MODULE II

MECHANISM OF HEAT TRANSFER BY CONDUCTION , CONVECTION, RADIATION AND EVAPORATION

2.1.1 Define conduction ,Convection, Radiation

2.1.2 Define thermal conductivity and Fourier’s law of thermal conduction

2.1.3 Derivation of conduction equation for a plane wall

2.1.4 Solve the simple problems based on Fourier’s law and conduction in plane wall

2.1.5 Derive the equation to calculate heat transfer through composite plane wall

2.1.6 Derive the equation to calculate heat transfer through cylindrical wall

2.1.7 Derive the equation to calculate heat transfer through spherical wall

2.1.8 Solve the problems using the equation derived

2.1.9 Explain the mechanism of natural convection

2.1.10 Explain the heat transfer in boiling liquid and regimes of boiling

2.1.11 An elementary idea of black body, gray body, emissivity, absorptivity, radiation laws and Stefan Boltzmann equation , Heat Transfer equipments

2.1.12 An idea of parallel flow, counter current flow and cross flow heat exchangers

2.1.13 Explain the working Shell and Tube Heat Exchanger and Double pipe heat exchanger with diagram

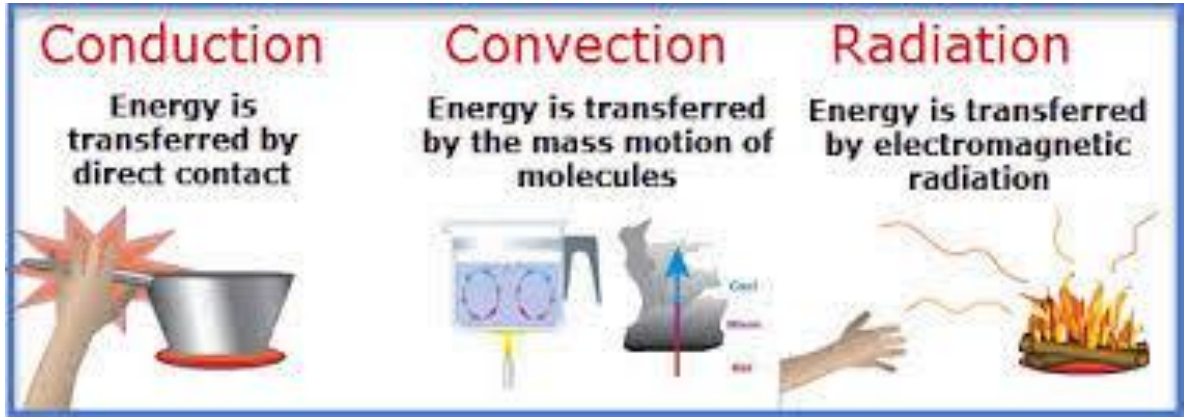
2.1.14 Mention the various types of evaporators and the basis for classification

2.1.15 Explain the working of horizontal, vertical and multiple effect evaporators

HEAT TRANSFER

- ✓ Deals with the study of rates at which exchange of heat takes place between a hot surface and a cold receiver.
- ✓ If two bodies at different temperatures are brought into thermal contact, heat flows from a hot body to a relatively cold body.
- ✓ The net flow of heat is always in the direction of decrease in temperature.
- ✓ Thus heat is defined as a form of energy which is in transit (transfer) between a hot source and a cold receiver.
- ✓ The transfer of heat depends upon the temperature of the bodies.

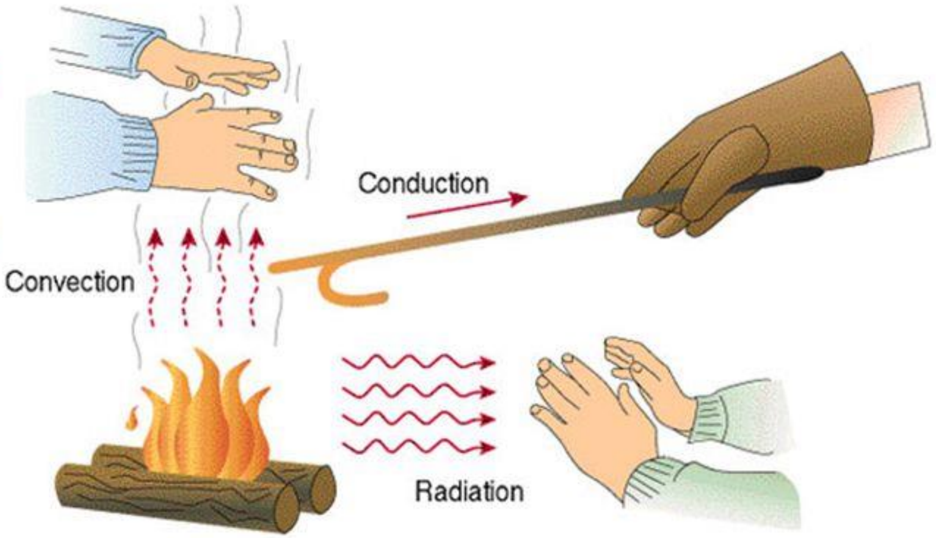
MODES OF HEAT TRANSFER



How is Heat Transferred?

There are THREE ways heat can move.

- Conduction
- Convection
- Radiation



MODES OF HEAT TRANSFER

HEAT TRANSFER

Conduction is the transfer of heat from one part of a body to another part of the same body or from one body to another which is in physical contact with it.

Convection is the transfer of heat from one point to another point within a fluid (gas or liquid) by mixing of hot and cold portions of the fluid. Convection is restricted to the flow of heat in fluids.

Radiation refers to the transfer of heat energy from one body to another through space by electromagnetic waves

Different ways of heat transfer

CONDUCTION

- Conduction refers to the mode of heat transfer in which heat flow though the material medium occurs without actual migration of particles of the medium from a region of higher temperature to a region of lower temperature
- Heat conduction occurs by the migration of molecules and more effectively by the collision of the molecules vibrating around relatively fixed positions

STEADY STATE UNIDIRECTIONAL HEAT CONDUCTION IN SOLIDS

- Steady state heat flow means the temperature at any location along the heat flow path does not vary with time and the rate at heat transfer does not vary with time
- Temperature varies with location but not with time

FOURIERS LAW/ LAW OF HEAT CONDUCTION

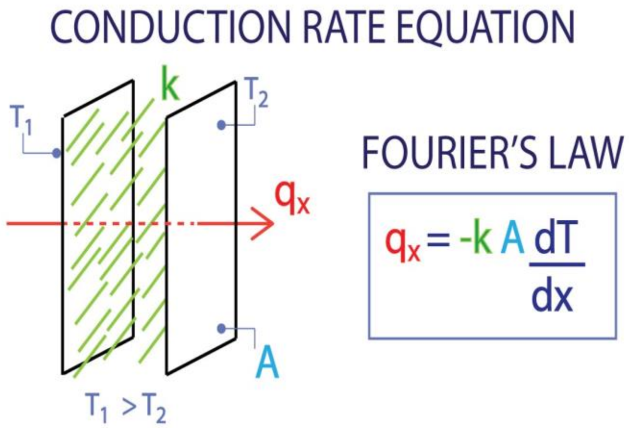
Fourier's law states that "rate of heat flow by conduction through a uniform (fixed) material is directly proportional to the area normal to the direction of the heat flow and the temperature gradient in the direction of heat flow.

OR

Fourier's law states that: "the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area."

Temperature gradient: the rate of change of temperature with displacement in a given direction, here temp gradient is negative since with an increase in n there is a decrease in T, i.e. temperature decreases in the direction of heat flow

FOURIERS LAW/ LAW OF HEAT CONDUCTION



Where,

'Q' is the rate of heat flow/transfer by conduction (Watts, W)

'K' is the thermal conductivity of body material ($Wm^{-1}K^{-1}$)

'A' is the cross-sectional area normal to direction of heat flow (m^2)

'dT/dx' is the temperature gradient (Km^{-1})

Heat flux is defines as the rate of heat flow per unit area or amount of heat transfer per unit area per unit time in W/m^2 (heat flux, q = Q/A)

$$\boxed{\underline{q} = -k\,\nabla T}$$

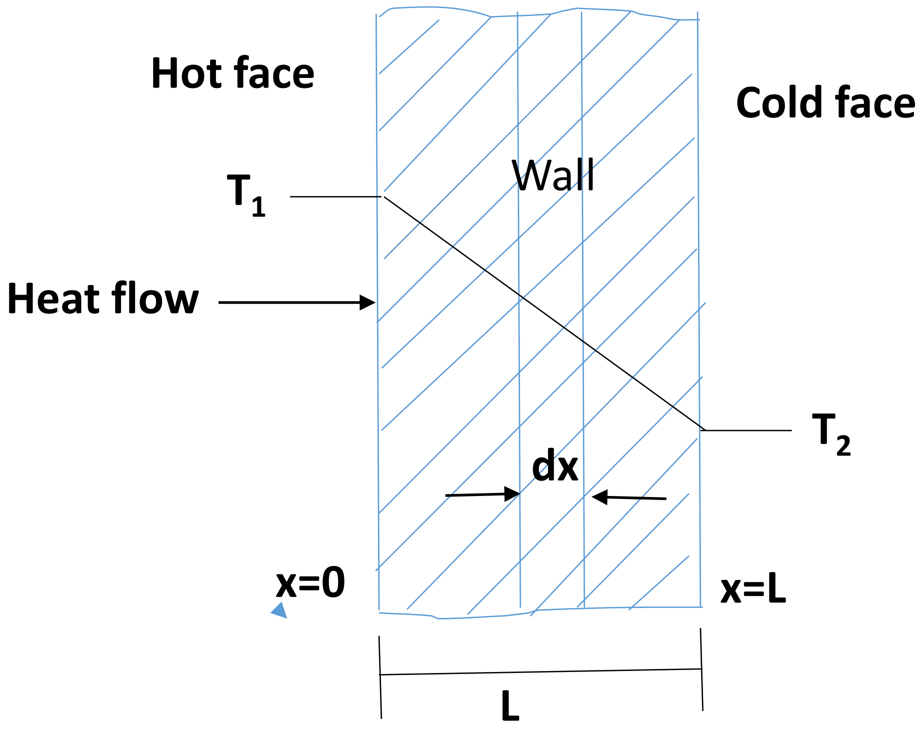
THERMAL CONDUCTIVITY

- Measure of the ability of a substance to conduct heat.
- **Thermal conductivity is the quantity of heat passing through a quantity of material of unit thickness with unit heat flow area in unit time when a unit temperature difference is maintained across the opposite faces of material.**
- Thermal conductivity depends on the nature of material and its temperature.
- Larger the values of K, higher will be the amount of heat conducted by that substance.
- It is a characteristics/transport properties of a material through which heat is flowing and varies with temperature.
- Thermal conductivities of solids are higher than that of liquids and liquids are having higher thermal conductivities than gases. { Metals : good conductors of heat}

CONDUCTION THROUGH PLANE WALL

- Consider that the wall is made of a material of thermal conductivity, K and is of uniform thickness (x) and constant cross sectional area (A).
- Assume that k is independent of temperature and area of wall is very large in comparison with the thickness so that heat losses from the edges are negligible.
- A hot face is at a temperature T_1 and cold face at a temperature T_2 and both are isothermal surfaces (Surface, at all points of which the temperature is the same).
- The direction of heat flow is perpendicular to the wall and T varies in the direction of x-axis.

Consider a plane / flat wall as in figure



CONDUCTION THROUGH PLANE WALL

As in steady state, Q is constant along the path of heat flow. The Fourier's law equation can be integrated over the entire path from =0 to x=L (total thickness of the wall)

$$\dot{Q}_{cond,wall} = -k\,A\,\frac{dT}{dx} \qquad \text{(Fourier's law of conduction)} \qquad \rightarrow \quad 1$$

The variables in (1) are x and T

$$\int_{x=0}^{x=L} \dot{Q}_{cond,wall}\,dx = -\int_{T_1}^{T_2} kA\,dT \qquad \dot{Q}_{cond,wall} = k\,A\,\frac{T_1 - T_2}{L} \qquad \rightarrow \quad 2$$

Rearranging the above equation

$$\boxed{\dot{Q}_{cond,wall} = \frac{T_1 - T_2}{\left(\frac{L}{kA}\right)}} \qquad \rightarrow \quad 3 \qquad \boxed{\text{Thermal resistance, } R_{wall} = \left(\frac{L}{kA}\right)}$$

$$\dot{Q}_{cond,wall} = \frac{T_1 - T_2}{(R_{wall})}$$

CONDUCTION THROUGH PLANE WALL

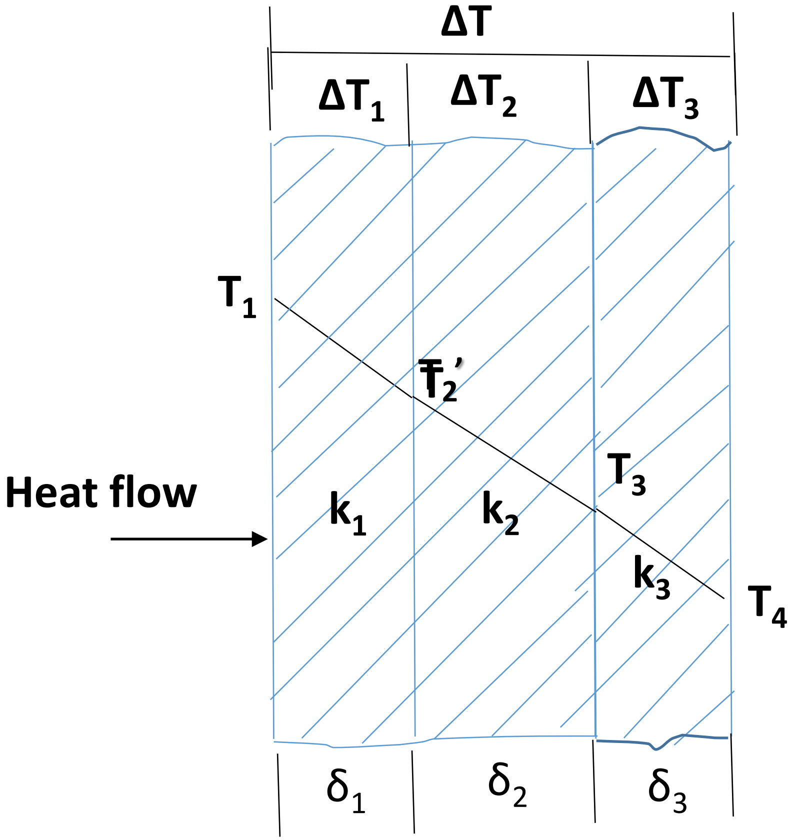
The reciprocal of resistance is called conductance, which for heat conduction is

Conductance = 1/ R = KA/L

Both the resistance and conductance depends upon the dimensions of a solid as well as on the thermal conductivity, a property of material.δ

CONDUCTION THROUGH COMPOSITE WALL

- Consider a flat wall constructed of a series of layers of three different materials.
- Let k_1, k_2 and k_3 be the thermal conductivities of the material of which layers are made.
- Let thickness of the layers be δ_1, δ_2 and δ_3 respectively.
- Let ΔT_1 be the temperature drop across the first layer, ΔT_2 that across the second layer and ΔT_3 that across the third layer.
- Let ΔT be the temperature drop across the entire composite wall.



CONDUCTION THROUGH COMPOSITE WALL

- Let T_1, T_2, T_3 and T_4 be the temperature at the faces of walls. T_1 is the temperature of the hot face and T_4 is the temperature of the cold face, assume that the layers are in excellent thermal contact.
- Let the area of the composite wall be A.

Over all temperature drop is related to the individual temperature drops over the layers by the equation

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

In the steady-state condition, the heat flow q is the same for all the layers and is constant. The equations of heat transfer through these layers

$$q = k_1 A \frac{T_1 - T_2}{\delta_1} \quad \text{for the first layer} \qquad \text{(i)}$$

$$q = k_2 A \frac{T_2 - T_3}{\delta_2} \quad \text{for the second layer} \qquad \text{(ii)}$$

$$q = k_3 A \frac{T_3 - T_4}{\delta_3} \quad \text{for the third layer.} \qquad \text{(iii)}$$

CONDUCTION THROUGH COMPOSITE WALL

The temperature differences across the layers, from above equations, are

$$T_1 - T_2 = q\left(\frac{\delta_1}{k_1 A}\right)$$

$$T_2 - T_3 = q\left(\frac{\delta_2}{k_2 A}\right)$$

$$T_3 - T_4 = q\left(\frac{\delta_3}{k_3 A}\right)$$

Adding the above equations, we get

$$T_1 - T_4 = q\left(\frac{\delta_1}{k_1 A} + \frac{\delta_2}{k_2 A} + \frac{\delta_3}{k_3 A}\right)$$

or

$$q = \frac{T_1 - T_4}{\dfrac{\delta_1}{k_1 A} + \dfrac{\delta_2}{k_2 A} + \dfrac{\delta_3}{k_3 A}}$$

R_1 , R_2, R_3 be the thermal resistance offered by layer 1,2 and 3

or

$$q = \frac{T_1 - T_4}{R_1 + R_2 + R_3}$$

CONDUCTION THROUGH COMPOSITE WALL

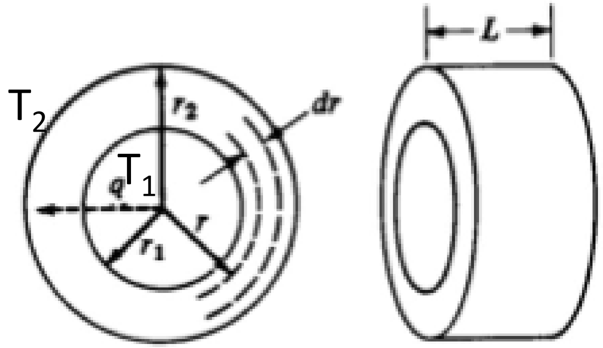
If R is the overall resistance, $R = R_1 + R_2 + R_3$

Therefore equation becomes $Q = \Delta T / R$

The temperatures at the interface of layers can be calculated using

$\Delta T / R = \Delta T_1 / R_1 = \Delta T_2 / R_2 = \Delta T_3 / R_3$

CONDUCTION THROUGH CYLINDER



- Consider a thick walled hollow cylinder of inside radius r_1, outside radius r_2, and length L. let k be the thermal conductivity of the material of cylinder

- let the temperature of inside and outside surface be T_1 and T_2 . Assume $T_1 > T_2$, heat flows from inside of the cylinder to outside

- Consider a very thin cylinder concentric with the main cylinder of radius r , where r is in between r_1 and r_2 , thickness of wall be dr

  - Rate of heat flow at any radius r is given by

$$q_r = -kA_r \frac{dT}{dr}$$

$$q_r = -2\pi krL \frac{dT}{dr}$$

❖ Rearranging the above equation and integrating between the limits

Heat conduction through hollow cylinder

$$\dot{Q}_{cond,cyl} = -k\,A\,\frac{dT}{dr}$$ (Fourier's law of conduction)

$$\int_{r_1}^{r_2} \frac{\dot{Q}_{cond,cyl}}{A}\,dr = -\int_{T_1}^{T_2} k\,dT$$

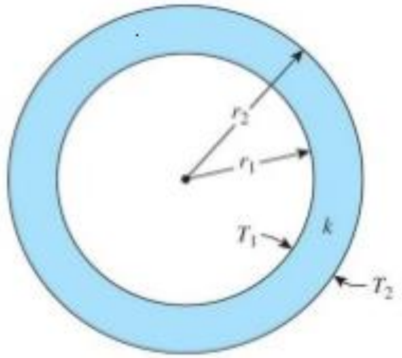
$A = 2\pi r L$

$$\dot{Q}_{cond,cyl} = 2\pi L k\,\frac{T_1 - T_2}{\ln(r_2/r_1)}$$

L= length of cylinder

$$\boxed{\dot{Q}_{cond,cyl} = \frac{T_1 - T_2}{\left(\frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L k}\right)}}$$ (Rearranging above equation)

$$\dot{Q}_{cond,cyl} = \frac{T_1 - T_2}{(R_{cyl})}$$ (Thermal Resistance Concept)

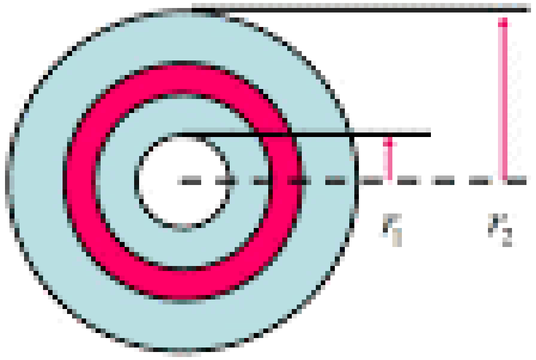


$$Q = -k\,\frac{2\pi L}{\ln\left(\frac{r_2}{r_1}\right)}(T_2 - T_1)$$

CONDUCTION THROUGH SPHERES

Geometric Considerations

Heat Conduction Through Hollow Spheres



$$\frac{Q}{A} = -k\frac{dT}{dr}$$

$$A = 4\pi r^2$$

$$\int \frac{Q}{4\pi r^2}dr = -k\int dT$$

Integrating both sides: $$\left(\frac{1}{r_1} - \frac{1}{r_2}\right)Q = -\frac{4\pi}{k}(T_2 - T_1)$$

$$\int_1^2 dt = -\int_1^2 \frac{\dot{Q}}{KA}dr$$

$$or, t_2 - t_1 = -\frac{\dot{Q}}{k}\int_1^2 \frac{dr}{4\pi r^2}$$

$$or, t_2 - t_1 = -\frac{\dot{Q}}{4\pi k}\left[-\frac{1}{r}\right]_1^2$$

$$or, t_1 - t_2 = -\frac{\dot{Q}}{4\pi k}\left[\frac{1}{r_1} - \frac{1}{r_2}\right]_1^2$$

$$or, \dot{Q} = \frac{4\pi k r_1 r_2 (t_1 - t_2)}{(r_2 - r_1)}$$

CONVECTION

- Convection is the transfer of heat from one point to another point within a fluid by mixing of hot and cold portions of the fluid.
- Heat transfer by convection occurs as a result of the movement of fluid on a macroscopic scale in the form of circulating current.
- The circulating currents may be set up either by heat transfer process itself or some external agency.
- There are two types of convection
    - Free or natural convection
    - Forced convection

FREE CONVECTION

- ✓ When the circulating currents arise from the heat transfer process itself
- ✓ i.e. from the density differences arising in turn due to temperature differences within the fluid mass, the mode of heat transfer is called free or natural convection.

Examples of natural convection:

Boiling water - The heat passes from the burner into the pot, heating the water at the bottom. Then it expands and rises because its density has become less than that of the remaining liquid. Cold water of higher density takes its place and moves down to replace it, causing a circular motion.

FORCED CONVECTION

- When the circulating currents are produced by an external agency, such as an agitator in a reaction vessel, pump, fan or blower, the mode of heat transfer is called forced convection.
- Here fluid motion is independent of density gradients.

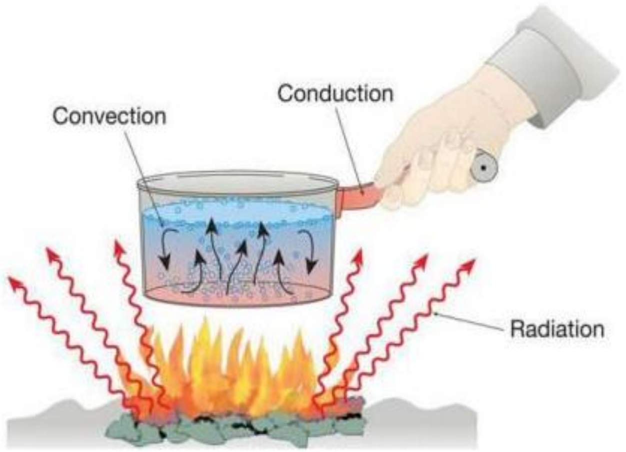
Examples

1. Heat flow to a liquid pumped through a heated pipe.
2. Heat or cool a home efficiently, such as using a fan.
3. Cooling of Internal combustion engines with fan in a radiator
4. Cooling in heat exchangers and in nuclear reactors

MECHANISM OF FREE CONVECTION

- In natural convection, the fluid motion occurs by natural means such as buoyancy.
- Buoyancy forces are developed due to density variations in the fluid caused by the temperature difference between the fluid and the adjacent surface.
- Since the fluid velocity associated with natural convection is relatively low, the heat transfer coefficient encountered in natural convection is also low.

RADIATION



- Radiation refers to the transport of energy through space by electromagnetic waves.
- Depends upon the electromagnetic waves as a means of transfer of energy from a source to a receiver.
- Mechanism of transmission is photon emission, this mode of energy transfer does not require any medium.
- The significance of this is that radiation will be the only mechanism for heat transfer whenever a vacuum is present.

Examples of heat transfer by radiation

- Transfer of heat from the sun to the earth
- Use of energy from the sun in solar heaters
- Heating of a cold room by a radiant electric heater

RADIATION

ABSORPTIVITY, REFLECTIVITY AND TRANSMISSIVITY

- Any substance receives and emits energy in the form of electromagnetic waves.
- When energy emitted by a heated body falls on a second body, it will be partly absorbed, partly reflected back and partly transmitted through the body.
- It is only the absorbed energy that appears as a heat in the body

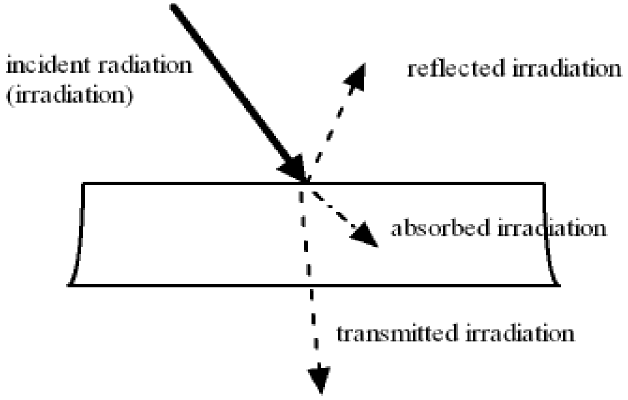
  I.e. incident radiation = heat absorbed + heat transmitted + heat reflected
- The proportions of the incident energy that are absorbed, reflected and transmitted depends on the characteristics of a receiver.

RADIATION

Fraction of the incident radiation on a body that is absorbed **absorptivity** (a).

Fraction of the incident radiation on a body that is reflected **reflectivity (r).**

Fraction of the incident radiation on a body that is transmitted through the body is known as **transmissivity (τ).**



The energy balance about a receiver on which the total incident energy falling is unity (sum of all fractions is unity) $a + r + \tau = 1$

For an opaque material, $a + r = 1$ since $\tau = 0$; For perfectly transparent $\tau = 1$, $a = r = 0$

For non-reflecting surfaces $r = 0$, $r = 1$, perfectly reflector $a = 1$, perfectly absorbing surface or a black surface

RADIATION

BLACK BODY

- A body for which $a = 1$, $r = \tau = 0$, i.e. which absorbs all the incident radiant energy is called a black body.
- It neither reflects nor transmits but absorbs all the radiations incident on it, so it is treated as an ideal radiation receiver.
- The black body radiates maximum amount of energy at a given temperature.
- Lamp black is the nearest to a black body which absorbs 96 % of the visible light.
- Both the absorptivity and emissivity of perfectly black body are unit.

RADIATION

Monochromatic emissive power: It is the radiant energy emitted from a body per unit area per unit time per unit wavelength. It is denoted by E_{λ}. It has the unit of $W/(m^2\ \mu m)$.

Monochromatic emissivity: it is the ratio of monochromatic emissive power of a body to that of a black body at the same wavelength and temperature.

Gray body

A gray body is defined a body whose absorptivity of a surface does not vary with variation in temperature and wavelength of the incident radiation. I.e. A body having the same value of the monochromatic emissivity at all wavelengths is called a gray body and the emissivity is independent of wavelength.

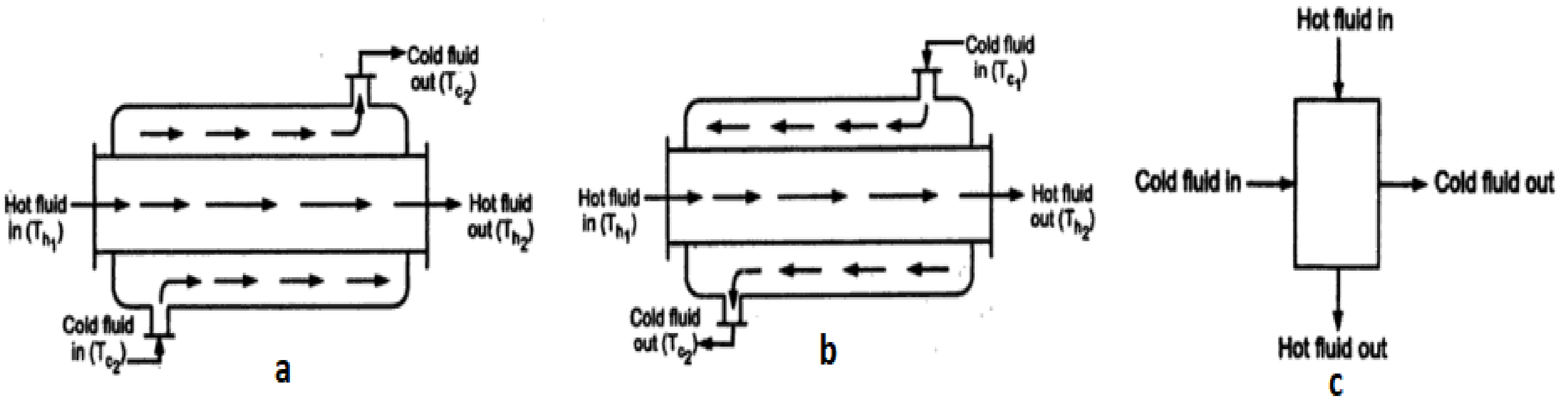
HEAT EXCHANGER FLOW PATTERNS

A heat exchanger is a device used for exchanging heat between two fluids that are at different temperatures. There are three basic flow patterns/ arrangements

- Parallel flow/ Co-current flow
- Counter current flow
- Cross-flow

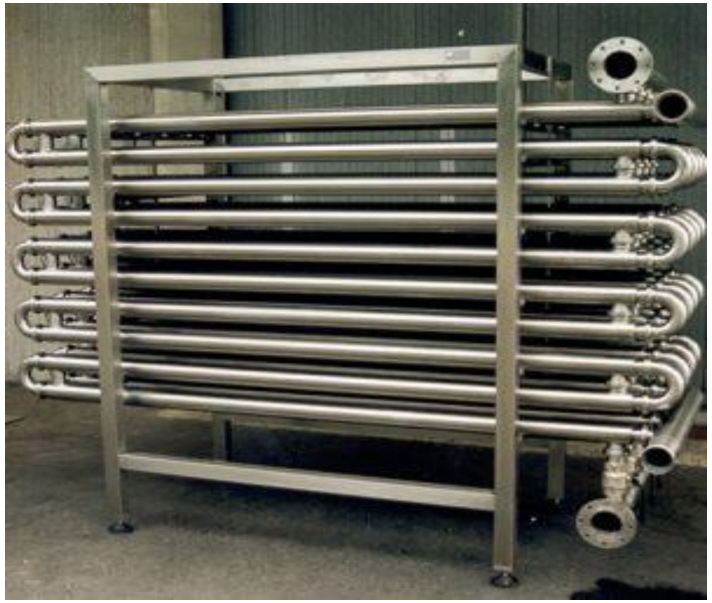
HEAT EXCHANGER FLOW PATTERNS

Double pipe heat exchanger wherein a hot fluid is flowing through the inside pipe and a cold fluid through the annual space.



When both the fluids flow in the same direction from one end of a heat exchanger to the other end, then the flow is called **co-current or parallel flow (a)**. When the fluids are flowing through the heat exchangers in opposite directions, then the flow is called **counter current flow (b)**. When the fluids are directed at right angles to each other through a heat exchanger, then the flow arrangement is called **cross flow (c)**.

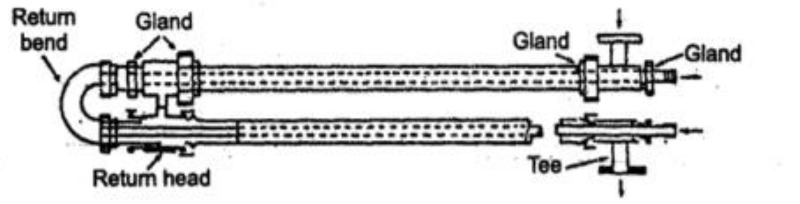
DOUBLE PIPE HEAT EXCHANGER



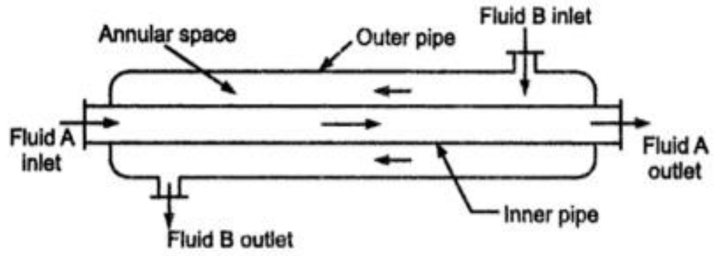
- Simplest type of heat exchanger used in industry and is used when the heat transfer area required is relatively small.
- Here one fluid flows inside a pipe and the other fluid flows between that pipe and another pipe that surrounds the first, i.e. a concentric tube construction.
- Flow in a double-pipe heat exchanger can be co-current or counter-current.
- There are two flow configurations: co-current is when the flow of the two streams is in the same direction, counter current is when the flow of the streams is in opposite directions.

DOUBLE PIPE HEAT EXCHANGER

- Consists of concentric pipes, connecting tees, return heads and return bends.
- Packing glands support the inner pipe within the outer pipe.
- Tees are provided with nozzles or screwed connections for permitting the entry and exit of the fluid.
- Return bend connects the two legs of the inner pipes to each other.
- In this type of exchanger, One of the fluid flows through the inside pipe and the other flows through the annular space between the two pipes.
- The wall of the inner pipe is the heat transfer surface.
- It is commonly used for decreasing the temperature of a hot fluid with the help of a cold fluid when flow rates are low.
- They are commonly used in refrigeration services.



Double pipe heat exchanger



: Schematic diagram of double pipe heat exchanger (counter current)

single hair-pin exchanger.

DOUBLE PIPE HEAT EXCHANGER

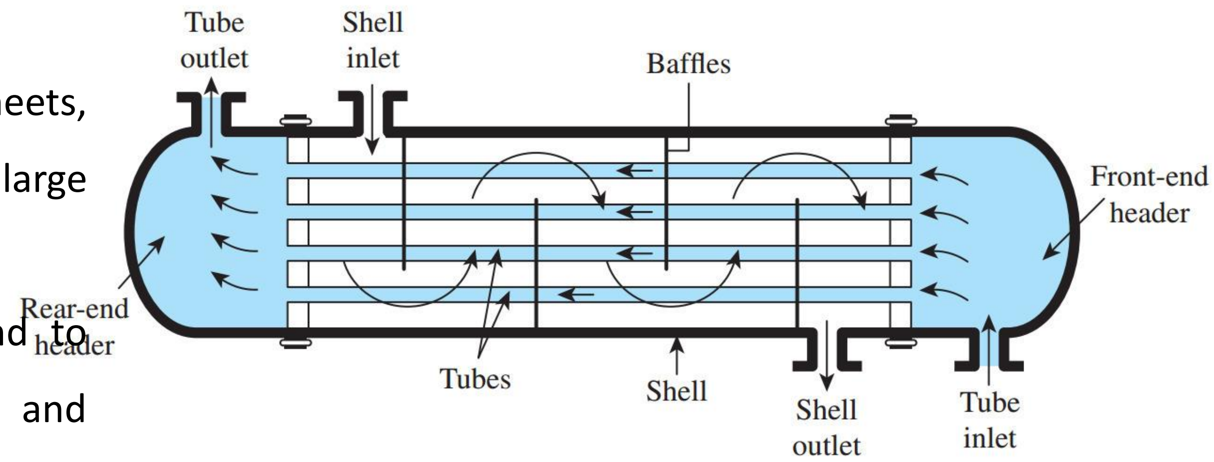
It is simple in construction, cheap and easy to clean.

The major disadvantages are:

- Small heat transfer surface in a large floor space as compared to other types
- Dismantling requires large time
- Maximum leakage points

These types of heat exchangers found their applications in heat recovery processes, air conditioning and refrigeration systems, chemical reactors, and food and dairy processes.

SHELL AND TUBE HEAT EXCHANGER



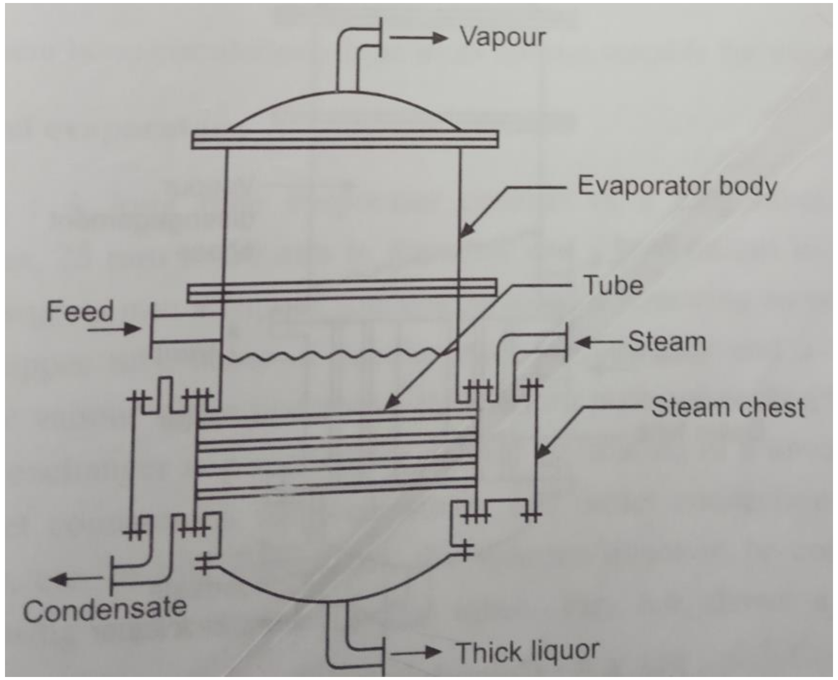
- Consists of number of parallel tubes, tube ends fixed in tube sheets, entire tube bundle enclosed in a close fitting cylindrical shell (large pressure vessel from carbon steel)
- Baffles – used inside the shell to hold tubes in position and to increase the rate of heat transfer by increasing velocity and turbulence of shell side fluid
- Heat transfer is offered by tubes
- One of the fluid flows through the tube, while outer fluid flows through the space created between tube and shell, outside the tubes
- Fluids are in thermal contact, but are physically separated by a metal wall of the tubes
- Heat flows through the metal wall of the tubes from hot fluid to cold fluid
- Fluid flowing through the tube - tube fluid
- Fluid flowing outside tube- shell fluid

EVAPORATORS

- Evaporation is a process in which a weak solution/liquor is concentrated by vapourising a portion of the solvent
- Here the solvent to be evaporated is generally water
- Concentrated solution/ thick liquor is the desired product
- Evaporation is generally followed by crystallisation and drying

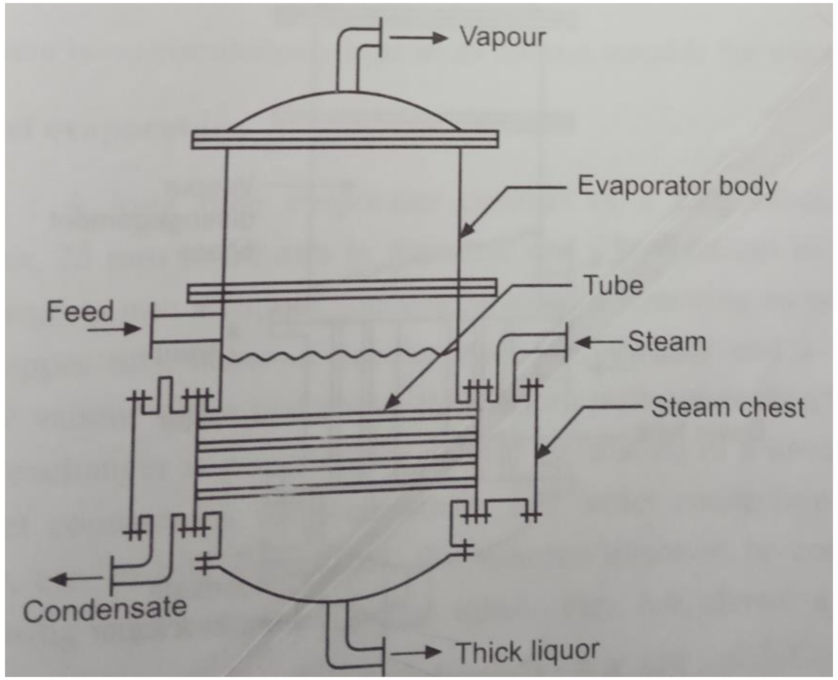
HORIZNTAL TUBE EVAPORATORS

- ✓ Consists of a vertical cylindrical shell incorporating a horizontal tube bundle at the lower portion of the shell
- ✓ Channels provided on either ends of the tube bundle for introduction of steam and withdrawal of condensate
- ✓ Vapour outlet provided on top cover, thick liquor outlet at the bottom
- ✓ Feed point located at a convenient point
- ✓ Steam admitted through the steam chests/ channels and flows through the tubes
- ✓ Liquid to be concentrated surrounds the tube
- ✓ Steam gets condensed by transferring its latent heat and condensate removed from the outlet provided at the bottom of the opposite steam chest



HORIZNTAL TUBE EVAPORATORS

- ✓ Heat given out by condensing steam will be gained by the solution in the evaporator and solution boils
- ✓ Vapours formed are removed from top, thick liquor removed from bottom



Advantages

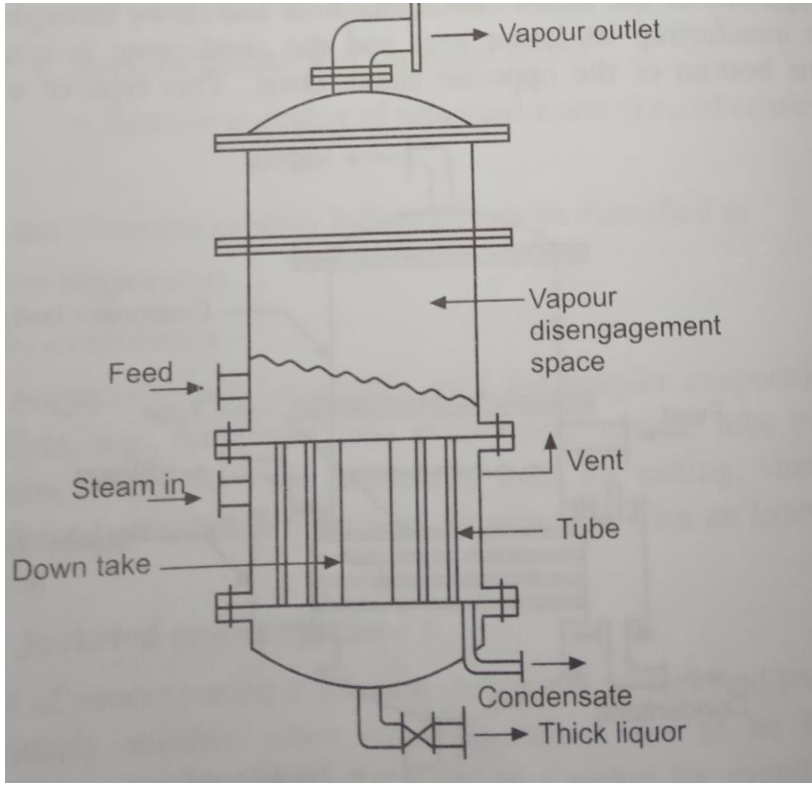
- ✓ Very low head room requirements, large vapour-liquid disengaging area

Disadvantages

- ✓ For small capacity services, not suitable for scaling and salting liquids

VERTICAL TUBE EVAPORATORS

- Consists of a vertical cylindrical shell incorporating a short vertical tube bundle at the lower portion of the shell
- Vapour outlet provided on top cover, thick liquor outlet at the bottom
- Down take provided at the centre of the tube bundle
- Solution to be evaporated is introduced to the tube, steam flows outside the tube in a steam chest
- Liquor covers the top of the tubes
- Heat transfer takes place by condensing steam on the outside of the tube
- Vapours formed rises through the tubes, comes to a liquid surface from which they are disengaged into vapour space and removed from vapour outlet
- Circulation of cold liquor is promoted by a central down take and concentrated solution removed from bottom



VERTICAL TUBE EVAPORATORS

ADVANTAGES	DISADVANTAGES
Inexpensive	Floor space required is large
Scaling can be easily removed by mechanical or chemical means	Amount of liquid hold up is large
Good heat transfer at reasonable cost	
High heat transfer coefficients	

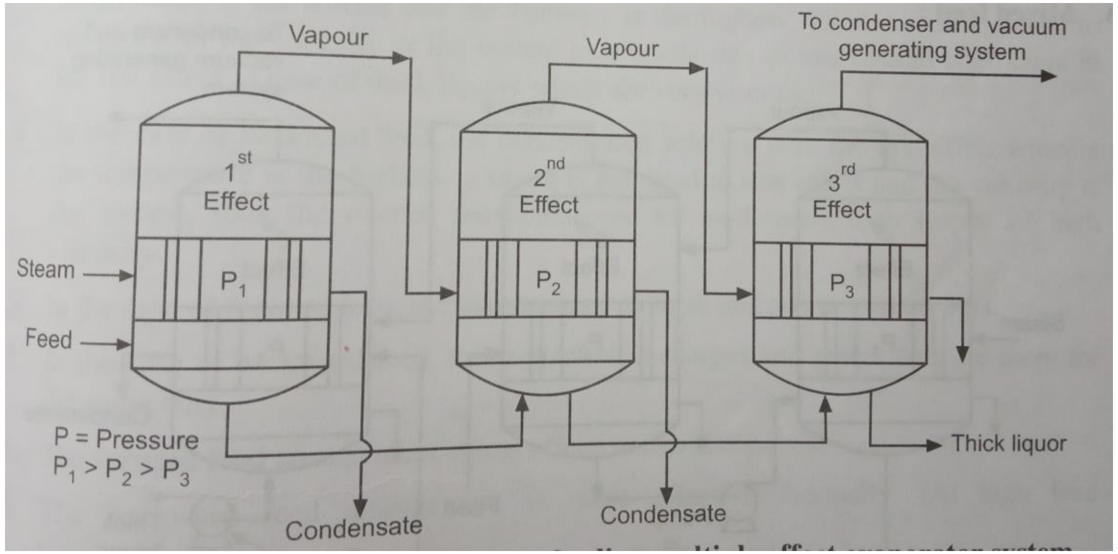
MULTIPLE EFFECT EVAPORATORS

- Here evaporators are arranged in series so that vapour from one evaporator is used as a heat medium for the next one that is operating under a pressure and temperature lower than the previous one
- Each unit in a series is called effect

METHOD OF FEEDING		
FORWARD FEED	BACKWARD FEED	MIXED FEED

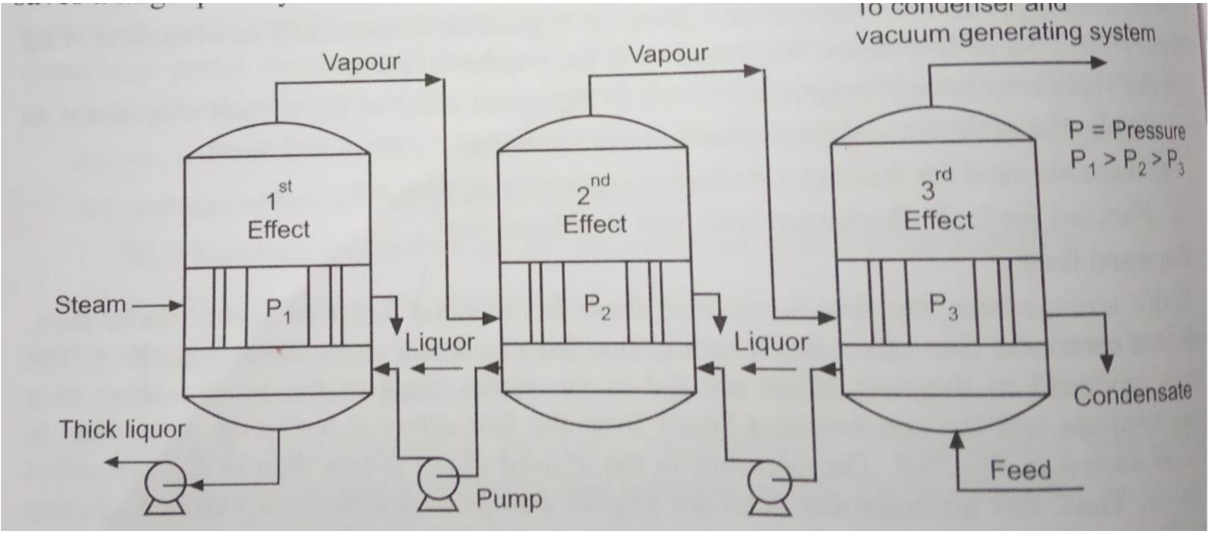
FORWARD FEED

- Liquid feed flows in the same direction as vapour flow
- Fresh feed enters the first effect and steam also fed to first effect
- Vapours produced are fed to steam chest of second effect as heating medium
- Concentrated liquor from first effect is fed to next effect in series



BACKWARD FEED

- Liquid feed and vapour flow in opposite direction to each other
- Fresh feed is admitted to last effect and pumped through other effects
- Steam admitted to steam chest of first effect and vapours produced are fed to steam chest of second effect
- Concentrated liquor is collected from the first effect



MIXED FEED

- Steam admitted to steam chest of first effect and vapours produced are fed to steam chest of second effect
- Feed solution is admitted to intermediate effect and flows to the first effect from which it is fed to the last effect for final concentration
- Concentrated liquor is collected from the third effect