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12

HEAT TRANSFER AND SOLAR ENERGY

In the previous lesson you have studied the laws of thermodynamics, which govern the flow and direction of thermal energy in a thermodynamic system. In this lesson you will learn about the processes of heat transfer. The energy from the sun is responsible for life on our beautiful planet. Before reaching the earth, it passes through vacuum as well as material medium between the earth and the sun. Do you know that each one of us also radiates energy at the rate of nearly 70 watt? Here we will study the **radiation** in detail. This study enables us to determine the temperatures of stars even though they are very far away from us.

Another process of heat transfer is **conduction,** which requires the presence of a material medium. When one end of a metal rod is heated, its other end also becomes hot after some time. That is why we use handles of wood or similar other bad conductor of heat in various appliances. Heat energy falling on the walls of our homes also enters inside through conduction. But when you heat water in a pot, water molecules near the bottom get the heat first. They move from the bottom of the pot to the water surface and carry heat energy. This mode of heat transfer is called **convection**. These processes are responsible for various natural phenomena, like monsoon which are crucial for existence of life on the globe. You will learn more about these processes of heat transfer in this unit.

OBJECTIVES

After studying this lesson, you should be able to :

- *distinguish between conduction convection and radiation;*
- *define the coefficient of thermal conductivity;*
- *define the emissive power and the absorptive power of a body;*

- *describe green house effect and its consequencies for life on earth; and*
- *apply laws governing black body radiation.*

12.1 PROCESSES OF HEAT TRANSFER

You have learnt the laws of thermodynamics in the previous lesson. The second law postulates that the natural tendency of heat is to flow spontaneously from a body at higher temperature to a body at lower temperature. The transfer of heat continues until the temperatures of the two bodies become equal. From kinetic theory, you may recall that temperature of a gas is related to its average kinetic energy. It means that molecules of a gas at different temperatures have different average kinetic energies.

There are three processes by which transfer of heat takes place. These are : *conduction*, *convection* and *radiation.* In conduction and convection, heat transfer takes place through molecular motion. Let us understand how this happens.

Heat transfer through *conduction* is more common in solids. We know that atoms in solids are tightly bound. When heated, they can not leave their sites; they are constrained to vibrate about their respective equilibrium positions. Let us understand as to what happens to their motion when we heat a metal rod at one end (Fig.12.1). The atoms near the end A become hot and their kinetic energy increases. They vibrate about their mean positions with increased kinetic energy and being in contact with their nearest neighbouring atoms, pass on some of their kinetic energy (K.E.) to them. These atoms further transfer some K.E to their neighboures and so on. This process continues and kinetic energy is transferred to atoms at the other end B of the rod. As average kinetic energy is proportional to temperature, the end B gets hot. Thus, *heat* is *transferred from atom* to *atom by conduction. In this process, the atoms* do *not bodily move* but *simply vibrate about their mean equilbrium positions and pass energy from one to another.*

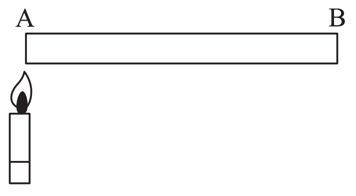


Fig. 12.1 : Heat conduction in a metal rod

In *convection,* molecules of fluids receive thermal energy and move up bodily. To see this, take some water in a flask and put some grains of potassium permanganate ($KMnO_4$) at its bottom. Put a bunsen flame under the flask. As the fluid near the bottom gets heated, it expands. The density of water decreases and the buoyant force causes it to move upward (Fig.12.2). The space occupied by hot water is taken

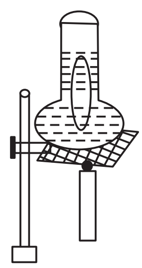


Fig. 12.2 : Convection currents are formed in water when heated

by the cooler and denser water, which moves downwards. Thus, a convection current of hotter water going up and cooler water coming down is set up. The water gradually heats up. These convection currents can be seen as $KMnO_4$ colours them red.

In *radiation,* heat energy moves in the form of waves. You will learn about the characteristics of these waves in a later section. These waves can pass through vacuum and do not require the presence of any material medium for their propagation. Heat from the sun comes to us mostly by radiation.

We now study these processes in detail.

12.1.1 Conduction

Consider a rectangular slab of area of cross-section **A** and thickness *d*. Its two faces are maintained at temperatures T_h and T_c ($< T_h$), as shown in Fig. 12.3. Let us consider all the factors on which the quantity of heat *Q* transferred from one face to another depends. We can intuitively feel that larger the area A, the greater will be the heat transferd ($Q \propto A$). Also, greater the thickness, lesser will be the heat transfer ($Q \propto 1/d$). Heat transfer will be more if the temperature difference between the faces, $(T_h - T_c)$, is large. Finally longer the time *t* allowed for heat transfer, greater will be the value of *Q*. Mathematically, we can write

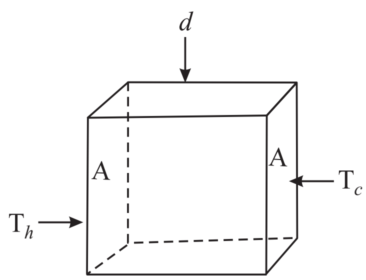


Fig. 12.3 : Heat conduction through a slab of thickness *d* and surface area *A*, when the faces are kept at temperatures T_h and T_c.

$$Q \propto \frac{A(T_h - T_c)\,.\,t}{d}$$

$$Q = \frac{KA(T_h - T_c)\,t}{d} \qquad (12.1)$$

where *K* is a constant which depends on the nature of the material of the slab. It is called the coefficient of thermal conductivity,or simply, **thermal conductivity** of the material. **Thermal conductivity** of a material is defined as the amount of heat transferred in one second across a piece of the material having area of cross-section $1 m^2$ and edge 1m when its opposite faces are maintained at a temperature difference of 1 K. The SI unit of thermal conductivity is $W\,m^{-1}\,k^{-1}$. The value of K for some materials is given in Table 12.1

Table 12.1 : Thermal Conductivity of some materials

Material	Thermal conductivity ($Wm^{-1}\,K^{-1}$)
Copper	400
Aluminium	240
Concrete	1.2
Glass	0.8
Water	0.60
Body talc	0.20
Air	0.025
Thermocole	0.01

Example 12.1 : A cubical thermocol 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 thermocol is 0.01 J s^{-1} m^{-1} $°C^{-1}$ and latent heat of fusion of ice is 335 J g^{-1}.

Solution : The quantity of heat transferred into the box through its one face can be obtained using Eq. (12.1) :

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

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

$$= 10496 \text{ J}$$

Since the box has six faces, total heat passing into the box

$$Q = 10496 \times 6 \text{ J}$$

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

$$m = Q/L$$

$$= \frac{10496\text{J}}{335 \text{ Jg}^{-1}} \times 6$$

$$= 313 \times 6 \text{ g} = 1878 \text{ g}$$

We can see from Table 12.1 that metals such as copper and aluminium 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 and thermocol have very low thermal conductivities. Substances having low value of K are sometimes called thermal insulators. We wear woollen clothes during winter because air trapped in wool fibres prevents heat loss from our body. Wool is a good thermal insulator because air is trapped between its fibres. The trapped heat gives us a feeling of warmth. Even if a few cotton clothes are put on one above another, the air trapped in-between layers stops cold. In the summer days, to protect a slab of ice from melting, we put it in a ice box made of thermocol. Sometimes we wrap the ice slab in jute bag, which also has low thermal conductivity.

12.1.2 Convection

It is common experience that while walking by the side of a lake or a sea shore on a hot day, we feel a cool breeze. Do you know the reason? Let us discover it.

Due to continuous evaporation of water from the surface of lake or sea, the temperature of water falls. Warm air from the shore rises and moves upwards (Fig.12.4). This creates low pressure area on the shore and causes cooler air

Notes

from water surface to move to 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 for conduction. However, the ***rate of heat transfer by convection depends on the temperature difference between the surfaces and also on their areas.***

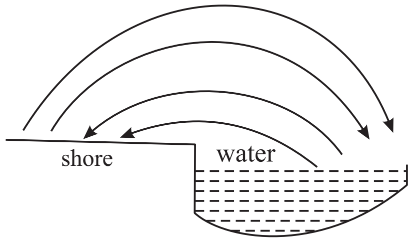


Fig. 12.4 : Convection currents. Hot air from the shore rises and moves towards cooler water. The convection current from water to the shores is experienced as cool breeze.

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

12.1.3 Radiation

Radiation refers to continuous emission of energy from the surface of a body. This energy is called radiant energy and is in the form of electromagnetic waves. These waves travel with the velocity of light (3×10^8 ms^{-1}) and can travel 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 their temperature. The sun, at 6000 K emits energy mainly in the visible spectrum. The earth at an ideal radiation temperature of 295 K radiates energy mainly in the far infra-red (thermal) region of electromagnetic spectrum. The human body also radiates energy in the infra-red region.

Let us now perform a simple experiment. Take a piece of blackened platinum wire in a dark room. Pass an electrical current through it. You will note that the wire has become hot. Gradually increase the magnitude of the current. After sometime, the wire will begin to radiate. 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. This takes place at nearly 525°C. With further increase in temperature, the colour of the emitted rediation will change from dull red to cherry red (at nearly 900°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? It shows that the *temperature of a luminous body can be estimated from its colour.* Secondly, *with increase in temperature, waves of shorter wavelengths* (since red light is of longer wavelength than orange. yellow etc.) *are also emitted with sufficient intensity*. Considering in reverse order, 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.

INTEXT QUESTIONS 12.1

1. Distinguish between conduction and convection.
2. Verify that the units of K are Js $^{-1}$ m^{-1} °C^{-1}.
3. Explain why do humans wrap themselves in woollens in winter season?
4. A cubical slab of surface area 1 m^2, thickness 1 m, and made of a material of thermal conductivity K. 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 numerical definition of K.
5. During the summer, the land mass gets very hot. But the air over the ocean does not get as hot. This results in the onset of sea breezes. Explain.

12.2 RADIATION LAWS

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 (sayλ_m).At 400°C, the λ_m will be about 5×10^{-4} cm or 5 μm (1 micron (μ) =10^{-6}m) for a copper block.The intensity decreases for wavelengths either greater or less than this value (Fig. 12.5).

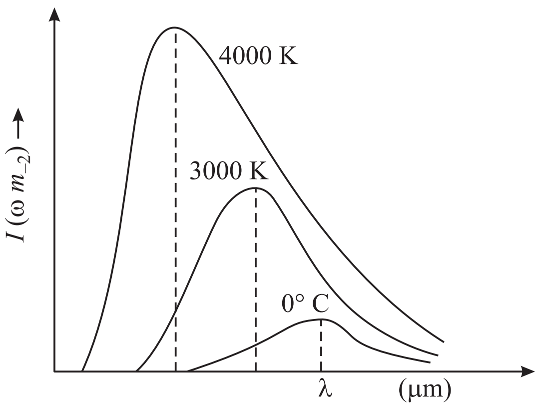


Fig. 12.5 : Variation in intensity with wavelength for a black body at different temperatures

Evidently area between each curve and the horizontial axis represents the total rate of radiation at that temperature. You may study the curves shown in Fig. 12.5 and verify the following two facts.

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

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

This second fact is expressed quantitatively by what is known as Wien's displacement law. It **states that λ_m *shifts towards shorter wavelengths as the temperature of a body is increased*.** This law is., strictly valid only for black bodies. Mathematically, ***we say that the product*** $\boldsymbol{\lambda_m}$ **T** ***is constant for a body emitting radiation at temperature*** **T*:***

$$\lambda_m T = \text{constant} \qquad (12.2)$$

The constant in Eqn. (12.2) has a value 2.884×10^{-3} mK. This law furnishes us with a simple method of determining the temperature of all radiating bodies including those in space. The radiation spectrum of the moon has a peak at λ_m = 14 micron. Using Eqn. (12.2), we get

$$T = \frac{2884 \text{ micron K}}{14 \text{ micron}} = 206\text{K}$$

That is, the temperature of the lunar surface is 206K

Wilhelm Wien
(1864 – 1928)

The 1911 Nobel Leureate in physics, Wilhelm Wien, was son of a land owner in East Prussia. After schooling at Prussia, he went to Germany for his college. At the University of Berlin, he studied under great physicist Helmholtz and got his doctorate on diffraction of light from metal surfaces in 1886.

He had a very brilliant professional carrer. In 1896, he succeeded Philip Lenard as Professor of Physics at Aix-la-chappelle. In 1899, he become Professor of Physics at University of Giessen and in 1900, he succeeded W.C. Roentgen at Wurzberg. In 1902, he was invited to succeed Ludwig Boltzmann at University of Leipzig and in 1906 to succeed Drude at University of Berlin. But he refused these invitations. In 1920, he was appointed Professor of Physics at munich and he remained there till his last.

12.2.1 Kirchhoff's Law

As pointed out earlier, when radiation falls on matter, it may be partly reflected, partly absorbed and partly transmitted. If for a particular wavelength λ and a given surface, r_λ, a_λ and t_λ, respectively denote the fraction of total incident energy reflected, absorbed and transmitted, we can write

$$1 = r_\lambda + a_\lambda + t_\lambda \qquad (12.3)$$

A body is said to be perfectly black, if $r_\lambda = t_\lambda = 0$ and $a_\lambda = 1$. It means that radiations incident on black bodies will be completely absorbed. As such, perfectly black body does not exist in nature. Lamp black is the nearest approximation to a black body. It absorbs about 96% of visible light and platinum black absorbs about 98%. It is found to transmit light of long wavelength.

A ***perfectly white body***, in contrast, 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.

This implies that good emitters are also good absorbers. But each body must either absorb or reflect the radiant energy reaching it. So we can say that a good absorber must be a poor reflector (or good emitter).

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 temperature 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 undergoes multiple reflections from the walls. Thus, if the reflecting power of the surface of the wall is r, and emissive power is e_λ, the total radiation escaping out is given by

$$E_\lambda = e_\lambda + e_\lambda r_\lambda + e_\lambda r^2 + e_\lambda r_\lambda^3 + ...$$

$$= e_\lambda (1 + r_\lambda + r_\lambda^2 + r_\lambda^3 + ...)$$

$$= \frac{e_\lambda}{1 - r_\lambda} \qquad (12.4)$$

But from Kirchoffs Law $\frac{e_\lambda}{a_\lambda} = E_\lambda$

$$e_\lambda = E_\lambda a_\lambda \qquad (12.5)$$

where E_λ is the emission from a black body. If now walls are assumed to be opaque (i.e. $t = 0$), from Eqn. (12.3), we can write

$$a_\lambda = 1 - r_\lambda \qquad (12.6)$$

Substituting this result in Eqn. (12.5), we get

$$e_\lambda = E_\lambda (1 - r_\lambda)$$

or

$$E_\lambda = \frac{e_\lambda}{1 - r_\lambda} \qquad (12.7)$$

On comparing Eqns. (12.4) and (12.7), we note that the radiation emerging out of the hole will be identical to the 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 for emission.**

Such an enclosure behaves as a perfectly black body towards incident radiation also. Any radiation passing into the hole will undergo multiple

reflections internally within the enclosure and will be unable to escape outside. This may be further improved by blackening the inside.Hence the enclosure is a perfect absorber and behaves as a perfectly black body.

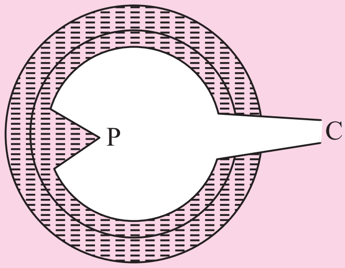
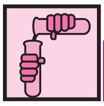


Fig. 12.6 : Fery's black body

Fig. 12.6 shows a black body due to Fery. There is a cavity in the form of a hollow sphere and its inside is coated with black material. It 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 render the body not perfectly black.



ACTIVITY 12.1

You have studied that black surface absorbs heat radiations more quickly than a shiny white surface. You can perform the following simple experiment to observe this effect.

Take two metal plates A and B. Coat one surface of A as black and polish one surface of B. Take an electric heater. Support these on vertical stands such that the coated black surface and coated white surface face the heater. Ensure that coated plates are equidstant from the heater. Fix one cork each with wax on the uncoated sides of the plates.

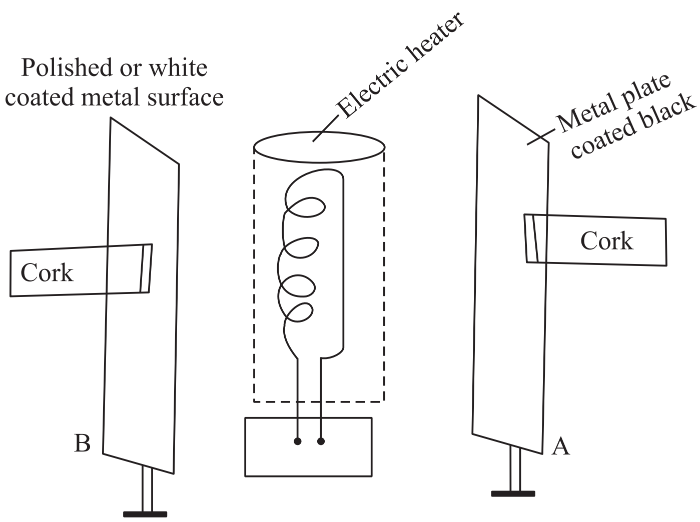


Fig. 12.7 : Showing the difference in heat absorption of a black and a shining surface

Switch on the electric heater. Since both metal plates are identical and placed at the same distance from the heater, they receive the same amount of radiation from it. You will observe that the cork on the blackened plate falls first. This is becasuse the black surface absorbs more heat than the white surface. This proves that black surfaces are good aborbers of heat radiations.

12.2.2 Emissive and Absorptive Power

Different bodies at the same temperature emit different amounts of thermal energy. The ability of a hot body to emit radiation is known as its **emissive power**. The total emissive power of a radiating body at a particular temperature is defined as the total amount of energy radiated per second per unit area of its surface. It also depends upon the temperature of the body above the surroundings. Its unit is $Jm^{-2}s^{-1}$. At the same temperature the total emissive power of a black body has the maximum value (E_b). The ratio of the total emissive power, E of a real body to the total emissive power E_b of a black-body at the same temperature is known as emissivity ε. Thus, emissivity,

$$\varepsilon = \frac{E}{E_b}$$

or

$$E = \varepsilon E_b$$

Note that both E and E_b are temperature dependent. Emissivity is also not a constant. It shows small variation with temperature.

When the radiant energy falls on a body, a part of the energy is absorbed. The ability of the body to absorb radiant energy falling on it is known as its **absorptive power**.

The total absorptive power of a body is defined as the ratio of the energy absorbed to the energy falling. The absorptive power (a) is the fraction of the incident energy which is absorbed. For a perfectly black body, $a = 1$.

Sometimes it is interesting to know the ability of a body to absorb radiation of a given wavelength. Under such situation, spectral absorptive power term, a_λ, is used. Thus, spectral absorptive power for perfectly black body $a_{b\lambda} = 1$.

It is experimentally found that the good emitters of thermal radiation are also good absorbers. This shows that the emissive power and absorptive power are closely related.

12.2.3 Stefan-Boltzmann Law

On the basis of experimental measurements, Stefan and Boltzmann concluded that the radiant energy emitted per second from a surface of area A is proportional to fourth power of temperature :

Notes

$$E = Ae\,\sigma\,T^4 \qquad (12.8)$$

where σ is ***Stefan-Boltzmann constant*** and has the value 5.672×10^{-8} $Jm^{-2}\,s^{-1}\,K^{-4}$. The temperature is expressed is kelvin, *e* is emissivity or relative emittance. It depends on 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.

From Eqn. (12.8) you may think that if the surfaces of all bodies are continually radiating energy, why don't they eventually radiate away all their internal energy and cool down to absolute zero. They would have done so if energy were not supplied to them in some way. In fact, all objects radiate and absorb energy simultaneously. If a body is at the same temperaturture as its surroundings, the rate of emission is same as the rate of absorption; there is no net gain or loss of energy and no change in temperature. However, if a body is at a lower temperture than its surroundings, the rate of absorption will be greater than the rate of emission. Its temperature will rise till it is equal to the room temperature. Similarly, if a body is at higher temperature, the rate of emission will be greater than the rate of absorption. There will be a net energy loss. Hence, when a body at a temperature T_1 is placed in surroundings at temperature T_2, the amount of net energy loss per second is given by

$$E_{net} = Ae\,\sigma\,(T_1^4 - T_2^4) \;\text{ for } T_1 > T_2 \qquad (12.5)$$

Example 12.2 : Determine the surface area of the filament of a 100 W incandescent lamp at 3000 K. Given $\sigma = 5.7 \times 10^{-8}$ W m^{-2} K^{-4}, and emissivity *e* of the filament = 0.3.

Solution: According to Stefan-Boltzmann law

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

where *E* is rate at which energy is emitted, *A* is surface area, and T is tempeature of the surface. Hence we can rewrite it as

$$A = \frac{E}{e\sigma T^4}$$

On substituting the given data, we get

$$A = \frac{100\text{ W}}{0.3 \times (5.7 \times 10^{-8}\text{ Wm}^{-2}\text{ K}^{-4} \times (3000\text{K})^4}$$

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

Now it is time for you to check your understanding.

Notes

INTEXT QUESTIONS 12.2

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 fact which we can obtain from the experimental study of the spectrum of black body radiation.
4. A person with skin temperature 28°C is present in a room at temperature 22°C. Assuming the emissivity of skin to be unity and surface area of the person as 1.9 m^2, compute the radiant power of this person.
5. Define the emissive and absorptive power of a body. What is a perfectly black body?

12.3 SOLAR ENERGY

You have learnt in your previous classes that sun is the ultimate source of all energy available on the earth. The sun is radiating tremendous amount of energy in the form of light and heat and even the small fraction of that radiation received by earth is more than enough to meet the needs of living beings on its surface. The effective use of solar energy, therefore, may some day provide solution to our energy needs.

Some basic issues related with solar radiations are discussed below.

1. Solar Constant

To calculate the total solar energy reaching the earth, we first determine the amount of energy received per unit area in one second. The energy is called **solar constant**. Solar constant for earth is found to be 1.36×10^3 W m^{-2}. Solar constant multiplied by the surface area of earth gives us the total energy received by earth per second. Mathematically,

$$Q = 2\pi R_e^2 C$$

where R_e is radius of earth and C is solar constant

Note that Only half of the earth's surface has been taken into account as only this much of the surface is illuminated at one time. Therefore,

$$Q = 2 \times 3.14 \times (6.4 \times 10^6 \text{ m})^2 \times (1.36 \times 10^3 \text{ W m}^{-2})$$
$$\simeq 3.5 \times 10^{17} \text{ W}$$
$$\simeq 3.5 \times 10^{11} \text{ MW}$$

To determine solar constant for other planets of the solar system, we may make use of Stefan-Boltzman law, which gives the total energy emitted by the sun in one second :

$$\in = (4\pi r^2)\,\sigma T^4$$

where r is radius of sun and T is its temperature.

If R is radius of the orbit of the planet, then

$$E = \frac{\in}{4\pi R^2} = \left(\frac{r}{R}\right)^2 \sigma T^4 \qquad (12.6)$$

And the solar constant (E′) at any other planet orbiting at distance R′ from the sun would be

$$E' = \left(\frac{r}{R'}\right)^2 \sigma T^4 \qquad (12.7)$$

Hence $$\frac{E'}{E} = \left(\frac{R}{R'}\right)^2 \qquad (12.8)$$

The distance of mars is 1.52 times the distance of earth from the sun. Therefore, the solar constant at mars

$$E' = E \times \left(\frac{1}{1.52}\right)^2$$

$$= 6 \times 10^2 \text{ W m}^{-2}$$

2. Greenhouse Effect

The solar radiations in appropriate amount are necessary for life to flourish on earth. The atmosphere of earth plays an important role to provide a comfortable temperature for the living organisms. One of the processes by which this is done is greenhouse effect.

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

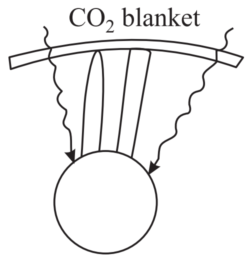


Fig. 12.8 : Green house effect

An analogous effect takes place in our atmosphere. The atmosphere, which contains a trace of carbon dioxide, is transparent to visible light. Thus, the sun's light passes through the atmosphere and reaches the earth's surface. The earth absorbs this light and subsequently emits it as infrared radiation. But carbon dioxide in air is opaque to infra-red radiations. CO_2 reflects these radiations back rather than allowing them to escape into the atmosphere. As a result, the temperature of earth increases. This effect is referred to as the ***greenhouse effect.***

Due to emission of huge quantities of CO_2 in our atmosphere by the developed as well as developing countries, the greenhouse effect is adding to global warming and likely to pose serious problems to the existence of life on the earth. A recent report by the UN has urged all countries to cut down on their emissions of CO_2, because glaciers have begun to shrink at a rapid rate. In the foreseable future, these can cause disasters beyond imagination beginning with flooding of major rivers and rise in the sea level. Once the glaciers melt, there will be scarcity of water and erosion in the quality of soil. There is a lurking fear that these together will create problems of food security. Moreover, changing weather patterns can cause droughts & famines in some regions and floods in others.

In Indian context, it has been estimated that lack of positive action can lead to serious problems in Gangetic plains by 2030. Also the sea will reclaim vast areas along our coast lie, inundating millions of people and bring unimaginable misery and devastation. How can you contribute in this historical event?

12.4 NEWTON'S LAW OF COOLING

Newton's law of cooling states that ***the rate of cooling of a hot body is directly proportional to the mean excess temperature of the hot body over that of its surroundings provided the difference of temperature is small. The law can be deduced from stefan-Boltzmann law.***

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

$$E = e\sigma(T^4 - T_0^4)A \qquad (12.9)$$

As $T^4 - T_0^4 = (T^2 - T_0^2)(T^2 + T_0^2) = (T - T_0)(T - T_0)(T^2 + T_0^2)$. Hence (12.10)

$$E = e\sigma(T - T_0)(T^3 + T^2 T_0 + T T_0^2 + T_0^3)A$$

If $(T-T_0)$ is very small, each of the term T^3, T^2T_0, TT_0^2 and T_0^3 may be approximated to T_0^3. Hence

$$\therefore \quad E = e\sigma(T - T_0)\,4T_0^3 A$$

$$= k(T - T_0)$$

where $k = 4e\sigma T_0^3 A$. Hence,

$$E \alpha (T - T_0) \qquad (12.11)$$

This is ***Newton's law of cooling.***

Notes

INTEXT QUESTIONS 12.3

1. Calculate the power received from sun by a region 40m wide and 50m long located on the surface of the earth?
2. What threats are being posed for life on the earth due to rapid consumption of fossil fuels by human beings?
3. What will be shape of cooling curve of a liquid?

WHAT YOU HAVE LEARNT

- Heat flows from a body at higher temperature to a body at lower temperature. There are three processes by which heat is transferred : conduction, convection and radiation.
- In conduction, heat is transferred from one atom/ molecule to another atom/ molecule 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

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

- *Wien's Law.* The spectrum of energy radiated 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

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

- 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 $1.36 \times 10^3\ Jm^{-2}\ s^{-1}$
- Newton's Law of cooling states that the rate of cooling of a body is linearly proportional to the excess of temperature of the body above its surroundings.

TERMINAL EXERCISE

1. A thermosflask (Fig.12.9) is made of a double walled glass bottle enclosed in metal container. The bottle contains some liquid whose 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.

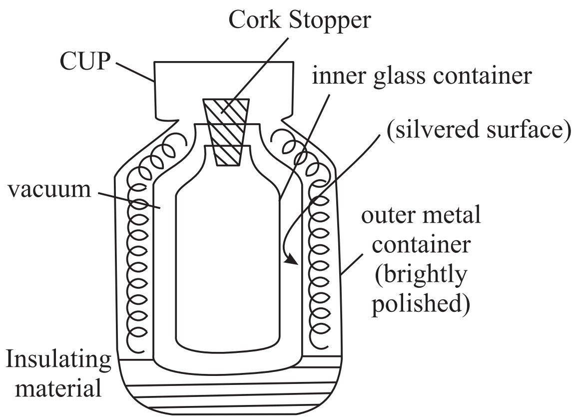


Fig. 12.9

2. The wavelength corresponding, to emission of energy maxima of a star is 4000 A°. Compute the temperature of the star.(1A° = 10^{-8} cm).
3. A blackened solid copper sphere of radius 2cm 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 bottm surface is 0.5cm thick and 50 cm in diameter 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 bottom of the pot 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 (transfer).
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 resistance 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?

Notes

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 smilar 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 two layers of cloth of equal thickness provide warmer covering than a single layer of cloth of double the thickness?
15. Can the water be boiled by convection inside an earth satellite?
16. A. 500 W bulb is glowing. 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 materials are identical in size and in dimensions. They are filled with equal quantity of ice at O°C. If ice in both vessles metls completely in 25 minutes and in 20 minutes respectively compare the (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} temperature different acrosss the ends of the rod be 50°C. Calculate the rate of heat flow.

ANSWERS TO INTEXT QUESTIONS

12.1

1. Conduction is the principal mode of transfer of heat in solids in which the particles transfer energy to the adjoining molecules.

   In convection the particles of the fluid bodily move from high temperature region to low temperature region and vice-versa.

2. $$K = \frac{Qd}{t\,A\,(Q_2 - Q_1)}$$

   $$= \frac{\text{J}}{\text{s}}\,\frac{\text{m}}{\text{m}^2\,{}^\circ\text{C}}$$

   $$= \text{J s}^{-1}\,\text{m}^{-1}\,{}^\circ\text{C}^{-1}$$

3. The trapped air in wool fibres prevents body heat from escaping out and thus keeps the wearer warm.
4. The coefficient of thermal conductivity is numerically equal to the amount of heat energy transferred in one second across the faces of a cubical slab of

surface area $1m^2$ and thickness 1m, when they are kept at a temperature difference of 1°C.

5. During the day, land becomes hotter than water and air over the ocean is cooler than the air near the land. The hot dry air over the land rises up and creates a low pressure region. This causes see breeze because the moist air from the ocean moves to the land. Since specific thermal capacity of water is higher than that of sand, the latter gets cooled faster and is responsible for the reverse process during the night causing land breezes.

12.2

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

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

$= 9.6\mu$

2. Hint: Because light colours absorb less heat.
3. Hint: (a) $\lambda_m T = S$ (b) $t = \sigma T^4$
4. 66.4 W.

12.3

1. Solar constant x .area

$= 2.7 \times 10^5$ W

2. Constant addition of CO_2 in air will increase greenhouse effect causing global warming due to which glaciers are likely to melt and flood the land mass of the earth.
3. Exponential decay

Answers to Terminal Problem

2. 7210 K
3. 71.6×50^{-11} W
5. 4.7×10^5 kg
9. 3 : 4
17. 4 : 5
18. 10.9 m °C^{-1} W^{-1}, 0.298 W