Chapter No 13

EVAPORATION

Q.1 Define Evaporation and write factors affecting rate of evaporation.

i. Evaporation is defined as the process of removal of water from an aqueous solution or food product to concentrate it.

ii. In evaporation, the vapour from the boiling liquid solution us removed and more concentrated solution remains.

The basic factors that affect the rate of evaporation are the:

a. Rate at which heat can be transferred to the liquid,
b. Quantity of heat required to evaporate each kg of water,
c. Maximum allowable temperature of the liquid,
d. Pressure at which the evaporation takes place,
e. Changes that may occur in the foodstuff during the course of the evaporation process.

Important practical considerations in evaporators are the:

a. Maximum allowable temperature, which may be substantially below 100°C.
b. Promotion of circulation of the liquid across the heat transfer surfaces, to attain reasonably high heat transfer coefficients and to prevent any local overheating,
c. Viscosity of the fluid which will often increase substantially as the concentration of the dissolved materials increases,
d. Tendency to foam which makes separation of liquid and vapour difficult.

Q.2 Explain Single Effect Evaporator.

i. Considered as a piece of process plant, the evaporator has two principal functions, to exchange heat and to separate the vapour that is formed from the liquid.

ii. The typical evaporator is made up of three functional sections:

   a. The heat exchanger, to exchange heat between heating medium and product medium

   b. The evaporating section, where the liquid boils and evaporates,

   c. The separator in which the vapour leaves the liquid and passes off to the condenser or to other equipment.

iii. In many evaporators, all three sections are contained in a single vertical cylinder. In the centre of the cylinder there is a steam heating section, with pipes passing through it in which the evaporating liquors rise.

iv. At the top of the cylinder, there are baffles, which allow the vapours to escape but check liquid droplets that may accompany the vapours from the liquid surface.

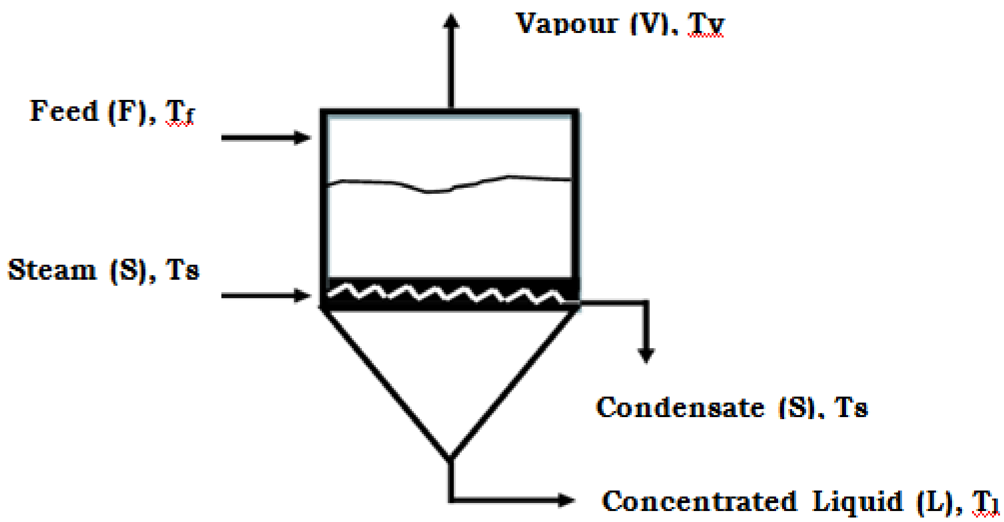


Fig. 7.1 Single effect Evaporator

Material balance over the Single effect evaporator

1. Mass Balance equation

$$F = V + L$$

2. Component Balance equation

$$F \cdot x_f = L \cdot x_l$$

Where, F = Feed rate

V= Vapour production rate

L = Concentration liquid rate

x_f, x_l = Solid content of the feed and concentration liquid

Energy balance over the Single effect evaporator

Energies of entering stream = Energies of leaving stream

Energy in Feed + Energy in Steam = Energy in Vapour + Energy in Condensate + Energy in Concentrated Liquid

$$F.\ h_f + S\ Hs = V.\ Hv + S.\ hs + L.\ h_L$$

$$F.\ h_f + S\ (Hs - h_L) = V.\ Hv + L.\ h_L$$

$$F.\ h_f + S\ \lambda s = V.\ Hv + L.\ h_L$$

If the condensate outlet temperature is less than the steam temperature

$$F.\ h_f + S\ [\lambda s + C_{pw}\ \Delta T] = V.\ Hv + L.\ h_L$$

Where, h_f = Enthalpy of Feed = $Cp_f\ \Delta T$

h_f = Enthalpy of Conc. Liquid = $Cp_L\ \Delta T$

Hv = Latent heat of vaporization at Pressure Pv

λs= Latent heat of condensation of steam

Hs = Enthalpy of Steam at Pressure Ps and Temperature Ts

hs = Enthalpy of Steam Condensate at Pressure Ps and Temp. Ts

The Heat transfer is given by equation

$$Q = U\ A\ \Delta Tm = U\ A\ (Ts - T_l)$$

Where, U = Overall Heat transfer coefficient ($W/m^{2\,0}C$)

A = Heat transfer area (m^2)

ΔTm = Maximum Temp. Difference (^0C)

Ts = Steam Temperature (^0C)

Steam Economy is the ratio of vapour produced to the steam required.

$$\text{Steam Economy} = \frac{\text{Vapour Produced}}{\text{Steam Required}} = \frac{V}{S}$$

Q. 3 Explain Multiple Effect Evaporators.

i. To reduce overall energy costs, evaporators may be placed in series such that the vapour from one evaporator is the heat source to evaporate water from the next unit in the series.

ii. In this system steam for evaporation is required for the first unit only. The latent heat of vaporization of the condensing steam provides energy to evaporate water in the first stage of the evaporator. Vapour from this stage is condensed in the next effect to vaporize the water there. This continues through all effects.

iii. In a multiple effect system, one kilogram of steam input will evaporate as many kilograms of water as there are effects."This would imply that for a triple effect system, one kilogram of steam would produce three kilograms of vapour.

Forward Feed Multiple effect Evaporator

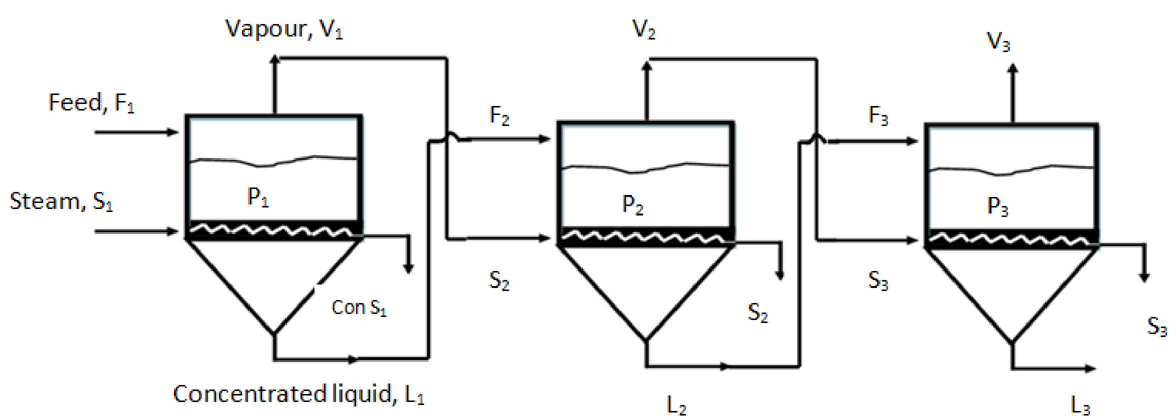


Fig. 7.2 Forward Feed Multiple effect Evaporators

i. In this type of evaporator the fresh feed is added to the first effect and flows to the next in the same direction as the vapour flow.

ii. This method of operation is used when the feed is hot or when the final concentrated product might be damaged at high temperature.

iii. The boiling point temperature decreases from effect to effect. This means that if the pressure of first effect is at P_1= 1 atm., the last will be under vacuum at a pressure P_3 i.e. $P_1>P_2>P_3$ and $T_1>T_2>T_3$.

Backward Feed Multiple effect Evaporator

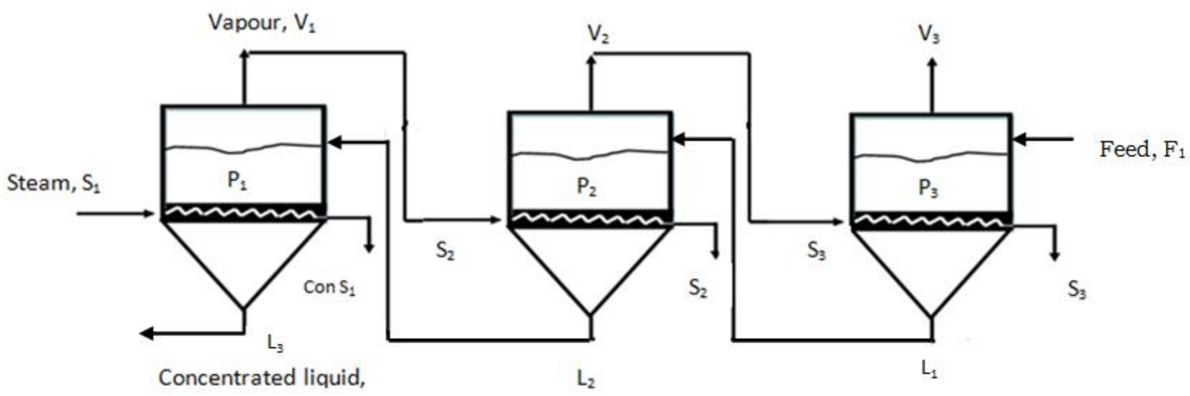


Fig. 7.3 Forward Feed Multiple Effect Evaporators

i. In the backward feed operation shown in Fig. 7.3 for triple effect evaporator, the fresh fed enters the last and coldest effect and continuous on until concentrated product leaves the first effect.

ii. This method of reverse feed is advantageous when the fresh feed is cold, since a smaller amount of liquid must be heated to the higher temperature in the second and the first effect. However, liquid pumps must be used in each effect, since the flow is from low to high pressure.

iii. This reverse feed method is also used when the concentrated product is highly viscous. The high temperatures in the early effects reduce the viscosity and give reasonable heat transfer coefficients.

3. Parallel Feed Multiple effect evaporator

i. Parallel feed in multiple effect evaporators involve the adding of fresh feed and withdrawal of concentrated product from each effect. The vapour from each effect is still used to heat next effect.

ii. This method of operation is mainly used when the feed is almost saturated and solid crystals are the product as in the evaporation of brine to make salt.

Problem 1 A single effect evaporator is required to concentrate a solution from the 10% solids to 30% solids at the rate of 250 kg/h. if the pressure in the evaporator is 77 kPa absolute, and if the steam is available at 200 kpa gauge, calculate the quantity of steam required per hour and the area of heat transfer surface if the overall heat transfer coefficient is 1700 J/m^2s^0C. Assume that the temperature of feed is 18^0C and that the boiling point of the solution under the pressure of 77 kPa absolute is 91^0C. Assume also the specific heat of the solution is same as that of the water that is 4.186 kJ/kg^0C and the latent heat of vaporization of the solution is the same as that of water under the same condition.

a. The condensing temperature of a steam at 200 kPa (guage) is 134^0C and latent heat 2164 kJ/kg
b. The condensing temperature at 77 kPa (abs.) is 91^0C and latent heat is 2281 kJ/kg.

Given:

i. $F=250$ kg/h
ii. $x_f=10$ %
iii. $x_L=30\%$
iv. $U=1700\ J/m^2s^0C$
v. $T_f=18^0C$
vi. $T_L=T_v=91^0C$
vii. $Cp_f= Cp_L=4.186\ kJ/kg^0C$

viii. λ=2164 kJ/kg

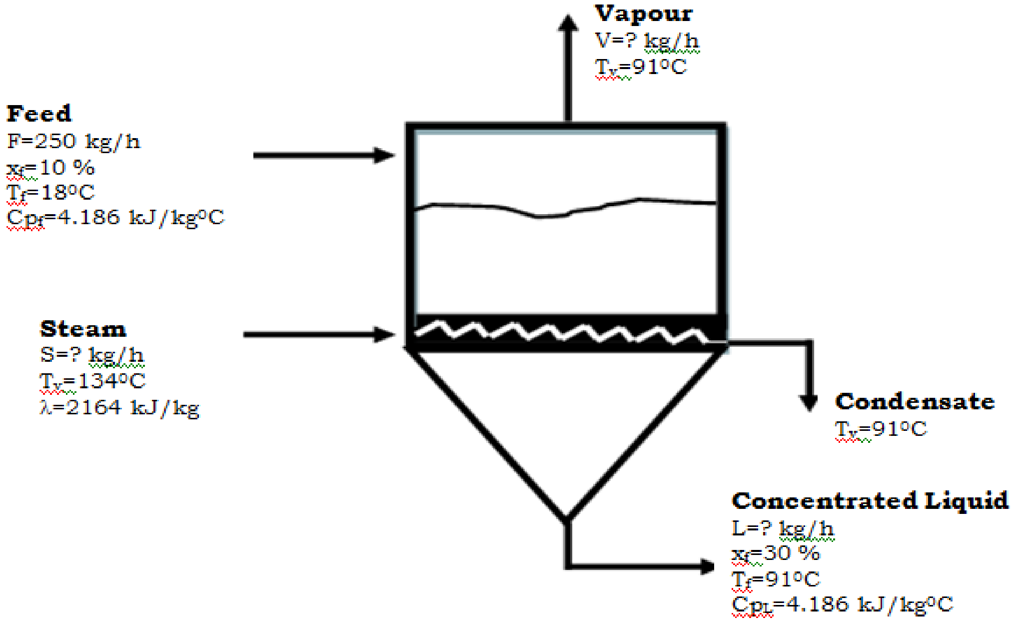
ix. Hv=2281 kJ/kg

x. L=?

xi. V=?

xii. A=?

Sol.



1. Material balance over the Single effect evaporator

Mass Balance equation

$$F = V + L$$

$$250 = V + L \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Component Balance equation

$$F \,.\, x_f = L \,.\, x_l$$

$$250 \times 10 = L \times 30$$

$$L = \frac{2500}{30}$$

$$L = 83.34 \text{ kg/h}$$

From equation 1;

$$V = 166.66 \text{ kg/h}$$

2. Energy balance over the Single effect evaporator

Energies of entering stream = Energies of leaving stream

Energy in Feed + Energy in Steam = Energy in Vapour + Energy in Condensate
+ Energy in Concentrated Liquid

$$F.\ h_f + S\ [\lambda s + Cp_w \Delta T] = V.\ Hv + L.\ h_L$$

$$F\ Cp_f\ \Delta T + S\ [\lambda s + Cp_w \Delta T] = V.\ Hv + L.\ Cp_L \Delta T$$

The Datum Temperature is 91^0C

$$250 \times 4.186 \times (18-91) + S\ [2164+4.186 \times (134-91)] = 166.66 \times 2281 + 83.34 \times 4.186 \times (91-91)$$

$$-76394.5+2343.998\ S = 380151.46 + 0$$

$$2343.998\ S = 456545.96$$

$$S = \frac{456545.96}{2343.998}$$

$$S = 194.78\ kg/h$$

Heat supplied by the steam,

$$Q = S\ [\lambda s + Cp_w \Delta T]$$

$$Q = 194.78 \times [2164+4.186 \times (134-91)]$$

$$Q = 456560.4224\ kJ/h$$

$$Q = \frac{456560.4224}{3600}$$

$$Q = 126.82\ kW = 126820\ W$$

The Heat transfer is given by equation

$$Q = U\ A\ \Delta Tm = U\ A\ (Ts - T_1)$$

$$126820 = 1700\ A\ (134 - 91)$$

$$A = \frac{126820}{1700 \times 43}$$

$$A = 1.734\ m^2$$

Ans:

i. **The Quantity of steam required = 194.78 kg/h**

ii. **The area of heat transfer surface = 1.734 m^2**

iii. **The Vapour Produced (V)=166.64 kg/h**

iv. **The Concentrated liquid = 83.34 kg/h**

Problem No. 2: Estimate the requirement of steam, heat transfer surface and the evaporating temperature in each effect, for a triple effect evaporator, evaporating 55 kg/h of a 10% solution up to 30% solution. Steam is available at 200 kPa gauge and the pressure in the evaporation space in the final effect is 60 kPa absolute. Assume that the overall heat transfer coefficient are 2270, 2000, 1420 J/m^{2}s^{0}C in the first, second and third effect respectively. Neglect sensible heat effect and assume no boiling point elevation, and equal heat transfer in each effect.

Problem No. 3 How much water would be required in a jet condenser to condense the vapours from an evaporator evaporating 5000 kg h^{-1} of water under a pressure of 15 cm of mercury? The condensing water is available at 18°C and the highest allowable temperature for water discharged from the condenser is 35°C.

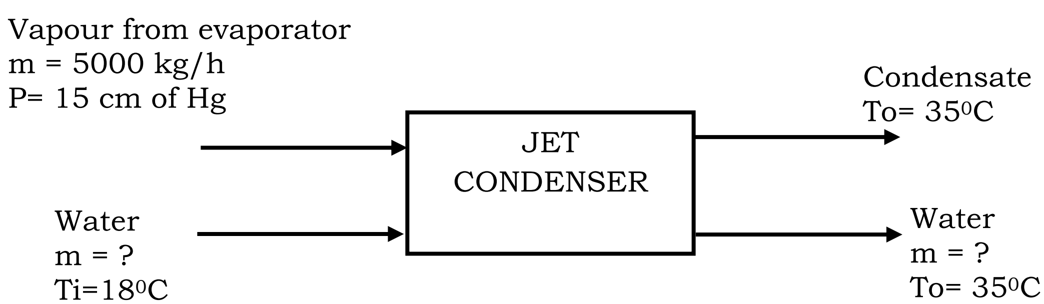
What heat exchange area would be required for a surface condenser working under the same conditions as the jet condenser, assuming a U value of 2270 J m^{-2} s^{-1} $°C^{-1}$ and disregarding any sub-cooling of the liquid.

Given:

i. Quantity of Condensate, m = 5000 kg/h
ii. Pressure in evaporator, Z = 15 cm of Hg
iii. Condensing water inlet temperature, Ti =18^0C
iv. Condensing water outlet temperature, To=35^0C
v. Mass of water required, m_w=?

Sol:

i. Block Diagram



ii. Heat balance

The pressure in the evaporator is 15 cm mercury $= Z\rho g$

$= 0.15 \times 3.6 \times 1000 \times 9.81$

$= 20$ kPa.

From Steam Tables, the condensing temperature of water under pressure of 20 kPa is 60°C and the corresponding latent heat of vaporization is 2358 kJ kg^{-1}.

Heat removed from condensate = m λ + m Cp ΔT

$= 5000 \times 2358 \times 10^3 + 5000 \times 4.186 \times 10^3 \times (60-35)$

$= 12300 \times 10^6$ J/h ....(1)

Heat taken by cooling water per kg = m_w Cp ΔT

$= m_w \times 4.186 \times 10^3 \times (35 - 18)$

$= 7.1 \times 10^4 \; m_w$ J ....(2)

From equation 1 and 2

$$12300 \times 10^6 = 7.1 \times 10^4 \; m_w$$

$$\mathbf{m_w = 1.7 \times 10^5 \; kg/h}$$

The temperature differences are small so that the arithmetic mean temperature can be used for the heat exchanger (condenser).

$$\text{Mean temperature difference} = \frac{(60-18)}{2} + \frac{(60-35)}{2}$$

$$= 33.5\ ^0C.$$

Quantity of heat required by condensate,

$$Q = UA\,\Delta T$$

$$12300 \times 10^6 = 2270 \times A \times 33.5 \times 3600$$

$$\mathbf{A = 45\ m^2}$$

Ans:

i. Mass flow rate of water required = **1.75×10^5 kg/h**

ii. Heat transfer area require = **45 m^2**