SECTION-01 - BE-01

BASICS OF SCIENCE AND ENGINEERING

PHYSICS

1. Units and Measurements
2. Classical Mechanics
3. Electric Current
4. Heat and Thermometry
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4. Heat and Thermometry

[1] Heat :

Heat is a form of energy that produces in us the sensation of warmth.

Heat is an energy which is transferred between two bodies or between body and its surrounding on account of the temperature difference between them.

We know that a hot cup of tea if left on the table, it cools down. And the ice–cold water if left on the table it warms up. In both cases, heat is transferred from one body at a higher temperature to another body at a lower temperature. Thus, heat is a form of energy that is transferred from one body at a higher temperature to another body at a lower temperature when they are placed in contact with each other.

[2] Unit of heat :

The SI unit of heat is joule (J). The cgs unit is erg. The practical unit of heat is a calorie.

One calorie is the amount of heat required to raise the temperature of 1 gram of water through 1 °C

(i.e. from 14.5°C to 15.5°C).

It is so because, the thermal heat capacity or specific heat of water at temperature 15°C is 1 cal $g^{-1}\,{}^{o}C^{-1}$.

Joule found that when mechanical work (W) is converted into heat (Q), the ratio of W and Q is always constant, represented by J i.e. $\frac{W}{Q} = J$ or $W = JQ$.

where J is Joule's mechanical equivalent of heat. J is not a physical quantity but a conversion factor involved when work is converted into heat or vice–versa. The value of J = 4.186 joule/calorie.

i.e. 1 calorie = 4.186 joule.

[3] Temperature :

We define the Temperature of a body as the degree of hotness or coldness of the body.

When two bodies at different temperatures are kept in contact with each other, the heat flows from a body at a higher temperature to a body at a lower temperature, till their temperatures become equal. We (c) may, therefore, redefine the temperature of a body as the thermal state/condition of the body, which would determine the direction of flow of heat when this body is placed in contact with another body.

If heat flows from body A to body B, then the temperature of body A is higher than that of B. If heat flows from body B to body A, then the temperature of body B is higher than that of A. If there is no transfer of heat between two bodies in contact, then the temperature of body A must be equal to that of body B.

Temperature is one of the seven fundamental quantities, like length, mass and time, in the SI.

- **Temperature scales :**

The following temperature scales are used :

(a) Celsius temperature scale (formerly called centigrade temperature scale). It was designed by Celsius in the year 1710. Here, the freezing point of ice at standard pressure is regarded as 0 °C and the boiling point of water at standard pressure is 100 °C. The space between these two fixed points is divided into 100 equal parts. Each part represents 1°C.

(b) Fahrenheit temperature scale. It was designed by Fahrenheit in the year 1717. Here, the freezing point of ice at standard pressure is regarded as 32 °F and the boiling point of water at standard pressure is 212 °F. The space between these two fixed points is divided into 180 equal parts. Each part represents 1°F

If t_C and t_F are temperature values of a body on celsius temperature scale and Fahrenheit temperature scale respectively then

$$\frac{t_C - 0}{100} = \frac{t_F - 32}{180}$$

From the above formula, relation between Fahrenheit and Celsius scale is as bellow :

$$t_f = 32 + \frac{9}{5}t_c \quad \text{or} \quad t_c = \frac{5}{9}(t_f - 32)$$

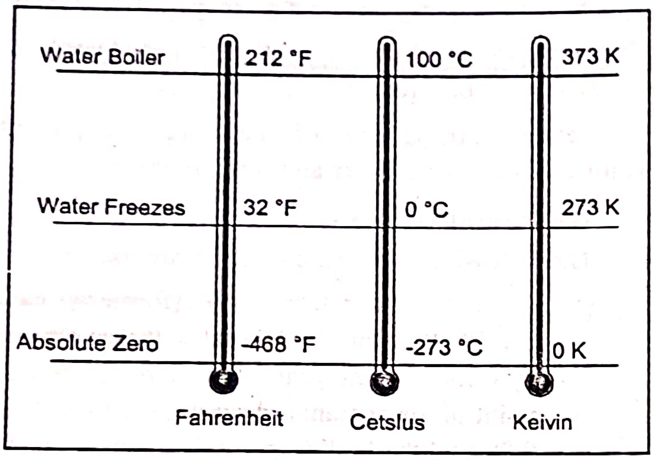
(c) **Absolute temperature scale :**

This temperature scale was designed by Lord Kelvin and is also known as Kelvin temperature scale.

According to ideal gas equation $PV = nRT$

This shows that for a given volume V of a gas, the pressure P exerted by the gas is directly proportional to temperature T of the gas. Here, n is number of moles of the gas.

The variation of pressure (P) with temperature T (°C) is shown in Fig.



When this graph is extrapolated, it meets the temperature axis at – 273.15 °C. Kelvin called this value of temperature absolute zero (0 K). This is because, at this temperature, the pressure P of gas would reduce to zero. Volume V of the gas would also become zero at this temperature. If we were to imagine going below this temperature, the volume of gas would be negative, which is impossible. This suggests that the lowest attainable temperature is absolute zero i.e. OA = – 273.15 °C. For the sake of convenience, we shall use 273 K instead of 273.15 K.

Kelvin designed the scale of temperature with its zero at –273.15 °C and size of each degree same as on Celsius scale. This scale of temperature was called the Absolute scale or Kelvin scale. Clearly,

$$t_c = t_k - 273.15 \quad \text{or} \quad t_k = t_c + 273.15$$

i.e., we add 273.15 to temperature value on Celsius scale to obtain temperature value on absolute scale. Similarly, we subtract 273.15 from temperature value on Absolute scale to obtain temperature value on Celsius scale.

The SI unit of temperature is kelvin (K). For day to day applications, Celsius (°C) and Fahrenheit (°F) is used.

The Kelvin temperature scale, Celsius temperature scale and Fahrenheit temperature scale are shown in Fig.

Example-1 : A person has fever 101. Which temperature scale is used here ? Convert this temperature into other two units.

Solution :

Conventionally, Fahrenheit scale is used to measure the temperature of fever.

So temperature is 101 °F.

$$t_c = \frac{5}{9}(t_f - 32)$$

$$= \frac{5}{9}(101 - 32)$$

$$= 38.33\ °C$$

And to convert in kelvin scale

$$t_k = t_c + 273$$
$$= 38.33 + 273$$
$$= 311.33\ K$$

Example-2 : At what temperature, if any do the following pairs of scales give the same reading ? (a) Celsius and Fahrenheit (b) Fahrenheit and Kelvin ?

Solution :

If the temperature is θ at which the reading of two scales coincides then

$$\frac{T_C - 0}{5} = \frac{T_F - 32}{9} = \frac{T_K - 273.15}{5}$$

(a) $\frac{\theta}{5} = \frac{\theta - 32}{9}$

$$9\theta - 5\theta = -160$$
$$4\theta = -160$$
$$\theta = -40^o$$

So, reading of fahrenheit and celsius scale coincides at – 40°.

(b) $\frac{\theta - 32}{9} = \frac{\theta - 273.15}{5}$

$$5\theta - 160 = 9\theta - 2458.35$$
$$4\theta = 2298.35$$
$$\theta = 574.6$$

Reading of fahrenheit and kelvin scale coincides at 574.6°.

[4] Modes of Heat–Transfer : Conduction, Convection and Radiation :

We have seen that heat flows from a object at high temperature to a object at temperature. But naturally we have the question, how does heat transfer between different parts of the same substance at different temperatures ?

Here, we will find the answer to this question. When the iron rod is heated at one end in the fire by holding other end in the hand as shown in the figure 3.3, then gradually the whole rod gets heated.

- **Convection :**

Convection is a mode of heat transfer from one part of the medium to another part by the actual movement of the heated particles of the medium.

It means, convection is the mode of heat transfer by actual motion of matter. Convection can be natural or forced.

In natural convection, the force of gravity plays an important role in the formation of convection current. For example, when we heat a liquid in a flask, the particles of the liquid at the bottom, get heated, become lighter and actually rise up. The cold liquid particles from above at lower temperature being heavy come down due to gravity and receive the heat. The process is repeated. In this way a thermal convection cycle is set up. All fluids (i.e., liquids and gases) are heated by convection.

Let us discuss an example of evacuating a warehouse for convection. To empty the warehouse each servant pick up a packet in their own way and puts it in the new warehouse from the old warehouse. This process continues until the warehouse is emptied. Here every servant moves from one place to another . The same process takes place in the convection of heat energy through molecules and the heat transfers to all parts of the fluids.

Natural convection is responsible for many familiar phenomena; like see breeze, trade wind etc.

In forced convection, the material particles of a medium are forced to move by a pump or by some other physical means. The common examples of forced convection systems are (i) forced–air heating systems in home (ii) the cooling system of an automobile engine and (iii) human circulatory system, i.e. , the circulation of blood in human body at constant temperature through heart which acts as a pump.

- **Radiation :**

Radiation is a mode of

heat transfer from the source to the receiver without any actual movement of source or receiver and also without heating the intervening medium.

For example, temperature of an object rises under direct sunrays. Heat from the sun comes to us through radiation. Similarly, we feel hot on standing/sitting near the fire, as the heat comes to us through radiation.

The transfer of heat by radiation needs no medium. The heat energy transferred by radiation is called radiant energy. All bodies (i.e., solids, liquids or gases) emit radiant energy whose temperature is more than 0 K. The radiant energy emitted by a body depends on three factors : (i) the temperature of the body (ii) nature of the radiating surface and (iii) area of the radiating surface. The electromagnetic radiation emitted by a body by virtue of its temperature is called heat radiation or thermal radiation. Heat radiations (also called thermal radiations) are the electromagnetic waves of wavelength range 8×10^{-7} m to 4×10^{-4} m. They belong to infrared region of electromagnetic spectrum. They are not visible to eye but produces the sensation of warmth. The heat radiation can travel through vacuum with the speed of light ($= 3 \times 10^{8}\ ms^{-1}$).

When the thermal radiation falls on a body, it is partly reflected and partly absorbed. The amount of radiant energy that a body can absorb out of the incident energy depends on the colour of the body. It is found that the black bodies absorb and emit radiant energy better than bodies of lighter colours.

- **Heat Capacity and Specific Heat :**

(1) Heat capacity :

Fill one of the two identical beakers with water and the second with oil of the same mass. Place both beaker above a burner so that they are both supplied with the same amount of heat. Oil will heat up faster than water. Why ?

As more and more heat is added to any object, its temperature also rises. But this increase in temperature varies according to each object. This shows that the capacity of each substance is different. This capacity is called "Heat capacity (Hc)"of that substance.

The ratio of the amount heat (Q) given to a body to the corresponding change in its temperature (ΔT) is called the heat capacity (H_c) of the body.

$$\text{Heat capacity} = \frac{\text{heat given to a body}}{\text{change in temperature}}$$

$$H_c = \frac{Q}{\Delta T}$$

The SI unit of heat capacity is $\frac{J}{K}$ but in practice we use $\frac{cal}{K}$ or $\frac{cal}{^oC}$.

Heat capacity of a body depends on the material of the body as well as on its mass. Different bodies of the same material but different mass have different values of heat capacity. For example, the value of heat required to raise the temperature of 1 litre water in small bowl from 30 °C to 35 °C is lower than the value of heat required to raise the same temperature of 5 litre water.

Here, the heat capacity of a body depends on its mass. We will think about a physical quantity which is independent of mass.

(2) **Specific Heat :**

Thus, "Heat capacity of a body per unit mass is known as specific heat of its material and its value depends only on the type of material of the body and not on its mass."

OR

The quantity of heat required per unit mass for unit change in the temperature of a body is called specific heat (denoted by C) of the material of the body. The unit of specific heat is

$$\text{specific heat} = \frac{\text{heat capacity}}{\text{mass}}$$

$$\therefore \; c = \frac{\Delta Q}{m\Delta T} \quad \text{unit of C is } \frac{J}{kg\,K} \text{ or } \frac{cal}{gK} \text{ or } \frac{cal}{g^oC}$$

$$\Delta Q = mC\,\Delta T$$

It is important to note here that in the case of a copper coin, we can talk about heat capacity of the coin but specific heat is of copper. None of the two quantities, heat capacity and specific heat, are constant quantities, as their values depend on the temperature at which the temperature interval ΔT is considered.

Specific Heat of Some Materials

Material	Specific Heat (C)		Material	Specific Heat (C)	
	Cal./g K	J/kg K		Cal./g K	J/kg K
Silver (Ag)	0.0564	236	Ice (–10 °C)	0.530	2220
Copper (Cu)	0.0923	286	Water (H_2O)	1.0	4190
Aluminium (Al)	0.2150	900	Sea–Water	0.93	3900

[5] Thermal Conductivity :

Each substance has different ability to conduct heat and electricity. The ability of a substance to conduct heat is called its "thermal conductivity". The thermal conductivity of a solid is the intrinsic ability of the solid to conduct heat through it. Heat conductivity differs from substance to substance. Different substance has different heat conductivity, but each substance has its unique heat conductivity. For example, copper, silver etc. are very good conductors of heat whereas glass, wood etc. are bad conductors. Generally, metals are good conductors of heat while amorphous substances are bad conductors. Conductivity depends on structure of a substance.

When one end of a metal rod is heated, heat flows by conduction from the hot end to the cold end. In this process, each cross–section of the rod receives some heat from the adjacent cross–section towards the hot end. A part of the heat received is spent in raising the temperature of the cross section. Another part of heat is lost to the surroundings and the rest of the heat is conducted away to the next cross–section towards the colder end. As temperature of every cross–section of the rod goes on increasing, the rod is said to be in variable state. In variable state of the rod, both the properties i.e. specific heat and thermal conductivity of material play their roles ; one in raising the temperature and the other in transmission of heat, respectively. After some time, a state is reached when temperature of every cross section of the rod becomes constant. It means there is no more absorption of heat. The heat that reaches any cross section is transmitted to the next.

This state of the rod, in which temperature of each part becomes constant and there is no further absorption of heat anywhere in the rod is called steady state. Note that in steady state, temperature of each part of the rod is constant but not same. The temperature decreases as we move away from the hot end of the rod. Specific heat has no role to play in the steady state. Thermal conductivity alone is effective in the steady state.

To define coefficient of thermal conductivity of the solid, let us consider a rectangular block of the solid in steady state. Let two opposite faces of a section of the block be maintained at a temperature difference (ΔT).

Let,

A = area of cross section of the hot face,

Δx = distance between the two faces,

T_1 = temperature of cold face,

$T_2 = (T_1 + \Delta T)$ = temperature of hot face.

Heat is conducted through the solid from hot face to the cold face. Let ΔQ be a small amount of heat conducted through the solid in a small time Δt.

Rate of conduction of heat = $\frac{\Delta Q}{\Delta t}$

It is found that the rate of heat–conduction is

(1) directly proportional to the area of cross–section A of the hot face, i.e., $\frac{\Delta Q}{\Delta t} \alpha A$

(2) directly proportional to the temperature difference (AT) between the two faces, i.e. $\frac{\Delta Q}{\Delta t} \alpha \Delta T$

(3) inversely proportional to the distance (Ax) between the two faces, i.e., $\frac{\Delta Q}{\Delta t} \alpha \Delta T$

Combining all these factors, we get

$$\frac{\Delta Q}{\Delta t} \propto A \frac{\Delta T}{\Delta x}$$

$$\therefore \frac{\Delta Q}{\Delta t} = KA \frac{\Delta T}{\Delta x} \quad .... (1)$$

Where, the proportionality constant K is called the coefficient of thermal conductivity of the solid. In Equatin (1), the ratio $\frac{\Delta T}{\Delta x}$ is called temperature gradiant, that represents the rate of fall of temperature with the distance between the two faces in the direction of the flow of heat.

If, $A = 1 \Rightarrow \frac{\Delta T}{\Delta x} = 1$, then from Equation (1)

$$\frac{\Delta Q}{\Delta t} = K \times 1$$

$$\therefore K = \frac{\Delta Q}{\Delta t}$$

The coefficient of thermal conductivity of a solid is equal to the rate of flow of heat per unit area per unit temperature gradient across the solid.

The value of coefficient of Thermal conductivity (K) depends only on the nature of the material of the solid.

From (1), $K = \frac{\Delta Q/\Delta t}{A\, \Delta T/\Delta x}$

$\therefore$ SI unit of K is $\frac{\text{joule/sec}}{m^2\, K/m} = Wm^{-1} K^{-1}$

Similarly, cgs unit of K is cal. s^{-1} cm^{-1} $^{\circ}C^{-1}$.

- **Applications of Thermal Conductivity :**

We have seen earlier that the thermal conductivity of different materials is different. The knowledge of the thermal properties of substances can determine which substance is used for what. For example, if the handle in a cooking utensil is made of rubber, it does not heat up quickly. But the vessel itself remains excellent if it is made of copper. The uses of heat conduction are as follows :

1. Thick walls are used in the construction of cold storage rooms. Brick being a bad conductor of heat is used to reduce the flow of heat from the surroundings to the rooms. Better heat insulation is obtained by using hollow bricks.
2. During winter, the temperature of a door and handle is less than the body temperature. Therefore, heat flows from the body into the

object touched. Since, metallic handle being a good conductor takes more heat from the finger touching it, we feel cold. Wooden door being a poor conductor takes less body heat and appears less cold.

3. Street vendors keep ice blocks packed in saw dust to prevent them from melting rapidly. The air filled in the fine pores of saw dust is an insulator of heat. This air does not allow heat from outside to pass to the ice thereby preventing its melting.

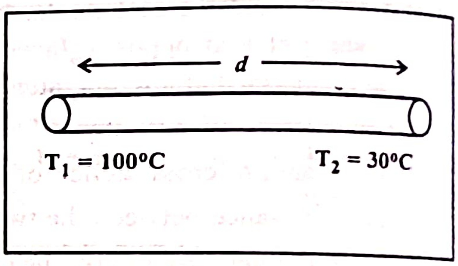
4. The handle of a cooking utensil is made of a bad conductor of heat, such as ebonite, to protect our hand from the hot utensil.

5. Two bedsheets used together to cover the body help retain body heat better than a single bedsheet of double the thickness. Trapped air being a bad conductor of heat, the layer of air between the two sheets reduces thermal conduction better than a sheet of double the thickness. Similarly, a blanket coupled with a bedsheet is a cheaper alternative to using two blankets.

6. Eskimos make igloos which are double walled house. Two walls are used so that the air which is trapped in between prevent conduction of heat from inside of the house to outside of the house, hence people inside would feel warm.

Example-1 : A copper rod 19 cm long and of 0.785 cm² area of cross section thermally insulated is heated at one end through 100°C while the other end is kept at 30°C. Calculate the amount of heat which will flow in 10 mintues along the way. Thermal conductivity of copper 380 W m⁻¹ K⁻¹.

Solution :



Area of cross-section of rad

$A = 0.785\ cm^2 = 785 \times 10^{-7}\ m^2$

Difference between the two ends

$d = 19\ cm = 0.19\ m$

Difference of temperature $(T_1 - T_2)$

$= 100 - 30 = 70°C$

Time for which heat flows

$t = 10 \times 60 = 600\ s$

Coefficient thermal conductivity of copper

$k = 380\ \frac{W}{mK}$

$$Q = \frac{kA(T_1 - T_2)t}{d}$$

$$= \frac{380 \times 785 \times 10^{-7} \times 70 \times 600}{0.19}$$

$Q = 6594$

$= 6.594\ kJ$

Example-2 : The total area of the glass window pane is 0.5 m². Calculate how much heat is conducted per hour through the glass window pane if thickness of the glass is 6.0 mm. The temperature of the inside is 23°C and of the outside surface is 2°C. Thermal conductivity of glass is 1.0 Wm⁻¹K⁻¹.

Solution :

Total area of cross-section $A = 0.5\ m^2$

Thickness of the glass pane $d = 6\ mm = 6 \times 10^{-3}\ m$

Difference of temperature

$(T_1 - T_2) = 23.2 = 21°C$

Time for when heat flows $t = 1\ hour = 60 \times 60 = 3600\ s$

Coefficient of thermal conductivity of glass pane

$$Q = \frac{kA(T_1 - T_2)t}{d}$$

$$= \frac{1 \times 0.5 \times 21 \times 3600}{6 \times 10^{-3}}$$

$Q = 6300000\ J$

$= 63 \times 10^5\ J$

Multiple Choice Questions (MCQs)

1. An ice box of Styrofoam (thermal conductivity = 0.01 J/m.s.K) is used to keep liquid cool. It has a total wall area, including lid of 0.8 m^2 and wall thickness of 2.0 cm. A bottle of water is placed in the box and filled with ice. If the outside temperature is 30°C, the rate of flow of heat into the box is .... in (J/s).

(A) 16 (B) 10
(C) 12 (D) 14

Ans. : (C)

Solution :

Here $K = 0.01\ J/ms^{-1}\ K^{-1}$, $A = 0.8\ m^2$,

$\Delta \times 2\ cm = 2 \times 10^{-2}\ m$

$\Delta T = 30°C$, $dQ/dt = ?$

$$\frac{dQ}{dt} = KA\frac{\Delta T}{\Delta x} = 0.01 \times 0.8 \times \frac{30}{2 \times 10^{-2}}$$

$$= \frac{8}{1000} \times \frac{30}{2} \times 100 = 12\ J/s$$

2. A waterheater with 2.2 litre water at 27°C is heated by operating coil heater of power 1 kW. The heat is lost to the atmosphere at constant rate 150 J//s , as its lid is kept open. In how much time will water heated to 80°C with the lid open ? (specific heat of water = 4.2 kJ/kg)

(A) 14 min (B) 9 min 36 sec
(C) 7 min (D) 6 min 2 sec

Ans. : (B)

Solution :

As shown in the figure, the net heat absorbed by the water to raise its temperature

= (1000 – 150) = 850 J/S

Now, the heat required to raise the temperature of water from 27°

C → 80°C is

$Q = mc\ \Delta t = 2.2 \times 4200 \times 53\ J$

Therefore the time required

$$t = \frac{Q}{850} = \frac{2.2 \times 4200 \times 53}{850} = 9\ \text{min}\ 36\ \text{sec}$$

3. **In which of the following process, convection does not take place primarily ?**

(A) boiling of water
(B) heating air around a furnace
(C) Sea and land breeze
(D) warming of glass of bulb due to filament

Ans. : (D)

Solution : Heat transfer of glass bulb from filament is through radiation. A medium is required for convection process.

As a bulb is almost evacuated, heat from the filament is transmitted through radiation.

4. A big piece of glass is first heated and then is allowed to cool. On cooling down, a crack is developed in it. One of the possible reasons for this is

(A) high melting point
(B) large thermal conductivity
(C) large specific heat
(D) small thermal conductivity

Ans. : (D)

5. A steel ball is brought in contact with an identical ball of wood, then they will be equally hot or cold at

(A) 98.4 °C (B) 98.4 K
(C) 98.4. °F (D) room temperature.

Ans. : (C)

6. A sphere, a cube and a thin circular plate, all of same materials and same mass, are heated to same high temperature. Which of them will cool fastest.

(A) Plate
(B) Sphere
(C) Cube
(D) All of them will cool at same time

Ans. : (A)

Solution : The circular plate has maximum surface area and as such it cools the fastest. For a given volume (mass in this case), a sphere has the least surface area and accordingly cools the slowest.

7. At atmospheric pressure, when equilibrium is established between pure water and ts vapour, temperature is taken ...... K.

(A) 100
(B) 273.15
(C) 373.15
(D) 273.16

Ans. : (C)

8. An optical pyrometer is used to measure

(A) light intensity
(B) low temperature
(C) high temperature
(D) light intensity and high temperature

Ans. : (C)

9. The bimetallic strips made of two different materials bend during temperature rise because ...... of both metallic strips.

(A) difference in linear expansion coefficient
(B) difference in the elastic properties
(C) difference in thermal conductivities
(D) none of above

Ans. : (A)

10. At what temperature do the Fahrenheit and Celsius scales coincide ?

(A) 0
(B) 20
(C) 40
(D) – 40

Ans. : (D)

11. Boiling point of water, which is used as one of the fixed point in the international practical scale K is given by...

(A) 100
(B) 212
(C) 273.15
(D) 373.15

Ans. : (D)

12. The instrument which measures the temperature of the source without direct contact is

(A) bimetallic thermometer
(B) mercury thermometer
(C) pyrometer
(D) thermocouple

Ans. : (C)

13. Bimetallic thermometers are ....if the temperature changes are rapid.

(A) unsuitable
(B) suitable
(C) costly
(D) complex

Ans. : (A)

14. In the optical pyrometers, temperature reading may be time consuming due to manual......balancing.

(A) fine
(B) null
(C) optical
(D) wheel

Ans. : (B)

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