Module V

EVAPORATION

Course material Adapted from:

1. Warren. L, McCabe, Julian ,C. Smith and Peter Harriott, "Unit Operations of Chemical Engineering", 7th Edn., McGraw Hill International Edition, NewYork 2005.

2. Holman. J.P., "Heat Transfer" , 9th Edn., Tata McGraw Hill Book Co., New Delhi, 2008.

3. R.C.Sachdeva, "Fundamentals of Engineering Heat and Mass Transfer",

4th Edition,New Age International Publishers,2010

4. http://nptel.ac.in/courses/103103032/- Dr. Anil Verma Dept. of Chemical Engineering,IIT Guwahati 5. www.che.utexas.edu/course/che360/lecture_notes/chapter_2.ppt

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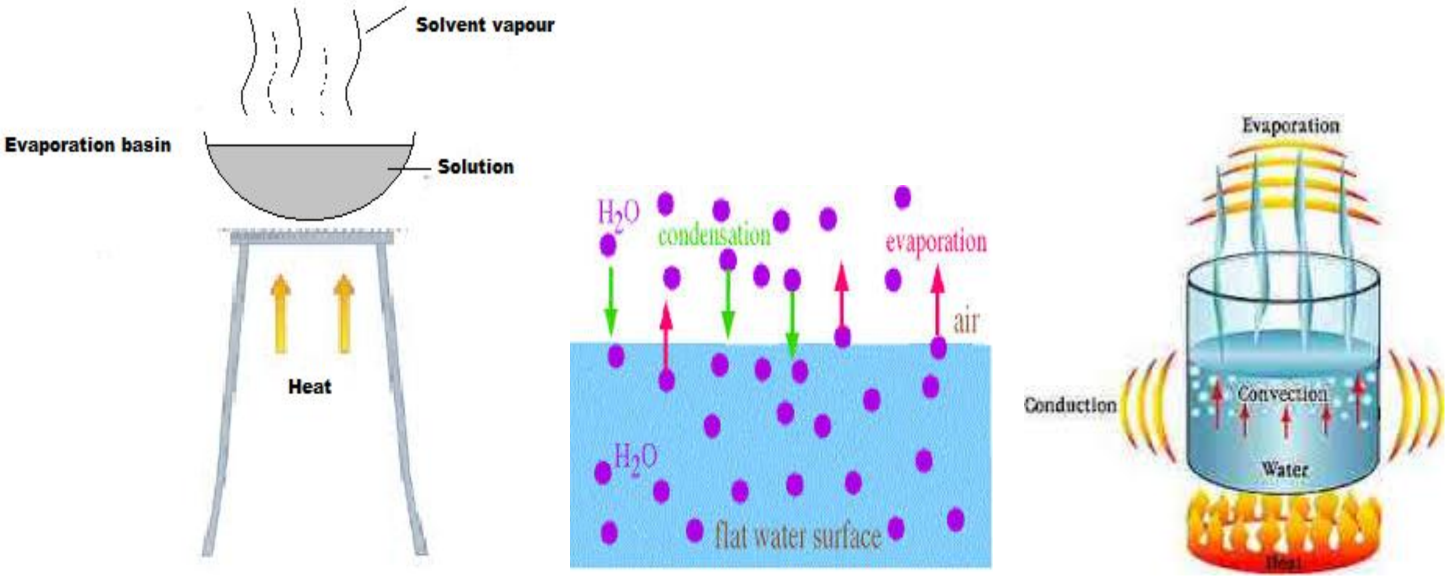
Introduction, single- and multiple- effect operation, long tube vertical evaporators, agitated-film evaporators, evaporator capacity, BPE and Duhring's rule, evaporator economy, enthalpy balances for single effect evaporator. Multiple effect evaporators, methods of feeding, capacity and economy of multiple effect evaporators, multiple effect calculations

Introduction

The objective of evaporation is to concentrate a solution consisting of a nonvolatile solute and a volatile solvent. Evaporation is conducted by vaporizing a portion of the solvent to produce a concentrated solution of thick liquor. Evaporation differs from drying in that the residue is a liquid, sometimes a highly viscous one rather than a solid. It differs from distillation in that the vapor usually is a single component, and even when the vapour is a mixture no attempt is made in the evaporation step to separate the vapour into fractions. It differs from crystallization in that emphasis is placed on concentrating a solution rather than forming and building crystals.



(a) (b (c)

Fig.1.(a),(b)& (c).Evaporation

Normally, in evaporation the thick liquor is the valuable product and the vapour is condensed and discarded. In one specific situation, however, the reverse is true. Mineral bearing water often is evaporated to give a solid free product for boiler feed for special process requirements or for human consumption. This technique is often called water distillation, but technically it is evaporation. Large scale evaporation processes have been developed and used for recovering potable water from seawater. Here the condensed water is the desired product. Only fraction of the total water in the feed is recovered, and the remainder is returned to the sea.

5.1. Liquid characteristics: The practical solution of an evaporation problem is profoundly affected by the character of the liquor to be concentrated. It is the wide variation in liquor characteristics (which demands judgment and experience in designing and operating evaporators)that broadens this operation from simple heat transfer to a separate art. Some of the most important properties of evaporating liquids are as follows:

5.1.1.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).

5.1.2.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.

5.1.3. 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.

5.1.4.Scaling

Many solutions 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.

5.1.5. 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.

5.2.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 has reasonable velocity in order to increase the heat transfer coefficient and removal of scales on the inner surface of the tube. The steam heated tubular evaporators may be classified as natural and forced circulation evaporators.

5.2.1.Single effect and multiple effect evaporation

When a single evaporator is used, the vapour from the boiling liquid is condensed and discarded. This method is called single-effect evaporation, and although it is simple, it utilizes steam ineffectively. To evaporate 1 kg of water from a solution calls for from 1 to 1.3 kg of steam. If the vapour from one evaporator is fed into the steam chest of a second evaporator and the vapour from the second is then sent to a condenser, the operation becomes double effect. The heat in the original steam is reused in the second effect, and the evaporation achieved by a unit mass of steam fed to the first effect is approximately doubled. Additional effects can be added in the same manner. The general method of increasing the evaporation per kg of steam by using a series of evaporators between the steam supply and the condenser is called multiple effect evaporation.

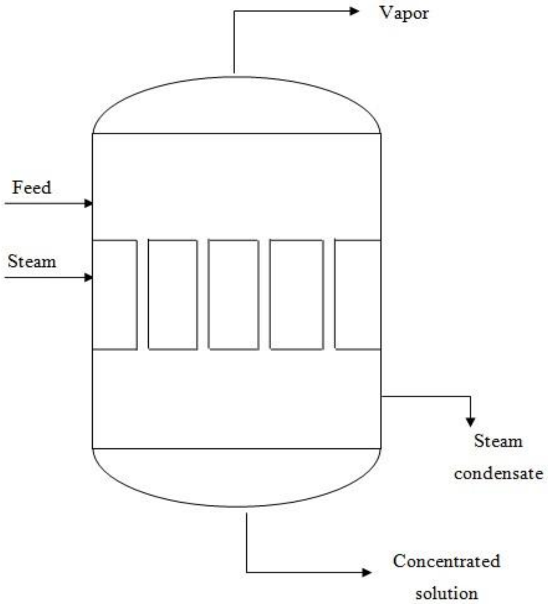


Fig.5.2.Single Effect Evaporation

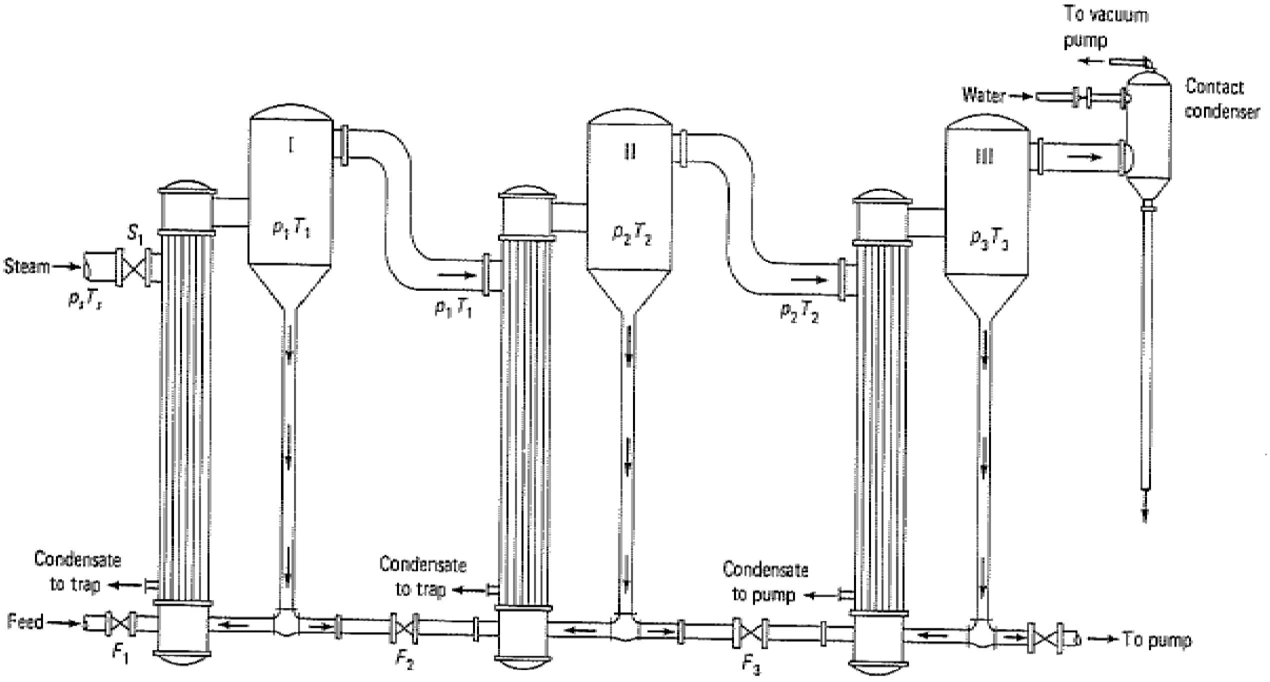


Fig. 5.3. Multiple effect evaporation

5.3. 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 number 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

5.4. Types of evaporators

The chief types of steam heated tubular evaporators are

1.Long tube vertical evaporators

(i)upward flow (climbing film)

(ii)Downward flow(falling flow)

(iii) Forced circulation

2. Agitated film evaporators

Based on method of operation evaporators can also be classified as
(i)Single effect evaporators (ii)multiple effect evaporators

5.4.1. Once through and circulation evaporators

Evaporators may be operated either as once through or as circulation units. In once through operation the feed liquor passes through the tubes only once, releases the vapour, and leaves the unit as thick liquor. All the evaporation is accomplished in a single pass. The ratio of evaporation to feed is limited in single pass units, thus the evaporators are well adapted to multiple effect operation, where the total amount of concentration can be spread over several effects. Agitated film evaporators are always operated once through; falling film and climbing film evaporators can also be operated in this way.

Once through evaporators are especially useful for heat sensitive materials. By operating under high vacuum, the temperature of the liquid can be kept low. With a single rapid passage through the tubes the thick liquor is at the evaporation temperature but a short time and can be quickly cooled as soon as it leaves the evaporator.

In circulation evaporators a pool of liquid is held within the equipment. Incoming feed mixes with the liquid from the pool, and the mixture passes through the tubes. Unevaporated liquid discharged from the tubes returns to the pool, so that only part of the total evaporation occurs in one pass. All forced circulation evaporators are operated in this way. Climbing film evaporators are usually circulation units.

The thick liquor from a circulation evaporator is withdrawn from the pool. All the liquor in the pool must therefore be at the maximum concentration. Since the liquid entering the tubes may contain several parts of thick liquor for each part of feed, its viscosity is high and the heat transfer coefficient tends to be low.

Circulation evaporators are not well suited to concentrating heat sensitive liquids. With a reasonably good vacuum the temperature of the bulk of the liquid may be nondestructive, but the liquid is repeatedly exposed to contact with hot tubes. Some of the liquid, therefore, may be heated to an excessively high temperature. Although the average residence time of the liquid in the heating zone may be short, part of the liquid is retained in the evaporator for considerable time. Prolonged heating of even a small part of a heat sensitive material like a food can ruin the entire product.

Circulation evaporators, can operate over a wide range of concentration between feed and thick liquor in a single unit, and are well adapted to single effect evaporation. They may operate either with natural circulation , with the flow through the tubes induced by density difference, or with forced circulation with flow provided by a pump.

5.4.2. Climbing film long tube vertical evaporator

A typical long tube vertical evaporator with upward flow of the liquid is shown in fig.5.4. The essential parts are (i) a tubular exchanger with steam in the shell side and liquid to be concentrated in the tubes (ii) a separator or vapour space for removing entrained liquid from the vapour. When it is operated as a circulation unit a return leg for the liquid from the separator to the bottom of the exchanger is provided. Inlets are provided for feed liquid and steam, and outlets are provided for vapour, thick liquor, steam condensate, and non condensable gases from the steam.

The tubular heater operates in exactly the same way as the natural circulation calandria. The tubes , however, are larger than in a calandria, they are typically 25 to 50mm in diameter and 3 to 10m long. Dilute feed enters the system and mixes with the liquid draining from the separator. Concentrated liquor is withdrawn from the bottom of the heater, the remaining liquor is partially vaporized as it rises through the tubes. The mixture of liquid and vapour from the top of the tubes flows into the sseparator, where its velocity is greatly reduced. To aid in eliminating liquid droplets the vapour impinges on and then passes around sets of baffle plates before leaving the separator.

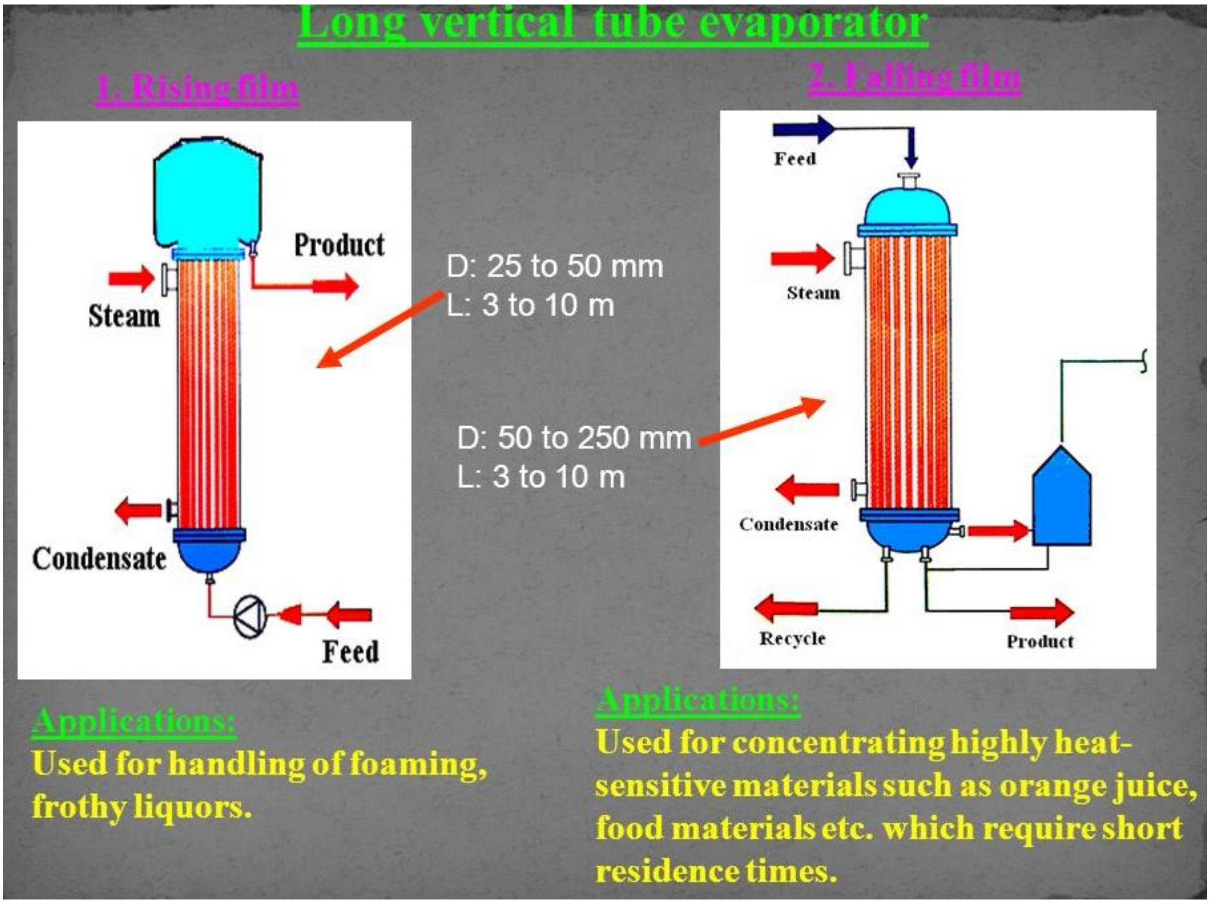
Long tube vertical evaporators are especially effective in concentrating liquids that tend to foam. Foam is broken when the high velocity mixture of liquid and vapour impinges against the vapour head baffle.

5.4.3. Falling film long tube vertical evaporator:

Concentration of highly heat sensitive materials such as orange juice requires a minimum time of exposure to a heated surface. This can be done in once through falling film evaporators, in which the liquid enters at the top, flows downstream inside the heated tubes as a film, and leaves from the bottom. The tubes are large, 50 to 250mm in diameter. Vapour evolved from the liquid is usually carried downward with the liquid and leaves from the bottom of the unit. In appearance these evaporators resemble long, vertical, tubular exchangers with a liquid-vapour separator at the bottom and a distributor for the liquid at the top.

The chief problem in a falling film evaporator is that of distributing the liquid uniformly as a film inside the tubes, This is done by a set of perforated metal plates above a carefully leveled tube sheet, by inserts in the tube ends to cause the liquid to flow evenly into each tube, or by spider distributors with radial arms from which the feed is sprayed at a steady rate on the inside surface of each tube. Still another way is to use an individual spray nozzle inside each tube.

When recirculation is allowable without damaging the liquid, distribution of liquid to the tubes is facilitated by a moderate recycling of liquid to the top of the tubes. This provides a larger volume of flow through the tubes than is possible in once through operation. For good heat transfer the Reynolds number of the falling film should be greater than 2000 at all the points in the tube. During evaporation, the amount of liquid is continuously reduced as it flows downward, and too great a reduction can lead to dry spots near the bottom of the tubes. Thus the amount of concentration that can be done in a single pass is limited.



Long vertical tube evaporator

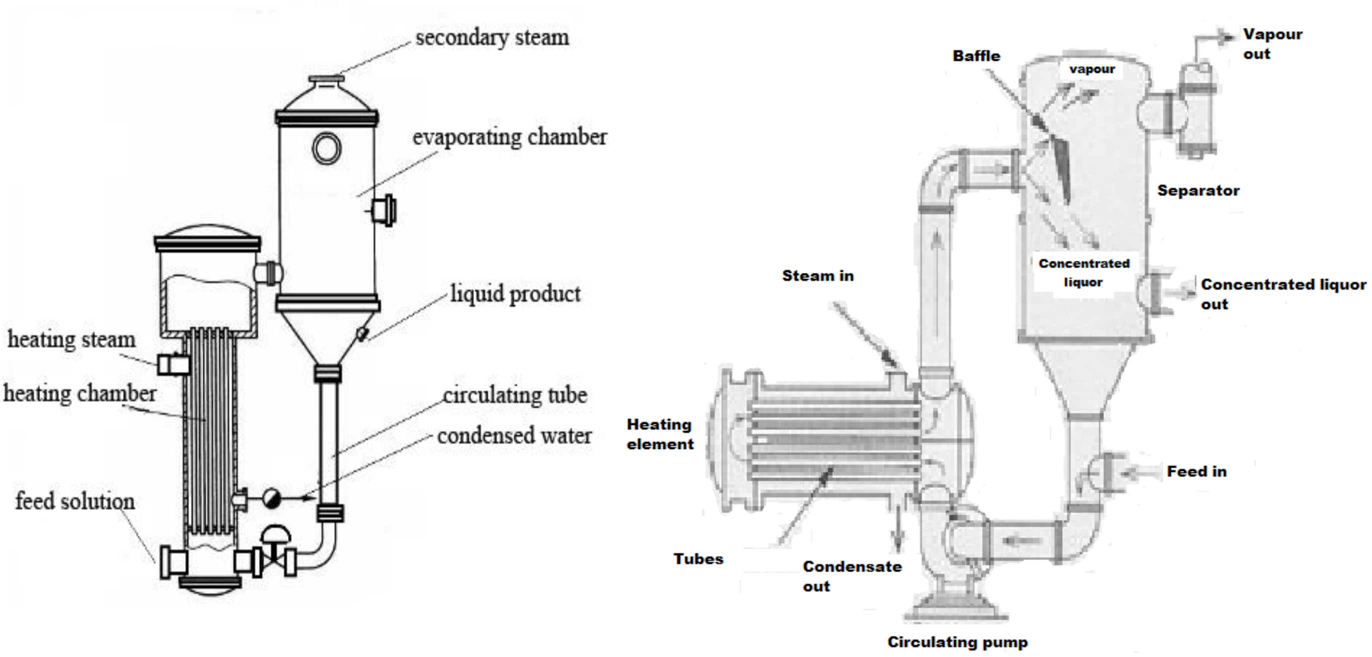
1. Rising film

2. Falling film

Applications:
Used for handling of foaming, frothy liquors.

Applications:
Used for concentrating highly heat-sensitive materials such as orange juice, food materials etc. which require short residence times.

Fig.5.4. Long Tube vertical evaporator



(a) **(b)**

Fig.5.5. Forced circulation Evaporator

5.4.4. Forced circulation Evaporator

In a natural circulation evaporator the liquid enters the tubes at 0.3 to 1.2 m/s. The linear velocity increases greatly as vapour is formed in the tubes, so that in general the rates of heat transfer are satisfactory. With viscous liquids, however, the overall coefficient in a natural circulation unit may be uneconomically low. Higher coefficients are obtained in forced circulation evaporators, an example of which is shown in fig.5.5. Here a centrifugal pump forces the liquid through the tubes at an entering velocity of 2 to 5.5m/s. The tubes are under sufficient static head to ensure that there is no boiling in the tubes, the liquid becomes superheated as the static head is reduced during flow from the heater to the vapor space, and it flashes into a mixture of vapour and spray in the outlet line from the exchanger just before entering the body of the evaporator. The mixture of liquid and vapour impinges on a deflector plate in the vapor space. Liquid returns to the pump inlet, where it meets incoming feed; vapour leaves the top of the evaporator body to a condenser or to the next effect. Part of the liquid leaving the separator is continuously withdrawn as concentrate.

In the design shown in fig.5.5.(b) the exchanger has horizontal tubes and is two pass on both tube and shell sides. In others, vertical single pass exchangers are used(fig.5.5.(a)). In both types the heat transfer coefficients are high, especially with thin liquids, but the greatest improvement over natural circulation evaporators is with viscous liquids. With thin liquids the improvement with forced circulation does not warrant the added pumping costs over natural circulation, but with viscous material the added costs are justified, especially when expensive metals must be used. An example is caustic soda concentration which must be done in nickel equipment. In multiple effect evaporators producing a viscous final concentrate the first effects may be natural circulation units and the later ones handling viscous liquid, forced circulation units. Because of the high velocities in a forced circulation evaporator, the residence time of the liquid in the tubes is short about 1 to 3 s so that moderately heat sensitive liquids can be concentrated in them. They are also effective in evaporating salting liquors or those that tend to foam.

5.4.5. Agitated –film evaporator

The principle resistance to overall heat transfer from the steam to the boiling liquid in an evaporator is on the liquid side. One way of reducing this resistance, especially with viscous liquids, is by mechanical agitation of the liquids film, as in the evaporator shown in fig.5.6. This is a modified falling film evaporator with a single jacketed tube containing an internal agitator. Feed enters at the top of the jacketed section and is spread out into a thin, highly turbulent film by the vertical blades of the agitator. Concentrate leaves from the bottom of the jacketed section, vapour rises from the vapourising zone into an unjacketed separator, which is somewhat larger in diameter than the evaporating tube. In the separator the agitator blades throw entrained liquid outward against stationary vertical plates. The droplets coalesce on these plates and return to the evaporating section. Liquid free vapour escapes through outlets at the top of the unit.

The chief advantage of an agitated film evaporator is its ability to give high rates of heat transfer with viscous liquids. The product may have a viscosity as high as 1000P at the evaporation temperature. As in other evaporators, the overall coefficient falls as the viscosity rises, but in this design the decrease is slow. With highly viscous materials the coefficient is appreciably greater than in forced circulation evaporators and much greater than in natural circulation units. The agitated film evaporator is particularly effective with such viscous heat sensitive products as gelatin, rubber latex, antibiotics and fruit juices. Its disadvantage are high cost ; the internal moving parts, which may need considerable maintenance and the small capacity of single units, which is far below that of multi tubular evaporators.

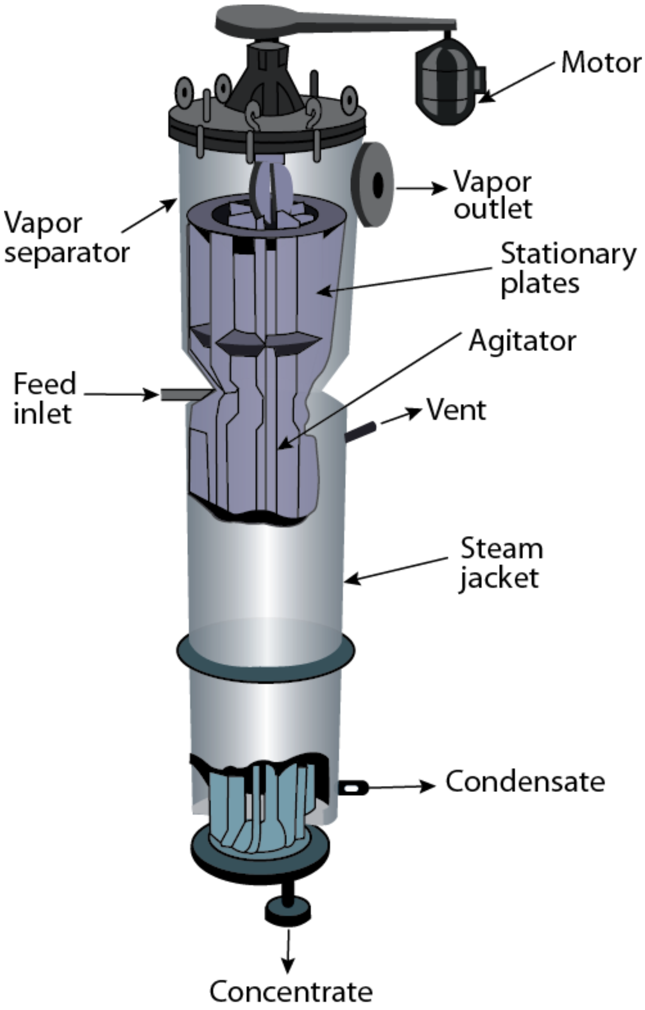


Fig.5.6. Agitated film evaporator

5.5. 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. 5.7 shows representative Dühring plots for a solution (non-volatile solute in water).

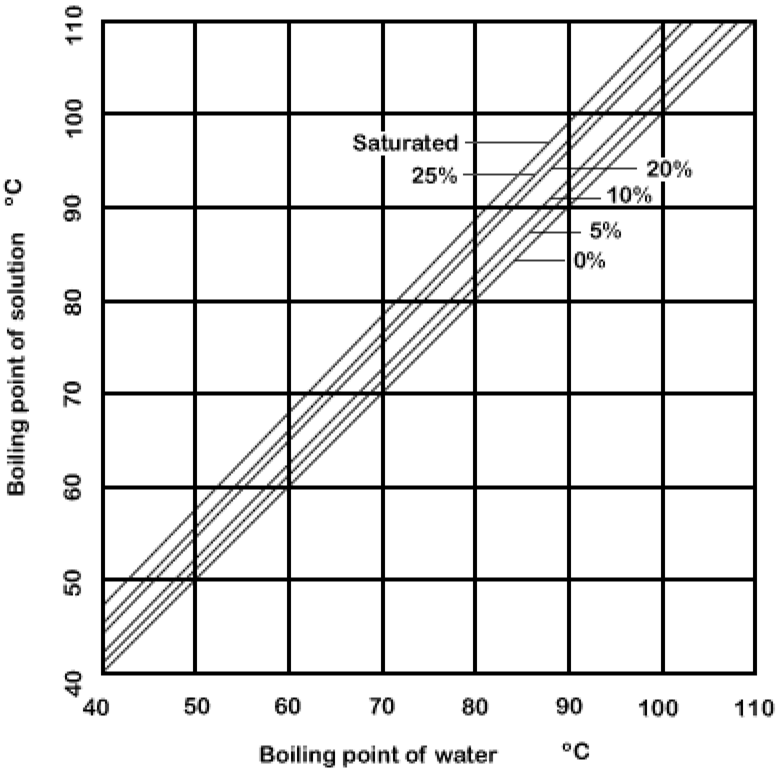


Fig.5.7 Duhring plot for boiling point of sodium chloride solutions

5.6. Method of feeding in Multiple effect evaporators

The fig. 5.8 a,b,c and d show the four different feeding arrangement of feed to the evaporators. In the fig.5.8 (a) 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. 5.8(b). 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.5.8.(b) . 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. Fig.5.8.(c) 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 5.8.(d) shows such arrangement.

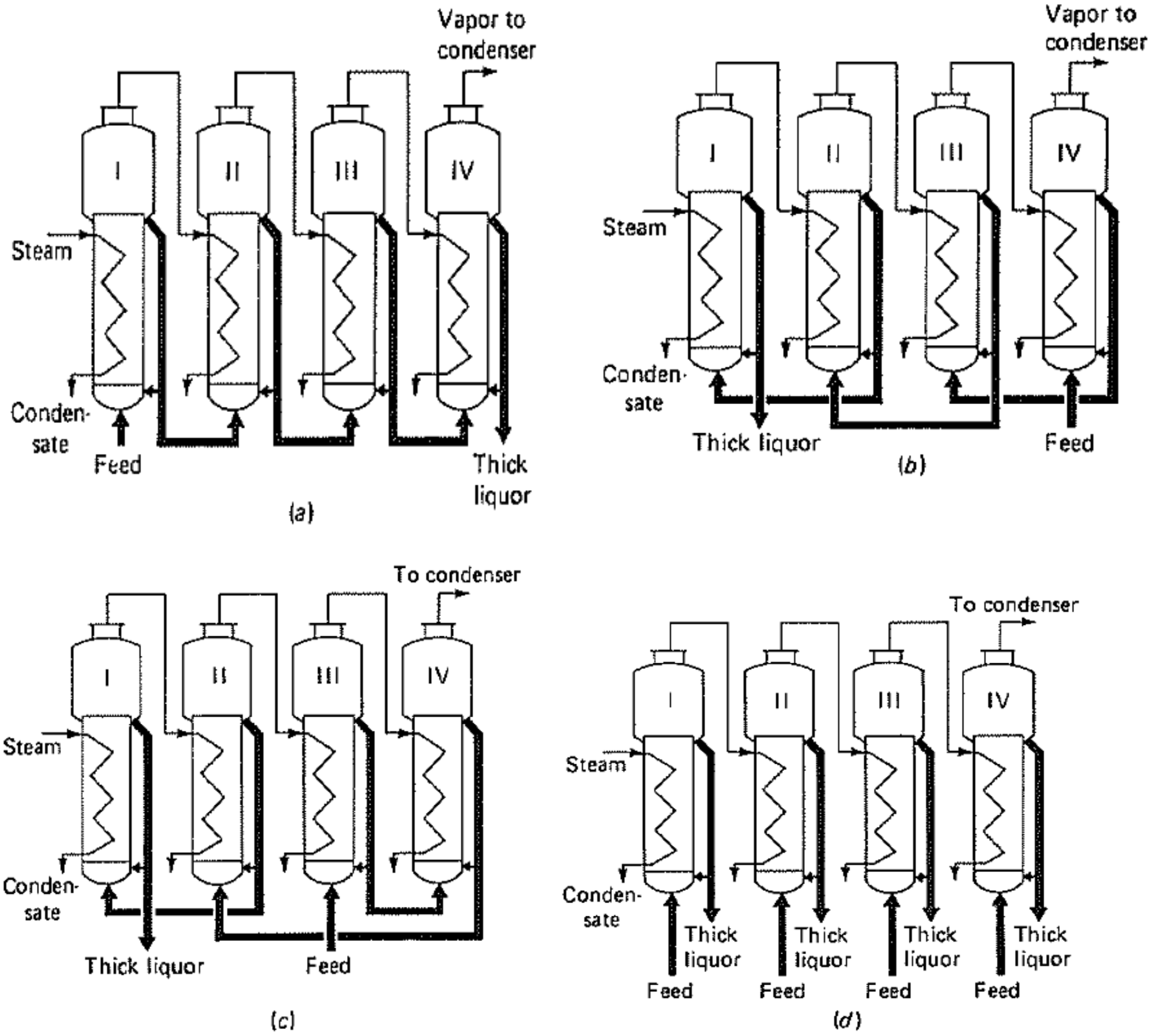


Fig. 5.8. Methods of feeding in Multiple Effect Evaporator

5.7. Enthalpy Balance

5.7.1. 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 of the condensable steam is negligible
3. No solid precipitates out from the concentrating solution

The enthalpy balance for the steam side is,

$$q_S = \dot{m}_s(h_s - h_c) = \dot{m}_s\lambda_s \quad (1)$$

Where, 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 liquor side is ,

$$q = (\dot{m}_f - \dot{m})H_v - \dot{m}_f H_f + \dot{m}H \quad (2)$$

Where, q = Rate of heat transfer from heating surface to the liquid

H_v = specific enthalpy of vapour

H = specific enthalpy of thick liquor

H_f = specific enthalpy of feed

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

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

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

$$q = \dot{m}_s\lambda_s = (\dot{m}_f - \dot{m})H_v - \dot{m}_f H_f + \dot{m}H \quad (3)$$

The area of heat transfer A can be calculated from

$$q = q_s = UA\Delta T \quad (4)$$

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

T_b = Saturated temperature of steam in the shell

T_s = Boiling point of the solution at the prevailing pressure

U = Overall heat transfer coefficient

5.8. 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.

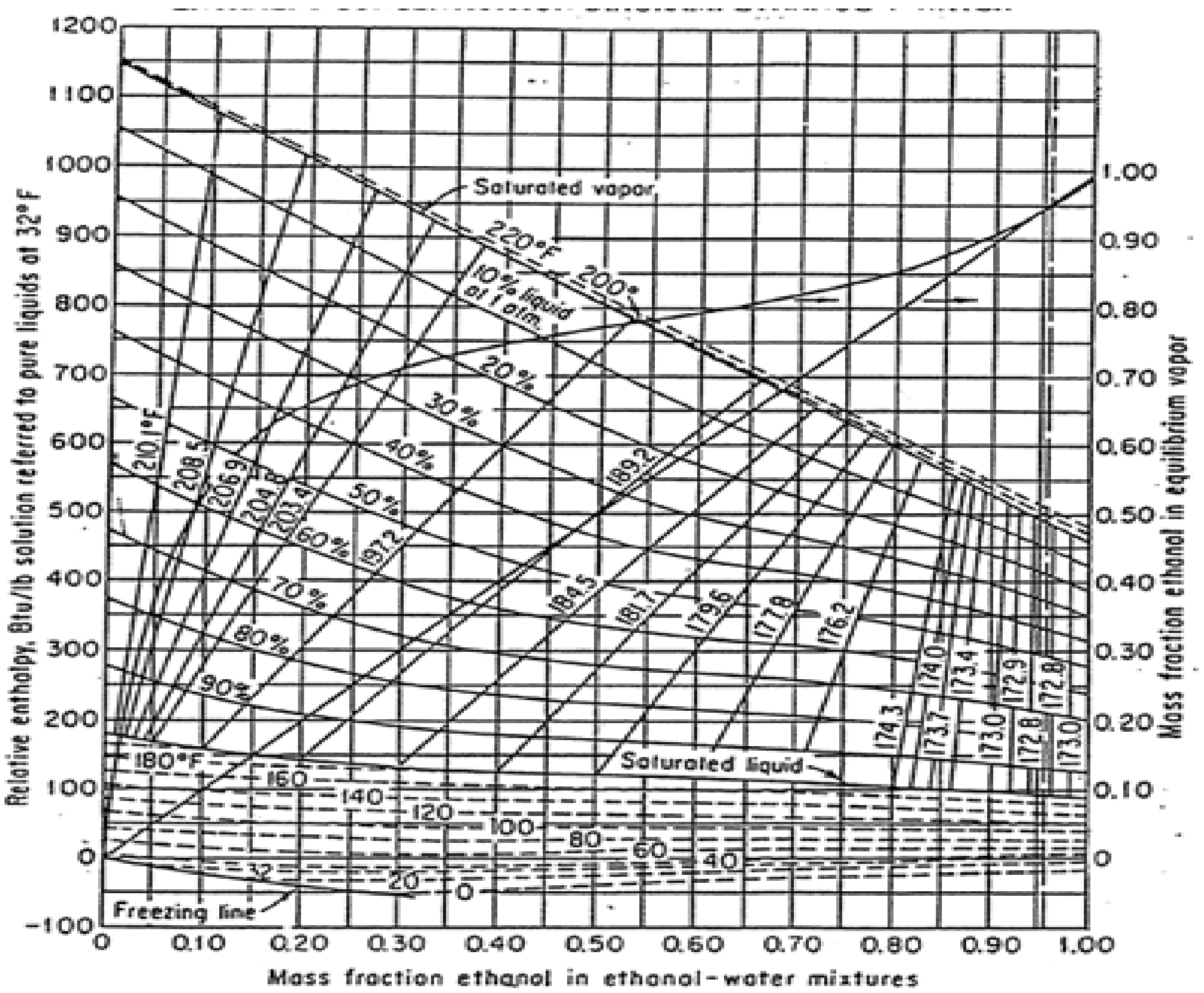


Fig.5.9. Enthalpy concentration diagram

5.9. Multiple effect evaporators

The steam goes into I-effect and heat the solution by the latent heat of condensation. The heating surface in the I effect will transmit per hour an amount of heat given by

the equation $\dot{q}_s = A_1 U_1 \Delta T_1$ (5)

If the heat required to boil the feed is negligible, it follows that practically all this heat 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,

$$\dot{q}_{v1} = A_2 U_2 \Delta T_2 \quad (6)$$

$\dot{q}_{v1} = q_s$

Similarly, for III-effect

$$A_1 U_1 \Delta T_1 = A_2 U_2 \Delta T_2 = A_3 U_3 \Delta T_3 = \dot{q} \quad (7)$$

It can be seen (eq.5.7) 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

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

$$= (T_s + T_{v3}) - \sum BPE \quad (8)$$

where,

T_s - Steam temperature (I-effect); T_{v3} - Vapor temperature leaving III-effect

BPE - boiling point elevation in the solution in various effects

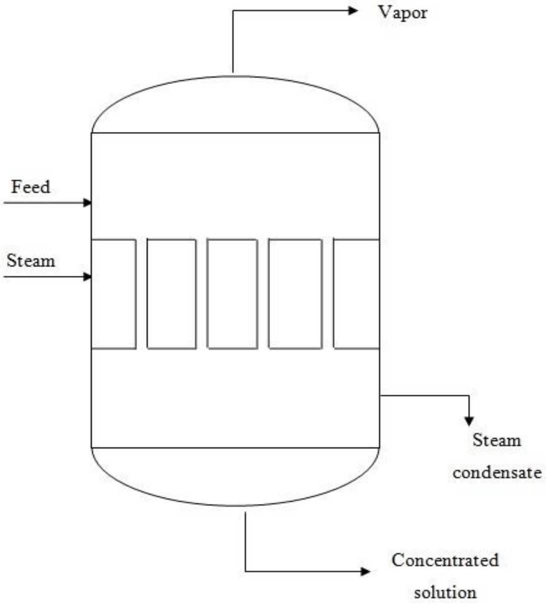
Problems

P.No.1. A single effect evaporator is used to concentrate 9070 kg/hr of 20% caustic soda solution to 50% solids. The gauge pressure of steam is 1.37atm. The absolute pressure in the vapor space is 100 mm Hg. There is a BPE of 22.78 °C. The overall heat transfer coefficient is estimated to be 1400 W/m^2 °C and the feed temperature is 37.8 °C. Calculate the (a) Amount of steam consumed (b) Economy (c) Heating surface required.

Data: Enthalpy of feed at 37.8 °C = 127.9245 kJ/kg
Enthalpy of thick liquor = 514.0239 kJ/kg
Enthalpy of vapour = 2672.46 kJ/kg
Heat of vaporization of steam at 1.37 atm = 2184.0201 KJ/ Kg
Condensation temperature of steam = 126.11°C

Solution:

Feed:



$\dot{m}_f = 9070$ kg/h

$x_f = 0.2$ $T_f = 37.8^oC$

$H_f = 127.92$ kJ/kg

Thick liquor:

x = 0.5

H = 514.02kJ/kg

Vapour:

P= 100mm Hg

H_v= 2672.46 kJ/kg

Steam:

P = 1.37atm

λs = 2184.0201 kJ/ kg

Condensate:

$T_S = 126.11^oC$

$$Q = \dot{m}_s \lambda_s = (\dot{m}_f - \dot{m})H_v - \dot{m}_f H_f + \dot{m}H$$

Component balance(solid)

$\dot{m}_f x_f = \dot{m} x$

$\dot{m}$ = 3628 kg/h

$\dot{m}_v$ = 5442 kg/h

$$q = \dot{m}_s \lambda_s = (\dot{m}_f - \dot{m})H_v - \dot{m}_f H_f + \dot{m}H$$

$$q = \dot{m}_s \lambda_s = (5442\ x\,2672.46) - (9070\ x\,127.92) + (3628\ x\,514.02)$$

$\dot{m}_s$ = 6981.69 kg/h= 1.9394 kg/s

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

$A = Q / U\, \Delta T$ = **57.94 m^2**

$\Delta T = Ts - T$

Steam economy:

kg of water vapourised/kg of steam = 5442 / 6981.69 = 0.7795

P.No.2. 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/m^2: in the I-effect,

1,800 W/m^2: in the II-effect,

1,500 W/m^2: 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.

Assignment:

1. A single effect evaporator is to concentrate 12000kg/hr of 20% solution of sodium hydroxide to 60% solid. Steam supplied for heating is saturated at 120°C. The absolute pressure in the vapor space is 10.34cm Hg. If the overall heat transfer coefficient is 1250W/m^2°C and the feed temperature is 35° C, calculate the steam consumption and the heating surface required. Assume, boiling point of water at 10.35cm Hg=72° C, latent heat of water at 72° C and 120° C as 2320kJ/kg and 2190 kJ/kg respectively. Specific heat of NaOH solution at 20% and 60% concentration as 3.7 and 3.1 kJ/kg°C respectively.
2. A single effect evaporator with a heating surface of 100m^2 is used to concentrate 10000kg/h of a 20% NaOH solution to 50% solids. The gauge pressure of steam is 1.5 atm. The absolute pressure in the vapour space is 100mm Hg. The temperature of the feed is 40°C. Calculate (i) Overall heat transfer coefficient (ii) Amount of steam consumed (iii) steam Economy

   Data: Boiling point of solution at 100mm Hg = 90°C ; enthalpy of feed at 40°C = 31 kcal/h ; enthalpy of thick liquor at 90°C = 124 kcal/h ; heat of vapourisation of steam at 1.5 atm = 530 kcal/kg; condensation temperature of steam 126°C; enthalpy of superheated vapour at 90°C and 100mm Hg = 644 kcal/kg
3. A single effect evaporator is to concentrate 1.25 kg/h of a 10% NaOH to 40% NaOH. Steam is available at a temperature of 274°C.The evaporator operating pressure is 13kN/m^2. Calculate (i)amount of steam consumed (ii) heating surface required .Data: Cp of 10% NaOH = 4 kcal/kg K ; Cp of 40% NaOH = 3.25 kcal/kg K ; Uo = 1.5 kCal /h m^2 K ; Boiling point elevation = 30K.
4. A forced circulation evaporator is to concentrate 20000kg/hr of 30% solution of sodium hydroxide to 50% solid. The gauge pressure of steam is 1.56 atm. The absolute pressure in the vapor space is 100 mm Hg. The temperature of the feed is 40°C. if the overall heat transfer coefficient is 2000W/m^2 K, calculate (a) The heat transfer area (b) The amount of steam consumed (c) The steam economy

DATA : Enthalpy of feed at 40°C = 40 Kcal / Kg

Boiling point of solution at 100 mm Hg =100°C

Enthalpy of thick liquor at 100°C = 130 Kcal / Kg

Enthalpy of super heated vapor at100°C and 100mmHg=670Kcal/ Kg

Heat of vaporization of steam at 1.5 atm = 530 Kcal / Kg

Condensation temperature of steam = 130°C

5. It is desired to concentrate 5000kg/hr of a solution of sodium hydroxide from 10% to 25%solids in a single effect evaporator. Steam is available at 110°C and the vapor space is maintained at 410 mm of Hg. The boiling point of water corresponding to the vapor space is 84°C. The solution has a boiling point elevation of 10°C. The enthalpies of the feed and thick liquor are 90 and 80 kcal/kg respectively and the enthalpy of vapor is 650kcal/kg. The feed enters at its boiling point corresponding to the vapor space pressure λs=534kcal/kg.(a) Calculate the steam consumption per hour (b) If the available heat transfer area is 35m^2, estimate the heat transfer coefficient.

6. A single effect evaporator is used to concentrate 0.075 kg/s of a 10% solution of caustic soda (Enthalpy=70kJ/kg) to 30%(Enthalpy=237kJ/kg). The unit employs forced circulation in which the liquor is pumped through the vertical tubes of the calendria which are 32mm OD by 28mm ID and 1.2 m long. Steam is supplied at 394 k, dry and saturated (λ=2200kJ/kg) and the boiling point rise of the 30% solution is 15k. If the overall heat transfer coefficient is 1.75 kw/m^2k, how many tubes are required? Assume atmospheric pressure. Enthalpy of superheated vapor may be taken as 2706 kJ/kg.

7. A triple effect evaporator concentrates a liquid with no appreciable elevation in boiling point. If the temperature of the steam to the first effect is 395 K and the vacuum in the last effect brings down the boiling point to 325 K, what are the approximate boiling points of liquid in first and second effect? Assume the overall heat transfer coefficient as 3.1, 2.3 and 1.1 kW/m^2 K in the first, second and third effects respectively.

8. It is desired to concentrate 22680 kg/h of a solution at 38°C and 10% solids to a product that contains 50% solids. Steam is available at 1.84 bar absolute and the last effect of a triple effect evaporator with nearly equal heat transfer surface in each effect will be assumed to operate at a vacuum of 100mm vacuum. Assume negligible BPE. Assume difference in pressure between effects to be equal. Calculate (i) steam consumption (ii)heating surface

required for each effect. Data: Overall heat transfer coefficient I effect = 3400 $W/m^2 K$; II effect = 1420 $W/m^2 K$; III effect = 710 $W/m^2 K$; Cp = 4187 J/kg K.
