UNIT - IV

THERMAL PHYSICS

1. NEWTON'S LAW OF COOLING

a.NEWTON'S LAW OF COOLING :

Newton's law of cooling states that the rate at which a hot body cools by radiation is directly proportional to the mean excess of temperature of the body over the surroundings.

Let us consider a hot body at a temperature $\theta_1{}^0$ C. After t seconds the temperature of the body falls to $\theta_2{}^0$C. Let θ_0C be the temperature of the surrounding.

When the temperature $\theta_1{}^0$C falls to $\theta_2{}^0$C, the mean temperature of the cooling body is $\frac{\theta_1+\theta_2}{2} = \theta$.

Since θ_0 is the temperature of the surrounding, the difference between the mean temperature of the cooling body and its surrounding temperature = $(\theta - \theta_0)$

Let the quantity of heat lost in t second be Q

Rate of cooling = Heat lost / Time taken

= Q /t

According to Newton's law of cooling, the rate of cooling is directly proportional to the mean excess of temperature over the surrounding.

$$Q/t \ \alpha \ (\theta - \theta_0)$$

or $$Q/t = K.(\theta - \theta_0)$$

where K is a constant

$$[Q/(\theta - \theta_0)t] = \text{a constant}$$

If m is the mass of the body and S the specific heat capacity, then.

$$Q = ms(\theta_1 - \theta_2)$$

$$\therefore \quad \frac{ms(\theta_1 - \theta_2)}{t} \propto \frac{(\theta_1 + \theta_2)}{2} - \theta_0$$

b. Verification of Newton's Law of cooling

A spherical calorimeter is filled with hot water whose temperature is greater than 80° C. By inserting a thermometer, the calorimeter is suspended in a stand. Due to heat radiation the temperature of the water falls. When the temperature reaches 80°C , a stop clock is started. For each degree fall of temperature the time is noted continuously. Time is noted till the temperature reaches 60°c. These readings are tabulated. The temperature of the room is noted. Let it be θ_0

Temp of water (degree)	Time taken for 1° C cooling (second)	Temp range	Time taken for 4°C fall of temp (t sec)	Execess of temp $\frac{(\theta_1 + \theta_2)}{2} - \theta_0$	$\left(\frac{(\theta_1 + \theta_2)}{2} - \theta_0\right) t$
		80 - 76 79 - 75			

For different range of temperature, the time taken for the cooling of 4°C should be calculated. For each range, finding the mean temperature $(\theta_1 + \theta_2)/2$, the mean excess of temperture $(\theta_1 + \theta_2)/2 - \theta_0$. should be calculated. Let t be the time taken for the cooling

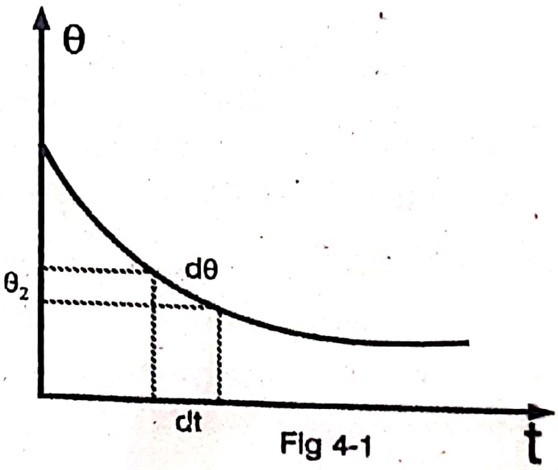

Fig 4-1

in this range. From this $[(\theta_1+\theta_2)/2 - \theta_0]t$ should be calculated. In a similar way for each range $[(\theta_1+\theta_2)/2 - \theta_0]t$ should be calculated. It will be a constant. For the different ranges the fall of temperature is 4^0C. Hence in each range the quantity of heat lost due cooling is the same. Hence $[(\theta_1+\theta_2)/2 - \theta_0]t$ is a constant. This verifies the Newton's law of cooling.

Newton's law of cooling can also be verified by drawing a cooling curve. By taking the time in X-axis and the temperature in Y - axis, a cooling curve may be drawn. This curve will be as shown in Fig 4.1. At any point of the curve $d\theta/dt$ is calculated. It is the slope at that point. The mean excess of temperature in this point is $(\theta - \theta_0)$. Now $(d\theta/dt)/(\theta - \theta_0)$ is calculated. Similary we can calculate $(d\theta/dt)/(\theta - \theta_0)$ at different points of the curve. It will be a constant. This verifies the Newton's law of cooling.

c. Specific Heat capacity of a liquid by cooling.

Newton's law of cooling can be used to determine the specific heat capacity of a liquid. A polished clean and dry empty spherical calorimeter is weighed. Let it be m_1 kgm. The calorimeter is filled with hot water. The temperature of the water should be above 80^0C. This calorimeter is suspended in a stand by means of a string and a thermometer is inserted.

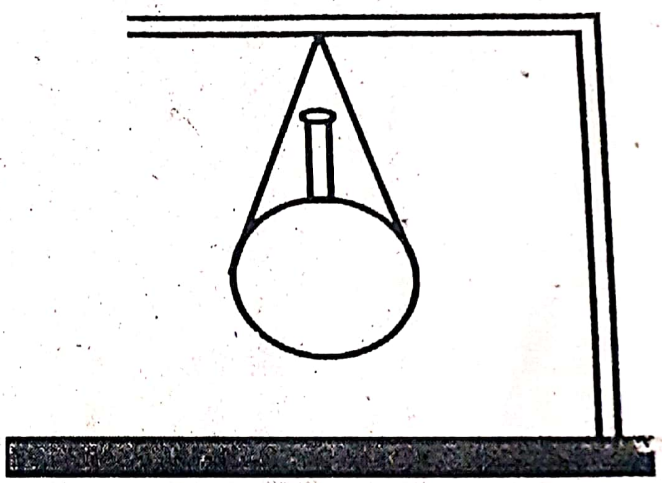

Fig 4-2

As the heat is slowly lost by radiation from its surface, its temperature falls freely. When the temperature reaches 80^0C a stop clock is started. Times are recorded continuously for each degree fall of temperature untill it reaches 60^0C. After cooling the calorimeter to room temperature, it is weighed with water. Let it be m_2 kgm.

After pouring the water out, the calorimeter is cleaned well and it is filled with hot liquid whose specific heat capacity is to be determined.

The temperature of the liquid should be above 80°C. The calorimeter is again allowed to cool under the similar condition and observations of temperature and time are recorded as before. After cooling to room temperature, the calorimeter is weighed with liquid. Let it be m_3 kgm The readings are tabulated.

Temp	Time		Range	Time for cooling 2°C		$\frac{t_2}{t_1}$
	Water	liquid		water	liquid	
				t_1	t_2	
			80-78 79-77 62-60			

From the tabular colomn, the time taken for cooling of 2°C for different ranges like 80-78-79-77 . . . 62-60 are calculated. For a particular range let t_1 and t_2 be the time taken for 2°C fall of temperature for water and liquid respectively. From this t_2 / t_1 is calculated for different range and the average is found out. Since all the conditions are the same, the rate of cooling for water and liquid at the given excess of temperature must be the same.

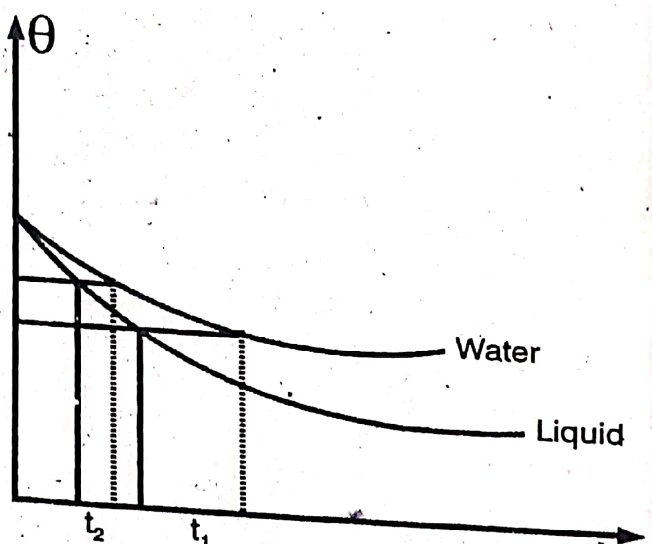

Fig 4-3

Rate of cooling of water

$= [m_1 s_1 + (m_2 - m_1) s_2] 2/t_1$ . . . (1)

where s_1 - the specific heat capacity of the material of the calorimeter

s_2 - the specific heat capacity of water.

Rate of cooling of liquid $= [m_1 s_1 + (m_3 - m_1) S] 2/t_2$ . . . (2)

where S is the specific heat capacity of liquid which is to determined.

According to Newton's law of cooling,

Rate of cooling of water = Rate of cooling of liquid.

$$[m_1s_1 + (m_2 - m_1)\, s_2]\, 2/t_1 = [m_1s_1 + (m_3 - m_1)\, S]\, 2/t_2$$

$$m_1s_1 + (m_3 - m_1)\, S = [m_1s_1 + (m_2 - m_1)\, s_2]\, t_2/t_1$$

or

$$(m_3 - m_1)S = [m_1s_1 + (m_2 - m_1)\, s_2]\, t_2/t_1 - m_1s_1$$

$$S = \frac{[m_1s_1 + (m_2 - m_1)\, s_2]\, t_2/t_1 - m_1s_1}{(m_3 - m_1)} \quad ..(3)$$

Using equation (3), the specific heat capacity of the liquid can be calculated.

The rate of cooling can also be calculated from the cooling curve. Taking the temperature in y-axis and the time in X-axis, a cooling curve is drawn and it is as shown in fig 4-3. From the graph the time taken for 1°C fall of temperature for water (t_1) and for liquid (t_2) is determined. From this t_2/t_1 is calculated. Using this the specific heat capacity of liquid S can be calculated.

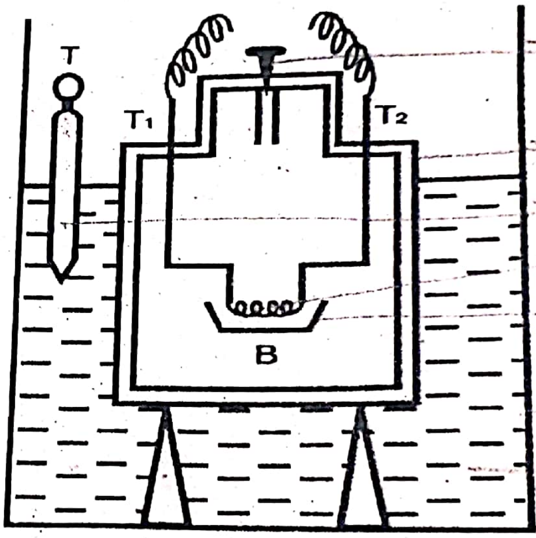

Fig 4-4

2. Bomb Calorimeter

Caloric value of a fuel is defined as the quantity of heat released when a unit quantity of fuel is completely burnt and the product of combustion are brought to the original temperature. It is measured in the unit of k. calorie \ kgm\ or Joule \kgm. Coal, petrol, disel, wood ect are used as fuel.

The caloric value of a fuel can be determined with the help of bomb calorimeter.

The bomb calorimeter is as shown in fig 4-4. D is a strong gun metal cylinder. This cylinder is fitted with an air tight lid of ebonite. The fuel in the form of a solid powder or liquid may be placed in a platinum bowl kept or suitably suspended inside the cylinder. The fuel can be heated electrically by a platinum spiral immersed in it. The cylinder is usually filled with oxygen. It's pressure will be of the order of 20 atmospheres. There is a regulator valve in the cylinder. This valve keeps the pressure constant. The gun metal cylinder is enclosed in a large calorimeter containing cold water. This arrangement is called bomb calorimeter.

Fuel of known mass (M) is placed in the platinum bowl. The cylinder is filled with high pressure oxygen and kept immersed in the cold water in the calorimeter. The initial temperature of water θ_1 is noted. By passing a strong current through the platinum spiral, the fuel is ignited. The fuel burns out completely in the atmosphere of oxygen. The heat generated is absorbed by calorimeter and water and hence temperature increases. The maximum temperature is noted. Let it be θ_2 . If W is the total thermal capacity of calorimeter and contents, the total heat absorbed by the system is W $(\theta_2 - \theta_1)$ Joule.

Caloric value of fuel $= W(\theta_2 - \theta_1)/M$ J/kgm

From this the caloric value of the fuel can be calculated.

3. Conduction

The transfer of heat from the hotter region of a body to its colder region without actual movement of particle is called heat conduction.

When one end of the rod is heated, the heat is conducted to the other end by the process of conduction. In metals heat is conducted by condúction.

a. Thermal conductivity

Consider a uniform rod of area of cross section A and length l. One end of the rod is heated to a steady temperature. Let θ_1 and θ_2 be the temperature at

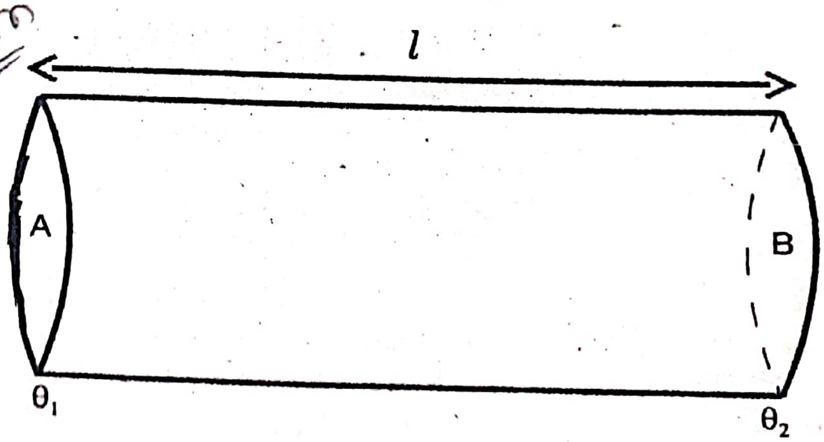

Fig 4-5

the ends of the rod. θ_1 is greater than θ_2. Heat is conducted from the region of higher temperature to the region of lower temperature. Let Q be the quantity of heat conducted in t seconds.

The quantity of heat Q conducted is

(1) directly proportional to the area of cross section ($Q \propto A$)

(2) directly proportional to the temperature difference between the ends [$(Q \propto (\theta_1 - \theta_2)$]

(3) inversely proportional to the length of the rod ($Q \propto 1/\ell$)and

(4) directly proportional to the time of conduction ($Q \propto t$)

∴ Quantity of heat conducted

$$Q \propto A.(\theta_1 - \theta_2) .t / \ell$$

or $$Q = K . A(\theta_1 - \theta_2) t / \ell \quad ...(1)$$

where K is a constant called the **coefficient of thermal conductivity** or simply **thermal conductivity.** 2M

$(\theta_1 - \theta_2) / \ell$ is the change of temperature with distance and is called **temperature gradient**

If $A = 1 m^2$, $(\theta_1 - \theta_2) / \ell = 1$, and $t = 1$ sec, then

$$Q = k \quad ...(2)$$

From this we can define the thermal conductivity.

The thermal conductivity of a material is defined as the heat energy conducted across unit area of cross-section in unit time, when the temperature gradient is unity.

Unit : $J S^{-1} m^{-1} K^{-1}$ or $W m^{-1} K^{-1}$

b. Good conductors and Bad conductors

Based on the thermal conductivity of materials, it can be divided into two types 1) good conductor 2) bad or poor conductors.

Good conductors : Material which have large thermal conductivity are called good conductors Through this heat is conducted easily. All metals are good conductor of heat.

Bad conductors : Material which have small thermal conductivity are called bad or poor conductors. Through this heat is conducted very slowly. Wood, glass, ebonite etc are examples for bad conductors.

C. Thermal conductivity of a Bad conductor - Lee's Disc Method

The thermal conductivity of bad conductors like ebonite can be determined by using Lee's disc method. The experimental arrangement is as shown in fig 4-6.

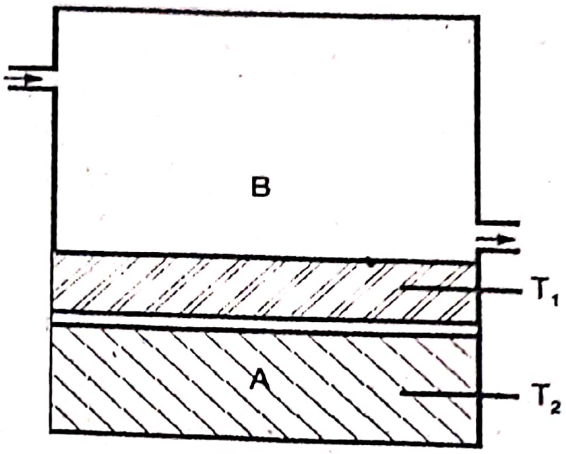

Fig 4-6

A is a thick brass disc. It is suspended in a stand using three strings. Over this an ebonite disc is placed. The diameter of this ebonite disc is the same as that of the brass disc. B is a steam chamber and its lower part is thick. There are two opening in the steam chamber. Through the opening in the upper part steam is passed and the steam come out through the opening in the lower part. There are holes in the steam chamber and also in the brass disc. Thermometers T_1 and T_2 are inserted through these holes.

Experiment : Steam is passed through the steam chamber. The heat is conducted from the steam chamber to brass disc through the bad conductor. Due to this, the temperature indicated by T_1 and T_2 increases After some time, there will be no increase in the temperature. Now it is in the steady state The steady temperatures θ_1 and θ_2 are noted. If d is the thickness of the bad conductor, the temperature gradient $=(\theta_1 - \theta_2)/d$

If r is the radius of the bad conductor, the area of the bad conductor $= \pi r^2$ .At steady state the heat conducted through the bad conductor is

$Q = K.\pi r^2.(\theta_1 - \theta_2)/d$ Joule

where K is the thermal conductivity which is to be determined.

Now the bad conductor is removed and the brass disc is directly heated.. The temperature indicated by T_2 increases. When the temperature reaches $(\theta_2+10)^\circ C$, the steam chamber is removed. The bad conductor is placed over the brass disc and it is allowed to cool. When the temperature reaches $(\theta_2+5)^\circ C$,a stop clock is started. Time is recorded for each degree fall of temperature continuously untill the temperature reaches $(\theta_2-5)^\circ C$

A graph is drawn taking the time in X-axis and the temperature in Y-axis. The graph will be as shown in fig 4-7.

At the steady temperature θ_2, its rate of cooling is calculated from the graph.

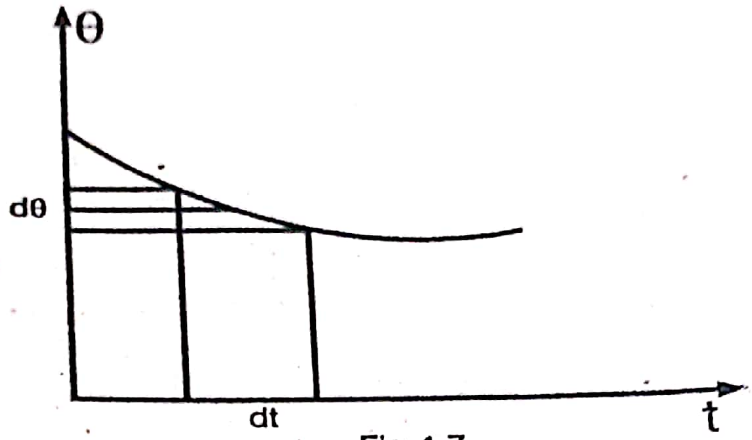

Fig 4-7

Rate of cooling

$R = d\theta / dt$.

Let M be the mass of brass disc, t be the thickness of the disc and S, the specific heat capacity of the material of the disc.

At the steady state the quantity of heat lost by radiation per second by the two flat surfaces and one curved surface of the brass disc = MSR Joule.

Hence the quantity of heat lost only by one flat surface and curved surface.

$$= MSR\,(\pi r^2 + 2\pi rt) / (2\pi r^2 + 2\pi rt)$$

$$= MSR\,(r + 2t) / 2(r+t) \qquad \ldots(2)$$

At steady state, the quantity of heat conducted through the bad conductor is equal to the quantity of heat lost per second by the brass disc.

$$K\pi r^2(\theta_1 - \theta_2) / d = MSR\,(r+2t)/2(r+t)$$

$$K = \frac{MSRd\,(r+2t)}{2\pi r^2(\theta_1 - \theta_2)\,(r+t)} \; W\,m^{-1}K^{-1} \qquad \ldots(3)$$

Using a screw gauge and vernier callipers the thickness of the bad conductor (d) and the thickness of the brass disc (t) can be measured. Hence using equation (3) the thermal conductivity of bad conductor can be calculated.

4. Stefan's law of Radiation

According to this law, the total heat radiated per second by unit area of a perfectly black body is directly proportional to the fourth power of its kelvin temperature.

If Q is the total heat energy radiated by unit area of a perfectly black body in one second at a temperature T K then

$$Q \propto T^4$$

or $$Q = \sigma T^4$$

where σ is a constant known as Stefan's constant. Its value is $5.6697 \times 10^{-8}\ W\,m^{-2}K^{-4}$

a. Solar constant

The centre of the solar system is the Sun. It radiates heat energy in all directions. Heat from it travels through vacuum and reaches the earth by radiation. This energy is absorbed and reflected by the dust particles in the atmosphere. Hence the amount of heat energy which reaches the earth is very small. By measuring this energy, the sruface temperature of the Sun can be calculated. For this we should know about the solar constant.

The amount of solar radiation received per minute by unit area of a black body held at right angle to the Sun's ray just beyond the atmospher, at the mean distance of the earth from the Sun, at noon at the mean solar day, is known as the solar constant.

Unit of solar constant is $J\ s^{-1}\ m^{-2}$. It's value is $1400\ JS^{-1}\ m^{-2}$.

b. Angstrom's Pyroheliometer.

The instrument used for measuring the solar constant are called pyroheliometer. The simplest apparatus in use for this purpose is Angstrom's Pyroheliometer.

Angstrom's Pyroheliometer is as shown in fig 4-8. It consists of two exactly indentical blackened strips S_1 and S_2 made of manganin or constantan. These two are mounted side by side inside a tube. One can be exposed to the solar radiation while other is completely shielded by a screen. A thermocouple of copper and constantan are kept very close to the backs of the strips S_1 and S_2.

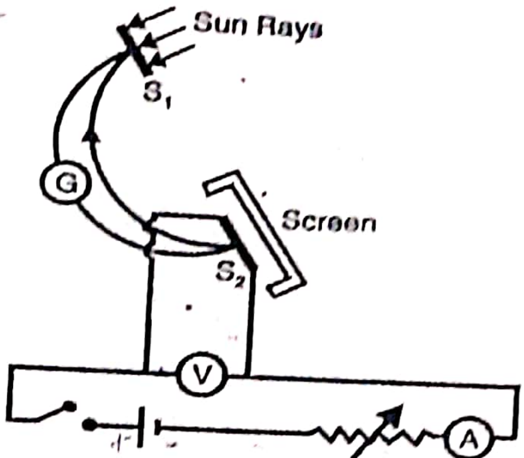

Fig 4-8

Sun rays are allowed to incident on the strip S_1 and hence its temperature rises. As a result, the temperature of the one of the junction of the thermocouple placed behind S_1 also increases and the galvanometer shows a deflection. Now a current is passed through the strip S_2 which is shielded by a screen As a result, the temperature of the strip S_2 increases. The current through the strip S_2 is adjusted such that its temperature rises to that of S_1. When the two strips are at the same temperature, there is no deflection in the galvanometer. Under this condition, the heat energy supplied electrically to S_2 is equal to the heat energy received by the strip S_1 from the Sun.

If V is the voltage applied to strip S_2 and I is the current, then the heat energy supplied in one second = V I joule ....(1)

If area of exposed surface is A and absorptive power is a and solar constant is S, then heat energy absorbed by S_1 is

$$= a\,S\,A \qquad ....(2)$$

Equating equation (1) and (2)

$$aSA = V\,I$$

$$S = V\,I / aA \quad JS^{-1}\,m^{-2} \qquad ....(3)$$

From this, solar constant can be calculated

c. Surface Temperature of the Sun

The surface temperature of the Sun can be calculated by assuming the Sun to radiate as a perfect black body. If T is the surface temperature of the Sun and σ is the Stefan's constant, then the quantity of heat energy radiated by the Sun per unit area in one second is σT^4. If 'r' is the radius of the Sun, the surface area is $4\pi r^2$. Hence the total amount of energy emitted by the Sun in 1 minitue.

$$E = 4\pi r^2 \sigma T^4$$

If R is the distance between the Sun and the Earth, the energy from the Sun is distributed to the area is $4\pi R^2$.

Hence the amount of energy received per unit area in the Earth

$$= E / 4\pi R^2$$

$$= 4\pi r^2 \sigma T^4 / 4\pi R^2$$

$$= r^2 \sigma T^4 / R^2$$

From the definition, it is equal to the solar constant.

$$S = r^2 \sigma T^4 / R^2$$

$$T = \left[\frac{R^2 S}{r^2 \sigma}\right]^{1/4}$$

From this the surface temperature of the Sun can be calculated.

Radius of the Sun $r = 6.96 \times 10^5$ k.m

$= 6.96 \times 10^8$ m

The average distance of earth from the Sun

$R = 1.496 \times 10^8$ k.m

$= 1.496 \times 10^{11}$ m

Solar constant $S = 1400 \text{ JS}^{-1} \text{ m}^{-2}$

Stefan's constant $\sigma = 5.6696 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$

$$T = \left[\frac{(1.496 \times 10^{11})^2}{(6.96 \times 10^8)^2} \times \frac{1400}{5.6696 \times 10^{-8}}\right]^{1/4}$$

$= 5812$ K

Surface temperature of the sun $= 5812$ K

Problems

1) A body cools from 50°C to 45°C in the first 5 minutes and in the next 5 minutes it cools from 45° to 41.5°C. Calculate temperature of the surrounings.

sol:

In the first 5 minutes $\theta_1 = 50°C$ and $\theta_2 = 45°C$. Let θ be the temperature of the room.

According to Newton's law of cooling