

## EVAPORATION

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

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

### Objective:

The objective of evaporation is to concentrate a solution consisting of non-volatile solute & volatile solvent.

In this operation, the solvent to be evaporated is generally water & concentrated solution / thick liquor is a product. The vapour generated usually has no value, it is condensed & discarded.

It differs from drying in that a residue is liquid rather than a solid.

It differs from distillation in that the vapour is usually a single component & even if it is a mixture, it is not separated into fractions.

It differs from crystallisation in that purpose is concentrating a soln rather than forming & building crystals.

Evaporation is generally followed by crystallisation & drying.

Evaporation is carried by supplying heat to a soln to vaporise solvent. Common heating medium (heat source) is generally low pressure steam but in some situation other sources that might be used are solar energy, fuel, electricity, hot oil & flue-gas. The heat is utilised to -

- i) increase the temp of the soln to its boiling point &
- ii) supply the latent heat of vaporisation of solvent.

Though the several state processes occur (heat transfer from heating medium to a soln through the solid surface, simultaneous heat & mass transfer from the liquid to vapour phase), the operation can usually be considered in terms of heat transfer from a heater to soln (heat transfer to boiling liquids) for design of evaporators.



There is a wide variation in characteristics of liquors to be concentrated that requires judgement & experience in designing & operating evaporators. Some of the properties of evaporating liquids that influence the process of evaporation are:

- i) Concentration: As the conc<sup>n</sup> increases, the soln become more & more individualistic. The viscosity & density increase with solid content. The boiling point of soln also increases considerably with solid content so that it may much higher than B.P of water.
- ii) Foaming: Some of the materials have tendency to foam that causes heavy entrainment (carry over a portion of liquid by rising vapour is called as entrainment).
- iii) Scale: Some solns deposit scale on heat transfer surfaces that results in reduction of heat transfer coefficient & hence heat transfer rate. It is therefore necessary to clean the tubes at definite intervals.
- iv) Temp. Sensitivity: Some materials especially pharmaceuticals & food products are damaged when heated to moderate temp ~~even~~ even for short times. For concentrating such materials special techniques are to be used that reduce temp & time of heating.
- v) Materials of Construction: Generally evaporators are made of mild steel whenever contamination & corrosion is a problem. Special materials such as copper, nickel, stainless steels may be used. Other liquid characteristics that must be considered in design are specific heat, freezing point, toxicity, explosion hazards, & radioactivity.

The selection of the evaporator for a particular application is based on the analysis of the factors such as the properties of liquid to be concentrated, operating cost, capacity, hold ups & residence time. High product viscosity, heat sensitivity, scale formation & deposition are the major problems encountered during operation of evaporators & should be taken into account while designing of evaporator for new installation.

Usually, the desired product of evaporation operation is the concentrated soln (called as thick liquor), but occasionally the evaporated solvent is the primary



product as, for example, in the evaporation of sea water to yield potable water.

Common examples of evaporation are:

Concentration of aqueous solutions of sugars, sodium chloride, sodium hydroxide, glycerol, milk & fruit juices.

Performance of tubular evaporators:

The performance of a steam heated tubular evaporator is evaluated in terms of i) Capacity & ii) Economy

Capacity: of an evaporator is defined as the number of kilogram of water vaporised/evaporated per hour.

The rate of heat transfer  $Q$ , through the heating surface of evaporator is the product of area of heat transfer, surface  $A$ , the overall heat transfer coefficient  $U$ , & the overall temp drop  $\Delta T$ .

$$Q = U \cdot A \cdot \Delta T$$

$\Delta T$  - is the temp diff b/n the heating medium & the boiling liquid (saturation temp of steam minus boiling pt of soln).

If the feed soln is at the boiling temp corresponding to the pressure in vapour space of evaporator, then all the heat transferred through heating surface is available for evaporation & capacity is proportional to rate of heat transfer. If cold feed soln is fed to evaporator, heat is required to increase its temp to the boiling point & it may be quite large & thus, capacity for given rate of heat transfer will be reduced accordingly as heat used to increase the temp to the boiling point is not available for evaporation. When the feed soln to the evaporator is at a temp higher than the b.p corresponding to pressure in the vapour space, a portion of feed evaporates adiabatically & capacity is greater than that corresponding to rate of heat transfer. It is called as



flash evaporation.

Evaporator economy: Economy of an evaporator is defined as the number of kilogram of water evaporated per kilogram of steam fed to the evaporator. It is also called as steam economy.

In single effect evaporation the amount 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 pressure increases tends to make the ratio of water vapour produced per kg of steam condensed less than unity.

Increase in economy of an evaporator is achieved by reusing the vapour produced.

The methods of increasing economy are:

- i) use of multiple effect evaporation system.
- ii) Vapour recompression.

In multiple effect evaporation system, the vapour produced in first effect is fed to the steam chest of 2nd effect as heating medium in which boiling takes place at low pressure & temp so on. Thus in triple effect evaporator, 1 kg of steam fed to 1st effect evaporates approximately 2.5 kg of steam.

Another method to increase the economy of an evaporator is to use principle of thermo compression. Here the vapour from the evaporator is compressed to increase its temp so that it will condense at a temp higher enough to permit its use as heating media in the same evaporator.

Boiling Point elevation:

As vapour pressure of most aqueous soln is less than that of water at any given temp, the boiling point of the soln is higher than that of pure water at given pressure.



The difference b/n the b.p. of a soln & that of pure water at any given pressure is known as b.p. rise or elevation of a soln. B.p. elevation is small for dilute solns & large for concentrated solns of inorganic salts.

B.p. elevation of strong solns 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 pure water at the same pressure. Hence, when the b.p. of the soln plotted against b.p. of water, straight line results.

Fig shows a plot for NaOH soln of various conc<sup>n</sup>.

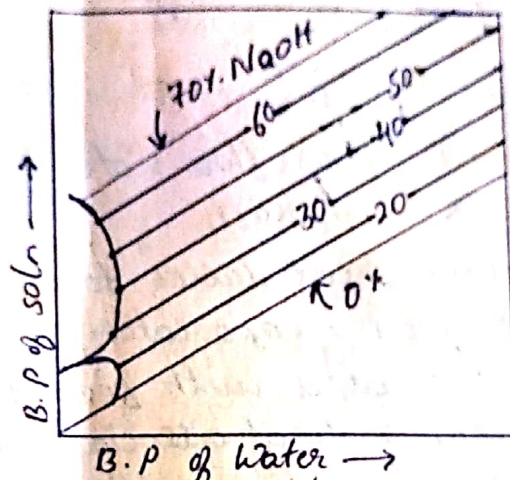
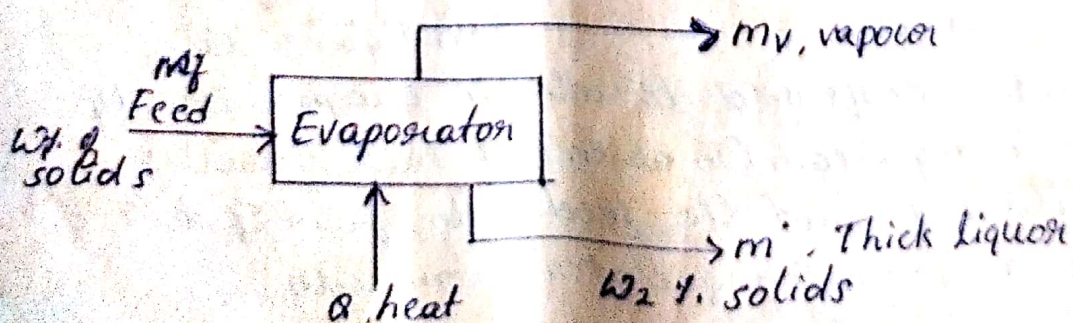


Fig: Dühring's plot of NaOH.

### Material & enthalpy balances for single-effect evaporator:

Consider that the evaporator is fed with  $m_f$  kg/h of weak soln containing  $w_1$  % solute & thick liquor is withdrawn at  $m'$  kg/h containing  $w_2$  % solids by weight. Let  $m_v$  be the kg/h of water evaporated. Then:



Overall material balance:

$$m_f = m' + m_v \quad \text{--- (1)}$$



Material balance of solute:

solute in feed = solute in thick liquor

$$\frac{w_1 \times m_f}{100} = \frac{w_2 \times m_i}{100}$$

$$w_1 \times m_f = w_2 m_i \quad \text{--- ②}$$

Let  $T_f$ ,  $T$  &  $T_s$  be the temps. of feed entering the evaporator, soln in the evaporator & condensing steam respectively.

Let ' $\lambda_s$ ' be the latent heat of condensation of steam at saturation temp & assume that only latent heat of condensation is used. Then, rate of heat transfer through heating surface from steam is:

$$Q_s = m_s \lambda_s \quad \text{--- ③}$$

where,  $m_s$  - mass flow rate of steam to the evaporator in kg/h

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

Heat associated with feed + Heat (latent) associated with steam = Heat associated with vapour leaving + Heat associated with thick liquor.

$$m_f H_f + m_s \lambda_s = m_v H_v + m' H' \quad \text{--- ④}$$

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

where  $H_v$ ,  $H_f$  &  $H'$  are enthalpy of vapour, feed soln & thick liquor resp.

Rearranging we get:

$$m_s \lambda_s = (m_f - m') H_v + m' H' - m_f H_f \quad \text{--- ⑤}$$

Heat transfer rate on steam side = Heat transfer rate on liquor side

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

$$Q_s = Q$$

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

$$m_s \lambda_s = m_f C_{pf} (T - T_f) + (m_f - m') \lambda_v \quad \text{--- ⑥}$$



where,

$C_{pf}$  = specific heat of feed soln

$\lambda_v$  = latent heat of evaporation from thick liquor  
For negligible boiling point rise  $\lambda_v = \lambda$

where,  $\lambda$  = latent heat of vaporisation of water at pressure in the vapour space & can be read from steam tables.

$$m_s \lambda_s = m_f C_{pf} (T - T_b) + (m_f - m') \lambda$$

$$m_s \lambda_s = m_f C_{pf} (T - T_b) + m_v \lambda \quad \text{--- (4)}$$

B.p of soln (T) at a pressure in the vapour space can be obtained by knowing b.p elevation & b.p of pure water at that pressure, e.g. if 'T' is the b.p of water at certain pressure of operation & 'P' is the b.p elevation, then;

$$T = T' + P$$

Area of heat transfer of an evaporator is calculated with the help of following eqn:

$$Q = U.A.\Delta T \quad \text{--- (5)}$$

$$Q \doteq m_s \lambda_s = U.A.\Delta T$$

where,  $U$  = overall heat transfer coefficient

$A$  = area of heat transfer

$\Delta T$  = temp diff

$$\Delta T = T_s - T$$

= condensing steam temp - B.p of soln

When  $Q$  is in W,  $U$  is in  $W/m^2.K$  &  $\Delta T$  in K, then  $A$  will be in  $m^2$ .

$\lambda_s$  = specific enthalpy of saturated steam - specific enthalpy of saturated water (i.e. of condensate).

### Evaporator Types:

Evaporators used in process industries can be classified as:

- i) Natural circulation evaporators &
- ii) Forced circulation "



Natural circulation evaporators are commonly employed for simpler evaporation operations singly or in multiple effect. E

E.g.: Jacketed pan or open pan evaporator

Horizontal tube "

Vertical tube "

Long tube "

While forced circulation evaporators are commonly employed for salting, viscous & scale forming solns. These units may be provided with external horizontal or vertical heating element.

### Open pan or Jacketed pan Evaporator:

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.

There 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.

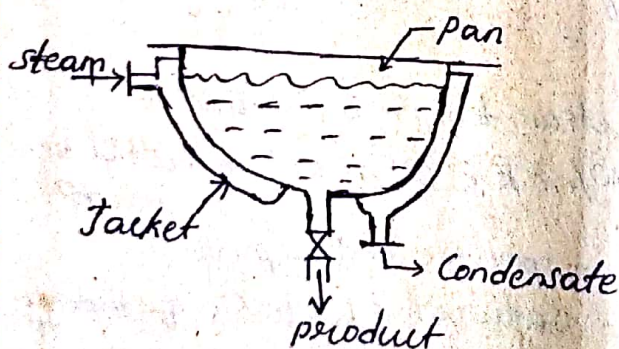


Fig: Jacketed pan evaporator

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:

It is the oldest type of evaporator. It consists of vertical cylindrical shell incorporating horizontal square tube bundle for introduction of steam & withdrawal of condensate. Shell is closed by dished heads at both the ends. Vapour outlet is provided on top cover & thick liquor outlet is provided at bottom. Feed point is located at convenient point. In this evaporator, steam is inside the tube & liquor to be concentrated, surrounds the tubes. Steam which is admitted through one of the steam chest/channel, flows through tubes. Steam gets condensed by transferring its latent heat & condensate is removed from outlet provided at bottom of opposite steam chest. This type of evaporator is shown in fig.

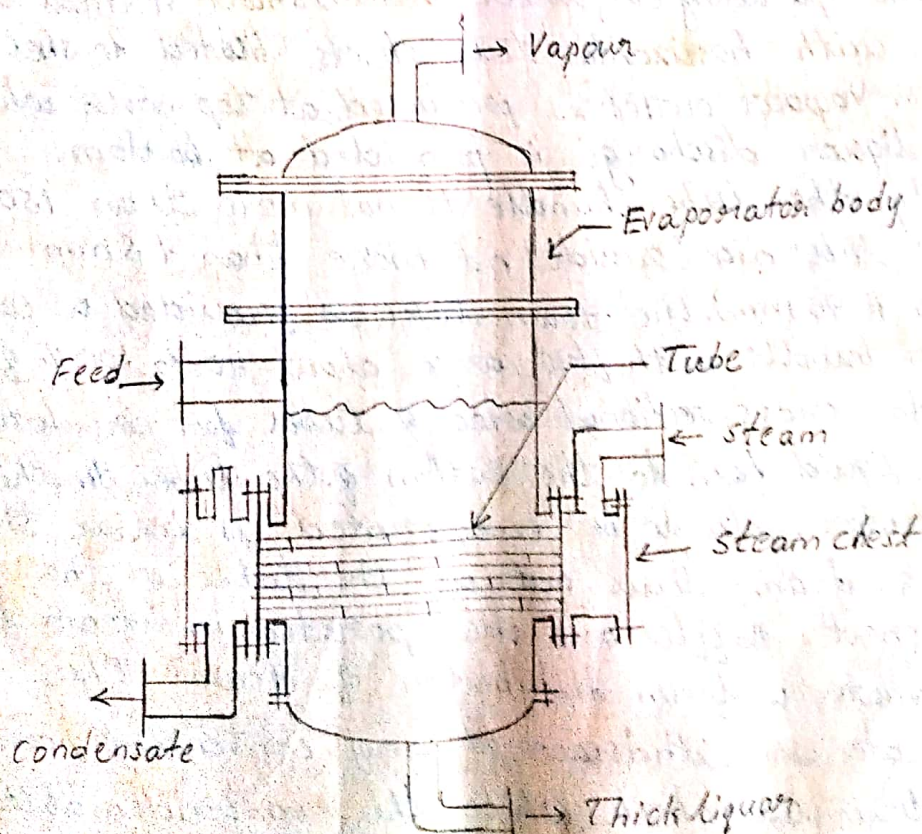


Fig: Horizontal tube evaporator



Heat given out by condensing steam will be gained by soln in the evaporator & soln boils. Vapour formed are removed from top while thick liquor is removed from the bottom. In this evaporator as evaporation occurs outside the tube eliminating scale formation problem inside the tubes. Small diameter tubes than any other types are used.

Very low head room requirements & large vapour liquid disengaging area, are among the main advantages of it.

It is not suited for scaling & scaling liquids or deposits from on outside of the tube.

It is commonly employed for small capacity services & for simpler problems of conc<sup>n</sup> i.e. for processes wherein the final product is liquor, such as industrial sirups.

Calendria - type / standard vertical tube evaporator or short tube evaporator:

Construction: It consists of vertical cylindrical shell incorporating (at lower position) short vertical tube bundle with horizontal tube sheets bolted to shell flanges. Vapour outlet is provided at top cover while thick liquor discharge is provided at bottom.

Usually the tube bundle is not more than 1500 mm high & tube dia (outside) not more than 75 mm (25 mm to 75 mm). The down take is provided at centre of tube bundle with flow area about 40 to 100% of the total cross sectional area of tubes for circulating cooler liquid back to the bottom of the tubes. In this evaporator, soln to be evaporated is inside the tubes & steam flows outside the tubes in the steam chest. Baffles are incorporated in steam chest to promote uniform distribution of steam. The condensate is withdrawn at any convenient point near lower tube sheet, while the non-condensable gas such as air is vented to atmosphere from point near the top tube sheet.



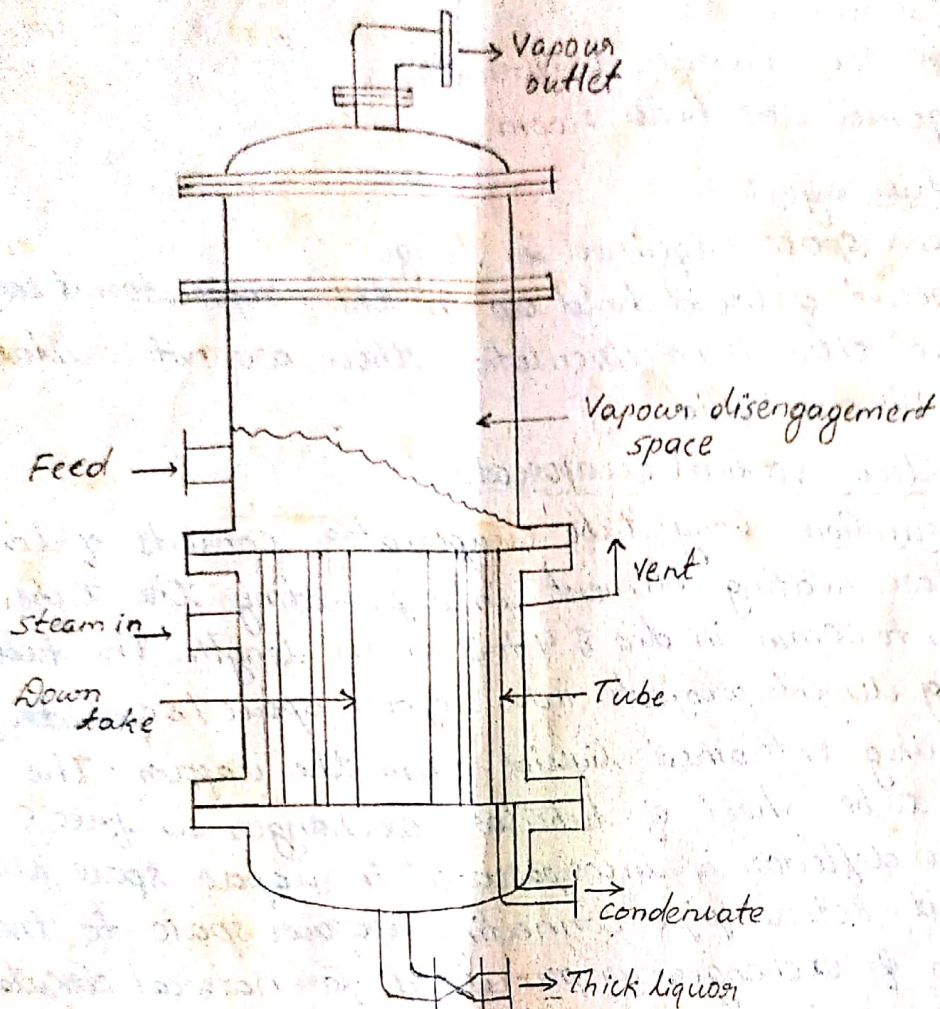


Fig: Calenderia type evaporator

Working: Thin liquor is introduced to the tube side & steam into the steam chest. The liquor covers the top of tubes. Heat transfer to the boiling liquid inside the tubes takes place from which they are condensing steam on outside of tubes. Vapour formed will rise through the tubes, come to the liquid surface from which they are disengaged into the vapour space & removed from the vapour outlet. Circulation of cold liquor is promoted by central downtake & concentrated, thick liquor is removed from the bottom of the evaporator.

Advantages:

- i. Relatively inexpensive.
- ii. As scaling occurs inside the tubes it can be easily removed by mechanical or chemical means.
- iii. Provide moderately good heat transfer at reasonable cost.
- iv. Can be put into more rigorous service than horizontal



- tube evaporators.
- v. High heat transfer coefficients
  - vi. Require 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 there are not suitable for viscous liquid.

#### Long tube Vertical evaporator:

Construction: Long tube evaporator consists of long tubular heating element incorporating the tubes 25mm to 50mm in dia & 4 to 8 m in length. The tubular heating element projects into vapour space / separator for removing entrained liquid from the vapour. The upper tube sheet of tubular exchanger is free & vapour deflector is incorporated in vapour space just above it. Return pipe connecting vapour space to the bottom of exchanger is provided for natural circulation of unevaporated liquid. It is provided with inlet connection for feed, steam & outlet connections for vapour, thick liquor, condensate etc. In this evaporator, the liquor to be concentrated is in tubes & condensing steam surrounds the tubes.

Working: In this evaporator, feed enters the bottom of the tubes, gets heated by condensing steam & starts to boil part way up the tubes & mixture of vapour & liquid issues from the top of tubes & finally impinge at high velocity on deflector. The deflector acts both as a primary separator & foam breaker. Separated liquid enters the bottom of exchanger & part of this liquid is taken as a product.

The long tube vertical evaporator competes most favourably with forced circulation evaporator as compared to other natural circulation evaporators.

This type of evaporator is widely used for handling of foamy, frothy liquors.



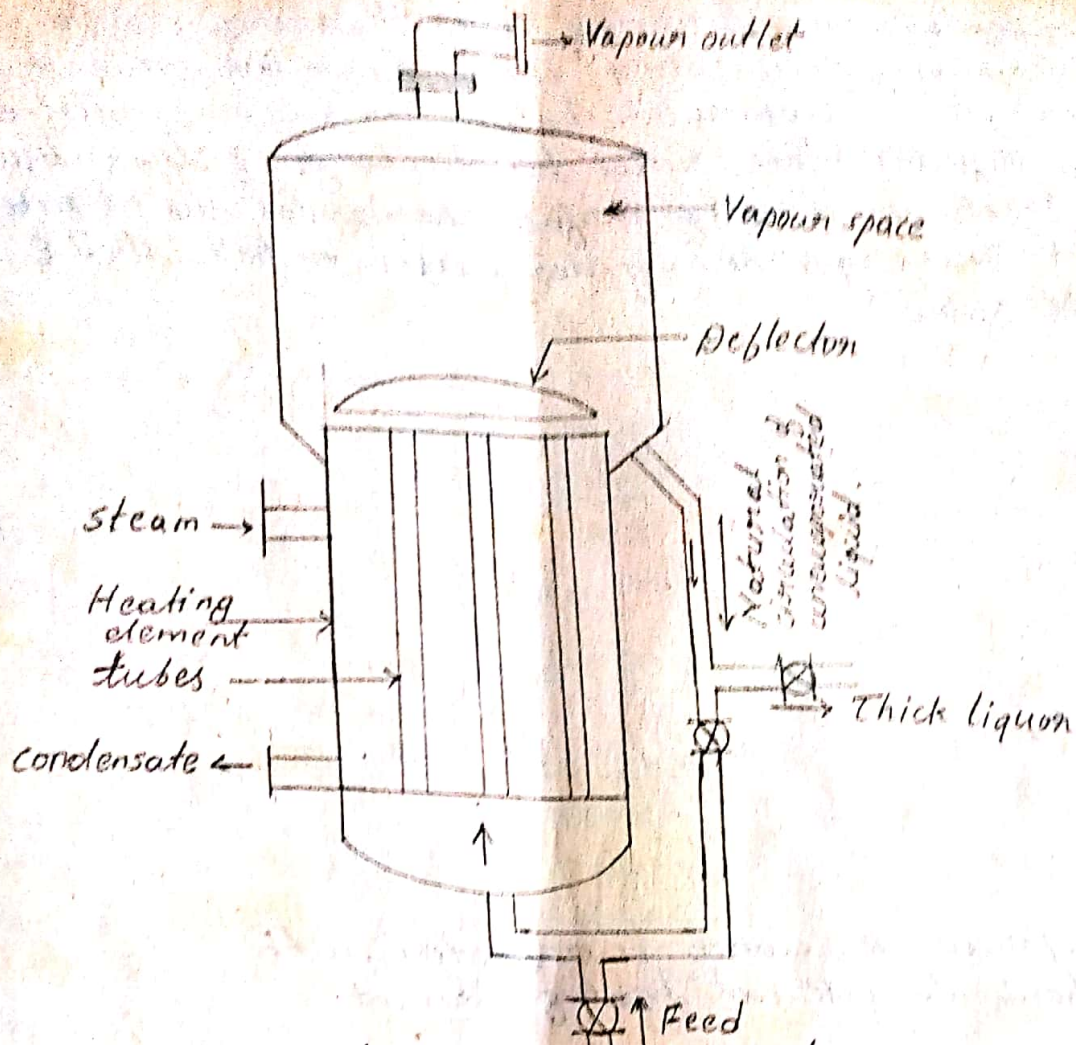


Fig: Long vertical tube evaporator.

### Forced Circulation Evaporator:

Whenever we are dealing with concentration problems involving solns of high viscosities, of scale forming tendencies there is no alternative but to use forced circulation evaporator as increasing the velocity of flow of liquor through tubes increases remarkably liquid film heat transfer coefficients & high velocity swirling by use of centrifugal pump prevents the formation of excessive deposits on heat transfer surfaces. In natural circulation evaporator, the liquid enters the tubes at a velocity of 0.3 to 1 m per sec; ~~in natural circulation evaporator~~ <sup>while in forced</sup> circulation evaporator, the liquid enters the tubes at a velocity is of the order of 2-6 m/sec. In forced circulation evaporator smaller diameter tubes are used than in natural circulation evaporator, generally not larger than 50 mm.

### Forced Circulation evaporator with horizontal External heating element:

Construction: Forced circulation evaporator with



horizontal external heating element is shown in fig. It consists of circulating pump, separating space or separator, evaporator body with vapour outlet at top, deflector plate, outlet for discharge of thick liquor and external heating surface - horizontal shell & tube heat exchanger having two passes on both shell & tube sides.

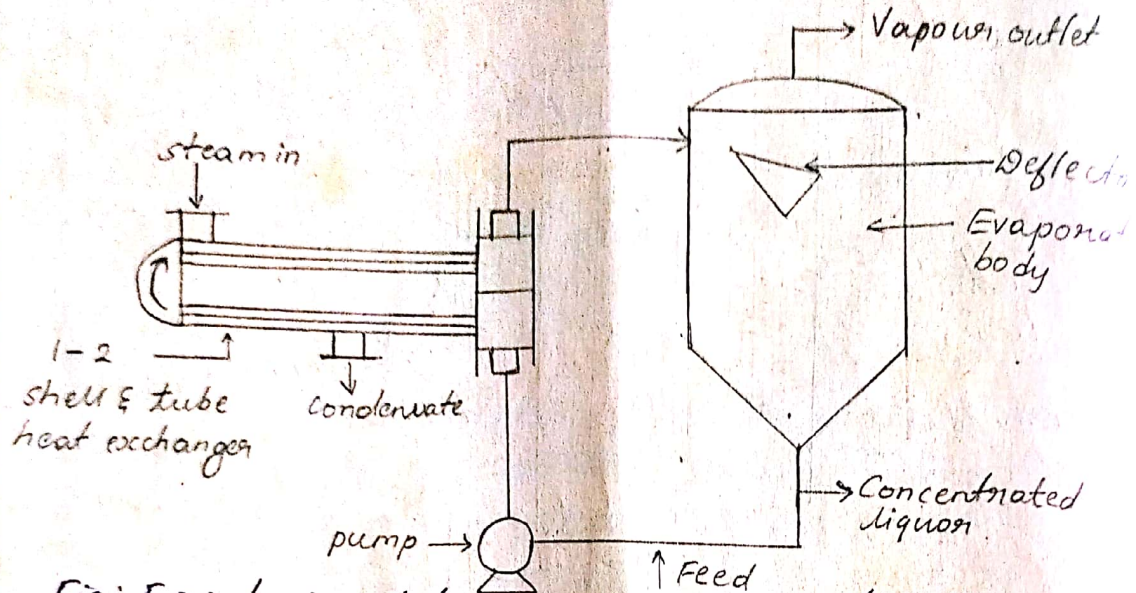


Fig: Forced circulation evaporator with horizontal external heating element

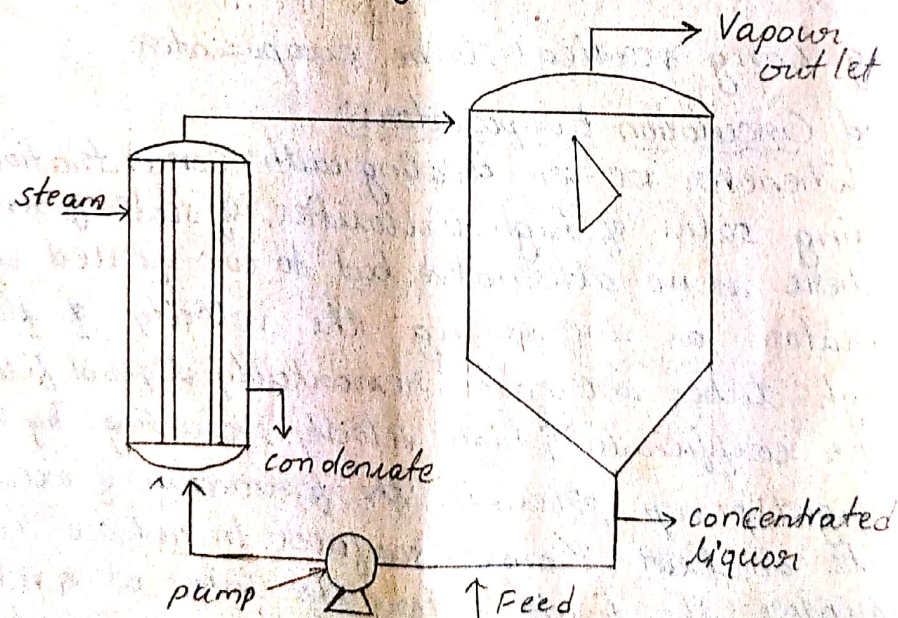


Fig: Forced circulation evaporator with vertical heating element

Working: Centrifugal pump forces the liquid through tubes at high velocity & is heated as it passes through tubes due to heat transfer from condensing steam on shell side. Boiling does not take place in tubes as they are under sufficient static head which raises the p.p. above that in separating space.



Soln becomes superheated & flashes into a mixture of vapour & liquid just before entering the separator due to reduction in static head when it flows from exchanger to separator. The two-phase mixture impinges on a deflector plate in separating space & vapour is removed from top & liquid is returned to centrifugal pump. The part of liquid/soln leaving the separating space is withdrawn as a concentrated liquor & make up feed is continuously introduced at pump inlet. In case of vertical heating element, single pass shell & tube heat exchanger is used.

#### Advantages of forced circulation evaporators:

1. High heat transfer coefficients are obtained even with viscous material.
2. Positive circulation & close control of flow.
3. 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.
4. Residence time of liquid in tube is very small (1-3s) because of high velocities in these units so that moderately heat sensitive liquids can be handled.

Main disadvantage lies in high pumping cost.

The forced circulation evaporators are commonly employed for crystalline product, viscous, salting, scaling & corrosive & foaming soln / liquids.

#### Multiple - Effect Evaporation:

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

The vapour coming out of evaporator can be used as heating media for another evaporator which will be operating at pressure lower than the pressure in the evaporator from which vapours are issuing so as to provide sufficient temp gradient for heat



transfer in that evaporator.

When single evaporator is put into service & vapour leaving the evaporator are condensed & discarded the method is known as single-effect evaporation. The economy of single effect evaporation is always less than one. Generally for evaporation of one kg of water from a soln, 1 to 1.3 kg of steam is required.

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

Multiple effect evaporation system is commonly used in large scale operations. In such system, evaporators are arranged in series so that the vapour from one evaporator ~~b/n the steam~~ is used as heat source for the next one that is operating under lower pressure & temp. Each unit in series is called as an effect. In case of triple-effect evaporator, if the 1st effect is operating at atmospheric pressure then the 2nd & 3rd effect operate under vacuum. Steam is fed to the 1st effect & vapour from 3rd-effect is condensed in condenser connected to a vacuum pump.

With multiple-effect evaporation system, it is possible theoretically to evaporate  $N$  kg of water from 1 kg of initial steam fed, where  $N$  is the number of effects.

If vapour (as heat source / as steam supply) from one evaporator is fed to the steam chest of the second evaporator, the system is called as double-effect evaporator system & so on.

Increasing the no of effects b/n steam supply & condenser increases the amount of evaporation per kg of steam fed to the 1st effect & also the operating cost will be less but capital cost, & repair & maintenance charges increase with increase in no of effects. Supervisory labour will be same for operating any no of effects. The optimum no of



effects for given duty must be found out by analysis of above cited factors. At optimum no. of effects minimum of total cost occurs on a plot of total cost against no. of effects.

Most common methods used in chemical industry for feeding the multiple evaporation system are:

1. Forward feed
2. Backward feed
3. Mixed feed.

1. Forward feed: In this arrangement, the liquid feed flows in the same direction as the vapour flow. Fresh feed enters the 1st effect & steam chest of 2nd effect as a heating media & concentrated liquor from 1st effect is fed to the next effect in series. The pressure in the 2nd effect is less than in the 1st effect & so on. For effectively utilising temp potential this arrangement is preferable.

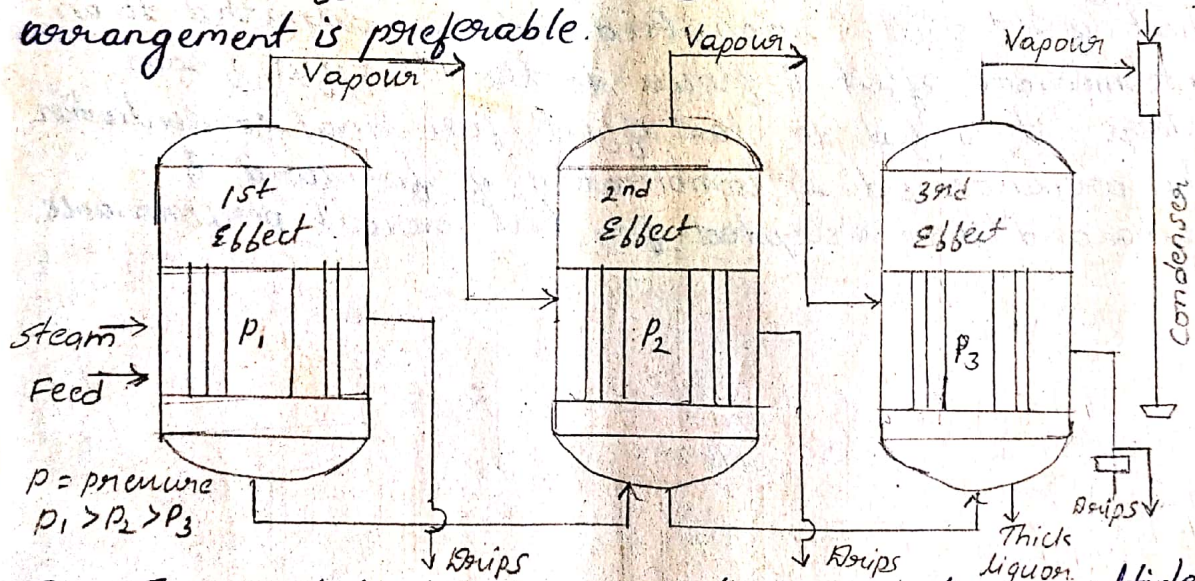


Fig: Forward feed arrangement for feeding multiple effect evaporator system.

2. Backward Feed: In this arrangement the feed & vapour flow in opposite direction. The fresh feed is admitted to the last effect & then pumped through other effects. The steam is admitted to the steam chest of 1st effect & vapour produced in 1st effect are fed to the steam chest of 2nd evaporator & so on. The pressure in 1st evaporator is highest & that in last evaporation is lowest. If the liquid is very viscous then we have to adopt backward arrangement as the tem



of the 1st effect is highest & corresponding viscosity will be less.

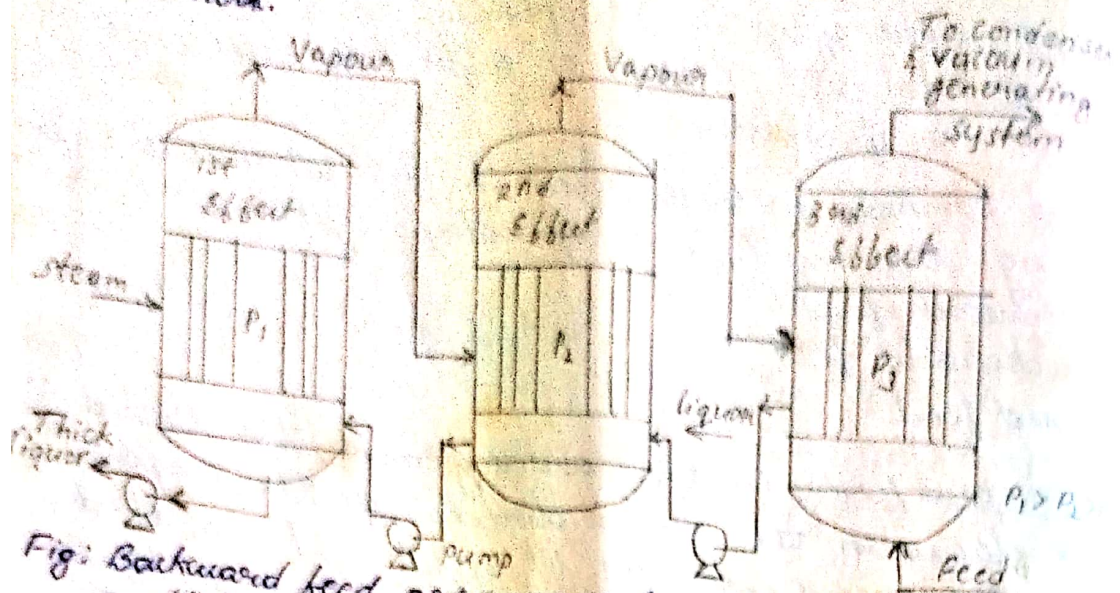


Fig: Backward feed arrangement for feeding multiple-effect evaporation system.

3. Mixed Feed: In this feed arrangement, steam is admitted to the steam chest of 1st effect & vapour leaving 1st effect evaporator are fed to the steam chest of 2nd effect & so on. Feed soln is admitted to an intermediate effect & flows to the 1st effect from where it is fed to last effect for final concentration. This arrangement is combination of forward & backward feed adopted for best overall performance.

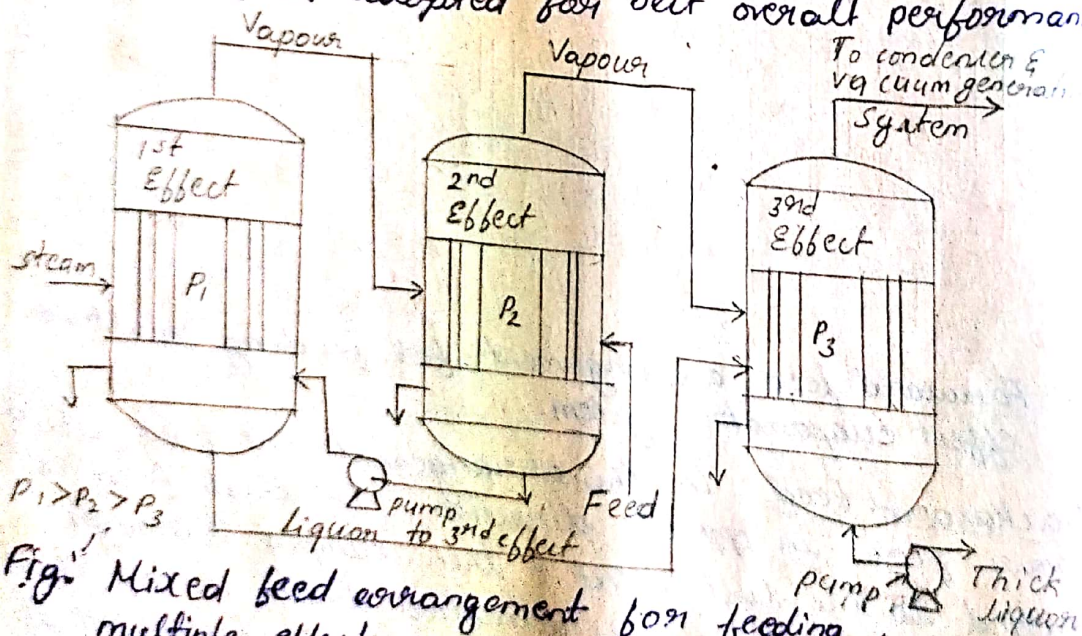


Fig: Mixed feed arrangement for feeding multiple effect evaporation system.

Comparison of forward & backward feed arrang

1. In forward feed, the flow of soln to be concentrated is parallel to steam/vapour flow.  
In backward feed, the flow of soln to be concentr-



ated is in opposite direction to that of steam/vapour (counter current).

2. FF arrangement does not need pump for moving the soln from effect to effect as vacuum is maintained on the last effect.

BF arrangement needs pumps for moving the soln from effect to effect as soln transfer of soln is to be done from evaporator operating at low pressure to that operating at high pressure.

3. In forward feed as all heating of cold feed soln is done in 1st effect, less vapour is produced per kg of steam fed, resulting into lower economy.

In BF, the soln is heated in each effect which usually results in better economy than that with FF.

4. With FF the most concentrated liquor is in the last effect wherein the temp is lowest & viscosity is highest. These conditions lead to reduction in capacity of the system as a whole due to low overall coefficient in last effect in case of thick liquors which are very viscous.

In case of BF, the concentrated liquor is in 1st effect wherein the temp is highest as steam is admitted to that & the viscosity is lowest, thus the overall coefficient can be moderately high inspite of high viscosity.

5. In case of FF, the maintenance charges & power cost is less. In case of BF, the maintenance charges & power cost is more for same duty.

6. FF arrangement is less effective thermally.

B.F arrangement is more effective thermally. At high values of feed temp.

7. FF is more economical in steam. At low values of feed temp, BF gives higher economy.

8. BFF is the commonest one, largely used as it is simple to operate. BF is not common as it necessitates the use of pump b/n effects.



The choice of optimum no. of effects will be dictated by an economic balance b/n the savings in steam obtained by multiple-effect evaporation & the added investment costs that results from the added area.

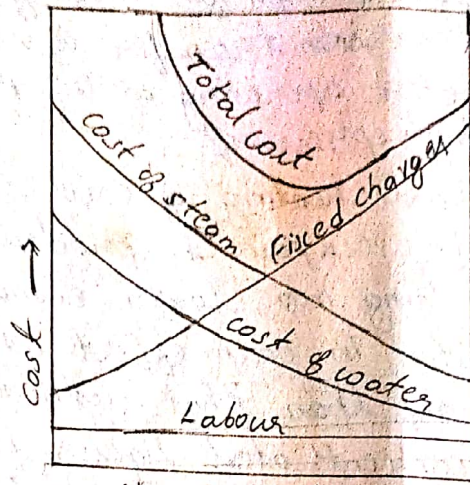


Fig: Optimum no. of effects in a multiple-effect evaporation system.

### Calculation of Multiple-Effect Evaporator:

Assumptions generally made in calculation procedure are:

- i) Equal heat transfer rate in each of the effects
- ii) equal heat transfer surface in each of the effect
- iii) equal evaporation in each of the effects.

Consider a case of tripple-effect evaporator.

Let  $Q_1, Q_2$  &  $Q_3$  be the heat transmitted in 1st, 2nd & 3rd step.

$A_1, A_2$  &  $A_3$  be the heat transfer surface of 1st, 2nd & 3rd effect step.

For tripple effect evaporator, we have

$$Q_1 = Q_2 = Q_3$$

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = U_3 A_3 \Delta T_3 \quad \text{--- (1)}$$

To obtain economy of construction, in practice, heat transfer rate area in all effects are equal.

so, with  $A_1 = A_2 = A_3$

$$\text{we get } U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3 \quad \text{--- (2)}$$

It follows from the eqn (2) that the temp drops in multiple effect evaporator are approximately



inversely proportional to the heat transfer coefficients.

$$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 \quad \text{--- (3)}$$

$$\Delta T_3 = \frac{U_1}{U_3} \Delta T_1 \quad \text{--- (4)}$$

where,  $\Delta T$  = overall temp drop over system

$$\Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3$$

$$\Delta T = \Delta T_1 \left[ \frac{U_1}{U_2} + 1 + \frac{U_1}{U_3} \right] \quad \text{--- (5)}$$

$$\Delta T = T_s - T_v \quad \text{--- (6)}$$

where,  $T_s$  = the saturation temp of condensing (1st effect) steam corresponding to steam pressure.

$T_{v3}$  = temp of the vapour corresponding to the pressure in the vapour space of 3rd effect.

	First effect	2 <sup>nd</sup> effect	3 <sup>rd</sup> effect
Steam	$T_s$	$T_{v1}$	$T_{v2}$
Liquor	$T_{L1}$	$T_{L2}$	$T_{L3}$
Vapour	$T_{v1}$	$T_{v2}$	$T_{v3}$
$\Delta T$	$T_s - T_{L1}$	$T_s - T_{L2}$	$T_s - T_{L3}$
BPE	$T_{L1} - T_{v1}$	$T_{L2} - T_{v2}$	$T_{L3} - T_{v3}$

Evaporation in each effect & steam consumption are computed with the help of material balance & energy balance eqn.

The areas of the individual effects are calculated as follows:

$$A_1 = \frac{m_s \lambda_s}{U_1 \Delta T_1} \quad \text{--- (7)}$$

$$A_2 = \frac{m_{v1} \lambda_{v1}}{U_2 \Delta T_2} \quad \text{--- (8)}$$

$$A_3 = \frac{m_{v2} \lambda_{v2}}{U_3 \Delta T_3} \quad \text{--- (9)}$$

If  $A_1 \neq A_2 \neq A_3$  & the deviation is more than  $\pm 10\%$ , a fresh trial with new temp distribution is performed. New temp drops are calculated as:

$$\Delta T_1 = \Delta T_1 \times \frac{A_1}{A_{\text{avg}}}, \quad A_{\text{avg}} = \frac{A_1 + A_2 + A_3}{3}$$



$$\Delta T_2' = \Delta T_2 \times \frac{A_2}{A_{avg}}$$

$$\Delta T_3' = \Delta T_3 \times \frac{A_3}{A_{avg}}$$

The above mentioned procedure is repeated till the deviation is within  $\pm 10\%$ .

1. What is the b.p. elevation of the soln & driving force for heat transfer?

Data: soln boils at a temp of 380 K (107°C) & b.p of water at a pressure in the vapour space is 373 K (100°C). Temp of condensing steam is 399 K (126°C) soln. B.P of soln =  $T = 380$  K

B.P of water =  $T' = 373$  K

B.P. elevation =  $T - T'$

$$= 380 - 373$$

$$= 7 \text{ K}$$

Saturation temp of condensing steam =  $T_s = 399$  K

Driving force for heat transfer =  $T_s - T$

$$= 399 - 380$$

$$= 19 \text{ K}$$

2. An evaporator operating at atm. pressure (101.325 kPa) is fed at the rate of 10,000 kg/h of weak liquor containing 4% caustic soda. Thick liquor leaving the evaporator contain 25% caustic soda. Find the capacity of the evaporator.

Soln:

Given: 10,000 kg/h of weak liquor entering the evaporator

Let  $m$  be the kg/h of thick liquor leaving the evaporator

Material balance of Caustic soda:

Caustic soda in feed = Caustic soda in thick liquor

$$0.04 \times 10000 = 0.25 \times m$$

$$m = 1600 \text{ kg/h}$$

Overall material balance:

kg/h of feed = kg/h water evaporated + kg/h of thick liquor

$$10000 = \text{kg/h water evaporated} + 1600$$

$$\text{water} = 10000 - 1600 = 8400 \text{ kg/h}$$

$$\text{Capacity of evaporator} = 8400 \text{ kg/h}$$



3. An evaporator is operating at atm pressure. It is desired to concentrate the feed from 5% solute to 20% solute (by weight) at a rate of 5000 kg/h. Dry saturated steam at a pressure corresponding to saturation temp of 399 K (126°C) is used. The feed is at (25°C) 298 K & b.p. (elevation) i.e. B.P.E. is 5 K. Overall heat transfer coefficient is 2350 W/m<sup>2</sup>.K. Calculate economy of evaporation & area of heat transfer to be provided.

Data: Treating soln as pure water & neglecting B.P.E.  
 Latent heat of condensation of steam at 399 K = 2185 kJ/kg  
 Latent heat of vaporisation / evaporation of water at 101.325 kPa & 373 K = 2257 kJ/kg  
 Specific heat of feed = 4.187 kJ/(kg.K).

Soln:

Given: 5000 kg/h of feed to evaporator.  
 Let  $m_f$ ,  $m_t$ ,  $m_v$  be the kg/h of feed, thick liquor & water vapour/water evaporated.

Material balance of solute:

solute in feed = solute in thick liquor

$$0.05 \times 5000 = 0.20 \times m_t$$

$$m_t = 1250 \text{ kg/h}$$

Overall material balance:

kg/h feed = kg/h water evaporated + kg/h thick liquor

$$\text{water evaporated} = m_v = 5000 - 1250 = 3750 \text{ kg/h}$$

Let  $m_s$  be kg/h of steam required (steam consumption)

$\Delta s$  = latent heat of condensation of steam at 399 K = 2185 kJ/kg

$\lambda_v = \lambda =$  latent heat of vaporisation of water at 373 K = 2257 kJ/kg

$T$  = temp of thick liquor

$$= T' + \text{B.P.E.} = 373 + 5 = 378 \text{ K}$$

$T_f$  = temp of feed = 298 K

$m_f = 5000 \text{ kg/h}$

$C_{p_f} = 4.187 \text{ kJ/kg.K}$

Heat balance over evaporator:

Heat lost by condensing steam (latent heat) =

Heat gained by soln to increase its temp to b.p. +

Heat required to vapourise



$$m_s \lambda_s = m_f c_{pf} (T - T_f) + m_w \lambda$$

$$m_s \times 2185 = 5000 \times 4.184 (378 - 298) + 3750 \times 2257$$

$$m_s = 4640.1 \text{ kg/h}$$

$$\text{Steam consumption} = 4640.1 \text{ kg/h}$$

$$\text{Economy of evaporation} = \frac{\text{kg/h water evaporated}}{\text{kg/h steam consumed}}$$

$$= \frac{3750}{4640.1} = 0.808$$

$$T_s = \text{saturation temp of steam} = 399 \text{ K}$$

$$\text{Temp of driving force} = \Delta T = T_s - T$$

$$= 399 - 378$$

$$= 21 \text{ K (21}^\circ\text{C)}$$

$$U = 2350 \text{ W/m}^2\cdot\text{K}$$

$$\text{Rate of heat transfer} = Q = m_s \lambda_s$$

$$= 4640.1 \times 2185$$

$$= 10138619 \text{ kJ/kg}$$

$$= \frac{10138619 \times 1000}{3600}$$

$$Q = 2816283 \text{ J/s @ W}$$

$$Q = U A \Delta T$$

$$A = \frac{Q}{U \Delta T} = \frac{2816283}{2350 \times 21}$$

$$= 57.07 \text{ m}^2$$

Heat transfer area to be provided = 57.07 m<sup>2</sup>.

4. A soln containing 10% solids is to be concentrated to a level of 50% solids. Steam is available at a pressure of 0.20 MPa [saturation temp of 393 K (120°C)]. Feed rate to the evaporator is 30000 kg/h. The evaporator is working at reduced pressure such that b.p is 323 K (50°C). The overall heat transfer coefficient is 2.9 kW/m<sup>2</sup>·K. Estimate steam economy & heat transfer surface for: i) Feed introduced at 293 K (20°C) ii) Feed introduced at 308 K (35°C).

Data: Specific heat of feed = 3.98 kJ/kg·K.  
 Latent heat of condensation of steam at 0.20 MPa = 2202 kJ/kg  
 Latent heat of vaporization of water at 323 K (heat at pressure in the vapor space) = 2383 kJ/kg.



Soln:

Given: 30000 kg/h of feed to the evaporator.

Let  $m_f$ ,  $m$  &  $m_v$  be the mass flow rate of feed, thick liquor & water vapour respectively.

Material balance of solids:

Solids in feed = solids in thick liquor

$$0.10 \times 30000 = 0.05 m$$

$$m = 6000 \text{ kg/h}$$

Overall material balance:

Feed = water evaporation + thick liquor

$$\begin{aligned} \text{Water evaporated} = m_v &= 30000 - 6000 \\ &= 24000 \text{ kg/h} \end{aligned}$$

I Feed at 293 K ( $T_f$ ):

$m_s$  = mass flow rate of steam in kg/h

$$m_f = 30000 \text{ kg/h}, m_v = 24000 \text{ kg/h}$$

$$C_{pf} = 3.98 \text{ kJ/kg} \cdot \text{K}$$

$T_s$  = saturation temp of steam = 393 K

$T$  = b. p of soln = 323 K

$\lambda_s$  = latent heat of condensation of steam at 0.20 MPa  
= 2202 kJ/kg

$\lambda$  = latent heat of vapourisation of water  
at 323 K = 2383 kJ/kg

Enthalpy balance over evaporator assuming no heat loss:

$$Q = m_s \lambda_s = m_f \cdot C_{pf} (T - T_f) + m_v \lambda_v$$

$$m_s \times 2202 = 30000 \times 3.98 \times (323 - 293) + 24000 \times 2383$$

$$m_s = 27599.5 \text{ kg/h}$$

Steam consumption = 27599.5 kg/h

$$\begin{aligned} \text{Steam economy} &= \text{water evaporated} / \text{steam consumed} \\ &= \frac{24000}{27599.5} = 0.87 \end{aligned}$$

$$\Delta T = T_s - T = 393 - 323 = 70 \text{ K}$$

$$U = 2.9 \text{ kW/m}^2 \cdot \text{K} = 2900 \text{ W/m}^2 \cdot \text{K}$$

Heat load = Rate of heat transfer =  $Q = m_s \lambda_s$

$$\begin{aligned} Q &= 27599.5 \times 2202 \\ &= 60774099 \text{ kJ/h} \end{aligned}$$



$$Q = \frac{60774099 \times 1000}{3600}$$

$$= 16881694 \text{ J/s or W}$$

$$Q = UA \Delta T$$

$$A = Q / U \Delta T$$

$$= \frac{16881694}{2900 \times 70} = 83.16 \text{ m}^2$$

II Feed at 308K;

Heat balance gives.

$$m_s \times 2202 = 30000 \times 3.98 \times (323 - 308) + 24000 \times 2383$$

$$m_s = 26786 \text{ kg/h}$$

$$\text{Steam consumption} = 26786 \text{ kg/h}$$

$$\text{Economy of evaporator} = \frac{24000}{26786} = 0.896$$

$$\text{Heat load} = \text{Rate of heat transfer} = Q = m_s \Delta T$$

$$Q = 26786 \times 2202$$

$$= 58982772 \text{ kJ/h}$$

$$= \frac{58982772 \times 1000}{3600}$$

$$Q = 16384103 \text{ J/s or W}$$

$$Q = UA \Delta T$$

$$A = Q / U \Delta T$$

$$= \frac{16384103}{2900 \times 70} = 80.71 \text{ m}^2$$

Heat transfer area required = 80.71 m<sup>2</sup>

As the feed temp goes down, economy decreases & as  $\Delta T$  &  $U$  do not change area increases due to increase in heat load.

$$T_f = 308 \text{ K} : \text{Economy} = 0.896, \text{ Area} = 80.71 \text{ m}^2$$

$$T_f = 293 \text{ K} : \text{Economy} = 0.87, \text{ Area} = 83.16 \text{ m}^2$$

5. A single effect evaporator is fed with 5000 kg/h of solution containing 1% solute by weight. Feed Temp is 303 K (30°C) & is to be concentrated to a soln of 2% solute by weight. The evaporator is at atmospheric pressure (101.325 kPa) & area of evaporator is 69 m<sup>2</sup>.



Saturated steam is supplied at 145.3 kPa at a heating medium. Calculate steam economy & overall heat transfer coefficient.

Data: Enthalpy of feed at 303 K = 125.79 kJ/kg  
Enthalpy of vapour at 101.325 kPa = 2676.1 kJ/kg  
Enthalpy of saturated steam at 145.3 kPa = 2691.5 kJ/kg  
Saturation temp of steam = 383 K (110°C)  
B.P. of soln = b.p. of water = 373 K  
Enthalpy of product = 419.04 kJ/kg  
Enthalpy of saturated water at 383 K = 461.30 kJ/kg

Soln:

Given: 5000 kg/h of feed to evaporator

Let  $m'$ ,  $m_v$  be the flow rate of product & water vapour

Material balance of solute:

$$0.01 \times 5000 = 0.02 \times m'$$

$$m' = 2500 \text{ kg/h}$$

Overall material balance:

Feed = water evaporated + thick liquor

$$\text{Water evaporated} = 5000 - 2500 = 2500 \text{ kg/h}$$

Assuming no heat loss, the heat balance is:

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

$$m_f = 5000 \text{ kg/h}$$

$$m' = 2500 \text{ kg/h}$$

where,

$$m_v = 2500 \text{ kg/h}$$

$H_f$ ,  $H'$ ,  $H_v$  are enthalpies of feed, thick liquor & water vapour resp.

$$H_f = 125.79 \text{ kJ/kg}$$

$$H' = 419.04 \text{ kJ/kg}$$

$$H_v = 2676.1 \text{ kJ/kg}$$

$\lambda_s$  = latent heat of condensing steam

= enthalpy of saturated steam - enthalpy of saturated water

$$= 2691.5 - 461.30$$

$$= 2230.2 \text{ kJ/kg}$$



$$5000 \times 125.79 + m_s (2230.2) = 2500 \times 419.04 + 2500 \times 2676.1$$

$$m_s = 3187.56 \text{ kg/h}$$

$$\text{Steam consumption} = \text{steam flow rate} = 3187.56 \text{ kg/h}$$

$$\text{Steam economy} = 2500 / 3187.56 = 0.784$$

$$\text{Rate of heat transfer, } Q = m_s \lambda_s$$

$$= 3187.56 \times 2230.2$$

$$= 71088963 \text{ kJ/h}$$

$$= \frac{71088963 \times 1000}{3600}$$

$$= 1974693.7 \text{ J/s} \text{ @ } W$$

$$\Delta T = T_s - T = 383 - 373 = 10 \text{ K}$$

$$Q = U A \Delta T$$

$$U = Q / (A \cdot \Delta T)$$

$$U = \frac{1974693}{69 \times 10} = 2862 \text{ W/m}^2 \cdot \text{K}$$

6. If the evaporator pressure is reduced to 38.58 kPa, what would be the change in heat transfer area? Use the same steam pressure & overall heat transfer coefficient as in ex. 5

Data: B.P of water/vap at 38.58 kPa = 348 K

Enthalpy of water vapour = 2635.3 kJ/kg

Enthalpy of product = 313.93 kJ/kg

Soln: Heat balance is

$$m_b H_b + m_s \lambda_s = m' H' + m_v H_v$$

$$5000 \times 125.79 + m_s \times 2230.2 = 2500 \times 313.93 + 2500 \times 2635.3$$

$$m_s = 2320.18 \text{ kg/h}$$

$$Q = m_s \lambda_s = 2320.18 \times 2230.2$$

$$= 5174465.4 \text{ kJ/h}$$

$$= \frac{5174465.4 \times 1000}{3600}$$

$$= 1437351.5 \text{ J/s or W}$$

$$Q = U A \Delta T$$

$$U = 2862 \text{ W/m}^2 \cdot \text{K}$$

$$\Delta T = 383 - 348 = 35 \text{ K}$$



$$A = Q / U \cdot \Delta T$$

$$= \frac{1437351.5}{2862 \times 35} = 14.35 \text{ m}^2$$

Heat transfer area decreases from  $69 \text{ m}^2$  to  $14.35 \text{ m}^2$ . In this case a condenser & vacuum pump should be used.

7. If the feed rate is increased to  $6000 \text{ kg/h}$  what would be the mass flow rate of product water evaporated & product concn? Use the same area, value of  $U$ , steam pressure, evaporator pressure & feed temp as in ex. 6.5

Feed is  $6000 \text{ kg/h}$  lead to evaporator