13

TRANSFER OF HEAT

13.1 INTRODUCTION

In the previous lesson, we have studied thermodynamics. From the first law of thermodynamics, we know that the heat energy flows from warmer bodies to cooler bodies. In the present lesson we will go on to learn about the processes or ways by which bodies heat or cool. We already have some idea regarding these processes of heat transfer. The radiant energy from the sun comes to us after passing through the vacuum space between the earth and sun. This energy is essential for life to survive on our planet earth. Do you know that each one of us radiates energy at the rate of nearly 70 watts? Here we will study the radiation in details. We will also learn about the method of finding the temperatures of stars which you know, are very far away from us.

The other processes of heat transfer require the presence of a material medium. When one end of a metal is heated, the other end also becomes hot. Heat energy falling on the walls of our homes enters the room through this process called conduction. Similarly when you heat water in a pot the water mlecules near the bottom get the heat first. They move from the bottom of the pot to the water surface by a process called convection. After turning off the heat you find that the hotter water is near the surface. The water near the base of the pot might be cooler. We will learn more about all the processes of heat transfer in this unit. We will also learn what role heat transfer plays in our lives. In the unit we will learn about the measurement of quantity of heat.

13.2 OBJECTIVES

After studying this lesson, you should be able to :

- *distinguish between the three modes of heat transfer namely conduction, convection and radiation.*
- *define the coefficient of thermal conductivity and solve problems based on conduction.*
- *describe the principle and construction of a perfectly black body and draw graph between intensity and wavelength of radiant energy at different temperatures.*
- *state Wien's Law and Stefan — Boltzmann Law, and solve problems based on these laws.*
- *explain phenomena based on heat transfer.*

13.3 PROCESSES OF HEAT TRANSFER

We have learnt the laws of thermodynamics in the previous lesson. According to the second law, heat by itself can flow only from a body at higher temperature to a body at lower temperature. The transfer of heat continues until the temperatures equalize. We also know that temperature of a gas is related to its average kinetic energy. In the kinetic theory of gases, the average kinetic energy of gas molecules is related directly to its temperature. Masses of the same gas at different temperatures have different average kinetic energy. When the two masses are mixed the gas molecules collide with each other many times. This results in a new average kinetic energy and a new final temperature. The transfer of heat, equivalently, takes place from a mass of the gas having higher average kinetic energy to the mass having lesser average kinetic energy.

There are three processes by which heat transfers. They are ***conduction, convection*** and ***radiation.*** In conduction and convection heat transfers through molecular motion. Let us understand how this happens.

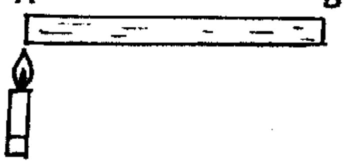

Fig. 13.1: *Heat Conduction in the metal rod from A to B*

(a) The process of ***conduction*** is more common in metals. The moelcules in such material are tightly bound. When heated they do not fly away. They are constraint to vibrate about their equilibrium positions. Let us heat a metal rod at the end A (Fig.13.1). The molecules near the end A become hot first. Their kinetic energy increases. They collide with their nearest neighbouring molecules and pass on to them some of their kinetic energy (K.E.). These molecules further collide with their own neighboures and transfer some K.E. to them. This process continues until the kinetic energy is transferred to molecules at the other end B of the rod. As average kinetic energy is proportional to the temperature, the end B gets hot. Thus, ***heat is transferred from molecule to molecule by conduction. In this process the molecules do not bodily move but simply vibrate.***

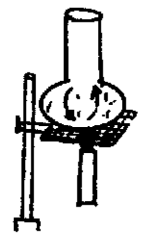

Fig. 13.2: Convection currents in water when heated.

(b) In ***convection*** the process is little different. The molecules of fluids when heated move up bodily. Let us take some water in a flask, and put some grains of potassium permangnate ($KMnO_4$) at its bottom and heat. As the fluid near the bottom gets heated it expands. The buoyant force causes its upward movement (Fig.13.2) to the surface. Its space is taken by the cooler and denser fluid which moves down. Thus a convection current of hotter fluid going up and cooler fluid going down are set. The fluid gradually heats up. These convection currents can be seen as $KMnO_4$ colours them red.

(c) In ***radiation*** heat energy moves in the form of waves. We will learn about the character of these waves later (Book 4). These waves can pass through vacuum and do not require the

presence of any material medium for their propagation. The heat from the sun comes to us mostly by radiation.

Let us study these processes in details.

13.3.1 Conduction

Consider a rectangular slab area A and thickness d. Its two faces are maintained at temperatures T_h and T_c by two reservoirs ($T_h > T_c$) (Fig. 13.3). Let us consider all the factors on which the quantity of heat transferred, Q from one face to another depends. We can intuitively feel that the larger the area, A the greater will be the heat transfer ($Q \alpha A$). Also the greater the thickness, d the lesser will be the heat transfer ($Q \alpha 1/d$). Heat transfer will be greater if the temperature difference between the face, ($T_h - T_c$) is greater. Finally the longer the time, t allowed for heat transfer the greater the Q.

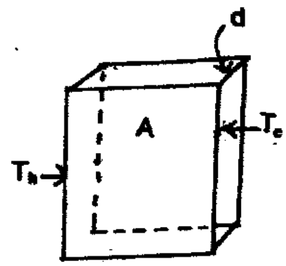

Fig. 13.3: Heat conduction through a slab of thickness d and surface area A, when the faces are kept at temp. T_h and T_c.

Thus, $$Q \,\alpha\, \frac{A(T_h - T_c)t}{d}$$

or $$Q = \frac{KA(T_h - T_c)t}{d} \qquad \dots (13.1)$$

Where K is a constant which depends on the nature of the material of which the slab is made. It is called the ***coefficient of thermal conductivity***, or simply, the thermal conductivity of the material. The value of K for some materials is given in Table 13.1.

***Exmple 13.1** : A cubical thermacole box, full of ice, has side 30 cm and thickness of 5.0 cm. If outside temperature is 45°C, estimate the amount of ice melted in 6 h. (K for thermacole is 0.01 J s^{-1} m^{-1} 6°C^{-1}, latent heat of fusion of ice is 335 J g^{-1}).*

Solution: The quantity of heat transferred into the box can be obtained using Eq. 13.1.

$$Q = \frac{KA(T_h - T_c)t}{d}$$

$= 0.01\ \text{J s}^{-1}\ \text{m}^{-1}\ {}^\circ\text{C}^{-1} \times 900 \times 10^{-4}\text{m}^2 \times 45\text{-C} \times 6 \times 60 \times 60\text{s} / 5 \times 10^{-2}\ \text{m}.$

$= 104976$ J

The mass of ice melted, m can be obtained by dividing Q by L.

$$m = Q/L$$

$$= \frac{104976\,\text{J}}{3235\ \text{Jg}^{-1}} \qquad = 313g$$

Table 13.1 : Thermal Conductivity of some materials

Material	Thermal conductivity in Js^{-1}m^{-1} °C^{-1}
Copper	400
Aluminium	240
Concrete	1.2
Glass	0 8
Water	0.60
Body Fat	0.20
Air	0.025
Thermacole	0.01

We can see from the Table 13.1 that metals such as copper have high thermal conductivity. This implies that heat flows with more ease through copper. This is the reason why cooking vessels and heating pots are made of copper. On the other hand air has very low thermal conductivity. Substances having low value of K are sometimes called thermal insulators. We wear woolen clothes during winter because wool prevents heat loss from our body. Wool is a good thermal insulator because air is trapped between its fibres. it reduces heat loss from our body. The trapped heat gives us a feeling of warmth. In the summer days when we have a slab of ice, we want to protect it from melting. We therefore put the ice in a ice box which is made of low thermal conductivity material such as thermacol. Sometimes we wrap the ice slab with jute bag which also has low thermal conductivity.

13.3.2 Convection

The process of convection is more common in fluids. When part of a fluid is heated it expands. It's density lowers and it rises due to buoyance. This results in a convection current which flows from hot region to cold region. As hot fluid leaves a region, pressure decreases. This causes colder fluid to move from surrounding to the low pressure region. This again results in convection current in the opposite direction. Suppose we are walking by the side of a lake or ocean on a hot day. We feel a cool breeze, why?

Due to continuous evaporation of water from its surface, the temperature of water falls. Warm air from the shore rises and moves towards the ocean/lake (Fig.13.4). This creates a low pressure area on the shore. This causes cooler air from water surface to move to the shore. We feel this breeze while walking on the shore. The net effect of these convection currents is the transfer of heat from the shore, which is hotter, to water, which is cooler. The rate of heat transfer, depends on many factors. There is no simple equation for convection as there is for conduction. However, the ***rate of heat transfer by convection depends on the temperature difference between the surfaces and also on their areas.***

Now let us check how much you have learnt about the methods of heat transfer.

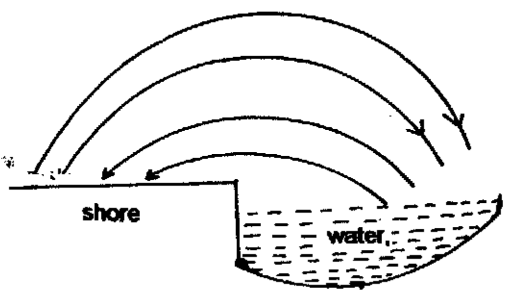

Fig. 13.4 : *Convection currents. Hot air from the shore rises and moves towards cooler water. The convenction current from water to the shores is experienced as cool breeze.*

INTEXT QUESTION 13.1

1) *Distinguish the difference between conduction and convection.*

....

2) *Verify that the units of K are J s^{-1} m^{-1} °C^{-1}.*

....

3) *Explain why do humans wrap themselves with woolens in winter season?*

....

4) *A rectangular slab of surface area 1m^2 and thickness 1 m is made up of a material of co-efficient of thermal conductivity K Jm^{-1} s^{-1} °C^{-1}. The opposite*

faces of the slab are maintained at 1°C temperature difference. Compute the energy transferred across the surface in one second, and hence give a verbal definition of K.

....

5) *During the summer the land mass of India gets very hot. But the air over the Indian ocean does not get as hot. This results in the onset of monsoons. Explain this phenomenon of monsoon scientifically.*

....

13.4 RADIATION

The term radiation refers to the continual emission of energy from the surfaces of all bodies. This energy is called the radiant energy and is in the form of electromagnetic waves. These waves travel with the velocity of light ($= 3 \times 10^8$ ms^{-1}) and are transmitted through vacuum as well as through air. They can easily be reflected from polished surfaces and focussed using a lens.

All bodies emit radiation with wavelengths that are chracteristic of the body's temperature. The sun, at 6000K, emits energy mainly in the visible spectrum. The earth at an ideal radiation temperature of 255K, radiates energy mainly in the far infrared (heat) region of electromagnetic specturm. The human body also radiates energy in the infrared region.

Let us now perform a simple experiment. Take a piece of blackened platinum wire in a dark room. Pass through it electrical current which serves to heat the wire. Gradually increase the magnitude of the current. After sometime the wire becomes warm and emits radiant energy. When you pass a slightly stronger current the wire will begin to glow with dull red light. This shows that the wire is just emitting red radiation of sufficient intensity to affect the human eye. Accurate observation has shown that this takes place at nearly 525°C. With increase in temperature, the colour of the emitted radiation will change from dull red to cherryred (at nearly 9000°C), to orange (at nearly 1100°C), to yellow (at nearly 1250°C), until at about 1600°C, it becomes white. What do you infer from this? Firstly, the temperature of a luminous body can be estimated from its colour. Secondly, with the increase in temperature, more waves of shorter wavelengths (since red light is of longer wavelength than orange, yellow etc.) are emitted by a heated body in sufficient intensity. Vice-versa you may argue that when the temperature of the wire is below 525°C, it emits waves longer than red, but these waves can be detected only by their heating effect.

13.4.1 Spectrum of the Radiant Energy

At any temperature the radiant energy emitted by a body is a mixture of waves of different wavelengths. The most intense of these waves will have a particular wavelength (say λ_m). At 400°C the λ_m will be about 5×10^{-4} cm or 5µm (1 micron $\mu = 10^{-6}$m) for a copper block. The intensity decreases for wavelengths either greater or less than this value (Fig. 13.5).

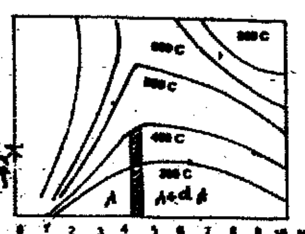

Fig. 13.5 : *Intensity and Wavelength*

Evidently area between each curve and the horizontal axis represents the total rate of radiation at that temperature (How?). You may study the curves shown in Fig. 13.5 and verify the following two facts.

1) The rate of radiation at a particular temperature (represented by the area between each curve and the horizontal axis) increases rapidly with temperature.

2) Each curve has a definite energy maximum and corresponding to that a wavelength λ_m (i.e. wavelength of the most intense wave). The λ_m shifts towards left, or towards shorter wavelengths with increasing temperature.

This second fact can be expressed quantitatively by what is known as Wien's displacement law.

13.4.2 Wien's Law

This law was actually deduced from thermodynamic considerations. It simply ***states that λ_m shifts towards shorter wavelenths as the temperature of a body is increased.*** This law is, strictly .vaid only for black bodies (about which we are going to discuss shortly). Mathematically

$$\lambda_m \propto \frac{1}{T}$$

$$\text{or, } \boxed{\lambda_m T = \text{constant}} \qquad \text{....(13.2)}$$

The constant in Eq. 13.2 is found to have a vlaue of 2884 micron-kelvin. This furnishes us with a simple method of determinig the temperature of all radiating bodies including those in the heavens. The radiation spectrum of the moon has a peak at λ_m = 14 microns. Using Wien's Law (Eq. 13.2) we

get $T = \dfrac{\text{constant}}{\lambda_m} = \dfrac{2884\,\text{micron}\,K}{14\,\text{microns}} = 206\,K$

Thus we deduce the temperature of the lunar surface to be 206K.

13.4.3 Emissive Power and Absorptive Power

The curves in Fig.13.5 clearly show that at a particular temperature and for a particular wavelength range λ to $d\lambda$, the rate of emission ***(i.e. amount of radiant energy emitted per square metre area of a surface, per second),*** per unit wavelength range, e_λ is constant. Hence at a given temperature and wavelength, the energy emitted by a surface can be best expressed in terms of e_λ. We will, hereafter, refer to e_λ as the ***emissive power*** of the surface at a given temperature and wavelength. For convenience, let us put e_λ in the form of a derivative.

Let, dE_λ = Amount of energy emitted by $\lambda_m{}^2$ area of a surface in one second within the wavelength range λ and $\lambda + d\lambda$ (of course, at a given temperature).

and, $d\lambda$ = Wavelength interval.

then $$e_\lambda = \frac{dE_\lambda}{d\lambda} \qquad \text{...(13.3)}$$

When radiation is incident over a surface, a part of it gets reflected, a part of it gets transmitted and rest are absorbed. Of course, for different surfaces, degrees of reflection, transmission and absorption will be different. We know from our experiences in everyday life that a bright polished surface reflects most of the radiation incident upon it, whereas a rough black surface absorbs most of the radiation falling on it. We define *absorptive power* a_λ of a surface, as

a_λ (at a given temperature and wavelength)

$$= \frac{\text{Total amount of radiation absorbed between } \lambda \text{ and } \lambda + d\lambda}{\text{Total amount of radiation incident between } \lambda \text{ and } \lambda + d\lambda} \quad \text{.........(13.4)}$$

13.5 BLACK BODY RADIATION AND KIRCHOFF'S LAW

As we have already pointed out, when radiation falls on matter, it may be partly reflected, partly absorbed and partly transmitted.

If for a particular wavelength λ, and for a given surface

r_λ = fraction of total incident energy reflected.

a_λ = fraction of total incident energy absorbed (absorptive power of the surface).

t_λ = fraction of total incident energy transmitted then obviously.

$$1 = r_\lambda + a_\lambda + t_\lambda \quad \text{.....(13.5)}$$

For perfectly black body, $r_\lambda = t_\lambda = 0$, and $a_\lambda = 1$.

Thus, radiations incident over black bodies will be totally absorved. Lamp black is the nearest approach to such a body. Apparently, it neither reflects nor transmits the light which falls on it, absorbs all, and hence appears black. But the perfectly black body does not exist in nature, for even the lamp black is found to transmit light of long wavelength. It absorbs about 96% of visible light, platinumpblack absorbs about 98%.

A ***perfectly white body***, in contrast, is defined as a body with $a_\lambda = 0$, $t_\lambda = 0$ and $r_\lambda = 1$. A piece of white chalk approximates to a perfectly white body.

13.5.1 Kirchoff's Law

We now want to discuss about what is known as ***Kirchoff's law*** which is true only for temperature radiation. The term temperature radiation needs a little elaboration. Material substances at all temperatures are found to radiate, at low temperatures radiation of long wavelengths and if raised to higher ***temperature radiation*** of smaller wavelengths. Such kind of radiation is temperature radiation. Other methods of making matter to emit radiation such as by passing electric discharge through its gaseous state, or by chemical actions as in flames, do not come under this category.

In order to deduce Kirchoff's law, we take an enclosed space and let its walls be opaque to radiation of all wavelengths. The walls are first imparted a uniform temperature and then thermally insulated from the surroundings. Imagine the enclosure to be filled with radiation being emitted by the walls having wavelength lying between λ and $\lambda + d\lambda$. Let a body A be placed inside it. It is not difficult to prove that whatever the initial temperature of a body might have been, it will ultimately acquire the temperature of the walls, i.e., A will come in thermal equilibrium with its immediate surroundings. Now, since the temperature is constant, the rate of emission of A must be equal to its rate of absorption of energy. For the given temperature of the body if e_λ is the emissive power of the surface then the energy emitted per square metre, per second, between λ and $\lambda + d\lambda$ will be $e_\lambda\ d_\lambda$ (Ref. Eq. 13.3). Let the energy falling on unit area per second within the same wavelength range and temperature be dQ. If for the given temperature and wavelength, absorptive power is a_λ, then the total energy absorbed per unit area per second will be a dQ (Ref. Eq. (13.4)].

Since, the body is in thermal equilibrium, energy emitted by the body can be equated, to the energy absorbed and we have,

$$e_\lambda \, d\lambda = a_\lambda \, dQ$$

or $$\frac{e_\lambda}{a_\lambda} = \frac{dQ}{d\lambda} \qquad \text{....(13.6)}$$

We know that for any given temperature, dQ is a constant. So for a fixed range of wavelength dλ, dQ will be constant. This implies that e_λ/a_λ is a cosntant for any surface. In case of a perfectly black body, let, E_λ be the emissive power and a_λ be the absorptive power, where of course, $a_\lambda = 1$. Using Eq. (13.6) for such a perfectly black body.

$$E_\lambda \, d\lambda = 1 \, dQ \qquad \text{...(13.7)}$$

$$\frac{dQ}{d\lambda} = E_\lambda \qquad \text{...(13.8)}$$

Eq. (13.6) and Eq. (13.7) give

$$\frac{e_\lambda}{a_\lambda} = E_\lambda \qquad \text{...(13.9)}$$

Eq. (13.8) is known as ***Kirchoff's law*** which can be stated as follows:

At any temperature the ratio of emissive power to the absorptive power of a substance is constant and equal to the emissive power of a perfectly black body.

We have proved the law here for bodies inside the enclosure. A little consideration will show that, since the emissive and absorptive power depend only upon the physical nature of the body and not upon its surroundings, the law will hold for all bodies under all conditions for pure temperature radiation.

This law clearly implies that bodies with high emissive powers (good emitters) will also have very high absorptive powers (good absorbers) since the ratio of these is constant for a given temperature and wavalength range. But since each body must either absorb or reflect the radiant energy reaching it, a good absorber must be a poor reflector (or good emitter).

13.5.2 Designing A Black Body

Kirchoff's law also enables us to design a perfectly black body for experimental purposes. We go back to an enclosure at constant tmperature containing radiations between wavelength range λ and $\lambda + d\lambda$. Now let us make a small hole in the enclosure and examine the radiation escaping out of it.This radiation is made up of single, double, triple, etc. reflection from the walls. Thus, if the reflecting power of the surface of the wall is r, while the emissive power is e_λ, the total radiation escaping out is

$$= e_\lambda + e_\lambda r + e_\lambda r^2 + e_\lambda r^3 + \ldots$$

$$= e_\lambda (1 + r + r^2 + r^3 + \ldots)$$

$$= \frac{e_\lambda}{1-r} \qquad \text{....(13.10)}$$

But from Kirchoff's Law $\frac{e_\lambda}{a_\lambda} = E$

or, $e_\lambda = Ea_\lambda$ ...(13.11)

Where E is the emission from a black body. If now walls are assumed to be opaque (i.e. $t = 0$) from Eq. (13.5.)

$a_\lambda = 1 - r$ ...(13.12)

Substituting from in Eq. (13.11), we get

$e_\lambda = E(1 - r)$

or $\frac{e_\lambda}{1-r} = E$ ...(13.13)

Comparing Eq. (13.10) and Eq.(13.15) it is clear that the radiation emerging out of the hole will be nearly identical with radiation from a perfectly black emissive surface. Smaller the hole, the more completely black the emitted radiation is. So we see that the uniformly heated enclosure with a small cavity behaves as a black body towards emission.

Again such an enclosure behaves as a perfectly black body towards incident radiation also. For any ray passing into the hole will be reflected internally within the enclosure and will be unable to escape outside. This may be further improved by blackening the inside. Hence the enclosre is a perfect absorber and behaves as a perfectly black body.

In Fig. 13.6, such a black body due to Fery has been shown. There is a cavity in the form of a hollow sphere with its inside coated with black material and has a small conical opening O. Note the conical projection P opposite the hole O. This is to avoid direct radiation from the surface opposite the hole which would otherwise make the body not perfectly black.

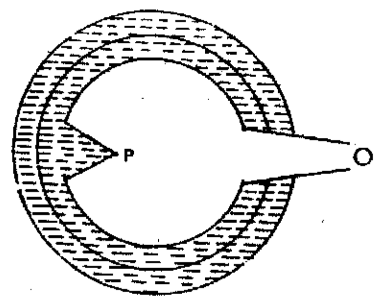

Fig. 13.6: *Fery's black body*

13.5.3 Stefan-Boltzmann Law

On the basis of experimental measurement Stefan and Boltzmann concluded that the ***radiant energy emitted per second from a surface of area A*** could be expressed by the relation

$$\boxed{E = Ae\sigma T^4} \qquad ....(13.14)$$

where σ is a constant, called ***Stefan-Boltzmann constant*** and has the value 5.672×10^{-8} J/m²sK⁴. T is the Kelvin temperature of the surface and e is a quantity, sometimes called the **emissivity** or **relative emittance**, it depends upon the nature of the surface and temperature. The value of e lies between 0 and 1 being small for polished metals and 1 for perfectly black materials.

One may tend to think from Eq. (13.14) that if the surfaces of all bodies are continually emitting radiant energy, why don't they eventually radiate away all their internal energy and cool down to a temperature of absolute zero [where $E = 0$ from Eq. (13.14)]. The answer is that they would do so if energy were not supplied to them in some way. In fact, all the objects are both radiating and absorbing radiant energy simultaneously. If a body is at the same temperature as its surroundings, the rate of emission is same as the rate of absorption. there is not net gain or loss of energy. and no change in temperature. However, if a body is at lower temperature than its surroundings, the rate of absorption will be greater than the rate of emission. Its temperature will rise till is equal to the room temperature. Similarly if a body is at higher temperature, the rate of emission will be greater than rate of absorption. There will be a net energy loss. Hence for such a body at a temperature T_1 with surroundings at a temperature T_2, the amount of net energy loss ($T_1 > T_2$) per second is

$$E_{net} = Ae\sigma\,(T_1^4 - T_2^4), \text{ for } T_1 > T_2 \qquad ...(13.15)$$

Example 13.2 : *Determine the surface area of the filament of a 100 W incandescant lamp at 3000 K. Given $\sigma = 5.7 \times 10^{-8}$ Wm^{-2} K^{-4}, and emissivity e of the filament = 0.3.*

Solution : According to Stefan-Boltzmann law

$$E = eA\sigma T^4$$

Where,

E = Rate of energy emitted = 100 W

A = Surface area

T = Tempeature of the surface = 3000 K

Hence, $A = \dfrac{E}{e\sigma T^4}$

$$= \frac{100}{0.3 \times 5.7 \times 10^{-8} \times (3000)^4}\,\text{m}^2$$

$$= 7.25 \times 10^{-5}\,\text{m}^2$$

Now it is time to check your understanding. Solve the following questions.

INTEXT QUESTION 13.2

1) *At what wavelength does a cavity radiator at 300K emit most radiation?*

....

2) *Why do we wear light colour clothing during summer?*

....

3) *State the important facts, which one can obtain from the experimental study of the spectrum of black body radiation.*

....

4) *A person of skin temperature 28°C is present in a room of tempeature 22°C.Assuming the emissivity of skin to be unity, and surface area of the person 1.9 m², compute the radiant power of this person.*

....

13.6 APPLICATIONS OF LAWS OF RADIATION IN DAILY LIFE

Laws of radiation have many applications in daily life situations. let us discuss three of them.

13.6.1 Solar Constant

Stefan-Boltzmann law can be used to determine the solar constant at different planets of the solar system. Let the radius of the sun be *r*, then total amount of energy ε emitted by the sun in one second (assuming sun to be a black body) using Eq. 13.14 is

$$\varepsilon = (4\,\pi\, r^2) \times (\sigma T^4) \quad \text{....(13.16)}$$

Where, T = Temperature of the sun

σ = Stefan-Boltzmann constant

Then the amount of energy E received per unit surface of the earth in one second is (using Eq.13.16)

$$E = \frac{\varepsilon}{4\pi R^2} = \left(\frac{r}{R}\right)^2 \sigma\, T^4 \quad \text{...(13.17)}$$

Where, R = Distance between the sun and the earth.

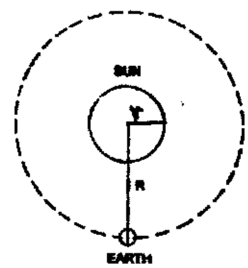

Fig. 13.7:

Eq. (13.17) gives the solar constant at the earth. If solar constant of any other plane is σ, distant R' from the sun is E', then

$$E' = \left(\frac{r}{R}\right)^2 \sigma T^4 \quad \text{...(13.18)}$$

Hence, $$\frac{E'}{E} = \left(\frac{R}{R'}\right)^2 \quad \text{...(13.19)}$$

From Eq. (13.19) it is clear that if E and are known E' can be calculated. The solar constant for the earth is found to be $1.36 \times 10^3\ Jm^{-2}\ s^{-1}$. The solar constant at mars whose distance from the sun is 1.52 times that of the earth,will be approximately $6 \times 10^2\ Jm^{-2}\ s^{-1}$ [Using Eq.(13.19)].

13.6.2 Greenhouse Effect

In a greenhouse, plants, flowers, grass etc. are enclosed in a glass structure. The glass allows short wavelength radiation light to enter. This radiation is absorbed by plant's matter. It is subsequently reradiated in the form of longer wavelength heat radiation, infrared. The longer wavelength radiations are not allowed to escape from the greenhouse as glass is effectively opaque to heat. That heat radiation is thus trapped in the greenhouse keeping it warm.

Similar effect takes place in our atmosphere. The atmosphere which contains a carbon dioxide blanket is transparent to visible light. Thus, the sun's light passes through the atmosphere and falls on the earth's surface. The earth absorbs, this light and subsequently emits it as infrared radiation. The carbon dioxide layer is opaque to infrared radiation. It is reflected, rather than transmitted, in the atmosphere, retaining the heat. This effect again is the ***greenhouse effect.***

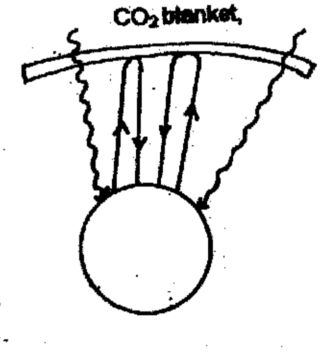

Fig. 13.8: Green house effect

13.6.3 Newton's Law of Cooling

Let us deduce Newton's law of cooling. Newton's law of cooling states ***that the rate of loss of heat (cooling) of a hot body is directly proportional to the mean excess of temperature of the hot body over that of its surrounding provided the difference of temperature is very small.***

Let a body at temperature T K be surrounded by another body at T_0K. The rate at which heat is lost per unit area per second by the hot body is

$$E = e\sigma\left(T^4 - T_o^4\right) \quad ...(13.20)$$

$$= e\sigma\left(T - T_o\right)\left(T^3 + T^2 T_o + T T_o^2 + T_o^3\right) \quad ...(13.21)$$

If $(T-T_0)$ is very small, $T \sim T_0$

$$T^3 \sim T_o^3, T^2T_o \sim TT_o^2 \sim T_o^3$$

$$E = e\sigma\left(T - T_o\right)4T_o^3$$

$$E = k\left(T - T_o\right).$$

$$where\ k = 4e\sigma\ T_o^3$$

or $$E\,\alpha\left(T - T_o\right) \quad ....(13.22)$$

This is the ***Newston's law of cooling.***
Take a pause and try to solve the following questions

INTEXT QUESTION 13.3

1. *How many watts of power will be received by a region 40m wide and 50m long located on the surface of the earth?*

   ....

2. *A planet which has rarer atmosphere is cooler. Explain.*

   ....

3. *Using the relation $a^2 - b^2 = (a + b)(a - b)$ establish Eq. 13.21 starting from Eq. 13.20.*

   ....

3.7 WHAT YOU HAVE LEARNT

- Heat by itself flows from a body at high temperature to a body at lower temperature. There are three processes by which heat is transferred. They are conduction, convection and radiation.
- In conduction heat is transferred by collision of molecules which vibrate about their fixed positions.
- In convection heat is transferred by bodily motion of molecules. In radiation heat is transferred through electromagnetic waves.
- The quantity of heat transferred by conduction is given by

  $$Q = \frac{K(T_h - T_c)At}{d}$$

- *Wein's Law.* The spectrum of radiant energy by a body at temperature T(K) has a maxima at wavelength λ_m, such that $\lambda_m T$ = constant (= 2880 μK)·
- Stefan-Boltzmann Law. The rate of energy radiated by a source at T(K) is given by $E = e\sigma AT^4$
- The absorptive power a is defined as

$$a = \frac{\text{Total amount of energy absorbed between } \lambda \text{ and } \lambda + d\lambda}{\text{Total amount of incident energy between } \lambda \text{ and } \lambda + d\lambda}$$

- The emissive power of a surface e_λ is the amount of radiant energy emitted per square metre area per second per unit wavelength range at a given temperature.

- The solar constant for the earth is 1.36×10^3 Jm^{-2} s^{-1}
- Newton's Law of cooling. The rate of cooling of a body is proportional to the excess temperature $E \alpha (T - T_o)$.

13.8 TERMINAL QUESTION

1. A thermosflask (Fig.13.9) is made of a double walled glass bottle enclosed in metal container.the bottle contains some liquid whole temperature we want to maintain. Look at the diagram carefully and explain how the construction of the flask helps in minimizing heat transfer due to conduction, convection and radiation.

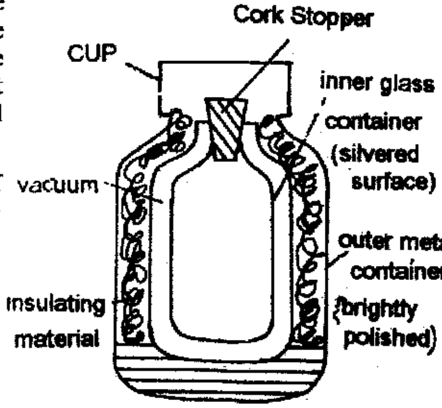

Fig. 13.9:

2. The wavelength corresponding to emission of energy maxima of a star is 4000°A. Compute the temperature of the star. (1°A=10^{-8} cm).
3. A blackened solid copper sphere of radius 2 cm is placed in an evacuated enclosure whose walls are kept at 1000°C. At what rate must energy be supplied to the sphere to keep its temperature constant at 127°C.
4. Comment on the statement "A good absorber must be a good emitter".
5. A copper pot whose bottom surface is 0.5 cm thick and 50 cm in diamter rests on a burner which maintains the bottom surface of the pot at 110°C. A steady heat flows through the bottom into the pot, where water boils at atmospheric pressure. The actual temperature of the inside surface of the pot bottom is 105°C. How many kilograms of water boils off in one hour.
6. Define the coefficient of thermal conductivity. List the factors on which it depends.
7. Distinguish between conduction and convection methods of heat transformer.
8. If two or more rods of equal area of cross-section are connected in series, show that their equivalent thermal resistance is equal to the sum of thermal resitance of each rod. [Note: Thermal resistance is reciprocal of thermal conductivity]
9. Ratio of coefficient of thermal conductivities of the different materials is 4:3. To have the same thermal resistance of the two rods of these materials of equal thickness, what should be the ratio of their lengths?
10. Why do we feel warmer on a winter night when clouds cover the sky than when the sky is clear?
11. Why does a peice of copper or iron appear hotter to touch than a similar piece of wood even when both are at the same temperature?
12. Why is it more difficult to sip hot tea from a metal cup than from a china-clay cup?
13. Why are the woollen clothes warmer than cotton clothes?
14. Why do who layers of cloth at equal thickness provide warmer covering than a single layer of cloth of double the thickness?
15. Can the water be boiled by connection inside an earth satellite?
16. A 500 W bulb is globing. We keep our one hand 5 cm above it and other 5 cm below it Why more heat is experienced at the upper hand?
17. Two vessels of different material are identical in size and in dimensions. They are filled with equal quantity of ice at 0°C. If ice in both vessles metls completely in 25 minutes and in 20 minutes than compare thermal conductivities of metals of both vessels.
18. Calculate the thermal resistivity of a copper rod 20.0 cm. length and 4.0 cm. in diamter.

Thermal conductivity of copper = 9.2×10^{-2} acrosss the ends of rod be 50°C, calculate the rate of heat flow.

ANSWERS TO THE INTEXT QUESTION

Intext question 13.1

1. The energy transferred is equal to *K*. the coefficient of thermal conductivity is the amount of heat energy transferred in one second across the faces of a rectangular slab of area $1m^2$, and thickness 1m, when they are kept at a temperature difference of 1°C.
2. The moisture laden air over the ocean is cooler than the air near the land. This causes convection currents. The hot dry air over the land rises up and creates a low pressure region. This causes the moist air from the ocean to move to the land. The water content of this air is so large that it appears as clouds and eventually we have monsoon showers over the land.

Intext question 13.2

1. $\lambda_m = \frac{\text{Wien's constant}}{\text{Temperature}}$

$$= \frac{2880 \mu K}{300 K}$$

$$= 9.6 \mu$$

2. Hint : woolens trap air which has low thermal conductivity.
3. 66.4 W.

Intext question 13.3

1. Solar constant × area

$$= 2.7 \times 10^5 \text{ W}$$

2. $\left(T^4 - T_o^4\right) = \left(T^2 - T_o^2\right)\left(T^2 + T_o^2\right)$

$$= (T - To)(T + T_o)\left(T^2 + T_o^2\right)$$

$$= (T - T_o)(T^3 + T^2\, T_o + T\, T_o^2 + T_o^3$$