

EVAPORATION

Evaporation is an operation that is carried out in the industry as a means of concentrating a weak liquor / solⁿ by vaporizing a portion of the solvent.

The weak liquor / solⁿ is composed of a non-volatile solute & a volatile solvent.

Ex:- Brine when heated with H₂O (solvent) is evaporated & the salt (solute) is produced.

Factors (Processing Factors) affecting evaporations ⇒

①. Concentration ⇒

As the concⁿ increases, the solⁿ becomes more & more individualistic.

②. Foaming ⇒

Some materials have tendency to foam that causes heavy entrainment. (Carry over of a portion of the liquid by the rising vapour is called as an entrainment.)

③. Scale ⇒

Some solⁿ deposits scale on the h.t. surfaces that results in reduction of the h.t. coefficient & also heat transfer rate. Therefore it is necessary to clean the tubes at definite intervals.

④. Material of Construction ⇒

Generally evaporators are made of mild steel. Corrosion & oxidation is not a problem special materials such as copper, nickel, stainless steels may be used. Other liquid characteristics that must be considered in the design are sp. heat, freezing pt., toxicity, explosion hazards & radioactivity.

Performance of tubular evaporator

The performance of a steam heated tubular evaporator is evaluated in terms of

- (a) capacity
- (b) Economy

Capacity \Rightarrow

Capacity of an evaporator is defined as the no. of kilogram of water vaporised or evaporated

Per hour. $Q = U A \Delta T$ $\Delta T =$ difference betⁿ the heating medium & Boiling liquor. or $T_{sat} - T_b$

If the feed solⁿ is at the boiling temp. corresponding to the pressure in the vapour space of an evaporator, then all the heat transferred through the heating surface is available for evaporation & the capacity is proportional to the heat transfer rate. \otimes

Economy \Rightarrow

Economy of an evaporator is defined as the no. of kg of water evaporated per kg of steam fed to the evaporator. It is also called as steam economy.

In a single effect evaporator the amt. of water evaporated per kg of steam fed is always less than one & hence economy is less than one. The fact that the latent heat of evaporation of water decreases as the pressure increases tends to make the ratio of water vapour produced per kg of steam condensed less than unity.

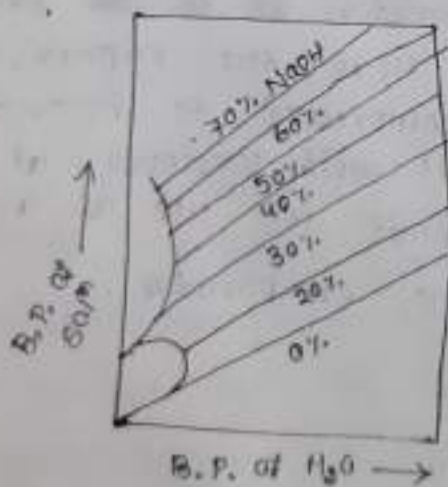
Boiling point elevation →

In actual practice, the B.P. of a solⁿ is affected by a B.P.E. & a liquid head.

As the vap. pressure of most aq. solⁿ is less than that of H₂O at any given temp., the B.P. of the solⁿ is higher than that of pure H₂O at a given pressure. "The difference betⁿ the B.P. of a solⁿ & that of pure H₂O at any given pressure is known as B.P. rise or elevation of the solⁿ." The B.P. of elevation is small for dilute solⁿ & large for concⁿ solⁿ of inorganic salts.

The B.P.E. of strong solⁿ can be obtained from an empirical rule known as Dühring's rule. It states that - "the B.P. of a given solⁿ is a linear function of the B.P. of the pure H₂O at the same pressure." So, when the B.P. of a solⁿ is plotted against the B.P. of H₂O, we get a straight line.

Fig. shows such a plot for an aq. solⁿ of caustic soda of various concⁿ.

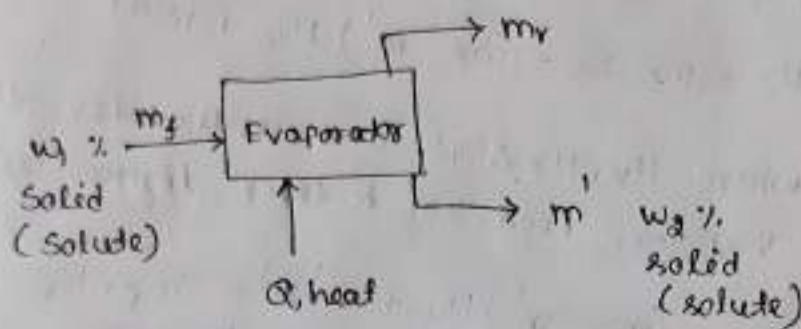


Dühring's plot for NaOH

Material & enthalpy balances for single effect evaporator

Consider an evaporator which is fed with m_f kg/h of the weak solⁿ containing $w_1\%$ solute & the thick liquor is withdrawn at m' kg/h containing $w_2\%$ solute by wt.

Let m_v be the kg/h of water evaporated.



Overall material balance :-

$$m_f = m_v + m' \longrightarrow \textcircled{1}$$

M.B. of solute

Solute in feed = Solute in thick liquor

$$\frac{w_1 \times m_f}{100} = \frac{w_2 m'}{100}$$

$$\Rightarrow w_1 \times m_f = w_2 \times m' \longrightarrow \textcircled{2}$$

Let T_f , T & T_s be the temp. of feed entering the evaporator, solution in the evaporator & condensing steam respectively.

Let λ_s be the latent heat of condensation of the steam at saturation temp.

Rate of h.t. through the heating surface from the steam side is $Q_s = m_s \cdot \lambda_s \longrightarrow \textcircled{3}$

where m_s = mass flow rate of the steam

to the evaporator in kg/hr

$$\lambda_s = \left(\text{sp. enthalpy of saturated steam} \right) - \left(\text{sp. enthalpy of saturated H}_2\text{O i.e. of condensate} \right)$$

Assuming heat losses to be negligible, the enthalpy balance over the evaporator is -

$$\left(\begin{array}{l} \text{Heat associated with} \\ \text{Feed} \end{array} \right) + \left(\begin{array}{l} \text{Heat (latent) associated} \\ \text{with steam} \end{array} \right) = \left(\begin{array}{l} \text{Heat associated} \\ \text{with vap. leaving} \end{array} \right) + \left(\begin{array}{l} \text{Heat associated} \\ \text{with thick liquor} \end{array} \right)$$

$$\Rightarrow m_f \cdot H_f + m_s \cdot \lambda_s = m_v \cdot H_v + m' H'$$

$$\Rightarrow m_f \cdot H_f + m_s \cdot \lambda_s = (m_f - m') H_v + m' H'$$

where H_v , H_f & H' are enthalpies of vapour, feed solⁿ & thick liquor respectively.

$$\Rightarrow m_s \cdot \lambda_s = (m_f - m') H_v + m' H' - m_f \cdot H_f \quad \text{--- (4)}$$

In case of solⁿ having negligible heats of dilution, the enthalpy balance can be written in terms of specific heats & temp. of the solⁿ.

Heat transferred to solⁿ in the evaporator by the condensing steam (in absence of heat losses) is utilised to heat the feed solⁿ from T_f to T & for the vaporisation of water from the solⁿ.

$$Q = m_f C_{pf} (T - T_f) + (m_f - m') \lambda_v \quad \text{--- (5)}$$

$$\left(\begin{array}{l} \text{Heat transfer rate} \\ \text{on the steam side} \end{array} \right) = \left(\begin{array}{l} \text{Heat transfer rate} \\ \text{on the liquor side} \end{array} \right)$$

$$\Rightarrow Q_s = Q \quad \text{--- (6)}$$

$$\Rightarrow m_s \cdot \lambda_s = m_f C_{pf} (T - T_f) + (m_f - m') \lambda_v \quad \text{--- (7)}$$

where C_{pf} = sp. heat of feed solⁿ

λ_v = latent heat of evaporation from thick liquor

Types of Evaporators \Rightarrow

Evaporators used in process industries can be classified as -

- (i) Natural circulation evaporators
- (ii) Forced circulation evaporators

Natural circulation evaporators are commonly employed for simple evaporations in single or multiple effect. Horizontal tube evaporator, vertical tube evaporator, open pan evaporators are the natural circulation evaporators.

Forced circulation evaporators are commonly employed for salting, viscous & scale forming solⁿ. These units are provided with external horizontal or vertical heating element.

Forced circulation evaporators with horizontal external heating element \Rightarrow

Construction \Rightarrow

It consists of a circulating pump, a separating space (separator), an evaporator body with a vapour outlet at the top, a deflector plate, an outlet for discharge of thick liquor & an external heating surface - a horizontal shell & tube heat exchanger having two passes on both ~~the~~ shell & tube sides.

Working \Rightarrow

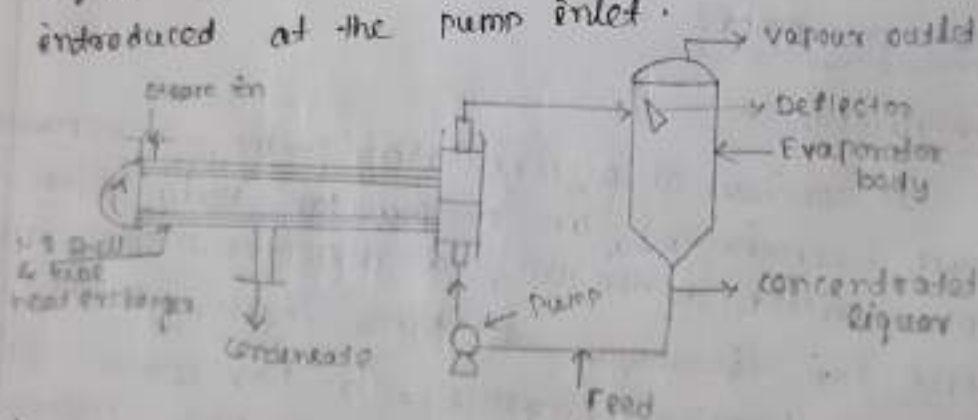
A centrifugal pump forces liquid through the tubes at high velocity & is heated as it passes through tubes due to h.t. from condensing steam on the shell side.

Boiling doesn't take place in the tubes as they are under sufficient static head which raises the boiling pt. above that in the separating space.

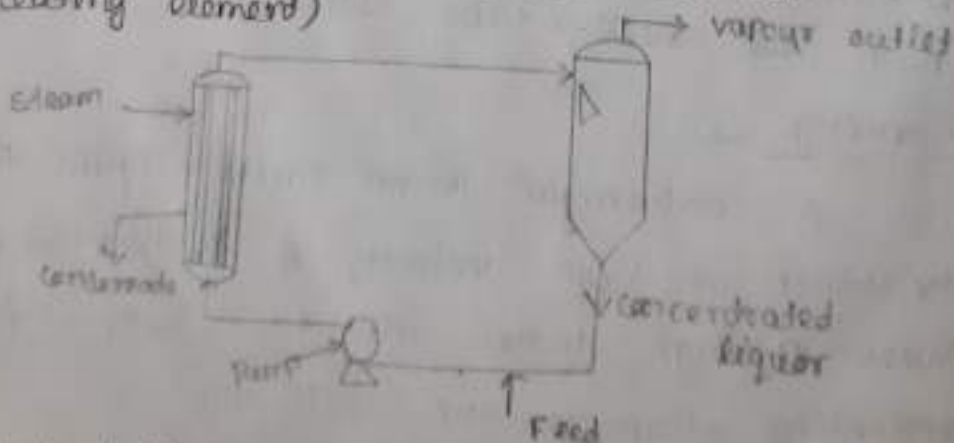
The solⁿ becomes superheated & flashes into a mix. of vapour & liquid just before entering the separator due to reduction in the static head when it flows from the exchanger to the separator.

The two-phase mixture impinges on a deflector plate in the separating space, & the vapours are removed from the top & the liquid is returned to the centrifugal pump.

Part of liquid or solⁿ leaving the separating space is withdrawn as concentrated liquor and make up feed is continuously introduced at the pump inlet.



(Forced circulation evaporator with horizontal external heating element)



Forced circulation evaporator with vertical heating element

Multiple effect evaporation →

When a single evaporator is put into service & vapours leaving the evaporator are condensed & discarded the method is called as single-effect evaporation.

The economy of a single effect evaporator is always less than one. Generally for evaporation of 1 kg of H_2O from a solⁿ, 1 to 1.3 kg of steam is required.

Method of increasing the evaporation per kg of steam by employing a series of evaporators betⁿ steam supply & condenser is known as multiple effect evaporator. It is one way to increase the economy of evaporator system.

Methods of Feeding In Multiple evaporation ⇒

Most of the evaporators use low pressure steam for heating purpose. Due to addition of heat to a solⁿ in the evaporator by condensation of steam, the solⁿ in the evaporator will boil. If the vapours leaving the evaporator are fed to some form of a condenser then the heat associated with the vapour will be lost and the system is said to make poor use of steam.

The vapour coming out of an evaporator can be used as heating media for the another evaporator which will be operating at the pressure lower than the pressure in the evaporator from which the

vapours are issuing so as to provide a sufficient temp. gradient for the h.t. in that evaporator.

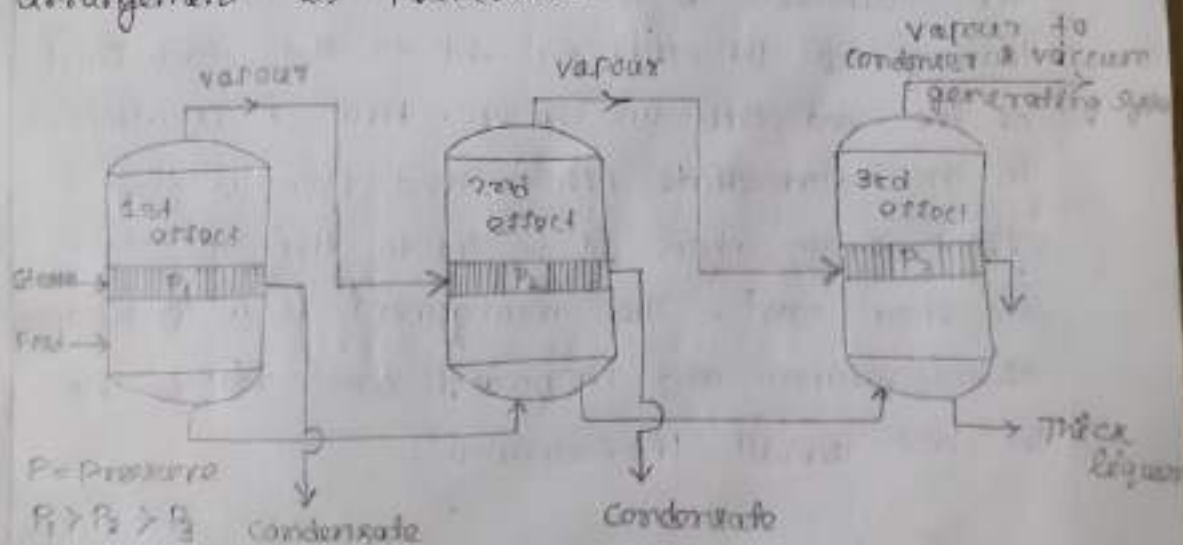
Most common methods used in chemical industry for feeding a multiple evaporation system are —

1. Forward Feed
2. Backward Feed
3. Mixed Feed

Forward Feed ⇒

In this arrangement, the liquid feed flows in the same dirⁿ as the vapour flow. Fresh feed enters the 1st effect and steam is also fed to the steam chest of the 1st effect. The vapours produced in the 1st effect are fed to the steam chest of the 2nd effect as a heating medium & the concentrated liquor from the 1st effect is fed to the next effect in series. The pressure in the 2nd effect is less than in the 1st effect and so on.

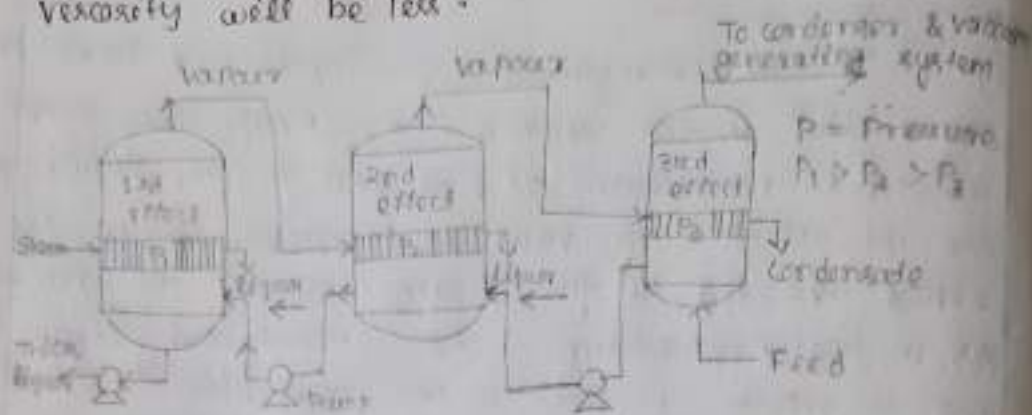
For effectively utilizing temp. potentials, this arrangement is preferable.



Backward Feed ⇒

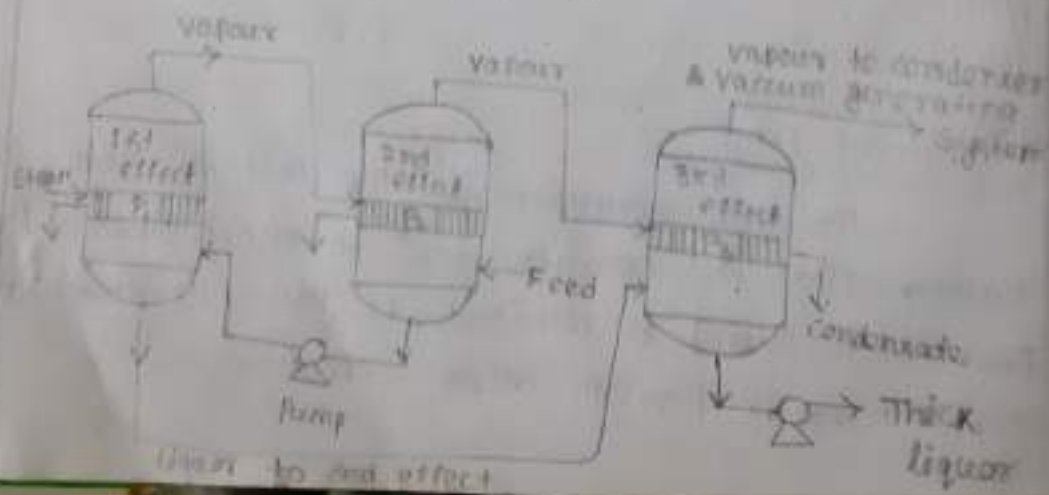
In this arrangement, the feed solⁿ and the vapour flow in opposite dirⁿ to each other. Fresh feed (then liquid) is admitted to the last effect and then pumped through other effects.

The steam is admitted to the steam chest of the 1st effect and the vapours produced in the 1st effect are fed to the steam chest of the 2nd effect (evaporator) and so on. The pressure in the 1st evaporator is highest and that in the last effect is lowest. If the liquid is very viscous then we have to adopt the backward feed arrangement as the temp. of the 1st effect is highest and the corresponding viscosity will be less.



Mixed Feed \Rightarrow

In this arrangement, steam is admitted to the steam chest of the 1st effect and the vapours leaving the 1st effect are fed to the steam chest of the 2nd effect and so on. Feed solⁿ is admitted to an intermediate effects and flows to the 1st effect from where it is fed to the last effect for final concⁿ. This arrangement is a combination of the forward and backward feed adopted for the best overall performance.



Comparison of Forward Feed and backward Feed

arrangements →

Forward Feed

1. In forward feed, the flow of the solⁿ to be concentrated is parallel to the steam or vapour flow.
2. Forward feed arrangement does not need a pump for moving the solⁿ from effect to effect as vacuum is maintained in the last effect.
3. In forward feed as all heating of the cold feed solⁿ is done in the 1st effect, less vapour is produced per kg of steam fed, resulting into a lower economy.
4. With forward feed, the most concentrated liquor is in the last effect wherein the temp. is lowest and the viscosity is highest. These conditions lead to reduction in the capacity of the system as a whole due to low overall coeff. in the last effect in case of thick liquor which are very viscous.

Backward Feed

1. In backward feed, the flow of the solⁿ to be concentrate is in opposite dirⁿ to that of steam or vapour. (counter current.)
2. Backward feed arrangement needs pumps for moving the solⁿ from effect to effect as transfer of the solⁿ is to be done from the evaporator operating at a low pressure to that operating at a high pressure.
3. In backward feed, the solⁿ is heated in each effect which usually results in better economy than that with forward feed.
4. In case of backward feed, the concentrated liquor is in the 1st effect wherein the temp. is highest as steam is admitted to that effect and the viscosity is lowest, thus the overall coeff. can be moderately high inspite of high viscosity.

Forward Feed

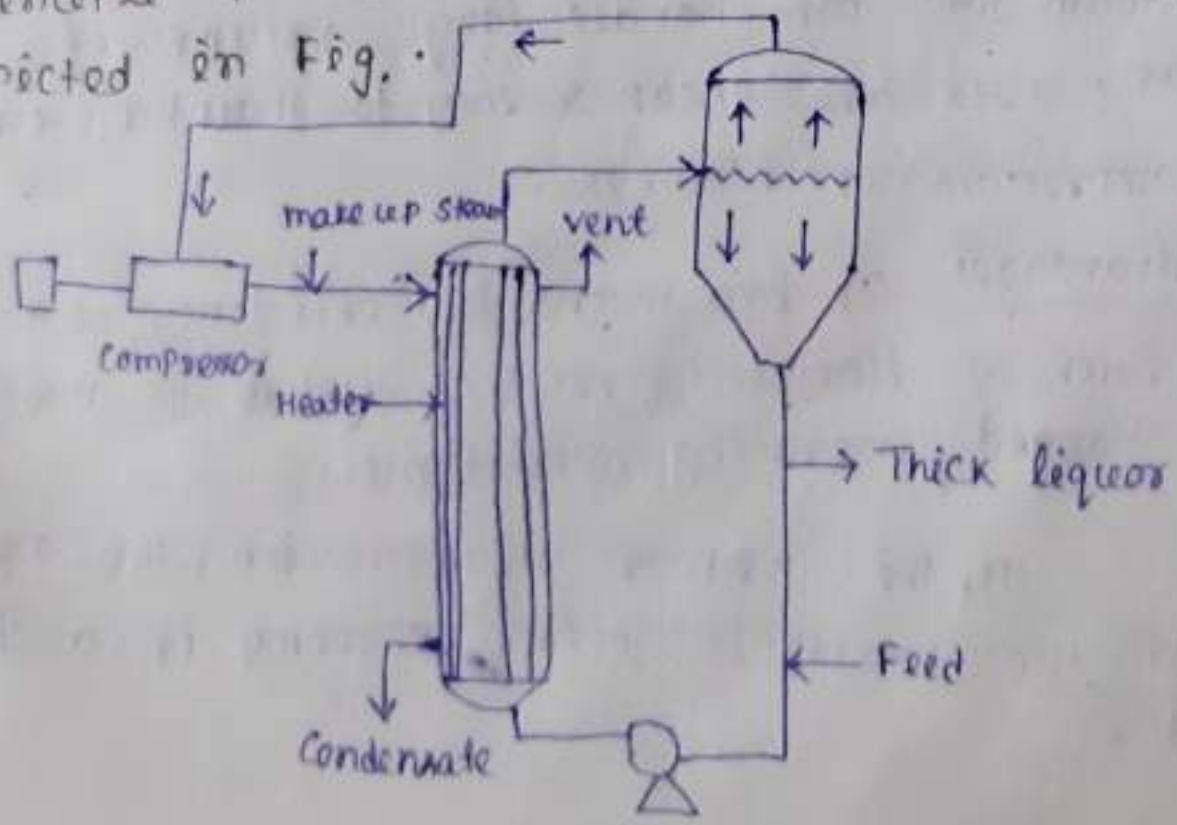
- ⑤ In case of forward feed, the maintenance charges & power cost is less.
- ⑥ Forward feed arrangement is less effective thermally.
- ⑦ Forward feed is more economical in steam.
- ⑧ Forward feed is the commonest one, largely used as it is simple to operate.

Backward Feed

- ⑤ In case of backward feed, the maintenance charges & power cost is more for the same duty.
- ⑥ Backward feed arrangement is more effective thermally. (At high values of feed temp.)
- ⑦ At low values of feed temp., backward feed gives higher economy.
- ⑧ Backward feed is not common as it necessitates the use of pump betⁿ effects.

Mechanical Recompression \Rightarrow

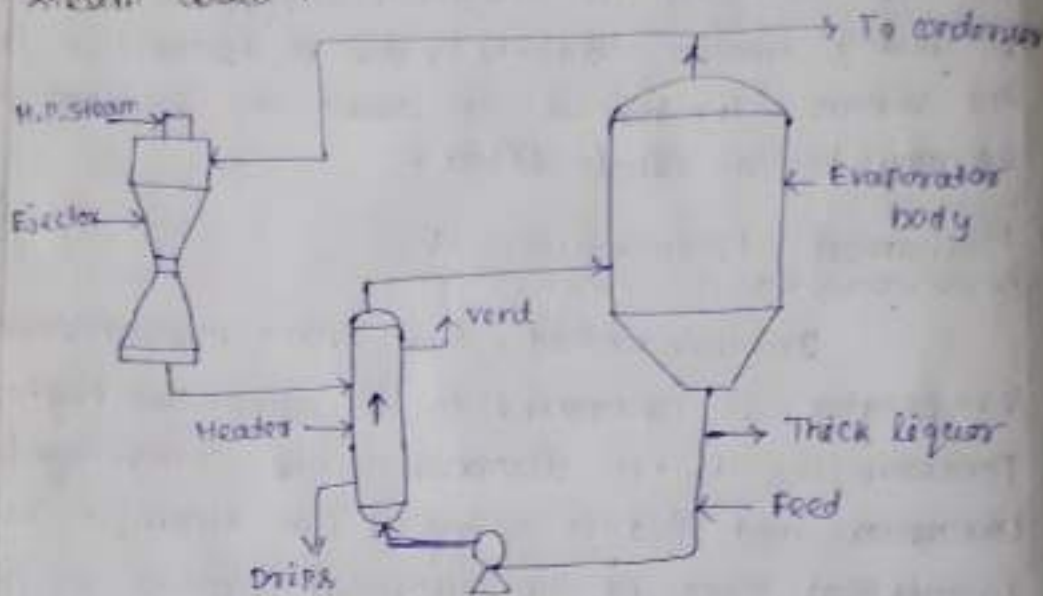
In this method, the vapours evolved from an evaporator is compressed to a somewhat higher pressure by a true displacement or centrifugal compressor and fed to a heater (as steam). As the saturation temp. of the compressed vapour is higher than the B.P. of the solⁿ, heat flows from the vapour to the solⁿ and more vapours are generated. The principle of mechanical vapour recompression is depicted in Fig.



It is used for the concⁿ of very dilute radioactive solⁿ & production of distilled water.

Thermal recompression →

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



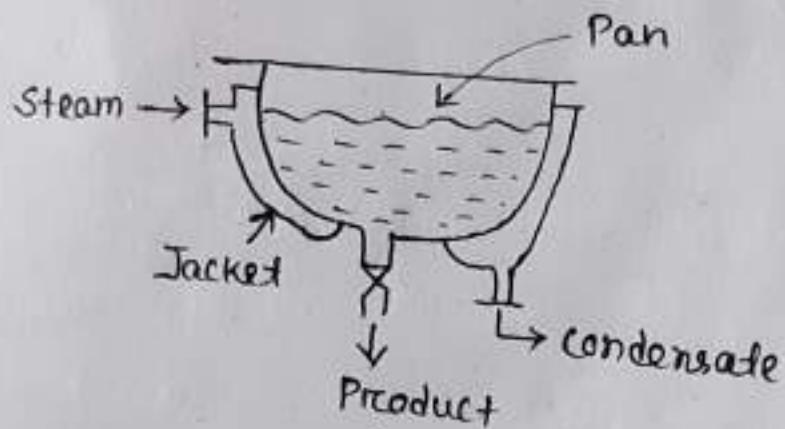
Thermal recompression is better suited than mechanical recompression to vacuum operation as steam jets can handle large volumes of vapour. Jets are cheap & easy to maintain compared to compressors or blowers.

- Disadvantages
- (1) low mechanical efficiency of the jets
 - (2) Lack of flexibility in the system to meet changed operating conditions.

By this vapour recompression, we can obtain the multiple effect economy in a single effect.

Open Pan evaporators / Jacketed pan evaporators →

The simplest method of concentrating a solⁿ is by use of jacketed pans, in which the condensing steam is used in jacket for evaporating a part of the solvent. Such type of evaporator is particularly suitable when small quantities are to be handled. These are available in great variety of materials.



Pans of stainless steel, copper, aluminium etc are widely used in the food process industries. Mild steel jacket may be welded to the pan. Pan is made of single sheet of metal for small size or several sheets joined by welding/brazing. Jacket is welded to the pan.

Jacket is provided with steam inlet at the top while condensate drain is provided at its bottom. Pan is provided at the bottom outlet for drain for its contents.

The solⁿ to be concentrated is taken into a pan & steam is admitted in the jacket. The evaporation is carried out for predetermined time to achieve desired concⁿ level. The thick liquor is then drained from outlet.

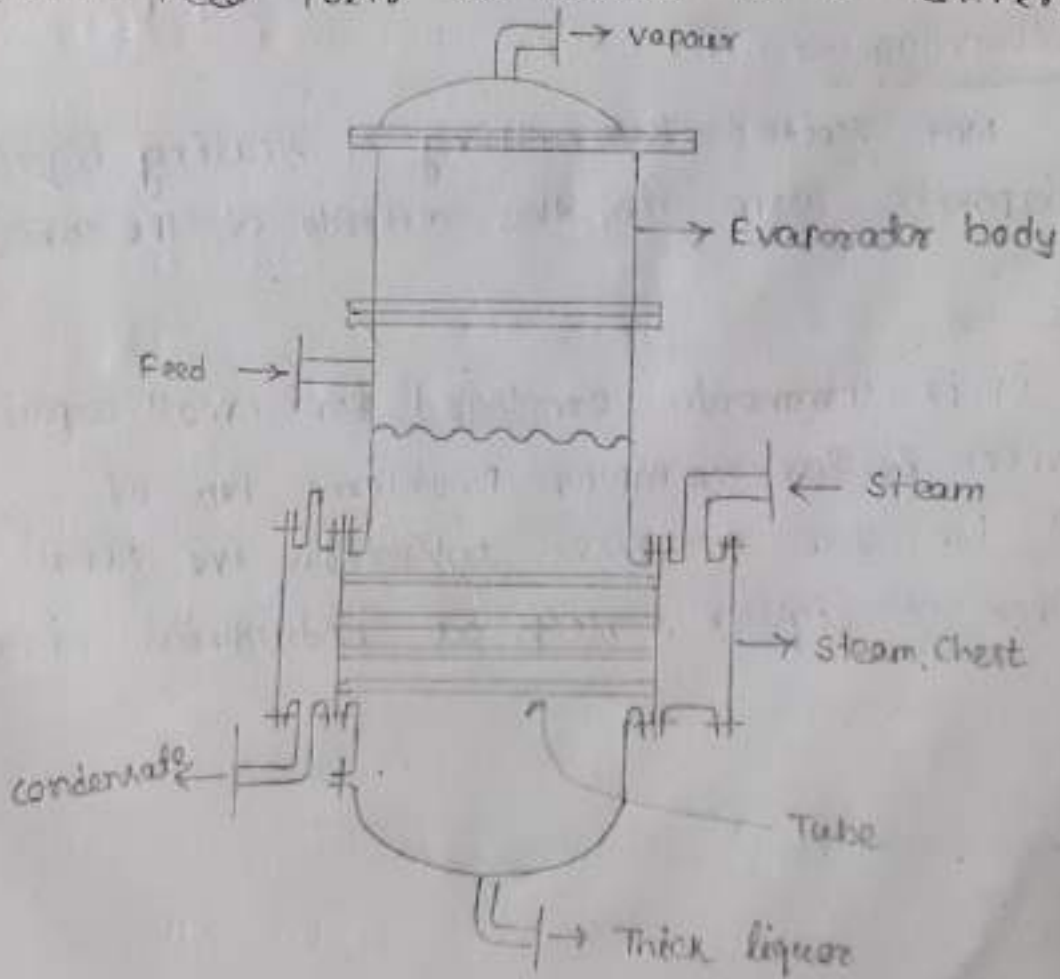
Horizontal tube evaporator ⇒

Construction ⇒

It is the oldest type of evaporator. It consists of a vertical cylindrical shell incorporating a horizontal square tube bundle at the lower portion of the shell.

Channels are provided on either ends of the tube bundle for introduction of steam & withdrawal of condensate. The shell is closed by dished heads at both the ends.

A vapour outlet is provided on the top cover & a thick liquor outlet is provided at the bottom. Feed point is located at a convenient point



working \Rightarrow

Steam is admitted through one of the steam chest or channel flows through the tubes. Steam gets condensed by transferring its latent heat & the condensate is removed from the outlet provided at the bottom of opposite steam chest.

Heat given out by the condensing steam will be gained by a solⁿ in the evaporator & the solution boils. Vapours formed are removed from the top while the thick liquor is removed from the bottom.

In this evaporator as evaporation occurs outside the tube, it eliminates scale formation problem inside the tubes.

Advantages \Rightarrow

- (1) very low head room required
- (2) Large vapour-liquid disengaging area

Disadvantages \Rightarrow

Not suited for salting & scaling liquids as deposits form on the outside of the tubes.

Use \Rightarrow

It is commonly employed for small capacity services & for simpler problems ~~for~~ of concⁿ i.e. for processes wherein the final product is liquor, such as industrial syrups.