

MODULE 2

Unit 1	Molar Heat Capacity of Gases
Unit 2	Conduction of Heat
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UNIT 1 MOLAR HEAT CAPACITY OF GASES

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1.0 INTRODUCTION

So far we have considered the specific heat capacities of solids and liquids especially when we have to determine how much heat energy is absorbed when they are heated. We have not considered the specific heat capacity of gases. This is due to the fact that the behaviour of gases is quite different from that of liquids and solids.

For example, in gases, we have to consider the following parameters (properties) when we are examining the behaviour of gases:

- the pressure (P)
- the volume (V)
- the temperature (T)
- the amount of gas in moles (n)

These properties have been studied under gas laws in the Unit 5. However one property that is crucial to the gases is the heat capacities under constant volume and under constant pressure. Since the amount of gases is in terms of number of moles, we shall therefore be talking about molar heat capacities of gases. Hence in this unit, we shall examine the concept of molar heat capacities of gases under these two conditions: constant volume and constant pressure.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- explain the work done by expanding volume of gas
- define molar heat capacity of a gas at constant volume
- define molar heat capacity of a gas at constant pressure
- explain the meaning of isothermal expansion
- explain the meaning of adiabatic expansion
- relate the molar heat capacity at constant pressure with that at constant volume.

3.0 MAIN CONTENT

3.1 Molar Heat Capacities of Gases

You will recall that in calculating the quantity of heat (**Q**) acquired by a solid or a liquid we used the expression:

$$Q = mc\Delta\theta \dots\dots\dots (6.1)$$

Where, m is the mass of the solid/liquid, c is specific heat capacity of the substance, and $\Delta\theta$ is the change in temperature.

It is more convenient to use the concept of mole to describe the amount of a substance especially gases. So, first we will learn about the mole.

By definition, one mole (1 mol) of any substance is the quantity of matter such that its mass in grammes is numerically equal to the molecular mass M (often called the molecular weight). So to calculate the number of moles n numerically, divide the mass m in grammes by the molecular mass M.

$$\begin{aligned} \therefore n &= \frac{m}{M} \\ \therefore m &= nM \dots\dots\dots (6.2) \end{aligned}$$

Therefore the Eq. (6.1), becomes:

$$\therefore Q = nMc\Delta\theta \dots\dots\dots (6.3)$$

$$\therefore \frac{Q}{n\Delta\theta} = Mc \dots\dots\dots (6.4)$$

The product Mc is called the molar heat capacity

$$\therefore C = Mc \frac{Q}{n\Delta\theta} \dots\dots\dots (6.5)$$

Which is defined as the quantity of heat Q in joules required to raise the temperature of 1 mole of gas through 1 K or 1°C .

$$\therefore Q = nC\Delta\theta \dots\dots\dots (6.6)$$

Note that small c is the specific heat capacity while the big C is the molar specific heat capacity. It is the molar heat capacity that is mostly associated with the gases though it could also be used for solids and liquids.

You would have noticed that the behaviour of gases under heat is quite different from the behaviour of solids and liquids. Molecules of a gas are moving about in different directions with different speeds at any instant. This therefore describes the random motion of the molecules.

The internal energy of the gas is therefore the Kinetic Energy (KE) of its random motion. This Kinetic energy, as will be shown later, depends on the temperature of the gas. The higher the temperature, the greater the internal energy (kinetic energy) of the gas. Therefore, now

an ideal gas is defined as one which obeys Boyle’s law and whose internal energy depends on the temperature of the gas and is independent of its volume.

3.1.1 Work Done by an Expanding Gas

Consider a given mass of gas in a container shown in fig. 6.1.

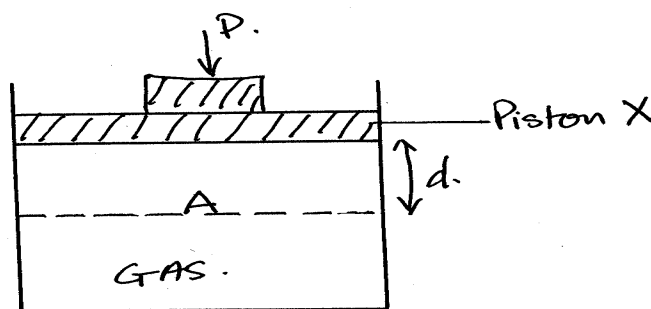


Fig. 6.1: Work Done by Expanding Gas

If the gas is warmed it expands, the gas does external work because it will be observed to have pushed back a piston X against some external pressure P .

The heat supplied is shared between the work done against the external work and in increasing the internal energy of the gas because the molecules move faster and its Kinetic energy is increased.

Hence, heat supplied = $\Delta Q = \Delta U + \Delta W \dots\dots\dots (6.7)$

Where, ΔQ is the increase in heat energy, ΔU is the increase in internal energy and ΔW is the work done as a result of expansion, work done against external pressure P .

The expression $\Delta Q = \Delta U + \Delta W$ is derived from the first law of thermodynamics which is also related to the law of conservation of energy which you will study later.

If the external pressure is constant with a value of P while the volume of the gas expands by ΔV , and if the area of the piston X is A , moving through a distance d , then the increase e in work done against the external pressure $P = \Delta W$

$$\begin{aligned} \Delta W &= \text{force} \times \text{distance} \\ \Delta W &= F \times d \dots\dots\dots (6.8) \end{aligned}$$

But as you know the pressure is defined as $P = \frac{F}{A}$

$$\begin{aligned} \therefore F &= PA \\ \therefore \Delta W &= PA = P\Delta V \quad (\text{where, } \Delta V = Ad) \\ \therefore \Delta Q &= \Delta U + P\Delta V \end{aligned}$$

In an ideal gas, the work done in separating molecules against attractive forces between them is ignored. This is not so with real gases where the Van der Waal's forces have to be considered. It is also assumed that there is no frictional force when the piston moves.

3.2 Molar Heat Capacities at Constant Volume and Constant Pressure

The heat capacity of a gas depends on the condition under which it is heated namely:

- at constant volume or
- at constant pressure

At constant volume, we would represent the molar heat capacity by C_V . At constant pressure, we would represent the molar heat capacity by C_P .

3.2.1 Molar Heat Capacity at Constant Volume C_V

At constant volume, the volume of the gas is kept at constant volume in such a way that there is no work done by the gas when it absorbs heat. The entire heat is therefore used in changing the internal energy of the gas.

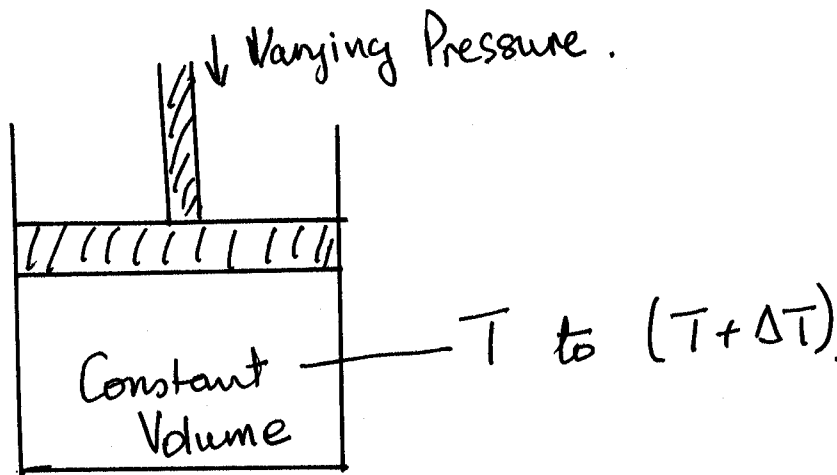


Fig. 6.2: Molar Heat Capacity at Constant Volume

The molar heat capacity at constant volume C_V , is therefore defined as the heat required to raise 1 mole of gas by 1 Kelvin (or 1 Celsius) degree when its volume is kept constant.

$$C_V = \frac{Q}{n\Delta\theta}$$

$$\therefore Q = n C_V \Delta\theta$$

where, n is the number of moles of gas, C_V is the molar heat capacity of the gas, and $\Delta\theta$ is change in temperature of the gas.

The unit of molar heat capacity at constant volume C_V is $J \text{ mol}^{-1}K^{-1}$ or $J \text{ mol}^{-1}^{\circ}C^{-1}$. The specific heat capacity at constant volume C_V is the heat required to raise the temperature of 1kg mass of the gas by 1K or $1^{\circ}C$.

The molar mass of hydrogen is 2g therefore 1kg = 1000g which is 500 times the mass of 1 mole.

$$\therefore C_V = 500 C_V \text{ for hydrogen}$$

Remember the unit of C_V is $J \text{ kg}^{-1}K^{-1}$ or $J \text{ kg}^{-1}^{\circ}C^{-1}$.

At constant volume, therefore, all the heat supplied to 1 mole of the gas is used in raising the internal energy of the gas.

From, $\Delta Q = \Delta U + P\Delta V$

Since no external work against pressure is done. Therefore $P\Delta V$ is zero. Substitute in the above Eq., we get

$$\therefore \Delta Q = \Delta U = nC_V (T_2 - T_1) = nC_V \Delta T$$

Where $n = 1$ mole

$$\therefore \Delta Q = C_V \Delta T \dots\dots\dots (6.9)$$

For an ideal gas in which there are no attractive forces among the molecules and each molecule has negligible volume C_V is independent of the volume of gas. If the temperature of the gas rises from T_1 to T_2 , the gain in internal energy (ΔU) is $C_V (T_2 - T_1)$ for one mole of gas no matter what volume the gas may be initially or may finally occupy. Thus the internal change in energy depends only on the temperature change.

3.2.2 Molar Heat Capacity at Constant Pressure C_P

In this case, we are supplying heat to the system where the pressure is constant. Thus, the heat is used in changing the internal energy of the gas as well as doing some work against the constant external pressure P (fig. 3.3).

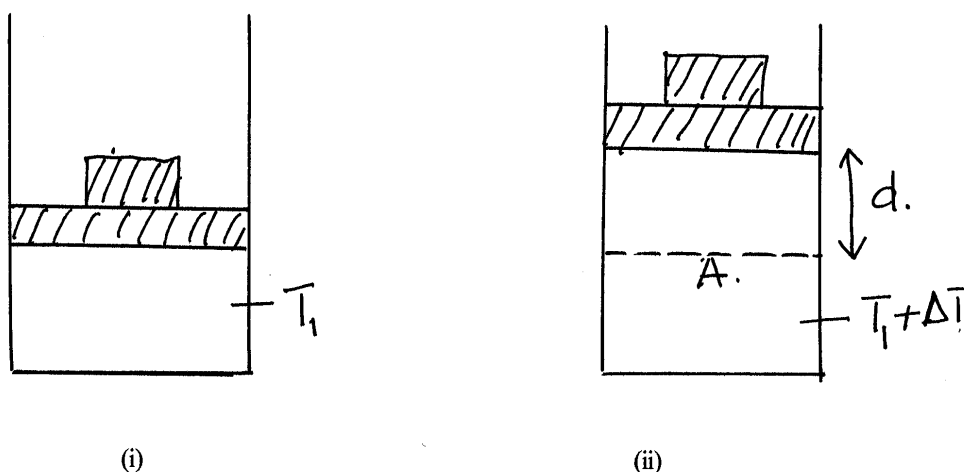


Fig. 6.3: Molar Heat Capacity at Constant Pressure

The molar heat capacity of a gas at constant pressure C_P is the heat required to raise the temperature of 1 mole of gas at constant pressure by 1K or 1°C.

$$C_P = \frac{Q}{n\Delta\theta} \dots\dots\dots (6.10)$$

Thus the unit of C_P is $J \text{ mol}^{-1}\text{K}^{-1}$ or $J \text{ mol}^{-1}\text{°C}^{-1}$

On the other hand, the specific heat capacity at constant pressure C_P is the heat required to raise the temperature of 1kg mass of a gas at constant pressure by 1kg (or 1°C).

When heat is supplied to change the temperature of the gas from T_1 to T_2 , there is change in volume ΔV (fig. 3.3(ii)) and increase in internal energy (ΔU). We have known that ΔU , the internal energy of the gas, which is independent of volume C_V , is for 1K or 1°C change in temperature.

From, $\Delta Q = \Delta U + \Delta W$

Where, ΔW is work done by the gas and $\Delta U = C_V\Delta T$ for 1 mole of gas.

$$\therefore \Delta Q = C_p \Delta T = C_v \Delta T + \Delta W \quad \# \text{ for 1 mole of gas} \dots\dots\dots (6.11)$$

But as we know that $\Delta W = P\Delta V$

$$\therefore C_p = C_v \Delta T + P\Delta V \dots\dots\dots (6.12)$$

For an ideal gas from the equation of state of a gas, we know that
 $PV = nRT$

If there is an increase in volume of ΔV when there is a change in temperature of ΔT , then

$$\begin{aligned} \therefore P(V + \Delta V) &= nR(T + \Delta T) \\ \therefore PV + P\Delta V &= nRT + nR\Delta T \\ \therefore P\Delta V &= nR\Delta T \end{aligned}$$

For 1 mole of gas $n = 1$

$$\begin{aligned} \therefore P\Delta V &= nR\Delta T \\ \therefore C_p &= C_v \Delta T + R\Delta V \end{aligned}$$

Where, $\Delta T = 1\text{K}$ or 1°C

$$\begin{aligned} \therefore C_p &= C_v + R \\ \therefore C_p - C_v &= R \dots\dots\dots (6.13) \end{aligned}$$

At constant pressure therefore, for an ideal gas C_p is always greater than C_v . The difference R is the external work done when the gas is warmed at constant pressure so that its temperature changes by 1K or 1°C .

SELF ASSESSMENT EXERCISE

One mole of a gas has volume of $2.23 \times 10^{-2} \text{m}^3$ at a pressure of $1.01 \times 10^5 \text{Pa}$ (N) at 0°C . If the molar cap city at constant pressure is $28.5 \text{J mol}^{-1} \text{K}^{-1}$. Calculate the molar heat capacity as constant volume.

3.3 Isothermal and Adiabatic Expansion of Gases

When a solid or liquid is heated, you would have observed that its volume increase very slightly. Thus the external work done against pressure is very small. Consequently the two molar heat capacities for solids and liquids are practically equal. That is, the specific heat capacities C_v and C_p are the same.

However, when real gases expand, some work is done against molecular attractive forces. This is the internal energy. The Van der waal's forces are appreciably significant in this case.

In $C_p - C_v = R$, R represents the external work done when an ideal gas expands at constant pressure. For real gases $C_p - C_v > R$ by the amount of internal work done when the gas expands at constant pressure.

When an ideal gas is allowed to expand under a constant temperature, the process is described as **isothermal expansion**.

Under this condition there is no change in internal energy because ΔU depends on ΔT .

From the First Law of Thermodynamics,

$$\Delta Q = \Delta U + P\Delta V$$

$$\therefore \Delta Q = \Delta U + P\Delta V \quad \text{since } \Delta U = 0 \text{ at isothermal condition (6.14)}$$

The heat supplied to maintain it at constant temperature then is equal to the external work done. Since the temperature is kept constant, an ideal gas therefore obeys Boyle's law

$$PV = \text{Constant}$$

during isothermal changes.

If a gas, on the other hand, is allowed to expand without heat entering or leaving the gas (by insulating its cylinder and piston) the energy needed for the external work is taken from the internal energy of the gas.

This process is described as **adiabatic expansion**.

$$\text{From,} \quad \Delta Q = \Delta U + P\Delta V$$

$$\text{Since,} \quad \Delta Q = 0$$

$$\therefore P\Delta V = - \Delta U \text{ (6.15)}$$

Consequently, the temperature of the system falls. Contrarily, when the gas is compressed under this condition (adiabatic condition), the work done on the gas produces a rise in internal energy, which is equal to the work done. This implies that the temperature of the gas rises. The gas is then said to have undergone **an adiabatic change when no heat enters or leaves the system**.

For adiabatic changes, it can be shown that

- $PV^\gamma = \text{Constant} \text{ (6.16)}$

Where, $\gamma = \frac{C_p}{C_v}$

- $TV^{\gamma-1} = \text{Constant} \dots\dots\dots (6.17)$

Note that isothermal and adiabatic formulae apply to changes in P, V and T which take place under reversible conditions.

The following assumptions are to be noted:

- no frictional force exists when a piston moves during the gas expansion or contraction.
- no heat is produced in the gas by eddies or swirls of gas during expansion or contraction.

4.0 CONCLUSION

In order to determine the quantity of heat lost or absorbed by a substance, we often use the specific heat capacity to do so as one of the properties. Another convenient property that we use is the molar heat capacity. This concept is used when the quantity of heat absorbed is to be determined with gases. The molar heat capacity of a gas is considered under constant volume or under constant pressure. When an amount of gas (n) absorbs heat under constant volume we use the molar heat capacity at constant volume C_V . Under this condition the heat absorbed is used to change the internal energy only.

Under constant pressure, the heat absorbed is used to change the internal energy of the gas as well as the work done against a constant pressure. C_P represents the molar heat capacity.

For one mole of gas, heat absorbed at constant volume is given by

$$\Delta Q = C_V \Delta T$$

At constant pressure

$$\Delta Q = nC_P = nC_V \Delta T + nR \Delta T$$

For one mole of gas where $n = 1$

$$\Delta Q = C_P = C_V \Delta T + R \Delta T$$

For one Kelvin rise in temperature

$$\Delta Q = C_P = C_V + R$$

$$\therefore C_P = C_V + R$$

5.0 SUMMARY

In this unit you have learnt:

- That on the expansion of a given mass of gas by heating, work is done;
- That molar heat capacity is used for the heat absorbed by a gas constant volume C_V and constant pressure C_P ;

- That there is a relationship between specific heat capacity c and molar heat capacity C ;
- Molar heat capacity at constant volume C_V is defined as the heat required to raise one mole of gas by 1K when its volume is kept constant;
- Molar heat capacity of a gas at constant pressure C_P is the heat required to raise the temperature of 1 mole of the gas at constant pressure by 1K;
- When a gas is allowed to expand at constant temperature the process is described as an isothermal expansion;
- When a gas is allowed to expand without heat entering or leaving the gas, the gas is said to undergo an adiabatic expansion;
- Work is done with rise in internal energy.

ANSWER TO SELF ASSESSMENT EXERCISE

From $PV = RT$

$$\begin{aligned} \therefore R &= \frac{PV}{T} \\ &= \frac{1.01 \times 10^5 \frac{\text{N}}{\text{m}^2} \times 2.23 \times 10^{-2} \text{m}^2}{273\text{K}} \\ &= 8.25\text{J mol}^{-1}\text{K}^{-1} \end{aligned}$$

From, $C_P = C_V + R$

$$\begin{aligned} \therefore C_V &= C_P - R \\ &= 28.5 = \frac{\text{J}}{\text{molK}} - 8.25 \frac{\text{J}}{\text{molK}} \\ &= 20.25\text{J mol}^{-1}\text{K}^{-1} \end{aligned}$$

6.0 TUTOR-MARKED ASSIGNMENT

Two grammes of a gas initially at 27°C is heated at constant pressure of $1.0 \times 10^5 \text{ pa}$ so that its volume increases from 0.250m^3 to 0.375m^3 , calculate:

- the external work done
- the increase in internal energy
- the heat supplied

(Relative molecular mass of the gas is 2g, $C_V = 20.2\text{J mol}^{-1}\text{K}^{-1}$ $C_P = 28.5\text{J mol}^{-1}\text{K}^{-1}$).

7.0 REFERENCES/FURTHER READING

- Awe, O. and Okunola, O. O. (1986). *Comprehensive Certificate Physics*, Ibadan: University Press Limited.
- Ference, M. (Jnr.), Lemon, H.B. and Stephenson, R. J. (1970). *Analytical Experimental Physics*, Chicago: The University of Chicago Press.
- Feynman, R. P., Leighton, R. B. and Sands, M. (1971). *The Feynman Lectures on Physics*, California: Addison – Wesley Publishing Company.
- Flowers, B. H. and Mendoza, E. (1970). *Properties of Matter*, London: John Wiley and Sons Limited.
- Noaks, M. A. (1963). *New Intermediate Physics*, Canada: Macmillan and company Limited.
- Soars, F. W., Zemansky, M.W. and Young, H. D. (1980). *College Physics*, London: Addison – Wesley Publishing Company.
- Tyler, F. (1983). *Heat and Thermodynamics*, London: Edward Arnold Publisher Limited.
- Wilkinson, J. (1983). *Essentials of Physics*, Australia: McMillan Education Publishers.
- Zemansky, M. W., (1968). *Heat and Thermodynamics*, New York: McGraw Hill Book Company.

UNIT 2 CONDUCTION OF HEAT

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1.0 INTRODUCTION

In Physics, we are not only interested in knowing the different forms of energy but how the heat energy may be transferred from one point to another. In this module, we shall consider the three ways by which heat energy is transferred from one source to another. This idea can be viewed as another property of matter, that is, that matter as solids, liquids and gases can act as medium of carrying heat energy from one point to another. The three modes of heat transfer are conduction, convection and radiation.

At the elementary level, one may be satisfied with the use of molecular theory in explaining the three modes of transfer of heat. However, at higher level, we shall go beyond this level by discussing quantitatively conduction of heat in terms of thermal conductivity of a solid and radiation of heat energy through space. We shall consider good and bad conductors (insulators) and conductors in series. We shall deal mainly with conduction of heat in this unit. Transfer by convection will be discussed in the next unit.

2.0 OBJECTIVES

At the conclusion of this unit, you should be able to:

- state the factors that affect thermal conductivity
- define the thermal conductivity of a good conductor and insulator
- measure the thermal conductivity of a good conductor
- measure the thermal conductivity of a bad conductor

- solve problems involving thermal conductivity.

3.0 MAIN CONTENT

3.1 Conduction of Heat Energy

Consider a long silver spoon dipped inside a hot soup. After sometime, the other end of the spoon becomes hot. The transfer of heat energy through the material by conduction could explain this observation.

You would have noted that one factor is obvious in this conduction of heat. That is, one end is at a higher temperature than the other. In the study of conduction of heat through solids, we would like to discuss what factors affect the rate of conduction of heat through solids. In the next sub-section, you will study about the factors that affect conduction.

3.1.1 Factors Affecting Conduction

Consider a state of material with parallel faces of cross-sectional area A at right angles to the direction of the flow of heat. The heat Q as shown in fig. 7.1 will flow from high temperature region θ_2 to a low temperature region θ_1 . That means θ_2 is greater than θ_1 . Let the distance between these temperatures regions be L .

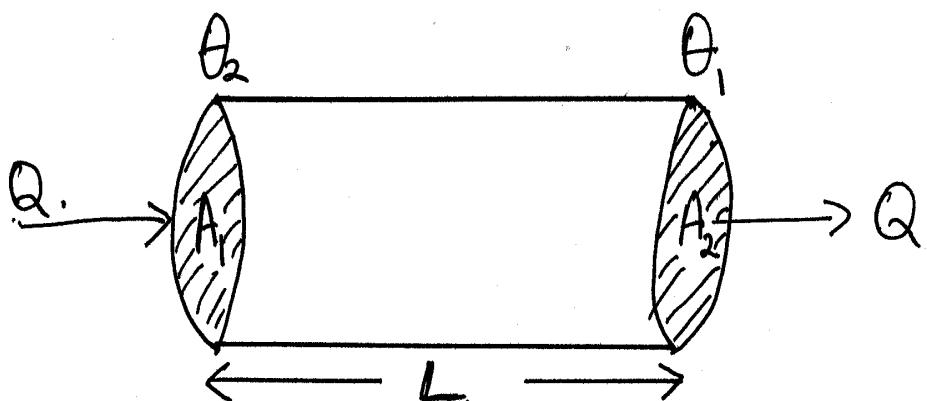


Fig. 3.1

If heat Q takes time t to be transferred across the section of this material of length L , experimentally it have shown that the rate at which the quantity Q is transferred with respect to the time within this region of length L is

- (i) Proportional to the cross-sectional area A :

$$\text{i.e. } \frac{Q}{t} \propto A \dots\dots\dots (7.1)$$

- (ii) Proportional to the temperature gradient within this region where the temperature gradient is defined as

$$\text{i.e. } \frac{Q}{t} \propto \frac{\theta_2 - \theta_1}{L} \dots\dots\dots (7.2)$$

Combining these two ideas (Eq. (7.1) and Eq.(7.2)) by saying that the rate of transfer of heat is proportional to the area and temperature gradient, give:

$$\begin{aligned} \text{i.e. } \frac{Q}{t} &\propto A \times \frac{\theta_2 - \theta_1}{L} \\ \therefore \frac{Q}{t} &= kA \frac{(\theta_2 - \theta_1)}{L} \dots\dots\dots (7.3) \end{aligned}$$

where, k is the constant of proportionality. k is a factor depending on the material.

SELF ASSESSMENT EXERCISE 1

State the factors that affect the conduction of heat.

3.1.2 Thermal Conductivity of a Material

We have been able to express the rate at which heat is transferred from a point A₁ to point A₂ in Fig. 7.1 as

$$\frac{Q}{t} = kA \frac{(\theta_2 - \theta_1)}{L}$$

k is therefore numerically equal to the heat transferred per second per unit area of cross-section when unit temperature gradient is set up normal to the area.

$$\begin{aligned} k &= \frac{\text{Rate x heat transferred}}{\text{Area x temperature gradient}} \\ k &= \frac{Q/t}{A (\theta_2 - \theta_1)} \dots\dots\dots (7.4) \\ &\quad \underline{\hspace{1cm}} \\ &\quad \quad \quad L \end{aligned}$$

UNIT of k: From Eq.(7.4), k can be expressed as:

k is a constant of proportionality known as the thermal conductivity for the material for Eq. (7.3) k is written as,

$$\begin{aligned} k &= \frac{Q/t}{\text{Area x temperature gradient}} \\ &= \frac{J/s}{m^2 \times (^{\circ}C)} \\ &= Js^{-1}m^{-1}C^{-1} \\ &= Wm^{-1}C^{-1} \end{aligned}$$

On in terms of the absolute scale, the unit of k can be written as

$$k = \text{Wm}^{-1}\text{K}^{-1}$$

Copper, which is a very good conductor of heat, has its value $k = 400 \text{ Wm}^{-1}\text{K}^{-1}$ and that of air $= 0.02 \text{ Wm}^{-1}\text{K}^{-1}$

One can define the thermal conductivity of a material:

“The thermal conductivity of a material is the rate of transfer of heat per unit area per unit temperature gradient through the face of the material with the face perpendicular to the direction of the transfer of heat provided steady state is maintained.”

Now you may ask: What does it mean by steady state situation?

A steady state is reached when the rate of transfer of heat through a given cross-sectional area does not change with respect to time. This therefore brings us to the point to show how a steady state is achieved and that is through lagging or unlagging. You will discover the meaning of lagging or unlagging in the next section.

3.2 Lagged and Unlagged Bars

Heat may be transferred under two conditions:

- Lagged material – when the material is lagged
- Unlagged material – when the material is unlagged

We shall now describe the conduction of heat through two bars – one lagged and the other unlagged.

In this section we shall consider the conduction of heat through:

- a uniform bar when lagged and when it is not lagged and
- a non-uniform bar when it is lagged.

3.2.1 Uniform Bar Lagged and Unlagged

In this case we are interested in studying how the temperature gradient varies with other factors such as the thermal conductivity k , the cross-sectional A and the rate of transfer of heat per second. Note that k varies with different materials but is constant for a particular material.

Let us consider a lagged bar PQ of length x , such that P is at temperature θ_2 while Q is at temperature θ_1 (Fig. 7.2)

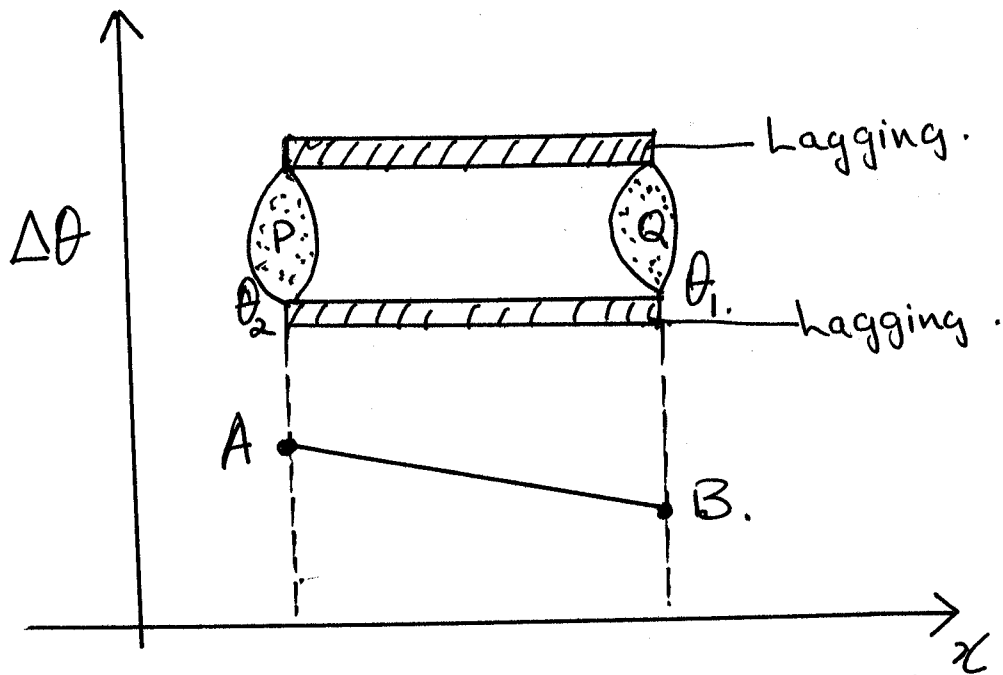


Fig. 7: Temperature Gradient for a Uniformly Lagged Bar

In this case θ_2 is greater than θ_1 . Hence, heat will be transferred from P to Q. If A is the uniform cross-sectional area of PQ, the rate of transfer of heat from P to Q is given as

$$\frac{Q}{t} = kA \frac{(\theta_2 - \theta_1)}{x}$$

$$\therefore \frac{(\theta_2 - \theta_1)}{x} = \frac{1}{KA} \times \frac{Q}{t}$$

i.e. temperature gradient = $\frac{1}{KA} \times \frac{Q}{t}$ (7.4)

Under steady state condition, for lagged bar, the part $\frac{Q}{t}$ is the same on the two surfaces P and Q since no heat is lost to the surrounding. Thus with k and A being constant, both sides of the equation are constant.

Consequently, for lagged uniform bar the temperature gradient is constant as indicated on the graph of $\theta_2 - \theta_1$ against x to produce the line AB. (Fig. 7.2). In simple words, temperature gradient, $\frac{Q}{t}$, flowing through every cross-section from the hot to cold end is constant as no heat passes through the sides.

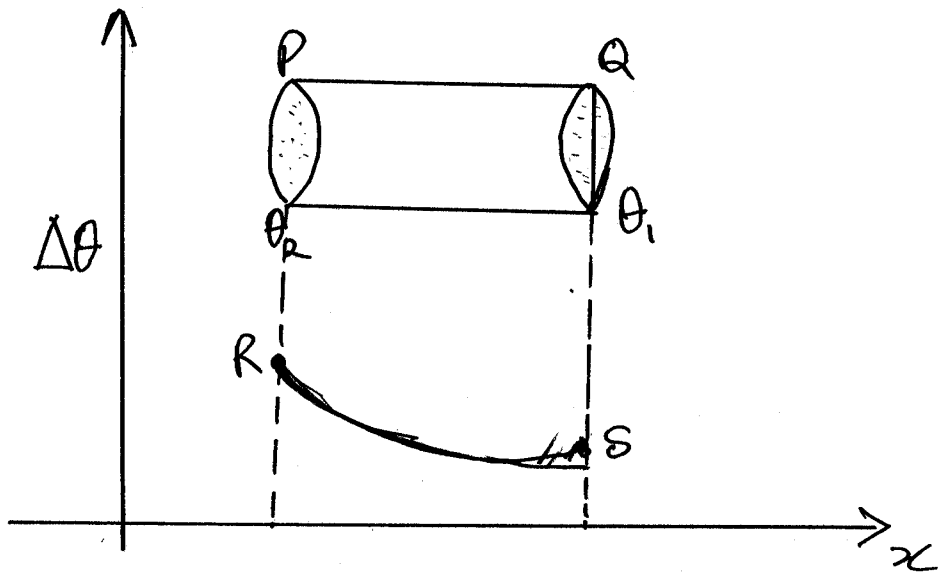


Fig. 7.3: Temperature Gradient for a Uniform Unlagged Bar

However, if the bar is unlagged, then from equation,

$$\frac{(\theta_2 - \theta_1)}{x} = \frac{1}{KA} \times \frac{Q}{t} \dots\dots\dots (7.5)$$

$\frac{Q}{t}$ under the unlagged condition will not be the same from face P to face Q. The value decreases from P to Q. Hence the gradient becomes smaller from the hot end P to the cold end Q. Thus the variation of the temperature gradient is a curve RS in fig. 7.3 with a diminishing gradient.

3.2.2 Non-Uniform Bar Lagged

Let us now consider another bar whose cross-sectional area is not uniform but is lagged as shown in fig, 7.4. It will be observed that

- (i) $\frac{Q}{t}$, the rate of transfer of heat will be the same at both ends because the material is lagged.
- (ii) The cross-sectional A, decreases from P to face Q, thus from the expression (7.4) the temperature gradient increases. This is shown by the gradient MN from hot end to cold end of the bar (fig. 7.4)

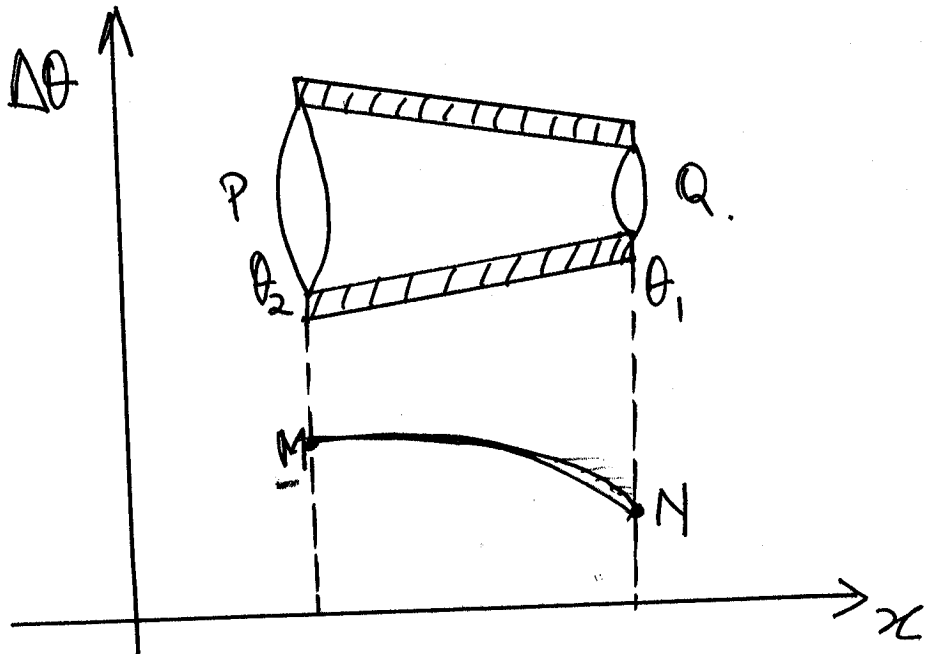


Fig. 7.4: Temperature Gradient – Non-Uniform Bar and Lagged

The concept of rate of transfer of heat $\frac{Q}{t}$ may be compared with the rate of flow of current I. From ohm's law,

$$I = \frac{V}{R} \dots\dots\dots (7.6)$$

Where, $I = \frac{\text{QUANTITY OF CHARGES (Q)}}{\text{TIME t TAKEN IN SECONDS}}$

But $R = \rho \frac{L}{A} \dots\dots\dots (7.7)$

Where, $R =$ resistance of the resistor
 $\rho =$ resistivity of the resistor
 $L =$ the length of the resistor
 $A =$ average cross-sectional area

Combining Eq. (7.6) and Eq. (7.7), we get

$$\begin{aligned} \therefore I &= \frac{V}{R} \times \frac{I}{R} \\ &= \frac{1}{\rho} \times \frac{A}{L} \times V \\ \therefore I &= \frac{1}{\rho} \times A \times \frac{V_2 - V_1}{L} \dots\dots\dots (7.8) \end{aligned}$$

Where, $\frac{1}{\rho}$ = electrical conductivity of wire and, $\frac{V}{L}$ = potential gradient

On comparing Eq. (7.8) $I = \frac{1}{\rho} A \frac{V_2 - V_1}{L}$ with

$$\text{Eq. (7.3), } \frac{Q}{t} = kA \frac{(\theta_2 - \theta_1)}{L}$$

where, k = the thermal conductivity

SELF ASSESSMENT EXERCISE 2

A long steel rod, insulated to prevent heat losses, has one end immersed in boiling water (at atmospheric pressure) and the other end in a water-ice mixture. If the steel rod is 100cm long and cross-sectional area of 5cm^2 , after establishing a steady state condition, how much heat per second is transferred from the steam bath to the ice-water mixture? (k for steel = $50\text{J}(\text{sm}^\circ\text{C})^{-1}$)?

3.3 Conduction of Heat through a Good Conductor and Bad Conductor in Series

In this section, we are interested in comparing the temperature gradient of the good conductor with that of the bad conductor. Consider a copper tank of thickness AB which is 5mm and lagged with a felt of thickness BC and 5cm as shown in fig 7.5.

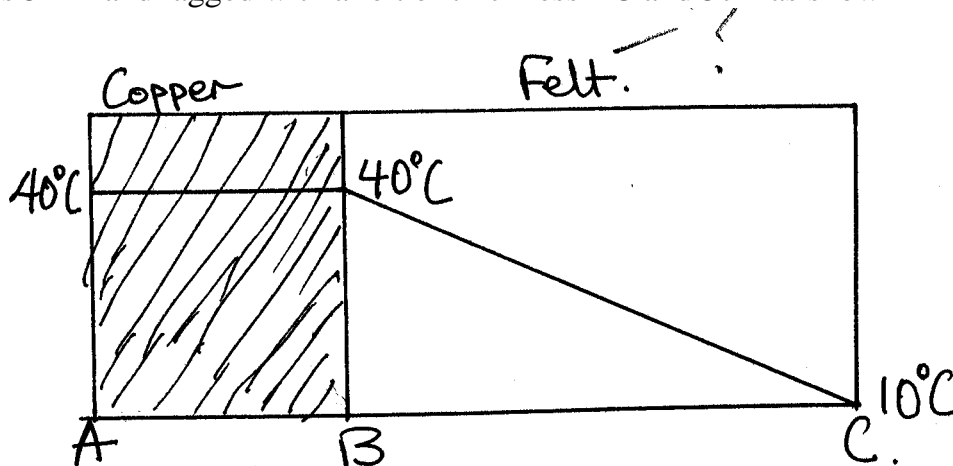


Fig. 7.5: Copper and Felt in Series

Suppose the temperature of the water in the copper tank is constant at 40°C throughout the thickness AB and the temperature of the outside of the felt is constant at 10°C .

Given that the thermal conductivity of copper is $400\text{Wm}^{-1}\text{C}^{-1}$ and that of the felt is $0.04\text{Wm}^{-1}\text{C}^{-1}$. At a steady state condition, the rate of heat transfer $\frac{Q}{t}$ is the same for copper (AB) and the felt (BC).

Using Eq. (7.4), the temperature gradient g is given as

$$g = \frac{1}{KA} \times \frac{Q}{t} \dots\dots\dots (7.9)$$

Let g_{cu} be the temperature gradient for copper and g_f be the temperature gradient for the felt.

$$\therefore g_{cu} = \frac{1}{g_{cu} A_{cu}} \times \frac{Q}{t} \text{ and } \dots\dots\dots (7.10)$$

$$g_f = \frac{1}{k_f A_f} \times \frac{Q}{t} \dots\dots\dots (7.11)$$

where, k_{cu} and k_f are the thermal conductivities for the copper and felt respectively.

A_{cu} and A_f are the cross-sectional areas of copper and felt respectively, which, in this case, are the same.

Now, dividing Eq. (7.10) by Eq. (7.11), we get

$$\text{Then, } \frac{g_{cu}}{g_f} = \frac{k_f}{K_{cu}} = \frac{0.04}{400} = \frac{4}{4000} = \frac{1}{1000}$$

$$g_{cu} = \frac{1}{1000} g_f$$

This shows that the temperature gradient of copper is 10,000 less than that of the felt. The consequence of this statement is that the temperature of the outer surface of the copper tank is not much less than its inner surface. Hence, the whole lot of the temperature drop from 40°C to 10°C occurs across felt, the bad conductor.

SELF ASSESSMENT EXERCISE 3

Assuming the thermal conductivities of air and brick are 0.02 and $0.6 \text{ W m}^{-1}\text{C}^{-1}$ respectively, calculate the thickness of air equivalent to a thickness of 30cm of brick if two of such brick walls are separated by air gap of 3cm . How much heat per minute would be transferred through them in the steady state when the outside temperatures of brick are 60°C and 10°C respectively and the area of cross-section of each is 2m^2 ?

3.4 Measuring the Thermal Conductivity of a Good Conductor

It is possible to determine the thermal conductivity of a metal bar such as copper or iron. The apparatus used in this determination is called the Searle’s apparatus (Fig. 7.9).

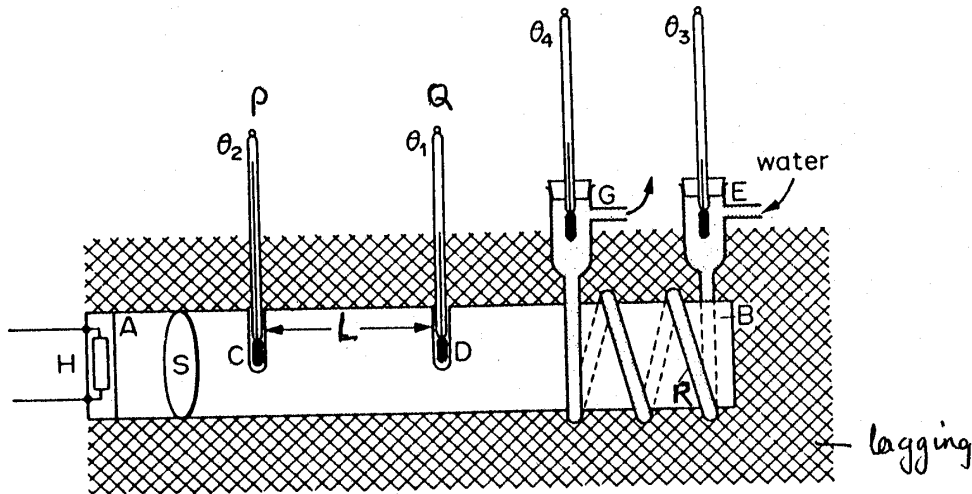


Fig. 7.9: Searle's Apparatus

The following are the essential features of the Searle's apparatus for measuring the thermal conductivity of a good conductor,

- A thick bar so that appreciable heat is transferred through a cross-section
- A reasonable long bar **AB** so that the temperature gradient can be measured accurately.
- A lagged bar so that no heat escapes and the heat being transferred is linear along the bar under steady state conditions.

Procedure

The procedure for measuring *k*, the thermal conductivity is as follows:

- The lagged bar is electrically heated at one end by an electric supply (H)
- The final steady state temperatures are measured by means of thermometers P and Q placed in deep holds bored in the bar at a known distance *L* apart. The temperature at P is θ_2 and that at Q is θ_1
- A coiled tube R is in thermal contact with the bar near the other end of the bar enables the heat transfer per second to be measured.
- Water from a constant pressure head flows steadily through the tubes R.
- The inlet and outlet temperatures θ_3 and θ_4 are measured
- The set up is left until the temperatures are steady
- The rate of transfer of water *m* is measured using a cylinder and a stop clock
- The cross-sectional area *S* of the bar is found using vernier calipers to measure the diameter.

The value of *k* can then be obtained from the relation

$$\frac{Q}{t} = mC_{\text{water}} (\theta_4 - \theta_3) = kA \frac{(\theta_2 - \theta_1)}{L} \dots\dots\dots (7.12)$$

Alternatively, $\frac{Q}{t}$ may be determined by measuring the current I and the potential difference V of the supply. Thus $\frac{Q}{t} = IV$. Thus neglecting the use of the resistance of the coil R .

3.5 Measuring the Thermal Conductivity of a Bad Conductor

This is another useful exercise in the laboratory for the determination of the thermal conductivity of a bad conductor. Lee designed the apparatus for this measurement. Hence, the name of apparatus – Lee's apparatus for measuring the thermal conductivity of a bad conductor (Fig. 3.10).

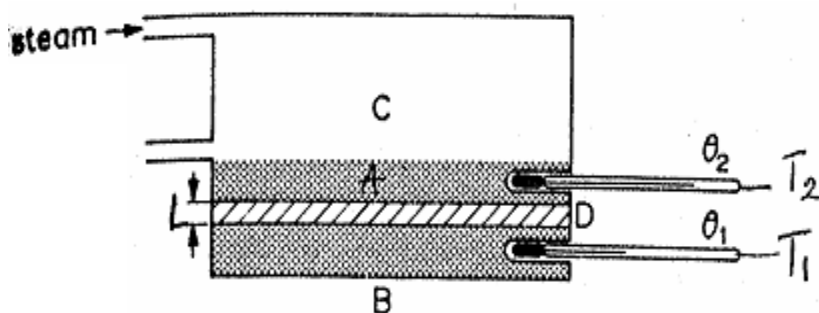


Fig. 7.10

The apparatus is made up of a top cylindrical steam chamber C. At the bottom of this chamber is a thick brass block A with a hole bored into it to hold a thermometer T_2 . Next to this brass block A is the bad conductor specimen D made up of a cardboard or glass in form of a disc with large diameter with small thickness d so that it gives a greater temperature gradient.

The bad conductor is sandwiched between the brass block A and another second cylindrical brass block B which also has a hole bored into it to hold another thermometer T_1 .

As a precaution, the slabs must be flat and clean. Some Vaseline may be smeared over it in order to improve thermal contact (Fig. 7.10). Heat therefore flows from chamber A through the specimen to the chamber B.

Steam is passed through chamber C until a steady state in temperatures θ_1 and θ_2 as measure by T_1 and T_2 respectively.

In this situation, the temperature gradient is $\frac{(\theta_2 - \theta_1)}{L}$

The next problem is centered on how to measure or determine the rate of loss of heat by chamber B. We therefore have to examine fig. 7.11 (i) and (ii).

The steam chamber C is removed with the brass block A. The specimen is left on top of the lower brass block B. The lower brass block B is then warmed gently by a Bunsen burner until its temperature is a few degrees above θ_1 , say 82°C . The burner is then removed and B is allowed to cool and the readings of its temperature fall with time are taken. The graph of θ is plotted against time t (Fig. 7.11 (ii)).

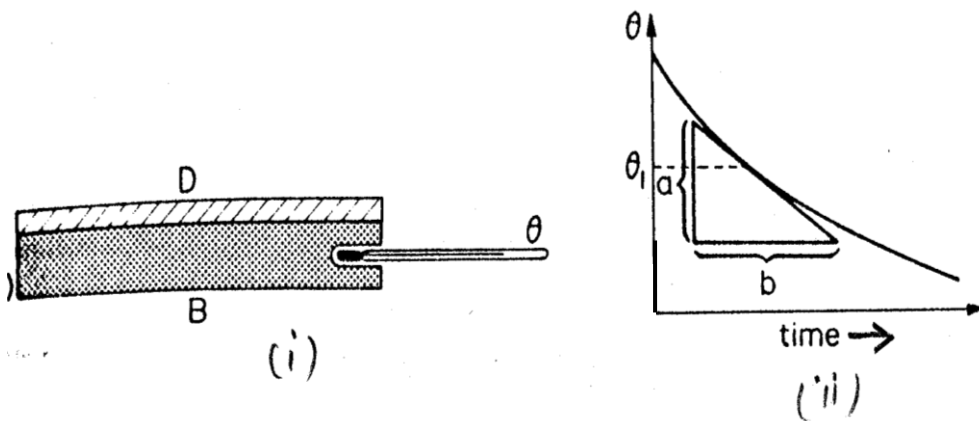


Fig. 7.11

The slope at temperature θ_1 is then determined as $\frac{a}{b}$

Let m be the mass of the brass B and C_{brass} the specific heat capacity of brass.

Therefore $\frac{Q}{t}$ = Rate of loss of heat by cooling

$$\text{at } \theta_1 = mC_{\text{brass}} \frac{a}{b}$$

When the temperature of B is steady, it is losing heat to the surrounding from side and base at exactly the same rate the base is receiving heat by conduction through the specimen D. Thus the rate of losing heat from B is equal to the rate of heat transfer through the specimen in steady state.

$$\therefore \frac{Q}{t} = kA \frac{(\theta_2 - \theta_1)}{d} = mC_{\text{brass}} \frac{a}{b} \dots\dots\dots (7.13)$$

Given the area A and the thickness L of the cardboard, K can be determined.

$$K = mC \frac{a}{b} \times \frac{L}{(\theta_2 - \theta_1)} \times \frac{1}{A} \dots\dots\dots (7.14)$$

4.0 CONCLUSION

In this unit we have studied one mode by which heat is transferred through matter-conduction. Conduction of heat through solids materials were examined especially through good and bad conductors of heat. The thermal conductivity of a solid material was considered as a property for the transfer of heat through solid materials.

The rate of transfer of heat in joules per second has been found to be proportional to the surface area of the solid material A , and the temperature gradient. If a conductor is of length L whose ends are at temperatures θ_2 and θ_1 and where θ_2 is greater than θ_1 , the temperature gradient is defined as the difference in the temperatures per unit length

$$\frac{(\theta_2 - \theta_1)}{L}$$

The rate of transfer of heat at steady state condition in the conduction of heat. To establish this condition implies that the material under consideration must be lagged i.e. insulated so that there is no loss of heat as the heat is being transferred from one end to another.

We would now consider another mode of transfer of heat through convection in the next unit.

5.0 SUMMARY

In this unit, you have studied the following:

- The concept of thermal conductivity is applied to both good and bad conductors of heat
- The thermal conductivity of a conductor is used to solve problems under steady state condition
- The rate of conduction of heat, the area of conduction, the thermal conductivity as well as the temperature are related as

$$\frac{Q}{t} = kA \frac{(\theta_2 - \theta_1)}{L}$$

- This relationship was used to consider the temperature gradient when a conductor is lagged or unlagged or when there is a variation in the surface areas when lagged
- One principle used in solving problems on conduction of heat through bad conductors of heat is the use of the equivalent material.
- Methods of how to determine the thermal conductivity of a good conductor and that of a bad conductor were described.

ANSWER TO SELF ASSESSMENT EXERCISE 1

The factors that affect the conduction of heat through a solid material are:

- (i) The cross-sectional area A
- (ii) The temperature difference
- (iii) The length of the material
- (iv) The time for the heat to be transferred

Note: (ii) and (iii) defines for us the concept of temperature gradient

$$\left(\frac{\theta_2 - \theta_1}{L} \right)$$

ANSWER TO SELF ASSESSMENT EXERCISE 2

$$\theta_2 = 100^\circ\text{C}$$

$$\theta_1 = 0^\circ\text{C}$$

$$L = 100\text{cm} = 1\text{m}$$

$$A = 5\text{cm}^2 = 5 \times 10^{-4}\text{m}^2$$

$$K = 50.2\text{J}(\text{s m}^\circ\text{C})^{-1}$$

$$\text{From, } \frac{Q}{t} = kA \frac{(\theta_2 - \theta_1)}{L}$$

$$\begin{aligned} \therefore \frac{Q}{t} &= 50.2\text{J/sm}^\circ\text{C} \times 5 \times 10^{-4}\text{m}^2 \times \frac{(100 - 0)^\circ\text{C}}{1\text{m}} \\ &= 50.2 \times 5 \times 10^{-4} \times 100\text{J/s} \\ &= 2.51\text{J/s} \\ &= 2.51 \text{ Watt} \end{aligned}$$

ANSWER TO SELF ASSESSMENT EXERCISE 3

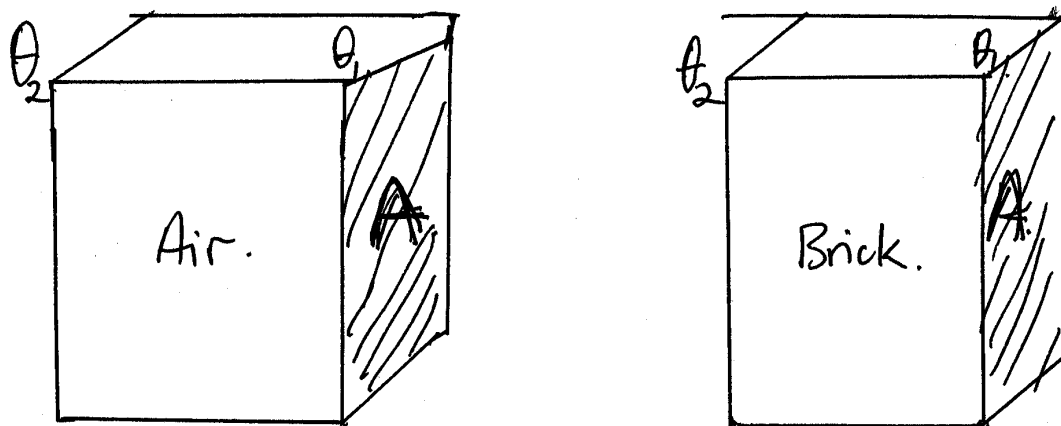


Fig. 7.6

- (a) Let the thickness of air be d_1 and that of the brick be d_2 which is given as 30cm = 0.3m. If they are at the same temperature difference $(\theta_2 - \theta_1)$ across the air and the brick. Then the rate of transfer of heat $\frac{Q}{t}$ is defined as

$$\frac{Q}{t} = k_1 A \frac{(\theta_2 - \theta_1)}{d_1} \quad \text{for air}$$

where, k_1 = thermal conductivity of air

$$\text{For the brick also, } \frac{Q}{t} = k_2 A \frac{(\theta_2 - \theta_1)}{d_2}$$

where, k_2 = thermal conductivity of the brick

Since $\frac{Q}{t}$ is the same for the two materials.

$$\therefore k_1 A \frac{(\theta_2 - \theta_1)}{d_1} = k_2 A \frac{(\theta_2 - \theta_1)}{d_2}$$

$$\therefore \frac{k_1}{d_1} = \frac{k_2}{d_2}$$

$$\therefore \frac{0.02 \text{Wm}^{-1} \text{C}^{-1}}{d_1} = \frac{0.6 \text{Wm}^{-1} \text{C}^{-1}}{0.3 \text{m}}$$

$$\begin{aligned} \therefore d_1 &= \frac{0.02 \times 0.3}{0.6} \text{m} \\ &= 0.01 \text{m} \\ &= 1.0 \text{cm} \end{aligned}$$

The thickness of air equivalent to that of the brick is 1.0cm.

(b)

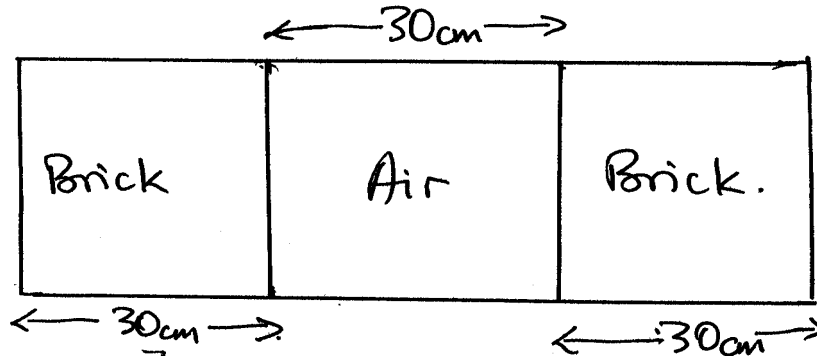


Fig. 7.7

If 30 cm of air is in series with the two bricks, then we have this new picture for the system (fig. 7.7).

From the solution in (a) this arrangement will be equivalent to the new picture in fig. 7.8.

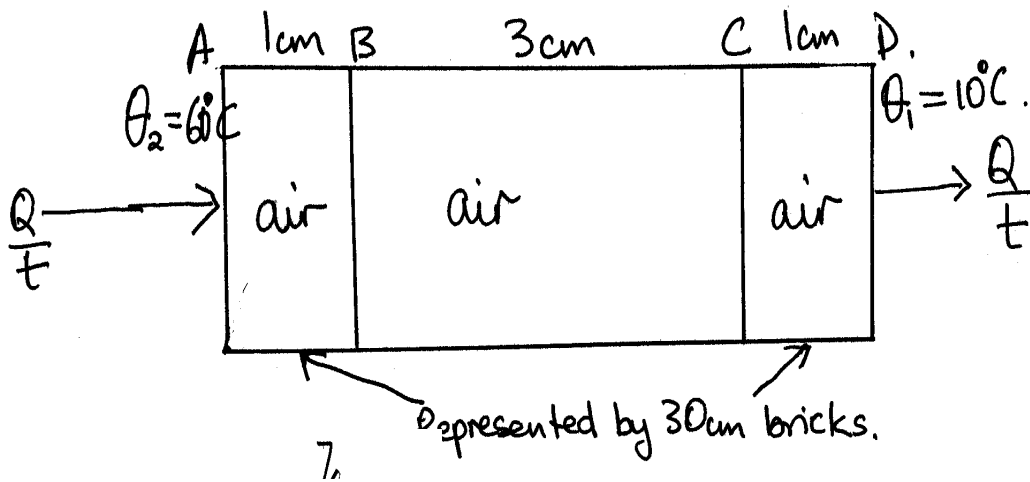


Fig. 7.8

We are interested in calculating the quantity of heat, Q per minute that will pass through from A to D.

$$\frac{Q}{t} = kA \frac{(\theta_2 - \theta_1)}{d}$$

where, k = thermal conductivity for air = $0.02 \text{Wm}^{-1}\text{C}^{-1}$

A = cross-sectional area of bricks = 2m^2

d = AD = 5cm = 0.05m

$(\theta_2 - \theta_1) = (60 - 10)^\circ\text{C} = 50^\circ\text{C}$ = the temperature difference

$$\begin{aligned}
 \therefore \frac{Q}{t} &= 0.02 \frac{\text{W}}{\text{m}^\circ\text{C}} \times 2\text{m}^2 \times \frac{50^\circ\text{C}}{0.05\text{m}} \\
 &= \frac{0.02 \times 2 \times 50\text{J}}{0.5} \frac{\text{J}}{\text{s}} \text{ for 1 minute we multiply by 60s} \\
 &= \frac{0.02 \times 2 \times 50\text{J}}{0.5} \times 60 \frac{\text{J}}{\text{min}} \\
 &= 2400\text{J/min}
 \end{aligned}$$

The heat energy transfer per minute is **2400J**.

6.0 TUTOR-MARKED ASSIGNMENT

1. A 100cm long copper rod, insulated to prevent heat losses has one end maintained at 150°C and the other at 0°C . If the copper rod has a cross-sectional area of 10cm^2 and after establishing a steady state condition, how much heat per second is transferred from 150°C end to 0°C end? (Thermal conductivity of copper = $385\text{J}(\text{s m}^\circ\text{C})^{-1}$)
2. In double-glazing, two sheets of glass 2mm thick are separated by 10mm of air. The temperatures of the outside glass surface are 20°C and 5°C respectively. Calculate the heat per second per unit area being transferred by conduction and the temperatures of the interior glass surfaces assuming steady state condition. (Thermal conductivities of glass and air are 0.03 and $0.02 \text{ Wm}^{-1}\text{C}^{-1}$ respectively.)
3. A closed metal vessel contains water (i) at 30°C and then (ii) at 75°C . The vessel has a surface area of 0.5m^2 and a uniform thickness of 4mm. If the outside temperature is 15°C , calculate the heat loss per minute by conduction in each case. (Thermal conductivity of the metal = $400\text{Wm}^{-1} \text{K}^{-1}$)
4. The following observations were made in an experiment to determine the thermal conductivity of aluminum by using

$$\theta_2 = 85^\circ\text{C}, \theta_1 = 65^\circ\text{C}, \theta_3 = 32^\circ\text{C} \text{ and } \theta_4 = 44^\circ\text{C}$$

Mass of water flowing in 1 minute = 9.9g. The distance between θ_2 and θ_1 = 0.4m. The diameter of the bar = 3cm.

7.0 REFERENCES/FURTHER READING

- Awe, O. and Okunola, O.O. (1986). *Comprehensive Certificate Physics*, Ibadan: University Press Limited.
- Ference, M. (Jnr.), Lemon, H.B. and Stephenson, RJ (1970). *Analytical Experimental Physics*, Chicago: The University of Chicago Press.
- Feynman, R.P., Leighton, R.B. and Sands, M (1971). *The Feynman Lectures on Physics*, California: Addison-Wesley Publishing Company.
- Flowers, B.H. and Mendoza, E (1970). *Properties of Matter*, London: John Wiley and Sons Limited.
- Noaks, M.A. (1963). *New Intermediate Physics*, Canada: Macmillan and company Limited.
- Soars, F.W., Zemansky, M.W. and Young, H.D. (1980). *College Physics*. London: Addison-Wesley Publishing Company.
- Tyler, F. (1966). *Heat and Thermodynamics*. London: Edwards Arnold Publisher Limited.
- Wilkinson, J. (1983). *Essentials of Physics*, Australia: Macmillan Education Publishers.
- Zemansky, M.W. (1968). *Heat and Thermodynamics*. New York: McGraw-Hill Book Company.

UNIT 3 **TRANSFER OF HEAT BY CONVECTION**

CONTENTS

- 1.0 Introduction
- 2.0 Objectives
- 3.0 Main Content
 - 3.1 Conduction of Heat in Fluids
 - 3.2 Convection in Fluids
 - 3.2.1 Natural and Forced Convection
 - 3.2.2 Convection of Heat in Liquids
 - 3.2.3 Convection in Gases
 - 3.3 Newton's Law of Cooling
- 4.0 Conclusion
- 5.0 Summary
- 6.0 Tutor-Marked Assignment
- 7.0 References/Further Reading

1.0 INTRODUCTION

In Module 2, unit 1, you have learnt about the transfer of heat through solids by conduction. You should have noticed that we did not discuss whether conduction takes place in liquids or gases.

You would also observe that in the transfer of heat by conduction, the material that makes up the solid does not move. The heat energy is simply passed from one molecule to the other i.e. from the hot end of the solid to the cold end of it.

The question you may logically ask is: "Does conduction take place in fluids (liquids and gases)?"

Thus, in this unit, we would show whether conduction takes place in fluids or not. This, therefore, brings us to the study of another mode of transfer of heat energy through matter described as CONVECTION. In the next unit, you will learn about the radiation which is another mode of transfer of heat in matter.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- show that conduction of heat does not take place in liquids and gases (fluids)
- explain the meaning of convection as a mode of transfer of heat in fluids
- differentiate between natural convection and forced convection of heat in matter
- state Newton's law of cooling.

3.0 MAIN CONTENT

3.1 Conduction of Heat in Fluids

Liquids and gases are usually referred to as fluids. *Does conduction of heat occur in them?* You should have realized that all liquids, except mercury, which is a metal, are poor conductors of heat. Air and gases, generally are even worse conductors of heat. This idea can be shown by placing a piece of ice wrapped inside a wire gauze and placed in a long test tube filled with water (Fig. 8.1).

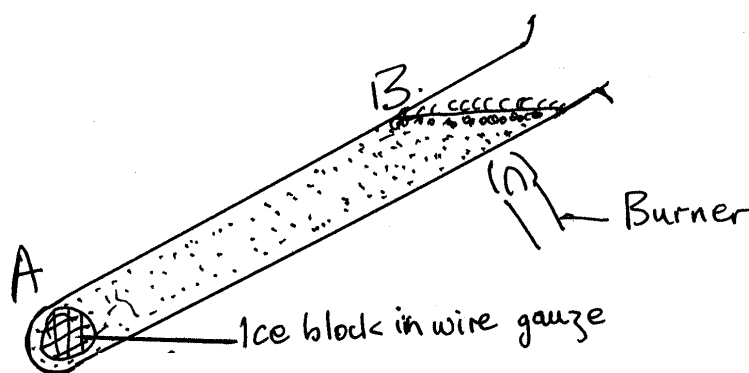


Fig. 8.1

The upper part of the tube **B** is observed to boil after heating it for some time. It will be observed that as the water boils the ice remains unmelted at the bottom of the tube. This means that the heat is not conducted down the tube. The heat stays at the top. Experiments have also shown that air is a poor conductor of heat. Steel wool, crumpled aluminum foil, wollen materials are bad conductors of heat because of the large number of small air pockets within these materials.

SELF ASSESSMENT EXERCISE 1

Describe an experiment to show that conduction of heat does not take place in a named liquid.

3.2 Convection in Fluids

The question you may ask now: If conduction of heat does not occur in fluids, how then is heat transferred in fluids?

Heat is transferred in fluids by convection. Convection is a mechanical displacement of heated part of a fluid. In simple words, it is a phenomenon of transfer of heat with the actual movement on the particles of the body. We usually place a pot of water on top of the cooker to get boiled water to prepare food or to bath if the weather is too cold. The liquid will be in contact with the solid wall of the container, which is usually a metal like an aluminum pot. The container is at a higher temperature than the fluid. The heat is transferred to the fluid. The heated portion of the fluid rises up while the cold fluid on the top comes down. This process continues until the water

begins to boil. The process may be explained in this manner. When the water molecules are heated, they expand and as a result of this expansion, the density of the molecules decreases such molecules thus experience an upthrust, according to Archimedes Principle, which makes them to float. Since nature does not allow a vacuum, the colder, heavier molecules take the place of the lighter ones. Thus a current of molecules is created within the liquid. The viscosity of the fluid i.e. fluid friction naturally influences the convectonal transfer of heat in fluids.

The term convection is usually applied to the transfer off heat in fluids from one point to another by the actual movement of the particles that make up the fluid.

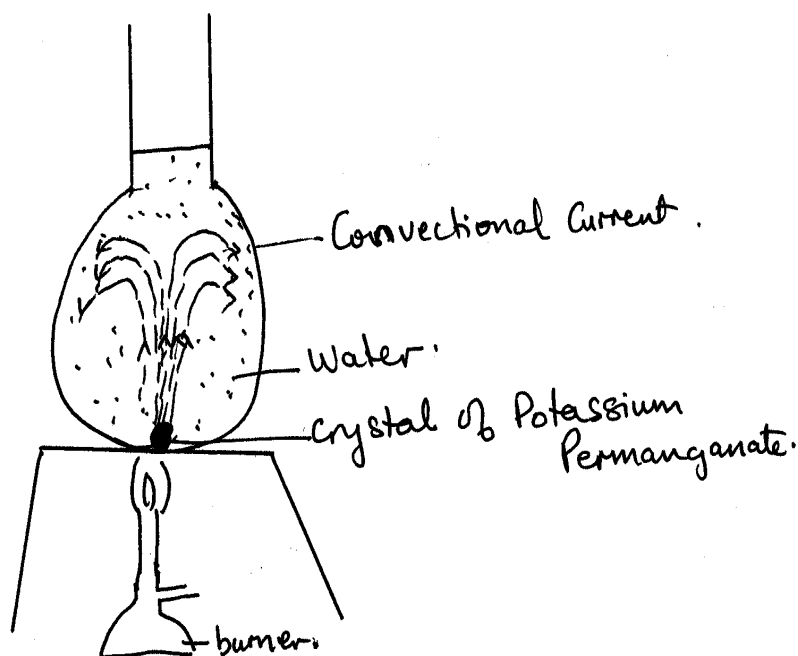
3.2.1 Natural and Forced Convection

When the material fluid carries the heat from one place to another due to the differences in density as a result of thermal expansion, the process of the heat transfer is called **natural convection**. An example of this occurs when water in a pot is made to boil.

On the other hand, when the material of the fluid is forced to carry the heat from one place to another by a blower or pump, the process is called **forced convection**. If you place your hot cup of tea or pap under a fan, the heat in the tea or pap will be reduced by forced convection.

3.2.2 Convection of Heat in Liquids

Convection in liquids may be demonstrated by placing a crystal of potassium permanganate carefully in a round bottomed flask and then heating the bottom of the flask gently (Fig. 8.2).



You will observe that a rising column of coloured water will occur in the flask. This shows that convection currents have been set up. This is a natural convection. This process again can be explained by the expansion of water molecules at the bottom of the flask due to the heat acquired. Their density decreases and as such, they float according to Archimedes' Principle. The heavier colder molecules then take the places of the hot ones and so a current is created within the bulk of the water. This is the principle applied in the domestic hot water system in cold countries. The hot water circulates by natural convection. However in large buildings, which have central heating systems, a pump is usually used to assist in the circulation of the hot water. This gives us an example of forced convection.

SELF ASSESSMENT EXERCISE 2

Explain why the coil (element) of an electric kettle is always placed at the bottom and not on top.

3.2.3 Convection in Gases

Convection in gases may be demonstrated experimentally by using a glass box with two chimneys A and B as shown in fig. 8.3.

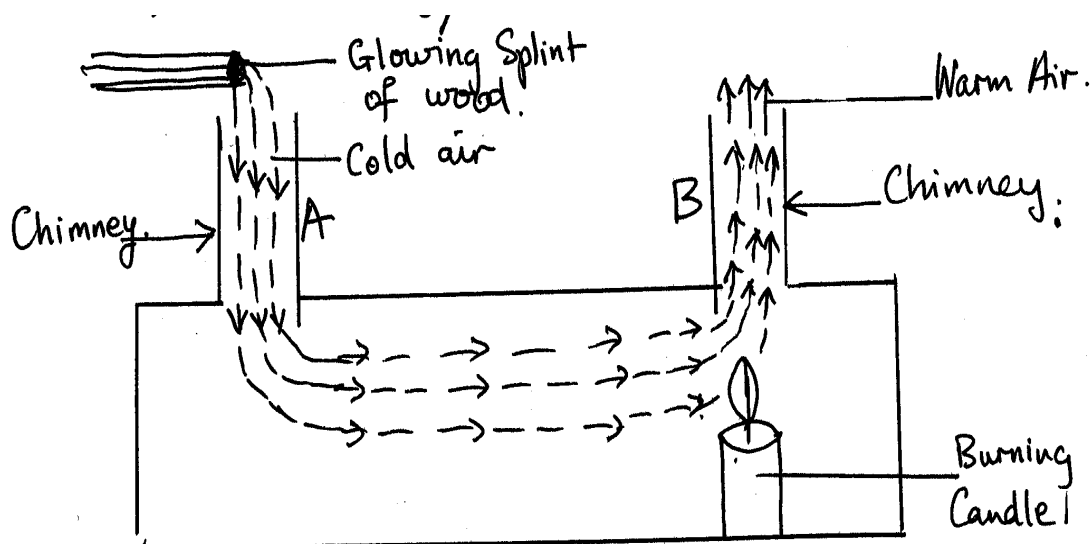


Fig. 8.3

Below chimney B, inside the box, is a burning candle. When a glowing splint of wood is placed above the chimney A, the smoke will be observed to take the path of a convectional current from chimney A to chimney B.

The hot air around the candle rises up and the cold air from A towards B as a result of the differences in temperatures and decreases in density on the expansion of the air particles.

This is the principle behind the formation of land and sea breezes.

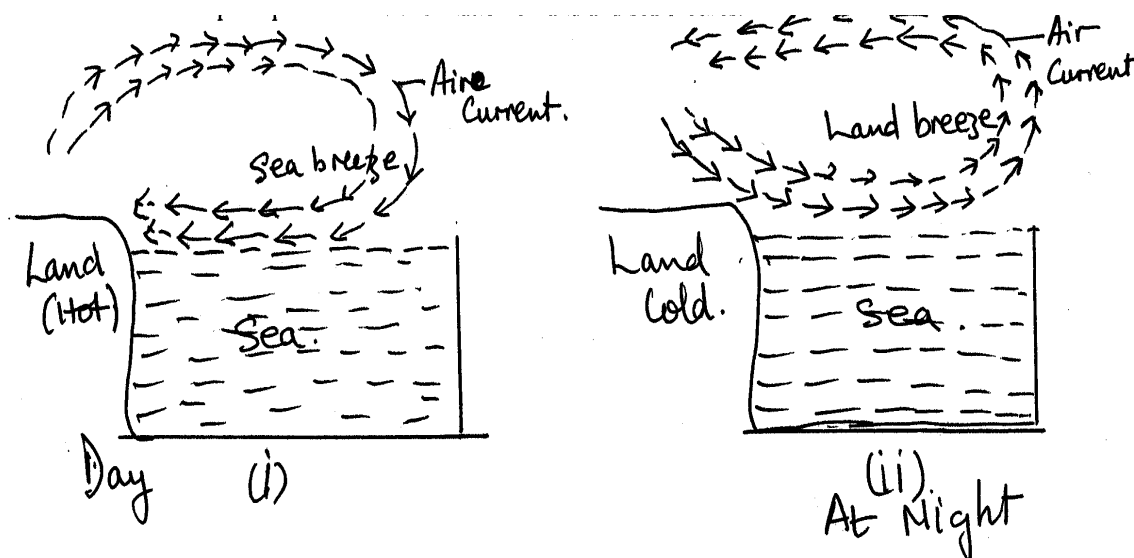


Fig. 8.4

Along the coastal regions we usually observe breeze flowing from the sea at day time which is always reversed in the night to constitute the land breeze.

During the day, the sun heats up both the land and the water. But as a result of the difference in the specific capacities of the land and water, the land is hotter than the water. Thus warm air rises up and its place taken up by the colder sea breeze (Fig. 8.4(i)).

During the night the land cools faster than the water. Thus the warm air above the water rises up and is replaced by the cold air from the land, thereby creating the land breeze (Fig 8.4 (ii)).

Example 8.1

Which of the following position in a room will be reasonable for anyone to place an air conditioner

- at a height near the ceiling of the room?
- at a height closes to the floor of the room?

Explain your choice.

3.3 Newton's Law of Cooling

You would have observed that when a hot body is left in the air it cools down. This can occur under natural convection or forced convection. It cools naturally when the air is still. But when there is a steady draught, it can be cooled under what we call

forced draught – as in ventilated cooling in a draught. Newton propounded the law of cooling which is satisfactory for all temperature excesses.

Newton’s law of cooling states that the rate of loss of heat by a hot body is proportional to the temperature difference between the hot body and its surroundings.

Suppose a body is at a temperature of $\theta^{\circ}\text{C}$ and is allowed to cool in an environment of temperature $\theta_0^{\circ}\text{C}$, Newton’s law stipulates that:

$$\frac{Q}{t} = k (\theta - \theta_0) \dots\dots\dots (8.1)$$

or $-\frac{Q}{t} = k (\theta - \theta_0) \dots\dots\dots (8.2)$

k is the constant of proportionality whose value depends on two factors (the negative sign shows that heat is lost to the surrounding):

- The nature of the exposed surface of the material – surface emissivity e
- It’s surface area A

$$\therefore -\frac{Q}{t} = eA (\theta - \theta_0) \dots\dots\dots (8.3)$$

Many scientists have actually worked on this Newton’s law of cooling. Preston, Dulong and Petit and Lorentz are examples of such people. The summary of their findings have shown that:

- For forced convection in a strong draught Newton’s law of cooling prevails, where the rate of loss of heat is proportional to temperature excess

$$\therefore -\frac{Q}{t} = \infty (\theta - \theta_0) \dots\dots\dots (8.4)$$

- For natural convection in still air, the five-fourth power law predominates. That is the rate of loss of heat is proportional to the (temperature excess)^{5/4}

$$\therefore -\frac{Q}{t} = \infty (\theta - \theta_0)^{5/4} \dots\dots\dots (8.5)$$

It is customary to use Newton’s law of cooling for heat loss in Calorimetry experiments.

4.0 CONCLUSION

In this unit, we have learnt that conduction does not take place in fluids (liquids and gases). In fluids the mode of transfer of heat that takes place is convection. This is the mode by which the molecules of the medium carry the heat energy from hotter region to the region to the colder region of the fluids.

We used the principle of expansion, which involves decrease in density of the medium, and Archimedes' Principle to explain convection in fluids. Newton's law of cooling was used to quantify the rate of loss of heat under natural or forced condition, which is proportional to the excess temperature of its temperature and its surrounding temperature. In the next unit we shall consider radiation as the third mode of transfer of heat in matter.

5.0 SUMMARY

In this unit you have learnt:

- Conduction does not take place in fluids;
- Heat is transferred in fluids (liquids & gases) by convection;
- There are natural and forced convection in fluids;
- Decrease in the molecules of fluids in the hotter region constitutes the convectional current in the fluids due to the expansion of the molecules;
- Convection involves the material medium in the transfer of heat in fluids;
- Newton's law of cooling may be used to explain loss of heat by convection under natural and forced condition; and
- Under the natural convection the five-fourth law of Newton's law predominates whereas in the forced convection rate of loss of heat is proportional to only the excess temperature.

ANSWER TO SELF ASSESSMENT EXERCISE 1

Refer to Text in Section 3.1.

ANSWER TO SELF ASSESSMENT EXERCISE 2

Refer to section 3.2.2 of unit 8.

6.0 TUTOR-MARKED ASSIGNMENT

1. What is the difference between natural convection and forced convection?
2. With the aid of diagrams how would you show convection of heat in:
 - (i) A liquid?
 - (ii) Air?

3. In most supermarket stores you may discover that the deep freezer, in which the frozen commodities such as chicken, fish, meat, shrimps, etc are displayed, could be left open without closing them. Explain why this action is advantageous to the storekeeper.
4. The figures below represent the temperature of a cooling calorimeter at different times.

Time in minutes	0	1	2	3	4	5	6
Temperature in °C	45.0	33.0	26.1	21.7	19.1	17.4	16.5

Use a graph sheet to plot the graph of time against the temperature where time is the vertical axis and temperature the horizontal axis. Determine the rate of fall of temperature at 2 min.

7.0 REFERENCES/FURTHER READING

- Awe, O. and Okunola, O.O. (1986). *Comprehensive Certificate Physics*, Ibadan: University Press.
- Ference, M. (Jnr.), Lemon, H.B. and Stephenson, RJ (1970). *Analytical Experimental Physics*, Chicago: The University of Chicago Press.
- Feynman, R.P., Leighton, R.B. and Sands, M (1971). *The Feynman Lectures on Physics*, California: Addison-Wesley Publishing Company Limited.
- Flowers, B.H. and Mendoza, E (1970). *Properties of Matter*, London: John Wiley and Sons Limited.
- Noaks, M.A. (1963). *New Intermediate Physics*, Canada: Macmillan and company Limited.
- Soars, F.W., Zemansky, M.W. and Young, H.D. (1980). *College Physics*. London: Addison-Wesley Publishing Company.
- Tyler, F. (1966). *Heat and Thermodynamics*. London: Edwards Arnold Publisher Limited.
- Wilkinson, J. (1983). *Essentials of Physics*, Australia: Macmillan Education Publishers.
- Zemansky, M.W. (1968). *Heat and Thermodynamics*. New York: McGraw-Hill Book Company.

UNIT 4 RADIATION

CONTENTS

- 1.0 Introduction
- 2.0 Objectives
- 3.0 Main Content
 - 3.1 Nature of Radiation
 - 3.1.1 Properties of Radiation
 - 3.1.2 Detecting Heat Radiation
 - 3.2 Black Body Radiation
 - 3.3 Prevost's Theory of Heat Exchange
 - 3.4 Stefan-Boltzmann Law of Radiation
 - 3.5 Practical Application of Transfer of Heat
- 4.0 Conclusion
- 5.0 Summary
- 6.0 Tutor-Marked Assignment
- 7.0 References/Further Reading

1.0 INTRODUCTION

So far in this second module, we have learnt about the first two modes of transfer of heat in matter. We observed that conduction of heat is effectively done through solids. However, some of these solid materials could be described as good conductors of heat i.e. metals while some are classified as bad conductors of heat. We used the property, thermal conductivity of each material to do this. We also observed that conduction of heat in fluids (liquids and gases) does not occur, instead, convection of heat predominates among fluids. Consequently, these two modes of transfer of heat require material medium before they take place. The third mode of transfer of heat is Radiation which we will now consider in this unit.

In this unit we would examine the nature of radiation of heat, its properties, how it can be detected and examine the laws governing the radiation of heat.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- explain the nature of radiation of heat
- state the properties of heat radiation
- detect heat radiation
- explain the meaning of black body radiation
- state Prevost theory of heat exchange
- state Stefan-Boltzmann law of radiation
- solve problems on radiation of heat.

3.0 MAIN CONTENT

3.1 Nature of Radiation

Have you ever sat near an oven or campfire before? How would you explain the heat transferred to you? Is it by conduction or convection? Remember what is between you and the source of heat is air. So, the idea of using conduction is ruled out. Again you recall that it is by the rising of hot air around the oven that heat is being transferred. But you are not above the source of heat but you are by the side. Hence, we cannot use the concept of convection to explain how the heat travels to you.

Now let us consider another example:

Have you ever considered how the heat from the sun comes to the earth?

The planet earth is many kilometers far away from the sun. The heat energy has to travel through empty space to reach the earth's atmosphere. Hence transfer of heat from the sun to the earth's atmosphere is mainly by what we describe as radiation.

Then now you may ask: what is Radiation?

Radiation is a way of heat transfer which does not require a material medium. This is in contrast to conduction or convection which needs a material medium to convey the heat energy.

Radiant energy consists of electromagnetic waves which travel with the speed of light. Radiation from the sun consists of the light and the ultra violet and infrared heat waves. All these travel with the speed of light. 3.0×10^8 m/s.

3.1.1 Properties of Radiation

Similar to light radiation, the study of which comes under waves and wave phenomena, heat radiation has the following properties:

- It can be reflected
- It can be refracted
- It can be diffracted
- It can be polarized
- It can produce interference
- It can be absorbed

Like light energy, it is in form of electromagnetic waves. However, its wavelength is longer than those of red light.

Heat radiation, which is invisible, is therefore called infrared radiation. The wavelength of light waves range from 4×10^{-7} m (400nm) in violet to 7.5×10^{-7} m (750nm) in red. Whereas infrared radiation ranges from 750nm to about 100.00nm.

Although, most objects emit heat radiation in the invisible part of their spectrum or range of wavelengths, some very hot objects such as the sun emit heat radiation in the visible part of their spectrum.

3.1.2 Detecting Heat Radiation

Experiments have shown that dull or black surfaces are the best radiators and absorbers of heat radiation respectively. However, bright, shiny, polished or silvery surfaces are the worst radiators and absorbers of heat radiation. ***But the question arises is: How do we detect heat radiation?***

Naturally our skins are capable of detecting heat radiation but a more sensitive and reliable instrument that is more commonly used to detect heat radiation is the THERMOPILE.

A thermopile is a series of arrangements of thermocouples made up of two dissimilar metals such as Bismuth (Bi), Antimony (Ag). Such arrangement can be used to detect and to give a rough measurement of the intensity of heat radiation.

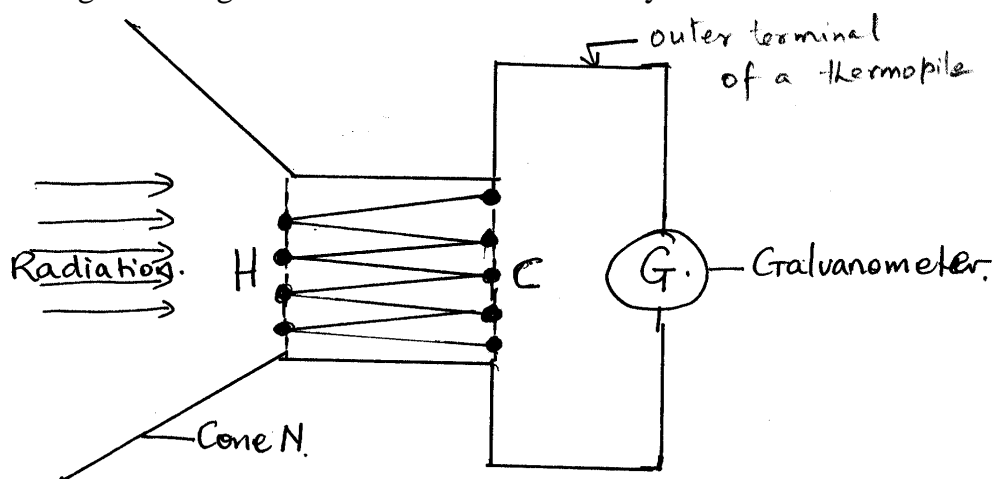


Fig. 9.1: A Thermopile

Refer to fig. 9.1. An arrangement H, made up of Bismuth-Antimony junctions are blackened so that any heat radiation falling on them warms up the junctions. A cone N is fitted on this end of the thermopile to prevent any stray radiation affecting these junctions. The other set of bismuth-antimony junctions C are silvered and remain cold or at a lower reference temperature C is shielded from the direct radiation.

The thermo-electric emf developed produces a deflection on a sensitive galvanometer G, connected to the outer terminals of the thermopile. The deflection is a measure of the intensity of the heat radiation. When calibrated, the actual intensity of heat radiation can be measured.

3.2 Black Body Radiation

You will recall that a black body is the best radiator or absorber of heat radiation that falls upon it. A perfectly black body is therefore defined as one which emits every wavelength with the maximum energy for each wavelength for the particular temperature of the body. This black body is also known as an ideal radiator. A good example of black body is a ceramic-lined closed container with a hole in it. It may also be empty tin with a hole punched on the lid.

Any radiation which enters the hole is reflected several times round the inside surface and tends to be trapped inside it (fig. 9.2).

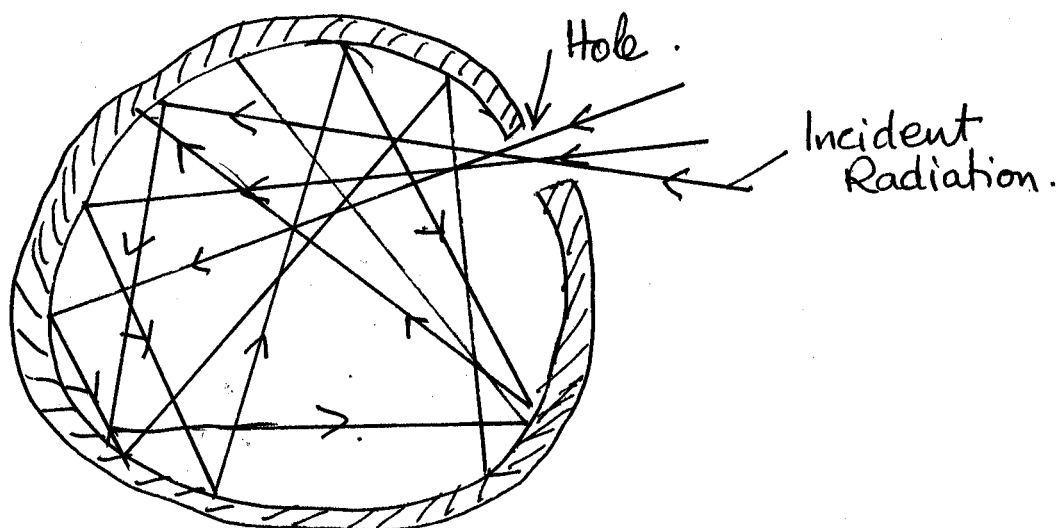


Fig. 9.2: Black Body Absorber at Temperature T

The absorber inside a black body may be silvery so that the reflection is high. With several reflections and absorption, the hole looks black. Since a good absorber of radiation is a good radiator, we can see that a hole in a closed container is also a black radiator (fig. 9.3).

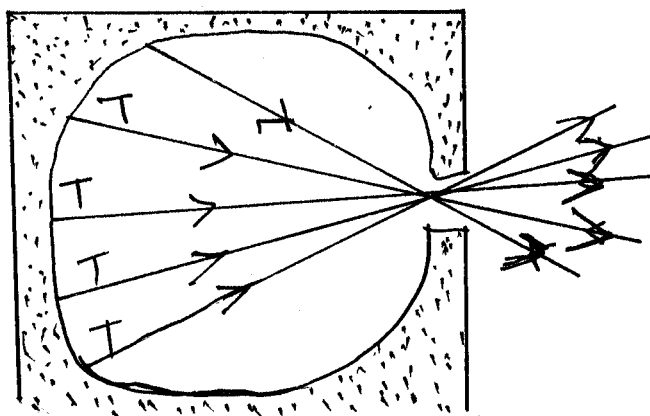


Fig. 9.3: Black Body Radiator

The inside is ceramic-lined and blackened to reduce quickly any reflected radiation and it is heated to a high temperature in a furnace or heat chamber. It should be noted that the radiation from a perfectly black body depends only on its temperature. It does not depend on the nature of the surface inside. Black body radiation is thus also called temperature radiation.

Non-black body radiators such as the hot filament of an electric lamp, may have some wavelengths of lower intensity compared with those emitted by a perfectly black body at the same temperature.

3.3 Provost's Theory of Heat Exchange

In the last section, you have studied about black body. Now, you will learn about Provost's theory. *In simple words, it states that when an object is at constant temperature or is in thermal equilibrium, it is losing and gaining heat at equal rates.*

Let us consider an enclosure P at constant temperature T. Inside this enclosure are two objects A and B. A is cold while object B is hot.

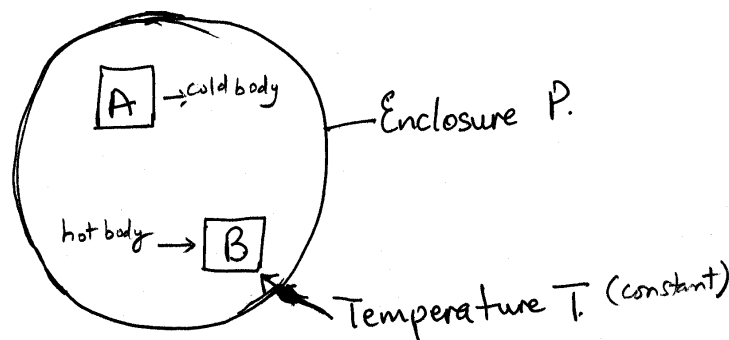


Fig. 9.4

Temperature T is however greater than the temperature of cold body T_A and less than the temperature of the hot body T^B .

$$T_B > T > T_A$$

At first, body A receives more radiation falling on it from B than it emits. Consequently, the temperature of A rises i.e. it warms up. Also, body B emits more radiation than it receives from A, hence the temperature of B decreases i.e. it cools down. Eventually, the equilibrium temperature T is attained. At this temperature both bodies are emitting and absorbing radiation at the same rate. The above process illustrates exchange of heat through radiation of bodies at different temperatures to reach a thermal equilibrium as opposed to what happens if they were to be in contact. However, if body A is a black body, then at temperature T, it radiates an appreciable amount of that heat at the same rate. If B is however a silvery surface, then, at temperature T, it radiates and absorbs less heat than A.

3.4 Stefan-Boltzmann Law of Radiation

Stefan found by experiment, while Boltzmann showed theoretically, that the total rate of radiation emitted per unit area by a perfectly black body was proportional to the fourth power of its absolute temperature (T) in Kelvin.

$$\frac{E}{tA} \propto T^4 \dots\dots\dots (9.1)$$

$$\therefore \frac{E}{tA} = \sigma T^4 \dots\dots\dots (9.2)$$

- Where, E = total heat energy emitted
- t = time of emission
- A = total surface area
- T = absolute temperature
- σ = constant known as Stefan constant

The value of σ = 5.7 x 10⁻⁸ Wm⁻²k⁻⁴.

For any other body or surface different from a black body

$$\frac{E}{tA} = e\sigma AT^4 \dots\dots\dots (9.3)$$

or $\frac{E}{tA} = e\sigma AT^4$

where, e = emissivity of the surface (e is a number characterizing the emitting properties of a particular surface).

But, the rate of emission is power, which can be represented as:

$$\frac{E}{t} = \text{Power } P \dots\dots\dots (9.4)$$

$$\therefore P = eA \sigma T^4 \dots\dots\dots (9.5)$$

If a black body X is placed inside an enclosure at a constant temperature T_o, then X will eventually reach the temperature T_o. From Prevost’s theory of heat exchanges, X receives from the enclosure as much radiation as it emits, which is σAT_o⁴.

If X is initially at temperature T inside an enclosure, the net heat per second radiated by X is

$$P = e\sigma A(T^4 - T_o^4) \dots\dots\dots (9.6)$$

SELF ASSESSMENT EXERCISE

A thin square steel plate 10 cm on a side is heated in a blacksmith forge to a temperature of 800°C . If the emissivity is unity, calculate the total rate of radiation of energy?

3.5 Practical Application of Transfer of Heat

When we talk about the modes of transferring heat, we also need to consider their practical applications. Let us now discuss some of these important practical applications.

Some of the practical applications include: the screening action of clouds, the green house and the “thermos” flask. Here, you will learn about the “thermos” flask fully to show how the knowledge of conduction, convection and radiation has been used to keep materials at constant temperatures without loss of heat.

The Thermos Flask

The thermos flask was originally designed for the purpose of storing liquefied gases. But now it is used for maintaining the temperature of hot and cold liquids for long periods. Some have been designed nowadays to keep hot or cold solid food as pack for lunch or dinner.

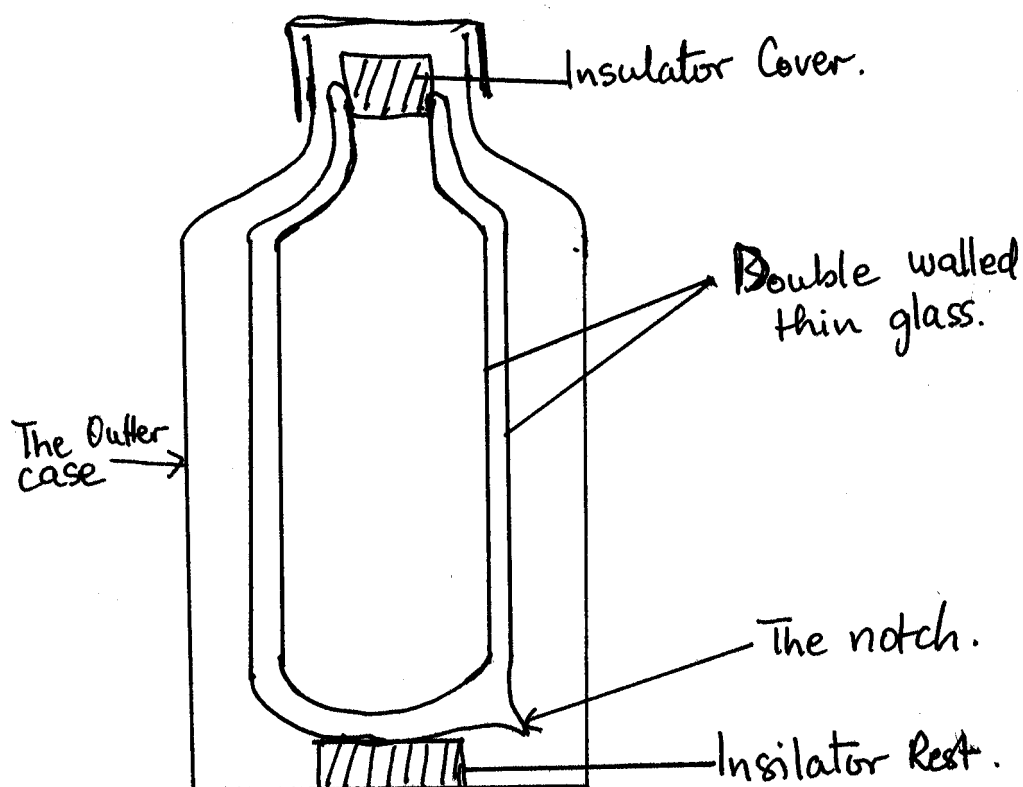


Fig. 3.5: The Thermos Flask

Basically, the flask is made up of double-walled thin glass. The space in between the flask is evacuated to create a vacuum between the walls of the glass. If you examine a broken flask you will observe a small protruding notch at the bottom. This is where the glass was sealed off after creating the vacuum with the glass walls.

The open end of the flask is covered with a cork stopper or a plastic cover, which are non-conductors of heat. The double walled vacuum flask is sealed again in an insulator in the entire case containing the flask.

The evacuated space of the flask is to prevent loss of heat by conduction and convection, which require material medium.

In order to minimize loss or gain of heat by radiation, the surfaces facing the evacuated space are covered with silver. Thus, radiant heat from the hot liquid is reflected back at the outer wall. If cold liquid is placed inside the flask, heat radiation from the surrounding is reflected back from the silvered face of the inner wall. Consequently, any radiant heat entering the vacuum space is accordingly arrested.

4.0 CONCLUSION

In this unit, you have learnt about the third mode of transfer of heat by radiation. This mode of transfer of heat does not require any material medium. Radiant energy is electromagnetic in nature. It is detected and measured by the thermopile. We also learnt that black bodies are good absorbers and emitters of radiant heat energy. Whereas silvery and shiny surfaces are good reflectors of radiant energy. Prevost's theory of heat exchanges was used to explain how thermal equilibrium is reached through radiation between two bodies at different temperatures. Finally, Stefan Boltzmann law of radiation was used to quantify the rate of emission of radiant energy per area as being proportional to the fourth power of its absolute temperature. We shall now turn our attention to the properties of materials in the next module.

5.0 SUMMARY

In this unit we have learnt:

- the concept of radiation of heat as a mode of heat transfer;
- that the radiant heat energy is electromagnetic in nature and this mode of transfer does not require a material medium;
- that radiant heat energy could be detected and measured by the thermopile;
- the concept of black body in terms of its ability to absorb or emit heat energy;
- that a black body is a good absorber and a good emitter of heat;
- that more exactly, a black body is one whose radiation depends on its temperature;
- how Prevost theory of heat exchanges produces thermal equilibrium between two objects at different temperature;
- how Stefan-Boltzmann law of radiation is used in solving problems on radiation of heat energy; and

- that the study of black body radiation is a prelude to the study of quantum theory which is part of your later physics course.

ANSWER TO SELF ASSESSMENT EXERCISE

$$\text{Total surface area} = 2 \times 10^{-4} \text{m}^2$$

$$\text{Temperature} = 800^\circ\text{C} = 1073\text{K}$$

From, Eq. 9.6,

$$P = \sigma e A T_o^4$$

Inserting these values in Eq. 9.6 above,

$$\sigma = 5.7 \times 10^{-8} \text{Wm}^{-2}\text{k}^{-4}$$

$$e = 1$$

$$A = 2 \times 10^{-4} \text{m}^2$$

$$T = 1073\text{k}$$

We get,

$$\begin{aligned} \therefore P &= 5.7 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{k}^4} \times 1 \times 2 \times 10^{-4} \text{m}^2 \times (1073)^4 \text{k}^4 \\ &= 5.7 \times 10^{-8} \times 1 \times 2 \times 10^{-4} \times (1073)^4 \text{W} \\ &= 5.7 \times 10^{-8} \times 2 \times 10^{-4} \times (1.073 \times 10^3)^4 \text{W} \\ P &= 15.12 \text{W} \end{aligned}$$

The concept of black body radiation will be revisited again at a higher level of your study of physics. Then you will learn the importance and the laws of black body radiation, which led to the development of the quantum theory of heat radiation.

6.0 TUTOR-MARKED ASSIGNMENT

1. Describe the nature of thermal radiation. How is thermal radiation detected and measured?
2. State the
 - (i) Prevost's theory of heat exchanges in radiation of heat.
 - (ii) Stefan-Boltzmann law of radiation.
3. A radiant wall heater black body radiator is a silica cylinder 1.0m long and radius 0.5mm. It is rated at 1KW. If the room temperature is 300K, estimate the working temperature of the heater, stating any assumptions. (Stefan constant = $5.7 \times 10^{-8} \text{Wm}^{-2} \text{K}^{-4}$).

7.0 REFERENCES/FURTHER READING

- Awe, O. and Okunola, O.O. (1986). *Comprehensive Certificate Physics*, Ibadan: University Press.
- Ference, M. (Jnr.), Lemon, H.B. and Stephenson, RJ (1970). *Analytical Experimental Physics*, Chicago: The University of Chicago Press, Chicago and London.
- Feynman, R.P., Leighton, R.B. and Sands, M (1971). *The Feynman Lectures on Physics*, California: Addison-Wesley Publishing Company Limited.
- Flowers, B.H. and Mendoza, E (1970). *Properties of Matter*, London: John Wiley and Sons Limited.
- Noaks, M.A. (1963). *New Intermediate Physics*, Canada: Macmillan and company Limited.
- Soars, F.W., Zemansky, M.W. and Young, H.D. (1980). *College Physics*. London: Addison-Wesley Publishing Company.
- Tyler, F. (1966). *Heat and Thermodynamics*. London: Edwards Arnold Publisher Limited.
- Wilkinson, J. (1983). *Essentials of Physics*, Australia: Macmillan Education Publishers.
- Zemansky, M.W. (1968). *Heat and Thermodynamics*. New York: McGraw-Hill Book Company.

UNIT 5 MOLECULAR PROPERTIES OF MATERIALS

CONTENTS

- 1.0 Introduction
- 2.0 Objectives
- 3.0 Main Content
 - 3.1 Concept of Molecules
 - 3.1.1 The Concept of the Atom
 - 3.1.2 Measuring the Size of a Molecule
 - 3.2 Molecular Motion
 - 3.3 Molecular Mass
 - 3.4 Molecular Volume
 - 3.5 Molecular Density
- 4.0 Conclusion
- 5.0 Summary
- 6.0 Tutor-Marked Assignment
- 7.0 References/Further Reading

1.0 INTRODUCTION

Matter is a substance that has mass and occupies space. Thus solids, liquids and gases are forms of matter. Modern ideas will include plasma as the fourth form of matter. Plasma occurs when atoms are ionized at high temperatures. At very high temperatures, a substance consisting of positive ions and electrons is known as plasma. Under this section, we shall therefore concentrate on the properties of solids, liquids and gases.

Water exists in form of solid (ice block), liquid (water) and gas (steam). *The question you may ask is: What makes water to exhibit these three states of matter? Can we explain these three different states?*

By the time one tries to answer these questions for water and for other substances on earth, one is mainly looking at the properties of matter from the molecular point of view.

The theory about the existence of atoms and molecules form the backbone for the explanation of how matter exists in three states in terms of the molecular forces that exist between the molecules. That is, the type of molecular forces that exist among molecules in matter help us to explain why water can exist in solid, liquid and gas.

In this unit and in other units to follow, we shall study the properties of mater.

From your elementary science, you will recall that two kinds of property of matter are considered:

- (i) the physical properties and
- (ii) the chemical properties

We shall be concerned here with the physical properties of matter. Your various courses in chemistry, now and in the nearest future, will deal at length with the chemical properties of matter. The knowledge of chemical properties will include the knowledge of matter as an acid or a base. One is required to know how an element or a compound reacts with the litmus papers (red and blue), its reactions with water, air (oxygen), acids, bases etc.

With regards to physical properties, we shall be interested in the structure, size, mass, volume, density, elasticity, conduction of electricity, heat etc. However, in this unit we shall be concerned with the molecular properties of matter.

2.0 OBJECTIVES

At the end of this unit, you should be able:

- explain the existence of molecules in matter
- recognize the molecular motion in matter
- measure the size of a molecule of a chosen liquid
- deduce the density of a molecule from its mass and volume.

3.0 MAIN CONTENT

3.1 Concept of Molecules

The idea of the atomic nature of matter dates as far back as the time the Greek Philosophers proposed that the smallest indivisible unit of matter is the atom. They further stated that two or more atoms combine together to form a molecule. This is what constitutes the molecular nature of matter.

In the modern concept of the atom, we now know that the atom is divisible. Furthermore, it is not the smallest unit of matter as experiments have shown that the atom is made up of a nucleus and electrons, and the nucleus consists of positively charged protons and neutrons. Neutrons have no charges. Thus the protons, neutrons and electron have been found to be fundamental particles of matter. The study of these particles will be done later. *Now, “Can you really imagine how small the atom of matter is?”*

3.1.1 The Concept of the Atom

If you take a piece of square yam, you may decide to start cutting it into equal pieces with a knife until such a time that you can no longer cut a piece into two. You may now use a fine blade and with the aid of a magnifying glass, you can continue to do the cutting. You may continue with this exercise under the microscope and ultimately under the electron microscope and you will find it extremely difficult to divide a piece of the yam. The limit of this divisibility is what the Greeks called the atom. Since,

we now know that the atom is divisible, it is defined as the smallest unit of matter that can take part in a chemical reaction. As we said earlier, a combination of atoms constitutes a molecule.

In this section, we want to quantitatively ascribe a figure to the size of a molecule. In other words, we want to answer the question: ***How big is the molecule of a particular substance?***

Is it possible to measure the average diameter of a molecule of a liquid such as paraffin or any other type of oil? To do this, we shall present you an analogue (example) on how to determine the diameter of a round bead without actually taking the bead and measuring it directly. We shall then use the analogue to demonstrate how to determine the diameter of a molecule, which you can not see with the naked eye. You can now imagine how small an atom is from this exercise.

An atom may then be considered as the tiniest form of matter that can exist by itself. However, some of these atoms do not exist alone, two or more of them combine to form a molecule. Examples of such molecules are: oxygen (O_2), Hydrogen (H_2), Water (H_2O), Sulphur (S_8) and Phosphorous (existing as P_4).

3.1.2 Measuring the Size of a Molecule

(a) An Analogue

In this measurement, we shall measure average diameter of a bead without measuring a bead physically. Now, let us discuss the procedure of environment.

1. Collection of beads which are assumed to be spherical.
2. The beads are then spread in a Petridish such that they form a layer of beads as shown in figure (i) from the side view.

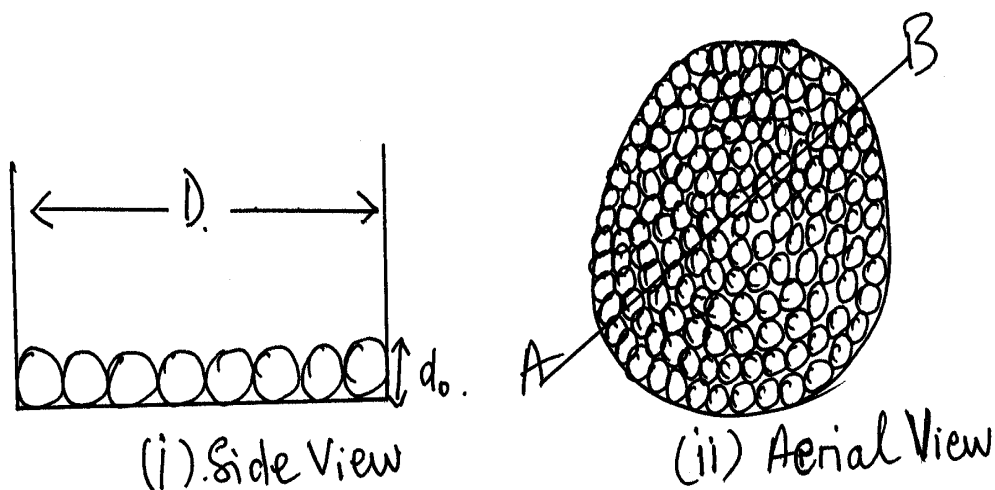


Fig. 10.1

Fig. 10.1 (i) shows the side view of the beads while fig. 10.1 (ii) shows the aerial view of the beads. It should be ensured that no bead is lying on top of the other.

3. In this position it is possible to estimate the volume occupied by the beads thus:

Volume (V) occupied = Circular Area x Height of Beads

$$V = \frac{\pi D^2}{4} \times d_o \dots\dots\dots (10.1)$$

where, D = diameter of the dish containing the beads

d_o = average diameter of the beads since they are of one layer.

4. Now, the beads are poured into a measuring cylinder and the volume is read as $V\text{cm}^3$. The beads are shaken very well in the cylinder to make sure that they are well packed together in order to attain the minimum value for the volume.

5. The volume V measured under step (3) above is equal to the volume V in step (4) using the conservation principle of matter and its volume.

Hence,

$$V (\text{cm}^3) = \frac{\pi D^2}{4} \times d_o$$

$$\therefore d_o = \frac{4 V\text{cm}^3}{\pi D^2 \text{cm}^2}$$

$$d_o = \frac{4 V}{\pi D^2} \text{ cm} \dots\dots\dots (10.2)$$

Thus the average diameter of the bead, d_o can be determined by using Eq. (10.2). One may verify the validity of this determination by measuring some of the beads with a micrometer screw gauge and then finding the average value. This is the approach that will be used to determine the average diameter of the molecules of an oil, say paraffin.

(b) Measuring the Molecular Size of Paraffin Oil

Use a wire loop to pick up a drop of paraffin oil as shown in figure 10.2.



Fig. 10.2

Place the oil drop near a meter rule and with the aid of a magnifying glass, read the diameter of the oil drop and record it as d .

Using mathematical expression, the volume of this oil drop is

$$V_1 = \frac{4}{3} \pi \left(\frac{d}{2}\right)^3 \dots\dots\dots (10.3)$$

Where, d is the diameter of the oil drop and $\frac{d}{2}$ is the radius of the oil drop.

Therefore, the Eq. (10.3) becomes

$$\begin{aligned} \therefore V_1 &= \frac{4}{3} \pi \frac{d^3}{8} \\ V_1 &= \frac{\pi d^3}{8} \dots\dots\dots (10.4) \end{aligned}$$

Now take a large bowl of water and sprinkle some talcum powder over the surface. Allow the oil drop to spread on the surface of the water. As the oil spreads, the powder will be observed to be receding to the side of the bowl. This process of spreading should be given enough time.

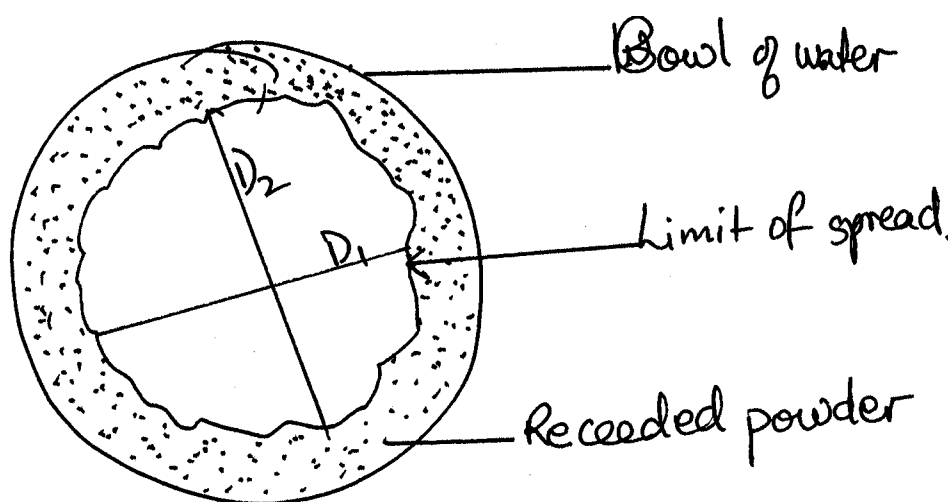


Fig. 10.3: Aerial View of Bowl

NOTE: Let the spread be like a circle of diameter D such that

$$D = \frac{D_1 + D_2}{2} \dots\dots\dots (10.5)$$

When the liquid is well spread as shown in figure 10.3, record the average diameter D of the spread using Eq. (10.5). This corresponds to the situation where molecules are of one layer.

If the average diameter of the molecules is d_o , then the volume of the molecules which occupy one layer is

$$V_2 = \pi \left(\frac{D}{2} \right)^2 \times d_o$$

$$V_1 = \pi \frac{D^2}{4} \times d_o \dots\dots\dots (10.6)$$

But this V_2 is assumed to be equal to V_1 which is $\frac{\pi d^2}{6}$

i.e. $V_1 = V_2 \dots\dots\dots (10.7)$

Using Eq. (10.7)

$$\therefore \frac{\pi d^3}{6} = \pi \frac{D^2}{4} d_o$$

We get the value of d_o as

$$d_o = \frac{\pi d^3}{6} = \pi \frac{4}{\pi D^2}$$

$$d_o = \frac{2}{3} \frac{d^3}{D^2} \dots\dots\dots (10.8)$$

Now, Can you cross check your answer as you did with the bead?

This is difficult question. There is no way you can cross check; however, the diameter of such measurement will be of the magnitude of 10^{-10} m. If your measurement is in the neighbourhood, then it is correct and valid enough.

3.2 Molecular Motion

The molecules of matter are always in random motion, whether in the form of solid, liquid or gas. It is easy to demonstrate this concept by considering the motion of molecules in liquids and gases.

Consider the spread of the odour from a very palatable dish or you may consider the production of foul air form the corner of a room. The odour from these sources soon

spread round to you. One may say that it is the wind that is responsible for the spreading. That may be true, but let us consider this experiment, which will show you what is described as molecular motion of matter.

The apparatus used in demonstrating molecular motion of matter is made up of a long glass tube with the two ends closed with the rubber bungs as shown in figure 10.4.

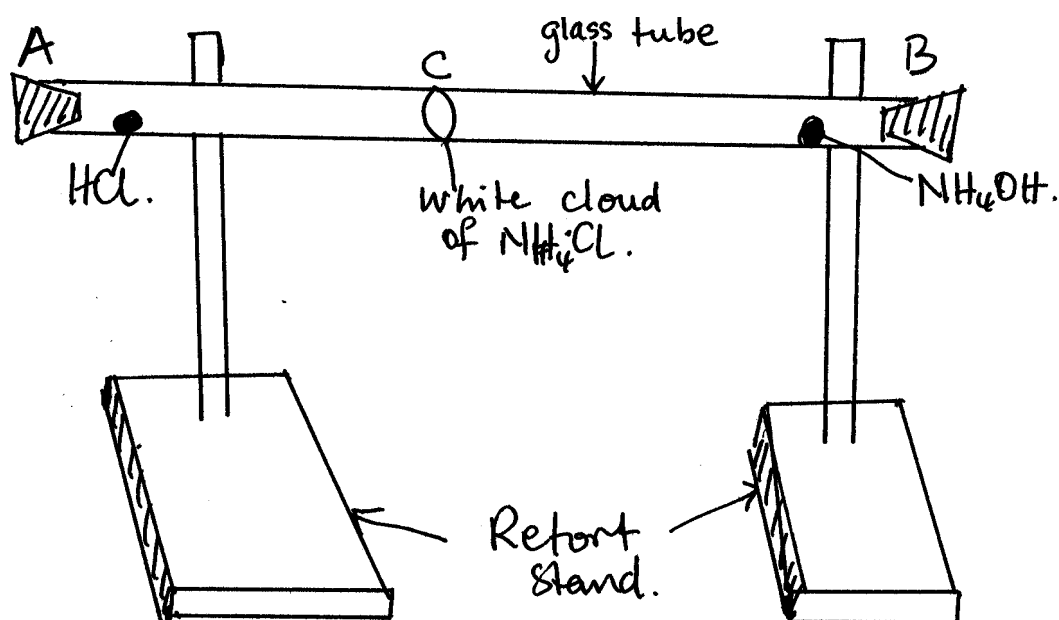
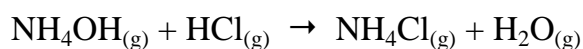


Fig. 10.4

A piece of absorbent cotton wool is soaked in concentrated hydrochloric acid (HCl) and then placed at one end A of the tube. Another piece of absorbent cotton wool is soaked in concentrated ammonium hydroxide (NH₄OH) and then placed at the other end B of the glass tube. The two rubber bungs are used to close the tube. After some time, it will be observed that a white band of ammonium chloride will be formed in the tube. This has shown that the molecules of the two compounds have moved towards C to form ammonium chloride there.



Besides showing the molecular motion of these gaseous substances, it is possible to show the relative speed at which the gases move. It will be noticed that the lighter gas (NH₃) ammonia, has moved a longer distance than the heavier one, hydrogen chloride (HCl).

Observe the relative position of the cloud to the two ends of the tube. This molecular motion may be described as diffusion. Diffusion takes place very much in nature. **It is defined as the process in which molecules move from area of high concentration to another area of low concentration until an equilibrium**

concentration is established within the system under consideration. The state of equilibrium in this case does not necessarily mean that the molecules have become stagnant. It is a dynamic equilibrium. The fact still remains that the molecules are forever in motion. The diffusion of molecules of a solid in liquid or liquid molecules in another liquid may also be used to demonstrate the motion of molecules of matter. First, let us consider solid molecules in a liquid. Place a copper sulphate crystal in a glass jar and then pour water into it very gently as shown in fig. 10.5

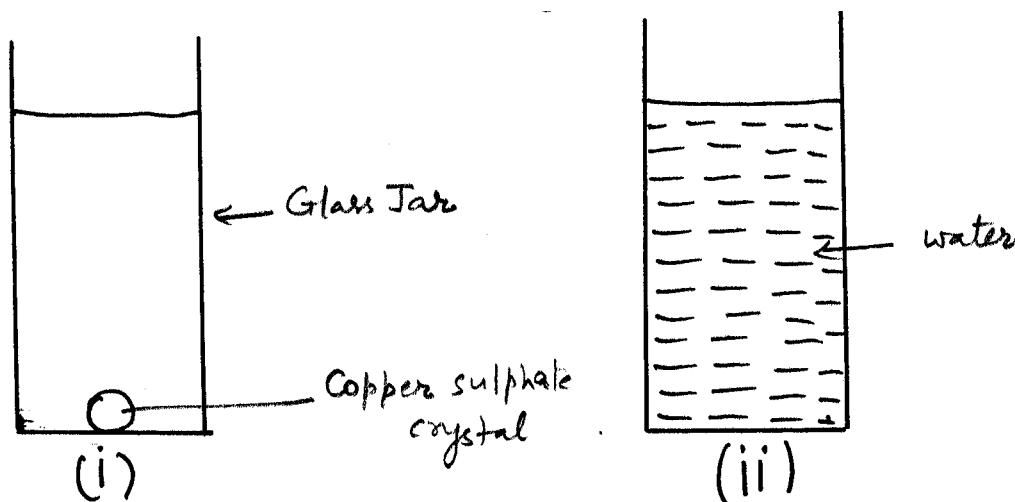


Fig. 10.5

Allow the jar and content to stay undisturbed for some days. It will be observed that a time will come when all the crystal would have diffused throughout the solution. This shows the motion of the solid molecules through the liquid water. It is also possible to pour water on a high concentrated copper sulphate solution or any other coloured solution as shown in figure 10.6.

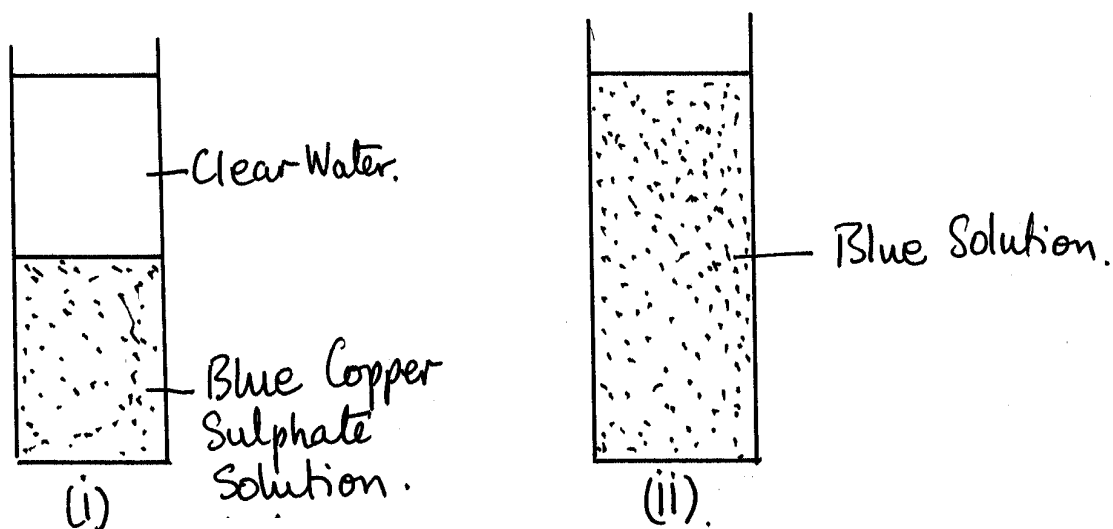


Fig. 10.6

- (i) Initially, there is a clear demarcation of water on top of the solution.
- (ii) After leaving the water and solution for a long time, it will be observed that the entire content becomes blue as a result of the motion of the molecules – the ever-moving molecules.

It is otherwise described as the Brownian motion. Recall also that molecular motion is described as being random.

3.3 Molecular Mass

You will recall from the definition of matter that it is anything that has mass and occupies space. Since our molecules have size, they also have mass. *The question that may arise is: How do we measure the mass of an atom or molecule?* This is done by the use of the mass spectroscopy. This technique has also enabled us to measure the masses of a proton, neutron and electron. The values are given as:

$$\begin{aligned} \text{Mass of proton} &= 1.673 \times 10^{-27} \text{ kg} \\ \text{Mass of a neutron} &= 1.675 \times 10^{-27} \text{ kg} \\ \text{Mass of an electron} &= 9.11 \times 10^{-31} \text{ kg} \end{aligned}$$

3.4 Molecular Volume

The volume occupied by a molecule is the molecular volume. It is another property of matter. Experimentally, we have also found the volume occupied by the molecules of a substance such as that of a gas.

From Avogadro's hypothesis, we can describe the volume occupied by a mole of a gas – hence we have the molar volume.

The molar volume of gases at standard temperature and pressure (S.T.P.) is 22.4 liters.

A mole of gas contains 6.0×10^{23} molecules.

Hence we can deduce the volume of one molecule to be

$$= \frac{22.4 \text{ Vcm}^3}{6 \times 10^{23}} \text{ litres} = 3.73 \times 10^{-23} \text{ litres}$$

3.5 Molecular Density

The density of a substance is the mass of that substance per unit volume. Thus molecular density defines the density of a molecule i.e. the mass of molecule in kg per 1m^3 volumes.

It tells us how heavy or light the molecule is. Hydrogen molecule has been found to be the lightest gas on earth. Hence its molecular density is the smallest in value.

4.0 CONCLUSION

Matter is made up of atoms and molecules, which may exist in solid, liquid or gas. The atom is made up of negatively charged electrons and the nucleus, which consists of positively charged protons and neutrons that have no charges. Some matter exists as atoms while others are made up of molecules, which are combinations of two or more atoms. It has been shown that it is possible to measure the size of a molecule of a substance which is of the order of magnitude of 10^{-10} m. Molecules of matter are forever in random motion when in liquid and gaseous states. In solid states, molecules are in fixed positions vibrating about a position. Associated with molecules of matter are their properties of mass, volume and density.

5.0 SUMMARY

In this unit you have learnt:

- About the atom as the smallest particle of matter that can take part in any chemical reaction,
- Two or more atoms combine to form a molecule,
- Matter exists in three states – solid, liquid and gas,
- The molecules of matter are forever in random motion,
- It is possible to determine the size of a molecule,
- The magnitude is of order of, 10^{-10} m.
- The molecular density is obtained from the knowledge of the mass and volume of the molecule.

6.0 TUTOR-MARKED ASSIGNMENT

1. How would you determine the diameter of a given sample of oil? Discuss the basic assumptions involved in such a measurement.
2. Describe an experiment to show that matter is in constant motion.
3. Differentiate between atoms and nucleus.

7.0 REFERENCES/FURTHER READING

- Awe, O. and Okunola, O.O. (1986). *Comprehensive Certificate Physics*, Ibadan: University Press.
- Ference, M. (Jnr.), Lemon, H.B. and Stephenson, RJ (1970). *Analytical Experimental Physics*, Chicago: The University of Chicago Press.
- Feynman, R.P., Leighton, R.B. and Sands, M (1971). *The Feynman Lectures on Physics*, California: Addison-Wesley Publishing Company Limited.
- Flowers, B.H. and Mendoza, E (1970). *Properties of Matter*, London: John Wiley and Sons Limited.
- Noaks, M.A. (1963). *New Intermediate Physics*, Canada: Macmillan and company Limited.
- Soars, F.W., Zemansky, M.W. and Young, H.D. (1980). *College Physics*. London: Addison-Wesley Publishing Company.
- Tyler, F. (1966). *Heat and Thermodynamics*. London: Edwards Arnold Publisher Limited.
- Wilkinson, J. (1983). *Essentials of Physics*, Australia: Macmillan Education Publishers.
- Zemansky, M.W. (1968). *Heat and Thermodynamics*. New York: McGraw-Hill Book Company.