Evaporation

Evaporation is the vaporization of a liquid. Chemical process industries, in general, use evaporator for the vaporization of a solvent from a solution. We have already discussed the heat transfer for boiling liquids in early chapter. However the evaporation is so important operation in chemical process industry that it is considered an individual operation. In this chapter we will focus on the evaporation with an objective to concentrate a solution consisting of a non-volatile solute and a volatile solvent. If we continue the evaporation process, the residual mater will be solid, which is known as drying. However, our aim is not to dry but to concentrate the solution, moreover, we will also not deal with the crystallization, in which the evaporation leads to formation of crystal in the solution. It is suggested that reader should learn the difference between evaporator, drying and crystallization.

As we will deal with the solution for the evaporation process, a few of the facts must be known about the solution properties.

Solution properties

Knowledge of solution properties is important for the design of the equipment for evaporation. Some of the important properties of the solution are given below,

Concentration

Initially, the solution may be quite dilute and the properties of the solution may be taken as the properties of solvent. As the concentration increases, the solution becomes viscous and heat transfer resistance increases. The crystal may grow on the heating coil or on the heating surface. The boiling points of the solution also rise considerably. Solid or solute contact increases and the boiling temperature of the concentrated solution became higher than that of the solvent as the same pressure (i.e. elevation in boiling point).

Foaming

Many of the materials like organic substance may foam during vaporization. If the foam is stable, it may come out along the vapor known as entrainment. Heat transfer coefficient changes abruptly for such systems.

Degradation due to high temperature

The products of many chemical, food, pharmaceutical industries etc. are very temperature sensitive and they may get damaged during evaporation. Thus special case or technique is required for concentrating such solution.

Scaling

Many solution have tendency to deposit the scale on the heating surface, which may increase the heat transfer resistance. These scales produce extra thermal resistance of significant value. Therefore, scaling in the equipment should not be ignored thus de-scaling becomes an important and routine matter.

Equipment material

The material of the equipment must be chosen considering the solution properties so that the solution should neither be contaminated nor react with the equipment material.

Evaporator

Equipment, in which evaporation is performed, is known as evaporator. The evaporators used in chemical process industries are heated by steam and have tubular surface. The solution is circulated in the tube and the tubes are heated by steam. In general the steam is the saturated steam and thus it condenses on the outer tube surface in order to heat the tube. The circulation of the solution in the tube have reasonable velocity in order to increase the heat transfer coefficient and remove of scales on the inner surface of the tube. The steam heated tubular evaporators may be classified as natural and forced circulation evaporators.

Natural circulation evaporator

In this category the main evaporators are,

1. Calandria type or short tube evaporator
2. Long tube vertical evaporator

As the name indicates, the circulation of the solution is natural and the density difference derives it. The solution gets heat up and partially vaporized as it flows up the tubes. The heated liquid flows up because of the density difference. Vapor-liquid disengagement occurs above the tube.

Thick liquor comes down from this down comer and withdrawn from the bottom. The natural-circulation evaporators may be used if the solution is quite dilute. In the dilute solution the natural circulation will be at sufficient speed. It may also be used when the solution does not have suspended solid particles. As the solution stays in the tube for larger time, the solution should not be heat sensitive.

The Calandria type or short-tube evaporators have short tubes as compared to the long tube evaporators. The short-tube evaporation uses circulation and solution flows many times in the evaporators. However, in case of the long tube evaporator the flow is once through.

Forced circulation evaporator

Natural circulation evaporators have many limitations (as mentioned earlier) through they are economical as compared to forced circulation evaporator. A forced circulation evaporator has a tubular exchanger for heating the solution without boiling. The superheated solution flashes in the chamber, where the solution gets concentrated. In forced circulation evaporator horizontal or vertical both type of design is in- practice. The forced circulation evaporators are used for handling viscous or heat sensitive solution.

Falling film evaporator

Highly heat sensitive materials are processed in falling film evaporators. They are generally once-through evaporator, in which the liquid enters at the top, flows downstream inside the heater tubes as a film and leaves from the bottom. The tubes are heated by condensing steam over the tube. As the liquid flows down, the water evaporates and the liquid gets concentrated. To have a film inside of the tube, the tube diameter is kept high whereas the height low to keep the residence time low for the flowing liquid. Therefore, these evaporators, with non-circulation and short resistance time, handle heat sensitive material, which are very difficult to process by other method. The main problem in falling film evaporator is the distribution of the liquid uniformly as a thin film inside the tube.

Performance of steam heated tubular evaporators

The performance of a steam heated tubular evaporator is evaluated by the capacity and the economy.

Capacity and economy

Capacity is defined as the no of kilograms of water vaporized per hour. Economy is the number

of kg of water vaporized per kg of steam fed to the unit. Steam consumption is very important to know, and can be estimated by the ratio of capacity divided by the economy. That is the steam consumption (in kg/h) is

Steam Consumption = Capacity / Economy

Single and multiple effect evaporators

In single effect evaporator, as shown in fig.1, the steam is fed to the evaporator which condenses on the tube surface and the heat is transferred to the solution. The saturated vapor comes out from the evaporator and this vapor either may be vented out or condensed. The concentrated solution is taken out from the evaporator.

Now we can see if we want the further concentrate, the solution has to be sent into another similar evaporator which will have the fresh steam to provide the necessary heat.

It may be noted that in this process the fresh steam is required for the second evaporator and at the same time the vapor is not utilized. Therefore it can be said the single effect evaporator does not utilized the steam efficiently. The economy of the single effect evaporator is thus less than one. Moreover, the other reason for low economy is that in many of the cases the feed temperature remains below the boiling temperature of the solution. Therefore, a part of the heat is utilized to raise the feed temperature to its boiling point.
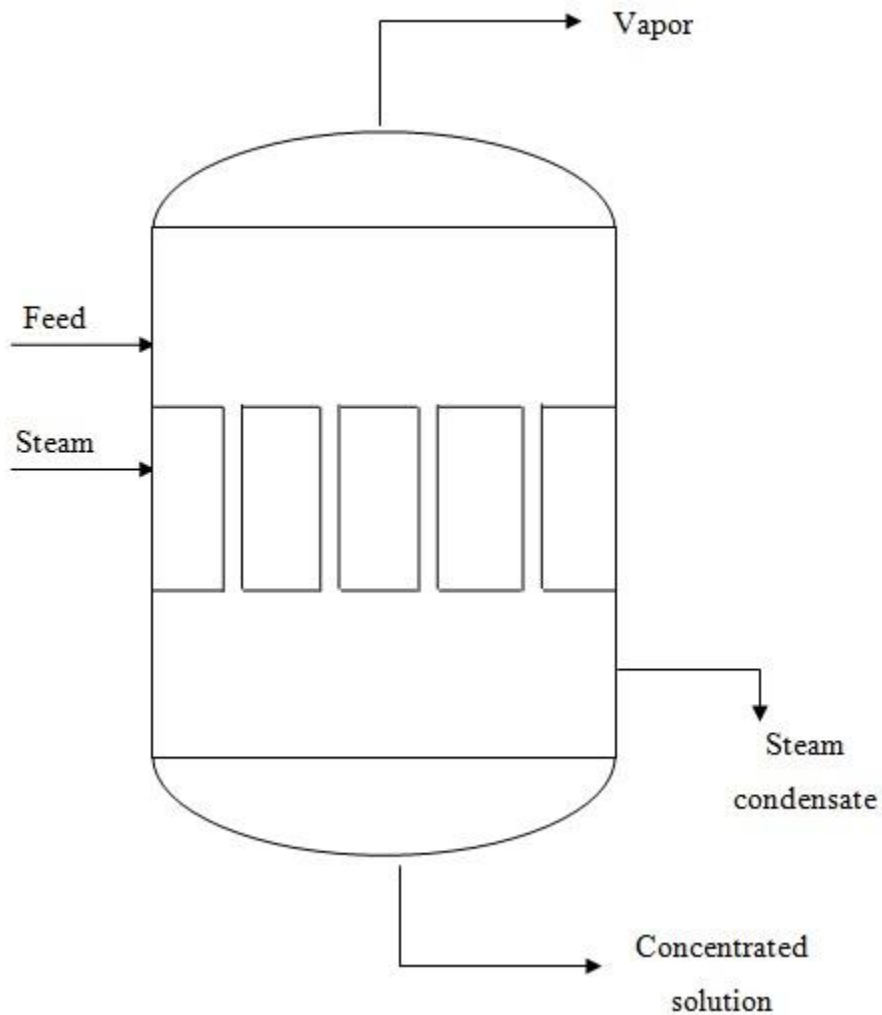
Fig.1: Single effect evaporator

In order to increase the economy we may consider the arrangement of the two evaporators as shown in the fig.2.

The figure 2 shows that the two evaporators are connected in series. The saturated vapor coming out from the evaporator-1 is used as steam in the second evaporator. Partially concentrated solution works as a feed to the second evaporator. This arrangement is known as double effect evaporator in forward feed scheme. A few of the important point that we have to note for this scheme is that the vapour leaving evaporator-2 is at the boiling temperature of the liquid leaving the first effect. In order to transfer this heat from the condensing vapor from the evaporator-1 to the boiling liquid in evaporator-2, the liquid in evaporator-2 must boil at a temperature

considerable less than the condensation temperature of the vaporization, in order to ensure reasonable driving force for heat transfer. A method of achieving this is to maintain a suitable lower pressure in the second effect so that the liquid boils at a lower temperature. Therefore, if the evaporator-1 operates at atmospheric pressure, the evaporator-2 should be operated at same suitable vacuum.
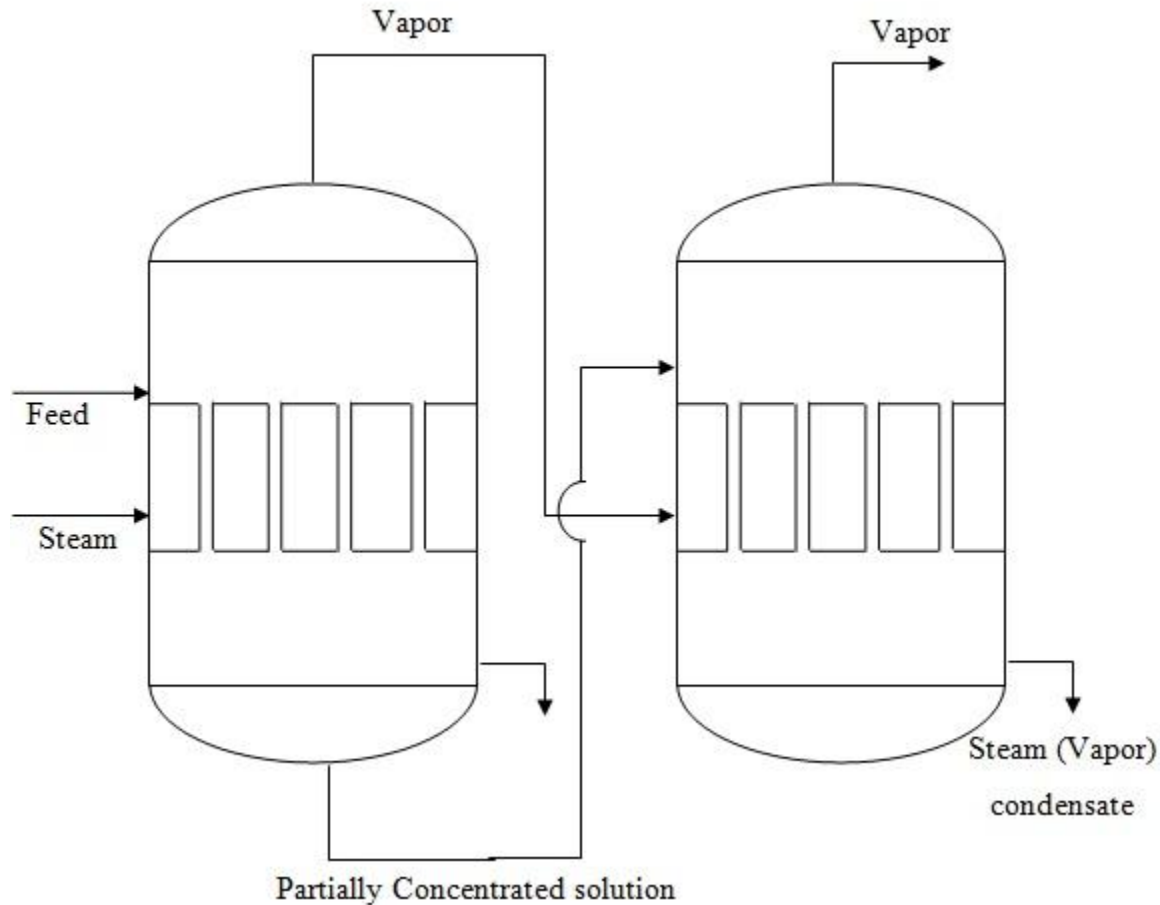

Fig.2: Double effect evaporator with forward feed scheme

The benefit of the use of multiple effect evaporators is that in this arrangement multiple reuse of heat supplied to the first effect is possible and results in improved steam economy.

Boiling point elevation

The evaporators produce concentrated solution having substantially higher boiling point than that of the solvent (of the solution) at the prevailing pressure. The increase in boiling point over that

of water is known as boiling point elevation (BPE) of the solution. As the concentration increases the boiling point of the solution also increases. Therefore, in order to get the real temperature difference (or driving force) between the steam temperature and the solution temperature, the BPE must be subtracted from the temperature drop. The BPE may be predicted from the steam table (in case water is a solvent).

An empirical rule known as Dühring rule is suitable for estimating the BPE of strong solution. The Dühring rule states that the boiling point of a given solution is a linear function of the boiling point of the pure water at the same pressure. Therefore, if the boiling point of the solution is plotted against that of the water at the same pressure, a straight line results. Different lines are obtained at different concentrations. The fig.3 shows representative Dühring plots for a solution (non-volatile solute in water).
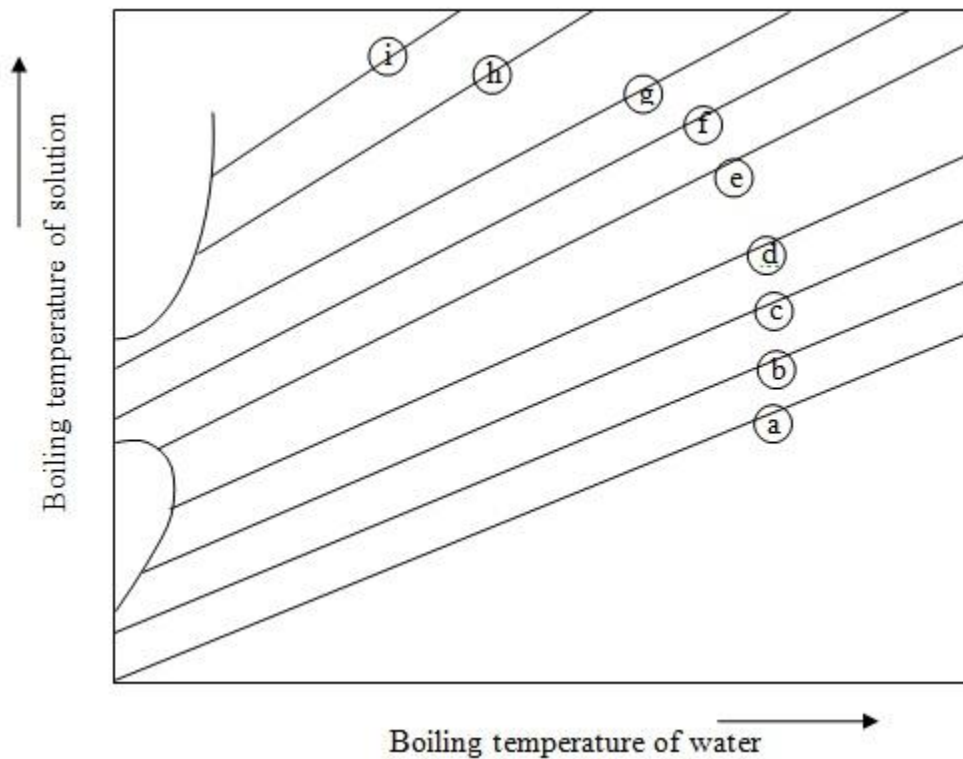

Fig.3: Representative Dühring lines for a system (non-volatile solute in water) mole fraction of solute in the solution (a) 0.1 (b) 0.2 (c) 0.25 (d) 0.39 (e) 0.35 (f) 0.45 (g) 0.5 (h) 0.6 (i) 0.7

The fig.3 helps to find out the boiling point of solution at moderate pressure. For example if a solution having 'x' mole fractions of solute have a pressure over it such that water boils at T° C, by reading up from the x-axis at T °C to the line for the x mole fraction solution and then moving horizontally to the y-axis, the boiling point of the solution can be found at that pressure.

Temperature profile in an evaporator

Let us consider the case of long-tube vertical evaporator heated by steam. After boiling and flashing of the superheated liquid, the disengagement of the vapor and liquid occur in vapor space of the evaporator and the recycled liquid flows down the external pipe. A part of this concentrated liquid is withdrawn as a product and the remaining part get mixed with a feed and again enter the evaporator tube. If T_{BP} is the boiling of the liquid in the evaporator as the prevailing pressure, then the temperature of the liquid in the tube will be T_{BP}. The temperature of the recycled stream entering the tubes will then also be T_{BP}, if the feed is sufficiently hot. Now, we will imagine how the temperature is changing in the tube. Let us see that when the liquid flows up in the tube, its temperature rises because at the bottom of the tube the pressure is higher (vapor chamber pressure + hydrostatic pressure + frictional loss) as compared to the top of the tube. Therefore, a liquid starts boiling at a level when its temperature rises to its saturation temperature at the pressure at that point. After the boiling in between the tube, as liquid goes up in the tube, the local temperature drops because of the reduction in the local pressure. It may also be mentioned that as the liquid moves up it gets concentrated and thus the boiling point of the solution also increases as the liquid traversed up in the tube. The liquid temperature profile in the tube is shown in the fig.4 for low (plot i) and high (plot ii) liquid velocity. The liquid temperature in the tubes increases up to certain height and then the temperature decreases due to the loss of superheat. At higher velocity the temperature raise is less and the liquid boils near the top of the tube. The plot (iii) shows the shell side temperature profile where steam is heating the tube. As can be seen, the slightly superheated steam enters the shell and soon the temperature of the steam losses its sensible heat and then condenses on the tubes and provide the latent heat of condensation (at temperature T_{steam}) to the tube and before boiling from the shell may get slightly sub-cooled. The plot (iv) is the boiling temperature of the water (T_w) at the pressure in the vapor chamber. Thus, the BPE=T_{BP}-T_w and the true temperature during force is the difference between the plot (iii) and the plot (i) or (ii).

It can be understood with the help of the discussion and fig.4 that the temperature changes all along the length of the tube. Thus, the real temperature driving force will be the difference in steam temperature and liquid temperature always the high. However, it is practically not easy to determine the temperature profile in the tube. Therefore, the driving force can be taken as $(T_{steam} - T_{BP})$ for the design purpose.

Heat transfer coefficient

The correlation used in the boiling and condensation may be used here. If the evaporator operates at very high liquid velocity so that the boiling occurs at the top end of the tube, the following correlation (eq. 9.1) may be used,

$$\frac{h_i D}{k} = 0.0278 Re^{0.8} Pr^{0.4}$$

where, D is the inner diameter of the tube, k is the thermal conductivity of the liquid or solution.
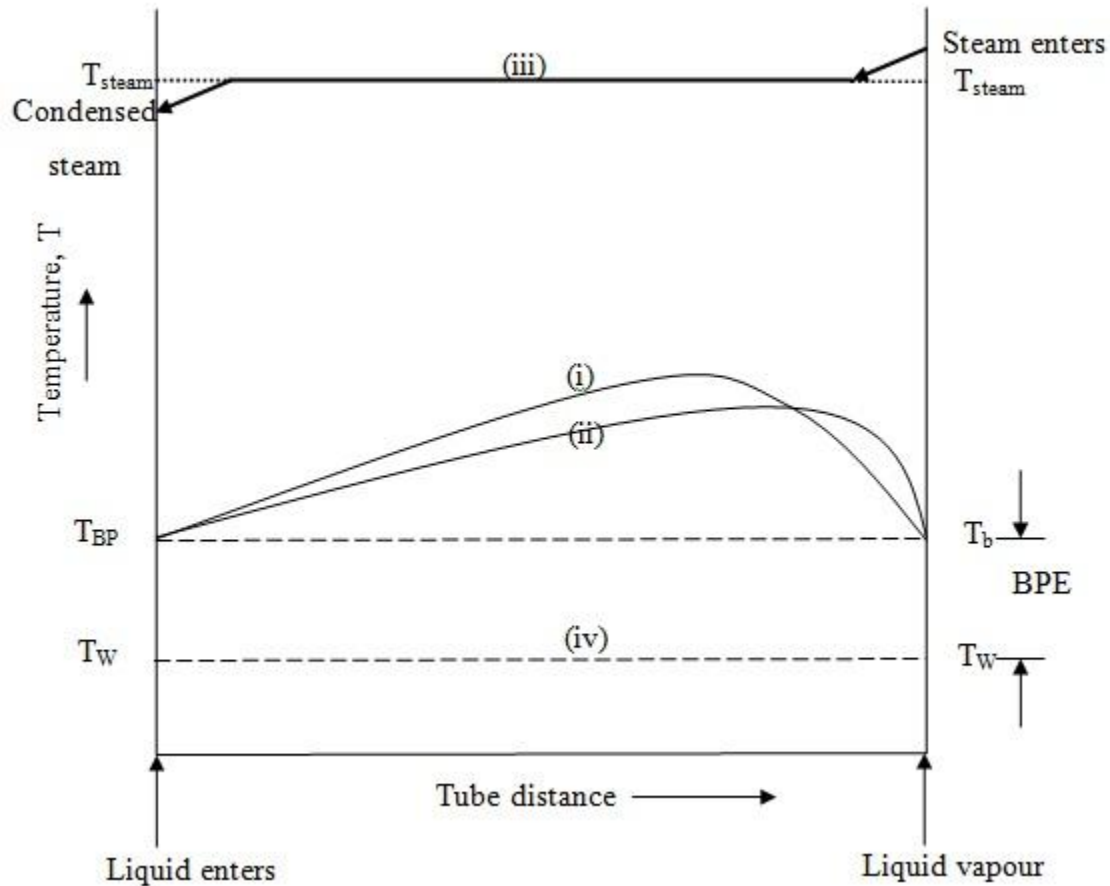
Fig.4: Temperature profiles in an evaporator

Fouling is a concern in the evaporator; therefore the following equation (eq.9.2) may be used for the overall heat transfer coefficient with time,

$$\frac{1}{U_{dirty}^2} = \frac{1}{U_{clean}^2} + \alpha t \qquad (9.2)$$

where, t is the time for where the evaporator is the operation, α is a constant for a particular liquid, U_{dirty} and U_{clean} all the overall heat transfer coefficient of the dirty and clean evaporator.

Method of feeding: Multiple effect evaporators

The fig.5, 6, 7, and 8 show the four different feeding arrangement of feed to the evaporators. In the fig.5 the liquid feed is pumped into the first effect and the partially concentrated solution is

sent to the second effect and so on. The heating steam is also sent through the first effect to another effect. This particular strategy is known as forward feed. In the forward feed the concentration of the liquid increases from first effect to the subsequent effects till the last effect. It may be noted that the first effect is that in which the fresh steam is fed, whereas the vapour generated in the first effect is fed to the next evaporator (connected in series with the first effect) is known as second effect and so on.

The forward feed requires a pump for feeding dilute solution to the first effect. The first effect is generally at atmospheric pressure and the subsequent effects are in decreasing pressure. Thus, the liquid may move without the pump from one effect to another effect in the direction of decreasing pressure. However, to take out the concentrated liquid from the last effect may need a pump.

The backward feed arrangement is very common arrangement. A triple-effect evaporator in backward arrangement is shown in the fig.6. In this arrangement the dilute liquid is fed to the last effect and then pumped through the successive effects to the first effect. The method requires additional pumps (generally one pump in between two effects) as shown in the fig.6. Backward feed is advantageous and gives higher capacity than the forward feed when the concentrated liquid is viscous, because the viscous fluid is at higher temperature being in the first effect. However, this arrangement provides lower economy as compared to forward feed arrangement.

The combination of forward-feed and backward-feed is known as mixed feed arrangement. In mixed feed the dilute liquid enters in between effects, flows in forward feed to the end of the effect and then pumped back to the first effect for final concentration. Figure 7 shows triple effect mixed feed arrangement. This mixed feed arrangement eliminates the need of a few of the pumps. Moreover, it still passes the most concentrated liquid through the first effect, which is having higher temperature among all the effect (being at highest pressure compared to other effects).

Another common evaporator arrangements, which is more common in crystallization is parallel feed where feed is admitted individually to all the effects. Figure 7 shows such arrangement.
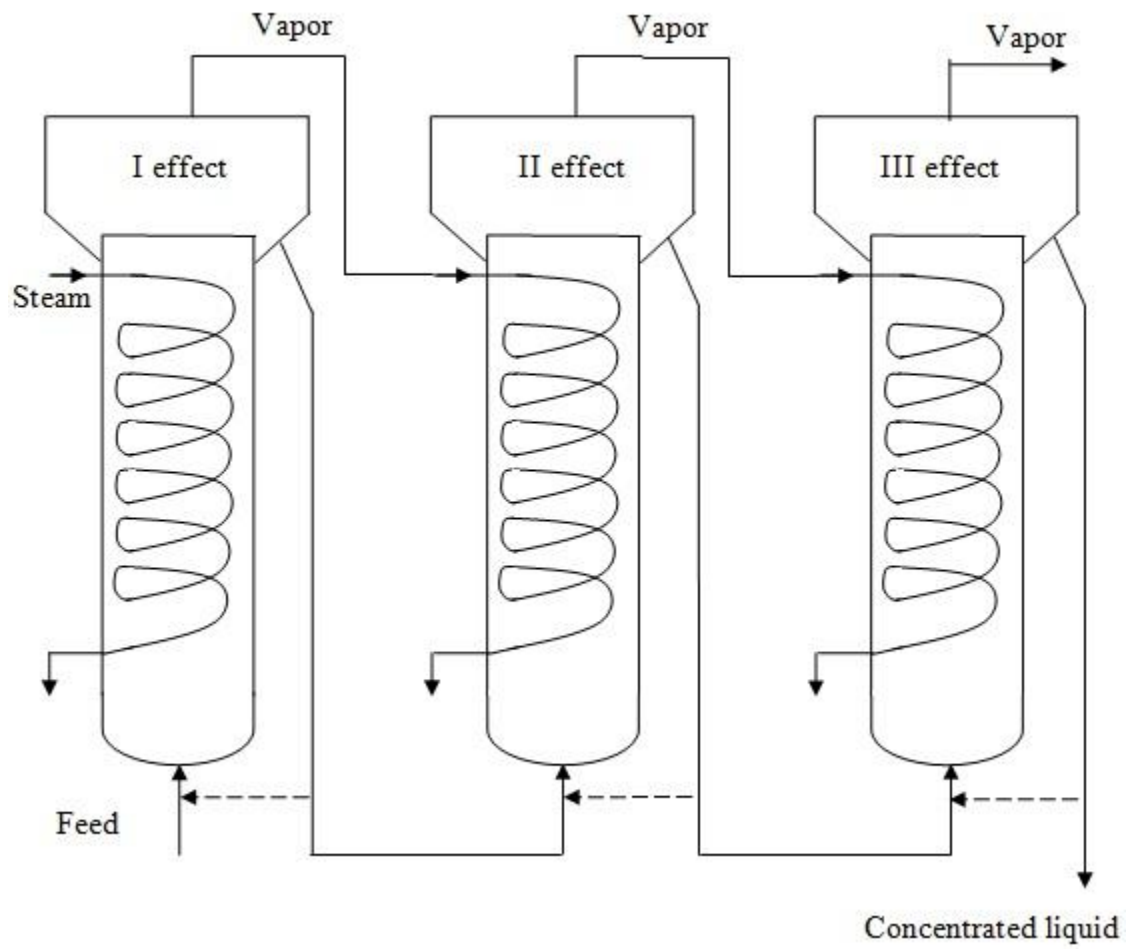
Fig.5: Forward feed arrangement in triple-effect evaporator (dotted line: recycle stream)
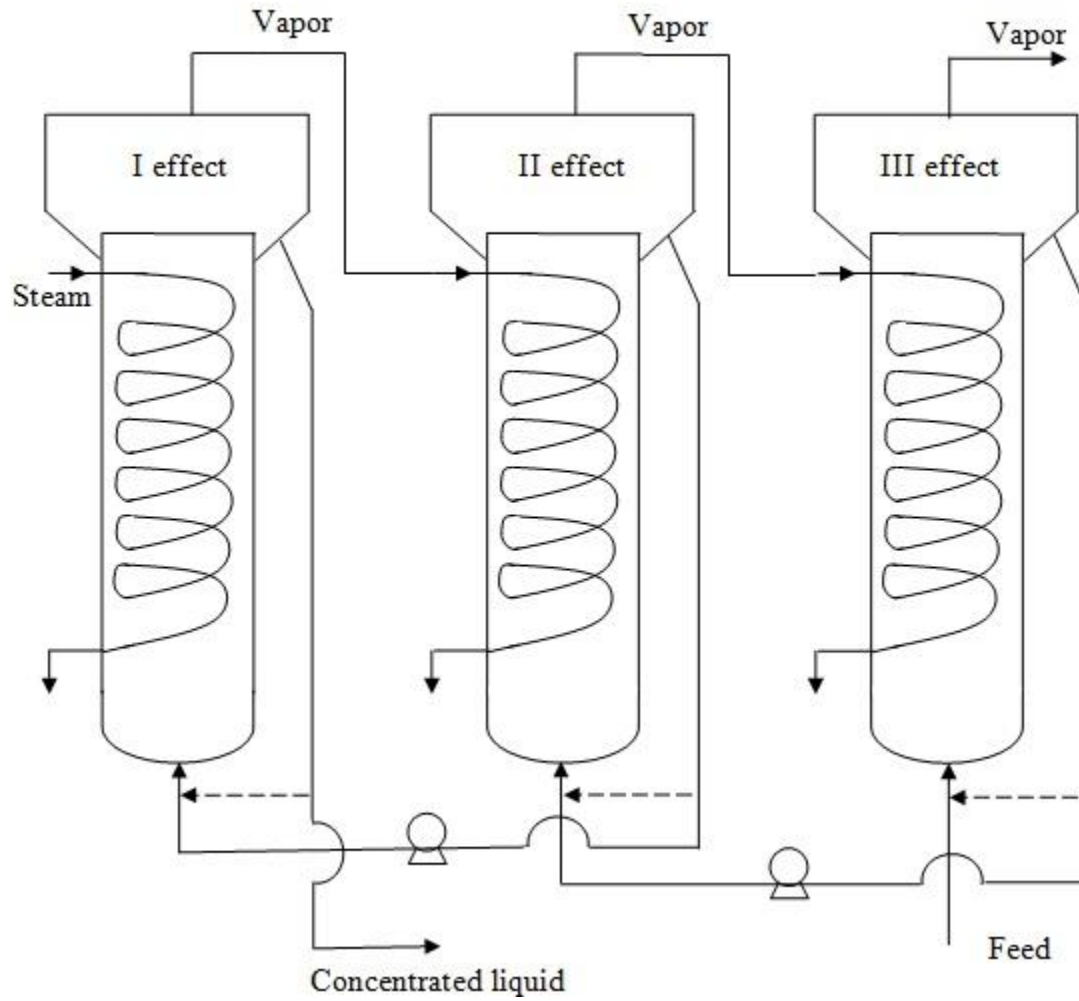
Fig.6: Backward feed arrangement in triple-effect evaporator (dotted line: recycle stream)
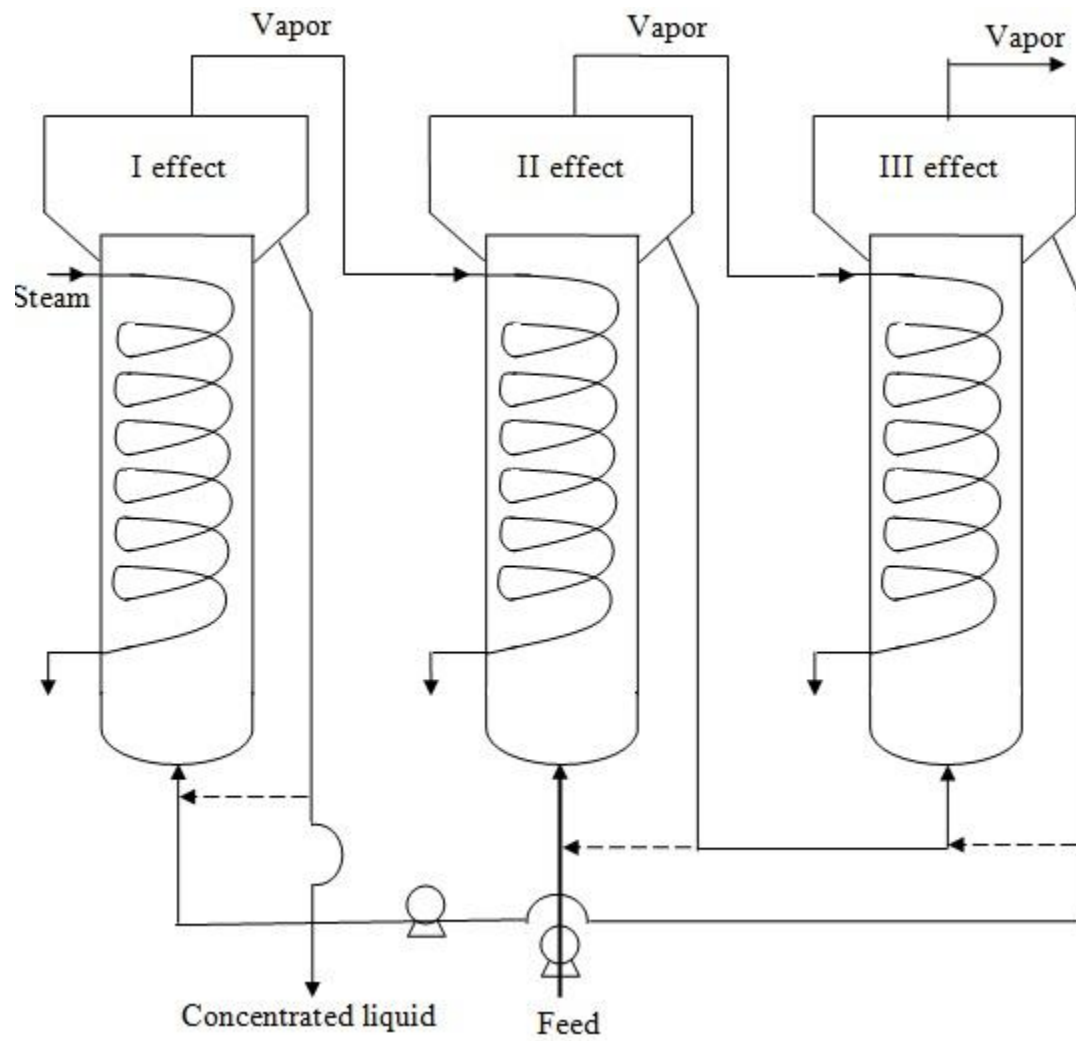
Fig.7: Mixed feed arrangement in triple-effect evaporator (dotted line: recycle stream)
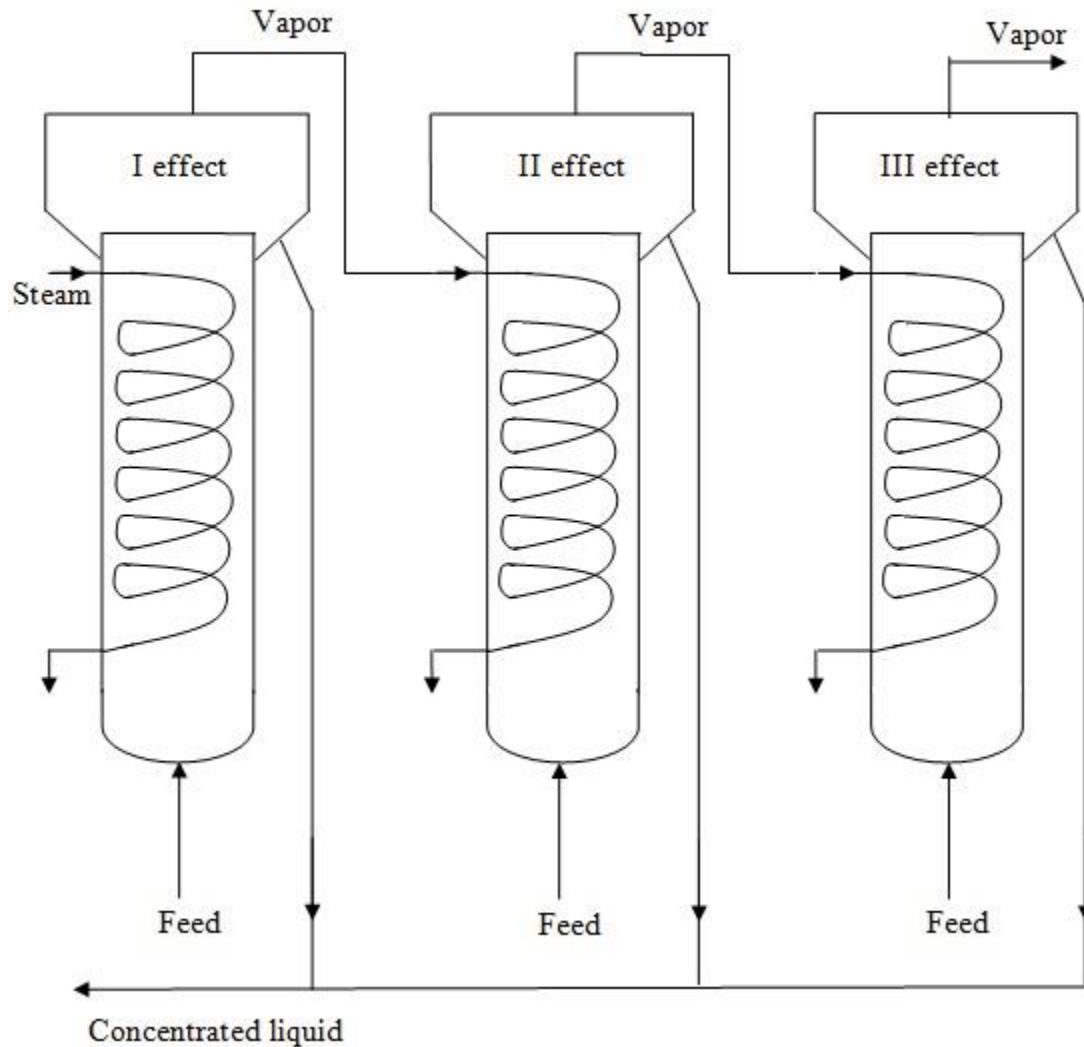
Fig.8: Parallel feed arrangement in triple-effect evaporator

Enthalpy Balance

Single effect evaporator

The latent heat of condensation of the steam is transferred to the boiling solution through the heating surface in order to vaporize the water. Thus, two enthalpy balances are required one for the liquid and another for the steam.

The following assumptions are required, in order to make the enthalpy balance,

1. Flow of non-condensable is negligible
2. The superheat and sub-cooling (see fig.4) of the condensable steam is negligible

3. No solid precipitates out from the concentrating solution

The enthalpy balance for the steam side is,

$$\dot{q}_s = \dot{m}_s(h_s - h_c) = \dot{m}_s \lambda_s$$

Where,

$\dot{q}_s=$ rate of heat transfer through heating surface from steam

$\dot{m}_s=$ flow rate of steam

λ_s = latent heat of condensation of steam

h_s = specific enthalpy of steam

h_c = specific enthalpy of condensate

Enthalpy balance for the liquid side is (eq.9.3),

$$\dot{q}_l = (\dot{m}_{fl} - \dot{m}_{cl})h_v - \dot{m}_{fl}h_{fl} + \dot{m}_{cl}h_{cl} \qquad\qquad (9.3)$$

Where,

$\dot{q}_l=$ rate of heat transfer from heating surface to the liquid

h_v = specific enthalpy of vapour

h_{cl} = specific enthalpy of concentrated liquid

h_{fl} = specific enthalpy of liquid feed

$\dot{m}_{fl}=$ flow rate of liquid feed

$\dot{m}_{cl}=$ flow rate of concentrated liquid

The enthalpy balance at steam side and liquid side will be same in the absence of any heat loss (eq.9.4). Thus,

$$(\dot{m}_{fl} - \dot{m}_{cl})h_v - \dot{m}_{fl}h_{fl} + \dot{m}_{cl}h_{cl} = \dot{m}_s \lambda_s \qquad\qquad (9.4)$$

The area of heat transfer A can be calculated from

$$\dot{q}_l = \dot{q}_s = U_D A \Delta T$$

When $\Delta T = (T_b - T_c)$;

T_b = Saturated temperature of steam in the shell

T_s = Boiling point of the solution at the prevailing pressure

U_D = Overall coefficient (dirty)

Effect of heat of dilution

Most of the solutions when mixed or diluted at constant temperature do not give significant heat effect. It is generally true for organic solutions (like sugar). However, many of the inorganic solutions (like sulfuric acid, potassium hydroxide, calcium carbonate etc.) evolve significant heat on dilution. Therefore, an equivalent amount of heat is required (in addition to the latent heat of vaporization), when dilute solutions of these inorganic chemicals are concentrated. Enthalpy-concentration diagram are helpful in order to find the enthalpy of the solution at different concentration of these chemicals in the solution.

Multiple effect evaporators

The steam goes into I-effect and heat the solution by the latent heat of condensation. If the heat required to boil the feed is negligible, it follows that practically all this heat

$$\dot{q}_s = A_1 U_1 \Delta T_1$$

must appear as latent heat in the vapor that leaves the I-effect and enter into II-effect as steam. The temperature of the condensate leaving the II-effect will be very near the temperature T_1 of the vapors from the boiling liquid in the I-effect. Thus, in steady state operation all the heat that was expanded in creating vapor in the I-effect must be given by when this same vapor condenses in the II-effect and so on.

The heat delivered into the II-effect will be,

$$\dot{q}_{v1} = A_2 U_2 \Delta T_2$$

The $\dot{q}_{v1} = \dot{q}_s$

Similarly, for III-effect

$$A_1 U_1 \Delta T_1 = A_2 U_2 \Delta T_2 = A_3 U_3 \Delta T_3 = \dot{q} \qquad (9.5)$$

It can be seen (eq. 9.5) that the temperature drops in a multiple effect evaporator is approximately inversely proportional to the heat-transfer coefficient.

The total available temperature drop will be given by eq.9.6,

$$\sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 \qquad (9.6)$$

$$= (T_s + T_{v3}) - \Sigma BPE$$

where,

T_s : Steam temp. (I-effect);

T_{v3} : Vapor temperature leaving III-effect

BPE : boiling point elevation in the solution in various effects

Problems:

1. A triple effect forward feed evaporator is used to concentrate a liquid which has marginal elevation in boiling point. The temperature of the stream to the first effect is 105°C, and the boiling point of the solution within third effect is 45°C. The overall heat transfer coefficients are, 2,200 W/m²: in the I-effect, 1,800 W/m²: in the II-effect and 1,500 W/m²: in the III-effect.

Find out at what temperatures the fluid boils in the I and II effects.

Solution:

Assumptions

1. We may assume that there is no elevation in boiling point in the evaporators.

2. Area of all the three evaporators are same $(A_I = A_{II} = A_{III} = A)$

Total temperature drop=(105-45)°C = 60 °C

the temperature drop across I-effect,

$$\Delta T_I = \frac{\frac{1}{2200}}{\frac{1}{2200} + \frac{1}{1800} + \frac{1}{1500}} \times 56 = 15.2\,°C$$

Similarly, the temperature drop across II-effect,

$$\Delta T_{II} = \frac{\frac{1}{1800}}{\frac{1}{2200} + \frac{1}{1800} + \frac{1}{1500}} \times 56 = 18.6\,°C$$

And the temperature drop across III-effect,

$$\Delta T_{III} = \frac{\frac{1}{1500}}{\frac{1}{2200} + \frac{1}{1800} + \frac{1}{1500}} \times 56 = 22.3\,°C$$

Therefore, the boiling point in the first effect will be = (105 − 15.2) °C = 89.8 °C

Similarly, the boiling point in the second effect will be = (89.8 − 18.6)°C = 71.2 °C.