Transmission of Heat

1. Conduction and Convection

1. In general heat travels from one point to another whenever there is a difference of temperatures.

2. Heat flows from a body at higher temperature to a lower temperature.

3. Heat is transferred by three distinct processes namely conduction, convection and radiation.

4. Conduction

a. Conduction is the slowest process.

b. Conduction is nil in vacuums.

c. Conduction is maximum in solids and minimum in gases.

d. In metals conduction is due to free electrons and in bad conductors conduction is due to collisions.

e. When a metal rod is heated continuously, after some time the temperature of any part of the rod does not change with time. Such a state is called steady state.

f. Under steady state the temperature gradient (temperature difference per unit length) and rate of flow of heat through the rod are constant.

$\frac{t_2 - t_1}{l}$ = Constant and $\frac{Q}{t}$ = Constant

g. Heat conduction does not depend on the mass but depends on dimensions.

h. The amount of heat (Q) flowing through a rod is directly proportional to

i) The area of cross section (A) of the rod

ii) Temperature difference $(\theta_1 - \theta_2)$ between the ends of the rod

iii) The time (t) of flow the heat through the rod and

iv) is inversely proportional to the length (l) of the rod.

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

Where K, is called the co-efficient of thermal conductivity of the rod

i. Unit of K : watt / m/k DF : $[MLT^{-3}K^{-1}]$

j. $\frac{Q}{t} = \frac{(\theta_1 - \theta_2)}{(l / kA)}$ Here $\frac{Q}{t} \rightarrow$ Heat current

k. Thermal resistance $= \frac{l}{KA}$ (K-sec/J)

l. Thermal conductivity of a conductor depends on the material of the rod and is independent of the dimensions of the rod.

m. Among solids silver is the best conductor (k = 1.01w/m/k)

n. Among liquids mercury is the best conductor (K_{Hg} = 0.02 W/m/k; K_{water} = 14×10-4 watt/k/m)

o. Among gases H_2 and He have high conductivity.($H_2 = 31.8\times10^{-5} W/m/k$ and He $= 33.9\times10^{-5} W/m/k$)

p. K of a good conductor is determined by Searle's method.

q. K of a bad conductor is determined by Lee's method.

r. Felt is a better insulator. The air enclosed in the fibers of the felt does not move.

s. Cloudy nights are warmer than clear nights because clouds (bad conductors) prevent heat from escaping into space.

t. A cooking vessel should have low specific heat and high thermal conductivity.

u. The thermometric conductivity or diffusivity is defined as the ratio of the coefficient of thermal conductivity to the thermal capacity per unit volume of the material.

Thermal capacity per unit volume $= \left(\frac{m}{V}\right)s = \square s$ where □ is density of substance.

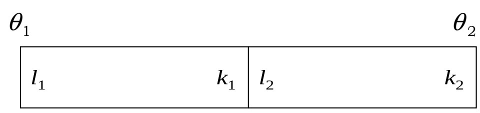
$\therefore \text{Diffusivity } D = \frac{K}{\rho s}$

5. Combinations

a) Series combination

Rate of flow of heat same.

$$\frac{K_1 A(\theta_1 - \theta)}{l_1} = \frac{K_2 A(\theta - \theta_2)}{l_2}$$

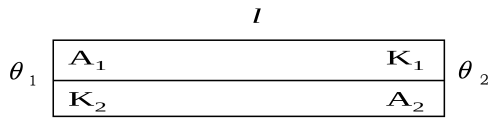


Interface temperature $\theta = \frac{K_1\theta_1 l_2 + K_2\theta_2 l_1}{K_1 l_2 + K_2 l_2}$ and $\frac{l_1 + l_2}{K} = \frac{l_1}{K_1} + \frac{l_2}{K_2}$

If $l_1 = l_2 = l,\ then \quad K = \frac{2K_1K_2}{K_1 + K_2}$

b) Parallel combination

$$K\left(A_1 + A_2\right) = K_1 A_1 + K_2 A_2$$



$$K = \frac{K_1 A_1 + K_2 A_2}{A_1 + A_2}$$

If $A_1 = A_2 = A$ then, $K = \frac{K_1 + K_2}{2}$

6. Ingen hausz experiment If $l_1, l_2, l_3 \ldots.$ are the lengths up to which is wax is melted on the rods of conductivities $K_1, K_2, K_3 \ldots$ $\frac{K_1}{l_1^2} = \frac{K_2}{l_2^2} = \frac{K_3}{l_3^2} = \ldots.$

7. When the temperature falls below 0°C say to □°C, the time taken for the thickness of ice growing from x_1 cm to x_2 cm on a lake is given by $t = \frac{\rho L}{2K\theta}(x_2^2 - x_1^2)$ where □ density of ice, K=coefficient of thermal conductivity of ice, L=latent heat of fusion of ice.

8. Convection

a. The transmission of heat from one part to another by the actual transfer of particles of matter is known as convection.

b. The process of transfer of heat from hotter part of the medium to the colder part of the medium by the bodily movement of the particles of the medium is called convection.

c. This is not possible in solids because of strong intermolecular forces.

d. Convection is possible only in fluids.

e. Land breeze and sea breeze are due to convection and high specific heat of water.

f. Convection of is of two types

i. **Natural convection** takes place in a still fluid. In natural convection heating is done from the bottom and cooling is done from the top. e.g., hot air rises by natural convection.

ii. **Forced convection** which takes place in a stream of a fluid. In forced convection heat transfer may take place in any direction.

e.g., cool air from open window enters the room and sends the hot air through ventilators.

g. Natural convection cannot take place in gravity free space.

h. The rate of heat convection is proportional to 1) temperature difference between object and the fluid (2) area of contact $\frac{Q}{t} = hA(\theta_1 - \theta_2)$

Where h is the convection co-efficient which depends on density, viscosity, specific heat thermal conductivity etc.

2. RADIATION

1. Thermal radiation

a. It is the process of transmission of heat from one place to another without any material medium.

b. It is the fastest process of transfer of heat.

c. Heat radiation travels with velocity of light.

d. It comes under infra-red radiation.

e. During radiation, medium do not get heated.

f. Heat radiation does not require any material medium.

g. Heat radiation obeys the laws of reflection, refraction etc and inverse square law ($I \alpha \frac{1}{d^2}$)

h. Heat radiation does not exhibit photo electric effect due to its law energy.

i. Bodies which allow heat radiation are called diathermanous. eg: vacuum.

j. Bodies which do not allow heat radiation are called athermanous. eg: wood.

k. Heat radiation belongs to continuous spectrum. This can be formed by rock salt and KCl prism.

l. Heat radiations can be measured with (a) Ether thermo scope, (b) Bolometer (wheat stone's Bridge) (c) Thermopile (d) Thermister (e) Radiation pyrometer.

m. In this process medium is not heated.

2. Black body

a. The amount of heat radiation falling on a body may be (1) absorbed (a) (2) reflected (r) and (3) transmitted (t) $\therefore a + r + t = 1$

b. If a = 0 and t = 0, then r = 1, the surface is a perfect reflector (or) perfect white body.

c. If a = 0 and r = 0 then t = 1. The body is a good transmitter.

d. If t = 0 and r = 0 then a = 1, then the surface is a perfect absorber (or) a perfect black body.

e. Space and Sun are treated as perfect black bodies.

f. The absorption is 96% for lamp black and 98% for platinum black.

g. Wein's black body and Ferry's black bodies are artificial black bodies.

h. The wave length (λ) of the heat radiation emitted depends on the temperature of the body.

3. Prevost's theory of heat exchanges

a. Every object emits and absorbs radiant energy at all temperatures except at absolute zero.

b. The energy emitted by a body does not depend on the temperature of the surroundings.

c. The rate of emission increases with the increase in the temperature of the body.

d. If the body emits more energy than absorbed its temperature decreases.

e. If the body absorbs more radiant energy than it emits, its temperature increases.

f. If two bodies continuously emit and absorb same amount of energy, then they are in dynamical thermal equilibrium.

4. Emissive power (e_λ)

a. The amount of energy emitted per second per unit surface area of a body at a given temperature for a given wavelength range (λ and $\lambda+d_\lambda$) is called emissive power.

b. At a given temperature if the radiations emitted have a wavelength difference d_λ, then the emissive power is equal to $e_\lambda d_\lambda$.

c. S.I unit of emissive power is Wm^{-2} and its dimensional formula is MT^{-3}.

5. Emissivity (e): The ratio of radiant energy emitted by a surface to radiant energy emitted by a black body under same conditions is called emissivity.

i) For a perfect black body emissivity e=1.

6. Absorptive power (a_λ)

a. At a given temperature, for a given wavelength range, the ratio of energy absorbed to the energy incident on the body is absorptive power.

$$a_\lambda = \frac{\text{Amount of radiant energy absorbed}}{\text{Amount of radiant energy incident}}$$

b. For a perfect black body, the absorptive power, a_λ=1.

c. A surface can have different absorptive powers for different wavelengths.

d. Whenever radiant energy is incident on a surface, a part of it is absorbed, a part of it is reflected and the remaining part is transmitted through it.

7. Reflecting power (r)

$$r = \frac{\text{Amount of radiant energy reflected}}{\text{Amount of radiant energy incident}}$$

8. Transmitting power (t)

$$t = \frac{\text{Amount of energy transmitted}}{\text{Amount of radiant energy incident}}$$

9. Kirchoff's law

i) The ratio of emissive power to absorptive power of a substance is constant.

ii) This constant is equal to the emissive power of a perfect black body at the given temperature and wavelength.

i.e., $\frac{e_\lambda}{a_\lambda} = \text{constant} = E_\lambda$

Where E_λ is the emissive power of perfect black body, e_λ and a_λ are emissive and absorptive powers of a given substance respectively.

iii) Good absorbers are good emitters.

iv) Poor absorbers are poor emitter.

10. Applications of Kirchhoff's law

i) A piece of blue glass absorbs red wavelengths at ordinary temperature. When it is heated strongly and cooled it appears brighter than a piece of red glass.

ii) A piece of yellow glass absorbs blue wavelengths at ordinary temperatures when heated in dark room it appears blue because it emits blue colour.

iii) Fraunhoffer lines in solar spectrum can be explained on the basis of Kirchhoff's law. They are absorption lines.

iv) Black surfaces are good absorbers and so good emitters but bad reflectors.

v) Highly polished surfaces are bad absorbers and so bad emitters but good reflectors.

11. Stefan's law

a. The amount of heat radiated by a black body per second per unit area is directly proportional to the fourth power of its absolute temperature.

$$E \alpha T^4 \Rightarrow E = \sigma T^4$$

Where σ=Stefan's constant

$=5.67\times10^{-8}\ Wm^{-2}k^{-4}$

b. Dimensional formula of Stefan's constant is $MT^{-3}T^{-4}$.

c. Radiant energy emitted by a hot body per second=$eA\sigma T^4$ where e is the emissivity of the hot body, A its surface area, T its absolute temperature and σ the Stefan's constant.

d. If the surface area of a body is more, it emits more heat energy. Hence it cools quickly.

e. A hot copper cube cools in a lesser time compared to a hot copper sphere of same mass because of least surface area for sphere.

f. Stefan's law holds good when the surrounding medium of the black body is vacuum.

12. Stefan-Boltzmann's law

If a black body at absolute temperature T is surrounded by an enclosure at absolute temperature To, then the rate of loss of heat energy by radiation per unit area is given by E=$\sigma(T^4 - T_o{}^4)$.

13. Newton's law of cooling

a. The rate of cooling of a hot body is directly proportional to the mean excess of temperature of the body above the surroundings, provided the difference in temperature of the body and the surroundings is small.

$$\frac{d\theta}{dt} = K\left(\frac{\theta_1 + \theta_2}{2} - \theta_s\right) \text{ where } K = \frac{4A\sigma\theta_s^3}{ms}$$

Here $\frac{d\theta}{dt}$=Rate of cooling.

θ_1, θ_2 are the initial and final temperature of the body respectively. θ_s is temperature of surroundings and K is the cooling constant.

b. Newton's law of cooling is applicable when (i) the heat lost by conduction is negligible and heat lost by the body is mainly by convection (ii) the hot body is cooled in uniformly stream lined flow of air or forced convection (iii) the temperature of every part of the body is same.

c. Newton's law holds good for small temperature differences upto 30°C. In case of forced convection the law holds good for large difference of temperatures.

d. Rate of loss of heat of a hot body due to cooling $\frac{dQ}{dt} = ms\frac{d\theta}{dt}$

Here m = mass of the body and s = specific heat of the body.

e. Specific heat of a liquid can be determined using Newton's law of cooling.

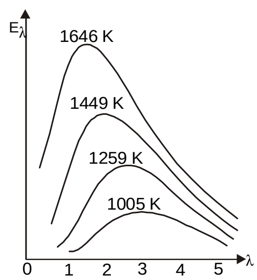
f. If m_1, m_2 and m_3 are masses of the calorimeter, water and liquid, s_1, s_2 and s_3 are the specific heats of the calorimeter, water and liquid and t_1 and t_2 are the times taken by water and liquid to cool from θ_2 to θ_1°C, then $\frac{m_1s_1 + m_2s_2}{m_1s_1 + m_3s_3} = \frac{t_1}{t_2}$.

g. Newton's law of cooling is a law connected with the process of convection.

h. It can be deduced from Stefan Boltzmann's law of radiation.

i. A cube, a sphere, a circular plate of same material and same mass are heated to the same high temperature. Among them the sphere cools at the lower rate because of its least surface area.

14. Distribution of energy in black body spectrum



i) The energy emitted by a black body contains large number of wavelengths.

ii) Energy emitted by a black body is not distributed uniformly among different wavelengths.

iii) At a given temperature, the energy increases with increasing wavelength and reaches a maximum value λ_m and decrease thereafter with increase in wavelength.

iv) As the temperature of black body increases, λ_m the wavelength corresponding to maximum energy decreases and shifts towards the shorter wavelength region.

v) The area under each curve represents total energy emitted by a black body at a particular temperature. The energy distribution curves can be explained by different laws of black body radiation like Wien's displacement law, Stefan's law, Ray Leigh-Jean's law and Planck's law.

vi) It can be deduced from Stefan Boltzmann's law of radiation.

15. Wien's displacement law

The wavelength λ_m corresponding to maximum energy emitted by a black body is inversely proportional to its absolute temperature.

$\lambda_m T = \text{constant}$.

The value of constant is 2.9×10^{-3} mK.

i) Radiation emitted by a black body normally per unit surface area per second in unit wavelength range is known as its "monochromatic emissive power".

ii) Wien's energy temperature displacement law states that monochromatic energy density, E_m of the radiation of black body is proportional to the fifth power of its absolute temperature.

$E_m T^{-5}$=constant.

16. Wien's formula

The amount of energy contained in a spectral region between wavelength, λ and $\lambda+d\lambda$ is given by $E_\lambda d_\lambda = \frac{A\lambda^{-5}}{e^{b/\lambda T}} d\lambda$. Where A, b are constants.

i) Wien's law is valid only for shorter wavelengths.

17. RayLeigh-Jean's law

The amount of energy contained in a spectral region between wavelengths, λ and $\lambda+d\lambda$ is given by $E_\lambda d_\lambda = \frac{8\pi KT}{\lambda^4} d\lambda$.

Where K = Boltzmann's constant.

i) Rayleigh-Jean's law holds good for longer wavelengths only.

ii) Planck's law :

iii) The entire region of black body radiant energy spectrum can be successfully explained by quantum theory proposed by Max Planck.

iv) Quantum theory proposes that any black body chamber contains simple harmonic oscillators of molecular dimensions.

v) The simple harmonic oscillators can absorb or emit energy (E) in discrete amounts only.

vi) The energy emitted in the form of discrete packets is proportional to its frequency i.e., $E \alpha \upsilon \Rightarrow E = h\upsilon$ where h = Planck's constant = 6.625×10^{-34} Js.

18. Planck's radiation law

The amount of energy contained in a spectral region between wavelengths λ and $\lambda + d\lambda$ is given by

$$E_{\lambda} d\lambda = \frac{8\pi hc}{\lambda^5 \left[e^{\frac{hc}{\lambda KT}} - 1 \right]} d\lambda$$