

EVAPORATION

Evaporation is an operation in which a weak solution/liquor is concentrated by vaporising a portion of the solvent.

The weak liquor/solution to be concentrated is composed of a non-volatile solute and a volatile solvent.

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

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

It differs from distillation in that the vapour is usually a single component rather than a mixture of components.

It differs from crystallisation in that the purpose is to concentrate a solution rather than to form and build crystals.

Evaporation is generally followed by crystallisation and drying.

Evaporation is carried by supplying heat to a solution to vaporise the solvent. The common heating medium (heat source) is generally a low pressure steam but in some situations other sources that might be used are : solar energy, fuel, electricity, hot oil and flue-gas.

In an evaporation operation, heat is utilized to :

- (i) increase the temperature of the solution to its boiling point (sensible heat) and
- (ii) supply the latent heat of vaporisation of the solvent.

In this operation, rate processes that occur are : heat transfer from a heating medium to a solution through the solid surface and simultaneous heat and mass transfer from a liquid to a vapour phase. Irrespective of this, the operation can usually be considered in terms of heat transfer from a heater to the solution (heat transfer to boiling liquids) for the design of evaporators.

Comparison of Evaporation and Drying :

1. Evaporation an operation in which a weak solution/liquor is concentrated by vaporising a portion of the solvent.
1. Drying is an operation in which the moisture of a substance (usually solid) is removed by thermal means.
2. Evaporation is a heat transfer operation.
2. Drying is a mass transfer operation.
3. Evaporation involves the removal of water as a vapour at its boiling point.
3. Drying involves the removal of water at a temperature below its boiling point.
4. In evaporation operation, the product obtained is a liquid (concentrated solution).
4. In drying operation, the product obtained is a solid.
5. In evaporation operation, we have to handle weak solutions.
5. In drying operation, we have to handle wet solids as well as solutions.
6. In evaporation, the heating medium is steam.
6. In drying, the heating medium is a hot air or hot gas.

7. Evaporator type : Long tube evaporator, short vertical tube evaporator, horizontal tube evaporator, etc.
7. Dryer types : Tray dryer, rotary dryer, spray dryer, etc.

Effect of properties of solution on evaporation operation :

A wide variation in properties of the solution to be concentrated requires judgement and experience in the design and operation of evaporators. Some of the properties of evaporating liquids that have effects on the process of evaporation are :

(i) **Concentration** : The viscosity and density of the solution increase with increase in concentration of the solution. The boiling point of the solution increases considerably as the concentration increases so that it may be much higher than B.P. of water at the same pressure.

(ii) **Foaming** : Some materials have a tendency to foam that causes heavy entrainment (the carry over of a portion of the liquid by the rising vapour is called an entrainment) and thus the loss of solution.

(iii) **Scale** : Some solutions deposit scale on the heat transfer surfaces. This causes reduction of the heat transfer coefficient and hence the rate of heat transfer. Therefore, it is necessary to clean the tubes after definite intervals of service.

(iv) **Temperature sensitivity** : Some materials such as pharmaceuticals and food products get thermally degraded when heated to moderate temperatures even for short periods. For concentrating such materials special techniques are to be used which reduce the temperature of operation and also the time of heating.

(v) **Corrosiveness** : Whenever contamination and corrosion is a problem, special materials such as copper, nickel, stainless steels may be used, otherwise mild steel is normally used for evaporators. Other liquid properties which must be considered in the design are specific heat, freezing point, toxicity, etc.

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

Usually, the desired product of an evaporation operation is the concentrated solution (thick liquor), but occasionally the evaporated solvent is the primary product as in the evaporation of sea water to obtain potable water.

Common examples of evaporation are :

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

Capacity and Economy of Evaporators :

Performance of tubular evaporators :

The performance of a steam heated tubular evaporator is evaluated in terms of (i) capacity and (ii) economy

Capacity : The 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 an evaporator, is defined as the product of the area of heat transfer surface A , the overall heat transfer coefficient U , and the overall temperature drop ΔT .

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

where ΔT is the temperature difference between the heating medium and the boiling solution (saturation temperature of steam minus the boiling point of solution).

... (6.1)

If the feed solution is at the boiling temperature corresponding to the pressure in the vapour space of an evaporator, then all the heat that is transferred through the heating surface is available for evaporation (i.e., for converting liquid to vapour) and the capacity is proportional to the heat transfer rate. If the cold feed solution is fed to the evaporator, heat is required to increase its temperature to the boiling point and it may be a quite large and thus, the capacity for a given rate of heat transfer will be reduced accordingly as heat used to increase the temperature to the boiling point is not available for evaporation. When the feed solution to the evaporator is at a temperature higher than the boiling point corresponding to the pressure in the vapour space, a portion of the feed evaporates adiabatically and the capacity is greater than that corresponding to the heat transfer rate. This process is called flash evaporation.

Evaporator economy : The 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 a single-effect evaporator the amount of water evaporated per kg of steam fed is always less than one and 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, i.e., water evaporated per kg of steam condensed less than unity.

The economy of an evaporator can be increased by reusing the vapour produced.

The methods of increasing the economy are :

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

In a multiple effect evaporation system, the vapour produced in the first effect is fed to the steam chest of the second-effect as a heating medium in which boiling takes place at low pressure and temperature and so on. Thus in a triple-effect evaporator, 1 kg of steam fed to the first-effect evaporates approximately 2.5 kg of water.

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 temperature so that it will condense at a temperature higher enough to make possible its use as a heating medium in the same evaporator.

Boiling point elevation :

In actual practice, the boiling point of a solution is affected by a boiling point elevation and a liquid head.

As the vapour pressure of most aqueous solutions is less than that of water at any given temperature, the boiling point of a solution is higher than that of pure water at a given pressure. **The difference between the boiling point of a solution and that of pure water at any given pressure is known as the boiling point rise/elevation of the solution.** The boiling point elevation is small for dilute solutions and large for concentrated solutions of inorganic salts.

The boiling point elevation can be obtained from an empirical rule known as *Duhring's rule*. It states that *the boiling point of a given solution is a linear function of the boiling point of pure water at the same pressure*. Thus, when the boiling point of a solution is plotted against the boiling point of water, we get a straight line. Fig. 6.1 shows such a plot for an aqueous solution of sodium hydroxide of different concentrations.

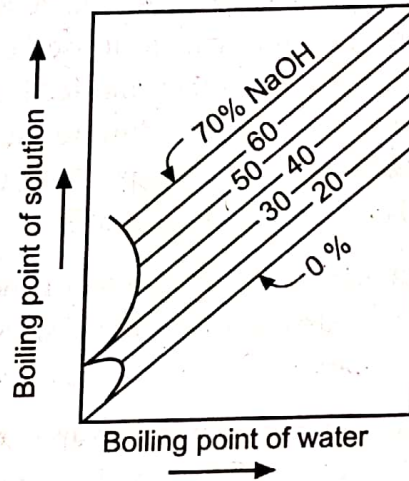


Fig. 6.1 : Duhring's plot for NaOH

Material and enthalpy balances for single-effect evaporator :

Consider an evaporator as shown in Fig. 6.2. It is fed at a rate of \dot{m}_f kg/h of a weak solution containing w_1 % solute and the thick liquor containing w_2 % solute by weight is withdrawn at a rate of \dot{m}' kg/h. Let \dot{m}_v be the kg/h of water evaporated from it.

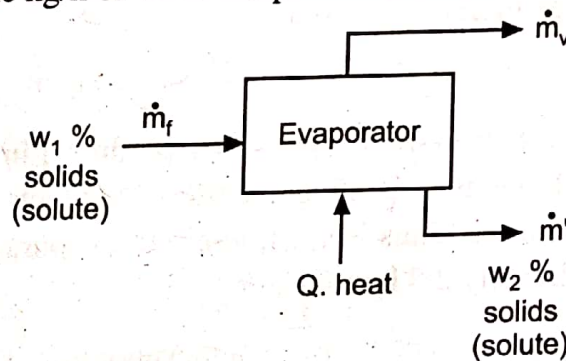


Fig. 6.2 : Block diagram of evaporator

Let us take the overall material balance and the material balance of the solute.

Overall material balance over evaporator :

kg/h weak solution = kg/h thick liquor + kg/h water evaporated

$$\dot{m}_f = \dot{m}_v + \dot{m}' \quad \dots (6.2)$$

Material balance of solute :

Solute in feed = Solute in thick liquor

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

$$w_1 \times \dot{m}_f = w_2 \dot{m}'$$

... (6.3)

Knowing three out of the above mentioned five quantities, we can find the values of the other two with the help of the above two equations.

Let T_f , T and T_s be the temperatures of the feed entering the evaporator, solution in the evaporators and condensing steam, respectively.

Let ' λ_s ' be the latent heat of condensation of steam at its saturation temperature and assume that only the latent heat of condensation is used. Then, the rate of heat transfer through the heating surface from the steam side is given by

$$Q_s = \dot{m}_s \lambda_s \quad \dots (6.4)$$

where \dot{m}_s is the mass flow rate of steam to the evaporator in kg/h.

Assuming negligible heat losses, the **enthalpy balance/heat balance** over the evaporator is :

Heat associated with feed + Heat (latent) associated with steam =

Heat associated with vapour leaving + Heat associated with thick liquor

$$\dot{m}_f \cdot H_f + \dot{m}_s \lambda_s = \dot{m}_v H_v + \dot{m}' H' \quad \dots (6.5)$$

$$\dot{m}_f \cdot H_f + \dot{m}_s \lambda_s = (\dot{m}_f - \dot{m}') H_v + \dot{m}' H' \quad \dots (6.6)$$

where H_v , H_f and H' are the enthalpies of the vapour, feed solution and thick liquor, respectively.

Rearranging Equation (6.6), we get

$$\dot{m}_s \lambda_s = (\dot{m}_f - \dot{m}') H_v + \dot{m}' H' - \dot{m}_f H_f \quad \dots (6.7)$$

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

In case of solutions having negligible heats of dilution, the enthalpy balance or heat balance can be written in terms of specific heats and temperatures of the solutions.

Heat transferred to the solution in the evaporator by condensing steam (in the absence of heat losses) is utilised to heat the feed solution from T_f to T and for the evaporation of water from the solution. Therefore,

$$\begin{aligned} Q_s &= Q \\ &= \dot{m}_f C_{pf} (T - T_f) + (\dot{m}_f - \dot{m}') \lambda_v \end{aligned} \quad \dots (6.8)$$

With $Q_s = \dot{m}_s \lambda_s$, it becomes

$$\dot{m}_s \lambda_s = \dot{m}_f \cdot C_{pf} (T - T_f) + (\dot{m}_f - \dot{m}') \lambda_v \quad \dots (6.9)$$

where C_{pf} = specific heat of feed solution

λ_v = latent heat of evaporation of water from thick liquor

For a negligible boiling point rise, $\lambda_v = \lambda$

where λ = latent heat of vaporisation of water at a pressure in the vapour space and can be read from steam tables

With this Equation (6.9) becomes

$$\dot{m}_s \lambda_s = \dot{m}_f C_{pf} (T - T_f) + (\dot{m}_f - \dot{m}') \lambda \quad \dots (6.10)$$

$$\dot{m}_s \lambda_s = \dot{m}_f \cdot C_{pf} (T - T_f) + \dot{m} \lambda \quad \dots (6.11)$$

The boiling point of a solution (T) corresponding to a pressure in the vapour space can be obtained by knowing the boiling point elevation and boiling point of pure water at that pressure, e.g. if T' is the boiling point of water at a certain pressure of the operation and 'P' is the boiling point elevation, then

$$T = T' + P$$

The heat transfer surface/area of an evaporator is calculated with the help of the following equation :

$$Q = U \cdot A \cdot \Delta T \quad \dots (6.12)$$

$$Q = \dot{m}_s \lambda_s = U \cdot A \cdot \Delta T \quad \dots (6.13)$$

where

U = overall heat transfer coefficient

A = area of heat transfer

and

ΔT = temperature difference

$\Delta T = T_s - T$

ΔT = Condensing steam temperature – Boiling point of solution

When 'Q' is in W, 'U' is in W/(m²·K) and ' ΔT ' is in K, then 'A' will be in m².

λ_s = Specific enthalpy of saturated steam

– Specific enthalpy of saturated water (i.e., of condensate)

Evaporator Types :

Evaporators used in the chemical process industries can be classified as :

(i) Natural circulation evaporators.

(ii) Forced circulation evaporators.

Natural circulation evaporators are commonly used for simpler evaporation operations singly or in multiple effect, e.g., horizontal tube evaporator, vertical tube evaporator etc., whereas forced circulation evaporators are commonly used for salting, viscous and scale forming solutions. The forced circulation units may be provided with an external horizontal or vertical heating element.

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/jacketed pan evaporator, condensing steam is fed to a jacket for evaporating a part of the solvent.

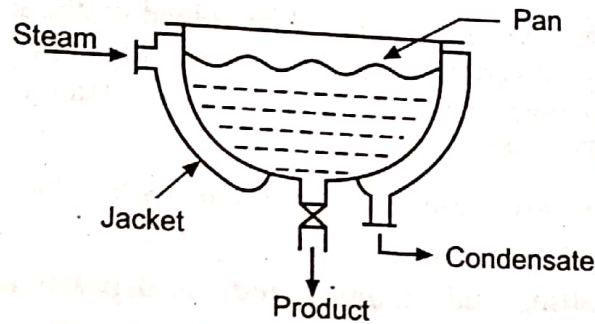


Fig. 6.3 : Jacketed pan evaporator

Pan is made of a single sheet of metal (for small sizes) or several sheets joined by welding / brazing. A 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 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 and withdrawal of condensate. The shell is closed by dished heads at both the ends. A vapour outlet is provided on the top cover and a thick liquor outlet is provided at the bottom. Feed point is located at a convenient point. In this evaporator, steam is inside the tube and the liquor to be concentrated surrounds the tubes. Steam which is admitted through one of the steam chests/channels and flows through the tubes. Steam gets condensed by transferring its latent heat and the condensate is removed from the outlet provided at the bottom of the opposite steam chest. This type of evaporator is shown in Fig. 6.4.

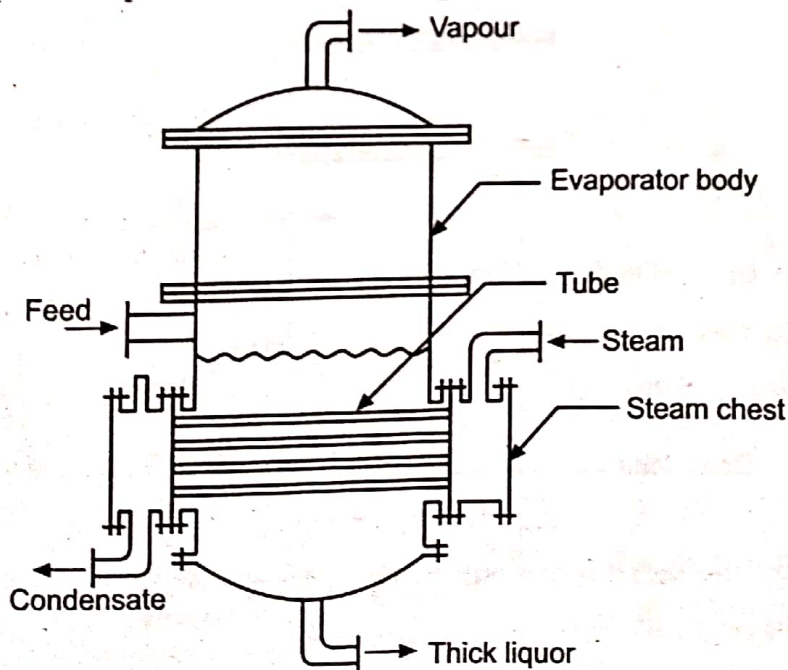


Fig. 6.4 : Horizontal tube evaporator

Heat Transfer

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

Main advantages : Very low head room requirements and large vapour-liquid disengaging area.

It is not suited for salting and scaling liquids as deposits form on the outside of the tubes.

It is commonly used for small capacity services and for simpler problems of concentrations, i.e., for processes wherein the final product is a liquor, such as industrial sirups.

Calendria - type / Standard vertical tube evaporator / Short tube evaporator :

Construction :

It consists of a vertical cylindrical shell incorporating a short vertical tube bundle at the lower portion with horizontal tube sheets bolted to the shell flanges. Vapour outlet is provided at the top cover while a thick liquor discharge is provided at the bottom. Usually the tube bundle is not more than 150 cm high and tube diameter (outside) not more than 75 mm (25 mm to 75 mm). A downtake is provided at the centre of the tube bundle having a flow area about 40 to 100 per cent of the total cross sectional area of the tubes for circulating the cooler liquid back to the bottom of the tubes. In this evaporator, the solution to be evaporated is inside the tubes and steam flows outside the tubes in a steam chest. Baffles are incorporated in the steam chest to promote uniform distribution of steam. The condensate is withdrawn at any convenient point near the lower tube sheet, while the non-condensable gas such as air is vented to the atmosphere from a point near the top tube sheet.

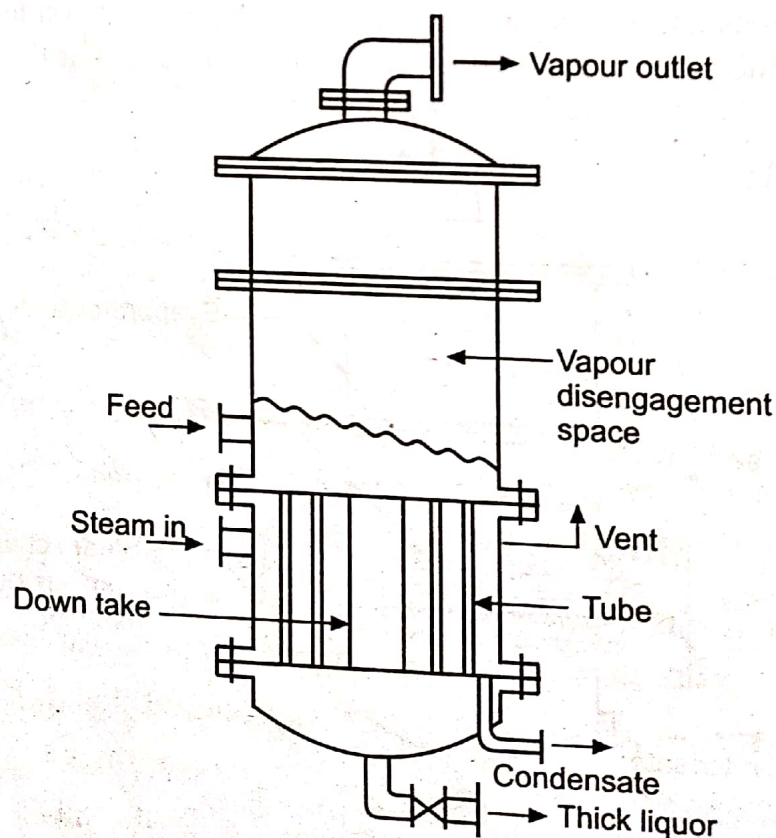


Fig. 6.5 : Calendria type evaporator

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

Construction : A long tube evaporator consists of a long tubular heating element incorporating tubes, 25 mm to 50 mm in diameter and 4 to 8 metres in length. The tubular heating element projects into a vapour space/separator for removing an entrained liquid from the vapour. The upper tube sheet of tubular exchanger is free and a vapour deflector is incorporated in the vapour space just above it. A return pipe connecting the vapour space to the bottom of the exchanger is provided for natural circulation of a unvaporised liquid. It is provided with inlet connections for feed, steam and outlet connections for vapour, thick liquor, condensate, etc. In this evaporator, the solution/liquor to be concentrated is in the tubes and condensing steam surrounds the tubes. Fig. 6.6 shows a long-tube vertical evaporator.

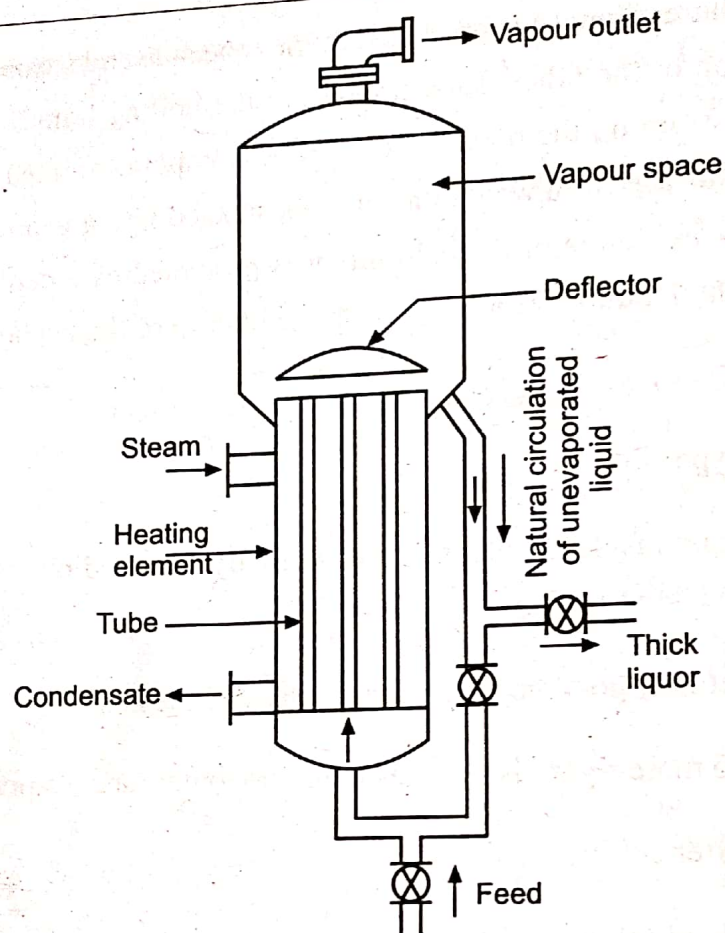


Fig. 6.6 : Long-tube vertical evaporator

Working :

In this evaporator, feed enters the bottom of the tubes, gets heated by the condensing steam, starts to boil part way up the tubes and a mixture of vapour and liquid issues from the top of tubes and finally impinges at a high velocity on a deflector. The deflector acts both as a primary separator and a foam breaker. Some part of the separated liquid is removed as a product and the remaining part is returned to the bottom of the evaporator.

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

It is used for the production of condensed milk and concentrating a black liquor in the pulp and paper industry.

Forced Circulation Evaporators :

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. In a natural circulation evaporator, the liquid enters the tube at a velocity of 0.3 to 1 metre per second, whereas in a forced circulation evaporator, the velocity is of the order of 2 to 6 metres per second. In the forced circulation evaporator, smaller diameter tubes are used compared to those in the natural circulation evaporator, generally not larger than 50 mm.

Forced circulation evaporators with a horizontal external heating element :

Construction :

Fig. 6.7 shows a forced circulation evaporator with a horizontal external heating element. 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 the discharge of thick liquor and an external heating surface - a horizontal shell and tube heat exchanger having two passes on the tube side.

Working :

A centrifugal pump forces the solution to be concentrated through the tubes at high velocity and is heated as it passes through the tubes due to heat transfer from the condensing steam on the shell side. Boiling does not take place in the tubes as they are under a sufficient static head, which raises the boiling point of the solution, above that in the separating space.

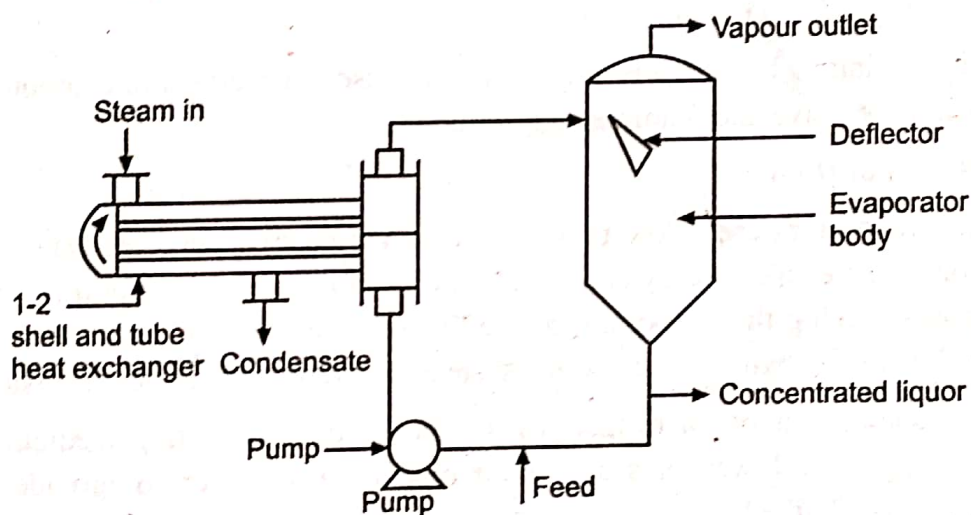


Fig. 6.7 (a) : Forced circulation evaporator with horizontal external heating element

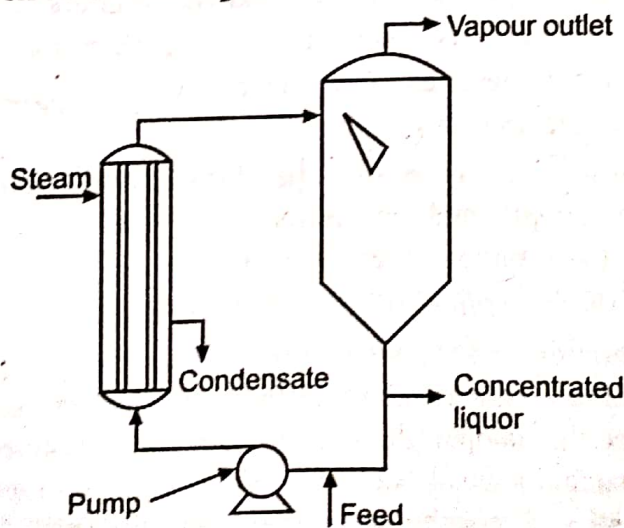


Fig. 6.7 (b) : Forced circulation evaporator with vertical heating element

The solution becomes superheated and flashes into a mixture of vapour and 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, and the vapours are removed from the top, and the liquid is returned to the centrifugal pump. Some part of the liquid/solution leaving the separating space is withdrawn as a concentrated solution and the makeup feed is continuously introduced at the pump inlet.

In case of a vertical heating element, single pass shell and tube heat exchanger is used.

Advantages of forced circulation evaporators :

1. High heat transfer coefficients are obtained even with viscous materials.
2. Positive circulation and 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 the tube is very small (1–3 s) because of high velocities in these units so that moderately heat sensitive liquids can be handled.

Main disadvantage : High pumping cost.

The forced circulation evaporators are commonly used for crystalline products, viscous, salting, scaling and corrosive and foam forming solutions.

Multiple-effect evaporation :

Most of the evaporators use a low pressure steam for heating purpose. Due to addition of heat to a solution in the evaporator by condensation of steam, the solution 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 vapours 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 a heating medium for another evaporator operating at a lower pressure and temperature in order to provide a sufficient temperature difference for the heat transfer in that evaporator.

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

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 the one way to increase the economy of evaporator systems.

The method of re-using the latent heat is called multiple-effect evaporation.

A multiple effect evaporation system is commonly used in large scale operations. In such a system, evaporators are arranged in series so that the vapour from one evaporator is used as a heat medium for the next one that is operating under at a pressure and temperature lower than the previous one. Each unit in such a series is called an **effect**. In case of a tripple-effect evaporator, if the first effect is operating at atmospheric pressure, then the second and third effect operate under vacuum. Steam is fed to the first effect and the vapour from the third-effect is condensed in

a condenser connected to a vacuum pump (which is used to maintain vacuum in the last two effects).

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

If the vapour from one evaporator is fed to the steam chest of the second evaporator as steam supply, the system is called as *double-effect evaporator system* and so on.

The methods used for feeding a multiple evaporation system are :

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

1. Forward feed :

In this arrangement, the thin liquid feed flows in the same direction as the vapour flow. Fresh feed enters the first effect and steam is also fed to a steam chest of the first effect. The vapours produced in the first effect are fed to the steam chest of the second effect as a heating medium and the concentrated liquor from the first effect is fed to the next effect in series, as shown in Fig. 6.8. The pressure in the second effect is less than in the first effect and so on. Thus, this arrangement does not require pumps to transfer concentrated solution from effect to effect. This is used when the feed is hot and the product may get damaged at high temperatures.

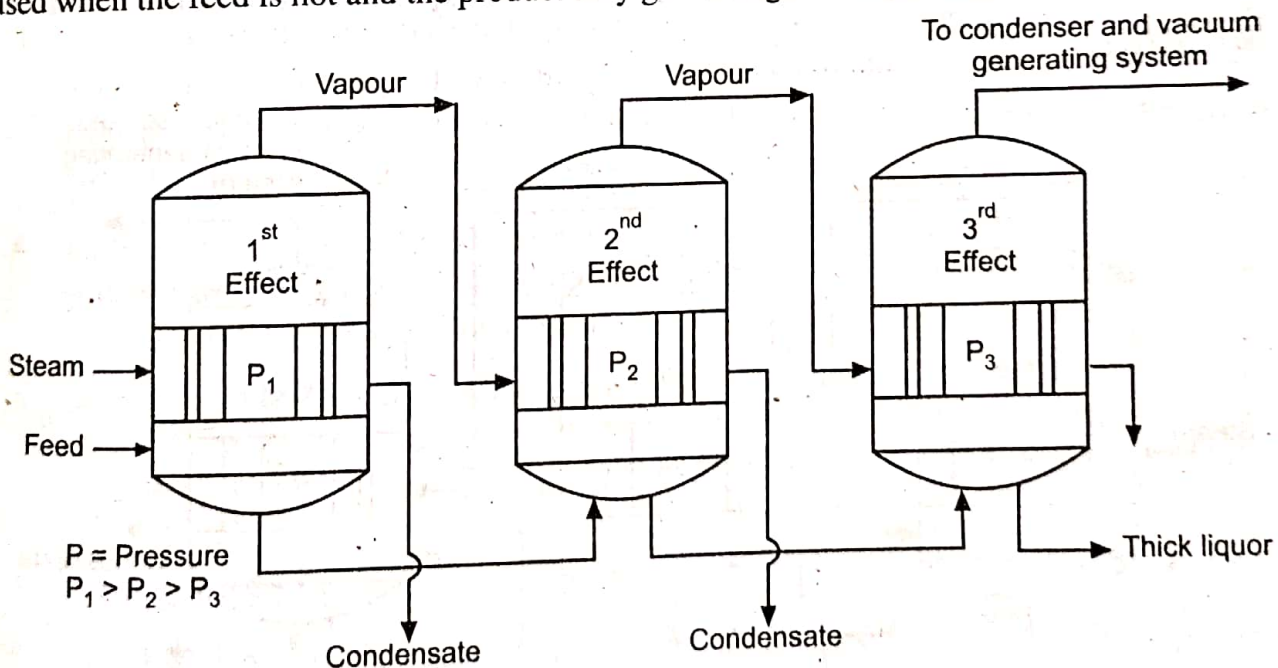


Fig. 6.8 : Forward feed arrangement for feeding multiple effect evaporator system

2. Backward feed :

In this arrangement the feed solution and the vapour flow in opposite directions to each other. Fresh feed (thin liquid) is admitted to the last effect and then pumped through the other effects. The steam is admitted to a steam chest of the first effect and the vapours produced in the first effect are fed to the steam chest of the second effect (evaporator) and so on. The pressure in the first effect is highest and that in the last effect is lowest. If the solution is very viscous then we have to adopt a backfeed arrangement as the temperature of the first effect is highest and thus the corresponding viscosity of the solution will be less. Fig. 6.9 shows this type of arrangement.

Since the feed flows in the direction of increasing pressure, pumps are used for the transfer of solution from one effect to another effect. It is used when the feed is cold, since it saves a large quantity of steam and increases the economy.

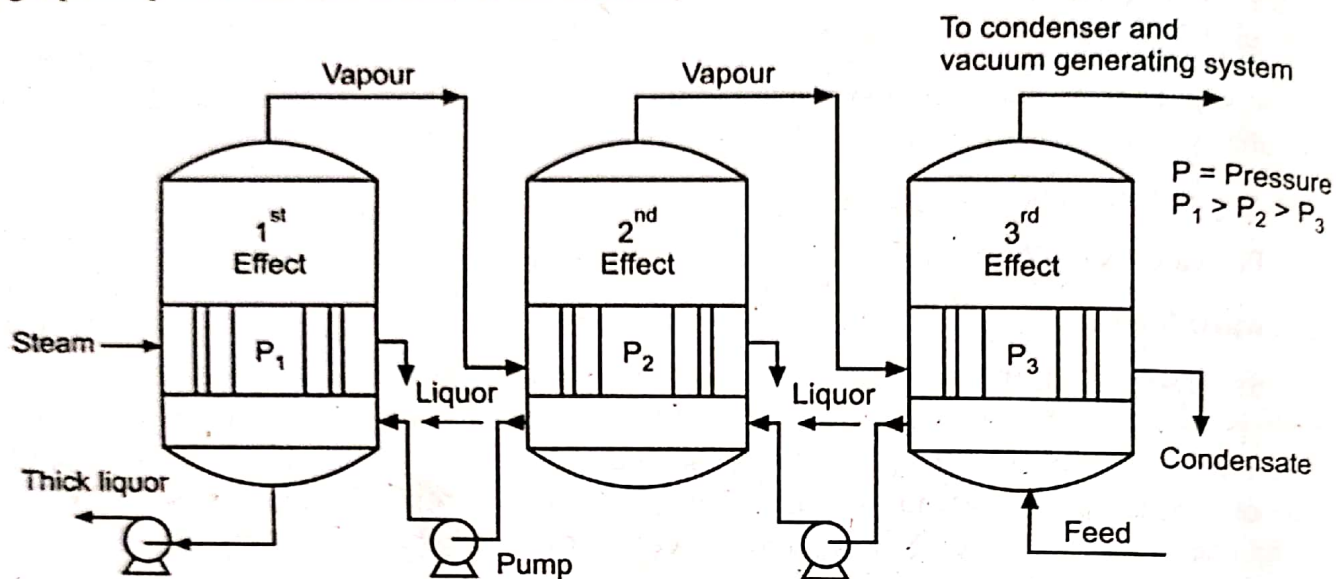


Fig. 6.9 : Backward feed arrangement for feeding multiple-effect evaporation system

3. Mixed feed :

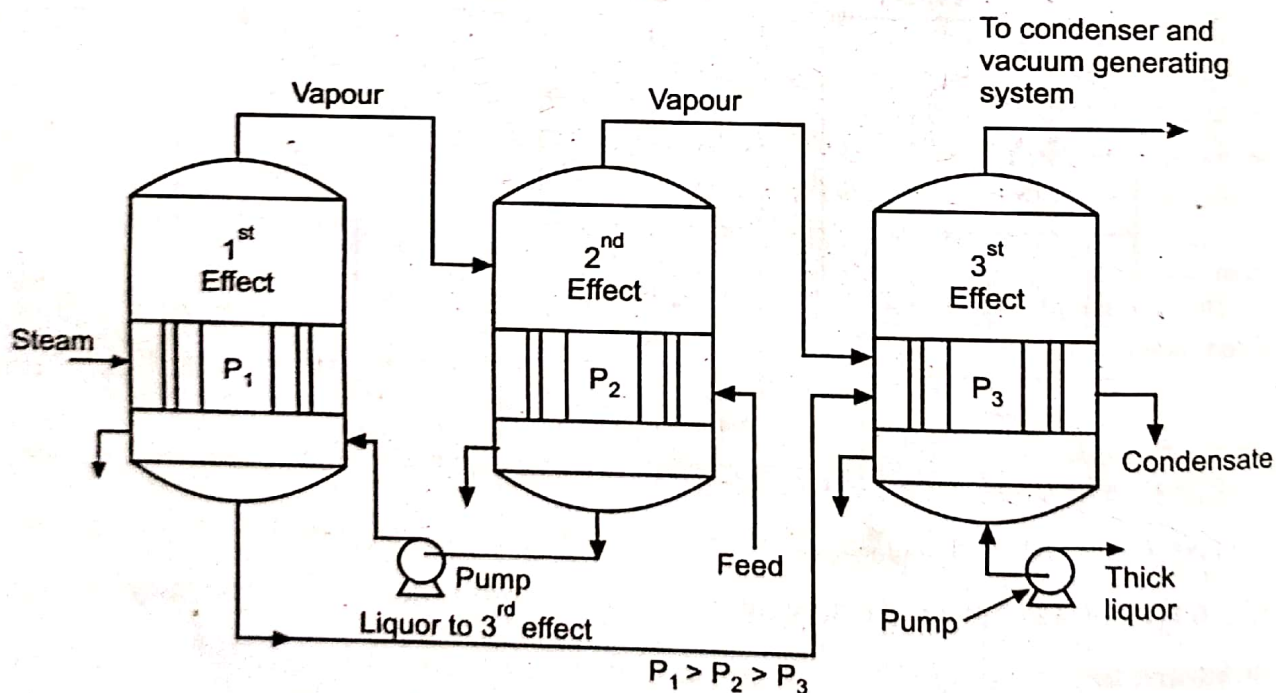


Fig. 6.10 : Mixed feed arrangement for feeding multiple-effect evaporation system

In this feed arrangement, steam is admitted to a steam chest of the first effect and the vapours leaving the first effect are fed to the steam chest of the second effect and so on. Feed solution is admitted to an intermediate effect and flows to the first effect from where it is fed to the last effect for final concentration. This arrangement is a combination of the forward and backward feed adopted for the best overall performance. Fig. 6.10 shows this type of arrangement.

Comparison of forward feed and backward feed arrangements :

1. In the forward feed, the flow of the solution to be concentrated is parallel to the steam/vapour flow.
 1. In the backward feed, the flow of the solution to be concentrated is in opposite direction to that of steam/vapour (counter current).
 2. Forward feed arrangement does not need pumps for moving the solution from effect to effect as vacuum is maintained in the last effect.
 2. Backward feed arrangement needs pumps for moving the solution from effect to effect as transfer of the solution is to be done from the evaporator operating at a low pressure to that operating at a higher pressure.
 3. In the forward feed as heating of the cold feed solution is done in the first effect, less vapour is produced per kilograms of steam fed, resulting into a lower economy.
 3. In the backward feed, the solution is heated in each effect which usually results in a better economy than that with a forward feed.
 4. With a forward feed, the most concentrated solution is in the last effect wherein the temperature is the lowest and the viscosity is the highest. These conditions lead to reduction in the capacity of the system as a whole due to low overall coefficient in the last effect in case of thick liquors which are very viscous.
 4. In the case of backward feed, the concentrated solution is in the first effect wherein the temperature is the highest as steam is admitted to that effect and the viscosity is the lowest, thus the overall coefficient can be moderately high inspite of high viscosity.
 5. In the case of forward feed, the maintenance charges and power cost are less.
 5. In the case of backward feed, the maintenance charges and power cost are more for the same duty.
 6. The forward feed arrangement is less effective thermally.
 6. The backward feed arrangement is more effective thermally. (At high feed temperatures).
 7. Forward feed is more economical in steam.
 7. At low values of feed temperature, backward feed arrangement gives higher economy.
 8. Forward feed is very common (largely used) as it is simple to operate.
 8. Backward feed is not common as it necessitates the use of pump between effects.
- The choice of optimum number of effects will be determined by an economic balance between the savings in steam obtained by using a multiple-effect evaporation system and the additional investment cost resulting from the added heat transfer area.

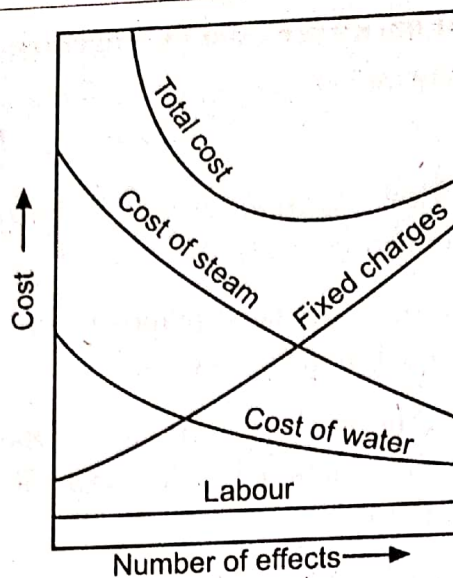


Fig. 6.11 : Optimum number of effects in a multiple-effect evaporation system

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 (a) mechanical recompression or (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. The principle of mechanical vapour recompression is shown in Fig. 6.12.

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

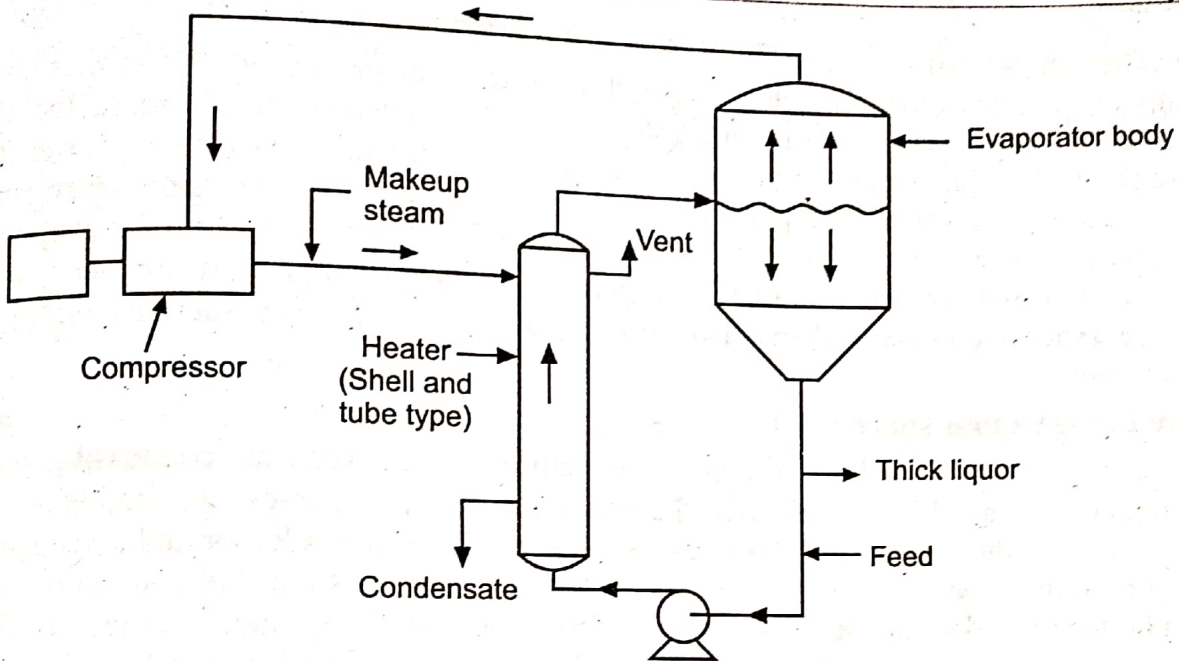


Fig. 6.12 : Mechanical recompression applied to forced circulation evaporator

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.

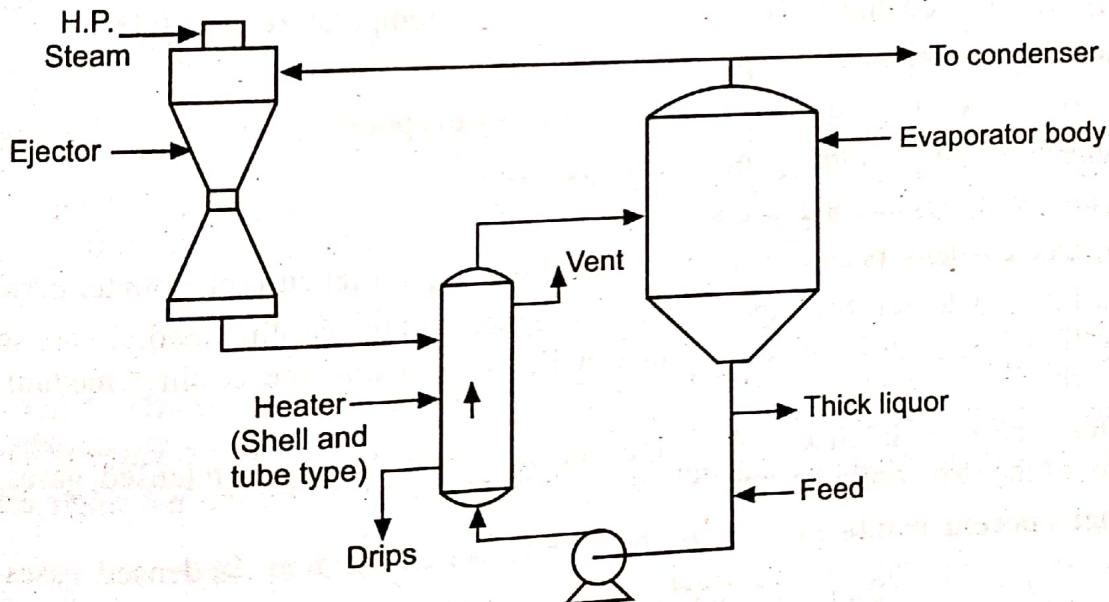


Fig. 6.13 : Thermal recompression

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 include : (i) low mechanical efficiency of the jets and (ii) lack of flexibility in the system to meet changes in the operating conditions.

By this method also, we can obtain the multiple-effect economy in a single-effect.

Choice of steam pressure :

In any evaporation operation, generally, a low pressure steam is used. We cannot use a high pressure steam that gives a larger temperature drop that consequently decrease the size and therefore the cost of the evaporator, since it is much more valuable as a source of power than as a source of heat. High pressure steam has a lower latent heat than a low pressure steam and hence the low pressure steam delivers more latent heat than the high pressure steam for evaporation of the solvent. Also the construction of the evaporator to hold the high pressure steam would be much more expensive (since it demands heavy thickness) than the construction to hold the low pressure steam.

Pressure in the vapour space :

It is always desirable to have a larger temperature drop between the condensing steam and the boiling point of a solution because as the temperature drop increases, the heating surface and in turn the cost of the evaporator decreases. By making use of a condenser and a vacuum pump, the pressure in the vapour space of the evaporator is made less than atmospheric. So by operating the evaporator at a pressure less than atmospheric, i.e., operating under a vacuum results in decrease in the boiling point of the solution which in turn leads to a larger value of temperature drop that decreases the required heat transfer surface.

It is not necessary to operate the evaporators under vacuum, but as it is economical to feed them with steam at a relatively moderate pressure, a vacuum is necessary in order to get an economical temperature drop (ΔT). There are certain cases where the operation under vacuum is necessary, for example, while dealing with heat sensitive materials (they may get decomposed/degraded if boiled at higher temperatures). Evaporators operating at high pressures requires much more expensive construction than when operating at lower pressures. Basically evaporators are operated under vacuum to obtain a larger temperature drop (ΔT).

Evaporator accessories :

These are devices that must be supplied with every evaporator.

(i) condensers (ii) vacuum pump / steam jet ejector.

There are two types of condensers :

(i) Surface condensers and (ii) Contact condensers : parallel current, counter current etc.

In a surface condenser, the vapour to be condensed and the cooling medium are separated by a metal wall, whereas in a contact condenser the vapour and the cooling medium/liquid are mixed directly.

Parallel-current condenser : It is the one in which the non-condensed gases leave at a temperature of the exit cooling water.

Counter-current condenser : It is the one in which the non-condensed gases leave at a temperature of the entering cooling water.

Wet condenser : It is the one in which the non-condensed gases and cooling water are removed by the same pump.

Dry condenser : It is the one in which the non-condensed gases and cooling water are removed by separate pumps.

Barometric condenser : It is the one that is placed high enough so that water escape from it by a barometric leg.

Low level condenser : It is the one in which water is removed by a pump.

In practice parallel current condensers are almost always wet condensers, while counter-current condensers are always dry.

Materials of construction for evaporators : Evaporator bodies are generally fabricated from mild steel as it is least expensive and easy to fabricate. For corrosive solutions, materials like monel, inconel and stainless steel are used. The tubes are made of copper, stainless steel and the tube sheet may be of cast bronze, nickel clad steel or stainless steel.

SOLVED EXAMPLES

Example 6.1 : Calculate the boiling point elevation of a solution and the driving force for heat transfer using the following data :

Data : Solution boils at a temperature of 380 K (107 °C) and the boiling point of water at a pressure in the vapour space is 373 K (100 °C)

Temperature of condensing steam is 399 K (126° C).

Solution : Boiling point of the solution = $T = 380 \text{ K}$

Boiling point of water = $T' = 373 \text{ K}$

Boiling point elevation = $T - T' = 380 - 373 \text{ K}$

= 7 K (or °C)

... Ans.

Saturation temperature of the condensing steam = $T_s = 399 \text{ K}$

Driving force for heat transfer = $T_s - T = 399 - 380$

= 19 K

... Ans.

Note : Whenever the pressure at which steam is available and pressure prevailing in the vapour space of an evaporator are given, then the steam table should be referred to find the temperature of steam, latent heat of condensation of steam based on a given steam pressure and the latent heat of evaporation of water, i.e., latent heat of vapour based on a pressure prevailing in the vapour space of the evaporator.

Example 6.2 : An evaporator operating at atmospheric pressure (101.325 kPa) is fed at the rate of 10000 kg/h of weak liquor containing 4 % caustic soda. Thick liquor leaving the evaporator contains 25% caustic soda. Find the capacity of the evaporator.

Solution :

Basis : 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 the feed = Caustic soda in the 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

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

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

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

... Ans.

Example 6.3 : An evaporator is operating at atmospheric pressure. It is desired to concentrate a feed from 5 % solute to 20 % solute (by weight) at a rate of 5000 kg/h. Dry saturated steam at a pressure corresponding to the saturation temperature of 399 K (126° C) is used. The feed is at 298 K (25° C) and the boiling point rise (elevation), i.e., B.P.E. (B.P.R.) is 5 K. The overall heat transfer coefficient is 2350 W/(m²·K). Calculate the economy of the evaporator and the area of heat transfer to be provided.

Data : Treating the solution as a pure water and neglecting the B.P.R., the latent heat of condensation of steam at 399 K is 2185 kJ/kg.

Latent heat of vaporisation of/evaporation of water at 101.325 kPa and 373 K = 2257 kJ/kg.

Specific heat of feed = 4.187 kJ/(kg·K)

Solution : Basis : 5000 kg/h of feed to the evaporator.

Let \dot{m}_f , \dot{m}' and \dot{m}_v be the kg/h of feed, thick liquor and water vapour / water evaporated.

Material balance of solute :

Solute in the feed = Solute in the thick liquor

$$0.05 \times 5000 = 0.20 \times \dot{m}'$$

$$\dot{m}' = 1250 \text{ kg/h}$$

Overall material balance (i.e., material balance over evaporator) :

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

$$\text{Water evaporated} = \dot{m}_v = 5000 - 1250 = 3750 \text{ kg/h}$$

Let \dot{m}_s be kg/h of steam required (steam consumption)

λ_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 = temperature of thick liquor

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

(λ_v is taken as equal to λ for the calculation purpose, since the effect of B.P.E. is to be neglected)

T_f = temperature of feed = 298 K

$$\dot{m}_f = 5000 \text{ kg/h}$$

$$C_{p_f} = 4.187 \text{ kJ/(kg·K)}$$

Let us calculate the economy.

Heat balance over evaporator :

Heat given out/lost by condensing steam (latent heat) =

= Heat gained by the solution to increase its temperature to boiling point
+ Heat required to vaporise / evaporate water

$$\dot{m}_s \lambda_s = \dot{m}_f C_{pf} (T - T_f) + \dot{m}_v \lambda$$

$$\dot{m}_s \times 2185 = 5000 \times 4.187 (378 - 298) + 3750 \times 2257$$

$$\dot{m}_s = 4640.1 \text{ kg/h}$$

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

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

$$= \frac{3750}{4640.1} = 0.808 \frac{\text{kg evaporation}}{\text{kg steam}}$$

... Ans.

Let us calculate the heat transfer area.

$$\begin{aligned} \text{Rate of heat transfer} = Q &= \dot{m}_s \lambda_s \\ &= 4640.1 \times 2185 \\ &= 10138619 \text{ kJ/kg} \\ &= \frac{10138619 \times 1000}{3600} \\ &= 2816283 \text{ J/s} \equiv 2816283 \text{ W} \end{aligned}$$

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

$$\begin{aligned} \text{Temperature driving force} = \Delta T &= T_s - T \\ &= 399 - 378 \\ &= 21 \text{ K (21}^\circ\text{C)} \end{aligned}$$

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

We have :

$$Q = UA \Delta T$$

$$\therefore A = Q / U \Delta T = 2816283 / (2350 \times 21)$$

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

$$\text{Heat transfer area to be provided} = 57.07 \text{ m}^2$$

... Ans.

Example 6.4 : A solution containing 10 % solids is to be concentrated to a level of 50 % solids. Steam is available at a pressure of 0.20 MPa [saturation temperature of 393 K (120° C)]. Feed rate to the evaporator is 30000 kg/h. The evaporator is working at reduced pressure such that boiling point is 323 K (50° C). The overall heat transfer coefficient is 2.9 kW/(m²·K). Estimate the steam economy and 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 vaporisation of water at 323 K (i.e. at pressure in the vapour space = 2383 kJ/kg).

Solution : Basis : 30000 kg/h feed to the evaporator.

Let \dot{m}_f , \dot{m}' and \dot{m}_v be the mass flow rate of feed, thick liquor and water vapour respectively.

Material balance of solids :

Solids in the feed = Solids in the thick liquor

$$0.10 \times 30000 = 0.05 \dot{m}'$$

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

Overall material balance :

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

$$\text{Water evaporated} = \dot{m}_v = 30000 - 6000 = 24000 \text{ kg/h}$$

(I) Feed at 293 K (T_f) :

\dot{m}_s = mass flow rate of steam in kg/h

$\dot{m}_f = 30000 \text{ kg/h}$, $\dot{m}_v = 24000 \text{ kg/h}$

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

T_s = saturation temperature of steam = 393 K

T = boiling point of solution = 323 K

λ_s = latent heat of condensation of steam at 0.20 MPa
= 2202 kJ/kg

λ = latent heat of vaporisation of water at 323 K = 2383 kJ/kg

Enthalpy balance over evaporator (assuming no heat loss) :

Heat gained out by steam = Heat gained by solution (sensible heat)

+ Heat required to evaporate water

$$Q = \dot{m}_s \lambda_s = \dot{m}_f \cdot C_{pf} (T - T_f) + \dot{m}_v \lambda$$

$$\dot{m}_s \times 2202 = 30000 \times 3.98 \times (323 - 293) + 24000 \times 2383$$

Solving, we get

$$\dot{m}_s = 27599.5 \text{ kg/h}$$

Steam consumption = 27599.5 kg/h

The steam economy is given by

Steam economy = kg/h water evaporated / kg/h steam consumed

$$= \frac{24000}{27599.5} = 0.87 \text{ kg evaporation/kg steam} \quad \dots \text{Ans. (I)}$$

$$\text{Heat load of evaporator} = \text{Rate of heat transfer} = Q = \dot{m}_s \lambda_s$$

$$Q = 27599.5 \times 2202$$

$$= 60774099 \text{ kJ/h}$$

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

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

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

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

The rate of heat transfer is given by

$$Q = U A \Delta T$$

$$\therefore A = \frac{Q}{U \Delta T} = \frac{16881694}{2900 \times 70} = 83.16 \text{ m}^2$$

$$\text{Heat transfer area required} = 83.16 \text{ m}^2$$

... Ans. (I)

(II) Feed at 308 K :

Heat balance over evaporator :

$$\dot{m}_s \lambda_s = \dot{m}_f C_{pf} [T - T_f] + \dot{m}_c \lambda_c$$

$$\dot{m}_s \times 2202 = 30000 \times 3.98 \times (323 - 308) + 24000 \times 2383$$

$$\dot{m}_s = 26786 \text{ kg/h}$$

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

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

$$= 0.896$$

... Ans. (II)

$$\text{Heat load of evaporator} = \text{Rate of heat transfer} = Q = \dot{m}_s \lambda_s$$

$$= 26786 \times 2202$$

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

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

$$= 16384103 \text{ J/s} \equiv 16384103 \text{ W}$$

We have :

$$Q = U A \Delta T$$

$$A = \frac{Q}{U \cdot \Delta T}$$

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

$$\text{Heat transfer area required} = 80.71 \text{ m}^2$$

... Ans. (II)

As the feed temperature goes down, economy decreases and since ΔT and U do not change, the area of heat transfer increases due to increase in the heat load.

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

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

Example 6.5 : An evaporator is to be fed with 5000 kg/h solution containing 10 % solute by weight. The feed at 313 K (40° C) is to be concentrated to the solution containing 40 % solute by weight under an absolute pressure of 101.325 kPa. Steam is available at an absolute pressure of 303.975 kPa [saturation temperature of 407 K (134° C)]. The overall heat transfer coefficient is 1750 W/(m²·K).

Calculate :

(i) the heat transfer area that should be provided

(ii) the economy of the evaporator.

Data : C_p of feed = 4.187 kJ/(kg·K)

Treat the solution as a pure water for the purpose of calculation of enthalpies.

Temperature, K	Enthalpy, kJ/kg	
	Vapour	Liquid
313 K		170
373 K	2676	419
407 K	2725	563

Solution : Basis : 5000 kg/h of feed to the evaporator.

Let \dot{m}_f , \dot{m}' be the kg/h of feed and thick liquor respectively.

Material balance of solute :

Solute in the feed = Solute in the thick liquor

$$0.10 \times 5000 = 0.40 \times \dot{m}'$$

$$\dot{m}' = 1250 \text{ kg/h}$$

Overall material balance :

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

$$\text{Water evaporated} = 5000 - 1500$$

$$\dot{m}_v = 3750 \text{ kg/h}$$

Let H_f , H' , H_v be the enthalpies of feed, thick liquor and water vapour, respectively.

λ_s = latent heat of condensing steam

= specific enthalpy of saturated steam – specific enthalpy of saturated water

= Enthalpy of water vapour – Enthalpy of liquid water at 407 K

$$= 2725 - 563 = 2162 \text{ kJ/kg}$$

$$\begin{aligned}\text{Pressure in the evaporator} &= 101.325 \text{ kPa} \\ \text{Boiling point of solution} &= \text{Boiling point of water at } 101.325 \text{ kPa} \\ &= 373 \text{ K}\end{aligned}$$

$$\begin{aligned}H_v &= \text{Enthalpy of water vapour at } 373 \text{ K} \\ &= 2676 \text{ kJ/kg}\end{aligned}$$

$$\begin{aligned}H' &= \text{enthalpy of product (thick liquor) at } 373 \text{ K} \\ &= 419 \text{ kJ/kg}\end{aligned}$$

$$\begin{aligned}H_f &= \text{enthalpy of feed at } 313 \text{ K} \\ &= 170 \text{ kJ/kg}\end{aligned}$$

Heat balance over evaporator :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}_v H_v + \dot{m}' H'$$

$$\text{Enthalpy of (feed) + (steam)} = \text{Enthalpy of (water vapour) + (thick liquor)}$$

$$5000 \times 170 + \dot{m}_s \times 2162 = 3750 \times 2676 + 1250 \times 419$$

$$\dot{m}_s = 4490.6 \text{ kg/h}$$

$$\text{Steam consumption} = 4490.6 \text{ kg/h}$$

$$\text{Steam economy of the evaporator} = \frac{\text{kg/h water evaporated}}{\text{kg/h steam consumed}}$$

$$= \frac{3750}{4490.6} = 0.835 \quad \dots \text{Ans. (ii)}$$

Alternatively :

$$Q = \dot{m}_s \lambda_s = \dot{m}_f C_{p_f} (T - T_f) + (\dot{m}_f - \dot{m}') \lambda_v$$

$$\dot{m}_f - \dot{m}' = 5000 - 1250 = 3750 \text{ kg/h}$$

$$\lambda_v = \text{latent heat of evaporation of water at pressure in the evaporator (i.e., at } 373 \text{ K)}$$

$$= 2676 - 419 = 2257 \text{ kJ/kg}$$

$$C_{p_f} = 4.187 \text{ kJ/(kg} \cdot \text{K)}$$

$$\dot{m}_s \times 2162 = 5000 \times 4.187 \times (373 - 313) + 3750 \times 2257$$

$$\dot{m}_s = 4495 \text{ kg/h} \dots \text{almost same as the previously calculated.}$$

$$T_s = \text{Saturation temperature of condensing steam} = 407 \text{ K}$$

$$T = \text{B.P. of solution} = 373 \text{ K}$$

$$\Delta T = T_s - T = 407 - 373 = 34 \text{ K}$$

$$U = 1750 \text{ W/(m}^2 \cdot \text{K)}$$

The rate of heat transfer is given by

$$Q = \dot{m}_s \lambda_s = U \cdot A \Delta T$$

$$Q = 4490.6 \times 2162 = 9708677.2 \text{ kJ/h} = 2696855 \text{ J/h} \equiv 2696855 \text{ W} = AU\Delta T$$

$$\therefore A = \frac{Q}{U \Delta T} = \frac{2696855}{1750 \times 34} = 45.32 \text{ m}^2$$

Heat transfer area to be provided = **45.32 m²**

... Ans.

Example 6.6 : A single effect evaporator is fed with 5000 kg/h of solution containing 1 % solute by weight. Feed temperature is 303 K (30° C) and is to be concentrated to a solution of 2 % solute by weight. The evaporation is at atmospheric pressure (101.325 kPa) and area of evaporator is 69 m². Saturated steam is supplied at 143.3 kPa as a heating medium. Calculate the steam economy and the 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 143.3 kPa = 2691.5 kJ/kg

Saturation temperature of steam = 383 K (110° C)

Boiling point of saturation = 373 K

Enthalpy of product = 419.04 kJ/kg

Enthalpy of saturated water at 383 K = 461.30 kJ/kg

Solution : Basis : 5000 kg/h of feed to the evaporator.

Let \dot{m}' , \dot{m}_v be the flow rate of product and water vapour.

Material balance of solute :

$$0.01 \times 5000 = 0.02 \times \dot{m}'$$

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

Overall material balance :

$$\text{Feed} = \text{water evaporated} + \text{thick liquor}$$

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

Assuming no heat loss, the heat/enthalpy balance is :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}' H' + \dot{m}_v H_v$$

where

$$\dot{m}_f = 5000 \text{ kg/h}$$

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

$$\dot{m}_v = 2500 \text{ kg/h}$$

H_f , H' , H_v are the enthalpies of feed, thick liquor and water vapour respectively.

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

$$H' = 419.04 \text{ kJ/kg}, \quad H_v = 2676.1 \text{ kJ/kg}$$

$$\lambda_s = \text{latent heat of condensing steam}$$

$$= \text{enthalpy of saturated steam} - \text{enthalpy of saturated water}$$

$$= 2691.5 - 461.30 = 2230.2 \text{ kJ/kg}$$

$$5000 \times 125.79 + \dot{m}_s (2230.2) = 2500 \times 419.04 + 2500 \times 2676.1$$

$$\dot{m}_s = 3187.56 \text{ kg/h}$$

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

$$\text{Steam economy} = \frac{\text{kg/h water evaporated}}{\text{kg/h steam required}} = \frac{2500}{3187.56} = 0.784$$

... Ans.

$$\begin{aligned} \text{Rate of heat transfer} &= \dot{m}_s \lambda_s \\ &= 3187.56 \times 2230.2 \\ &= 71088963 \text{ kJ/h} \\ &= \frac{71088963 \times 1000}{3600} = 1974693.4 \text{ J/s (i.e. W)} \end{aligned}$$

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

Let us calculate U .

$$\begin{aligned} \text{We know that : } Q &= U A \Delta T \\ U &= Q/(A \Delta T) \\ U &= \frac{1974693.4}{69 \times 10} = 2862 \text{ W/(m}^2 \cdot \text{K)} \end{aligned}$$

$$\text{Overall heat transfer coefficient} = 2862 \text{ W/(m}^2 \cdot \text{K)}$$

... Ans.

Example 6.7 : If the evaporator pressure is reduced to 38.58 kPa, what would be the change in heat transfer area ? Use the same steam pressure and overall heat transfer coefficient as in Example 6.6.

Data :

$$\text{Boiling point of water / solution at 38.58 kPa} = 348 \text{ K}$$

$$\text{Enthalpy of water vapour} = 2635.3 \text{ kJ/kg}$$

$$\text{Enthalpy of product} = 313.93 \text{ kJ/kg}$$

Solution : Enthalpy balance over evaporator :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}' H' + \dot{m}_v H_v$$

$$5000 \times 125.79 + \dot{m}_s \times 2230.2 = 2500 \times 313.93 + 2500 \times 2635.3$$

$$\dot{m}_s = 2320.18 \text{ kg/h}$$

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We have :

$$Q = \dot{m}_s \lambda_s = 2320.18 \times 2230.2$$

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

$$= \frac{5174465.4 \times 1000}{3600} = 1437351.5 \text{ J/s} \equiv 1437351.5 \text{ W}$$

We know that :

$$Q = U A \Delta T$$

where

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

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

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

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

... Ans.

Heat transfer area in this case is 14.35 m^2 .

The heat transfer area decreases from 69 m^2 to 14.35 m^2 .

In this case, a condenser and vacuum pump should be used.

Example 6.8 : If the feed rate is increased to 6000 kg/h , what would be the mass flow rate of product, water evaporated and product concentration ? Use the same area, value of U , steam pressure, evaporator pressure and feed temperature as in Example 6.6.

Solution : Basis : 6000 kg/h of feed to the evaporator.

Heat balance over evaporator :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}' H' + \dot{m}_v H_v \quad \dots (1)$$

$$6000 \times 125.79 + 3187.56 \times 2230.2 = \dot{m}' \times 419.04 + \dot{m}_v \times 2676.1$$

Overall material balance :

$$\dot{m}_f = \dot{m}' + \dot{m}_v$$

$$\therefore 6000 = \dot{m}' + \dot{m}_v$$

$$\dot{m}' = 6000 - \dot{m}_v$$

Substituting for \dot{m}' , Equation (1) gives

$$6000 \times 125.79 + 3187.56 \times 2230.2 = (6000 - \dot{m}_v) \times 419.04 + \dot{m}_v \times 2676.1$$

$$\dot{m}_v = 2370.1 \text{ kg/h}$$

$$\therefore \dot{m}' = \dot{m}_f - \dot{m}_v = 6000 - 2370.1 = 3629.9 \text{ kg/h}$$

$$\text{Water evaporated} = 2370.1 \text{ kg/h}$$

$$\text{Mass flow rate of product} = 3629.9 \text{ kg/h}$$

Let x be the wt. % solute in the product.

... Ans.

Material balance of solids :

$$0.01 \times 6000 = \frac{x}{100} \times 3629.9$$

$$x = 1.653$$

Concentration of product/thick liquor = 1.653% by weight

... Ans.

Example 6.9 : A single effect evaporator is to concentrate 20000 kg/h of a solution having a concentration of 5 % salt to a concentration of 20 % salt by weight. Steam is fed to the evaporator at a pressure corresponding to the saturation temperature of 399 K (126° C). The evaporator is operating at atmospheric pressure and the boiling point rise is 7 K. Calculate the heat load and steam economy.

Data : Feed temperature = 298 K (25° C)

Specific heat of feed = 4.0 kJ/(kg·K)

Latent heat of condensation of steam at 399 K = 2185 kJ/kg

Latent heat of vaporisation of water at 373 K = 2257 kJ/kg

Solution : Basis : 20000 kg/h of solution to the evaporator.

Evaporator is operating at atmospheric pressure, i.e., at 101.325 kPa. The boiling point of pure water at 101.325 kPa is 373K (100° C).

Let \dot{m}_f , \dot{m}' and \dot{m}_v be the flow rates of feed, thick liquor and water vapour, respectively.

Material balance of salt :

Salts in the feed = Salts in the thick liquor

$$0.05 \times 20000 = 0.20 \times \dot{m}'$$

$$\dot{m}' = 5000 \text{ kg/h}$$

Overall material balance over evaporator :

Feed = Water evaporated + Thick liquor

$$\text{Water evaporated} = \dot{m}_v = 20000 - 5000$$

$$\dot{m}_v = 15000 \text{ kg/h}$$

$$\lambda_s = 2185 \text{ kJ/kg}$$

$$\lambda_v = \lambda = 2257 \text{ kJ/kg}$$

$$C_{pf} = 4.0 \text{ kJ/(kg·K)}$$

$$T_f = 298 \text{ K}$$

$$\begin{aligned} \text{Boiling point of the solution} = T &= T' + \text{B.P.R.} \\ &= 373 + 7 = 380 \text{ K} \end{aligned}$$

$$\begin{aligned}\text{Temperature of condensing steam} &= \text{Saturation temperature of steam} \\ &= 399 \text{ K}\end{aligned}$$

Heat balance over evaporator :

$$\text{Heat load} = Q$$

$$Q = \dot{m}_s \lambda_s = \dot{m}_f C_{pf} (T - T_f) + \dot{m}_v \cdot \lambda$$

$$\dot{m}_s \times 2185 = 20000 \times 4.0 (380 - 298) + 15000 \times 2257$$

$$\dot{m}_s = 18496.6 \text{ kg/h}$$

$$\text{Steam consumption} = 18496.6 \text{ kg/h}$$

$$\begin{aligned}\text{Economy of evaporator} &= \frac{15000}{18496.6} \\ &= 0.811\end{aligned}$$

... Ans.

Heat load of evaporator :

$$\begin{aligned}Q &= \dot{m}_s \lambda_s \\ &= 18496.6 \times 2185 \\ &= 4041507.1 \text{ kJ/h} \\ &= \frac{4041507.1 \times 1000}{3600} \\ &= 1122641 \text{ J/s}\end{aligned}$$

$$\text{Heat load} = 1122641 \text{ W}$$

... Ans.

Multiple-Effect Evaporators (Triple-Effect Evaporator) Calculations :

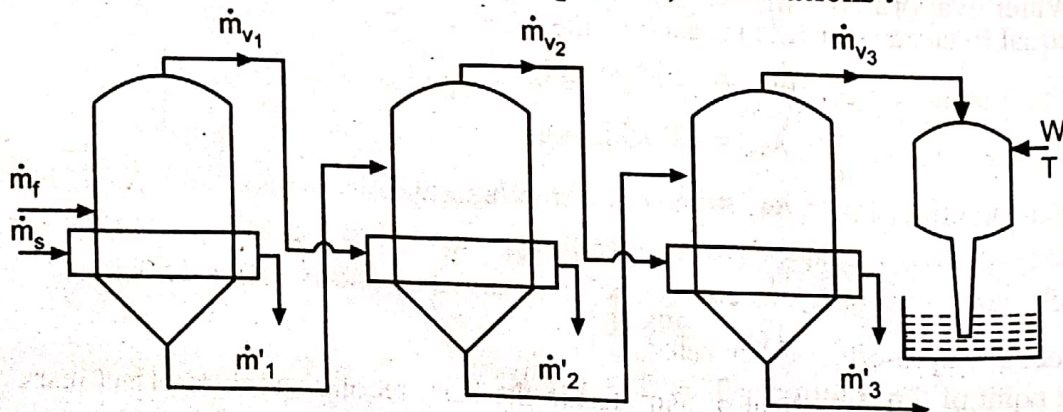


Fig. 6.14

Enthalpy/heat balance over individual effects are :

For the first effect :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}_{v_1} H_{v_1} + \dot{m}_1 H_1$$

For the second effect :

$$\dot{m}_1 H_1 + \dot{m}_{v_1} \lambda_{v_1} = \dot{m}_{v_2} H_{v_2} + \dot{m}_2 H_2$$

For the third effect :

$$\dot{m}_2 H_2 + \dot{m}_{v_2} \lambda_{v_2} = \dot{m}_{v_3} H_{v_3} + \dot{m}_3 H_3$$

where H_f , H_v and H are the enthalpies of various streams and λ_{v_1} , λ_{v_2} , λ_{v_3} are the latent heats corresponding to the pressures in the respective effects.

For a barometric condenser,

$$\dot{m}_{v_3} \lambda_{v_3} = \dot{m}_w C_{pw} (T_{v_3} - T)$$

where

$$\dot{m}_{v_3} = \text{Water flow rate, kg/h}$$

$$T_{v_3} = \text{Temperature of vapour corresponding to the pressure in the third effect.}$$

$$T = \text{Inlet temperature of cooling water}$$

$$\text{Available } \Delta T = \text{Apparent } \Delta T - \text{BPR}$$

$$\text{Apparent } \Delta T = T_s - T_v$$

where T_v is the temperature of water vapour corresponding to the pressure existing in an effect (in the case of a multiple-effect evaporator).

Calculation of Multiple-Effect Evaporators

Assumptions generally made in the calculation procedure are :

- (i) equal heat transfer rate in each of the effects,
- (ii) equal heat transfer surface in each of the effects, and
- (iii) equal evaporation in each of the effects.

In actual practice, however, the above cited assumptions cannot hold good simultaneously. With equal heat load, a trial and error procedure is adopted to get equal heat transfer area in each effect. The actual evaporation in each effect is obtained by subsequent calculations.

Consider a tripple-effect evaporator.

Let Q_1 , Q_2 and Q_3 be the heat transmitted in the first, second and third-effect respectively.

ΔT_1 , ΔT_2 and ΔT_3 are the corresponding temperature drops.

Enthalpy/heat balance over individual effects are :

For the first effect :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}_{v_1} H_{v_1} + \dot{m}_1 H_1$$

For the second effect :

$$\dot{m}_1 H_1 + \dot{m}_{v_1} \lambda_{v_1} = \dot{m}_{v_2} H_{v_2} + \dot{m}_2 H_2$$

For the third effect :

$$\dot{m}_2 H_2 + \dot{m}_{v_2} \lambda_{v_2} = \dot{m}_{v_3} H_{v_3} + \dot{m}_3 H_3$$

where H_f , H_v and H are the enthalpies of various streams and λ_{v_1} , λ_{v_2} , λ_{v_3} are the latent heats corresponding to the pressures in the respective effects.

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In actual practice, however, the above cited assumptions cannot hold good simultaneously. With equal heat load, a trial and error procedure is adopted to get equal heat transfer area in each effect. The actual evaporation in each effect is obtained by subsequent calculations.

Consider a tripple-effect evaporator.

Let Q_1 , Q_2 and Q_3 be the heat transmitted in the first, second and third-effect respectively.

ΔT_1 , ΔT_2 and ΔT_3 are the corresponding temperature drops.

Heat Transfer

U_1 , U_2 and U_3 be the overall heat transfer coefficient in the first, second and third-effect, respectively.

A_1 , A_2 and A_3 be the heat transfer surface of the first, second and third-effect, respectively.

For a tripple effect evaporator, we have

$$\begin{aligned} Q_1 &= Q_2 = Q_3 \\ U_1 A_1 \Delta T_1 &= U_2 A_2 \Delta T_2 = U_3 A_3 \Delta T_3 \end{aligned} \quad \dots (1)$$

To obtain the economy in the construction of evaporators, heat transfer areas in all effects are equal.

Therefore, with $A_1 = A_2 = A_3$, we get

$$U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3 \quad \dots (2)$$

It follows from the Equation (2) that the temperature drops in the multiple effect evaporator system are approximately inversely proportional to the heat transfer coefficients.

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

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

where, ΔT = overall temperature drop over the system

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

$$\Delta T = \Delta T_1 [1 + U_1/U_2 + U_1/U_3] \quad \dots (5)$$

Also $\Delta T = T_s - T_{v3} \quad \dots (6)$

where T_s = saturation temperature of condensing (first effect) steam corresponding to steam pressure. T_{v3} = temperature of the vapour corresponding to the pressure in the vapour space of third-effect. With equation (6) overall temperature drop is calculated. With the help of equations (3), (4) and (5) and values of U_1 , U_2 and U_3 , the temperature drops in each of the effects are calculated and hence the temperature distribution in each of the effects.

	First effect	Second effect	Third effect
Steam	T_s	T_{v1}	T_{v2}
Liquor	T_{L1}	T_{L2}	T_{L3}
Vapour	T_{v1}	T_{v2}	T_{v3}
ΔT	$T_s - T_{L1}$	$T_s - T_{L2}$	$T_s - T_{L3}$
BPR/BPE	$T_{L1} - T_{v1}$	$T_{L2} - T_{v2}$	$T_{L3} - T_{v3}$

Knowing the temperature distribution, enthalpies of various streams are obtained.

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

The areas of the individual effects are calculated as follows :

$$A_1 = \frac{\dot{m}_s \lambda_s}{U_1 \Delta T_1} \quad \dots (7)$$

$$A_2 = \frac{\dot{m}_{v1} \lambda_{v1}}{U_2 \Delta T_2} \quad \dots (8)$$

and $A_3 = \frac{\dot{m}_{v2} \lambda_{v2}}{U_3 \Delta T_3} \quad \dots (9)$

If $A_1 \neq A_2 \neq A_3$, and the deviation is more than $\pm 10\%$, a fresh trial with a new temperature distribution should be performed. The new temperature drops are calculated as :

$$\Delta T'_1 = \Delta T_1 \times \frac{A_1}{A_{\text{avg}}}, \quad A_{\text{avg}} = \frac{A_1 + A_2 + A_3}{3}$$

$$\Delta T'_2 = \Delta T_2 \times \frac{A_2}{A_{\text{avg}}}$$

$$\Delta T'_3 = \Delta T_3 \times \frac{A_3}{A_{\text{avg}}}$$

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

Example 6.10 : A tripple-effect evaporator is concentrating a solution that has no appreciable boiling point elevation. The temperature of steam to the first effect is 381.3 K (108.3° C) and the boiling point of the solution in the last effect is 324.7 K (51.7° C). The overall heat transfer coefficients in the first, second and third-effect are 2800, 2200 and 1100 W/(m²·K), respectively. At what temperatures will the solution boil in the first and second effects ?

Solution : Total temperature drop = $\Delta T = 381.3 - 324.7 = 56.6 \text{ K}$

$$\Delta T = \Delta T_1 [1 + U_1/U_2 + U_1/U_3]$$

$$56.6 = \Delta T_1 [1 + 2800/2200 + 2800/1100]$$

$\therefore \Delta T_1 = 11.75 \text{ K}$

$$\Delta T = \Delta T_2 [1 + U_2/U_1 + U_2/U_3]$$

$$56.6 = \Delta T_2 [1 + 2200/2800 + 2200/1100]$$

$$\Delta T_2 = 14.95 \text{ K}$$

and $\therefore \Delta T_3 = 56.6 - [11.75 + 14.95]$
 $= 29.9 \text{ K}$

$$\Delta T_1 = T_s - T'_1$$

$\therefore T'_1 = 381.3 - 11.75 = 369.55 \text{ K (96.55° C)}$

$$\begin{aligned}\Delta T_2 &= T'_1 - T'_2 \\ T'_2 &= 369.55 - 14.95 \\ &= 354.6 \text{ K (81.6 } ^\circ\text{C)}\end{aligned}$$

Boiling point in the first effect = **369.55 K (96.55° C)**

Boiling point in the second effect = **354.6 K (81.6° C)**

... Ans.

... Ans.

Example 6.11 : A double-effect evaporator is used to concentrate 10,000 kg/h of caustic soda solution from 9% to 47% by wt. NaOH. For this purpose, a backward feed arrangement is used. The feed enters the evaporator at 309 K (36° C). Process steam at 686.616 kPa.g is available and in the second effect a vacuum of 86.66 kPa is maintained. Design a suitable forced circulation system with equal heating surface in both the effects. Calculate the steam consumption and evaporation in each effect. Neglect boiling point rise. The overall heat transfer coefficients in the first and second effects are 2326 and 1744.5 W/(m²·K), respectively. Take a specific heat of 3.77 kJ/(kg·K) for all caustic streams.

Solution : 10,000 kg/h of feed.

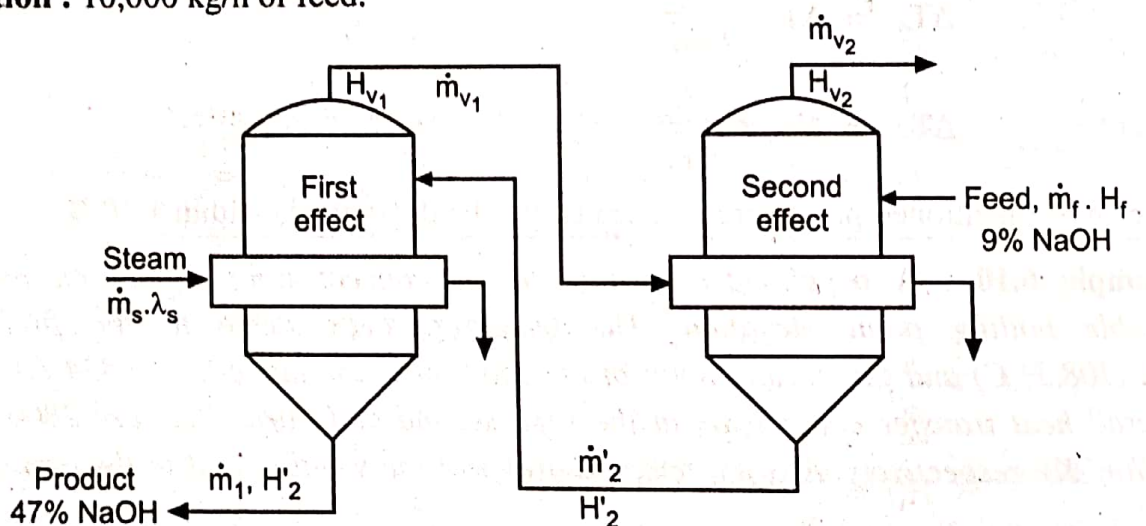


Fig. E 6.11

Overall material balance :

$$\dot{m}_f = \dot{m}_1 + \dot{m}_{v1} + \dot{m}_{v2}$$

Material balance of solute :

$$0.09 \times 10000 = 0.47 \times \dot{m}_1$$

$$\dot{m}_1 = 1915 \text{ kg/h}$$

$$\text{Steam pressure} = 686.616 \text{ kPa.g.}$$

$$= 686.616 + 101.325 = 787.941 \text{ kPa}$$

Hence, saturation temperature,

$$T_s = 442.7 \text{ K (169.7 } ^\circ\text{C)}$$

$$\text{Vacuum in the second effect} = 86.660 \text{ kPa}$$

$$\text{Absolute pressure in the second effect} = 101.325 - 86.660$$

$$= 14.665 \text{ kPa}$$

$$\begin{aligned}\text{Corresponding temperature} &= 326.3 \text{ K } (53.3^\circ\text{C}) \\ \text{Overall temperature drop} &= \Delta T = 442.7 - 326.3 \\ &= 116.4 \text{ K } (^\circ\text{C})\end{aligned}$$

Assuming heat loads to be equal in both the effects,

$$\begin{aligned}Q_1 &\approx Q_2 \\ U_1 A_1 \Delta T_1 &= U_2 A_2 \Delta T_2\end{aligned}$$

For equal heat transfer surface,

$$\begin{aligned}U_1 \Delta T_1 &= U_2 \Delta T_2 \\ \Delta T_1 &= \frac{U_2}{U_1} \Delta T_2 = \frac{2326}{1744.5} \Delta T_2 = 0.75 \Delta T_2\end{aligned}$$

$$\begin{aligned}\Delta T &= \Delta T_1 + \Delta T_2 = 0.75 \Delta T_2 + \Delta T_2 \\ 116.4 &= 1.75 \Delta T_2\end{aligned}$$

$$\Delta T_2 = 66.5 \text{ K, and } \Delta T_1 = 49.9 \text{ K}$$

Since there is no B.P.R.

$$\Delta T_1 = T_s - T_{v1}$$

where T_{v1} – temperature in the vapour space of first effect

$$T_{v1} = T_s - \Delta T_1 = 442.7 - 49.9$$

$$T_{v1} = 392.8 \text{ K } (119.8^\circ\text{C})$$

$$\begin{aligned}T_{v2} &= T_{v1} - \Delta T_2 \\ &= 392.8 - 66.5 = 326.3 \text{ K } (53.3^\circ\text{C})\end{aligned}$$

Enthalpies of various streams :

H_f = feed enthalpy

$$\begin{aligned}H_f &= 3.768 \times (309 - 273) \\ &= 135.66 \text{ kJ/kg}\end{aligned}$$

$$\begin{aligned}H_1 &= \text{enthalpy of the final product} \\ &= 3.768 (392.8 - 273) \\ &= 451.4 \text{ kJ/kg}\end{aligned}$$

$$\begin{aligned}H_2 &= \text{enthalpy of the intermediate product} \\ &= 3.768 (326.3 - 273) = 200.83 \text{ kJ/kg}\end{aligned}$$

For steam at 442.7 K (169.7 °C), $\lambda_s = 2048.7 \text{ kJ/kg}$

For vapour at 392.8 K (119.8 °C)

$$H_{v1} = 2705.22 \text{ kJ/kg, } \lambda_{v1} = 2202.8 \text{ kJ/kg}$$

For vapour at 326.3 K (53.3 °C)

$$\begin{aligned}H_{v2} &= 2597.61 \text{ kJ/kg} \\ \lambda_{v2} &= 2377.8 \text{ kJ/kg}\end{aligned}$$

Material balances and energy balance around the effects :

First effect :

Material balance over first effect :

$$\dot{m}_2 = \dot{m}_1 + \dot{m}_{v1} \quad \dots (1)$$

Enthalpy/Energy balance over first effect :

$$\dot{m}_s \lambda_s + \dot{m}_2 H_2 = \dot{m}_{v1} H_{v1} + \dot{m}_1 H_1 \quad \dots (2)$$

Second effect :

Material balance over second effect :

$$\dot{m}_f = \dot{m}_2 + \dot{m}_{v2} \quad \dots (3)$$

$$\therefore \dot{m}_2 = \dot{m}_f - \dot{m}_{v2} \quad \dots (3A)$$

Energy balance over second effect :

$$\dot{m}_{v1} \lambda_{v1} + \dot{m}_f H_f = \dot{m}_{v2} H_{v2} + \dot{m}_2 H_2 \quad \dots (4)$$

Overall material balance :

$$\begin{aligned} \dot{m}_f &= \dot{m}_v + \dot{m}_1 \\ \dot{m}_v &= \dot{m}_{v1} + \dot{m}_{v2} \\ \dot{m}_v &= \dot{m}_f - \dot{m}_1 = 10000 - 1915 = 8085 \text{ kg/h} \\ \dot{m}_{v2} &= \dot{m}_v - \dot{m}_{v1} \quad \dots (5) \end{aligned}$$

Substituting for \dot{m}_{v2} from Equation (5) and \dot{m}_2 from Equation (3A) into Equation (4) gives

$$\begin{aligned} \dot{m}_{v1} \lambda_{v1} + \dot{m}_f H_f &= (\dot{m}_v - \dot{m}_{v1}) H_{v2} + (\dot{m}_f - \dot{m}_{v2}) H_2 \\ \dot{m}_{v1} \lambda_{v1} + \dot{m}_f H_f &= (\dot{m}_v - \dot{m}_{v1}) H_{v2} + [\dot{m}_f - (\dot{m}_v - \dot{m}_{v1})] H_2 \quad \dots (6) \end{aligned}$$

Only unknown in the above equation is \dot{m}_{v1}

$$2202.8 \dot{m}_{v1} + 10000 \times 135.66 = (8085 - \dot{m}_{v1}) \times 2597.61 + [10000 - (8085 - \dot{m}_{v1})] \times 200.83$$

$$2202.8 \dot{m}_{v1} + 1356600 = 21001677 - 2597.66 \dot{m}_{v1} + 2008300$$

$$- 1623710.6 + 200.83 \dot{m}_{v1}$$

$$4599.58 \dot{m}_{v1} = 20029666$$

$$\dot{m}_{v1} = 4354.7 \text{ kg/h}$$

$$\begin{aligned} \dot{m}_{v2} = \dot{m}_v - \dot{m}_{v1} &= 8085 - 4354.7 \\ &= 3729.3 \text{ kg/h} \end{aligned}$$

Substituting \dot{m}_{v1} , \dot{m}_{v2} , \dot{m}_1 and \dot{m}_f and thermal quantities in Equation (2), we get

$$\dot{m}_s = 5557 \text{ kg/h}$$

Heat transfer area :

First effect :

$$\begin{aligned} A_1 &= \frac{Q_1}{U_1 \Delta T_1} = \frac{\dot{m}_s \lambda_s}{U_1 \Delta T_1} \\ A_1 &= \frac{5557 \times 2048.7 \times 10^3}{2326 \times 49.9 \times 3600} = 27.25 \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Second effect : } A_2 &= \frac{Q_2}{U_2 \Delta T_2} = \frac{\dot{m}_{v1} \lambda_{v1}}{U_2 \Delta T_2} \\ &= \frac{4354.7 \times 2202.8 \times 10^3}{1744.5 \times 66.5 \times 3600} \\ &= 22.97 \text{ m}^2 \end{aligned}$$

Since $A_1 \neq A_2$ and the difference is more than 10%, a second trial is required.

$$\text{Second trial : } A_{\text{avg}} = \frac{A_1 + A_2}{2} = \frac{27.25 + 22.97}{2} = 25.11 \text{ m}^2$$

$$\Delta T'_1 = \Delta T_1 \times \frac{A_1}{A_{\text{avg}}} = \frac{49.9 \times 27.25}{25.11} = 54.2 \text{ K}$$

$$\Delta T'_2 = \Delta T - \Delta T'_1 = 116.4 - 54.2 = 62.2 \text{ K}$$

Temperature distribution :

$$T_{v1} = T_s - \Delta T'_1 = 442.7 - 54.2 = 388.5 \text{ K (115.5 } ^\circ\text{C)}$$

$$T_{v2} = T_{v1} - \Delta T'_2 = 388.5 - 62.2 = 326.3 \text{ K (53.3 } ^\circ\text{C)}$$

Enthalpy of streams :

$$H_f = 135.66 \text{ kJ/kg}$$

$$H'_1 = 3.768 (388.5 - 273) = 424.81 \text{ kJ/kg}$$

$$H'_2 = 200.83 \text{ kJ/kg}$$

Vapour at 388.5 K (115.5 °C)

$$H_{v1} = 2699.8 \text{ kJ/kg}$$

$$\lambda_{v1} = 2214.92 \text{ kJ/kg}$$

Substituting the new values, enthalpy balance for the second effect, i.e., Equation (5) becomes

$$\dot{m}_{v1} \times 2214.92 + 10000 \times 135.66 = (8085 - \dot{m}_{v1}) 2597.01 + [10000 - (8085 - \dot{m}_{v1})] \times 200.83$$

Solving, we get : $\dot{m}_{v1} = 4343 \text{ kg/h}$

$$\begin{aligned} \dot{m}_{v2} &= \dot{m}_v - \dot{m}_{v1} = 8085 - 4343 \\ &= 3742 \text{ kg/h} \end{aligned}$$

Enthalpy (energy) balance of the first effect :

$$\dot{m}_s \lambda_s + \dot{m}_2 H_2' = \dot{m}_{v1} H_{v1} + \dot{m}_1 H_1'$$

$$\dot{m}_2 = \dot{m}_1 + \dot{m}_{v1}$$

$$= \dot{m}_f - \dot{m}_v + \dot{m}_{v1}$$

$$= \dot{m}_f - (\dot{m}_{v1} + \dot{m}_{v2}) + \dot{m}_{v1} = \dot{m}_f - \dot{m}_{v2}$$

$$\therefore \dot{m}_s \lambda_s + (\dot{m}_f - \dot{m}_{v2}) H_2' = \dot{m}_{v1} H_{v1} + \dot{m}_1 H_1'$$

$$\begin{aligned} \dot{m}_s \times 2048.7 + (10000 - 3742) \times 200.83 \\ = 4343 \times 2699.8 + 1915 \times 424.81 \end{aligned}$$

Solving, we get

$$\dot{m}_s = 5516 \text{ kg/h}$$

Area of heat transfer :

First effect :

$$\begin{aligned} A_1 &= \frac{Q}{U \cdot \Delta T} = \frac{\dot{m}_s \lambda_s}{U \cdot \Delta T} = \frac{5516 \times 2048.7 \times 10^3}{2326 \times 54.2 \times 3600} \\ &= 24.9 \text{ m}^2 \end{aligned}$$

$$\text{Second effect : } A_2 = \frac{Q}{U \cdot \Delta T} = \frac{\dot{m}_{v1} \lambda_{v1}}{U \cdot \Delta T} = \frac{4343 \times 2214.92 \times 10^3}{1744.5 \times 62.2 \times 3600} = 24.62 \text{ m}^2$$

It seems that : $A_1 \approx A_2$

Therefore, the area in each effect can be 24.90 m² (recommending a higher value).

\therefore Steam consumption = 5516 kg/h

Evaporation in the first effect = 4343 kg/h

Evaporation in the second effect = 3742 kg/h

Example 6.12 : A lye containing 7% glycerine by weight is to be concentrated in a triple-effect evaporator to obtain a crude containing 40% glycerine. The feed rate of lye is 10000 kg/h. Based on the following data, calculate :

(i) the steam economy and (ii) the area of calandria heating surface for each evaporator assuming that all the three effects have equal area and condenser water required.

Data : Feed temperature = 353 K (85°C)
 Steam pressure available = 313 kPa
 Last effect's pressure = 15.74 kPa
 Overall heat transfer coefficients :
 First effect : 710 W/(m²·K)
 Second effect : 490 W/(m²·K)
 Third effect : 454 W/(m²·K)

The elevation in the boiling point is 10 K in each effect. The average specific heat of glycerol solution is 3.768 kJ/(kg·K). Condenser water is available at 303 K (30°C).

Assume : $\Delta T_1 = 14.5$ K, $\Delta T_2 = 16$ K and $\Delta T_3 = 19.5$ K.

Forward-feed arrangement is to be used.

Solution : 10000 kg/h of feed to the triple-effect evaporator system.

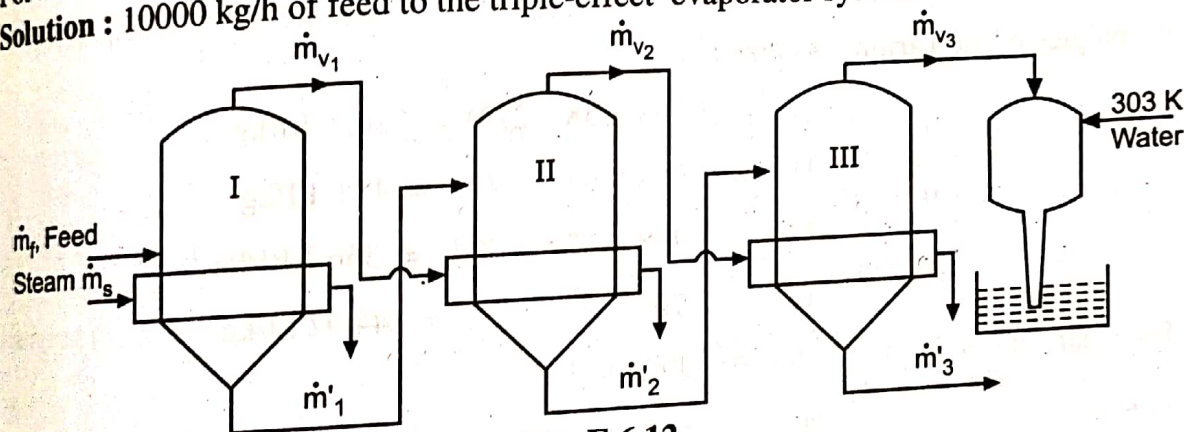


Fig. E 6.12

Overall material balance :

Feed = Water evaporated + Thick liquor

$$\dot{m}_f = \dot{m}_v + \dot{m}_3$$

and

$$\dot{m}_v = \dot{m}_{v1} + \dot{m}_{v2} + \dot{m}_{v3}$$

Overall glycerine balance :

Glycerine in lye = Glycerine in crude/thick liquor

$$0.07 \times 10000 = 0.40 \dot{m}_3$$

$$\dot{m}_3 = 1750 \text{ kg/h}$$

$$\dot{m}_v = \dot{m}_f - \dot{m}_3 = 10000 - 1750 = 8250 \text{ kg/h}$$

Steam pressure : 313 kPa

$\therefore T_s$ (from steam table) = 408 K (135°C)

Pressure in the last effect = 15.74 kPa

$\therefore T_{v3}$ = Vapour temperature = 328 K (55°C)

$$\begin{aligned}\text{Overall apparent } \Delta T &= T_s - T_{v3} \\ &= 408 - 328 = 80 \text{ K}\end{aligned}$$

$$\text{BPR}_1 = \text{BPR}_2 = \text{BPR}_3 = 10 \text{ K}$$

$$\Sigma \text{BPR} = 30 \text{ K}$$

$$\therefore \text{True overall } \Delta T = 80 - 30 = 50 \text{ K}$$

$$\Delta T_1 = 14.5 \text{ K}$$

$$\Delta T_2 = 16 \text{ K}$$

$$\Delta T_3 = 19.5 \text{ K}$$

Temperatures (K) of various streams are :

	1 st effect	2 nd effect	3 rd effect
Steam	408	383.5	357.5
Liquor	393.5	367.5	338
Vapour	393.5	357.5	328

Enthalpies of the various streams :

$$H_f = 3.768 (358 - 273) = 320.3 \text{ kJ/kg}$$

$$H_1 = 3.768 (393.5 - 273) = 454 \text{ kJ/kg}$$

$$H_2 = 3.768 (367.5 - 273) = 356.1 \text{ kJ/kg}$$

$$H_3 = 3.768 (338 - 273) = 244.92 \text{ kJ/kg}$$

$$\text{For steam at 408 K : } \lambda_s = 2160 \text{ kJ/kg}$$

$$\text{For } \dot{m}_{v1}, \quad H_{v1} = 2692 \text{ kJ/kg}$$

$$\lambda_{v1} = 2228.3 \text{ kJ/kg}$$

$$\text{For } \dot{m}_{v2}, \quad H_{v2} = 2650.8 \text{ kJ/kg}$$

$$\lambda_{v2} = 2297.4 \text{ kJ/kg}$$

$$\text{For } \dot{m}_{v3}, \quad H_{v3} = 2600.5 \text{ kJ/kg}$$

$$\lambda_{v3} = 2370 \text{ kJ/kg}$$

Material and energy balances for the effects :

First effect :

Material balance :

$$\dot{m}_f = \dot{m}_{v1} + \dot{m}_1$$

$$\therefore \dot{m}_1 = \dot{m}_f - \dot{m}_{v1} = 10000 - (8250 - \dot{m}_{v2} - \dot{m}_{v3})$$

$$\dot{m}_1 = 1750 + \dot{m}_{v2} + \dot{m}_{v3}$$

Energy balance :

$$\dot{m}_s \lambda_s + \dot{m}_f H_f = \dot{m}_{v1} H_{v1} + \dot{m}_1 H_1 \quad \dots (3)$$

$$\dot{m}_s \times 3160 + 10000 \times 320.3 = (8250 - \dot{m}_{v2} - \dot{m}_{v3}) \times 2692 + (1750 + \dot{m}_{v2} + \dot{m}_{v3}) 454$$

or $2160 \dot{m}_s + 2238 (\dot{m}_{v2} + \dot{m}_{v3}) = 19800500 \quad \dots (4)$

Second effect :

Material balance :

$$\dot{m}_1 = \dot{m}_{v2} + \dot{m}_2 \quad \dots (5)$$

Energy balance :

$$\dot{m}_1 H_1 + \dot{m}_{v1} \lambda_{v2} = \dot{m}_{v2} H_{v2} + \dot{m}_2 H_2 \quad \dots (6)$$

Substituting for \dot{m}_1 from Equation (2) and \dot{m}_2 from Equation (5) and with the numerical values for the quantities, Equation (6) becomes

$$\begin{aligned} (1750 + \dot{m}_{v2} + \dot{m}_{v3}) \times 454 + (8250 - \dot{m}_{v2} - \dot{m}_{v3}) \times 2228.3 \\ = \dot{m}_{v2} \times 2650.8 + (1750 + \dot{m}_{v2} + \dot{m}_{v3} - \dot{m}_{v2}) \times 356.1 \end{aligned}$$

or $4425.1 \dot{m}_{v2} + 2130.4 \dot{m}_{v3} = 18554800 \quad \dots (7)$

Equation (7) gives a relation between \dot{m}_{v2} and \dot{m}_{v3} as under,

$$\dot{m}_{v3} = 8709.54 - 2.076 \dot{m}_{v2} \quad \dots (8)$$

Third effect :

Material balance :

$$\dot{m}_2 = \dot{m}_{v3} + \dot{m}_3 \quad \dots (9)$$

$$\dot{m}_2 = \dot{m}_{v3} + 1750 \quad \dots (10)$$

i.e.

Energy balance :

$$\dot{m}_2 H_2 + \dot{m}_{v2} \lambda_{v2} = \dot{m}_{v3} H_{v3} + \dot{m}_3 H_3 \quad \dots (11)$$

$$(\dot{m}_{v3} + 1750) \times 356.1 + \dot{m}_{v2} \times 2297.4 = \dot{m}_{v3} \times 2600.5 + 1750 \times 244.92 \quad \dots (12)$$

Substituting the value of \dot{m}_{v3} from Equation (8), Equation (12) becomes

$$\begin{aligned} [8709.54 - 2.076 \dot{m}_{v2} + 1750] \times 356.1 + 2297.4 \dot{m}_{v2} \\ = [8709.54 - 2.076 \dot{m}_{v2}] \times 2600.5 + 1750 \times 244.92 \end{aligned}$$

Solving, we get

$$6956.78 \dot{m}_{v2} = 19353126.58$$

$$\dot{m}_{v2} = 2782 \text{ kg/h}$$

Substituting the value of \dot{m}_{v2} in Equation (8), we get

$$\begin{aligned} \dot{m}_{v3} &= 8709.54 - 2.076 \times 2782 \\ &= 2934.1 \text{ kg/h} \end{aligned}$$

$$\therefore \dot{m}_{v1} = 8250 - (2782 + 2934.1) = 2533.9 \text{ kg/h}$$

With the values of \dot{m}_{v2} and \dot{m}_{v3} , Equation (4) yields

$$\dot{m}_s = 3244.4 \text{ kg/h}$$

Heat transfer area :

$$A_1 = \frac{\dot{m}_s \lambda_s}{U_1 \times \Delta T_1} = \frac{3244.4 \times 2160}{710 \times 14.5} \times \frac{10^3}{3600}$$

$$A_1 = 189.1 \text{ m}^2$$

$$A_2 = \frac{\dot{m}_{v1} \times \lambda_{v1}}{U_2 \times \Delta T_2} = \frac{2533.9 \times 2228.3}{490 \times 16} + \frac{10^3}{3600} = 200 \text{ m}^2$$

$$A_3 = \frac{\dot{m}_{v2} \times \lambda_{v2}}{U_3 \times \Delta T_3} = \frac{2782 \times 2297.4}{454 \times 19.5} \times \frac{10^3}{3600} = 200.5 \text{ m}^2$$

The deviation in the heat transfer areas (Calculated) is within $\pm 10\%$ (Permissible).
Hence, the maximum area i.e. A_1 can be recommended for all effects.

$$\text{Area in each effect (A)} = 200.5 \text{ m}^2$$

$$\text{Steam economy of the evaporator system} = \frac{8250}{3244.4} = 2.55 \text{ kg evaporation/kg steam}$$

Condenser water requirement :

$$\begin{aligned} Q_c &= \text{Heat removed from vapour} \\ &= \dot{m}_{v3} \times \lambda_{v3} \\ &= 2934.1 \times 2370 = 6953817 \text{ kJ/h} \end{aligned}$$

Cooling water is at 303 K (30°C)

Condensing temperature is 328 K (55°C)

$$\text{Rise in temperature of water} = 328 - 303 = 25 \text{ K}$$

$$\begin{aligned} \text{Cooling water rate } (\dot{m}_w) &= \frac{Q_c}{C_p \Delta T} = \frac{6953817}{4.187 \times 25} \\ &= 66432.4 \text{ kg/h} \\ &= 66.432 \text{ t/h} \end{aligned}$$

Example 6.13 : 14.4 tonnes per hour (4 kg/s) of a liquor containing 10% solids is fed at 294 K (21 °C) to the first effect of a triple-effect unit. Thick liquor containing 50% solids is to be withdrawn from the third effect, which is at a pressure of 13.172 kPa. The liquor will be assumed to have a specific heat of 4.18 kJ/(kg·K) and to have no B.P.R. Dry saturated steam at pressure of 205 kN/m² is fed to a heating medium of the first effect. Assume the overall heat transfer coefficients of 3.10, 2.00 and 1.10 kW/(m²·K) for the first, second and third effects respectively. Find the heat transfer area of each effect, steam consumption and steam economy if the three effects are to have the same heat transfer area.

Assume $\Delta T_1 = 18 \text{ K}$, $\Delta T_2 = 17 \text{ K}$ and $\Delta T_3 = 34 \text{ K}$

Forward-feed arrangement is to be used.

Solution : Basis : 4 kg/s weak liquor fed to the first evaporator.

Saturation temperature of steam at 205 kN/m² = 294 K (121°C).

At a pressure of 13.172 kPa, boiling point of water is 325 K (52°C)

Total temperature drop = $\Delta T = 394 - 325 = 69 \text{ K}$

At $T_s = 394 \text{ K}$, $\lambda_s = 2200 \text{ kJ/kg}$ (from steam table)

$$\Delta T_1 = 18 \text{ K}$$

$$\therefore T_1 = 394 - 18 = 376 \text{ K}$$

$$\text{At } T_1 = 376 \text{ K}, \quad \lambda_{v1} = \lambda_1 = 2249 \text{ kJ/kg}$$

$$\Delta T_2 = 17 \text{ K}$$

$$\therefore T_2 = 376 - 17 = 359 \text{ K}$$

$$\text{At } T_2 = 359 \text{ K}, \quad \lambda_{v2} = \lambda_2 = 2293 \text{ kJ/kg}$$

$$\Delta T_3 = 34 \text{ K}$$

$$\therefore T_3 = 359 - 34 = 325 \text{ K}$$

$$\text{At } 325 \text{ K}, \quad \lambda_{v3} = \lambda_3 = 2377 \text{ kJ/kg}$$

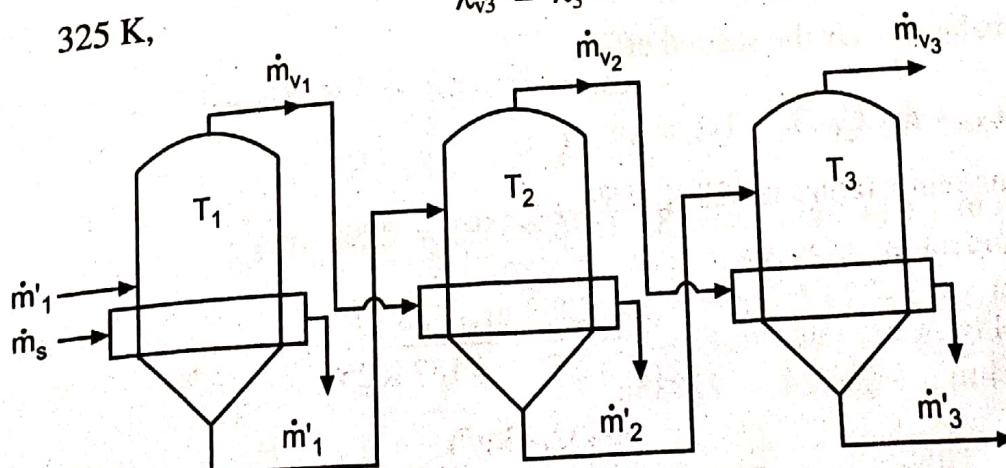


Fig. E 6.13

Overall material balance :

$$\dot{m}_f = \dot{m}_v + \dot{m}_3$$

Material balance of solids over the evaporation system :

$$0.1 \times 4 = 0.50 \times \dot{m}_3$$

$$\dot{m}_3 = 0.8 \text{ kg/s}$$

$$\text{Total evaporation} = \dot{m}_v = \dot{m}_f - \dot{m}_3$$

$$= 4 - 0.8$$

$$= 3.2 \text{ kg/s}$$

we have

$$\dot{m}_v = \dot{m}_{v1} + \dot{m}_{v2} + \dot{m}_{v3}$$

First Effect :

Material balance over the first effect :

$$\dot{m}_f = \dot{m}_{v1} + \dot{m}_1$$

$$4.0 = \dot{m}_{v1} + \dot{m}_1$$

Enthalpy balance over the first effect :

$$\dot{m}_s \lambda_s = \dot{m}_f C_{pf} (T_1 - T_f) + \dot{m}_{v1} \lambda_{v1}$$

$$2200 \times \dot{m}_s = 4 \times 4.18 \times (376 - 294) + 2249 \dot{m}_{v1}$$

$$2200 \dot{m}_s = 1371.04 + 2249 \dot{m}_{v1}$$

Second Effect :

Material balance over the second effect :

$$\dot{m}_1 = \dot{m}_{v2} + \dot{m}_2$$

Enthalpy balance over the second effect :

$$\dot{m}_{v1} \lambda_{v1} + \dot{m}_1 C_p (T_1 - T_2) = \dot{m}_{v2} \lambda_{v2}$$

$$2249 \times \dot{m}_{v1} + (4 - \dot{m}_{v1}) \times 4.18 \times (376 - 359) = 2293 \dot{m}_{v2}$$

$$2249 \dot{m}_{v1} + 284.24 - 71.06 \dot{m}_{v1} = 2293 \dot{m}_{v2}$$

$$2177.94 \dot{m}_{v1} + 284.24 = 2293 \dot{m}_{v2}$$

$$\dot{m}_{v1} = 1.053 \dot{m}_{v2} - 0.1305$$

Third Effect :

Material balance over the third effect :

$$\dot{m}_2 = \dot{m}_{v3} + \dot{m}_3$$

Enthalpy balance over the third effect :

$$\dot{m}_{v2} \lambda_{v2} + \dot{m}_2 C_p (T_2 - T_3) = \dot{m}_{v3} \lambda_{v3}$$

$$2293 \dot{m}_{v2} + (\dot{m}_3 + \dot{m}_{v3}) \times (4.18) \times (359 - 325) = 2377 \dot{m}_{v3}$$

$$2293 \dot{m}_{v2} + (0.8 + \dot{m}_{v3}) \times (142.12) = 2377 \dot{m}_{v3}$$

$$2293 \dot{m}_{v2} + 113.7 + 142.12 \dot{m}_{v3} = 2377 \dot{m}_{v3}$$

$$\dot{m}_{v3} = 1.026 \dot{m}_{v2} + 0.051 \quad \dots (2)$$

We have :

$$\dot{m}_v = 3.2 = \dot{m}_{v1} + \dot{m}_{v2} + \dot{m}_{v3}$$

Substituting the values of \dot{m}_{v1} and \dot{m}_{v3} from Equations (1) and (2) gives

$$3.2 = (1.053 \dot{m}_{v2} - 0.1305) + \dot{m}_{v2} + (1.026 \dot{m}_{v2} + 0.051)$$

$$3.079 \dot{m}_{v2} = 3.2795$$

$$\dot{m}_{v2} = 1.065 \text{ kg/s}$$

$$\begin{aligned} \dot{m}_{v1} &= 1.053 \dot{m}_{v2} - 0.1305 \\ &= 1.053 \times 1.065 - 0.1305 \\ &= 0.991 \text{ kg/s} \end{aligned}$$

$$\begin{aligned} \dot{m}_{v3} &= 1.026 \dot{m}_{v2} + 0.051 \\ &= 1.026 \times 1.065 + 0.051 \\ &= 1.144 \text{ kg/s} \end{aligned}$$

We have :

$$2200 \dot{m}_s = 1371.04 + 2249 \dot{m}_{v1}$$

$$2200 \dot{m}_s = 1371.04 + 2249 \times 0.991$$

$$\dot{m}_s = 1.636 \text{ kg/s}$$

$$\text{Steam economy of the evaporator system} = \frac{\dot{m}_v}{\dot{m}_s} = \frac{3.2}{1.636} = 1.956 \approx 2.0 \text{ kg evaporation/kg steam}$$

... Ans.

First effect : $A_1 = \frac{\dot{m}_s \lambda_s}{U_1 \Delta T_1} = \frac{1.626 \times 2200 \times 10^3}{3.10 \times 10^3 \times 18} = 64.50 \text{ m}^2$

Second effect : $A_2 = \frac{\dot{m}_{v1} \cdot \lambda_{v1}}{U_2 \Delta T_2} = \frac{0.991 \times 2249 \times 10^3}{2.0 \times 10^3 \times 17} = 64.96 \text{ m}^2$

Third effect : $A_3 = \frac{\dot{m}_{v2} \lambda_{v2}}{U_3 \Delta T_3} = \frac{1.065 \times 2293 \times 10^3}{1.10 \times 10^3 \times 34} = 65.3 \text{ m}^2$

Areas calculated are within the deviation of $\pm 10\%$.

We must provide the maximum area obtained in each effect ... accepted practice.

\therefore Area of heat transfer in each effect = **65.3 m²**

... Ans.

Example 6.14 : 1060 kg/h of 4% (by weight) caustic soda solution is fed to a quadruple-effect evaporator. Thick liquor leaving the last evaporator contains 25% caustic soda by weight. The dry saturated steam at 0.7 MPa·g is fed to the first effect. The feed solution enters the first evaporator at 303 K (30°C). The operating pressure in the first, second and third effects are 0.37, 0.235 and 0.08 MPa·g, respectively. The fourth effect (the last effect) operates at 50.66 kPa (vacuum of 380 torr). Neglecting the boiling point rise in each of the effects, calculate the steam economy of the evaporator system.

Heat capacity data :

	Heat capacity, kJ/(kg·K)
Feed	0.04
Solution leaving the first effect	3.977
Solution leaving the second effect	3.936
Solution leaving the third effect	3.894
Solution leaving the fourth effect	3.873

Solution : Basis : 1060 kg/h of weak liquor flow rate.

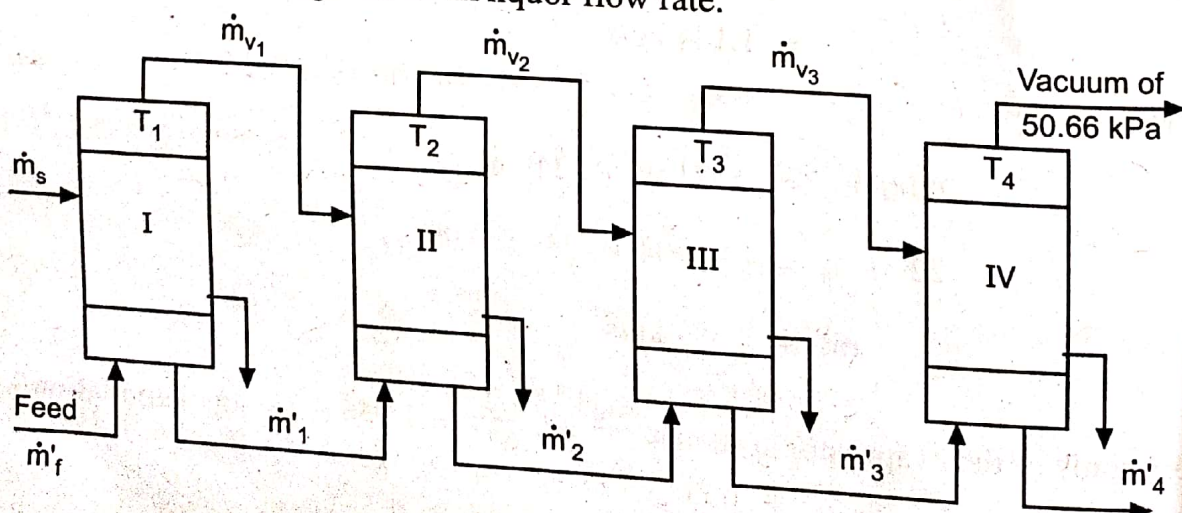


Fig. E 6.14

Overall material balance :

$$\dot{m}_f = \dot{m}_v + \dot{m}_4$$

Overall caustic soda material balance :

$$0.04 \times 1060 = 0.25 \times \dot{m}_4$$

$$\dot{m}_4 = 169.6 \text{ kg/h}$$

Thick liquor leaving the fourth effect = 169.6 kg/h

Total evaporation in all four effects = $\dot{m}_v = \dot{m}_f - \dot{m}_4$

$$\dot{m}_v = 1060 - 169.6$$

$$= 890.4 \text{ kg/h}$$

We have,

$$\dot{m}_v = \dot{m}_{v1} + \dot{m}_{v2} + \dot{m}_{v3} + \dot{m}_{v4}$$

From steam table :

First effect : $P_1 = 0.37 \text{ MPa} \cdot \text{g} = 370 \text{ kPa} \cdot \text{g}$

$$T_1 = 422.6 \text{ K (149.6}^\circ\text{C)} \text{ and } \lambda_1 = 2114.4 \text{ kJ/kg}$$

Second effect : $P_2 = 0.235 \text{ MPa} \cdot \text{g} = 235 \text{ kPa} \cdot \text{g}$

$$T_2 = 410.5 \text{ K (137.5}^\circ\text{C)} \text{ and } \lambda_2 = 2151.5 \text{ kJ/kg}$$

Third effect : $P_3 = 0.08 \text{ MPa} \cdot \text{g} = 80 \text{ kPa} \cdot \text{g}$

$$T_3 = 390.2 \text{ K (117.2}^\circ\text{C)} \text{ and } \lambda_3 = 2210.2 \text{ kJ/kg}$$

Fourth effect : $P_4 = 50.66 \text{ kPa}$

$$T_4 = 354.7 \text{ K (81.7}^\circ\text{C)} \text{ and } \lambda_4 = 2304.6 \text{ kJ/kg}$$

Latent heat of steam at $0.7 \text{ MPa} \cdot \text{g} = 700 \text{ kPa} \cdot \text{g}$ is

$$\lambda_s = 2046.3 \text{ kJ/kg}$$

Let \dot{m}_f , \dot{m}_1 , \dot{m}_2 and \dot{m}_3 be the kg/h feed to I, II, III and IV effects. \dot{m}_4 be the kg/h product from the IV effect. \dot{m}_{v1} , \dot{m}_{v2} , \dot{m}_{v3} and \dot{m}_{v4} be the kg/h of water vapour leaving I, II, III and IV effects respectively.

First effect :

Material balance :

$$\dot{m}_f = \dot{m}_1 + \dot{m}_{v1}$$

Enthalpy balance :

$$\dot{m}_s \lambda_s = \dot{m}_f C_{pf} (T_1 - T_f) + \dot{m}_{v1} \lambda_1$$

$$2046.3 \dot{m}_s = 1060 \times 4.04 (422.6 - 303) + 2115.4 \dot{m}_{v1}$$

$$\begin{aligned}
 \dot{m}_8 &= 250.3 + 1.033 \dot{m}_{v1} \\
 &= 250.3 + 1.033 (\dot{m}_f - \dot{m}_1) \\
 &= 250.3 + 1.033 (1060 - \dot{m}_1) \\
 \dot{m}_8 &= 1345.30 - 1.033 \dot{m}_1
 \end{aligned}$$

Second effect : Material balance : $\dot{m}_1 = \dot{m}_2 + \dot{m}_{v2}$

Enthalpy balance :

$$\begin{aligned}
 \dot{m}_{v1} \lambda_1 &= \dot{m}_1 C_{p1} (T_2 - T_1) + \dot{m}_{v2} \lambda_2 \\
 (1060 - \dot{m}_1) &= \dot{m}_1 \times 3.977 (410.5 - 422.6) + (\dot{m}_1 - \dot{m}_2) \times 2151.4 \\
 \therefore \dot{m}_1 &= 531.38 + 0.510 \dot{m}_2
 \end{aligned}$$

Third effect :

Material balance :

$$\dot{m}_2 = \dot{m}_3 + \dot{m}_{v3}$$

Enthalpy balance :

$$\begin{aligned}
 \dot{m}_{v2} \lambda_2 &= \dot{m}_2 C_{p2} (T_3 - T_2) + \dot{m}_{v3} \lambda_3 \\
 (\dot{m}_1 - \dot{m}_2) 2151.5 &= \dot{m}_2 \times 3.936 (390.2 - 410.5) + (\dot{m}_2 - \dot{m}_3) \times 2210.2 \\
 \dot{m}_1 - 1.99 \dot{m}_2 &= -1.027 \dot{m}_3
 \end{aligned}$$

Fourth effect :

Material balance :

$$\dot{m}_3 = \dot{m}_4 + \dot{m}_{v4}, \text{ but } \dot{m}_4 = 169.6 \text{ kg/h}$$

Enthalpy balance :

$$\begin{aligned}
 \dot{m}_{v3} \lambda_3 &= \dot{m}_3 C_{p3} (T_4 - T_3) + \dot{m}_{v4} \lambda_4 \\
 (\dot{m}_2 - \dot{m}_3) \times 2210.2 &= \dot{m}_3 \times 3.894 \times (354.7 - 290.2) + (\dot{m}_3 - 169.6) \times 2304.6 \\
 \therefore \dot{m}_2 - 1.98 \dot{m}_3 &= -176.84
 \end{aligned}$$

From Equation (3), we have

$$\dot{m}_1 = 1.99 \dot{m}_2 - 1.027 \dot{m}_3$$

Substituting the value of \dot{m}_1 from Equation (5) into Equation (2), we get

$$1.99 \dot{m}_2 - 1.027 \dot{m}_3 = 531.38 + 0.510 \dot{m}_2$$

$$\therefore \dot{m}_2 = 559.04 + 0.694 \dot{m}_3$$

Substituting the value of \dot{m}_2 from Equation (6) into Equation (4), we get

$$359.04 + 0.694 \dot{m}_3 - 1.98 \dot{m}_3 = -176.84$$

$$\therefore \dot{m}_3 = 416.7 \text{ kg/h}$$

From Equation (4),

$$\dot{m}_2 - 1.98 \times 416.7 = -176.84$$

$$\therefore \dot{m}_2 = 648.23 \text{ kg/h}$$

From Equation (2),

$$\dot{m}_1 = 862 \text{ kg/h}$$

and from equation (1),

$$\dot{m}_s = 455 \text{ kg/h}$$

$$\text{Steam consumption} = 455 \text{ kg/h}$$

... Ans.

$$\text{Steam economy of the quadrapule evaporator system} = \frac{\dot{m}_v}{\dot{m}_s} = \frac{890.4}{455}$$

$$= 1.957 \text{ kg evaporation/kg steam}$$

... Ans.

Example 6.15 : A single-effect evaporator is used to produce 5000 kg/h of NaOH thick liquor. Evaporation is carried out in this evaporator of 10 % by weight NaOH solution to obtain 50% by weight NaOH solution. The evaporator is a calendria type consisting of number of tubes (vertical) which are 32 mm in outside diameter and 28 mm in inner diameter and 2.5 m long. This solution is pumped through the tubes, whereas the steam is fed the steam chest around the tubes. Due to fouling, the inside surface of the tube is layered with a 0.25 mm thick layer of thermal conductivity 2.25 W/(m.K). Saturated steam is supplied as a heating medium at a pressure of 357 kN/m² absolute and the evaporator is operated under a vacuum of 250 mmHg. There is a negligible entrainment and condensate is removed at the saturation temperature of steam. If the heat transfer coefficients on the solution side and steam side are 4500 and 9000 W/(m².K), determine (i) the capacity of the evaporator, (ii) the steam consumption, (iii) the steam economy, and (iv) the number of tubes required for the calendria.

Data : Boiling point rise of 50% by NaOH solution is 18.5 K (18.5°C). Enthalpies of the feed solution, vapour and thick liquor are 138, 2675 and 568 J/g, respectively. The thermal conductivity of the tube material is 45 W/(m².K).

Solution : Basis : 5000 kg/h of 50% NaOH solution/thick liquor

$$\dot{m}_1 = 5000 \text{ kg/h}$$

$$\dot{m}_f = \text{Mass flow rate of feed.}$$

Heat Transfer

Material balance of NaOH :

NaOH in weak solution = NaOH in thick liquor

$$0.10 \dot{m}_f = 0.5 \times 5000$$

$$\dot{m}_f = 25000 \text{ kg/h}$$

\therefore

Overall material balance :

$$\dot{m}_f = \dot{m}_l + \dot{m}_v \quad \therefore \dot{m}_v = 25000 - 5000 = 20000 \text{ kg/h}$$

$$\text{Water evaporated} = 20000 \text{ kg/h}$$

$$\text{Steam pressure} = 357 \text{ kN/m}^2$$

From steam table : $T = 412 \text{ K}$ (139°C), $H = 2732 \text{ kJ/kg}$, $\lambda = 2143 \text{ kJ/kg}$

$$\text{Vacuum in the evaporator} = 250 \text{ mm Hg}$$

$$\therefore \text{Pressure in the evaporator} = 760 - 250 = 510 \text{ mm Hg}$$

From steam table : Saturation temperature = 352 K (79°C)

$$H = 2659 \text{ kJ/kg}, \lambda = 2285.3 \text{ kJ/kg}$$

$$T_s = \text{Saturation temperature of steam} = 412 \text{ K}$$

$$\text{Boiling point of the solution} = T' = 352 + \text{B.P.R.} = 352 + 18.5 = 370.5 \text{ K}$$

Heat balance of evaporator :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}_v H_v + \dot{m}_l H_l$$

where

$$H_f = 138 \text{ kJ/kg}, \lambda_s = 2143 \text{ kJ/kg}, H_v = 2659 \text{ kJ/kg}$$

$$H_l = 568 \text{ kJ/kg}$$

$$\therefore 25000 \times 138 + \dot{m}_s (2143) = 20000 \times 2659 + 5000 \times 568$$

$$\therefore \dot{m}_s = 24531 \text{ kg/h}$$

$$\therefore \text{Steam consumption} = 24531 \text{ kg/h} \quad \dots \text{Ans. (i)}$$

$$\text{Capacity of the evaporator} = 20,000 \text{ kg/h} \quad \dots \text{Ans. (ii)}$$

$$\text{Economy of the evaporator} = 20000/24531 = 0.815 \text{ kg evaporation/kg steam}$$

$\dots \text{Ans. (iii)}$

$$\Delta T = T_s - T' = 412 - 370.5 = 41.5 \text{ K}$$

$$h_i = 4500 \text{ W/(m}^2 \cdot \text{K)}, h_o = 9000 \text{ W/(m}^2 \cdot \text{K)}$$

$$D_o = 32 \text{ mm} = 0.032 \text{ m}, D_i = 28 \text{ mm} = 0.028 \text{ m}$$

$$x_1 = (32 - 28)/2 = 2 \text{ mm} = 0.002 \text{ m}$$

$$D_w = (32 - 28)/\ln(32/28) = 29.95 \text{ mm} = 0.02995 \text{ m}$$

$$x_2 = 0.25 \text{ mm} = 0.025 \times 10^{-3} \text{ m}$$

$$h_{i0} = h_i \times \frac{D_i}{D_o} = 4500 \times \frac{0.028}{0.032} = 3975.5 \text{ W/(m}^2 \cdot \text{K)}$$

$$k_1 = k \text{ for tube material} = 45 \text{ W/(m} \cdot \text{K)}$$

$$k_2 = k \text{ for scale} = 2.25 \text{ W/(m} \cdot \text{K)}$$

The overall heat transfer coefficient for this case is given by

$$\frac{1}{U_o} = \frac{1}{h_i} + \frac{1}{h_{io}} + \frac{x_1}{k_1} \frac{D_w}{D_o} + \frac{x_2}{k_2}$$

$$U_o = \frac{1}{9000} + \frac{1}{3975.5} + \frac{0.002}{45} \times \frac{0.02995}{0.032} + \frac{0.25 \times 10^{-3}}{2.25}$$

$$U_o = 1940.4 \text{ W/(m}^2 \cdot \text{K)}$$

$$U = 1940.4 \text{ W/(m}^2 \cdot \text{K)}$$

$$Q = \dot{m}_s \lambda_s = 24531 \times 2143 = 52569933 \text{ kJ/h} = 14602759 \text{ W}$$

The rate of heat transfer is given by

$$Q = UA \Delta T$$

$$A = Q/U \Delta T = 14602759/(1940.4 \times 41.5) = 181.34 \text{ m}^2$$

We know that,

$$A = n \pi_o D_o L$$

where n is the number of tubes in the calandria.

$$n = A/\pi_o D_o L = 181.34/(\pi \times 0.032 \times 2.5) = 721.5$$

$$\therefore \text{Number of tubes required} = 722$$

... Ans.

Example 6.16 : A single-effect evaporator is used to concentrate 4536 kg/h of a 20% NaOH solution entering at 333 K (60°C) to a product containing 50% NaOH. The pressure of saturated steam used is 172.4 kPa and the pressure in the vapour space of the evaporator is 11.7 kPa. The overall heat transfer coefficient is 1560 W/(m²·K). Calculate the amount of steam used, the steam economy and the heating surface area.

Data : Boiling point of 50% NaOH solution = 362.5 K (89.5°C)

Boiling point rise = 40.6 K (40.6°C)

Heat capacity of superheated steam = 1.88 kJ/(kg·K)

h_f for 20% NaOH at 333 K = 214 kJ/kg

h_L for 50% NaOH at 362.5 K = 505 kJ/kg

Solution : Basis : 4536 kg/h of feed solution

$$\therefore \dot{m}_f = 4536 \text{ kg/h}$$

Material balance of NaOH :

$$0.20 \times 4536 = 0.50 \cdot \dot{m}_1$$

$$\dot{m}_1 = 1814.4 \text{ kg/h}$$

Thick liquor flow rate = 1814.4 kg/h

Water evaporated = 4536 - 1814.4 = 2721.6 kg/h

Pressure in the vapour space = 11.7 kN/m²

Saturation temperature (from steam table) = 321.90 K (48.90°C)

Boiling point of water = 321.90 K (48.90°C)

Boiling point of solution (given) = 362.5 K

Boiling point rise = $262.5 - 321.9 = 40.6 \text{ K}$ (40.6°C)

Steam pressure = $172.4 \text{ kPa} = 0.1724 \text{ MPa}$

From steam table : Saturation temperature of steam, $T_s = 388.5 \text{ K}$

λ for steam = 2214 kJ/kg

Pressure in the vapour space is 21.7 kPa .

Enthalpy of vapour based on a saturated vapour at the pressure in the vapour space
= 2590.3 kJ/kg (from steam table)

$H_v = 2590.3 \text{ kJ/kg}$

This H_v is based on the saturated vapour instead of on the superheated vapour.

If the enthalpy of the vapour H_v is based on a saturated vapour at the pressure in the vapour space instead of on a superheated vapour (at 262.5 K and 11.7 kPa pressure), it will introduce a small error in the calculated quantities.

Enthalpy balance over evaporator :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}_l H_l + \dot{m}_v H_v$$

$$4536 \times 214 + \dot{m}_s (2214) = 1814.4 \times 505 + 2721.6 \times 2590.3$$

$$\dot{m}_s = 3159.6 \text{ kg/h}$$

$$\text{Steam consumption} = \mathbf{3159.6 \text{ kg/h}}$$

... Ans.

$$\text{Steam economy of the evaporator} = 2721.6/3159.6 = \mathbf{0.861 \text{ kg evaporation/kg}}$$

... Ans.

$$\Delta T = T_s - \text{B.P. of solution}$$

$$= 388.5 - 362.5 = 26 \text{ K}$$

$$U = 1560 \text{ W/(m}^2 \cdot \text{K)}$$

$$Q = \dot{m}_s \lambda_s = 3159.6 \times 2214 = 6995534.4 \text{ kJ/h} = 1943154 \text{ W}$$

$$Q = UA \Delta T$$

$$A = Q/(U \Delta T) = 1943154/(1560 \times 26) = 47.91 \text{ m}^2$$

$$\therefore \text{Heat transfer area} = \mathbf{47.91 \text{ m}^2}$$

... Ans.

(Enthalpy of superheated vapour at 362.5 K and 11.7 kPa can be obtained from steam table and may be used in the enthalpy balance equation.)

Enthalpy of superheated vapour = Enthalpy of saturated vapour + Heat of superheat

$$\text{Enthalpy of superheated vapour} = H_v = 2590.3 + 1.88 \times 40.6 = 2666.63 \text{ kJ/kg}$$

Calculations considering enthalpy of superheated vapour :

Enthalpy balance over evaporator :

$$\dot{m}_f H_f + \dot{m}_s \lambda_s = \dot{m}_l H_l + \dot{m}_v H_v$$

$$4536 \times 214 + \dot{m}_s (2214) = 18.44 \times 505 + 2721.6 \times 2666.63$$

$$\dot{m}_s = 3253.42 \text{ kg/h}$$

$$\text{Steam consumption} = \mathbf{3253.42 \text{ kg/h}}$$

$$\text{Economy of evaporator} = 2721.6 / 3253.42 = \mathbf{0.84}$$

... Ans.

... Ans.

Heat transferred :

$$Q = \dot{m}_s \lambda_s = 3253.42 \times 2214 = 7203072 \text{ kJ/h} = 2000853 \text{ W}$$

$$A = Q/U \Delta T = 2000853/1560 \times 26 = 49.33 \text{ m}^2 \quad \dots \text{Ans.}$$

$$\left[\begin{array}{l} \% \text{ error in the heat transfer area} \\ \text{considering only saturated vapour} \end{array} \right] = \frac{49.33 - 47.91}{47.91} \times 100 = 2.96$$

If the enthalpy of water vapour H_v were based on the saturated vapour at the pressure in the vapour, instead of on the superheated vapour, the error introduced is of only 2.96 percent.