TRASMISSION OF HEAT: RADIATION

POINTS TO REMEMBER

1. Thermal radiation does not require a material medium.
2. It is the fastest process of transfer of heat.
3. Heat radiation travels with velocity of light.
4. It comes under infra-red radiation.
5. During radiation, medium do not get heated.
6. Heat radiation obeys the laws of reflection, refraction etc and inverse square law $(I \alpha \frac{1}{d^2})$
7. The amount of heat radiation falling on a body may be (1) absorbed (a) (2) reflected (r) and
   (3) transmitted (t) $\therefore a + r + t = 1$
   If a = 0 and t = 0, then r = 1, the surface is a perfect reflector (or) perfect white body.
   If a = 0 and r = 0 then t = 1. The body is a good transmitter.
   If t = 0 and r = 0 then a = 1, then the surface is a perfect absorber (or) a perfect black body.
8. **Prevost Theory of heat exchanges:**
   Every body above absolute zero emits and also absorbs heat radiation continuously. If the rate of emission is less than the rate of absorption the body gets heated.If the rate of emission is more than the rate of absorption the body gets cooled.If the rate of emission and absorption are equal, the body is said to be in thermal equilibrium.
9. **Emissive power:** Emissive power of a body at a temperature is defined as the energy radiated by the body per second per unit area.
10. **Emissivity:** Emissivity is defined as the ratio of the emissive power of the body to that of black body at the same temperature $e_\lambda = \frac{dE_\lambda}{d\lambda}$.
11. **Absorptive Power:** The ability of absorbing radiation falling on a body is known as absorptive power
12. **Absorptivity:** Absorptivity is the ratio of energy flux absorbed in certain time to the total energy flux incident on the body in the same time
13. **Kirchoff's Law:** The ratio of the emissivity of a body to its absorptivity is same for all bodies at a given temperature and is equal to the emissivity of a black body
14. **Stefan's Law:** The amount of heat radiated per second per unit surface area of a black body is proportional to the fourth power of the absolute temperature of the body. $E \alpha T^4 \Rightarrow E = \sigma T^4$ where T is a constant called Stefan's constant. σ = 5.67×10^{-8} walts/m^2/k^4
    For any body other than black body $E = e\sigma T^4$
    If T_0 is the temperature of the surroundings. $E = e\sigma\left(T^4 - T_0^4\right)$ (For any body)
    $E = \sigma\left(T^4 - T_0^4\right)$ (For black body) (Stefan- Boltzmann law)
15. **Newton's Law of cooling:** The rate of fall of temperature of what body is proportional to the difference between the mean temperature of the body and the

temperature of the surroundings $\frac{d\theta}{dt}\alpha\left(\frac{\theta_1+\theta_2}{2}-\theta_0\right)$ where θ_0 the temperature of the surroundings.

16. Newton's law of cooling is used to determine the specific heat of liquids.
17. **Wein's displacement Law**:
    The relation between energy and wave length emitted from a black body is given by $\lambda_m T = \text{cos tan } t$

SHORT ANSWER QUESTIONS

1. Explain Kirchhoff's law of radiation and give one application of the law (June2010, May2009, May: 2008, March: 2004, March: 2005,)

Ans: **Statement: The** ratio of the emissivity of a body to its absorptivity is same for all bodies at a given temperature and is equal to the emissivity of a black body at the same temperature.

Mathematically

$\frac{e_{\lambda_1}}{a_{\lambda_1}} = \frac{e_{\lambda_2}}{a_{\lambda_2}} = ... = e_{\lambda_b}$ = Emissivity of a black body

The quantities e_1 and a_1 can vary for different bodies, but their ratio is same for all bodies. This confirms that a good absorber is a good emitter.

From the above law it can be concluded that (1) The emissive power of a surface is directly proportional to the absorptive power i.e $e_\lambda \propto a_\lambda$

(2) Since E_1 increases with temperature, the ratio $\frac{e_\lambda}{a_\lambda}$ also increases with the temperature

(3) Emissivity of a body is equal to its absorptive power.

Applications of Kirchoff's law:

1. A china dish with a black spot is heated to high temperature and kept in a dark room. The black spot appears bright which absorbs heat at a high temperature and emits at low temperature.
2. A red glass heated to high temperature kept in a dark room appears green. Red and green are complementary colours.

2. Does thermometers measure the temperature of empty space? Explain

Ans: No, because temperature is the average kinetic energy of molecules.

According to kinetic theory of gases

Average K.E molecules = 3/2 KT,

Where T is the absolute temperature

K = Boltzmann's constant

$KE \propto T$

In vacuum or empty space there is no existence of medium.

So temperature is not measurable by using thermometers due to non existence of medium.

3. Why is it more comfortable to hold a cup of hot tea by handle rather than by wrapping our hands around the cup.

Ans : By decreasing the area of contact with the hot substance the rate of flow of heat can be decreased. Hence less heat flows through the handle and holding the cup at its handle is more comfortable.

4. Explain why good absorbers are good emitters.

Ans: According to kirchhoff's law "The ratio of the emissivity of a body to its absorptivity is same for all bodies at a given temperature and is equal to the emissivity of a black body at the same temperature".

Mathematically

$\frac{e_{\lambda_1}}{a_{\lambda_1}} = \frac{e_{\lambda_2}}{a_{\lambda_2}} = ... = e_{\lambda_b}$ = Emissivity of a black body

The quantities e_1 and a_1 can vary for different bodies, but their ratio is same for all bodies. This confirms that a good absorber is a good emitter.

Example: A china dish with a black spot is heated to high temperature and kept in a dark room. The black spot appears bright which absorbs heat at a high temperature and emits at low temperature.

5. Explain why relatively less hot iron rod appears red than rod at high temperature.

Ans: Wave length at which maximum power is emitted decreases as temperature increases. Hence iron rod emits maximum power at red wave length (long wave length) when temperature is less $\lambda_{max}.T$ = constant

(Wien's displacement law)

Hence relatively less hot iron rod appears red than rod at high temperature.

4. Would loss of heat be reduced or increased by increasing the air gap between the double paned windows than the usual necessary gap. Explain (consider convection)

Ans. When air gap between the double paned window is increased, convection currents are increased which transfer heat energy. Hence loss of heat is increased with the increase in the air gap. Hence more heat flows through the window from high temperature to low temperature.

6. Explain Stefan's law of Radiation? (March2010, March 2009, March2007, March2004)

Ans: **<u>Statement:</u>** The amount of heat radiated per second per unit surface area of a black body is proportional to the fourth power of the absolute temperature of the body. $E \alpha T^4 \Rightarrow E = \sigma T^4$ where T is a constant called Stefan's constant. σ = 5.67×10^{-8} walts/m^2/k^4

For any body other than black body $E = e_\lambda \sigma T^4$ Where e_λ is emissivity of body

If T_0 is the temperature of the surroundings. $E = e_\lambda \sigma \left(T^4 - T_0^4\right)$ (for any body)

$E = \sigma \left(T^4 - T_0^4\right)$ (for black body) (Stefan- Boltzmann law)

7. 4. A body cools from 60^0C to 40^0C in 20 minutes. What will be its temperature after next 40 minutes if the temperature of its surroundings is 10^0C. (March2011)

Sol: From Newton's law of cooling, $\frac{d\theta}{dt} \alpha \left(\frac{\theta_1 + \theta_2}{2} - \theta_0\right)$

$$\frac{(60-40)}{20}\alpha\left(\frac{60+40}{2}-10\right) \quad \text{and} \quad \left(\frac{40-x}{40}\right)\alpha\left(\frac{40+x}{2}-10\right)$$

Dividing, $x = 20^0 C$

VERY SHORT ANSWER QUESTIONS

1. Define emissive power and emissivity.?

Ans: Emissive power: Emissive power of a body at a temperature is defined as the energy radiated by the body per second per unit area.

Emissivity: Emissivity is defined as the ratio of the emissive power of the body to that of black body at the same temperature $e_\lambda = \frac{dE_\lambda}{d\lambda}$.

2. Why do animals curl in order to save themselves from extreme cold conditions? (May 2007)

Ans. By curling themselves, the surface area of the animal body which is exposed to the atmosphere can be reduced.

3. Cooking utensils are coated black outside, why? (March 2009)

Ans. Black surface is a good absorber and good emitter.

4. State Prevost's theory of heat exchanges.?

Sol: Every body emits thermal radiation at all temperatures above absolute zero and exchanges heat energy with the surroundings (i.e.,) the body supplies heat to the surroundings and in turn receives the heat from them**.**

5. Define absorptive power of a body. What is the absorptive power of a perfect black body?

Sol: The ratio of energy flux observed in a certain time to the total energy flux incident on the body in the same times is known as absorptive power (or) absorptivity (α)

Absorptive power of a perfect black body is one at all wavelength.

6. State Newton's law of cooling.?

Sol: The rate of loss of heat is directly proportional to the difference in the temperature between the body and its surrounding, provided the temperature difference is small and the nature of the radiating surface remains the same.

$$\frac{dE}{dt} \propto (T - T_s)$$

7. State the conditions under which Newton's law of cooling is applicable.?

Sol: Newton's law of cooling is applicable where

1) Loss of heat is negligible by conduction and only when it is due to convection.
2) Loss of heat occurs in a stream lined flow of air (i.e.,) forced convection.
3) Temperature of the body is uniformly distributed over it.
4) Temperature differences are moderate (i.e.,) upto 30K.

8. The roof of buildings is often painted white during summer. Why?

Sol: The roofs of buildings are often painted white during summer since white is a perfect reflector and bad absorber of radiation.

9. Why do two layers of cloth of equal thickness provide warmer covering than single layer of cloth of double the thickness?

Sol: The air trapped between the two layers is a poor conductor of heat. Hence two thin blankets are warmer than a single blanket of double the thickness.

10. A body with large reflectivity is a poor emitter. Explain.?

Sol: A body with large reflectivity is a poor absorber of heat. Since poor absorbers of heat are poor emitters also, a body with large reflectivity is a poor emitter.

11. a) Which is the fastest mode of transfer of heat? b) In which methods of heat transfer, gravity does not play any part?

Sol: a) Heat radiation
b) Conduction and Radiation.

12. Ventilators are provided in rooms just below the roof. Why?

Sol: The air respirated out is hotter and hence rarer. Hence it rises up in the room and leaves the room through the ventilators. Hence the ventilators arranged in rooms just below the roof.

13. Does a body radiate heat at $0^0 K$? Does it radiate heat at $0^0 C$?

Sol: 1) At $0^0 K$ the body stops radiating
2) At $0^0 C$ the body radiates heat.

SOLVED PROBLEMS:

1. Find the temperature of an oven if it radiates 8.28 cal per second through an opening whose area is 6.1cm^2. Assume that the radiation is close to that of a black body.

Sol: $$\text{E} = \frac{8.28}{6.1} = \frac{8.28 \times 4.2}{6.1 \times 10^{-4}} = 5.7 \times 10^4 \,\text{Wat/m}^2$$

Using Stefan-Boltzmanns law, $\text{E} = \sigma \text{T}^4$, where $\sigma = 5.67 \times 10^{-8} \,\text{W/m}^2.\text{K}^4$

Or $$\text{T}^4 = \frac{\text{E}}{\sigma} = \frac{5.7 \times 10^4}{5.67 \times 10^{-8}} = 1 \times 10^{12} \,\text{K}^4$$

$$\therefore \text{T} = 10^2 \,\text{K} = 1000\text{K}$$

2. If a black body is radiating at T = 1650 K, at what wavelength is the intensity maximum?

Sol: From Wien's law, $\lambda_{\text{max}} \text{T} = 2.9 \times 10^{-3} \,\text{mK}$

T = 1650K

$$\lambda_{\text{max}} = \frac{2.9 \times 10^{-3}}{1650} = 1.8 \mu\text{m}$$

3. A sphere with diameter of 80 cm is held at a temperature of 250^0C and is radiating energy. If the intensity of the radiation detected at a distance of 2.0 m from the sphere's centre is 102W/m^2, what is the emissivity of the sphere?

Sol: Using the inverse square law of intensity

$$\frac{I_2}{I_1}=\frac{r_1^2}{r_2^2} \Rightarrow I_2=I_1\left(\frac{r_1^2}{r_2^2}\right)=102\left(\frac{2.0}{0.4}\right)^2=2.55\times10^3\,\text{W/m}^2$$

The power P at the surface of the sphere is $I_2\left(4\pi r_2^2\right)=2.55\times10^3\times4\pi\left(0.4\right)^2$.

$\sigma=5.67\times10^{-8}\,\text{W/m}^2\text{K}^4;\ A=4\pi r_2^2=4\pi\left(0.4\right)^2\,\text{m}^2;\ T=250+273=523\text{K}$

According to Stefan's law $E=e_\lambda\sigma AT^4$

$$2.55\times10^3\times4\pi\left(0.4\right)^2=e_\lambda\times5.67\times10^{-8}\,\text{W/m}^2.\text{K}^4\times4\pi\left(0.4\right)^2\,\text{m}^2\times\left(523\text{K}\right)^4$$

$$\therefore e_\lambda=\frac{2.55\times10^3}{5.67\times10^{-8}\times\left(523\right)^4}=0.61$$

4. A body cools from 60^0C to 40^0C in 7 minutes. What will be its temperature after next 7 minutes if the temperature of its surroundings is 10^0C.?

Sol: From Newton's law of cooling, $\frac{d\theta}{dt}\alpha\left(\frac{\theta_1+\theta_2}{2}-\theta_0\right)$

$$\frac{(60-40)}{7}\alpha\left(\frac{60+40}{2}-10\right) \quad \text{and} \quad \left(\frac{40-x}{7}\right)\alpha\left(\frac{40+x}{2}-10\right)$$

Dividing, $x=28^0\text{C}$

5. Two spheres made of same material have their radii in the ratio 1:3. They are heated to the same temperature and kept in the same cool surroundings at a moderate temperature. Show that the ratio of their initial rates of fall of temperature is 3:1 if the bodies are cooled by natural convection and radiation.?

Sol: $Q=ms\theta \Rightarrow \frac{dQ}{dt}=ms\frac{d\theta}{dt}$

From Stefan- Boltzmann law $\frac{dQ}{dt}=eA\sigma\left(T^4-T_0^4\right)$

$$\therefore\ ms\frac{d\theta}{dt}=eA\sigma\left(T^4-T_0^4\right)\ or\ \frac{d\theta}{dt}=\frac{eA\sigma\left(T^4-T_0^4\right)}{ms}\ \ or\ \ \frac{d\theta}{dt}\ \alpha\ \frac{1}{\rho r s}$$

$$\therefore \frac{\left(d\theta/dt\right)_1}{\left(d\theta/dt\right)_2}=\frac{r_2}{r_1}=\frac{3}{1}$$

Exercise 1:

1. The surface of the sun has temperature of about 6000 K and the radius of the sun is 6.96×10^8 m. Calculate the total energy radiated by the sun each second. Assume that the emissivity of the sun is 0.965.

Ans: T = 6000 K ; r = 6.96 x 10^8 m ; e = 0.965

$A=4\pi r^2=4\times3.14\times\left(6.96\times10^8\right)^2=608.426\times10^{16}\,\text{m}^2$

$\sigma=5.67\times10^{-8}\,\text{w/m}^2\text{k}^4$

Total energy radiated by the sun each second, E = $eA\sigma T^4$

$$E = 0.965 \times 608.426 \times 10^{16} \times 5.67 \times 10^{-8} \times (6000)^4 = 4.3\ 10^{26}\ \text{J/sec}$$

2. If the maximum intensity of radiation for a black body is found at 2.65 μ m ,what is the temperature of the radiating body ?

Ans : λ_{max} = 2.65 mm = 2.65×10^{-6} m.

But, λ_{max} T = constant = 2.90×10^{-3} mK.

$$T = \frac{2.90x10^{-3}}{\lambda_{max}} = \frac{2.90x10^{-3}}{2.65x10^{-6}} = 1094\ K$$

3. An incandescent light bulb has a tungsten filament that is heated to a temperature 3.00×10^3 K when an electric current passes through it. If the surface area of the filament is approximately 1.00×10^{-4} m^2 and it has an emissivity of 0.32, what is the power radiated by the bulb?

Ans: T = 3.00×10^3 K ; A = 1.00×10^{-4} m^2 ; e = 0.32

According to Stefan's law

Power radiated by the bulb (P) = eAσ T^4

where σ = 5.67×10^{-8} w/m^2k^4

P = $0.32 \times 1 \times 10^{-4} \times 5.67 \times 10^{-8} \times (3 \times 10^3)^4$ = 146.96W

4. A body cools down from 60ºC to 50ºC in 5 minutes and to 40ºC in another 8 minutes. Find the temperature of the surroundings.

Ans: From Newton's law of cooling

$$\frac{(60-50)}{5}\alpha\left(\frac{60+50}{2}-\theta\right) \quad \text{and} \quad \left(\frac{50-40}{8}\right)\alpha\left(\frac{50+40}{2}-\theta\right)$$

Dividing, $\theta = 28.34^oC$

5. A body at 50ºC cools in surroundings maintained at 30ºC. Calculate the temperature at which the rate of cooling is half that of the beginning.

Ans : $\frac{(\theta-\theta_s)}{dt} = \frac{1}{2}\frac{(\theta-\theta_s)}{dt} \Rightarrow \frac{(\theta-30)}{dt} = \frac{1}{2}\frac{(50-30)}{dt} \Rightarrow \theta = 40^0 C$

6. A body is found to cool from 50ºC to 40ºC in 5 minutes, from 45ºC to 40ºC in next 6 minutes. Calculate the temperature of surroundings.

Ans: From Newton's law of cooling,

$$\frac{(50-40)}{5}\alpha\left(\frac{50+40}{2}-\theta\right) \quad \text{and} \quad \left(\frac{45-40}{6}\right)\alpha\left(\frac{45+40}{2}-\theta\right)$$

Dividing, $\theta = 40.7^oC$

7. A metal ball kept in a cooling room, cools from 72ºC to 60ºC in 10 minutes; and to 52ºC in next 10 minutes. Calculate the temperature of the cooling room.

Ans : From Newtons law of cooling,

$$\frac{(72-60)}{10}\alpha\left(\frac{60+52}{10}-\theta\right) \quad \text{and} \quad \left(\frac{45-40}{6}\right)\alpha\left(\frac{45+40}{2}-\theta\right)$$

Dividing, $\theta = 36^0 c$

ASSESS YOURSELF:

1. Guess some properties of thermal radiation?

Ans: i) Radiation travels in straight lines.

ii) Can propagate through vacuum with speed of light $C = 3\times10^{8}\,ms^{-1}$

iii) Radiation obeys laws of reflection, refraction and total internal reflection and exhibits interference, diffraction polarization and inverse square law of intensity

iv) Radiation rises the temperature of the body on which it falls.

2. When we sit in front of a fire with closed eyes we can feel significant warmth in our eyelids. When pair of glasses was put on your eyelids we don't feel that warmth? Why?

Ans: Fire radiates EM waves with large fraction of radiation falling in the infrared part of the spectrum. Glass absorbs such infrared radiation. Hence when we on the glasses much of radiation is blocked from reaching our eyelids and feel cooler.

3. Is a black body black?

Ans: No. Blackness refers to ideal property of absorbing the entire radiation incident on the body our eyes are only sensitive to visible light. If the body absorbs all the radiations it is described as black body. A black body could appear possibly as red, white or any other colour depending on its temperature.

4. If it is true that all the bodies radiate energy, why we are not able to see all the objects in a dark room?

Ans: At room temperature, energy radiated is primarily in the infrared region of electromagnetic radiation our eye can not defect this radiation. Hence we can not see the objects in a dark room.