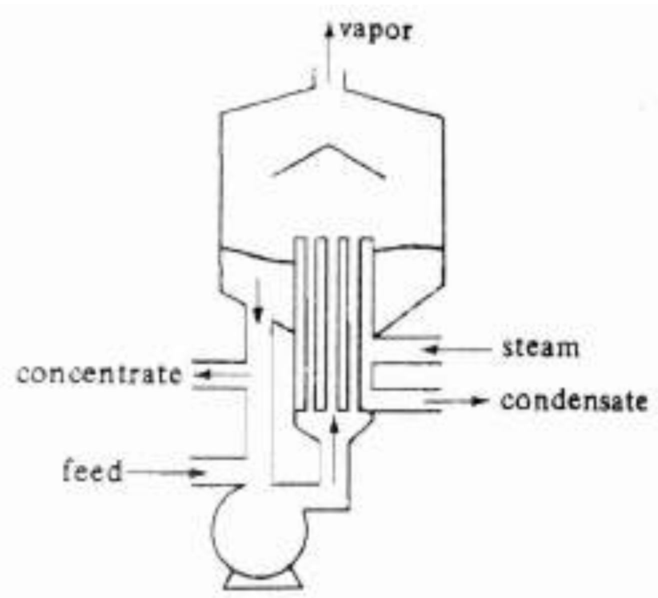
Since the heat transfer coefficient on the steam side is very high compared to that on the evaporating-liquid side, high liquid velocities are desirable. In a long tube vertical type evaporator, the liquid is inside the tubes.



The tubes are 3 to 10 m long and the formation of vapour bubbles inside the tubes causes a pumping action, which gives quite high liquid velocities. Generally, the liquid passes through the tubes only once and is not recirculated. Contact times can be quite low in this type. In some cases, as when the ratio of feed to evaporation rate is low, natural recirculation of the product through the evaporator is effected by adding a large pipe connection between the outlet concentrate line and the feed line.

- This is widely used for producing condensed milk and concentrating a black liquor in the paper and pulp industry.

Forced circulation type evaporator:



Whenever we are dealing with concentration problems involving solutions of high viscosities (or) of scale forming tendencies we have to make use of forced circulation evaporators as increasing the velocity of flow of liquor through tubes increases remarkably the liquid film heat transfer coefficients and the high velocity resulting by use of a centrifugal pump prevents the formation of excessive deposits on the heat transfer surfaces.

This could also be done in the long-tube vertical type evaporator by adding a pipe connection shown with a pump between the outlet concentrate line and the feed line. In the forced-circulation type, however, the vertical tubes are usually shorter than in the long-tube type. Additionally, in some cases a separate and external horizontal heat exchanger is used. **I**t's main disadvantage is high pumping cost.

Advantages:

(i) High heat transfer coefficients are obtained even with viscous materials.

(ii) Positive circulation and close control of flow.

(iii) Whenever there is a tendency to form scale or deposit salts, use of forced circulation units prevents the formation of excessive deposits due to high velocities.

(iv) Residence time of liquid in the tube is very small (1– 3 s) because of high velocities in these units so that moderately heat sensitive liquids can be handled.

-The forced circulation evaporators are

commonly used for crystalline products, viscous, salting, scaling and corrosive and foam forming solutions.

Multiple effect evaporator/multiple stage evaporator:

- Evaporators are classified by the number of effects. In a single-effect evaporator, steam provides energy for vaporisation and the vapour is condensed and discarded from the system.
- In single effect evaporator, the economy is nearly always less than one. Generally, for evaporation of 1 kg of water from a solution, 1 to 1.3 kg of steam is required. But in multiple effect evaporator, it may be considerably greater.
- The method of increasing the evaporation per kilogram of steam by using a series of evaporators between steam supply and condenser is known as multiple-effect evaporation. It is a method of reusing latent heat.It is the one way to increase the economy of evaporator systems.
- In multiple effect evaporators, we increase

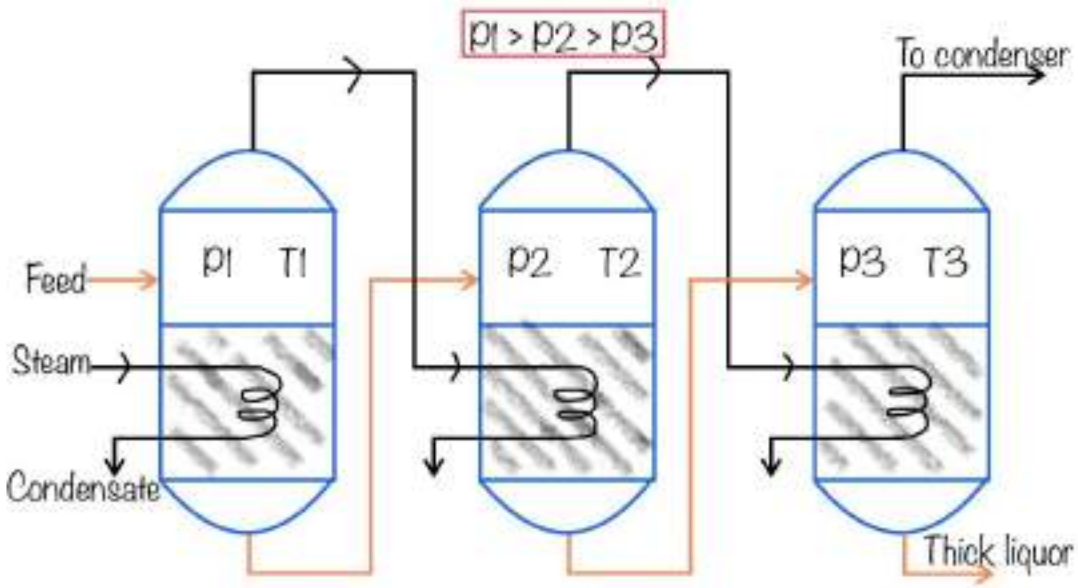
the economy at a cost of reduced capacity.

- In a double-effect evaporator, the vapour from the first effect is used to provide energy for the second vaporisation unit. This cascading of effects can continue for many stages. Multiple-effect evaporators can remove much larger amount of solvent than is possible in a single effect evaporator,
- In a multiple effect arrangement, the latent heat of the vapour from an effect is used to heat the effect following it.
- The numbering of the effects is independent of the order in which liquor is fed to them; they are always numbered in the direction of decreasing pressure (or steam flow)

- We always provide the steam to the first effect which is at the highest pressure. Vapour from Effect **I** will be used to heat Effect **II**, which consequently will operate at lower pressure. This continues until the last effect. When moving from one effect to next, pressure drop is always maintained there to facilitate the travel of hot vapour from one effect to the next and also to maintain the driving force for evaporation by keeping an appreciable difference between the steam temperature and boiling point of the feed in that corresponding effect.
- Usually all the effects in an evaporator will be physically the same in terms of size, construction, and heat transfer area. Unless thermal losses are very large, they all will have the same capacity as well.
- Evaporator effects may receive their feed in several different ways.

Different types of feed arrangement/methods of feeding:

1. Forward feed arrangement:



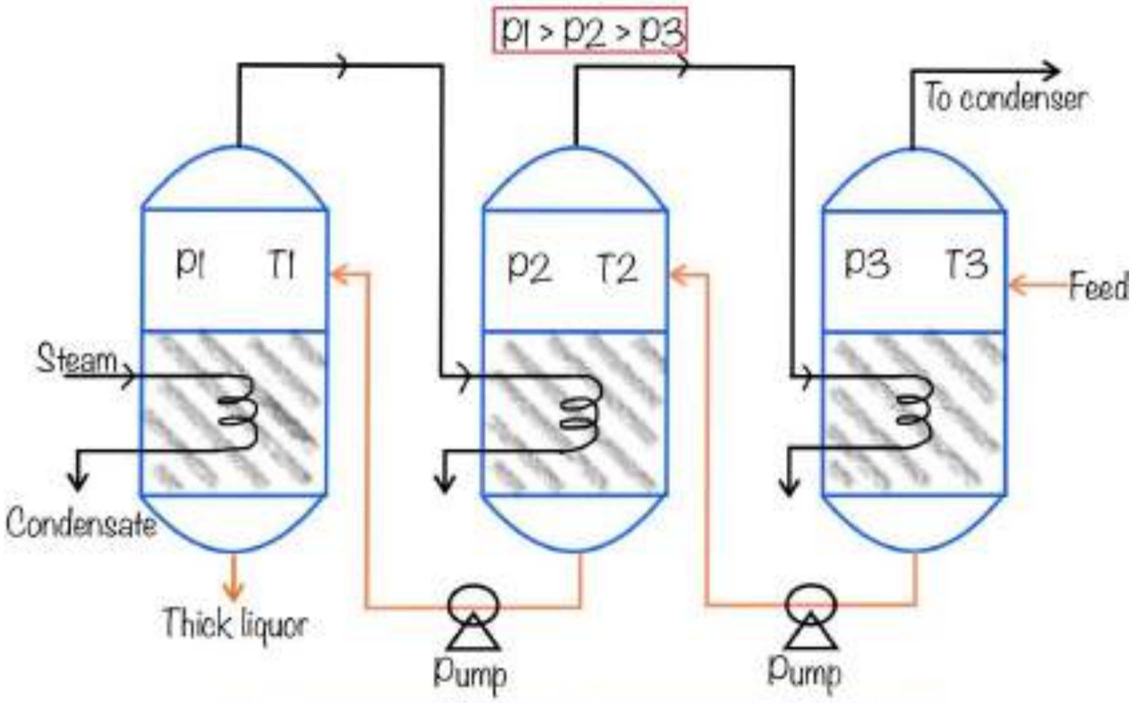
(FORWARD FEED ARRANGEMENT)

- The usual method of feeding a multiple-effect evaporator is to feed the thin liquid into the first effect and send it in turn through the other effects.
- Here the feed enters in a direction parallel to the steam.
- This pattern of liquid flow is the simplest.
- It requires a pump for feeding dilute solution to the first effect, since this effect is often at about atmospheric pressure, and a pump to remove thick liquor from the last effect. The transfer from effect to effect, however, can be done without pumps, since

the flow is in the direction of decreasing pressure.

- In between first and last effect, only control valves are required in the transfer lines.
- The concentration of the liquid increases from the first effect to the last.
- In this arrangement, the product is coming out at a lowest temperature.
- It is used when the feed is hot or when the final concentrated product may be damaged at High temperature.

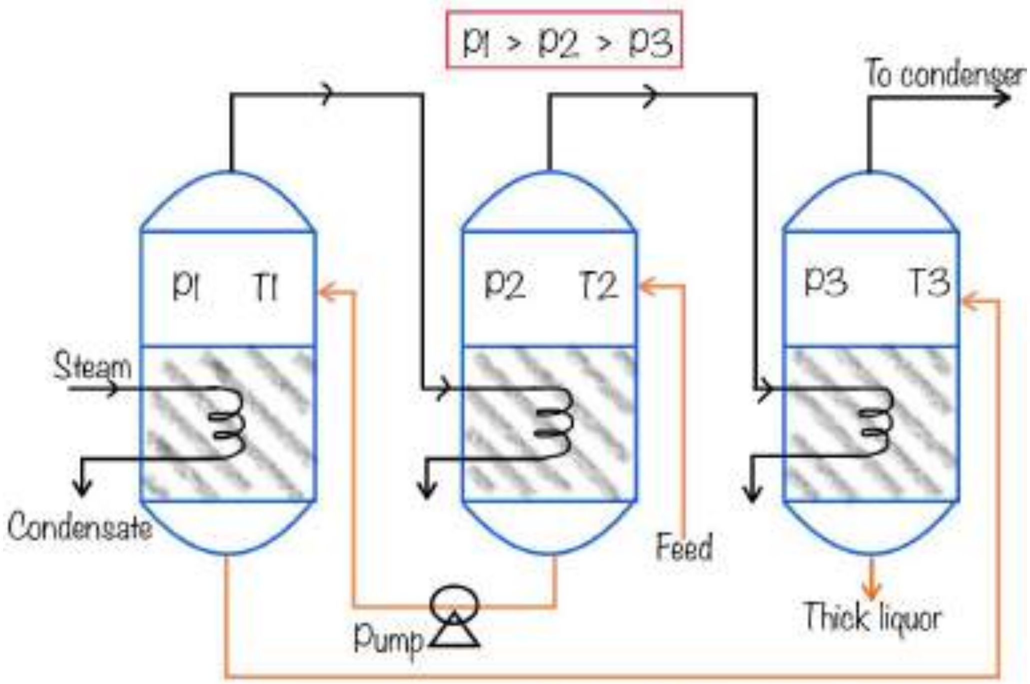
2. Backward feed arrangement:



(BACKWARD FEED ARRANGEMENT)

- In backward feed arrangement, the feed enters in opposite direction to that of the steam.
- Here, dilute liquid is fed to the last effect and then pumped through the successive effects to the first.
- As the flow is from low pressure to high pressure, this method requires a pump between each pair of effects in addition to thick liquor pump and feed pump.
- Backward feed is used when the thick liquor is viscous feed. Because, in this arrangement, the feed enters at the last effect which is at lowest temperature and continues to flow until the product will come from the 1st effect which is at highest temperature and hence viscosity get decreases.
- Backward feed usually gives a higher capacity than forward feed when the concentrated liquor is viscous.
- But backward feed can give a lower economy than forward feed when the feed is cold.

3. **Mixed feed arrangement:**



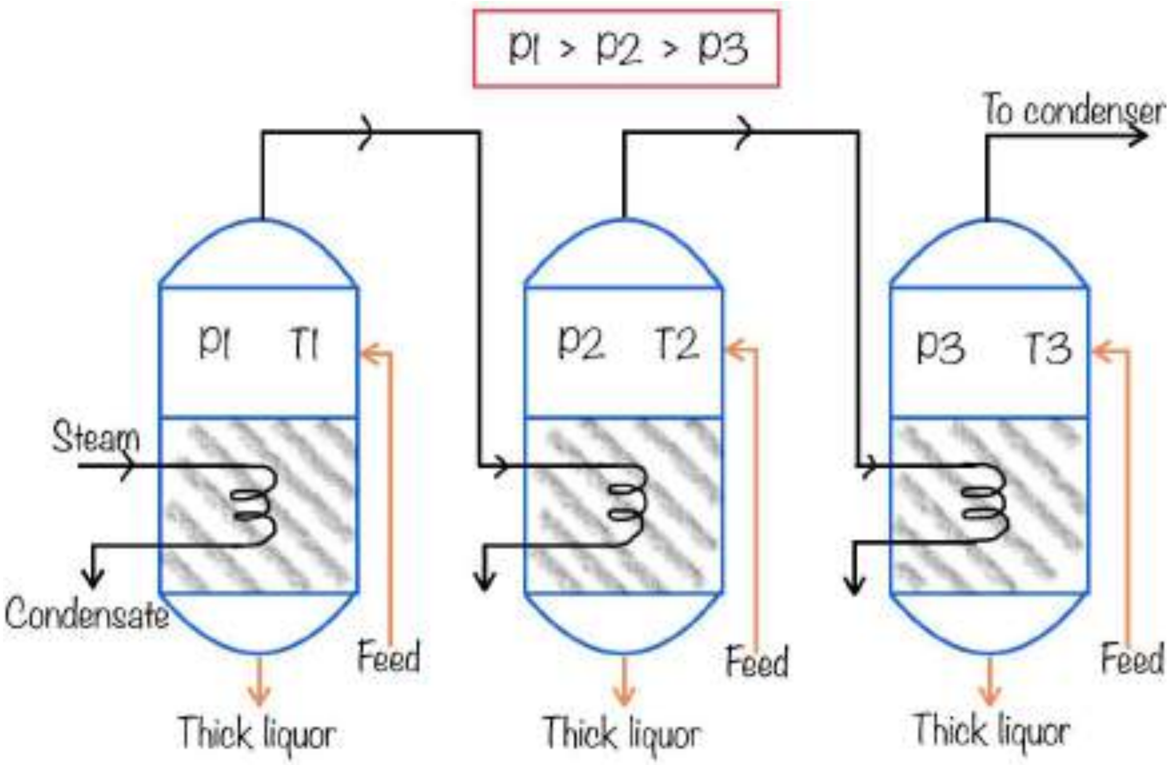
(MIXED FEED ARRANGEMENT)

- In this arrangement, both forward feed and backward feed is involved.
- In mixed feed arrangement, the thin liquor enters an intermediate effect, then moves in one direction, reach the end and then moves to the other end.
- When we have more than 3 effects, then the dilute liquid enters an intermediate effect, flows in forward feed to the end of the series, and is then pumped back to the first effects for final concentration.
- This eliminates some of the pumps needed in backward feed and yet permits the final

evaporation to be done at the highest temperature.

4. **Parallel feed arrangement:**

- In parallel feed arrangement, the feed stream is split and a portion of feed is fed to each effect.
- In this type of arrangement, there is no transfer of liquid from one effect to another.
- Here, we add fresh feed to each effect and withdraw concentrated product from each effect.
- The vapour from each effect is still used to heat the next effect.
- This method is used when the feed is almost saturated and solid crystals are the product, as in the evaporation of brine to make salt.



(PARALLEL FEED ARRANGEMENT)

Vapour Recompression:

Thermal energy in the vapour generated from a boiling solution can be utilised to vaporise more water if there is a temperature drop for heat transfer in the desired direction. In multiple-effect evaporation systems, this temperature drop is created by gradually lowering the boiling point of the solution in a series of evaporators by operating them successively under lower absolute pressures.

The desired driving force (i.e., temperature drop) can also be created by increasing the pressure (therefore, the condensing temperature) of the vapour generated by either of the two ways:

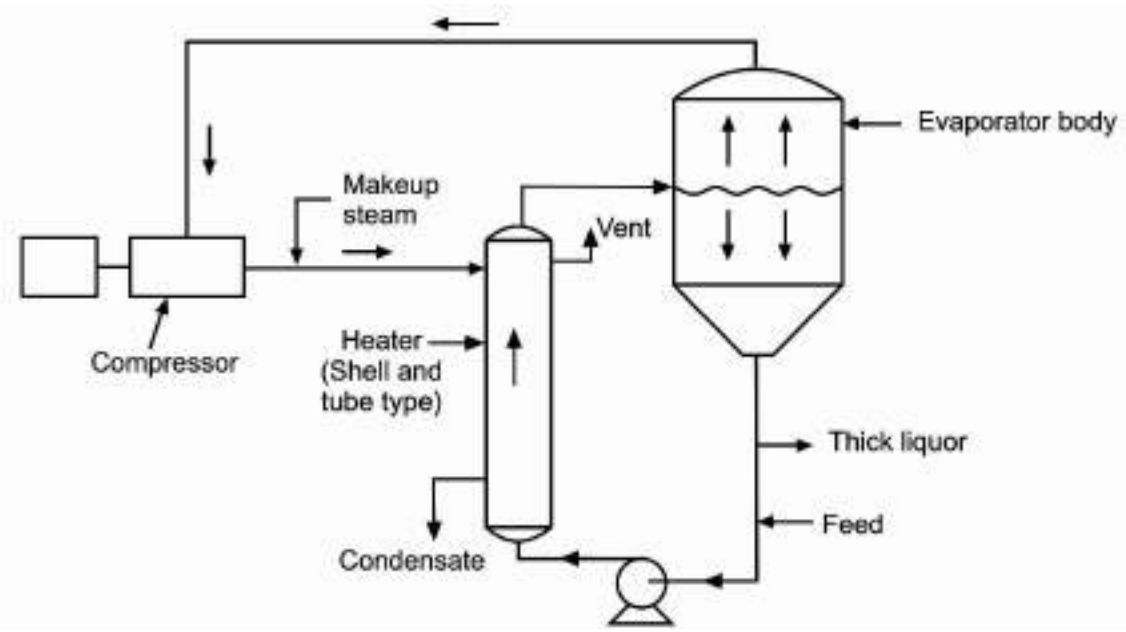
(a) mechanical recompression
(b) thermal recompression

The compressed vapour having a higher condensing temperature is fed to the steam chest of the evaporator from which it is generated. Therefore, the economy of an evaporator is also increased by recompressing the vapour from the evaporator and condensing it in the steam chest of the same evaporator. In this method, the vapours from the evaporator are compressed to a saturation pressure of steam in order to upgrade the vapours to the condition of the original steam to allow their use as the heating medium. The cost of compression is usually smaller than the value of latent heat in the vapour. By this technique we can obtain the multiple effect economy in a single effect.

Mechanical Recompression:

In this method, the vapour generated from an evaporator is compressed to a certain higher pressure by a positive displacement or centrifugal compressor and fed to a heater. As the saturation temperature of the compressed vapour is higher than the boiling point of the solution, heat flows from the vapour to the solution and more vapours are generated.

It is used for the concentrations of very dilute radioactive solutions and production of distilled water.



Thermal Recompression:

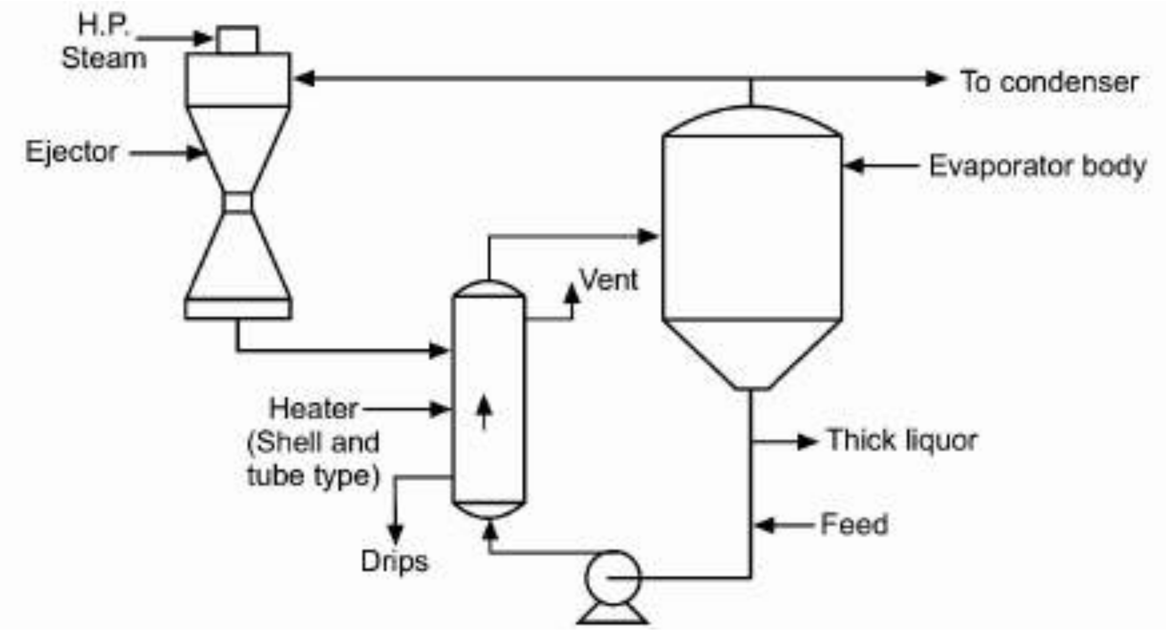
In this method, the vapour is compressed by means of a steam jet ejector. Here the high pressure steam is used to draw and compress the major part of vapours from the evaporator, while the remaining part of vapours is separately condensed for compensating motive steam added.

Thermal recompression is better than mechanical recompression as a substitute to vacuum operation as steam jets can handle large volumes of vapour. Jets are cheap and easy to maintain compared to compressors/blowers.

Disadvantages of thermal recompression:

(i) low mechanical efficiency of the jets.

(ii) lack of flexibility in the system to meet changes in the operating conditions.


H.P.
Steam
To condenser
Ejector
Evaporator body
Vent
Heater
(Shell and
tube type)
Thick liquor
Feed
Drips