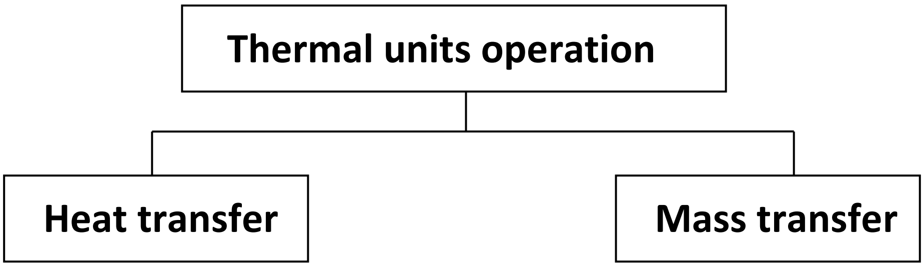


Heat transfer:

Heat is an energy in transmit as a result of temperature difference.

Chemical processes:

Furnaces, evaporators, driers, reaction vessels, distillation units.

Modes (Methods) of heat transfer:

Heat is transferred by three methods:

1. Conduction
2. Convection
3. Radiation

Conduction:

The diffusion of energy in solids is due to random molecular motion.

Convection:

It occurs as a result of movement of fluid in the form of eddies or currents.

Radiation:

It is an energy transfer by electromagnetic waves.

Steady state heat transfer by conduction:

It means that temperature (T) and heat rate (q) do not change with time during the heat transfer.

Fourier's law of heat transfer by conduction:

$q = -KA\frac{dT}{dx}$

q - heat rate (w),

K - thermal inductively(W/m.^{o}K),

A - area (m^2),

dT = Temperature difference (^{o}K)

(dx) Thickness in (m).

Thermal conductivity (k)

It is a physical property of material for heat transfer by conduction.

"It can be obtained by experimental methods".

It **depends** upon:

1. Material nature.

Metals → high (k)

Nonmetallic materials → low (k)

2. Temperature.

$K_{solid} >>> K_{liquid} > K_{gas}$

Conduction through a single plane wall:

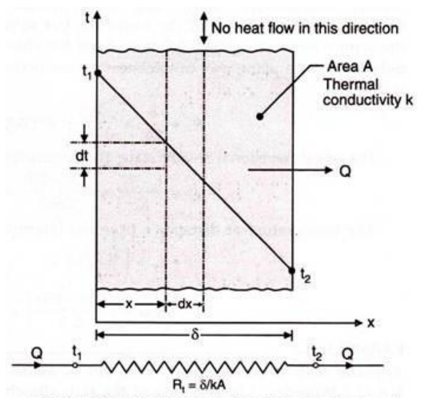


Fig. 3.1. Steady state conduction through a plane wall

$$q = -k.A\frac{dt}{dx}$$

$$q\int_{x1}^{x2} dx = -k.A\int_{T1}^{T2} dt$$

$$q\,x\,] = -k.A\ T\,]$$

$$q\,(x_2 - x_1) = -KA\,(T_2 - T_1)$$

$$q = \frac{KA\,(T_1 - T_2)}{\triangle X}$$

$$q = \frac{T_1 - T_2}{\frac{\triangle X}{KA}} \quad \text{........(1)}$$

Ex: The inner and outer temperatures of a wall furnace are (1073 °K) and (473 °K), The wall is constructed with (0.24m) material and of (0.07W/m. °K) thermal conductivity. Find the heat loss per unit area of a furnace wall.

$$q = \frac{KA\,(T_1 - T_2)}{\triangle X}$$

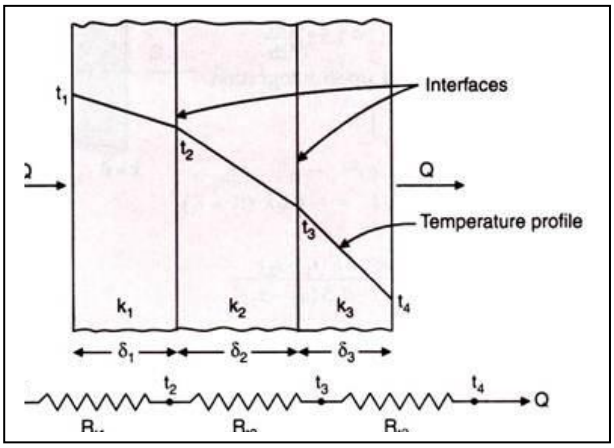
$$q = \frac{0.07\,(1)(1073-473)}{0.24} = 175\text{w}$$

Conduction through composite plane wall:

$$q = \frac{K_1\,A\,(T_1 - T_2)}{\triangle X_1}$$

$$q = \frac{K_2\,A\,(T_2 - T_3)}{\triangle X_2}$$

$$q = \frac{K_3\,A\,(T_3 - T_4)}{\triangle X_3}$$



$$T_1 - T_2 = \frac{q\,\triangle X_1}{K_1\,A}$$

$$T_2 - T_3 = \frac{q\,\triangle X_2}{K_2\,A}$$

$$T_3 - T_4 = \frac{q\,\triangle X_3}{K_3\,A}$$

$$T_1 - T_4 = \frac{q\,\triangle X_1}{K_1\,A} + \frac{q\,\triangle X_2}{K_2\,A} + \frac{q\,\triangle X_3}{K_3\,A}$$

$$T_1 - T_4 = q\left(\frac{\triangle X_1}{K_1\,A} + \frac{\triangle X_2}{K_2\,A} + \frac{\triangle X_3}{K_3\,A}\right)$$

$$\therefore q = \frac{T_1 - T_4}{\frac{\triangle X_1}{K_1\,A} + \frac{\triangle X_2}{K_2\,A} + \frac{\triangle X_3}{K_3\,A}} \quad \text{.......... 2}$$

Thermal resistance (R):

$$R = \frac{\Delta x}{kA}$$

Ex: A furnace wall is constructed with (0.11m) of fire brick, (0.043 w/m. °K) and (0.23m) of ordinary brick, (0.333w/m. °K) the inner and outer temperature are (1043 °K), (373 °K). Find:

(1) The heat loss per ($1m^2$) of wall.

(2) Junction temperature

<u>Solution</u>:

$$q = \frac{T_1 - T_3}{\frac{\triangle X_1}{K_1\,A} + \frac{\triangle X_2}{K_2\,A}} = \frac{1043 - 373}{\frac{0.11}{0.043(1)} + \frac{0.23}{0.333(1)}}$$

q = 206.280w

$$q = \frac{T_1 - T_2}{\frac{\triangle X_1}{K_1\,A}} \Rightarrow 206.280 = \frac{1043 - T}{\frac{0.11}{0.043(1)}} \Rightarrow T_2 = 515.44K^{\circ}$$

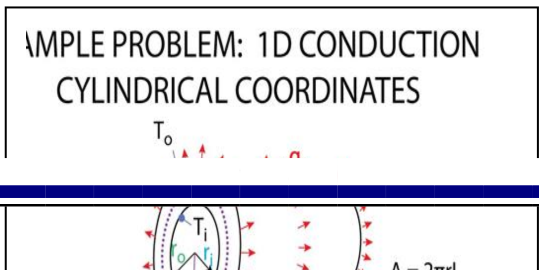
Ex: A reactor wall is constructed with (225mm) of fire brick, (120mm), insulating brick, and (225mm) of ordinary brick, the inside and outside temperatures are (1200k) (330k), and the thermal conductivities are (1.4) (0.2) (0.7) w/m.k. Find:

(1) The heat loss per unit area.

(1) Temperatures of the junction

<u>Solution</u>:

<u>Conduction through cylindrical wall</u>:



$q = -KA\frac{dt}{dr}$

$q = -K(2\overline{\wedge}rL)\frac{dt}{dr}$

$q\int_{r_1}^{r_2}\frac{dr}{r} = -2\overline{\wedge}LK\int_{T1}^{T2} dT$

$q \ \ln\ ]_{r1}^{r2} = -2\overline{\wedge}LKT\ ]_{t1}^{t2}$

$q(\ln r_2 - \ln r_1) = -2\overline{\wedge}LK(T_2 - T_1)$

$q \ \ln\frac{r_2}{r_1} = = -2\overline{\wedge}LK(T_1 - T_2) = \frac{2\overline{\wedge}LK\,(T_2 - T_1)}{\ln\frac{r2}{r1}}$ ……….. (3)

Ex: Calculate the heat loss from a pipe of (10m) length, and external diameter (6cm) coated with insulating material (5cm) thick, ($k= 0.055$ w/m. ^oK), the inside and outside temperatures are (467 ^oK) and (299 ^oK).

Solution:

$r_1 = \frac{6}{2} = 3cm = \frac{3}{100}\ 0.03m$

$r_1 = 3 + 5 = 8cm = \frac{8}{100}\ 0.08m$

$q = \frac{2\overline{\wedge}LK\,(T_1 - T_2)}{Ln\frac{r2}{r1}}$

$q = \frac{2\times3.14\times10\times0.055\,(467-299)}{Ln\frac{0.08}{0.03}} = \frac{580.27}{0.9808}$

$q = 591.5w$

Conduction through composite cylindrical wall:

$$q = \frac{2\overline{\wedge}L\,(T_1 - T_2)}{\frac{Ln\frac{r2}{r1}}{K_1} + \frac{Ln\frac{r3}{r2}}{K_2}} \quad \ldots\ldots\ldots\ldots\ldots (4)$$

Ex: a pipe of (26cm) diameter is coated with insulation, Consisting two layers, the inner layer has (4cm) thick and (0.075 W/m.°K), and the second layer has (5cm) thick and (0.06w/m. °K). If the inner temperature is (633 °K) and outer temperature is (313 °K). Find:

(1) The heat rate per (1m) of pipe length.

(2) Temperature of junction

Solution:

Conduction through hollow spherical wall:

$$q = -KA\frac{dt}{dr}$$

$$q = -K\,4\overline{\wedge}r^2\frac{dt}{dr}$$

$$q\int_{r_1}^{r_2}\frac{dr}{r2} = -4\overline{\wedge}K\int_{T1}^{T2} dT$$

$$q\int_{r_1}^{r_2} r^{-2}\,dr = -4\overline{\wedge}K\int_{T1}^{T2} dT$$

$$q\,\frac{r-}{-1}\,] = -4\overline{\wedge}KT\,]$$

$$-q\ \frac{1}{r}] = -4\bar{\lambda}K\ (T_2 - T_1)$$

$$-q\ (\frac{1}{r_2} - \frac{1}{r_1}) = -4\bar{\lambda}K\ (T_2 - T_1)$$

$$q\ (\frac{1}{r_1} - \frac{1}{r_2}) = -4\bar{\lambda}K\ (T_2 - T_1) \Rightarrow q = \frac{4\bar{\lambda}K\ (T_1 - T_2)}{(\frac{1}{r^1} - \frac{1}{r^2})} \ \ldots\ldots\ldots\ (5)$$

Ex: A hollow spherical body has (0.3m) thick, (1m) inside diameter and (1.6 w/m. °K). Find the rate of heat transfer if inner and outer temperatures are (500 °K) and (300 °K).

<u>Solution</u>:

$r_1 = \frac{1}{2} = 0.5m$

$r_2 = 0.5 + 0.3 = 0.8m$

$k = 1.6\ \frac{w}{m.k}$

q = ?

$T_1 = 500k^{\circ}$

$T_2 = 300k^{\circ}$

$$q = \frac{4\bar{\lambda}K\ (T_1 - T_2)}{(\frac{1}{r^1} - \frac{1}{r^2})}$$

$$q = \frac{4 \times 3.14 \times 1.6 \times (500 - 300)}{(\frac{1}{0.5} - \frac{1}{0.8})}$$

$$q = \frac{4019.2}{2 - 1.25} = \frac{4019.2}{0.75}$$

q = 5358 w

Heat transfer by convection:

Diffusion of energy due to random molecular motion and energy transfer due to bulk motion.

Convection

Free convection (Natural) | **Forced convection**

Free convection (Natural):

Circulating currents are produced due to the difference in density.

Forced convection:

Circulating currents are produced by an external agency such as agitator.

Newton`s law of heat transfer by convection:

$q = \frac{KA\,(T_1 - Tw_1)}{\triangle X}$ ، $(h = \frac{k}{\triangle X})$

$q = hA\,(T_1 - T_{W1})$

$\frac{1}{h}$ = Thermal resistance

Factors effecting on heat transfer coefficient (h):

1. Surface shape

2. Surface dimensions (L)

3. Temperature (T)

4. Density (ρ)

5. Viscosity (μ)

6. Specific heat capacity (cp)

7. Thermal conductivity (k)

8. Velocity (u)

9. Surface roughness.

$$h = f(u, L, \mu, \rho, k, cp, \beta_g, \Delta T)$$

<u>The main dimensionless groups</u>:

1. Reynold`s number (Re)

$$Re = \frac{u \rho d}{\mu}$$

2. Prandtle number (Pr)

$$Pr = \frac{cp\mu}{k}$$

3. Nusselt number (Nu)

$$Nu = \frac{hd}{k}$$

4. Grashof number (Gr)

$$Gr = \frac{d^3 \rho 2 \beta g \Delta T}{\mu^2}$$

Where:

ρ = Density of fluid (kg/m^3)

U= Velocity of fluid (m/sec)

d= Diameter of tube (m)

μ= Dynamic viscosity (kg/m.sec)

g= Acceleration of gravity (m/sec^2)

β= Thermal expansion factor ($1/k^o$)

Cp= Specific heat (kJ /kg.k)

K= Thermal conductivity for fluid (w/m.k)

Nu= f (Re, Gr, Pr)

Nu= f (Gr, Pr) for free convection

Nu= f (Re, Pr) for forced convection

<u>Forced convection in tubes</u>:

1.for turbulent flow inside tubes (heating and cooling)

$Nu = 0.023\,(Re)^{0.8}\,(Pr)^{n}$

n=0.4 for heating

n=0.3 for cooling

$T = \frac{Tin+Tout}{2}$

Ex: Find the value of heat transfer coefficient by convection for water side of a single pass condenser if inside diameter is (2.3cm) and water enters at ($290.7k^o$) and leaves at ($295.3k^o$), Given:

u= 2.13m/sec.

<u>Solution</u>:

$T = \frac{Tin+Tout}{2} = \frac{290.7+295.3}{2} = 293k$

$K = 0.598\ w/m.k^{\circ}$

$\rho = 1000\ kg/m^3$

$\mu = 0.001\ kg/m.sec$

Cp = 4186 J/kg.k

$Nu = 0.023\,(Re)^{0.8}\,(Pr)^{n=0.4}$

$Pr = \frac{Cp}{k} = \frac{4186\times0.001}{0.598} = 7$

$$Re = \frac{\rho\, ud}{\mu} = \frac{1000 \times 2.13 \times 0.023}{0.001} = 48990$$

$Nu = 0.023\ (Re)^{0.8}\ (Pr)^{0.4}$

$Nu = 0.023\ (48990)\ (7) = 283.3$

$$Nu = \frac{hd}{k} \Rightarrow 283.3 = \frac{h \times 0.023}{0.598}$$

$$h = 7365.8\ \frac{w}{m\ .k^{\circ}}$$

2. For viscous liquids

$$Nu = 0.027\ (Re)^{0.8}\ (Pr)^{0.33}\ (\frac{\mu}{\mu w})^{0.14}$$

3. For heating of liquids: (stream line flow)

$$Nu = 1.86\ (Re)\ (Pr)\ (\frac{d}{l}).^{1l3}\ \ (\frac{\mu}{\mu\, w})^{0.14}$$

Forced convection outside tubes

1. For hot gas past single cylinder.

$Nu = 0.3\ (Re)^{0.6}$

2. For flow a right angle to tubes bundles.

$Nu = 0.33\ (Re)^{0.6}\ (Pr)^{0.3}$

<u>Heat transfer by natural convection</u>

1. From vertical surfaces

$Nu = 0.13\ (Gr.\ Pr)^{0.33}$ (Turbulent flow) ($Gr.\ Pr = 10^9 - 10^{12}$)

$Nu = 0.59\ (Gr.\ Pr)^{0.25}$ (Laminar flow) ($Gr.\ Pr = 10^4 - 10^8$)

$H = 1.31\ (\Delta T)$ Turbulent flow for air

$H = 1.42\ (\frac{\Delta T}{l})$ Laminar flow for air

2. From horizontal surface

$$Nu = 0.525\,(Gr.\,Pr)^{0.25} \qquad (Gr.\,Pr) > 10^4$$

Ex: Air at (300C°) flows over a flat plate of dimensions (0.5m) by (0.25m) if heat transfer coefficient is ($250 w/m^2.K^o$), determine the heat transfer rate from air to one side of plate when the plate is maintained at (40C°)

$T_1 = 300 + 273 = 573k^\circ$

$T_{w1} = 40 + 273 = 313k^\circ$

$A = (\ell)\times(w)$

$q = hA\,(T_1 - T_{w1}) \Rightarrow (T_2 - T_1) \Rightarrow q = 250\times0.5\times0.25\,(573 - 313)$

$q = 8125w^\circ$

Heat transfer by the combined effect of conduction and convection:

In most industrial operations heat transfers from hot fluid to cold fluid through a plane wall.

<u>Heat transfer between two fluids through a plane wall</u>:

1. heat transfer by convection from hot fluid to the surface wall.

$$q = hi\,A\,(T_1 - T_2) \longrightarrow T_1 - T_2 = \frac{q}{hi\,A} \;\;\text{...........}\;(1)$$

2. heat transfer by conduction through the wall.

$$q = \frac{KA\,(T2 - T3)}{\Delta x} \longrightarrow T_2 - T_3 = \frac{q\,\Delta x}{KA} \text{ .... (2)}$$

3. heat transfer by convection from the wall to cold fluid

$$q = ho\,A\,(T_3 - T_4) \longrightarrow T_3 - T_4 = \frac{q}{ho\,A} \text{ .... (3)}$$

$$T_1 - T_4 = \frac{q}{hi\,A} + \frac{q\triangle\times}{k\,A} + \frac{q}{ho\,A}$$

$$T_1 - T_4 = \frac{q}{A}\left(\frac{1}{hi} + \frac{\triangle\times}{k} + \frac{1}{ho}\right)$$

$$q = \frac{A\,(T\ \ - T\ )}{\left(\frac{1}{hi} + \frac{\triangle\times}{k} + \frac{1}{ho}\right)}$$

$$q = uA\,(T_1 - T_4)$$

$$u = \frac{1}{\left(\frac{1}{hi} + \frac{\triangle\times}{k} + \frac{1}{ho}\right)}$$

hi= heat transfer coefficient between hot fluid and surface ($w/m^2.K^o$)

ho = heat transfer coefficient between surface and cold fluid ($w/m^2.K^o$)

U= local over all heat transfer coefficient ($w/m^2.K^o$)

For two layer wall:

$$u = \frac{1}{\left(\frac{1}{hi} + \frac{\triangle\times}{k} + \frac{\triangle\times}{k} + \frac{1}{ho}\right)}$$

$$q = uA\,(T_1 - T_5)$$

Ex: Find the heat transfer rate from gas to water through

1. a Clean steel wall of ($32\ w/m.\ K^o$) and (5mm) thick.

2. steel wall coated with rusting of (100mm) and (1.5w/m.k)

Given the temperatures of gas (1073K^o) and water at (473K^o)

hi= 120 (w/m^2.K^o) , ho= 3000 (w/m^2.K^o)

<u>Solution</u>:

1- $u = \dfrac{1}{(\frac{1}{hi} + \frac{\triangle\times}{k} + \frac{1}{ho})}$

$u = \dfrac{1}{\frac{1}{120} + \frac{0.005}{32} + \frac{1}{3000}} = 113.341\dfrac{w}{m.k}$

$q = uA\ (T_1 - T_2) \Rightarrow q = 113.341\times 1\times(1073 - 473)$

$q = 68004.6w$

2- $u = \dfrac{1}{(\frac{1}{hi} + \frac{\triangle\times}{k} + \frac{\triangle\times}{k} + \frac{1}{ho})} = \dfrac{1}{\frac{1}{120} + \frac{0.005}{32} + \frac{0.1}{1.5} + \frac{1}{3000}}$

$u = 13.246\ \dfrac{w}{m.k}$

$q = uA\ (T_1 - T_5) \Rightarrow q = 13.246\times 1\times(1073 - 473)$

$q = 7947.6w$

<u>Heat transfer between two fluids through cylinder wall</u>:

1.heat transfer by convection from hot fluid to inside surface

$q= hi\ Ai\ (T_1 - T_2)$

q= hi 2 ⊼ ri L ($T_1 - T_2$) ………(1)

2. heat transfer by conduction through cylindrical wall.

$$q = \frac{2 \barwedge K\, L\, (T2 - T3)}{\ln \frac{ro}{ri}} \;\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

3. heat transfer by convection from outside surface to cold fluid.

$$Q = ho\ Ao\ (T_3 - T_4)$$

$$q = ho\ 2 \barwedge ro\ L\ (T_3 - T_4) \;\ldots\ldots\ldots(3)$$

$$(T_1 - T_2) = \frac{q}{hi2 \barwedge riL} \;\ldots\ldots\ldots\ldots(1)$$

$$(T_2 - T_3) = \frac{q\, \ell n\, (\frac{ro}{ri})}{2 \barwedge kL} \;\ldots\ldots\ldots\ldots(2)$$

$$(T_3 - T_4) = \frac{q}{ho2 \barwedge roL} \;\ldots\ldots\ldots\ldots(3)$$

$$(T_1 - T_4) = q \left(\frac{1}{2 \barwedge riLhi} + \frac{\ell n \frac{ro}{ri}}{2 \barwedge kL} + \frac{1}{2 \barwedge roLho} \right)$$

$$q = \frac{(T\ - T\ ) \times Ai}{\left(\frac{1}{2 \barwedge riLhi} + \frac{\ell n \frac{ro}{ri}}{2 \barwedge kL} + \frac{1}{2 \barwedge roLho} \right) \times Ai}$$

$$Ai = 2 \barwedge riL$$

$$q = ui\ Ai\ (T_1 - T_4)$$

Ui= over all heat transfer coefficient with respect to inner surface area.

$$ui = \frac{1}{\frac{1}{hi} + \frac{ri\, \ell n \frac{ro}{ri}}{k} + \frac{1}{roho}}$$

$$q = \frac{(T\ - T\ ) \times Ao}{\frac{1}{2 \barwedge riLhi} + \frac{\ell n \frac{ro}{ri}}{2 \barwedge kL} + \frac{1}{2 \barwedge roLho} \times Ao}$$

$$q = uo\ Ao\ (T_1 - T_4)$$

$$ui = \frac{1}{\frac{ro}{ri\,hi} + \frac{ro\,\ell n \frac{ro}{ri}}{k} + \frac{1}{ho}}$$

Uo= over all heat transfer coefficient with respect to outer surface area.

Ex: Find the over all heat transfer coefficient with respect to out surface area for a tube of copper condenser if the inside radius is (17mm) and (19mm) outside radius. Given: hi= 1400 ($w/m^2.K^o$) , ho= 10000 ($w/m^2.K^o$) , K= 300 ($w/m.K^o$) , T1= 700, T2=300, L= 1m. Find heat rate.

1- $$uo = \frac{1}{\frac{ro}{ri\,hi} + \frac{ro\,\ell n \frac{ro}{ri}}{k} + \frac{1}{ho}}$$

$$uo = \frac{1}{\frac{0.019}{0.017\times 1400} + \frac{0.019\,\ell n \frac{0.014}{0.017}}{300} + \frac{1}{10000}} \Rightarrow uo = 1104.599 \frac{w}{m\,.k}$$

2- $q = uo\ Ao\ (T_1 - T_4)$ $\qquad$ $Ao = 2\pi roL$

$q = 1104.5 \times 2 \times 3.14 \times 0.019 \times 1 \times (700 - 300)$

$q = 52715.576w$

Heat Exchangers (H. E)

He they are used for heat exchanging between two fluids of different temperatures, e.g, (coolers, heaters, condensers, steam, generators).

Type of heat exchangers according to fluid flow arrangement

- Parallel flow (H.E)
- counter flow (H. E)
- cross flow (H. E)

Cold and hot fluid enter (H. E) in the same direction

cold and hot fluid enters in opposite direction

cold and hot fluid enter at acute angle on each other

Energy balance for heat exchanger:

$qh = Mh\ (Hh_2 - Hh_1) = Mh\ Cph\ (Th_2 - Th_1)$

$qc = Mc\ (Hc_2 - Hn_1) = Mc\ Cpc\ (Tc_2 - Tc_1)$

$+\ qc = -\ qh$

$qh = Mh\ Cpc\ (Th_1 - Th_2)$

$qc = Mc\ Cpc\ (Tc_2 - Tc_1)$

$Mc\ Cpc\ (Tc_2 - Tc_1) = -\ Mh\ Cph\ (Th_2 - Th_1)$

$Mc\ Cpc\ (Tc_2 - Tc_1) = Mh\ Cph\ (Th_1 - Th_2)$

*Mc (mass flow rate)

Cpc (heat capacity "cold")

Cph (heat capacity "hot")

<u>Energy balance for condenser</u>:

Condenser is a heat exchanger used for condensation steam which must be either

1. Saturated vapor

2. Supper heated vapor

1.When vapour and condensate at the same temperature

$$qh = Mh\ \lambda \text{ (latent heat of evaporation)}$$

$$Mc\ Cpc\ (Tc_2 - Tc_1) = Mh\ \lambda$$

2. If T condensate < T saturation

$$Mc\ Cpc\ (Tc_2 - Tc_1) = Mh\ \lambda + Mh\ Cph\ (Th_1 - Th_2)$$

Logarithmic mean temperature difference $(\Delta T)_{lm}$

$$Q = U\ A\ (\Delta T)_{lm}$$

$$(\Delta T)_{lm} = \frac{\Delta T2 - \Delta T1}{\mathrm{lm}\,\frac{\Delta T2}{\Delta T1}}$$

Ex: It is desired to cool aniline from (366K°) to (388K°) in a double pipe heat exchanger (H.E) of ($6.4m^2$) surface area. Toluene is used for cooling with rate of (1.1Kg/s)at (310K°) the flow rate of aniline is (1.25kg/s) and the type of flow is counter flow. Calculate:

1.outlet temperature of toluene (Tc_2)

2.logarithmic mean temperature difference $(\Delta T)_{lm}$

3.the over all heat transfer coefficient (U)

Given: Cph= 2.21 , Cpc= 1.88 KJ /Kg. K°)

Solution:

1- $MhCph\ (Th_1 - Th_2) = McCpc\ (Tc_2 - Tc_1)$

$1.25 \times 2.21\ (366 - 388) = 1.1 \times 1.88\ (Tc_2 - 310)$

$77.35 = 2.068\ (Tc_2 - 310)$

$\frac{77.35}{2.068} = Tc_2 - 310 \Rightarrow 37.4 = Tc_2 - 310$

$Tc_2 = 37.4 + 310 = 347.4k^{\circ} \simeq 347k^{\circ}$

2- $\triangle T\ell n = \frac{\triangle T - \triangle T}{\ell n \frac{\triangle T}{\triangle T}} = \frac{28 - 19}{\ell n \frac{28}{19}} = 23.2k$

$q = MhCph\ (Th_1 - Th_2)$

$q = 1.25 \times 2.21\ (366 - 388)$

$q = 77.35\ kw$

$q = uA\ (\triangle T)$

$77.35 = u \times 6.4 \times 23.2$

$u = \frac{77.35}{6.4 \times 23.2} = 0.521\ \frac{kw}{m\ .k}$

Shell and tube heat exchanger:

It is used in industry to get high surface area. It consist of a bundle of tubes in annular cylinder.

Types of shell and tubes:

1.(1 - 1) H. E (single pass (H. E))

2.(1 – 2) H. E }
3.(2 – 4) H. E } (multi pass (H. E))

Advantages of multi pass (H. E)

1. very high surface area (A high)

2. It can be used for heating and condensation all kinds of vapors.

3. High over at heat transfer coefficient (U high)

Disadvantages of multi pass (H. E)

1.Heat losses due to friction

2.Difficult in construction

3.Difficult in maintenance

Correction factor for mean temperature difference (F):

$Q = U\,A\,(\Delta T)_{lm}\,.\,F$

$$Z = \frac{Th_1 - Th_2}{Tc_2 - Tc_1}$$

$$E = \frac{Tc_2 - Tc_1}{Th_1 - Th_2}$$

Ex: A hot fluid is to be cooled from (478K°)in (368k°) in (2 – 4)pass (H. E) by using cooling water, which enters (310k°) and leaves at (368k°) If the mass flow rate of hot fluid is (0.22Kg/s) and (Cph=2.5KJ/Kg. k°), (Cpc=4.2KJ/Kg. k°), ($U=230 w/m^2.k$) Find:

1.Heating surface area (A)

2.Mass flow rate of cold fluid (Mc)

Solution:

1. $\triangle T\ell n = \frac{\triangle T - \triangle T}{\ell n \frac{\triangle T}{\triangle T}}$

$\triangle T\ell n = \frac{110 - 58}{\ell n \frac{110}{58}} = 81.25k^\circ$

$qh = MhCph\,(Th_1 - Th_2)$

$q = 0.22 \times 2.5 \times (478 - 368)$

q = 60500w

$$Z = \frac{Th_1 - Th_2}{Tc_2 - Tc_1} = \frac{478-368}{368-310} = 1.9$$

$$E = \frac{Tc_2 - Tc_1}{Th_1 - Th_2} = \frac{368-310}{478-310} = 0.35$$

F = 0.97

q = uA (△T) ℓn.F

60500 = 230 × A × 81.25 × 0.97

$$A = \frac{60500}{230 \times A \times 81.25 \times 0.97} = 3.34 m^2$$

qc = McCpc (Tc_1 – Tc_2)

60500 = Mc × 4.2 × 1000 × (368 – 310)

$$Mc = \frac{60500}{4200 \times 58} = 0.2483 \text{ kg/sec.}$$

Shell side film coefficient (ho)

Heat transfer can be increased in case of using baffles.

Tubes arrangement:

Square pitch (ho min, U min)

Triangular pitch (ho max, U max)

$$\frac{hoDe}{K} = 0.36 \left(\frac{U\,De}{U}\right)^{0.55} \left(\frac{Cp\,\mu}{K}\right)^{0.33} \left(\frac{\mu}{\mu\,K}\right)^{0.14}$$

$$de = \frac{4\left\{Pt^2 - \frac{\bar{\lambda}\,do^2}{4}\right\}}{\bar{\lambda}do} \qquad \text{for square pitch}$$

$$de = \frac{4\left\{\frac{1}{2}Pt^2 - \frac{\bar{\lambda}\,do^2}{4}\right\}}{\frac{1}{2}\bar{\lambda}do} \qquad \text{for triangular pitch}$$

de = shell side equivalent diameter

Pt = distance from center to center of tube

$A_{flow} = \frac{Ds\ .C.B}{Pt}$

Ds = inside diameter of shell

C = clearance

B = distance between two baffles.

$C = P_t - do$

M = . U. A

Fouling factor (fouling resistance "Rf")

$Rf = \frac{1}{Ud} - \frac{1}{Uc}$

Ex: (4kg/s) of nitro benzene is to cooled from (400k) to (315k) by heating a stream of benzene from (305k) to (345k). a tubular heat exchanger is available with (0.44m I.D) shell filled with (166 tubes) of (19mm O.d) and (15mm I.d) each (5m long), the tubes are arranged in two passes on (25mm) square pitch with baffles. Spacing (150mm). there are two passes on shell side and operation is with benzene passing through tubes, the film coefficient on tube side is (1200 $w/m^2.k$) calculate fouling factor scale resistance could be allowed if these units were used for benzene. Given: Cp=2380J/kg. k $\mu = 0.7 \times 10^{-3}$ kg/m. s K= $0.15 w/m^2$. f= 0.8 $\frac{\mu}{\mu w} = 1$

Solution:

M = 4Kg/s

Ds = 0.44

$do = \frac{19}{1000} = 0.019m$

$do = \frac{15}{1000} = 0.015m$

$L = 5m$

$Pt = \frac{25}{1000} = 0.025m$

$B = \frac{150}{1000} = 0.15\ m$

<u>Solution</u>:

$C = P_T - do = 0.025 - 0.019 = 0.006m$

$A_{flow} = \frac{Ds.C.B}{Pt} = \frac{0.44 \times 0.006 \times 0.15}{0.025}\ 0.0158m^2$

$m = \ uA_{flow}$

$u = \frac{m}{A} = \frac{4}{0.0158} = 253.2\ Kg/m.s$

$de = \frac{4\left[p - \frac{\bar{\lambda}do}{4}\right]}{\bar{\lambda}do}$

$de = \frac{4\left[(0.025) - \frac{\bar{\lambda}(0.019)}{4}\right]}{3.14 \times 0.019} = 0.023m$

$\frac{ho\ de}{k} = 0.36\ (\frac{ude}{\mathcal{M}})^{0.55}\ (\frac{cp\ \mathcal{M}}{k})^{0.33}\ (\frac{\mathcal{M}}{\mathcal{M}w})^{0.14}$

$\frac{ho \times 0.023}{0.15} = 0.36\ (\frac{253.2 \times 0.023}{0.7 \times 10})\ (\frac{2380 \times 0.7 \times 10}{0.15})$

$\therefore ho = 744.22\ \frac{w}{m.k}$

$\frac{1}{uc} = \frac{1}{ho} + \frac{1}{hi} + (\frac{do}{di})$

$\frac{1}{uc} = \frac{1}{744.22} + \frac{1}{1200} + (\frac{0.019}{0.015}) \Rightarrow uc = 416.667$

$q = MhCph\ (Th_1 - Th_2)$

q = 4×2380 (400 – 315)

q = 809200w

Ao = $\overline{\pi}$ dLn

Ao = 3.14×0.019×5×166×2 = 99.1

$\triangle T\ell n = \frac{\Delta T - T}{\ell n \frac{\Delta T}{\Delta T}} = \frac{55-10}{\ell n \frac{55}{10}}$ = 26.4K

q = ud×Ao×$\triangle T\ell n$.F

80q200 = ud×99.1×26.4×0.8

ud = 386.6 $\frac{w}{m\,.k}$

Rf = $\frac{1}{ud} - \frac{1}{uc}$

Rf = $\frac{1}{386.6} - \frac{1}{416.1667}$ = 0.00019 $\frac{m\,.k}{w}$

Heat transfer by radiation

A heated body emits energy in the form of electromagnetic waves in all directions, and when falling on a second body in partially absorbed and partially reflected and transmitted as shown below.

$A + r + t = 1$

1. For liquid $t = 0$ $a + r = 1$

2. For gas $r = 0$ $a + t = 1$

3. For black body $t = 0, r = 0$ $a = 1$

Factors effecting on absorptivity and reflectivity of solid:

1.Ts

2.λ waves

3.incident angle

4. properties of surface

5.natural of surface

Emissivity (e):

The ratio of energy emitted by body to that emitted by a black body at the same temperature has been defined as

$$E = \frac{E}{Eb} = \frac{a}{ab}$$

Grey body:

A body which has constant value of emissivity (e)

Black body:

A body which absorbs all the radiation falling on it

$A_b = 1$ $e = 1$

Radiation laws:

1.stffan – Boltzmann Law

$$qr = e\ б\ A\ T\ 4$$

qr (total energy emitted per unit time)

e (emissivity)

б (Stefan – Boltzmann constant "5.67 x $10^{-8} w/m^2. K^4$)

2.Kirshhoffs Law

$$\frac{E1}{a1} = \frac{E2}{a2} = \frac{E}{a}$$

$$E\ \lambda = a\ \lambda - \text{for } \lambda = (0 - \infty)$$

Radiation between surfaces

$$q = e\ A\ б\ T^4$$

radiation between black bodies (parallel plates)

$$q_{12} = б\ A\ T^4{}_1 - б\ A\ T^4{}_2$$

$$q_{12} = б\ A\ (T^4{}_1 - T^4{}_2)$$

$q_{12} = б\ A\ F\ (T^4{}_1 - T^4{}_2)$, F (geometric factor)

1.Radiation between non black bodies for two drayed parallel surfaces.

$$q_{12} = \frac{б\ A(T^4 - T^4)}{\frac{1}{e_1} + \frac{1}{e_2} - 1}$$

2. for surface completely surrounded by other one.

$$q = \frac{A1\ б\ \left(T^4 - T^4\right)}{\frac{1}{e1} + \frac{A1}{A2}\left(\frac{1}{e2} - 1\right)}$$

Ex: Two large metallic surfaces for furnace wall have temperatures of (T_1 = 500K) and (T_2 = 300K) and (e_1= e_2 = 0.3) the space between two surfaces filled with insulated material. Calculate the net radiation heat transfer between them.

<u>Solution</u>:

$$q_{12} = \frac{\text{б}\, A(T_1{}^4 - T_2{}^4)}{\frac{1}{e_1} + \frac{1}{e_2} - 1}$$

$$q_{12} = \frac{5.67\times10^{-8}\times1\,((500)^4 - (300)^4)}{(\frac{1}{0.3} + \frac{1}{0.3} - 1)} = 544.28\text{w}$$

Ex: A body has ($0.4m^2$) surface area and emissivity (e_1=0.35) and temperature (T_1=700k) is completely enclosed by a body of ($3.6m^2$), (e_2=0.75) and (T_2=310k). Find the net heat transfer between them.

<u>Solution</u>:

$$q_{12} = \frac{\text{б}\, A1(T_1{}^4 - T_2{}^4)}{\frac{1}{e_1} + \frac{A_1}{A_2}(\frac{1}{e^2} - 1)}$$

$$q_{12} = \frac{5.67\times10^{-8}\times0.4\,((700)^4 - (310)^4)}{\frac{1}{0.35} + \frac{0.4}{3.6}(\frac{1}{0.75} - 1)} =$$

Heat transfer with phase change

Condensation | Boiling

<u>Heat transfer from the condensation of vapors</u>:

When a saturated vapor is brought in contact with cooling surface heat is transferred from vapour to surface and a film of condensate product.

(e.g. condensation of vapors, water vapor, hydrocarbons vapor, and volatile materials).

States of condensate vapor:

1. Condensable vapor

2. Condensable vapor contains gas mixture of non – condensate gas and vapor.

3. Condensable vapor contains mixture of condensate materials.

Types of condensation

Film type condensation	Drop wise condensation
1.Athin continuous of condensate.	1.droplets from in places and grow and their volume increase.
2.the condensate flow under gravity.	2.the condensate flows under gravity and vapor friction.
3.heat transfer through film is by conduction.	3.heat transfer is by convection.
4.(K) is high. (low h)	4.(h) is high. (low K)
5.more often occur.	5.less often occur.

Film type condensation heat transfer coefficient:

Nussle assumption:

1.Ts, Tv = constant

2.U= 0

3.physical properties at $T_m = \frac{Ts+Tv}{2}$

4.heat transfer is by conduction.

$$hx = \frac{Kf}{\Delta x}$$

1.for vertical surface.

$$h = 1.13 \left\{\frac{Kf^3 \quad (\rho L - \rho v)\lambda g}{\mu L (Tv - Ts) L}\right\}$$

2.for horizontal tube.

$$h = 0.725 \left\{\frac{Kf^3 \quad (\rho L - \rho v)\lambda g}{\mu L (Tv - Ts) D}\right\}$$

3.for raw of horizontal tube.

$$h = 0.725 \left\{\frac{Kf^3 \quad (\rho L - \rho v)\lambda g}{\mu L (Tv - Ts) D n^{\frac{2}{3}}}\right\}$$

Heat transfer to boiling liquids:

In chemical plants liquids are boiled either on

1.submerged surface by (mechanical agitation), or

2.inside of vertical tubes (by pump)

The boiling of liquids under either of these conditions normally leads to formation of vapor first in the form of bubbles and later as vapor phase above liquid inter face in order to occur boiling a small (ΔT) must exist between vapor and liquid.

$$q = hA (T_s - T_{sat}) \quad (T_s > T_{sat})$$

here the bubbles formed on heated surface move the liquid vapour inter face by natural convection.

Types of boiling:

1.Inter face evaporation

2.Nucleate boiling

3.Film boiling

$q = h\,A\,(Ts - T_{sat})$ Newton`s Law

$\frac{q}{A} = h\,(Ts - T_{sat})$

1.free convection boiling (A – B)

- (ΔT) is low

- small and few bubbles

- Nu = f (Pr. Gr)

2. Nucleate boiling (B – C)

- High (ΔT) and (h)

- Large bubbles

- High (h)

3. (Partial film boiling) transition. (C – D)

- Film of vapor on surface

- Drop in (h)

4. Stable film boiling (D – E)

- The film of vapor cover the surface

- Drop in (h)

5. after (E)

- Radiation occurs

- Low (h)

Heat transfer coefficient depend on:

1. (ΔT)

2. Physical and thermal properties.

3. Nature of surface.

EVAPORATION

It is one of the main methods used in chemical industries for concentration of aqueous solution in evaporator.

<u>Factors effecting on selection evaporator</u>:

1. Properties of liquor. { Cp
   - Toxicity
   - Dangerous
   - Radiation
   - Freezing

2. Capacity

3. Capital and running costs.

4. Resident time.

<u>Evaporator problems</u>

1. Foaming.	2. Heat sensitivity.
3. Scale formation.	4. Corrosion
5. Concentration	6.High product viscosity.

Kinds of evaporators

- Natural circulation evaporators
- forced circulation evaporators
  - With external heating surface
  - With internal heating surface
    1. high cost.
    2. resident time is high.
    3. high velocity.
    4. (U) is high.
- film type evaporators
  - falling film evaporator
    1. residnt time is low.
    2. used for sensitive heating materials.
    3. (U) is high.
  - agitated film evaporator
    1. used for Viscous liquors.

Natural circulation evaporators:

horizontal tubes evaporators

1. cheap.
2. easy to install.
3. good heat transfer.
4. used for non–crystalline liquors and for non–viscous.
5. operated batch or continuous.
6. D = (0.4 – 3.6) m, h= (2.4 – 3) m, id= 20 – 30 mm

vertical tubes evaporator

1. good circulation.
2. heating elements can easily by removed.
3. used for viscous liquors.
4. easy for maintenance.
5. L= 0.8 – 1.8 Id = 37 – 75mm.

long vertical tubes evaporators

1. used for sensitive heat materials.
2. used for foaming liquor.
3. L = 3.6 – 6m id = 0.03 – 0.0

Performance of evaporators:

1.**Capacity** (c): (السعة) amount of water evaporated per unit time (kg/s).

2.**Economy** (E): (الكفاءة الاقتصادية) amount of water evaporated per 1 Kg of steam consumed.

$E \leq 1$ for single effect evaporators.

$E > 1$ for multi effect evaporators.

Performance = $\frac{C}{E} = \frac{Kg}{s}$ (كفاءة الأداء , الأدائية)

Evaporator capacity:

$q = U\,A\,(\Delta T) = U\,A\,(T_s - T_{sat})$

1.If $T_f = T_{sat}$ all heat transfer used for evaporation. (saturated feed)

2.If $T_f < T_{sat}$ (C) is low. (cold feed)

3.If $T_f > T_{sat}$ (flash evaporation) (C) is high. (super saturated feed)

Factors effecting on temperature difference (ΔT):

1.Temperature of solution (T_f)

2.(ΔP) between steam and evaporator.

3.Head(height) of solution in evaporator (Z)

4.Velocity of solution in pipes.

Factors affecting on boiling points temp. in evaporators

1.Boiling point elevation and Duhring`s rule.

- Vapor pressure (P) of solution < vapor pressure of pure water
- Boiling point of solution > boiling point of pure water

Durling`s rule: Boiling point of solution is a linear function of boiling point of pure water at the same pressure.

2.liquid head (Z) and friction (f)

Boiling point $\propto$ Z.

Boiling point $\propto$ F.

Evaporator economy (E)

E $\propto$ No. of stages.

E $\propto T_f$

Material and energy balance of single effect evaporator:

Overall material balance(O.M.B)

$m_f = m + V$ ....(1)

Solute M. B.:

$m_f \ x_f = m\,x + V\,y$ (y=o)

$m_f \ x_f = m\,x$ ....(2)

Energy balance(E. B.):

$m_s\,\lambda_s = (m_f - m)\,\lambda + m_f\,Cp\,(T - T_f)$ .... (3)

Ex: It is desired to concentrate a solution of organic material from 10% to 50% in a single effect evaporator working under vacuum pressure of (13.3 kN/m^2) by using steam at (205kN/m^2). Find:

1.amount of steam consumed

2.heating surface area.

3. Economy

Given: Mf=10kg/s, T=324, Cpf=3.77 kJ/kg. K, U=2.85 Kw/m^2.K, for the following case:

1. T_f = 294 ° K   2. T_f = 324 ° K   3. T_f = 365 ° K

<u>Solution</u>:

$m_f \; X_f = m X + V y$

$10 \times 0.10 = M \times 0.50 \Rightarrow M = \frac{10\times0.10}{0.50} = 2$ kg/s.

$Mf = M + V \Rightarrow 10 = 2 + v \Rightarrow V = 10 - 2 = 8$ kg/s.

1. $Ms\ \lambda s = (Mf - m)\ \lambda + MfCpf\ (T - Tf)$

   $Ms \times 2200 = (10 - 2) \times 2380 + 10 \times 3.77\ (324 - 294)$

   $Ms = 9.17$

   $Ms\ \lambda sq = uA\ (T_s - T)$

   $9.17 \times 2200 = 2.85 \times A \times (394 - 324)$

   $A = \frac{9.17\times2200}{2.85\times70} = 101.123 m^3$

   $E = \frac{mf - m}{ms} = \frac{10-2}{9.17} = 0.87$

2. $Ms \times 2200 = (10 - 2) \times 2380 + 10 \times 3.77\ (324 - 294)$

   $Ms = \frac{8\times2380}{2200} = 8.655$

   $8.655 \times 2200 = 2.85 \times A \times (394 - 324)$

   $A = \frac{8.655\times2200}{2.85\times70} = 95.444 m^2$

   $E = \frac{10-2}{8.655} = 0.924$

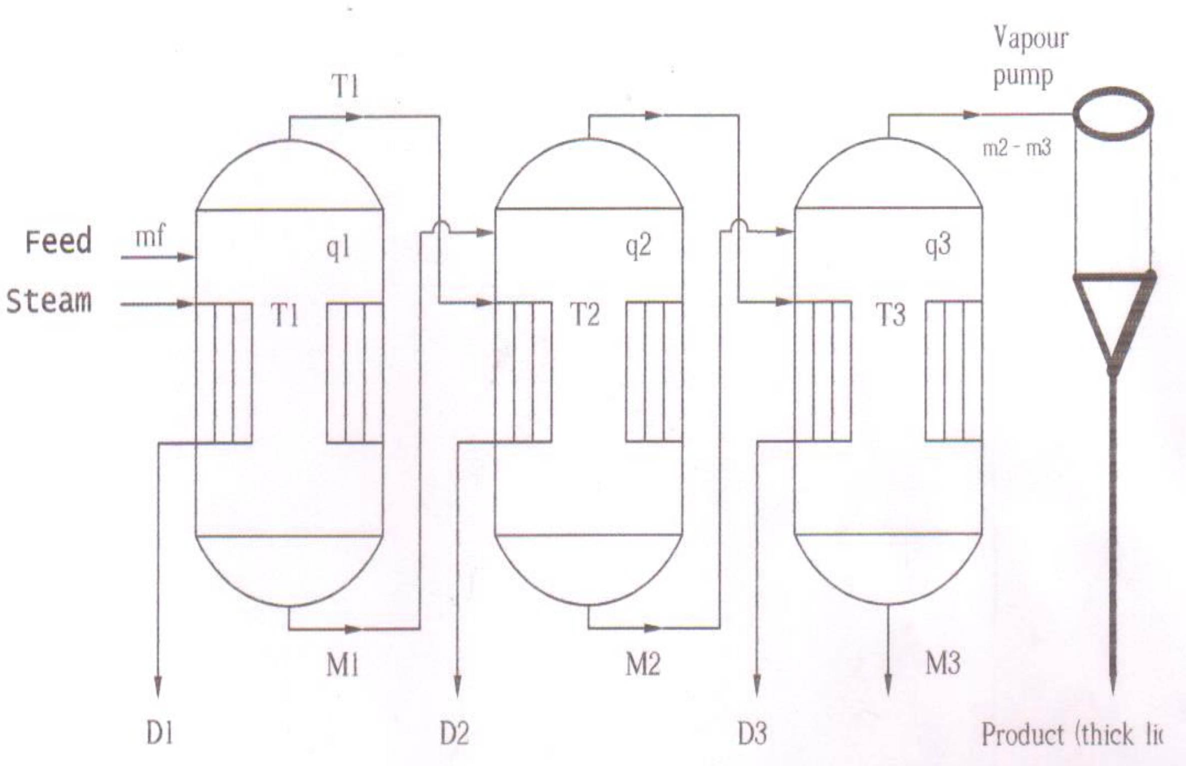
3.

3. Forward feed

- solution moves easy between evaporators.

- not required pumps.

- need control valves.



$P_1 > P_2 > P_3$

$T_1 > T_2 > T_3$

$q_1 = U_1 A_1 \Delta T1 \quad (\Delta T1 = Ts - T1)$

$q_2 = U_2 A_2 \Delta T2 \quad (\Delta T2 = T1 - T2)$

$q_3 = U_3 A_3 \Delta T3 \quad (\Delta T3 = T2 - T3)$

$q_1 = q_2 = q_3 = q$

$A_1 = A_2 = A_3 = A$

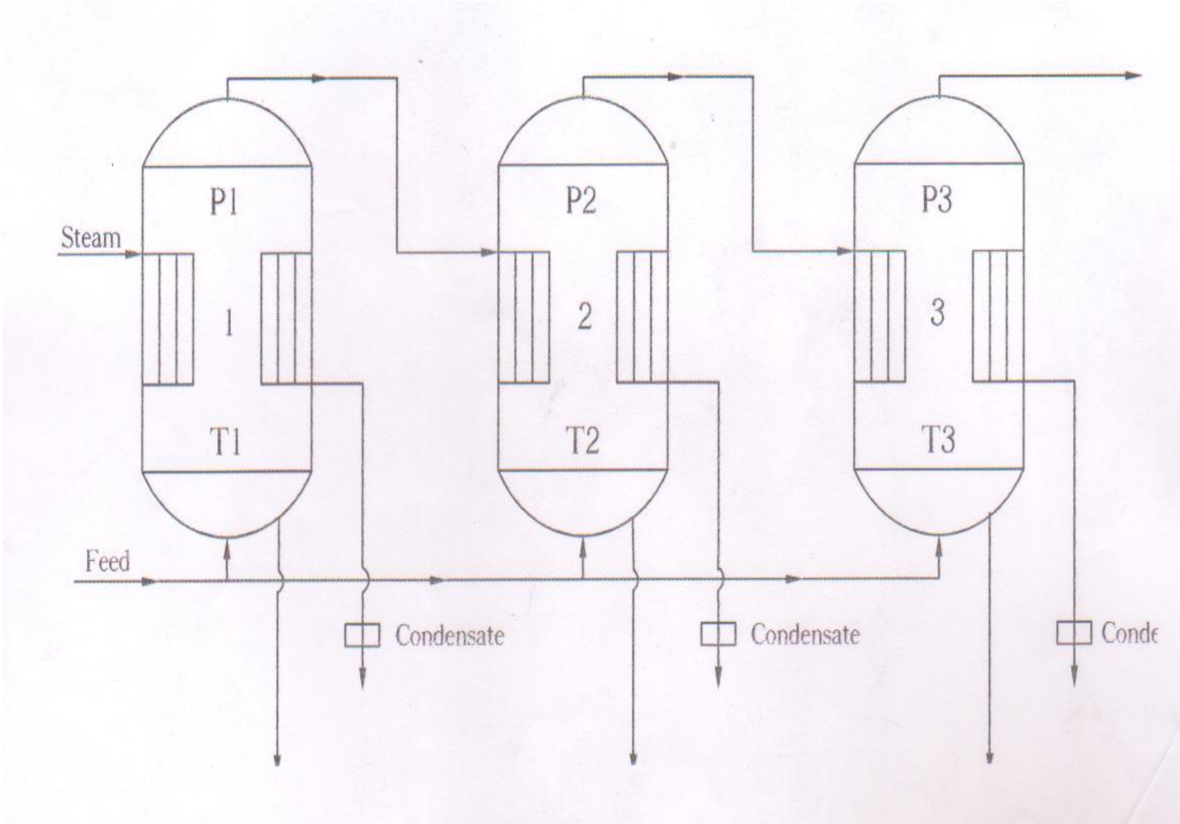
$\frac{q}{A} = U1\, \Delta T1 = U2\, \Delta T2 = U3\, \Delta T3$

Methods of feeding in multi effect evaporators

1.<u>paralell feed</u>

- product from each evap.

- used for crystalline solution.



2.<u>back flow feed</u>

- need pump.

- give high.