Paper No. : 04
Paper Title: Unit Operations in Food Processing
Module- 14:Evaporation

14.1 Introduction

Evaporation is a common unit operation in food processing industries in which partial removal of water takes place from an aqueous solution. The removal of water in the form of vapour is achieved by the process of vaporization or boiling of aqueous solution. Evaporation is confined to the preservation of liquid foods by concentrating them as a result, microbiological damage is checked and shelf life increased. One more advantage is the reduction in mass and volume of material, resulting in reduced cost of packaging, storage and transportation. The application of evaporation in food industries includes concentration of aqueous solution of sugar, milk, sodium chloride, fruit juices etc. In all the cases, the concentrated solutions are the required products and removed water is discarded. But, in processes like desalination, water is the required product. Sometimes, evaporation is used as an intermediate operation mainly before drying, particularly in spray drying. This helps increased economy of dryer, as the removal of huge amount of water in processes like spray drying is a costly affair.

While selecting the adaptability of evaporation in different food products, one cannot overlook the physico-chemical changes that take place due to processing factors like exposure of products to high temperature and pressure conditions, which reduces the product quality in terms of vitamin and essential volatile components. One major cause of concern is the concentration of liquid solution. As the evaporation proceeds, the relatively dilute solution concentrates; as a result heat transfer coefficients reduce and load on the pumping system increases. The boiling point of solution rises as the solute concentration increases, as a consequence, the temperature difference which is the driving force in heat transfer between the steam and boiling point of aqueous solution decreases. To keep boiling point of liquid food as low as possible, the evaporators are operated under vacuum, because reduced pressure reduces the boiling point temperature. As the boiling point temperature reduces, the thermal degradation to foods minimizes. One disadvantage of low temperature operation would be increased viscosity of solution, causing reduced heat transfer.

The solubility of solids in a solution decreases with increase in concentration. The insoluble solids called scales are deposited on the wall of the evaporator, which reduces the overall heat transfer coefficients. Fouling may occur which causes microbiological damage to the products. Solubility is related to the crystallization process, the soluble solids at high temperature (super saturation) when cooled crystallization occurs, which is undesirable in concentration process as it may cause blockage to the evaporator.

14.2 Evaporators and their types

The equipments used to evaporate water from an aqueous solution are called evaporators. The schematic diagram of a single effect evaporator is given in fig. 14.1. The system consists of the following components;

i. an evaporation chamber,

ii. a heat exchanger to supply heat to vaporize water,

iii. a condenser to suck the vapour from the evaporation chamber and

iv. a steam jet ejector to remove non condensable gases

The main components of the evaporator are the evaporation chamber and the heat exchanger which occupies a part of evaporation chamber. The rate of evaporation in an evaporator is determined by the amount of heat transferred to the solution by the heat exchanger. The steam gives off its latent heat to the surface of the exchanger which is in contact with the feed solution. The latent heat at atmospheric pressure is 2257 kJ/kg. Since, steam enters at superheated condition the heat supplied is more than 2257 kJ/kg steam. If there are no losses, same amount of heat is available to the solution to reach to the boiling point at prevailing pressure inside the evaporator. But, practically the heat losses cannot be avoided. There are many factors like steam saturation level, temperature and pressure at which steam is supplied, heat transfer area, the feed solution temperature, viscosity of feed, the fouling factor etc. decides the rate of heat transfer. Steam after it gives off all the heat is collected in the form of condensate liquid. The evaporation chamber or vapour chamber is the largest visible part of evaporator. This allows the separation of vapour from feed solution. The vapour temperature is the saturation steam temperature at the absolute pressure inside the chamber. If the boiling point rise is neglected the boiling temperature of feed, vapour temperature and product temperature are same i.e. they are in thermal equilibrium. The vapour formed must be removed from the vapour chamber to allow the space for evaporation, otherwise the accumulated vapour would increase the absolute pressure inside the chamber, as a result the boiling point will rise and the temperature difference will decrease. Surface condenser is used to recover vapour from the chamber like the cases where some valuable components are driven out by vapour and are collected from subsequent operations. They are very expensive, so seldom used in food industries. The common condensers are direct contact water cooled condensers. The vapor enters a water spray chamber which is connected to a barometric leg. The barometric leg full of water balances the pressure inside the chamber and atmosphere. It maintains vacuum in the vapour chamber intact. The temperature of the water-condensate mixture must be below the vapour temperature to allow the vapour flow from the chamber to the condenser. In order to check the flow of feed solution with the vapour baffle plates are installed near the vapour outlet. Some amount of vapour may not condensate in water spraying chamber. They are removed by a steam jet ejector, where high pressure steam is passed through a narrow opening and the non condensible vapour is sucked along with the high velocity steam due to low pressure generation. The evaporator is also called as ‘effect’.

The orientation of heat exchanging area i.e. steam tubes on the chamber and the means of agitation/circulation provided evolved different types of evaporators. Some common types of evaporators will be discussed in this text. All evaporators are continuous types.

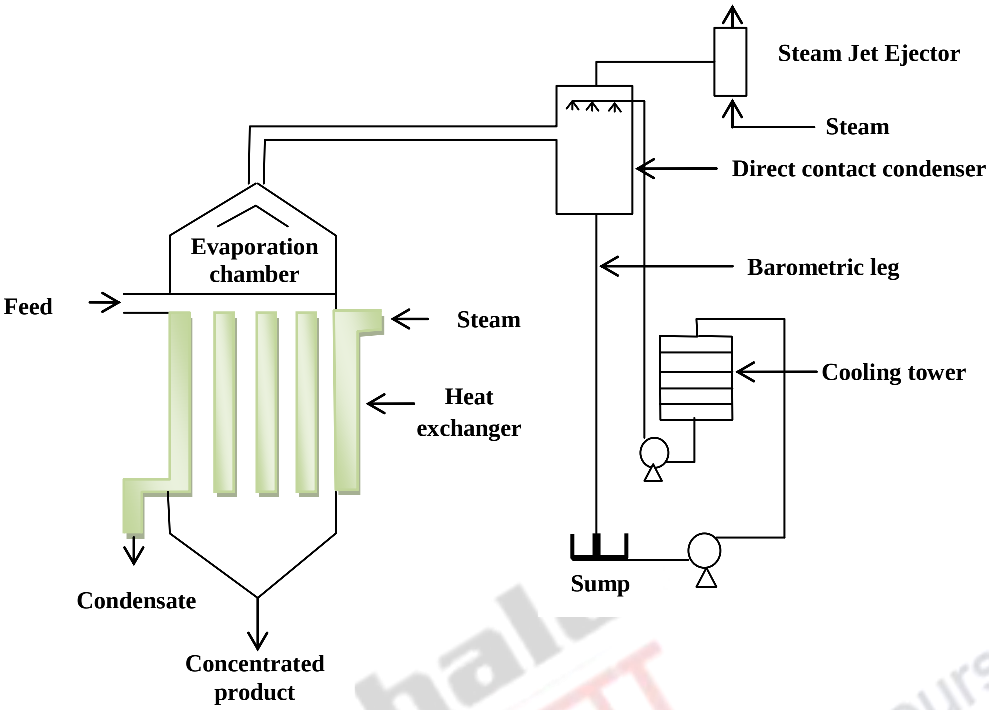


Fig.14.1 Schematic diagram of a single effect evaporator

1. *Horizontal short tube evaporator*

The steam tubes or bundles are oriented horizontally in the evaporator (Fig14.2a). Steam enters at one end of the tube, gives up latent heat and condensate leaves out from the other end. The feed liquid covers the steam bundles from outside surface of the tubes where heat transfer takes place. Since the circulation of feed is poor, low viscosity solutions can only be used in this case. Heat transfer coefficient of feed must be high to compensate non agitation of standing feed in the vapour chamber. The product should be non corrosive to the pipes.

2. *Vertical short tube evaporator*

The tubes are arranged vertically inside which feed solution passes. The vapour condensed outside the tube bundles (Fig14.2b). The lighter liquid because of boiling and decreased density moves up and heavier liquid moves down through a central larger pipe. Heat transfer increases due to natural circulation of liquid. Viscous liquids cannot climb on the tubes, so viscous products are not evaporated in vertical short tube evaporators. The length of tubes varies from 0.5 to 2.0 m with diameter of tube ranging between 25 to 75 mm. The central tube occupies 25 to 40% of the total tube area. This evaporator is generally use for evaporation of sugar and salt solutions.

3. *Vertical long tube evaporator*

Vertical long tube evaporator is a little modification of vertical short tube evaporator. The liquid tubes are 3 to 10 m long. Central downstream feed tube is not required since the liquid is fed from the bottom and climbs up the tubes once. As the liquid passes through the narrow tubes, the bubbles formed due to evaporation of liquid drags the liquid and don’t allow liquid movement downward. Agitation and circulation provided by vapour bubbles is high, so the heat transfer in this case is high. The contact time is very less due to high velocity liquid, thereby thermal damage to the product is very less. The liquid vapour mixture enters a separation chamber, where baffle plates are provided to facilitate vapour separation. The concentrated solution is collected from the bottom of the separator or if desired concentration is not achieved, is recycled with the fresh feed (Fig14.2c). Milk is concentrated in this evaporator mostly.

4. Falling film evaporator

The feeding position on the long tube evaporators can be provided at the top instead of bottom feeding. The long tube evaporator with top feeding is called as falling film evaporator. The vapour formed inside the tube descends as a jet at high velocity. Heat sensitive foods like fruit juices are concentrated in falling film evaporators. The descending liquid moves at higher velocity compared to ascending liquid, because ascending liquid moves against the direction of gravitational force. So, the residence time in falling film is very less (in the range of 5 to 10 s) compared to ascending long tube evaporator.

5. Forced circulation evaporator

The circulation velocity can be achieved by externally mounted feed pump (Fig14.2d). The tube length in forced circulation evaporator need not be long to achieve film velocity. The circulation velocity of liquid generally varies from 2 to 6 m/s inside the tube. High viscous liquids can be evaporated in this evaporator as adequate force is applied by the pump to move the viscous liquid in the tube.

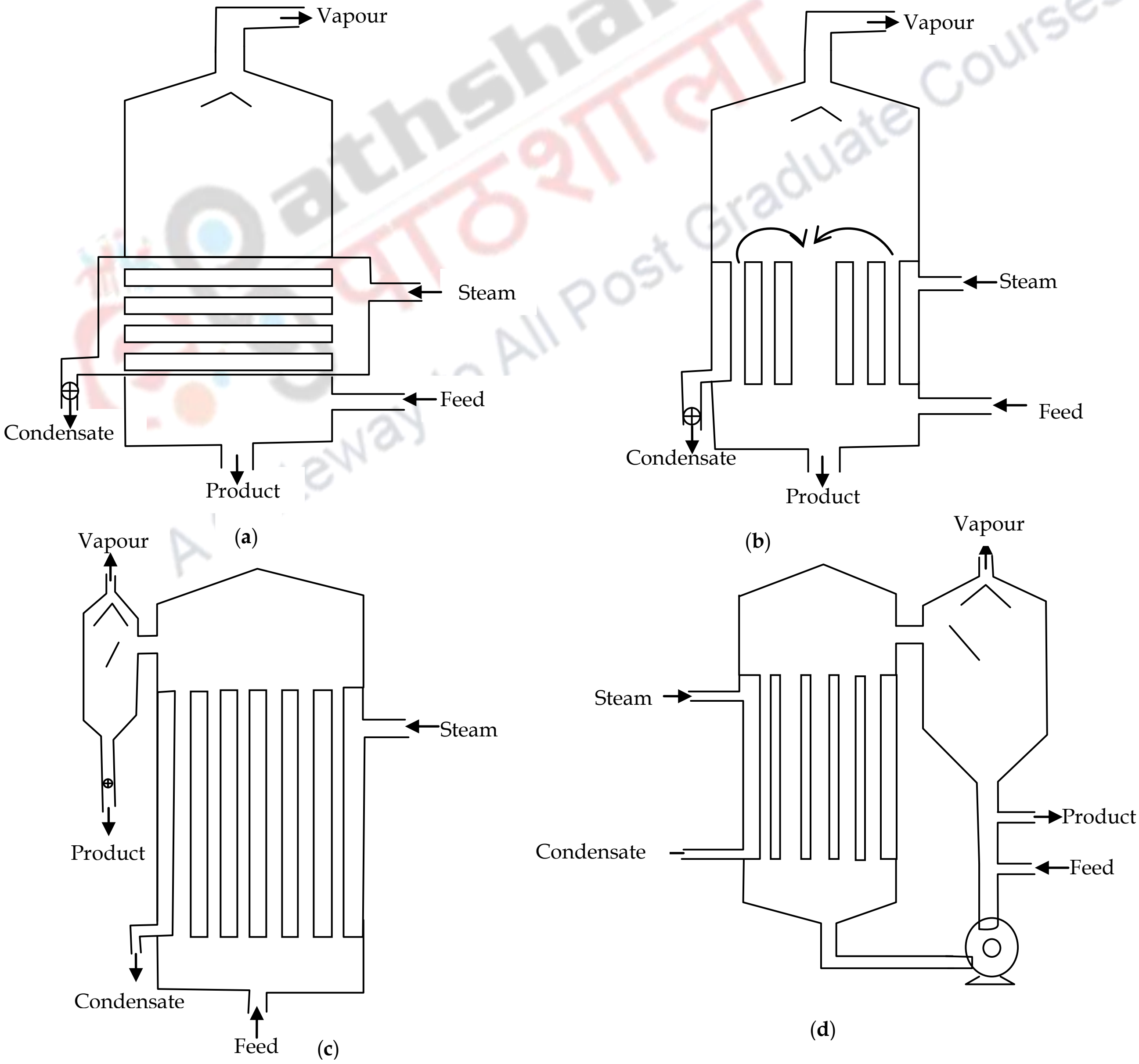


Fig. 14.2: (a) Horizontal short tube; (b) Vertical short tube; (c) Vertical long tube; (d) Forced circulation evaporators

Apart from these types of evaporators, there are other evaporators like scrapped surface, open pan, agitated film evaporators used in food industries. However, the falling film evaporator is most common among all the evaporators.

14.3 Heat transfer calculation in single effect evaporator

The schematic diagram of a single effect evaporator is given in fig.14.3. The feed solution enters the evaporator at the rate of F kg/h, the solute concentration x_f, temperature of feed T_f and enthalpy H_f. The concentrated solution leaves out at the rate of C kg/h at T_c having solute concentration x_c and enthalpy H_c. The rate of vapour removal is V kg/h at vapour condition T_v and H_v. Since the vapour is in pure form the solute concentration x_v is zero. Steam enters the condensation chamber in saturated form at S kg/h which has temperature and enthalpy of T_s and H_s respectively. Since vapour condenses and gives up only the latent heat, condensate leaves at the same rate and temperature, but the enthalpy is reduced to h_s. Since vapour and liquid are in equilibrium state, the temperature inside the evaporator, T_e, T_v and T_c are same. The boiling temperature T_e corresponds to saturation vapour pressure of P_e inside the evaporator.

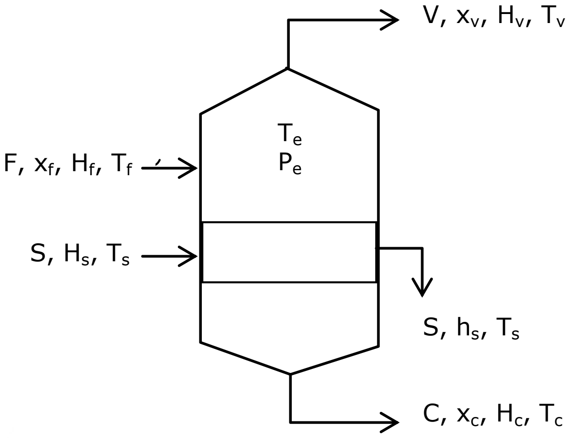


Fig. 14.3 Single effect evaporator with heat and mass flow

Since, the system is in steady state, mass entering is equal to mass leaving.
Total mass balance;

$$\boldsymbol{F = C + V} \quad \dots (14.1)$$

Total solute/solid balance;

$$\boldsymbol{Fx_f = Cx_c + Vx_v} \quad \dots (14.2)$$

Since $\boldsymbol{x_v = 0}$, $\boldsymbol{Fx_f = Cx_c}$ … (14.3)

Total enthalpy balance;

$$heat\ in\ steam + heat\ in\ feed = heat\ in\ product + heat\ in\ vapour + heat\ in\ condensate$$

$$\boldsymbol{FH_f + SH_s = CH_c + VH_v + Sh_s} \quad \dots (14.4)$$

But, Latent heat of condensation, $\boldsymbol{\lambda = H_s - h_s}$ … (14.5)

Substituting Eq.(14.5) into Eq.(14.4), we get

$$\boldsymbol{FH_f + S\lambda = CH_c + VH_v} \quad \dots (14.6)$$

Total heat transferred to the evaporator is $\boldsymbol{S\lambda}$. This total heat transferred must be equal to the heat gain.

$$\boldsymbol{Q = S\lambda = UA(T_S - T_e)} \quad \dots (14.7)$$

Where, U is overall heat transfer coefficient and A is the surface area of heat transfer of evaporator. Once A is determined we can design the evaporator size.
If the heat capacity of feed and product are known, we can find out the enthalpies.

14.4 Economy of evaporator

14.4.1 Steam economy (E_s)

The capacity of evaporator is defined as the amount of vapour evaporated i.e. V kg/h. The steam economy is determined by evaluating how much of steam S kg/h is consumed against V kg/h vapour evaporation.

So, steam economy $\boldsymbol{E_S = \frac{V}{S}}$ …. (14.8)

Steam economy mostly depends on how best we can use the heat in evaporation system. But, in single effect evaporator it is seen that, almost 1 kg steam is required to form 1 kg vapour, i.e. steam economy is one. Maximum heat is lost through the vapour. There are some techniques by which we can improve the economy by utilizing the wasting heat of vapour. They are;

a. Multiple effect evaporator

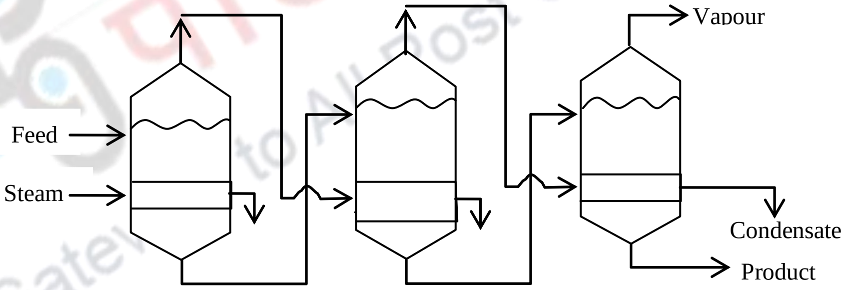
b. Mechanical vapour recompression

c. Thermal vapour recompression

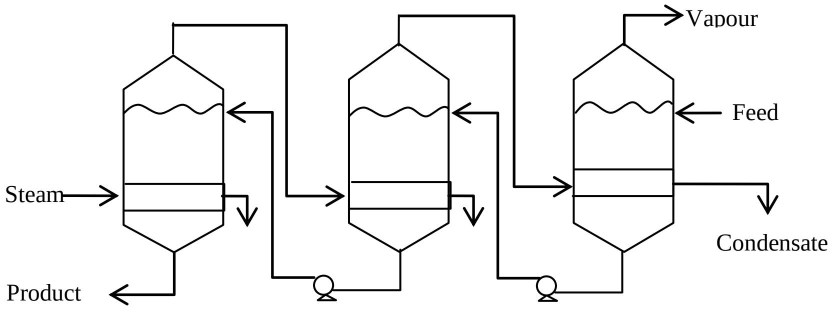
14.4.2 Multiple effect evaporator

It is already been mentioned, the single unit of evaporator is called an ‘effect’. If the evaporator units of identical size are used in series, the evaporation system is called as multiple effect evaporator. The vapour of first effect is used as the heat source in the second effect and the concentrated liquid of first effect is fed to second effect for further concentration. This arrangement is maintained in subsequent effects also. The steam economy is increased as the steam is applied once and vapour formation in all effects is huge. So, overall economy of evaporator is increased. In triple effect evaporator, with the use of 1 kg steam, almost 3 kg vapour is formed, i.e. number of effect we use, same number of vapour evaporated. In food processing industries generally triple effect evaporators are used. Since, the vapour temperature of the first effect is the heating temperature for second effect, the temperature difference between the heating temperature of vapour and boiling temperature of the liquid decreases. To maintain the temperature difference high, the second effect and subsequent effects are operated at vacuum in gradual manner. If we see closely, the advantage of steam economy is overshadowed by the maintenance cost of the additional evaporators.

The multiple effect evaporators are classified according to the direction of feed and steam.



(a)



(b)

Fig.14.4. Schematic diagram of (a) forward feed triple effect evaporator; (b) backward feed triple effect evaporator

a) Forward feed

Fig. 14.4a shows a schematic diagram of forward feed triple effect evaporator. The steam is fed to the first effect, the vapour formed is passed to the calandria of second effect and the vapour formed in the second effect is passed to third effect. The feed solution is fed to first effect, the concentrated solution of first effect is fed to the second effect and the further more concentrated solution of second effect is fed to the third effect. Ultimately, the required concentration product is collected from the third effect and vapour is vented out which is at very low temperature. No pumps are required to move the concentrated liquid from one effect to subsequent effect since product flow from high pressure to low pressure effects. However, a pump is required to feed the liquid to first effect since the first effect is at atmospheric pressure. These types of evaporators are used when the feed temperature is too high to carry over the enthalpy to subsequent effects.

b) Backward feed

In backward feed evaporator the feed is fed from the third effect and the steam is supplied from the first effect in the opposite direction (Fig.14.4b). By doing so, the most concentrated solution is exposed to high temperature in first effect and the dilute solution is exposed to lower temperature in third effect. The more viscous solution when exposed to high heat the flow ability is maintained by decreasing its viscosity, thereby the overall heat transfer is not hampered. One disadvantage of this system is the use of pumps to pass the feed from low pressure to high pressure effects, thus increased cost of system. More viscous products use backward feed evaporators.

c) Mixed feed

In this mixed feed system, the feed is fed from the intermittent effect and passed in the forward direction parallel to the flow of steam. The relatively concentrated solution is then pumped to the left over first few evaporators in the backward flow fashion. The use of some pumps is avoided unlike backward feed evaporators, and at the same time more concentrated product is achieved.

14.4.3 Heat transfer in multiple effect evaporator

The driving force of heat transfer in the evaporator is the temperature difference. In multiple effect evaporator, there must exist some temperature difference in each effect i.e. the boiling temperature of first effect T_1 ^{0}C should be greater than the boiling temperature T_2 ^{0}C and T_3 ^{0}C of second and third effects respectively. The reduced boiling point temperature is achieved with reduction in pressure. Thus, $P_1 > P_2 > P_3$.

Now, if the boiling point rise is negligible, the total temperature drop will be

$$\Delta T_{overall} = T_s - T_v \ \dots (14.9)$$

Where T_s and T_v are the temperatures of saturated steam and the saturated vapour of the last effect. The detailed material balance can be achieved with some assumptions made as follows.

1. The latent heat of evaporation does no change markedly with pressure drop
2. Heat needed to heat up the feed up to boiling temperature is negligible compared to heat required for vapour formation
3. Heat losses and boiling point elevation are negligible.

With these assumptions we can say, the amount of vapour produced in effect are same.

So, $$S = V_1 = V_2 = V_3 \ \dots (14.10)$$

From the eq (14.10) we can conclude that the heat transfer in each effect is same.

$$Q_1 = Q_2 = Q_3 \ldots (14.11)$$

Or, $$U_1A_1(T_s - T_1) = U_2A_2(T_1 - T_2) = U_3A_3(T_2 - T_3) \ \ldots (14.12)$$

The total heat transfe $Q = U_{overall} A \sum \Delta T \ \ldots (14.13)$

Where, $U_{overall} = \frac{1}{1/U_1 + 1/U_2 + 1/U_3} \ \ldots (14.14)$

Let us assume the areas and the overall heat transfer coefficients of all the effect are same.

$$A_1 = A_2 = A_3 \quad \ldots (14.15)$$

$$U_1 = U_2 = U_3 \quad \ldots (14.16)$$

So, the total vapour evaporated from the system is

$$V = \frac{UA(T_s - T_3)}{\lambda} \ \ldots. (14.17)$$

One conclusion we draw from the above relations is that, the single effect evaporator with its overall heat transfer coefficient same as that of multiple effect, the area same as the area of one effect and the temperature difference same as the overall temperature difference of multiple effect will have same capacity Q. Here it is evident that the evaporation capacity is independent of number of effect.

14.4.4 Mechanical Vapour Recompression (MVR) system

The enthalpy of vapour which is generally wasted is reused as steam in the evaporator. The reduced enthalpy of vapour from that of the live steam can be made up by compressing the vapour using a mechanical compressor. The principle of increased enthalpy with pressure is depicted in Mollier diagram. The inevitable loss of vapour is compensated with the supply of same amount of make up live steam to the evaporator. A major disadvantage of MVR system is the handling of large volume of vapour which requires a high capacity compressor. The running cost of compressor must be balanced with the steam economy of the evaporator.

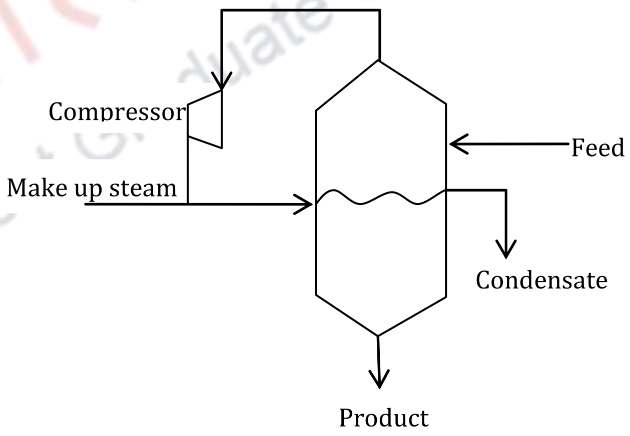


Fig.14.5 Mechanical Vapour Recompression (MVR) system

14.4.5 Thermal Vapour Recompression (TVR) system

In order to avoid the difficulties in handling huge volume of vapour, thermal vapour recompression system is used. A steam jet ejector is the heart of the TVR system. Steam jet ejector is a device in which a high pressure steam passes through a narrow space, thus creates reduced pressure zone by increasing the velocity of steam. The design is similar to a nozzle with converging and diverging sides (Fig.14.6). A part of vapour from the evaporator is allowed to mix with the high pressure steam near the throat of the nozzle at

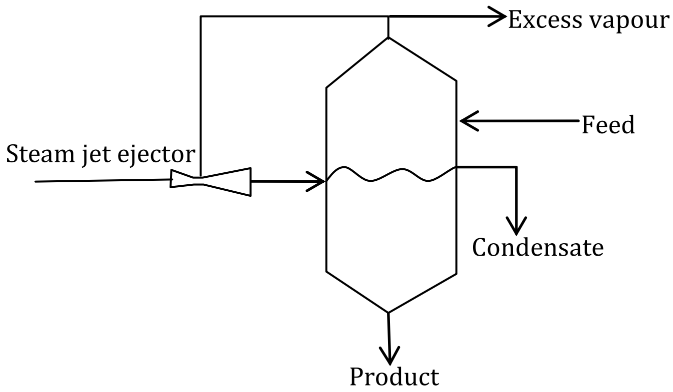


Fig.14.6 Thermal Vapour Recompression (TVR) system

right angle. Due to pressure difference between the evaporator and ejector, vapour is automatically dragged with the high jet steam which is then re-circulated to the evaporator. One advantage of TVR system is that it can handle high volume of vapour without any use of mechanical high friction moving parts. But, some precision should be maintained in the processing conditions like temperature and pressure for greater efficiency.

14.5 Boiling point elevation

Boiling point elevation or boiling point rise of a solution is defined as the increase in boiling point over the boiling point of pure water at a particular pressure.

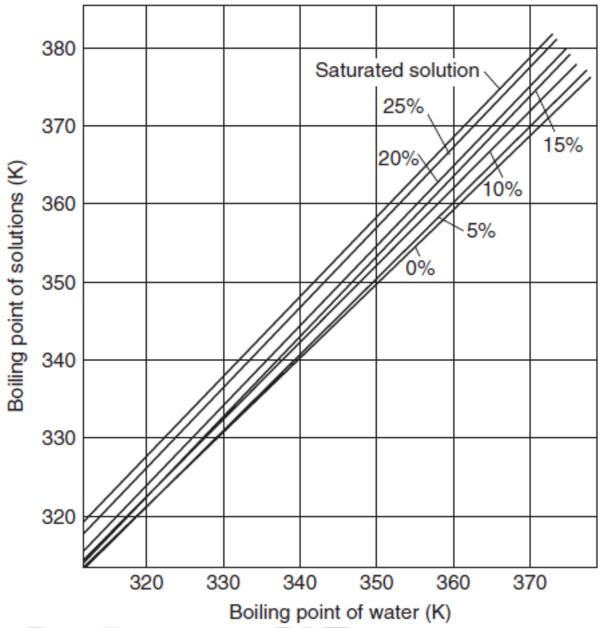


Fig.14.7 Duhring's Chart illustrating the influence of solute concentration on boiling point rise (Courtesy: Elsevier publ.)

Duhring's rule states that a linear relationship exists between the boiling point temperature of solution and the boiling point temperature of pure water at same pressure. This rule is valid in moderate range of temperature. Duhring's chart for sodium chloride solution at different concentration is shown in fig 14.7. From the figure it is concluded that at a particular boiling temperature of water, the boiling point of solution rises with the increased concentration. Say for example, at 0% concentration the salt behaves like water, the boiling points of both are same. Take the boiling temperature of 350 ^{0}K. When the concentration increases to 10%, the boiling point of solution becomes 354 ^{0}K. Hence, the boiling point rise is 4 ^{0}K at 10% salt concentration. Boiling point rise has a detrimental effect on the economy of evaporator as it reduces the temperature difference between the steam and the boiling solution, thus the heat transfer rate decreases.

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