Chapter-4

Rate of Heat Flow (Transfer Of Heat)

Conduction:-

The transfer of heat in a device from one point to another point without transfer particle is called conduction.
Example - Heat transferred in metal.

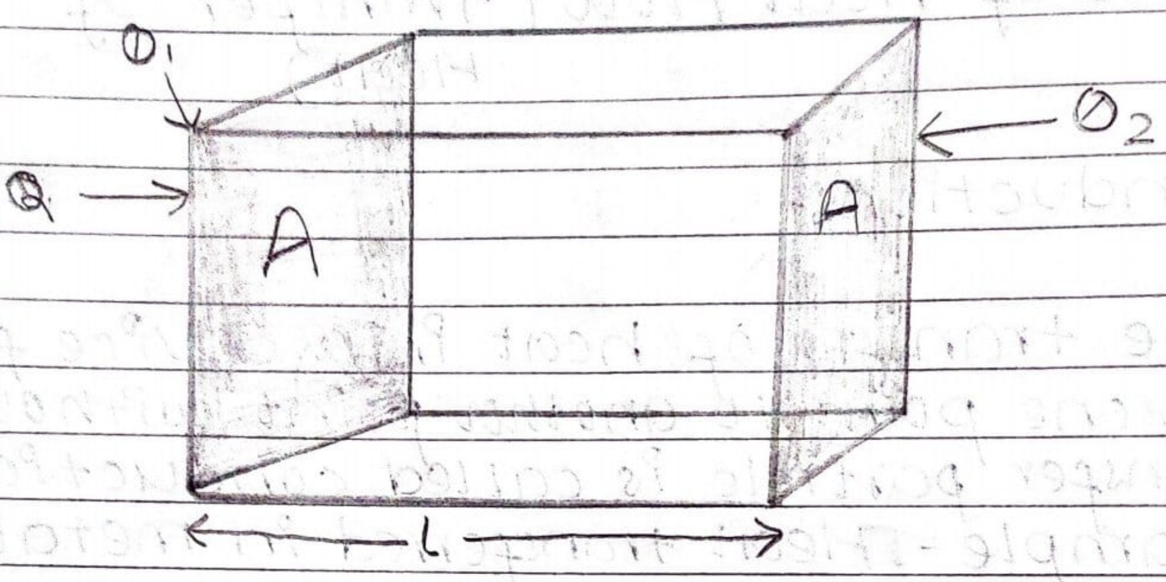
Convection:-

The transfer of heat in a medium from one point to another point with transfer of particle is called convection.
Example- Heat transferred in a liquid

Radiation:-

The transfer of heat in space from one point to another point without medium but with transfer of particles is called radiation.
Example- solar radiation

Thermal conductivity:-



Consider a cuboid having length 'l' and cross-sectional area of one phase is 'A'. Let, θ_1 be the temperature of one face of cuboid (solid) due to supply heat and θ_2 be the temperature of opposite face of cuboid. Then, heat is transferred in a cuboid from one face to another face.

Experimentally, it is found that heat transfer in a medium is:

i. directly proportional to temperature difference between two faces.

i.e. $Q \propto (\theta_1 - \theta_2)$

ii. directly proportional to cross-sectional area of the face.

i.e. $Q \propto A$

iii. directly proportional to time at which heat transfer in a medium.

i.e. $Q \propto t$

iv. inversly proportional to length of the cuboid.

i.e. $Q \propto \frac{1}{l}$

combining all above eqns.

$$Q \propto \frac{At(\theta_1 - \theta_2)}{l}$$

$$Q = \frac{K\ t\ A(\theta_1 - \theta_2)}{l}$$

where K is proportionality constant called thermal conductivity. It depends upon the nature of material. i.e. thermal conductivity of Fe, Cu and Al are different.

Also,

$$\frac{Q}{t} = \frac{KA(\theta_1 - \theta_2)}{l}$$

which is power.

As we know,

$$P = \frac{Q}{t} \quad \left(\because P = \frac{W}{t} = \frac{Q}{t} \right)$$

$$\therefore P = \frac{KA(\theta_1 - \theta_2)}{l}$$ heat is energy

so, power is the rate of transfer of heat.

Determination of Thermal conductivity by Searle's method:-

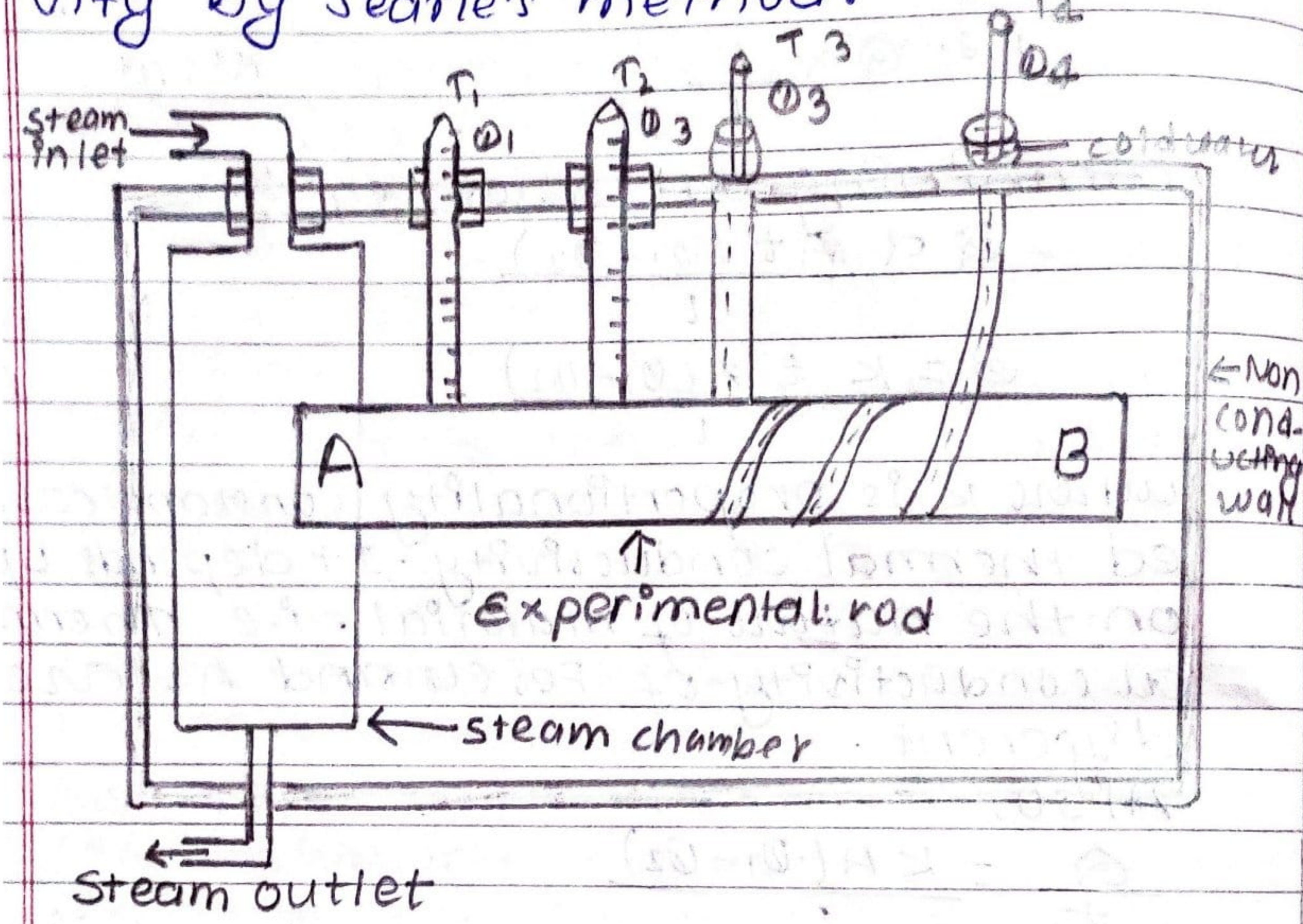


Fig:- Experimental verification and arrangement of shearle's method.

The experimental arrangement to determine thermal conductivity by shearle's method is as shown in the figure. It consists a experimental rod AB whose thermal conductivity is to be determined is placed inside non conducting wall of system / jacket such that end 'A' of rod is placed inside the steam chamber and end B is wrapped by cold water circulating copper tube. Two thermometer T_1 and

T_2 are placed at a distance 'l' in a rod which can measure temperature difference at a distance 'l' of rod. Thermometer T_4 and T_3 are placed at two end of copper tube which measures the temperature difference between cold water and circulating water.

Now, steam is passed through steam inlet valve such that end A of rod AB gets heated and heat starts to transfer from end A to B of rod such that the temperature on all thermometer goes on increasing. After time 't' all thermometer give steady value. Let θ_1, θ_2, θ_3 and θ_4 be the steady values (reading of) all thermometer respectively. For steady state, the heat absorb by circulating water having mass 'm' is equal to heat transfer in experimental rod.

i.e.
Heat transfer by rod = Heat absorb by circulating water

again,
total heat transfer in rod at time 't' is:

$$Q_1 = \frac{KAt(\theta_1 - \theta_2)}{l}$$

{where K is thermal conductivity of a rod and A is the cross-sectional Area of that rod} and total heat absorbed by circulating water is: {

$$Q_2 = mS_w(\theta_3-\theta_4)$$

{where S_w is specific heat capacity of water}

From (i)

$$Q_1 = Q_2$$

$$\frac{KAt(\theta_1-\theta_2)}{L} = mS_w(\theta_3-\theta_4)$$

$$\boxed{\therefore K = \frac{mS_w L(\theta_3-\theta_4)}{At(\theta_1-\theta_2)}}$$

which is the required expression for thermal conductivity.

Using this relation only, Searle's determines thermal conductivity of given rod.

Applications of conduction:-

i) After a car is turned on, engine becomes hot. It happens due to conduction.

ii) A radiator

iii) Cooking of food in metal utensils.

iv) Thermal treatment of pain by hot water bag.

v) conduction helps sound to reach the other person when you speak into the telephone as your sound waves are converted into electric signals which travel to the person on the other side through conduction.

vi) conduction of heat through atmosphere makes the earth warm.

Applications of convection:-

i) Car engines are cooled by convection currents in the water pipes.

ii) Land and sea breezes are caused due to convection currents.

iii) Rising air over the land are convection currents and used by glibler pilots to keep their gliders in the sky.

iv) Air conditioner, refrigerators are the applications of convection.

v) Hot air ballon is also an example of convection.

Radiation

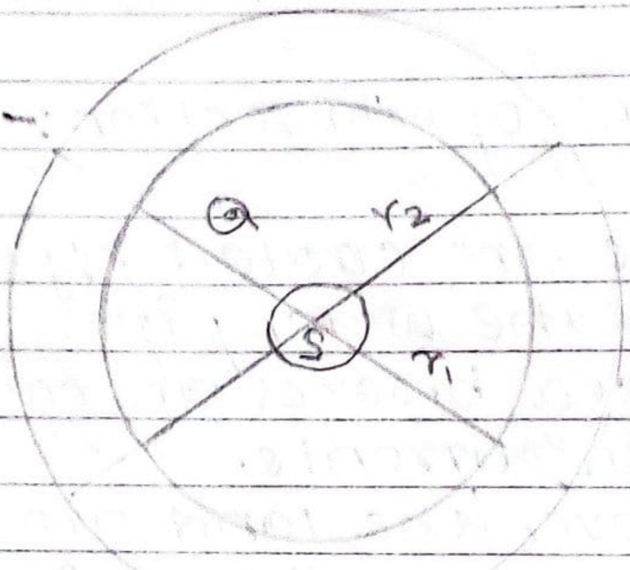
Intensity (I OR E) :-

The intensity of heat energy is defined as heat energy radiate per unit area per second.

i.e. $I = \frac{Q}{At}$

(where, Q is heat energy)
It's SI unit is $J m^{-2} s^{-1}$ or $watt/m^2$

Inverse square law:-



consider source 's' is placed at a point in the space. Let, I_1 and I_2 be the intensities of heat radiation at a distance r_1 and r_2 from the source respectively. Now, we have, the intensity of heat radiation is :

$$I = \frac{Q}{At}$$

(where Q is energy radiate by a source)

For a distance r_1, the energy radiates per second by a source is:

$$Q_1 = \frac{Q}{t}$$

$$= A \times I$$

$= I_1 \times 4\pi r_1^2$

Similarly, head radiation for r_2 distance from the source per second is :

$Q_2 = I_2 \times 4\pi r_2^2$

Since, heat radiation by a source is same such that,

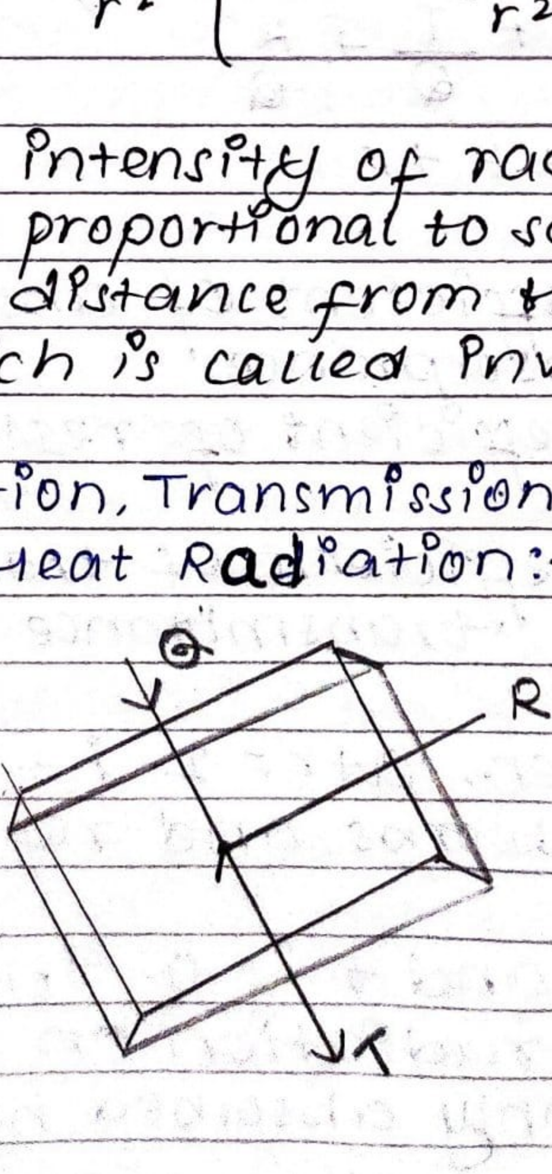
$I_1 \times 4\pi r_1^2 = I_2 \, 4\pi r_2^2$

$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$

$\therefore E \propto \frac{1}{r^2} \left(I \propto \frac{1}{r^2} \right)$

So, the intensity of radiate heat is inversly proportional to square of perpendicular distance from the source of heat which is called inverse square law.

Reflection, Transmission and Absorption of Heat Radiation:-



When energy radiates or falling on the surface of a material then a part of energy is reflected, a part of energy is absorbed. and a part of energy is transmitted. so, total energy of heat radiation is equal to sum of energy of heat absorbed, reflected and transmitted.

i.e. $Q = A + T + R$

(where, Q is total heat energy radiates on the material's surface. A is heat energy absorbed, R is heat energy reflected and T is heat energy transmitted)

OR, dividing both sides by Q

$$1 = \frac{A}{Q} + \frac{T}{Q} + \frac{R}{Q}$$

$$\boxed{1 = a + t + r}$$

where,

$a = \frac{A}{Q}$ = coefficient of absorption or absorptance

$r = \frac{R}{Q}$ = coefficient of reflection

$t = \frac{T}{Q}$ = coefficient of transmission or transmittance

If, $t = 0$. Then, $a + r = 1$ i.e. radiate heat is only absorbs and reflected.

again. if r and t is 0. Then, $a = 1$ ie. total heat radiation on surface of material is only absorbed neither transmitted nor reflected such that, that material appears to black. such body is called black body.

Black body and Black body radiation:-

A perfect black body is that body which absorbs all wavelength of heat radiation fall on it. That body neither reflect nor transmit heat. such that, it appears black.

when such body is heated, it emmits radiation called black body radiation. The wave length of this radiation is independent with material of a body and depends upon the temperature of a body and material.

In nature, there is no known perfectly black body but surface coated with lamp black absorbs (96% - 98%) of incident radiation. such surface of a body is considered as perfectly black body.

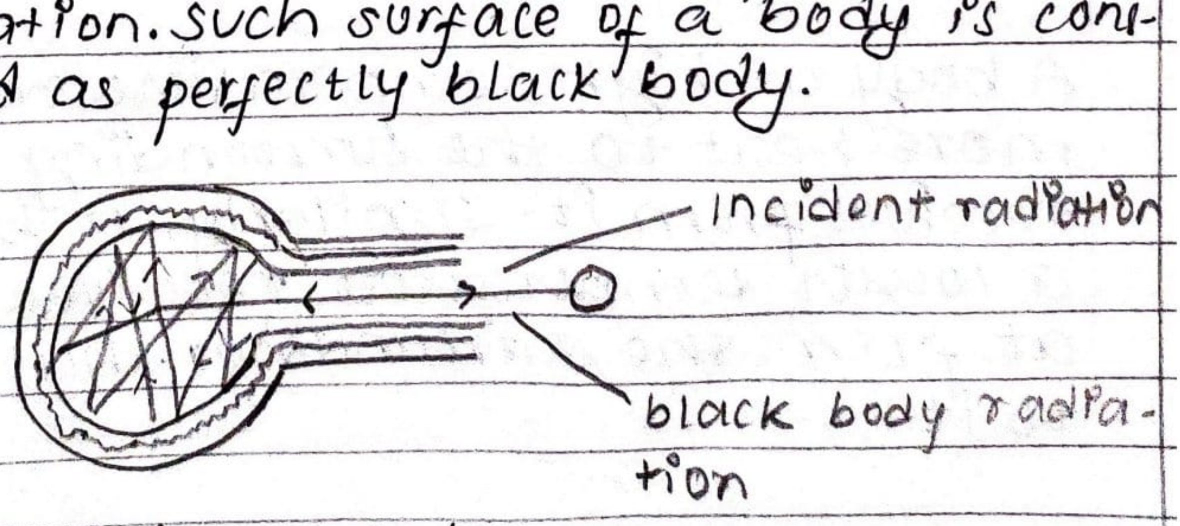


Fig:- Feri Black Body

Feri Black body:-

Ferry designed a artificial black body as shown in figure. He took a hollow double walled sphere which was blackened from inside by coming with lamp black. It consists a small hole/opening on one side and a conical projection 'p' just opposite to it. A heating coil is placed between the walls to heat the body. Any radiation entering the hole is reflected multiple times in inner walls of sphere and after few reflections, almost all of the radiation is absorbed.

Prevast Theory:-

Every body emits head radiations at all infinite temperatures as well as it absorbs radiations from the surroundings. For example, if we touch someone, they might feel our skin as either hot or cold.

A body at high temperature radiates more heat to the surrounding than it receives from it. Similarly, a body at a lower temperature receives more heat from the surroundings that it loses to it.

Prevost applied the idea of 'thermal equilibrium' to radiation. He suggested that all bodies radiate energy but hot bodies radiate energy (more heat) than the cooler bodies. At point of time the rate of exchange of heat from both the bodies will become the same. Now the bodies are said to be in 'thermal equilibrium.'

Only at absolute zero temperature a body will stop emitting.

Therefore, Prevast theory states that all bodies emit thermal/heat radiation at all temperatures above absolute zero irrespective of the nature of the surroundings.

Stefan's Boltzmann Theorem:-

It states, "the amount of heat energy radiates per second per unit area is directly proportional to fourth power of absolute temperature."

Let E be the amount of heat energy radiates per second per unit area of body and T be the absolute temperature of body.

Then,

$E \propto T^4$

$E = \sigma T^4$

where, σ is proportionally constant called stefan's constant. It's value is 5.67×10^{-8} watt $m^{-2} K^{-4}$.

The power radiate by a black body is

$P = E \times A$

$P = \sigma T^4 \times A$

$\boxed{P = \sigma A T^4}$

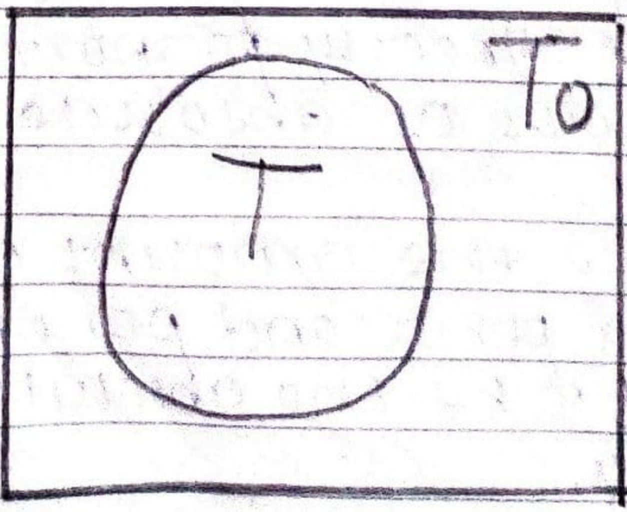
If the body is not perfectly black body, then power radiate by body is:

$P = e \cdot \sigma \cdot A \cdot T^4$

consider a hot body having absolute temperature 'T' is enclosed by a material having absolute temperature T_0. Then, power of heat radiate by hot body is

$P_{radiate} = A \times E$

$= \sigma . T^4 \times A$



And, power absorbed by material:

$$P_{absorb} = \sigma A T_0^4$$

Net transfer of power = $P_{radiate} - P_{absorb}$

$$= \sigma A T^4 - \sigma A T_0^4$$

$$= \sigma A (T^4 - T_0^4)$$

If body isnot perfectly black body. Also, the net energy transfer by body is:

$$P_{rad} = e\sigma T^4$$

$$P_{abs} = e\sigma T_0^4$$

Net transfer of power = $P_{rad} - P_{abs}$

$$= e\sigma (T^4 - T_0^4)$$

Emmissivity (e) :-

The ratio of heat radiates by unperfectly black body per unit area per second at certain temperature to the heat radiate by perfectly black body per unit area per sec at same temperature. It is denoted by e.