4024 THERMAL ENGINEERING

MODULE 4

SALEEM N
LECTURER IN ME, KGPTC

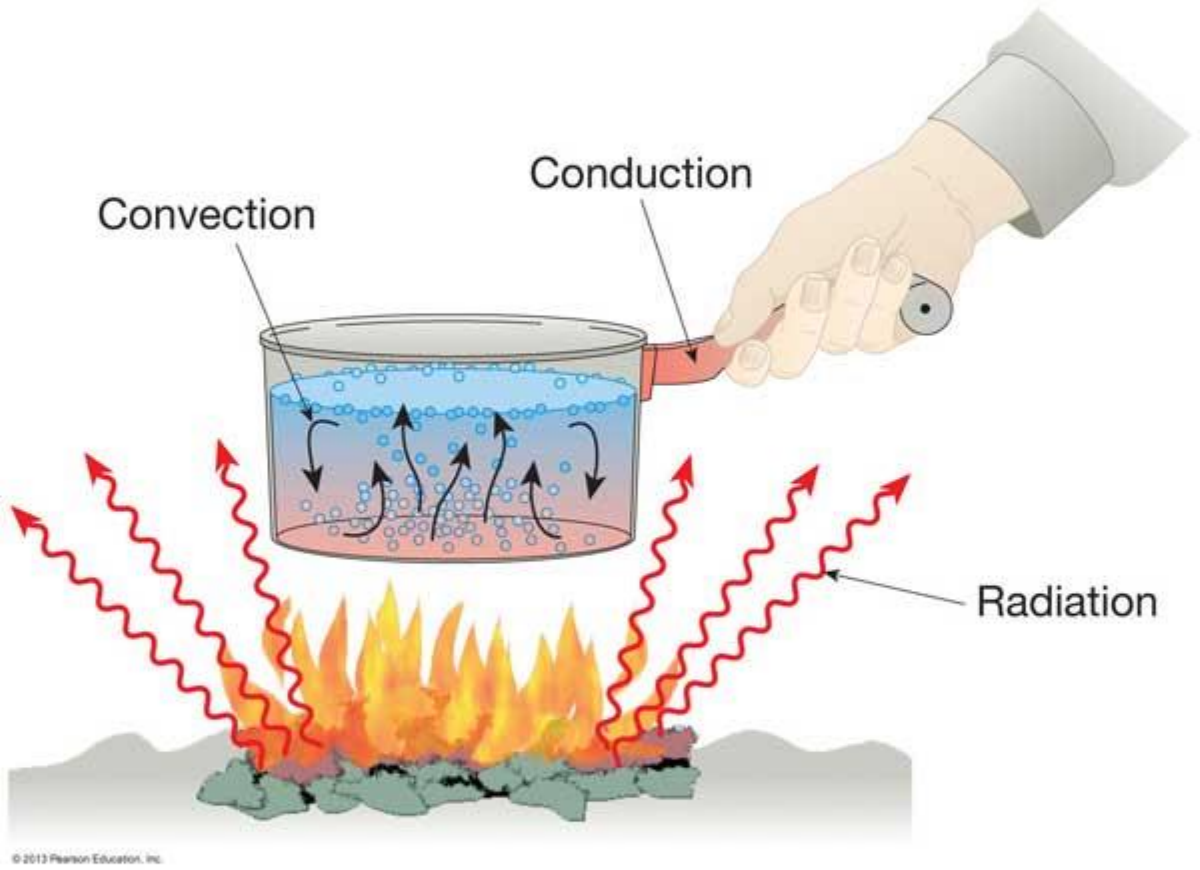
- 4.1.0 Explain the heat transfer and heat exchanger
- 4.1.1 Understand the various modes of Heat Transfer
- 4.1.2 Explain the three modes of heat transfer, conduction, convection and radiation
- 4.1.3 Explain Fourier's law of thermal conduction
- 4.1.4 Define Thermal conductivity
- 4.1.5 Simple problems on conduction through a plane wall and through a composite plane wall
- 4.1.6 Explain the thermal radiation – reflection, absorption and transmission
- 4.1.7 Define absorptivity, reflectivity and transmissivity
- 4.1.8 Explain the concept of a Black Body
- 4.1.9 Explain Stefan – Boltzman's law of total radiation
- 4.1.10 Explain the concept of Grey body
- 4.1.11 Explain Newton Rikhman equation of Thermal convection
- 4.1.12 Explain free convection and forced convection

- 4.2.0 Explain the basic principles of heat exchangers
- 4.2.1 Classify the heat exchangers – Recuperator type and regenerative type, parallel flow, counter flow type & cross flow.
- 4.2.2 Explain the concept of overall heat transfer coefficient & LMTD
- 4.3.0 Appreciate the air compressors
- 4.3.1 Explain the construction and working of Air compressors
- 4.3.2 State the function of an air compressor
- 4.3.3 State the uses of compressed air
- 4.3.4 Classify the air compressors
- 4.3.5 Explain with simple sketches the working of reciprocating (single stage and two stage) compressors, rotary (fans and blowers) compressors, centrifugal compressors and axial flow compressors.
- 4.3.6 State the expressions for work done on air and power required to drive compressors (single stage and two stages only) with the help of p-v diagrams (no derivation)
- 4.3.7 Compute the work done on air and power required to drive the compressor (single and two stage only)
- 4.3.8 State the functions of intercoolers
- 4.3.9 List the advantages of multistage compression
- 4.3.10 Define the efficiencies of air compressors – Mechanical efficiency, Isentropic efficiency, Isothermal efficiency & Volumetric efficiency
- 4.3.11 State the expression for volumetric efficiency in terms of clearance volume and stroke volume (no proof)
- 4.3.12 Compute the various efficiencies using the expressions mentioned in 4.1.8
- 4.3.13 Explain the effect of clearance on the volumetric efficiency of the compressor

HEAT TRANSFER

HEAT TRANSFER

- It is the science concerned with the determination of the rate at which heat energy is transferred from one body to another by virtue of temperature difference.
- Modes of heat transfer
- 1) Conduction
- 2) Convection
- 3) Radiation



CONDUCTION

- It is the only mode of heat transfer in a solid medium.
- It is an atomic or molecular process.
- In this, heat is transferred from particle to particle without the movement of particles.
- Eg:- heat loss from furnaces, hot pipes etc.

CONVECTION

- In this transfer of heat energy by the flow of fluid elements or liquid or gas from one point to another which is at a different temperatures.
- In this heat is transferred from particle to particle with the movement of particle.
- Eg:- water tube boiler, radiator of car etc.

RADIATION

- In this heat is transferred in the form of electromagnetic waves.
- Heat transfer due to radiation takes place from one body to another directly without affecting the medium through which heat travels, like the throw of an object.

FOURIER'S LAW OF HEAT CONDUCTION

- The rate of flow of heat through a simple homogenous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and to change of temperature with respect to the length of the path of the heat flow.
- $Q \propto A \frac{dT}{dx}$
- Where, Q = Heat flow through a body per unit time in watts (W)
- A = Surface area of heat flow in m^2
- dT = Temperature difference of the faces of block of thickness 'dx' through which heat flow in K.
- dx = Thickness of body in the direction of flow in 'm'.

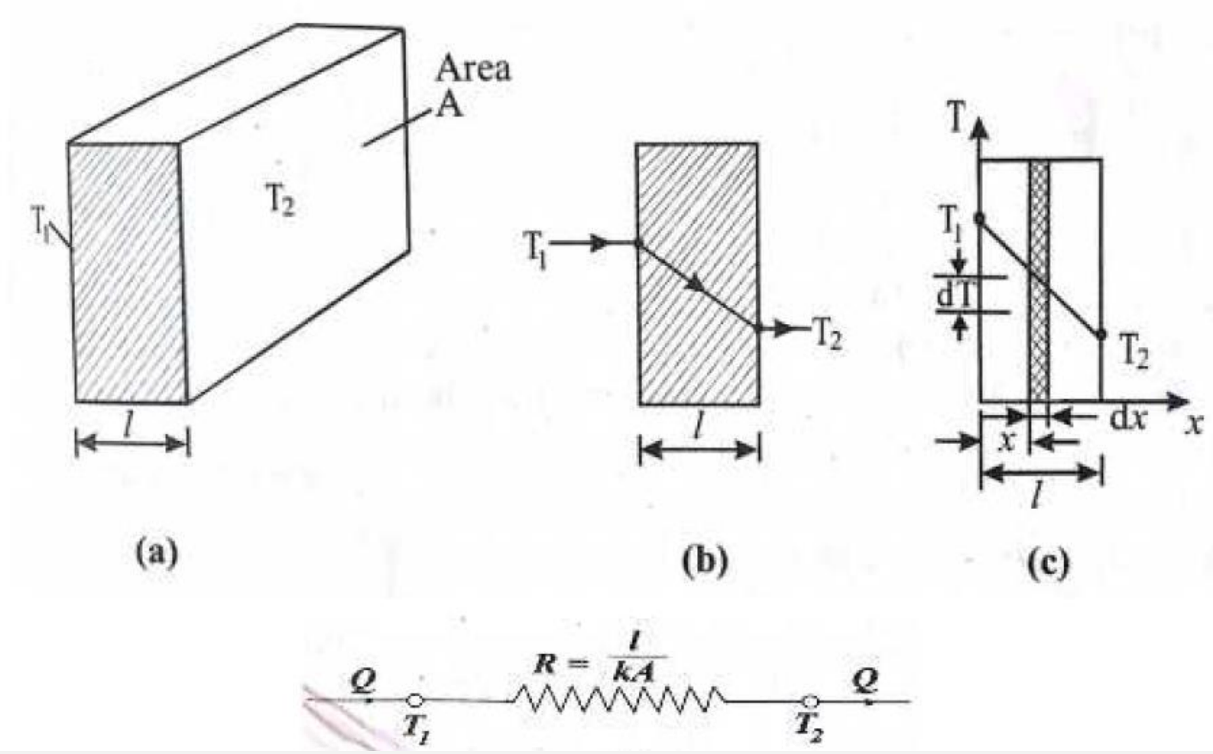
- **$Q = -k\,A\,\frac{dT}{dx}$**
- k = Constant of proportionality and is known as thermal conductivity of the body.
- **Negative sign indicates that decreasing temperature along with the direction of increasing thickness.ie, $\frac{dT}{dx}$ or temperature gradient is always negative.**
- Fourier law is also written as, **$Q = -\frac{dT}{\frac{dx}{kA}}$**
- Where, $\frac{dx}{kA}$ is known as **thermal resistance (R)**
- Ie, **$R = \frac{dx}{kA}$**

THERMAL CONDUCTIVITY

- k = - $\frac{Q}{A}\frac{dx}{dT}$
- It is the amount of energy conducted through a body of unit area, and unit thickness in unit time, when the difference in temperature between the faces causing heat flow is unity.
- Its unit is W/mK

CONDUCTION THROUGH A PLANE WALL

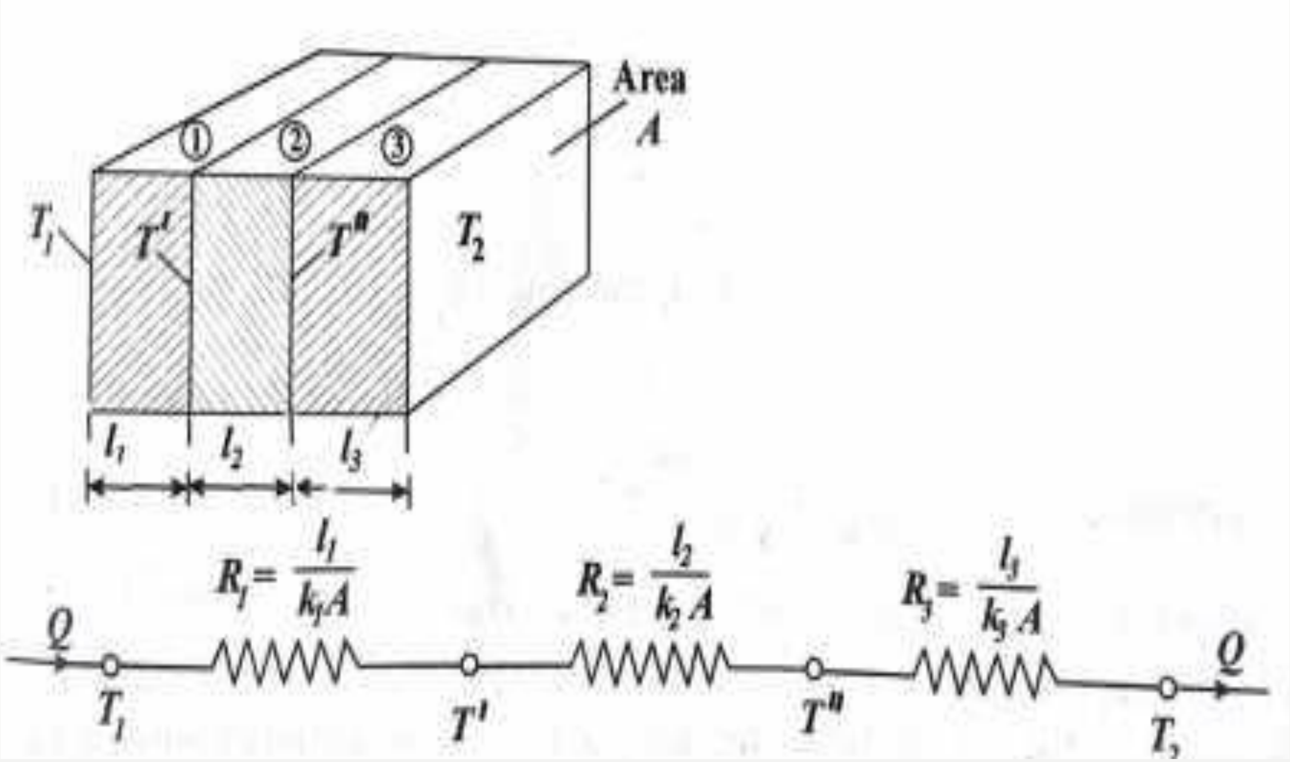
- Consider heat conduction through a homogenous wall of thickness *l* with constant thermal conductivity *k* and constant cross sectional area A normal to the direction of heat flow as shown.



- Let the wall faces are at different temperatures. Here the boundary conditions are, at x = 0, T = T_1 , at x = l, T = T_2
- Ie change in temperature, dT = T_2 - T_1
- According to fourier's law, **Q = -k A** $\frac{dT}{dx}$
- $$= -\mathbf{k}\ \mathbf{A} \frac{(\boldsymbol{T_2 - T_1})}{\boldsymbol{l}}$$
- $$= \mathbf{k}\ \mathbf{A} \frac{(\boldsymbol{T_1 - T_2})}{\boldsymbol{l}}$$
- $$= \frac{(T_1 - T_2)}{\frac{l}{kA}}$$
- $$\mathbf{Q} = \frac{(\boldsymbol{T_1 - T_2})}{\boldsymbol{R}}$$
- Where, R = $\frac{l}{kA}$ **thermal resistance.**

CONDUCTION THROUGH A COMPOSITE WALL

- Consider heat conduction through a composite wall consisting of three layers of materials 1,2 and 3 having thickness l_1 ,l_2 and l_3 and thermal conductivities k_1,k_2 and k_3 respectively.
- The area of heat conduction ‘A’ is constant.
- Therefore the rates of heat flow at steady state through the individual layers are equal.

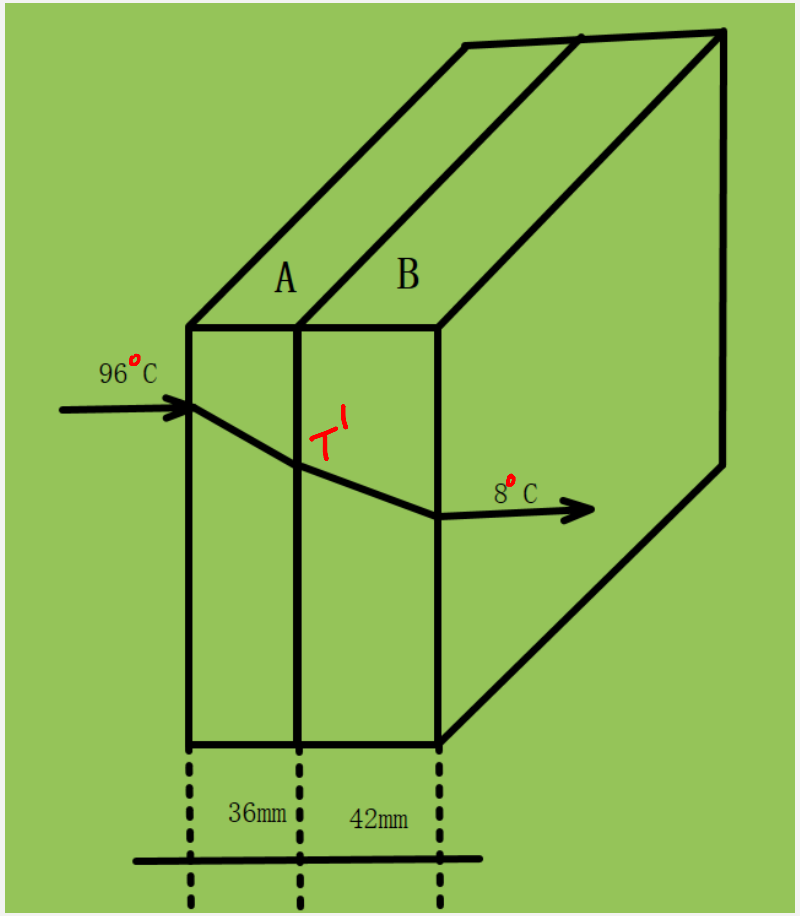


- The rates of heat flow through the walls are given by Fourier's law.
- Layer 1:
- Q = $k_1 A \frac{(T_1 - T^l)}{l_1}$
- $T_1 \ - \ T^l = Q \left(\frac{l_1}{k_1 \ A}\right)$
- $T_1 \ - \ T^l = Q \ R_1$ ……………………….(1)
- Layer 2:
- Q = $k_2 A \frac{(T^l - T^{ll})}{l_2}$
- $T^l - T^{ll} = Q \left(\frac{l_2}{k_2 \ A}\right)$
- $T^l - T^{ll} = Q \ R_2$ ……………………......(2)

- Layer 3:
- Q = $k_3 A \frac{(T^{ll} - T_2)}{l_3}$
- $T^{ll} - T_2$ = Q ($\frac{l_3}{k_3\ A}$)
- $T^{ll} - T_2$ = Q R_3 ……………………....(2)
- Adding equation (1), (2) and (3)
- $T_1\ -\ T^{l} + T^{l} - T^{ll} +\ T^{ll} - T_2$ = Q R_1 + Q R_2 + Q R_3
- T_1 - T_2 = Q ($R_1 + R_2 + R_3$)
- **Q =** $\frac{(\boldsymbol{T_1 - T_2})}{(R_1 + R_2 + R_3\ )}$
- Ie in general,
- Rate of heat transfer = Temperature difference/ Thermal resistance

Q.1. Heat is conducted through a composite plate composed of two parallel plates of different materials A and B of thermal conductivities 134 W/mK and 60 W/mK and thickness 36 mm and 42 mm respectively. The temperature of outer surface of slab A and B are 96^0C and 8^0C respectively. Find the rate of heat transfer and interface temperature if the cross sectional area of plate across direction of heat flow is 10 m^2.

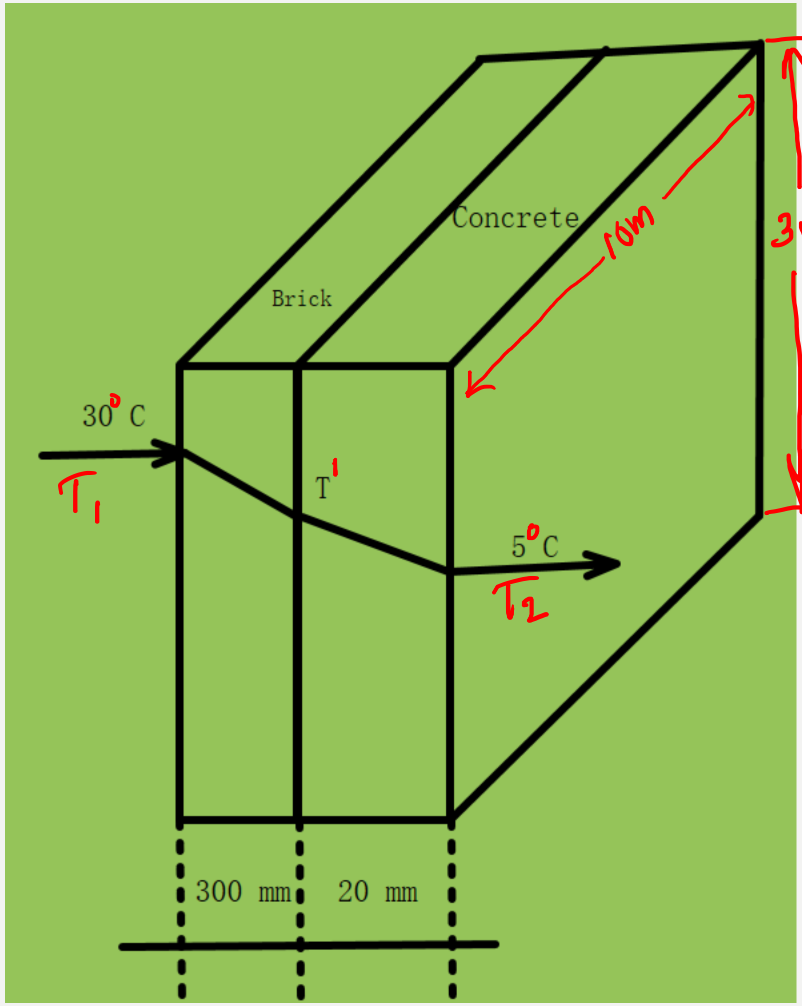
- Given data:
- $k_1 = 134$ W/mK
- $k_2 = 60$ W/mK
- $l_1 = 36$ mm $= 0.036$ m
- $l_2 = 42$ mm $= 0.042$ m
- $T_1 = T_A = 96^0C = 96 + 273 = 369$ K
- $T_2 = T_B = 8^0C = 8 + 273 = 281$ K
- $A = 10\ m^2$
- $Q = ?$
- $T^l = ?$



- $\mathbf{Q} = \dfrac{(T_1 - T_2)}{(R_1 + R_2)}$
- $R_1 = \dfrac{l_1}{k_1\,A}$
- $= \dfrac{0.036}{134\,x\,10}$ = 2.68 x 10^{-5} K/W
- $R_2 = \dfrac{l_2}{k_2\,A}$
- $= \dfrac{0.042}{60\,x\,10}$ = 7 x 10^{-5} K/W
- $\mathbf{Q} = \dfrac{(T_1 - T_2)}{(R_1 + R_2)}$
- $= \dfrac{(369-281)}{(2.68\,x\,10^{-5} + 7\,x\,10^{-5})}$
- = 909090.9 W
- **Q** = 909.09 kW
- Q = $\dfrac{(T_1 - T^l)}{R_1}$
- 909090.9 = $\dfrac{(369 - T^l)}{2.68\,x\,10^{-5}}$
- T^l = 344.6 K
- Ie, interface temperature = 344.6 K

Q.2. A brick wall 300 mm thick is faced with concrete 20 mm thick. If the temperature of the brick face is 30^0C and that of concrete is 5^0C. Determine the heat loss per hour through a wall of 10 m length and 3 m height. Determine the interface temperature. Thermal conductivities of brick and concrete are 0.69 W/m^{0}C and 0.93 W/m^{0}C

- Given data:
- l_1 = 300 mm = 0.3 m
- l_2 = 20 mm = 0.02 m
- $T_1 = 30^0C$
- $T_2 = 5^0C$
- Length = 10 m
- Height = 3 m
- Area = 10 x 3 = 30 m^2
- k_1 = 0.69 W/m^{0}C
- k_2 = 0.93 W/m^{0}C
- T^l = ?, Q = ?



- **Q** = $\dfrac{(T_1 - T_2)}{(R_1 + R_2)}$
- $R_1 = \dfrac{l_1}{k_1\ A}$
- $= \dfrac{0.3}{0.69\ x\ 30}$ = 0.0145 K/W
- $R_2 = \dfrac{l_2}{k_2\ A}$
- $= \dfrac{0.02}{0.93\ x\ 30}$ = 7.16 x 10^{-4} K/W
- **Q** = $\dfrac{(T_1 - T_2)}{(R_1 + R_2)}$
- $= \dfrac{(30-5)}{(0.0145 + 7.16\ x\ 10^{-4})}$
- **Q** = 1643 W
- = 1643 J/s

- Rate of heat transfer per hour,
- Q = 1643 x 3600 = 5914800 J
- Q = $\dfrac{(T_1 - T^l)}{R_1}$
- 1643 = $\dfrac{(30 - T^l)}{0.0145}$
- T^l = 6.2 ^{0}C
- Ie, interface temperature = 6.2 ^{0}C

THERMAL RADIATION

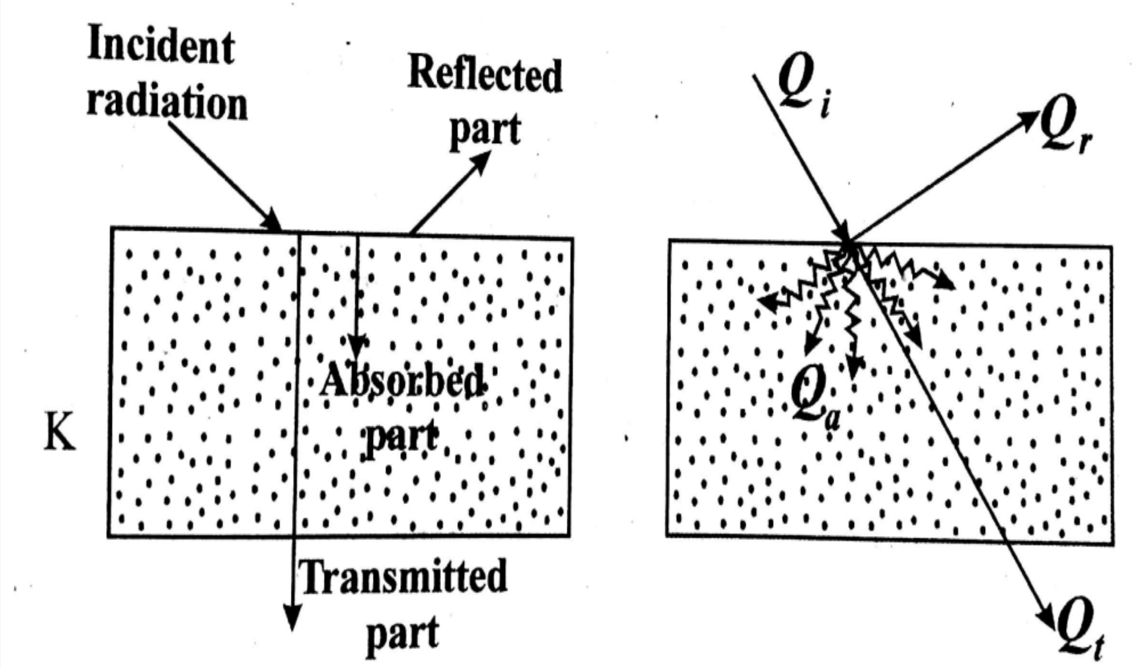
- The transmission of thermal energy without any physical contact between the bodies is known as thermal radiation.
- It is emitted by a body in the form of electromagnetic waves.
- A body at absolute zero temperature does not emit any radiation.

BASIC CONCEPTS OF RADIATION FROM A SURFACE

- If Q_i is the incident radiant energy falling on a body as shown in fig.

- Some part of it will be absorbed say Q_a, some part of it is reflected from the surface say Q_r and some will be transmitted through the body say Q_t, then the energy balance yields.

- $Q_i = Q_a + Q_r + Q_t$



- Dividing the above equation by Q_i, we have
- $\frac{Q_a}{Q_i} + \frac{Q_r}{Q_i} + \frac{Q_t}{Q_i} = 1$
- If α is the fraction of total energy absorbed, ρ is the fraction of total energy reflected and τ is the fraction of total energy transmitted, then we have,
- $\alpha + \rho + \tau = 1$
- A surface which absorbs incident radiation of all wave length is black, where as a surface that reflects incident radiation of all wave length is called white.

- Most solids do not transmit any radiation.
- The word opaque describes a body that transmits none of the energy that is incident upon it.
- In such case, we have , $\tau = 0$, and $\alpha + \rho = 1$
  - For an opaque black surface, $\rho = 0$ and $\tau = 0$, ie $\alpha = 1$
  - For an opaque white surface, $\alpha = 0$, and $\tau = 0$, ie $\rho = 1$
  - A body which transmits all the incident radiation is called absolute transparent or diathermaneous body.
  - The required condition for absolute transparent body is $\tau = 1$, $\alpha = 0$ and $\rho = 0$.

ABSORPTIVITY OR ABSORBING POWER

- The fraction of incident radiation absorbed by a body is called absorptivity.
- It is defined as the ratio of the amount of heat energy absorbed to the amount of heat energy incident on it.
- **Absorptivity =** $\dfrac{\boldsymbol{Amount\ of\ radiation\ absorbed,\ Qa}}{\boldsymbol{Total\ incident\ radiation,\ Qi}}$

REFLECTIVITY OR REFLECTING POWER

- The fraction of incident radiation reflected by a body is called reflectivity.
- It is defined as the ratio of the amount of heat energy reflected to the amount of heat energy incident on it.
- **Reflectivity =** $\dfrac{\textit{Amount of radiation reflected, Qr}}{\textit{Total incident radiation, Qi}}$

TRANSMISSIVITY OR TRANSMITTING POWER

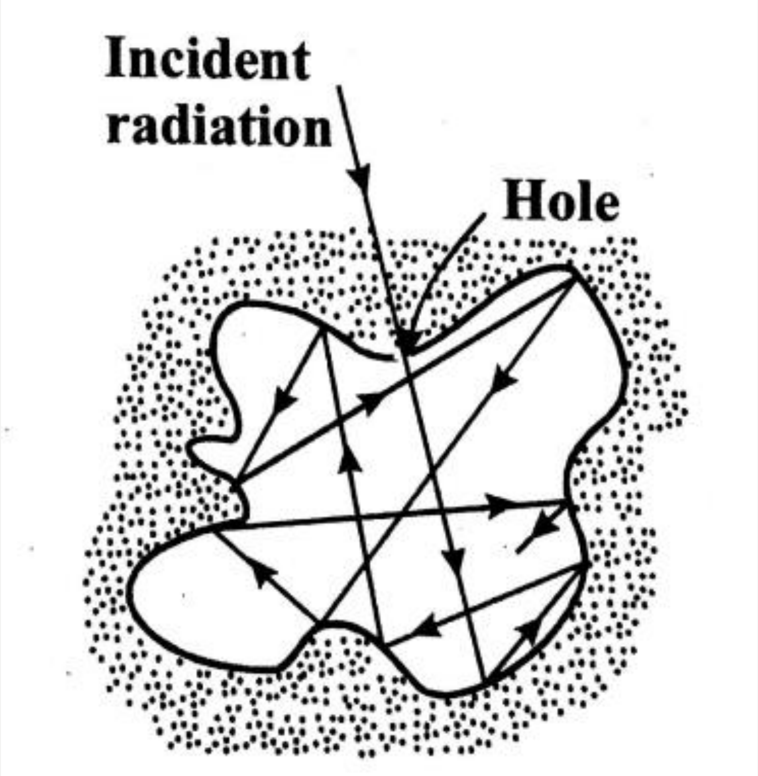
- The fraction of incident radiation transmitted by a body is called transmissivity.
- It is defined as the ratio of the amount of heat energy transmitted to the amount of heat energy incident on it.
- **Transmissivity =** $\dfrac{\textit{Amount of radiation transmitted}, Qt}{\textit{Total incident radiation}, Qi}$

CONCEPT OF BLACK BODY

- A black body is a surface that has the following properties.

1. A black body completely absorbs the incident radiation irrespective of its wave length. It is black because it does not reflect any radiation.
2. It is a perfect emitter. No other surface can emit more radiation than a black body provided they are at the same temperature.
3. Emission from a black body occurs in all possible directions.

- If radiation enters a cavity in a body through a small aperture then it may so happen that the incident radiations undergoes repeated reflections on the wall of the cavity as shown in fig. and is eventually absorbed completely. Thus a cavity approximates the black body behaviour.



RADIATING POWER OR EMISSIVE POWER

- Emissive power of a substance is defined as the amount of heat radiated by a unit surface of the body in one second when the temperature difference between the body and the surrounding is unit degree and is denoted by E.
- $E = I\,\alpha$
- Where, I = The radiation intensity or radiant energy received by the body per unit time per unit area.
- α = Absorptivity of the body.

EMISSIVITY

- It is defined as the ratio of the energy emitted by a real surface to that emitted by a black body at the same temperature.
- It has a value between zero and infinity.
- It is usually denoted by ε.
- $\boldsymbol{\varepsilon = \frac{E}{E_b}}$
- Where,
- E = Emissive power of the body
- E_b = Emissive power of black body.

STEFAN-BOLTZMANN LAW

- This law states that the emissive power of a black body is directly proportional to the fourth power of its absolute temperature.
- **$E_b \alpha T^4$**
- **$E_b = \sigma T^4$**
- Where,
- E_b = Emissive power of the black body in W/m^2
- σ = Stefan-Boltzmann constant
- = $5.67 \times 10^{-8}\ W/m^2K^4$
- T = Absolute temperature in K

- If the body is not perfectly black body and has emissivity ε then the above law becomes,
- **$E_g = \varepsilon \sigma T^4$**
- E_g = Emissive power of real body or gray body in W/m^2
- **Total radiation or emissive power on a surface area A is,**
- **$E = \varepsilon \sigma A T^4$**
- Where, E = Emissive power of black body or gray body in watts.

GRAY BODY

- Any real substance emits (or absorbs) less radiation than a black body at the same temperature.
- Also the emissivity and the absorptivity of a real surface or surface may vary with its temperature or the wave length of the radiation emitted or absorbed.
- When the emissivity of a non-black surface is constant at all temperature and throughout the entire range of wave length, the surface is called a gray body.
- Thus a gray body is also an ideal body, but its ε and α values are both less than unity and are independent of wave length.

NEWTON RIKHMAN LAW OF THERMAL CONVECTION

- The appropriate rate equation for the convective heat transfer between a surface and an adjacent fluid is described by Newton's law of cooling and the equation is called Newton Rickman equation of thermal convection.
- $Q = hA(T_s – T_f)$
- Q = Convective heat transfer in watts (W)
- h = Heat transfer coefficient in W/m^2K
- A = Surface area in m^2
- T_s = Surface temperature of a solid in K
- T_f = Temperature of the fluid in K

TYPES OF CONVECTION

- Heat transfer by convection is classified into two

1. Free or Natural convection
2. Forced convection

FREE OR NATURAL CONVECTION

- When temperature difference produces a density difference which results in movement of fluid, the process is called free or natural convection.
- Higher temperature fluid particles have lighter density rises up and lower temperature fluid particles have heavier density settles down.

FORCED CONVECTION

- When the motion of the fluid is produced by an external mechanical device such as a pump, fan, blower etc. the process is called forced convection.
- Here the fluid is made to flow along the hot surface and heat is transmitted from the wall to the fluid.

HEAT EXCHANGER

- A heat exchanger is a device used for the effective transfer of heat energy between two fluids (hot fluid to cold fluid) that are at different temperatures.
- Eg:- Automobile radiators, evaporators and condensers in air-conditioning plants and refrigerators, air heaters, coolers, boilers etc.
- The main function of a heat exchanger is to transfer heat energy from a hot fluid to a cold fluid, with maximum rate and minimum investments and running costs.

CLASSIFICATION

- **Nature of heat exchange process**

1. Direct contact (or open) heat exchangers.
2. Indirect contact heat exchangers

a) Regenerators

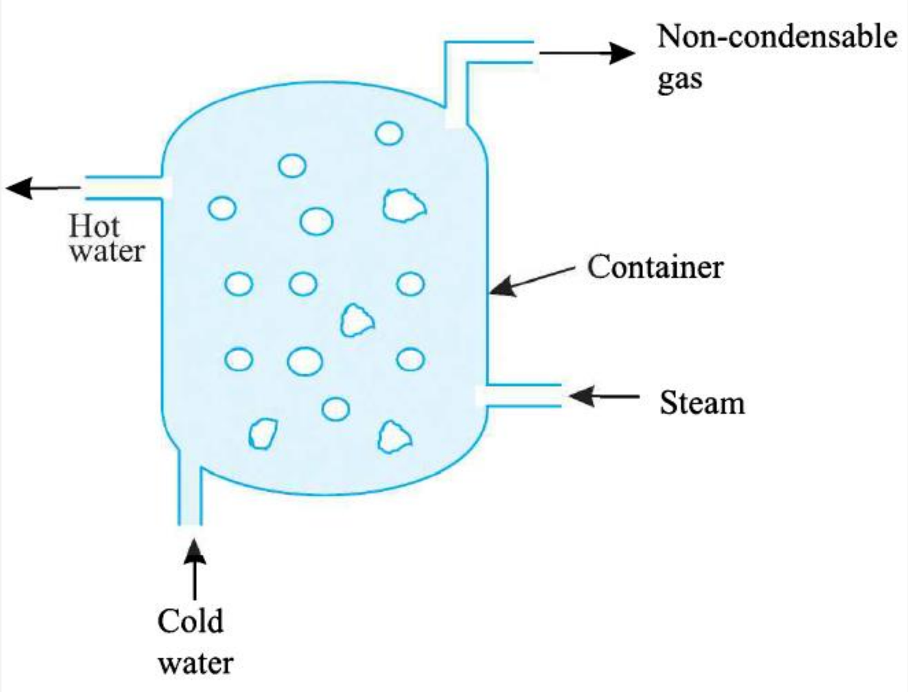
b) Recuperators

- **Relative direction of fluid motion**

1. Parallel flow or unidirectional flow
2. Counter-flow
3. Cross flow

DIRECT CONTACT (OR OPEN) HEAT EXCHANGERS

- A heat exchanger in which two fluids exchange heat by coming into direct contact is called a direct contact or open heat changer.
- In this exchange of heat takes place by direct mixing of hot and cold fluids.
- Eg: Cooling towers, direct contact feed heaters



Direct contact or open heat exchanger.

INDIRECT CONTACT HEAT EXCHANGERS

- In this type of heat exchanger, the heat transfer between two fluids could be carried out by transmission through wall which separates the two fluids.
- This type includes the following :
- (a) Regenerators.
- (b) Recuperators or surface exchangers.

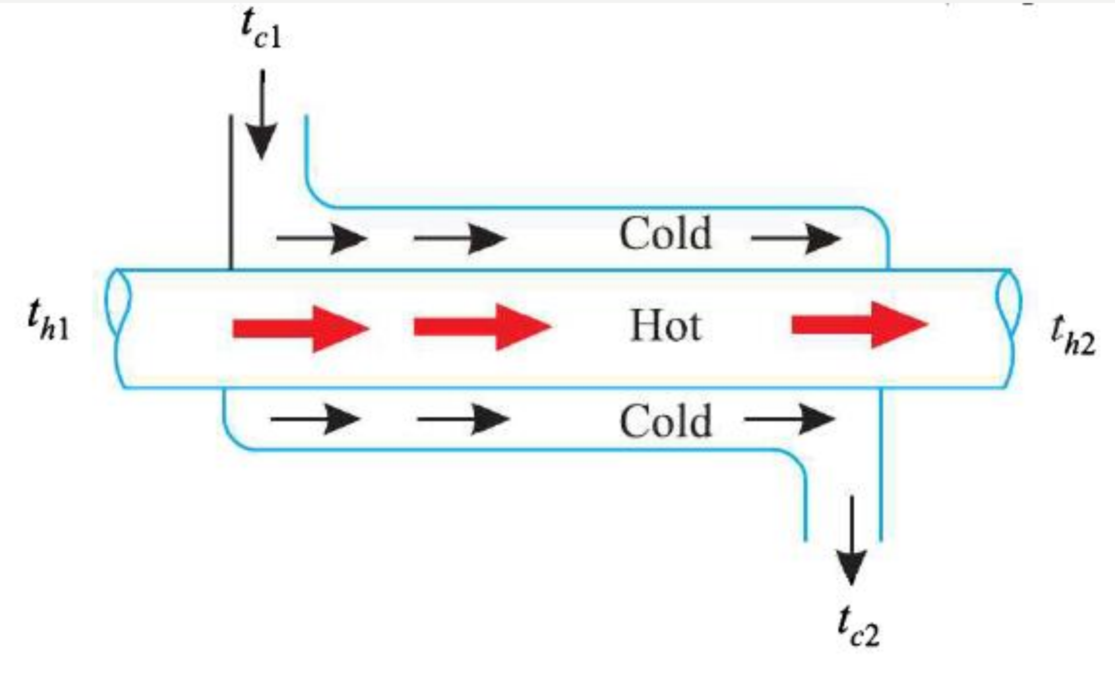
REGENERATORS

- A periodic flow type of heat exchanger is called regenerator.
- In this type of heat exchanger, the same space is alternatively occupied by the hot and cold fluids.
- The heat carried away by the hot fluid is absorbed by the high heat capacity material in the generator and subsequently given over to the cold fluid when it pass through it.
- Eg:- IC engines and gas turbines

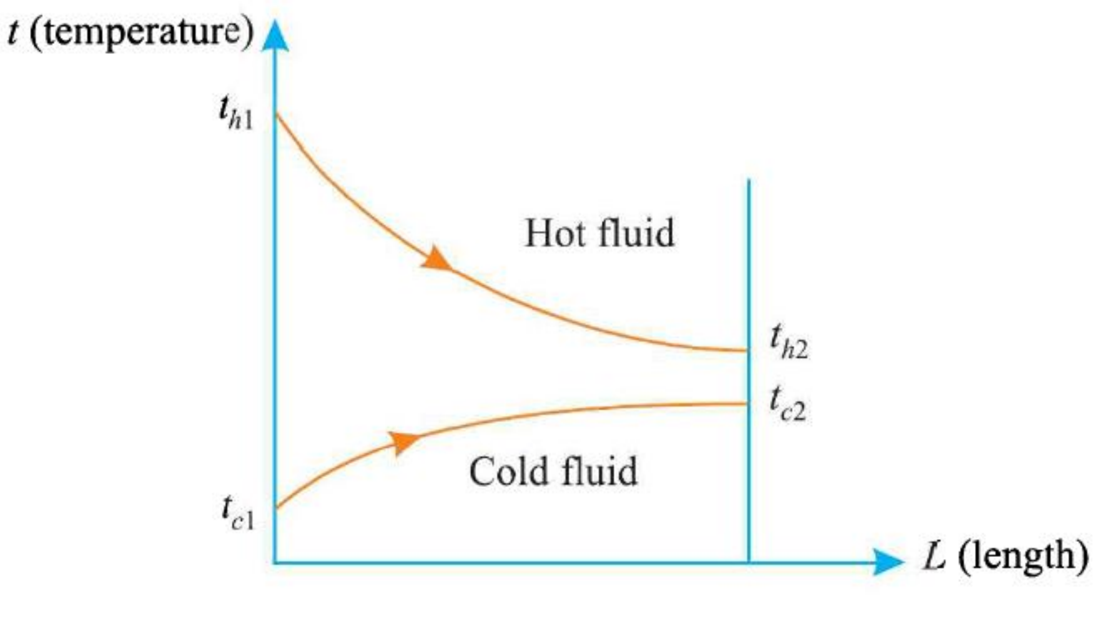
RECUPERATORS OR SURFACE EXCHANGERS

- It is the most important type of heat exchanger in which the flowing fluids exchanging heat are on either side of dividing wall (in the form of pipes or tubes).
- These heat exchangers are used when two fluids cannot be allowed to mix.
- Eg:- Automobile radiators, oil coolers etc.

PARALLEL FLOW OR UNIDIRECTIONAL FLOW HEAT EXCHANGERS



(a)

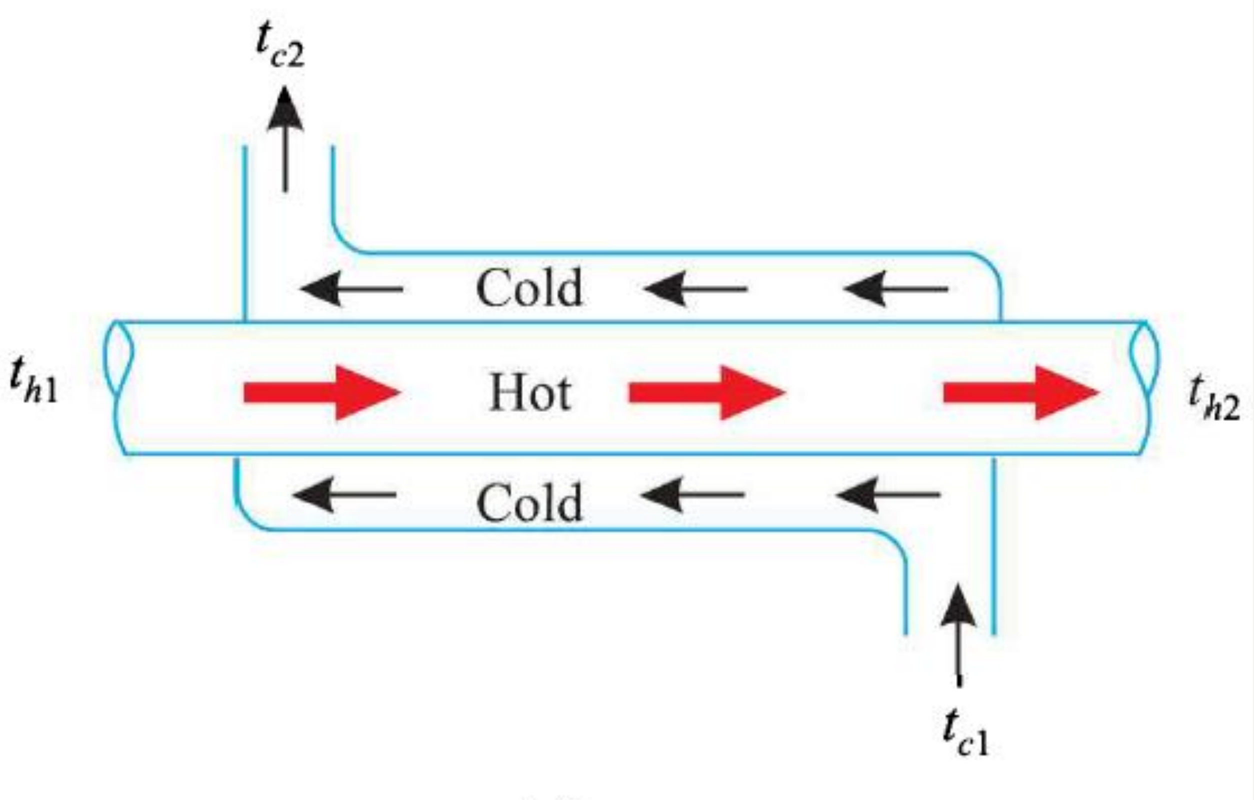


(b)

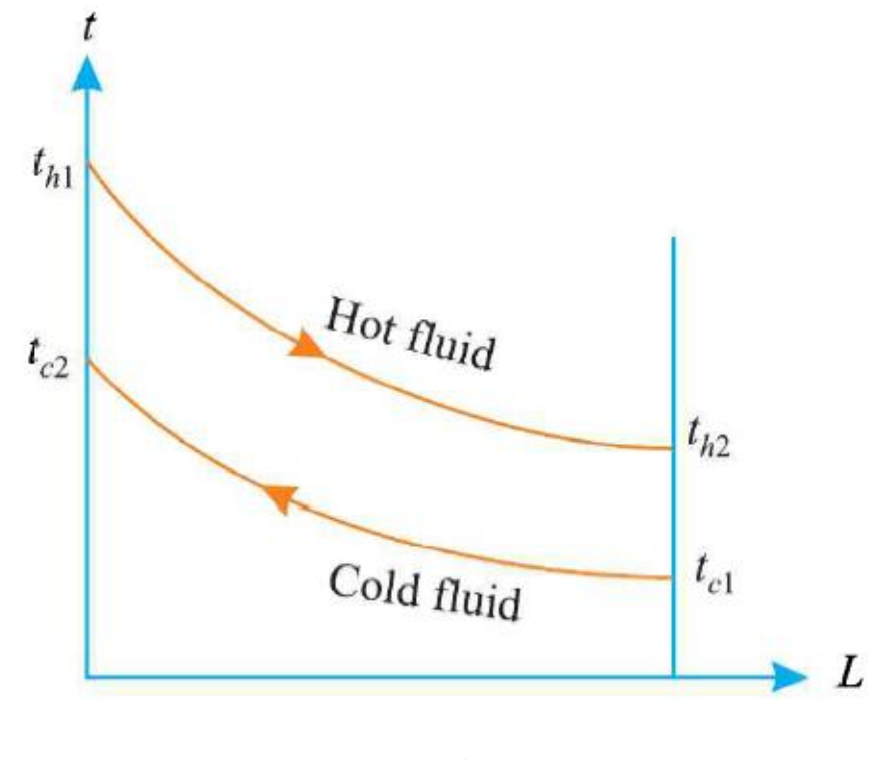
Parallel flow heat exchanger.

- In this the two fluid streams (hot and cold) travel in the same direction.
- The two streams enter at one end and leave at the other end.
- The temperature difference between hot and cold fluids goes on decreasing from inlet to outlet.
- Since this type of heat exchanger needs a large area of heat transfer, it is rarely used in practice.
- Eg:- Oil coolers, water heaters etc.

COUNTER-FLOW HEAT EXCHANGERS



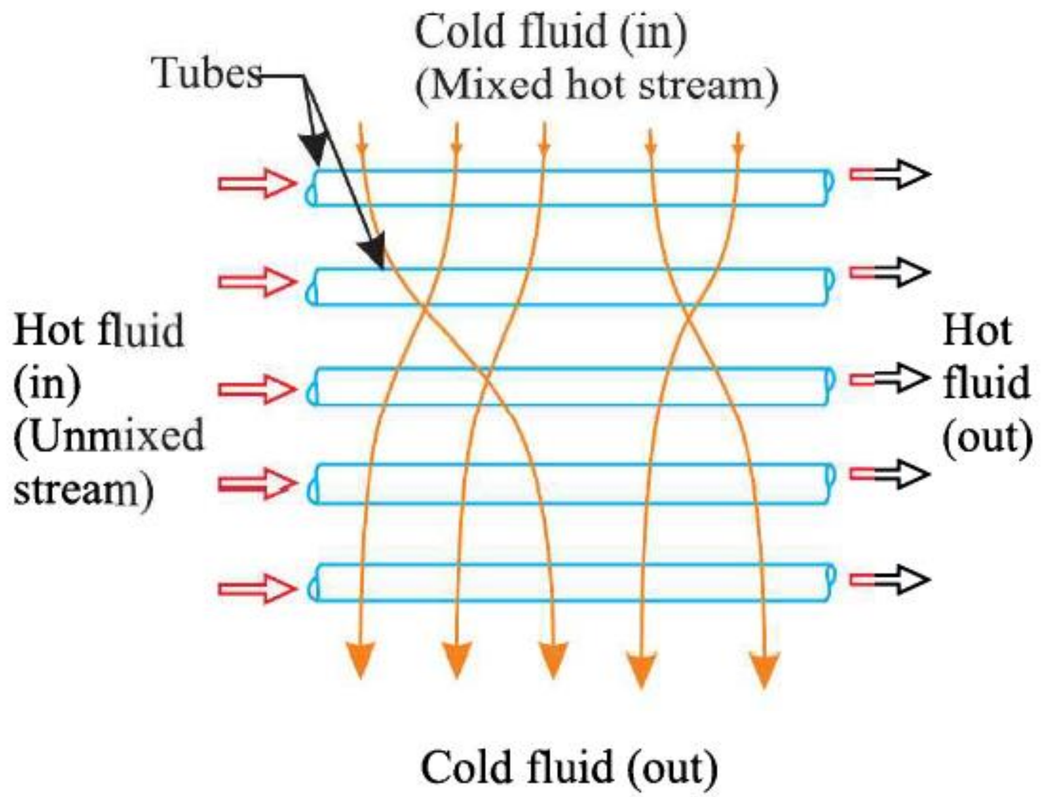
(a)



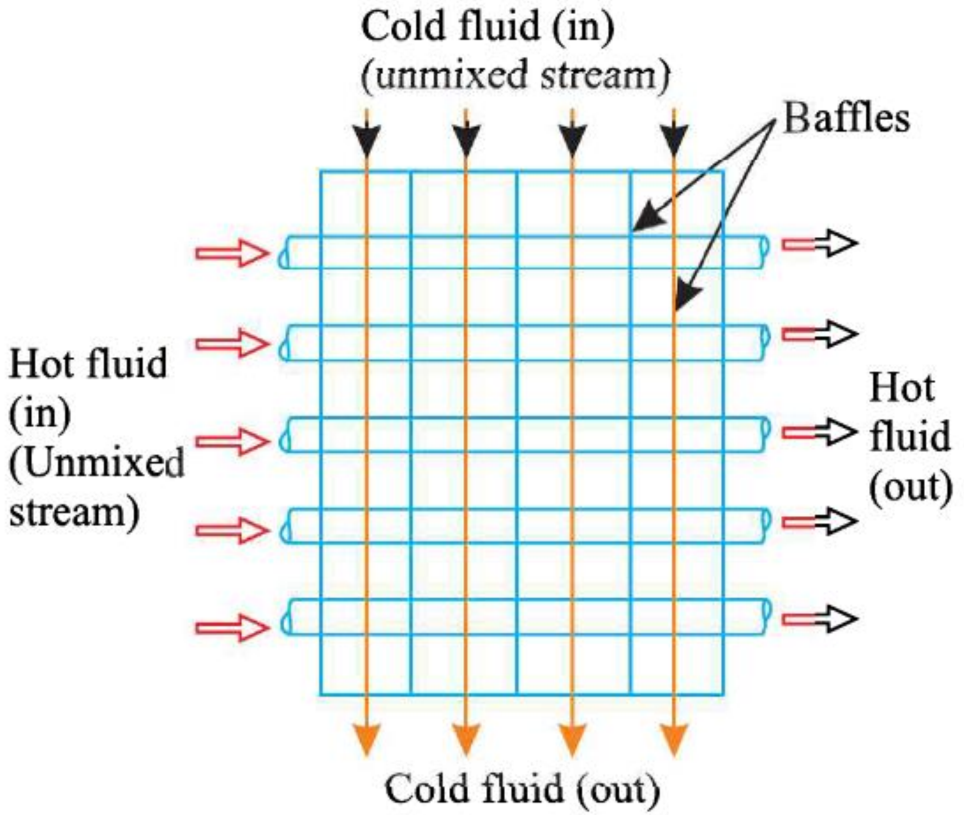
(b)
Counter-flow heat exchanger

- In this the two fluids flow in opposite directions.
- The hot and cold fluids enter at the opposite ends.
- The temperature difference between the two fluids remains more or less nearly constant.
- This type of heat exchanger gives maximum rate of heat transfer for a given surface area.
- Hence such heat exchangers are most favoured for heating and cooling of fluids.

CROSS-FLOW HEAT EXCHANGERS



(*a*)

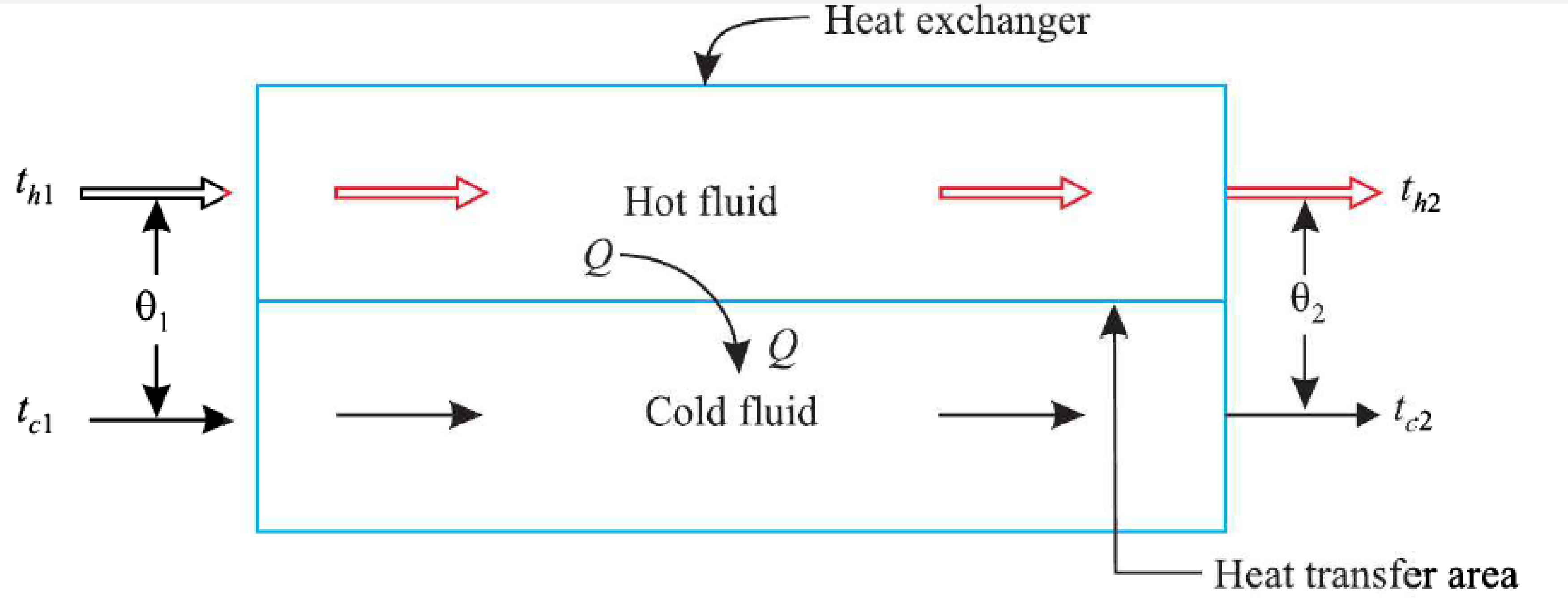


(*b*)

- In this, the two fluids (hot and cold) cross one another in space, usually at right angles.
- In fig (a), hot fluid flows in the separate tubes and there is no mixing of the fluid streams.
- The cold fluid is perfectly mixed as it flows through the exchanger.
- The temperature of this mixed fluid will be uniform across any section and will vary only in the direction of flow.
- Eg:- Cooling unit of refrigeration system
- In fig (b), each of the fluids flows a prescribed path and is unmixed as it flows through heat exchanger.
- Hence the temperature of the fluid leaving the heater section is not uniform.
- Eg:- Automobile radiators.

OVERALL HEAT TRANSFER COEFFICIENT (U)

- Figure shows the overall energy balance in a heat exchanger.



Overall energy balance in a heat exchanger.

- Let,
- $\dot{m}$ = Mass flow rate in kg/s
- c_p = Specific heat of fluid at constant pressure in J/kg^{0}C
- t = Temperature of fluid in ^{0}C
- Δt = Temperature drop or rise of a fluid across the heat exchanger.
- Superscripts h and c refers to hot and cold fluids.
- Superscripts 1 and 2 refers to inlet and outlet conditions.
- Assuming that there is no heat loss to the surroundings and potential and kinetic energy changes are negligible, from the energy balance of a heat exchanger, we have:

- Heat given up by the hot fluid, $Q = m_h\, c_{ph}\, (t_{h1} - t_{h2})$
- Heat picked up by the cold fluid, $Q = m_c\, c_{pc}\, (t_{c2} - t_{c1})$
- Total heat transfer rate in the heat exchanger, $Q = UA\theta_m$
- Where,
- U = Overall heat transfer coefficient between the two fluids.
- A = Effective heat transfer area.
- θ_m = Approximate mean value of temperature difference or logarithmic mean temperature difference (LMTD)

LOGARITHMIC MEAN TEMPERATURE DIFFERENCE (LMTD)

- LMTD is defined as the temperature difference which, if constant, would give the same rate of heat transfer as actually occurs under variable conditions of temperature difference.
- $\theta_m = \dfrac{\theta_1 - \theta_2}{\ln \dfrac{\theta_1}{\theta_2}}$

AIR COMPRESSORS

- Air compressor is a machine which compresses the air to a high pressure.
- The air compressor sucks the air from atmosphere, compresses it and then delivers it under high pressure to a storage vessel.
- From the storage tank the high pressure air may be conveyed by the pipe line to the place where it is required.
- The air compressor must be driven by a prime mover.

APPLICATIONS OF COMPRESSED AIR

- To run compressed air engines
- To operate pneumatic brakes for automobiles
- For providing air blast for blast furnace.
- For pumping water from deep well (air lift pump).
- For spray painting works.
- For boosting (or) supercharging of IC engines.
- To drive pneumatic tools such as concrete breaking, rock drilling, chipping etc.
- For spraying fuel into the combustion chamber of diesel engine (air blast injection).

CLASSIFICATION OF AIR COMPRESSORS

- Method of compression

1. Reciprocating compressors
2. Rotary compressors

- Number of stages

1. Single stage
2. Multi stage

- Pressure limit

1. Low pressure (<1 MN/m^2)
2. Medium pressure (1 MN/m^2 – 8 MN/m^2)
3. High pressure (8 MN/m^2 – 10 MN/m^2)
4. Super high pressure (> 10 MN/m^2)

- Capacity

1. Low capacity:- Compressor delivers $0.15 m^3/sec$ of compressed air
2. Medium capacity:- Compressor delivers $0.15\text{-}5 m^3/sec$ of compressed air
3. High capacity:- Compressor delivers more than $5 m^3/sec$ of compressed air

- Method of cooling

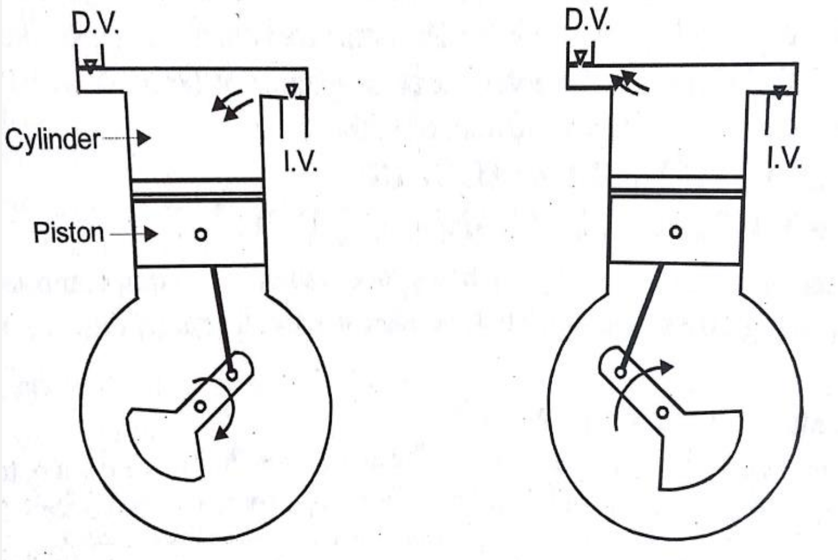
1. Air cooled compressors
2. Water cooled compressors

RECIPROCATING COMPRESSORS

- It is further classified as single acting or double acting.
- In single acting compressor, air is supplied to one side of the piston.
- In double acting compressor the air is admitted alternatively to each side of the piston.
- The output of the double acting compressor is almost two times the output of a single acting compressor.

SINGLE STAGE RECIPROCATING COMPRESSOR

- The compressor is driven by a prime mover (electric motor or engine).
- The rotary motion of the engine is converted into the reciprocating motion of the piston by the crank shaft and connecting rod.
- During the downward stroke of the piston (suction stroke) the pressure inside the cylinder falls below the atmospheric pressure.
- Now the inlet valve opens and atmospheric air is drawn into the cylinder till the piston reaches bottom dead centre (BDC).
- During upward stroke (compression stroke) the piston travels from bottom dead centre (BDC) to top dead centre(TDC).

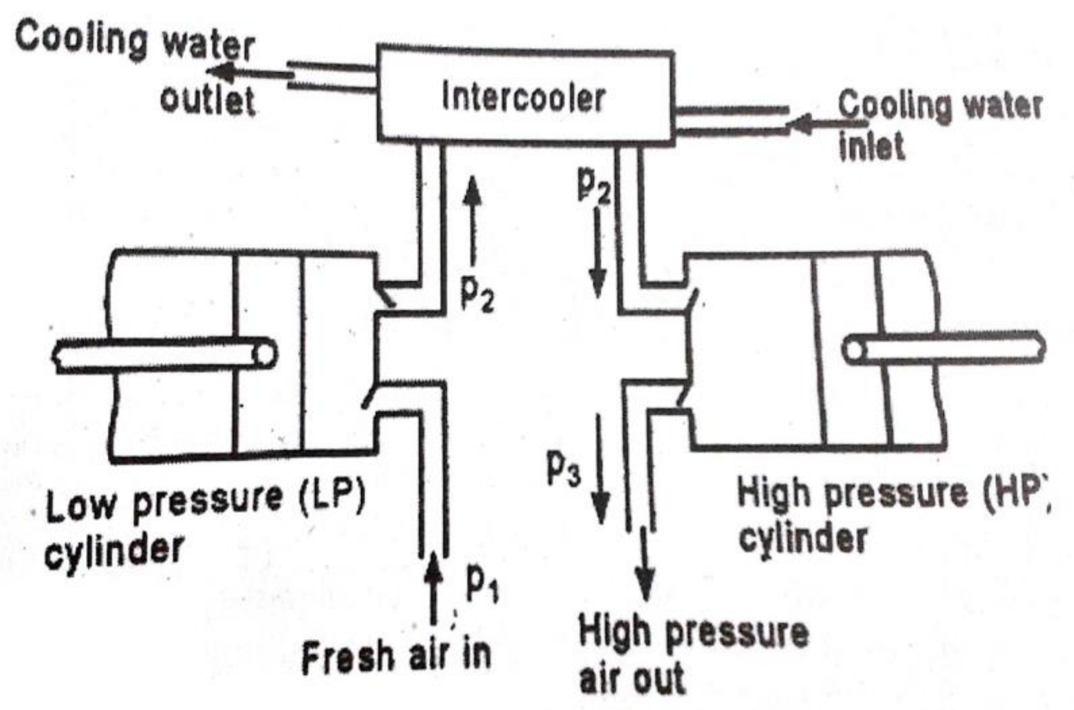


a) Suction stroke (b) Delivery stroke
Working of single stage reciprocating aircompressor

- When the air pressure inside the cylinder rises above atmospheric, the inlet valve closes.
- The pressure increases steadily.
- When the air pressure exceeds the resistance of the spring on delivery valve, the delivery valve opens.
- Now the compressed air is discharged through the outlet valve to the air receiver tank.
- At the end of compression stroke, a small volume of compressed air will be left in the clearance space.
- When the piston moves down for the next suction stroke, the air in the clearance space expands, the pressure falls down.
- The inlet valve again opens and the cycle is repeated.

MULTI STAGE RECIPROCATING COMPRESSOR

- It consists of two cylinders.
- They are high pressure (HP) and low pressure cylinders (LP).
- The multi stage compressor uses an intercooler.
- When the prime mover is started, the fresh air from atmosphere is drawn into low pressure cylinder with pressure p_1 and temperature T_1(suction stroke).
- The suction stroke ends when the piston reaches BDC.
- Now when the piston moves from bottom dead centre to top dead centre the air is compressed and the pressure is increased to p_2 and temperature to T_2.



- The air in the LP cylinder is delivered to the intercooler at a pressure of p_2 and temperature T_2.
- The air is now cooled in the intercooler at constant pressure p_2 by circulating water from temperature T_2 to the temperature T_3.
- If the intercooling is completed, the temperature T_3 of the air leaving the intercooler drops to a temperature which is more than T_1 but less than T_2.
- The cool air at the pressure p_2 is now drawn in the high pressure cylinder during its suction stroke.
- The air is then compressed to the final pressure p_3 and delivered to the receiver tank at constant pressure p_3.

ROTARY COMPRESSORS

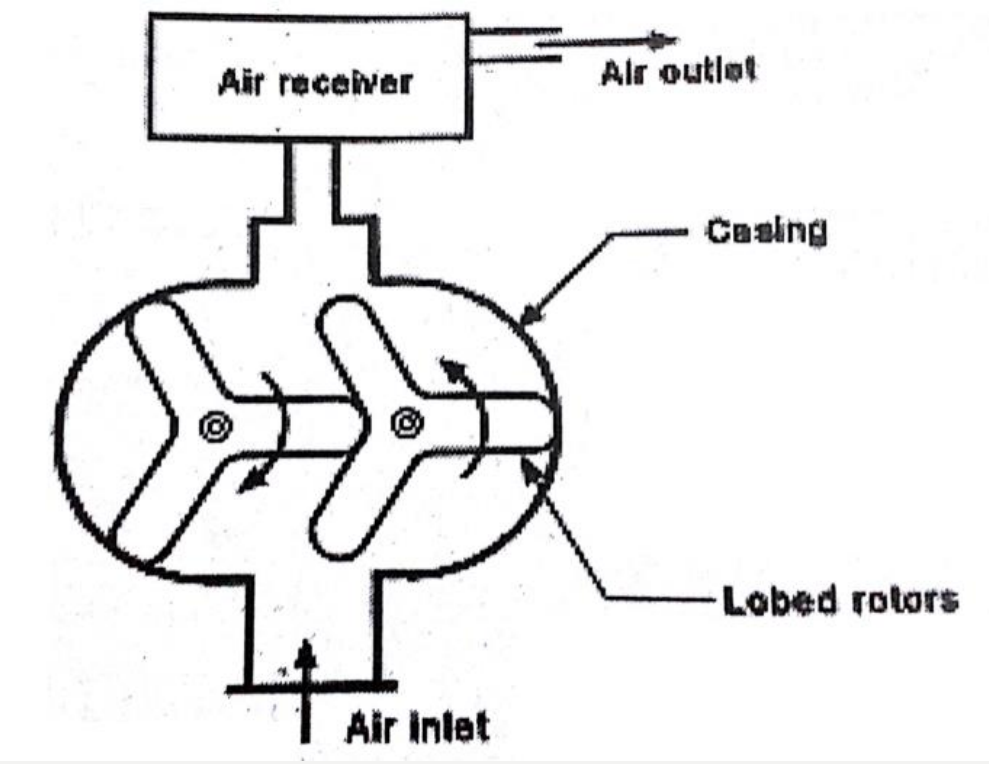
- It is further classified as,

1. Positive displacement compressor.
2. Non-positive displacement compressor.

- In positive displacement compressor air is trapped in between two sets of engaging surfaces and change in pressure is either by back flow or both by squeezing action and back flow of air.
- Eg:- Roots blower, vane blower and screw compressors
- In non-positive displacement compressors, the air is not positively contained within specified boundaries but in continuous steady flow throughout the machine.
- Eg:- Radial or centrifugal compressors and axial compressors

ROOTS BLOWER

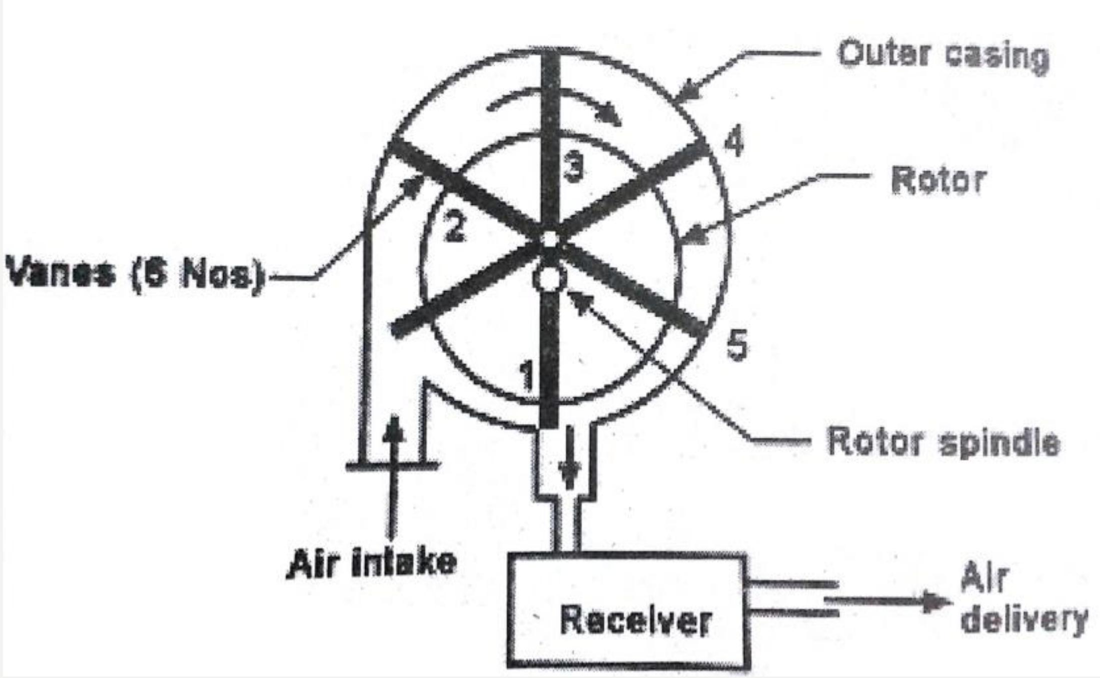
- It consists of two rotors, which is mounted on parallel axis.
- Each rotor consists of lobs and rotates in opposite direction.
- One rotor is connected with prime mover and the other rotor is gear driven from the first.
- When the two rotor lobs engage, the space between them is reduced in volume.
- So the air trapped between them is compressed and the compressed air is discharged to the receiver tank.
- These types of blowers are used for super charging of IC engines.



VANE BLOWERS

- It consists of the following elements.

1. A rotor mounted eccentrically in outer casing.
2. A set of vanes mounted on the rotor and rotating concentrically in the outer casing
3. Intake and delivery ports. The intake port is larger than the delivery port.

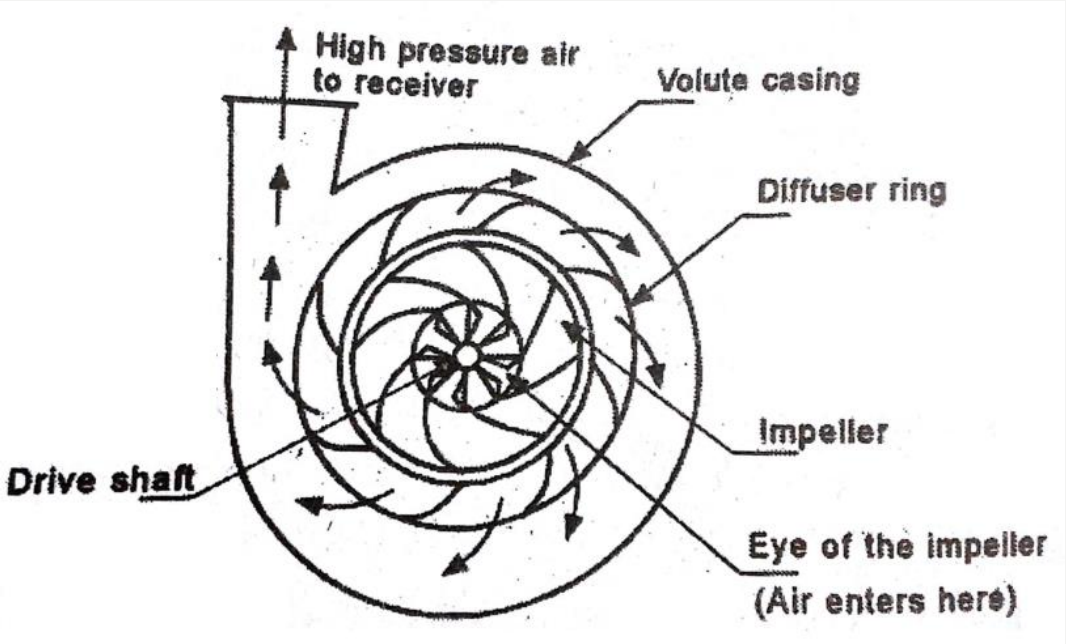


- The rotor rotates in a clockwise direction.
- The vane will start collecting air after it leaves the position marked 1 and no more air will be sucked after the vane moves to the position 2.
- The compression of air trapped between the vanes takes place in between the rotor and casing.
- Compression starts at the point 3 and ends at the point 5.
- Compressed air is then discharged to the receiver.
- The efficiency of the vane blowers are high and it is possible to drive at high speeds.
- These types of blowers are used in super charging of aero engines.

CENTRIFUGAL COMPRESSORS

- It consists of the following elements.

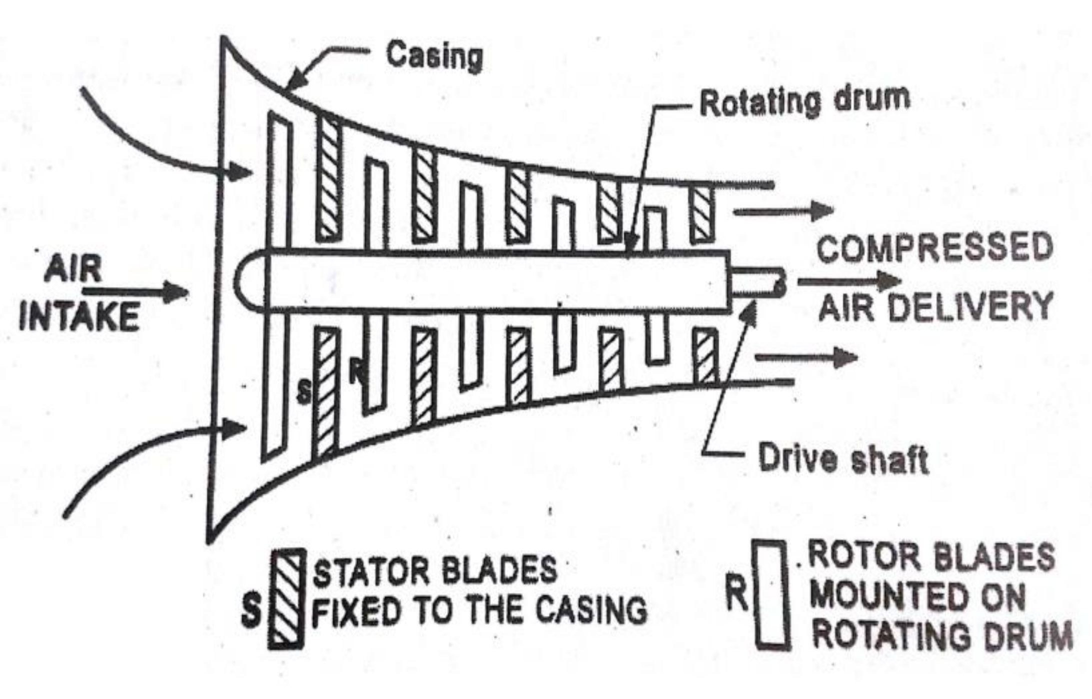
1. Casing:- It covers the rotating impellers
2. Rotating impellers:- The impeller is provided with radial vanes. The air is supplied to these vanes by inlet valve.
3. Diffuser:- It is housed in a radial portion of casing.



- The air enters the eye of the impeller with a low velocity and atmospheric pressure.
- Due to centrifugal action of the impeller air moves radially outwards.
- During this movement the air is guided by impeller vanes.
- As a result the pressure and temperature of the air increases.
- The velocity of the air also increases.
- The air now enters the diffuser.
- In the diffuser the air velocity further increases.
- The kinetic energy of the air is converted into pressure energy.
- As a result there is further rise in the pressure.
- Finally the air at high pressure is delivered to the receiver.
- They are used for supercharging of IC engines and for producing air blast to furnaces.

AXIAL FLOW COMPRESSORS

- In this the air enters and leaves the compressor in a direction parallel to the axis of the machine.
- It consists of a rotor and stator, provided with stator blades and rotor blades.
- The stator blades are fixed to the casing whereas rotor blades are mounted on the rotating drum.



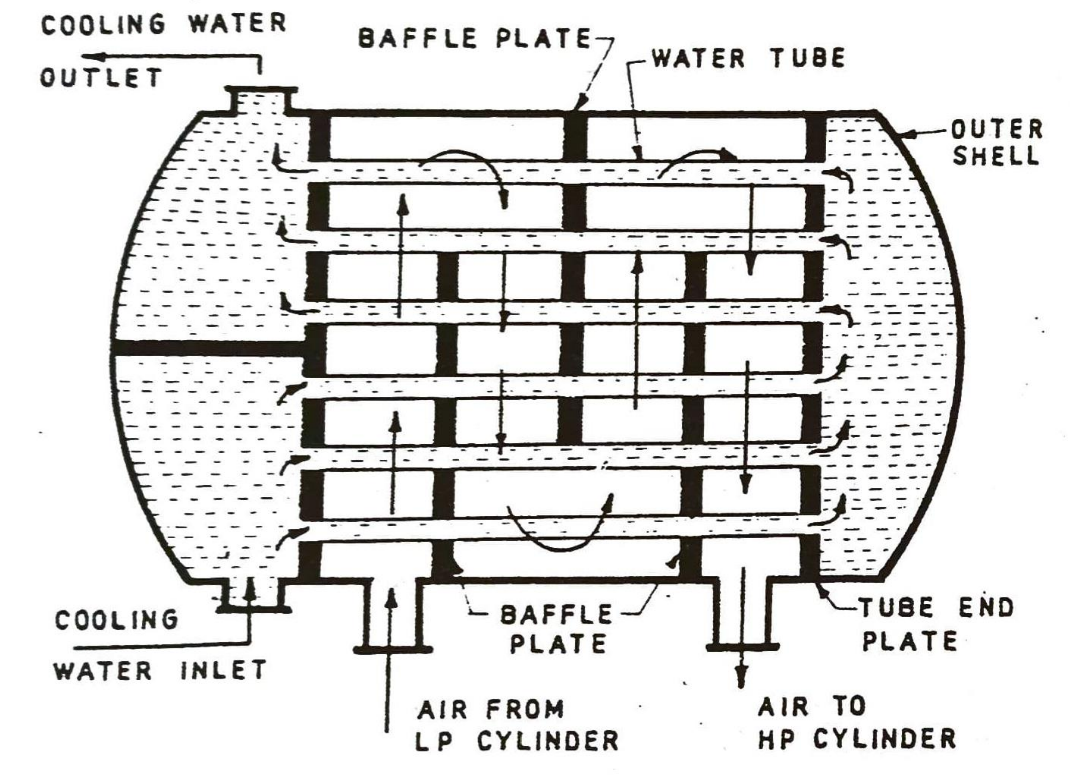
- The area is reduced from inlet to outlet of the compressor.
- This helps for maintaining the velocity of the air throughout the length of the compressor.
- The drum rotates the air flow through alternatively arranged stator and rotor blades.
- When passing through the blades, the air is compressed between blades and also between blades and casing.
- The compressed air is delivered to the receiver tank.
- The axial flow compressors are used in high pressure application such as gas turbines and aircrafts.

INTERCOOLER

- An intercooler is a heat exchanger in which heat is removed from air after it has been compressed.
- The main function of intercooler is to cool air before it enters the next stage of compression.
- The lower density of cool air makes it easier to compress than hot air.

WORKING

- The coolant used may be water or any other fluid, passes through the tubes secured between two end plates and the air circulated over the tubes through a system of baffles.
- Baffles are provided for ensure maximum contact between the tube and air by passing the air in circuitous path.



Intercooler

- Air from low pressure cylinder is admitted first into the intercooler.
- The heat of compressed air generated in low pressure cylinder is exchanged to the circulating water and in this process the compressed air is cooled.
- The cooled air from the intercooler leaves to the high pressure cylinder.
- The cooling water enters at one end of the bottom set of tubes, flows through them and reaches the other end of the shell.
- The water then rises up and flows in opposite direction through the upper half of the tubes and finally leaves through the outlet.

ADVANTAGES OF MULTI-STAGE COMPRESSION

1. It improves volumetric efficiency for the given pressure ratio.
2. Saving in work is obtained as compared to single stage compression for the same delivery pressure.
3. The strength and size of cylinders can be adjusted to suit the volume and pressure of air.
4. Cheaper materials may be used for the construction as the operating temperatures are lower.
5. Effective lubrication due to lower working temperature.
6. The leakage loss is reduced considerably.
7. It reduces the cost of the compressor.
8. Maintenance cost is reduced.
9. It has better mechanical balance and good cooling during compression.
10. With reasonable volumetric efficiency, higher delivery pressure can be obtained.
11. Power can be saved for given pressure ratio.

EFFICIENCY'S OF AIR COMPRESSORS

1. Isothermal efficiency
2. Adiabatic or Isentropic efficiency
3. Mechanical efficiency
4. Volumetric efficiency

ISOTHERMAL EFFICIENCY

- It is also called compressor efficiency or compression efficiency.
- It is the ratio of work (power) required to compress the air isothermally to the actual work (power) required to drive the compressor.
- **Isothermal efficiency =** $\frac{Isothetmal\ workdone}{Actual\ power\ input}$

ADIABATIC OR ISENTROPIC EFFICIENCY

- It is the ratio of work (power) required to compress the air adiabatically to the actual work (power) required to drive the compressor.
- **Adiabatic efficiency** $= \dfrac{\text{Adiabatic workdone}}{\text{Actual power input}}$

MECHANICAL EFFICIENCY

- It is the ratio of indicated power of the compressor to the power supplied to drive the compressor.
- **Mechanical efficiency =** $\dfrac{\textit{Indicated power}}{\textit{Power supplied to compressor}}$
- $= \dfrac{\textit{Indicated power}}{\textit{Brake power}}$
- Power required to compress the air is called cycle power or indicated power of the compressor.
- The power required for driving the compressor is called shaft power or brake power of the compressor.

VOLUMETRIC EFFICIENCY

- It is defined as the ratio of actual volume of free air taken into the cylinder per cycle to the swept volume of the cylinder.
- **Volumetric efficiency =** $\frac{Volume\ of\ free\ air\ \ taken\ per\ cycle}{Swept\ volume\ of\ the\ cylinder}$
- Also defined as the ratio of mass of free air induced into the cylinder per cycle to the mass of air corresponding to swept volume calculated at free air conditions of pressure and temperature.
- **Volumetric efficiency =**

$$\frac{Mass\ of\ free\ air\ \ taken\ in\ per\ cycle}{Mass\ of\ air\ corresponding\ to\ swept\ volume\ at\ free\ air\ condition}$$