Unit 8

Thermal Properties of Matter

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- define temperature (as quantity which determines the direction of flow of thermal energy).
- define heat (as the energy transferred resulting from the temperature difference between two objects).
- list basic thermometric properties for a material to construct a thermometer.
- convert the temperature from one scale to another (Fahrenheit, Celsius and Kelvin scales).
- describe rise in temperature of a body in terms of an increase in its internal energy.
- define the terms heat capacity and specific heat capacity.
- describe heat of fusion and heat of vaporization (as energy transfer without a change of temperature for change of state).
- describe experiments to determine heat of fusion and heat of vaporization of ice and water respectively by sketching temperature-time graph on heating ice.
- explain the process of evaporation and the difference between boiling and evaporation.
- explain that evaporation causes cooling.

Conceptual linkage

This unit is built on

Temperature Scales - Science-IV

Evaporization - Science-V

Thermal Expansion - Science-VIII

This unit leads to:

Thermodynamics - Physics-XI

Major Concepts

Figure 8.1: Heat is needed for cooking.

- list the factors which influence surface evaporation.
- describe qualitatively the thermal expansion of solids (linear and volumetric expansion).
- explain thermal expansion of liquids (real and apparent expansion).
- solve numerical problems based on the mathematical relations learnt in this unit.

INVESTIGATION SKILLS

The students will be able to:

- demonstrate that evaporation causes cooling.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- explain that the bimetallic strip used in thermostat is based on different rate of expansion of different metals on heating.
- describe one everyday effect due to relatively large specific heat of water.
- list and explain some of the everyday applications and consequences of thermal expansion.
- describe the use of cooling caused by evaporation in refrigeration process without using harmful CFC.

We use heat not only for cooking but also for doing other jobs. For example, changing heat to mechanical energy, electrical energy, etc. This can be done only if we have basic understanding about heat. Heat is an important concept in Physics. People have been trying to explain the nature of heat throughout the history of mankind. A quantitative study of thermal phenomena requires a careful definition of such important terms **as heat, temperature** and **internal energy.** In this unit, we shall discuss various concepts related to heat, temperature, measurements of temperature and various thermal phenomena.

8.1 TEMPERATURE AND HEAT

When we touch a body, we feel it hot or cold. The temperature of a body tells us how hot or cold a body is. Thus

Temperature of a body is the degree of hotness or coldness of the body.

A candle flame is hot and is said to be at high temperature. Ice on the other hand is cold and is said to be at low temperature. Our sense of touch is a simple way to know how much hot or cold a body is. However, this temperature sense is some what approximation and unreliable. Moreover, it is not always safe to touch a hot body. What we need is a reliable and practicable method to determine the relative hotness or coldness of bodies.

To understand the concept of temperature, it is useful to understand the terms, **thermal contact** and **thermal equilibrium**. To store ice in summer, people wrap it with cloth or keep it in wooden box or in thermos flask. In this way, they avoid the thermal contact of ice with its hot surroundings otherwise ice will soon melt away. Similarly, when you place a cup of hot tea or water in a room, it cools down gradually. Does it continue cooling? It stops cooling as it reaches the room temperature. Thus, temperature determines the direction of flow of heat. Heat flows from a hot body to a cold body until thermal equilibrium is reached.

What happens when we touch a hot body? Take two bodies having different temperatures. Bring them in contact with each other. The temperature of the hot body falls. It looses energy. This energy enters the cold body at lower temperature. Cold body gains energy and its temperature rises. The transfer of energy continues till both the bodies have the same temperature. The form of energy that is transferred from a hot body to a cold body is called heat. Thus

Heat is the energy that is transferred from one body to the other in thermal contact with each other as a result of the difference of temperature between them.

DO YOU KNOW

The crocus flower is a natural thermometer. It opens when the temperature is precisely 23°C and closes when the temperature drops.

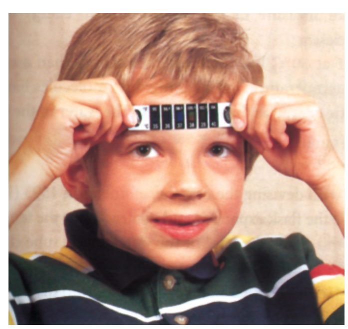


Figure 8.2: A strip thermometer

Heat is therefore, called as the **energy in transit.** Once heat enters a body, it becomes its **internal energy** and no longer exists as heat energy.

What is internal energy of a body?

The sum of kinetic energy and potential energy associated with the atoms, molecules and particles of a body is called its internal energy.

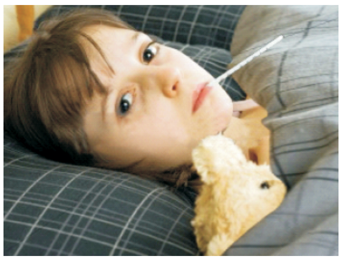


Figure 8.3: A thermometer shows body temperature.

Internal energy of a body depends on many factors such as the mass of the body, kinetic and potential energies of molecules etc. Kinetic energy of an atom or molecule is due to its motion which depends upon the temperature. Potential energy of atoms or molecules is the stored energy due to intermolecular forces.

8.2 THERMOMETER

A device that is used to measure the temperature of a body is called **thermometer.** Some substances have property that changes with temperature. Substances that show a change with temperature can be used as a thermometric material. For example, some substances expand on heating, some change their colours, some change their electric resistance, etc. Nearly all the substances expand on heating. Liquids also expand on heating and are suitable as thermometric materials. Common thermometers are generally made using some suitable liquid as thermometric material. A thermometric liquid should have the following properties:

- It should be visible.
- It should have uniform thermal expansion.
- It should have a low freezing point.
- It should have a high boiling point.
- It should not wet glass.
- It should be a good conductor of heat.
- It should have a small specific heat capacity.

Mini Exercise

1. Which of the following substances have greater average kinetic energy of its molecules at 10°C?
   (a) steel (b) copper
   (c) water (d) mercury
2. Every thermometer makes use of some property of a material that varies with temperature. Name the property used in:
   (a) strip thermometers
   (b) mercury thermometers

LIQUID-IN-GLASS THERMOMETER

A liquid-in-glass thermometer has a bulb with a long capillary tube of uniform and fine bore such as shown in figure 8.4. A suitable liquid is filled in the bulb. When the bulb contacts a hot object, the liquid in it expands and rises in the tube. The glass stem of a thermometer is thick and acts as a cylindrical lens. This makes it easy to see the liquid level in the glass tube.

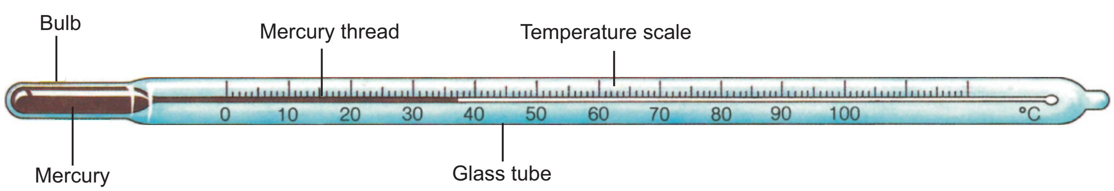


Figure 8 4: A mercury - in - glass thermometer

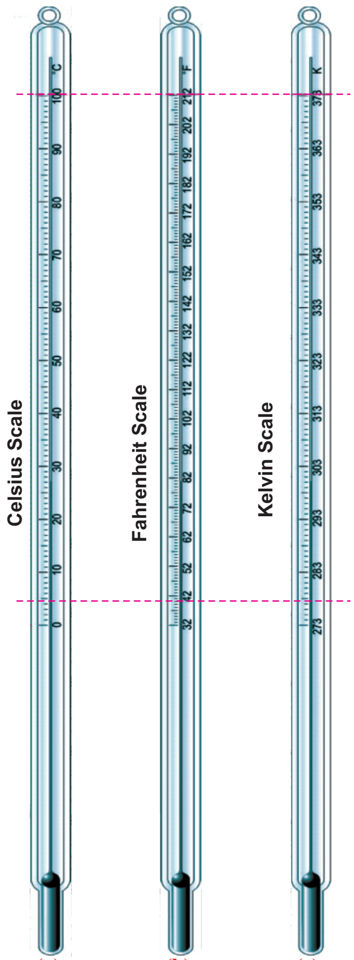
Mercury freezes at-39 °C and boils at 357 °C. It has all the thermometric properties listed above. Thus mercury is one of the most suitable thermometric material. Mercury-in-glass thermometers are widely used in laboratories, clinics and houses to measure temperatures in the range from -10 °C to 150 °C.

LOWER AND UPPER FIXED POINTS

A thermometer has a scale on its stem. This scale has two fixed points. The lower fixed point is marked to show the position of liquid in the thermometer when it is placed in ice. Similarly, upper fixed point is marked to show the position of liquid in the thermometer when it is placed in steam at standard pressure above boiling water.

SCALES OF TEMPERATURE

A scale is marked on the thermometer. The temperature of the body in contact with the thermometer can be read on that scale. Three scales of temperature are in common use. These are:



(a) (b) (c)

Figure 8.5: Various scales of temperature.

Do You Know?

Sun's core	15 000 000 °C
Sun's surface	6000 °C
Electric lamp	2500 °C
Gas lamp	1580 °C
Boiling water	100 °C
Human body	37 °C
Freezing water	0 °C
Ice in freezer	-18 °C
Liquid oxygen	-180 °C

(i) Celsius scale or centigrade scale

(ii) Fahrenheit scale

(iii) Kelvin scale

On Celsius scale, the interval between lower and upper fixed points is divided into 100 equal parts as shown in figure 8.5(a). The lower fixed point is marked as 0 °C and the upper fixed point is marked as 100 °C.

On Fahrenheit scale, the interval between lower and upper fixed points is divided into 180 equal parts. Its lower fixed point is marked as 32 °F and upper fixed point is marked as 212 °F (Figure 8.5-b).

In SI units, the unit of temperature is kelvin (K) and its scale is called Kelvin scale of temperature as shown in figure 8.5 (c). The interval between the lower and upper fixed points is divided into 100 equal parts. Thus, a change in 1°C is equal to a change of 1K. The lower fixed point on this scale corresponds to 273 K and the upper fixed point is referred as 373 K. The zero on this scale is called the absolute zero and is equal to -273 °C.

CONVERSION OF TEMPERATURE FROM ONE SCALE INTO OTHER TEMPERATURE SCALE

From Celsius to Kelvin Scale

The temperature T on Kelvin scale can be obtained by adding 273 in the temperature C on Celsius scale. Thus

$$T\,(\text{K}) = 273 + C \quad \dots \quad \dots \quad \dots \quad (8.1)$$

EXAMPLE 8.1

What will be the temperature on Kelvin scale of temperature when it is 20 °C on Celsius scale?

SOLUTION

$C = 20\ °\text{C}$

as $T = 273 + C$

$T = 273 + 20 = 293\ \text{K}$

FROM KELVIN TO CELSIUS SCALE

The temperature on Celsius scale can be found by subtracting 273 from the temperature in Kelvin Scale. Thus

$$C = T\,(\text{K}) - 273 \qquad \dots \quad \dots \quad (8.2)$$

EXAMPLE 8.2

Change 300K on Kelvin scale into Celsius scale of temperature.

SOLUTION

$T = 300\text{ K}$

Since $C = T\,(\text{K}) - 273$

$\therefore \quad C = (300 - 273)\ ^\circ\text{C}$

or $\quad C = 27\ ^\circ\text{C}$

FROM CELSIUS TO FAHRENHEIT SCALE

Since 100 divisions on Celsius scale are equal to 180 divisions on Fahrenheit scale. Therefore, each division on Celsius scale is equal to 1.8 divisions on Fahrenheit scale. Moreover, 0°C corresponds to 32°F.

$$\therefore \quad F = 1.8C + 32 \qquad \dots \quad \dots \quad (8.3)$$

Here F is the temperature on Fahrenheit scale and C is the temperature on Celsius scale.

EXAMPLE 8.3

Convert 50°C on Celsius scale into Fahrenheit temperature scale.

SOLUTION

$C = 50\ ^\circ\text{C}$

Since $F = (1.8 \times C + 32)$

$F = (1.8 \times 50 + 32)$

or $F = 122\ ^\circ\text{F}$

Thus, 50 °C on Celsius scale is 122 °F on Fahrenheit scale.

DO YOU KNOW?

A clinical thermometer is used to measure the temperature of human body. It has a narrow range from 35 °C to 42 °C. It has a constriction that prevents the mercury to return. Thus, its reading does not change until reset.

FROM FAHRENHEIT TO CELSIUS SCALE

From equation 8.3, we can find the temperature on Celsius scale from Fahrenheit Scale.

EXAMPLE 8.4

Convert 100 °F into the temperature on Celsius scale.

SOLUTION

$F = 100\ °F$

Since $1.8\,C = F - 32$

$\therefore\ = 100 - 32$

or $1.8\,C = 68$

or $C = 68/1.8$

or $C = 37.8\ °C$

Thus, 100°F is equal to 37.8°C.

Table 8.1: Specific heat of some common substances

Substance	Specific heat $Jkg^{-1}K^{-1}$
Alcohol	2500.0
Aluminium	903.0
Bricks	900.0
Carbon	121.0
Clay	920.0
Copper	387.0
Ether	2010.0
Glass	840.0
Gold	128.0
Granite	790.0
Ice	2100.0
Iron	470.0
Lead	128.0
Mercury	138.6
Sand	835.0
Silver	235.0
Soil (dry)	810.0
Steam	2016.0
Tungsten	134.8
Turpentine	1760.3
Water	4200.0
Zinc	385.0

8.3 SPECIFIC HEAT CAPACITY

Generally, when a body is heated, its temperature increases. Increase in the temperature of a body is found to be proportional to the amount of heat absorbed by it. It has also been observed that the quantity of heat ΔQ required to raise the temperature ΔT of a body is proportional to the mass m of the body. Thus

$$\Delta Q \propto m\,\Delta T$$

or $$\Delta Q = c\,m\,\Delta T \quad \dots\ \dots\ \dots\ \dots \quad (8.4)$$

Here ΔQ is the amount of heat absorbed by the body and c is the constant of proportionality called the specific heat capacity or simply specific heat.

The specific heat of a substance is defined as

Specific heat of a substance is the amount of heat required to raise the temperature of 1 kg mass of that substance through 1K.

Mathematically,

$$c = \frac{\Delta Q}{m\,\Delta T} \quad \dots\ \dots\ \dots\ \dots\ \dots\ \dots \quad (8.5)$$

In SI units, mass m is measured in kilogramme (kg), heat ΔQ is measured in joule (J) and temperature increase ΔT is taken in kelvin (K). Hence, SI unit of specific heat is $Jkg^{-1}K^{-1}$. Specific heats of some common substances are given in Table 8.1.

IMPORTANCE OF LARGE SPECIFIC HEAT CAPACITY OF WATER

Specific heat of water is 4200 $Jkg^{-1}K^{-1}$ and that of dry soil is about 810 $Jkg^{-1}K^{-1}$. As a result the temperature of soil would increase five times more than the same mass of water by the same amount of heat. Thus, the temperature of land rises and falls more rapidly than that of the sea. Hence, the temperature variations from summer to winter are much smaller at places near the sea than land far away from the sea.

Water has a large specific heat capacity. For this reason, it is very useful in storing and carrying thermal energy due to its high specific heat capacity. The cooling system of automobiles uses water to carry away unwanted thermal energy. In an automobile, large amount of heat is produced by its engine due to which its temperature goes on increasing. The engine would cease unless it is not cooled down. Water circulating around the engine as shown by arrows in figure 8.6 maintains its temperature. Water absorbs unwanted thermal energy of the engine and dissipates heat through its radiator.

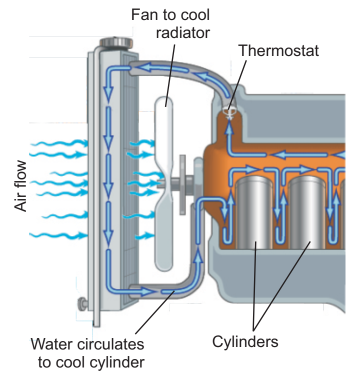


Figure 8.6: A Cooling system in automobile.

In central heating systems such as shown in figure 8.7, hot water is used to carry thermal energy through pipes from boiler to radiators. These radiators are fixed inside the house at suitable places.

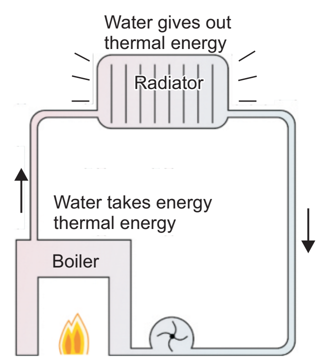


Figure 8.7: Central heating system

EXAMPLE 8.5

A container has 2.5 litres of water at 20°C. How much heat is required to boil the water?

SOLUTION

Volume of water = 2.5 litres

Mass of water m = 2.5 kg

(since density of water is 1000 kgm^{-3} or 1kgL^{-1})

Specific heat of water	c	$= 4200\ \text{Jkg}^{-1}\ \text{K}^{-1}$
Initial temperature	t_1	$= 20^{\circ}\text{C}$
Final temperature	t_2	$= 100^{\circ}\text{C}$
Temperature Increase	ΔT	$= t_2 - t_1$
		$= 100^{\circ}\text{C} - 20^{\circ}\text{C}$
		$= 80\ ^{\circ}\text{C}$ or $80\ \text{K}$
Since	Q	$= c\, m \Delta T$
$\therefore$	Q	$= 4200\ \text{Jkg}^{-1}\text{K}^{-1} \times 2.5\ \text{kg} \times 80\ \text{K}$
or	Q	$= 840\ 000\ \text{J}$

Thus, required amount of heat is 840 000 J or 840 kJ.

HEAT CAPACITY

How much heat a body can absorb depends on many factors. Here we define a quantity called heat capacity of a body as:

Heat capacity of a body is the quantity of thermal energy absorbed by it for one kelvin (1 K) increase in its temperature.

Thus, if the temperature of a body increases through ΔT on adding ΔQ amount of heat, then its heat capacity will be $\frac{\Delta Q}{\Delta T}$

Putting the value of ΔQ, we get

$$\text{Heat capacity} = \frac{\Delta Q}{\Delta T} = \frac{m\, c\, \Delta T}{\Delta T}$$

$$\therefore \text{Heat capacity} = mc \quad \ldots \ldots \ldots \ldots \quad (8.6)$$

Equation (8.6) shows that heat capacity of a body is equal to the product of its mass of the body and its specific heat capacity. For example, heat capacity of 5 kg of water is (5 kg **x** 4200 $\text{Jkg}^{-1}\ \text{K}^{-1}$) 21000 JK^{-1}. That is; 5 kg of water needs 21000 joules of heat for every 1 K rise in its temperature. Thus, larger is the quantity of a substance, larger will be its heat capacity.

DO YOU KNOW?

The presence of large water reservoirs such as lakes and seas keep the climates of nearby land moderate due to the large heat capacity of these reservoirs.

8.4 CHANGE OF STATE

Matter can be changed from one state to another. For such a change to occur, thermal energy is added to or removed from a substance.

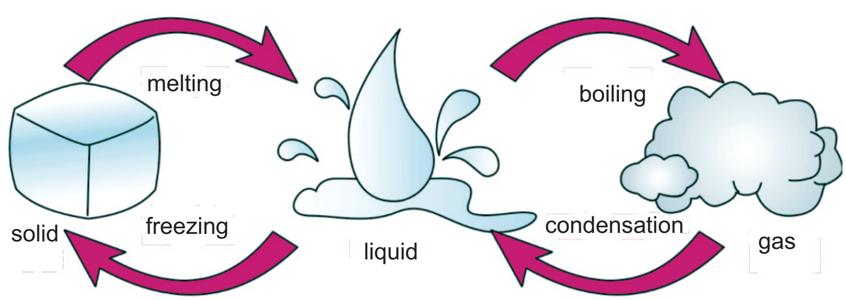


Figure 8.8: Heat energy brings about change of state in matter

ACTIVITY 8.1

Take a beaker and place it over a stand. Put small pieces of ice in the beaker and suspend a thermometer in the beaker to measure the temperature of ice.

Now place a burner under the beaker. The ice will start melting. The temperature of the mixture containing ice and water will not increase above 0°C until all the ice melts and we get water at 0°C. If this water at 0°C is further heated, its temperature will begin to increase above 0 °C as shown by the graph in figure. 8.9.

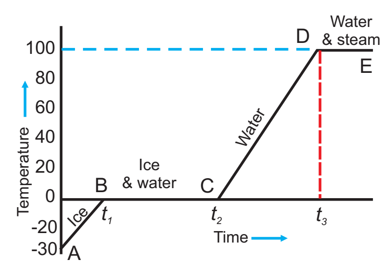


Figure 8.9: A graph of temperature and time showing change of state of ice into water and steam.

Part AB: On this portion of the curve, the temperature of ice increases from -30 °C to 0 °C.

Part BC: When the temperature of ice reaches 0 °C, the ice water mixture remains at this temperature until all the ice melts.

Part CD: The temperature of the substance gradually increases from 0 °C to 100 °C. The amount of energy so added is used up in increasing the temperature of water.

Part DE: At 100 °C water begins to boil and changes into steam. The temperature remains 100 °C till all the water changes into steam.

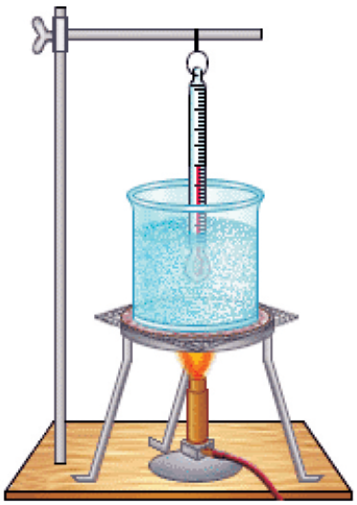


Figure 8.10: Heating ice

8.5 LATENT HEAT OF FUSION

When a substance is changed from solid to liquid state by adding heat, the process is called melting or fusion. The temperature at which a solid starts melting is called its **fusion point** or **melting point.** When the process is reversed i.e. when a liquid is cooled, it changes into solid state. The temperature at which a substance changes from liquid to solid state is called its **freezing point.** Different substances have different melting points. However, the freezing point of a substance is the same as its melting point.

Heat energy required to change unit mass of a substance from solid to liquid state at its melting point without change in its temperature is called its latent heat of fusion.

It is denoted by H_f

$$H_f = \frac{\Delta Q_f}{m}$$

or $$\Delta Q_f = m H_f \quad \ldots \ldots \ldots \ldots \ldots (8.7)$$

Ice changes at 0 °C into water. Latent heat of fusion of ice is 3.36×10^5 Jkg^{-1}. That is; 3.36×10^5 joule heat is required to melt 1 kg of ice into water at 0 °C.

EXPERIMENT 8.1

Take a beaker and place it over a stand. Put small pieces of ice in the beaker and suspend a thermometer in the beaker to measure the temperature. Place a burner under the beaker. The ice will start melting. The temperature of the mixture containing ice and water will not increase above 0°C until all the ice melts. Note the time which the ice takes to melt completely into water at 0°C.

Continue heating the water at 0°C in the beaker. Its temperature will begin to increase. Note the time which the water in the beaker takes to reach its boiling point at 100°C from 0°C.

Draw a temperature-time graph such as shown in figure 8.11. Calculate the latent heat of fusion of ice from the data as follows:

Let mass of ice = m

Finding the time from the graph:

Time taken by ice to melt completely at 0°C $= t_f \quad = t_2 - t_1 \quad = 3.6$ min.

Time taken by water to heat from 0°C to 100°C $= t_o \quad = t_3 - t_2 \quad = 4.6$ min.

Specific heat of water c $= 4200\ \text{Jkg}^{-1}\text{K}^{-1}$

Increase in the temperature of water $= \Delta T = 100\ ^{o}\text{C} \quad = 100\ \text{K}$

Heat required by water from 0°C to 100°C $= \Delta Q = m\,c\,\Delta T$

$$= m \times 4200\ \text{Jkg}^{-1}\text{K}^{-1} \times 100\ \text{K}$$

$$= m \times 420\ 000\ \text{Jkg}^{-1}$$

$$= m \times 4.2 \times 10^{5}\ \text{Jkg}^{-1}$$

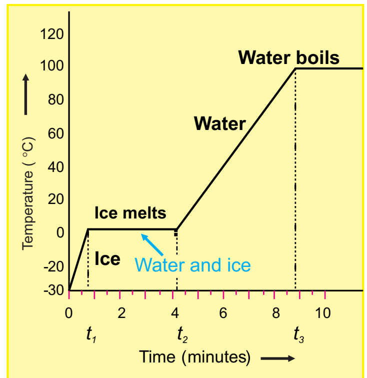


Figure 8.11: Temperature-time graph as ice changes into water that boils as heating continues.

Heat A Q is supplied to water in time t_o to raise its temperature from 0°C to 100°C. Hence, the rate of absorbing heat by water in the beaker is given by

$$\text{Rate of absorbing heat} = \frac{\Delta Q}{t_o}$$

$$\therefore \text{ Heat absorbed in time } t_f = \Delta Q_f = \frac{\Delta Q \times t_f}{t_o}$$

$$= \Delta Q \times \frac{t_f}{t_o}$$

Since $\Delta Q_f = m \times H_f$ (from *eq. 8.7*)

Putting the values, we get

$$m \times H_f = \text{m} \times 4.2 \times 10^{5}\ \text{Jkg}^{-1} \times \frac{t_f}{t_o}$$

or $$H_f = 4.2 \times 10^{5}\ \text{Jkg}^{-1} \times \frac{t_f}{t_o}$$

The values of t_f and t_o can be found from the graph. Put the values in the above equation to get

$$H_f = 4.2 \times 10^{5}\ \text{Jkg}^{-1} \times \frac{3.6\ \text{min.}}{4.6\ \text{min.}}$$

$$= 3.29 \times 10^{5}\ \text{Jkg}^{-1}$$

The latent heat of fusion of ice found by the above experiment is $3.29 \times 10^{5}\ \text{Jkg}^{-1}$ while its actual value is $3.36 \times 10^{5}\ \text{Jkg}^{-1}$.

8.6 LATENT HEAT OF VAPORIZATION

When heat is given to a liquid at its boiling point, its temperature remains constant. The heat energy given to a liquid at its boiling point is used up in changing its state from liquid to gas without any increase in its temperature. Thus

The quantity of heat that changes unit mass of a liquid completely into gas at its boiling point without any change in its temperature is called its latent heat of vaporization.

It is denoted by H_v

$$H_v = \frac{\Delta Q_v}{m}$$

or $$\Delta Q_v = m H_v \quad \ldots \ldots \ldots \ldots \ldots (8.8)$$

When water is heated, it boils at 100°C under standard pressure. Its temperature remains 100°C until it is changed completely into steam. Its latent heat of vaporization is 2.26×10^6 J kg^{-1}. That is; one kilogramme of water requires 2.26×10^6 joule heat to change it completely into gas (steam) at its boiling point. The value of melting point, boiling point, latent heat of fusion and vaporization of some of the substances is given in Table 8.2.

Table 8.2: Melting point, boiling point, latent heat of fusion and latent heat of vaporization of some common substances.

Substance	Melting point (°C)	Boiling point (°C)	Heat of fusion (kJkg^{-1})	Heat of vaporization (kJkg^{-1})
Aluminium	660	2450	39.7	10500
Copper	1083	2595	205.0	4810
Gold	1063	2660	64.0	1580
Helium	-270	-269	5.2	21
Lead	327	1750	23.0	858
Mercury	-39	357	11.7	270
Nitrogen	-210	-196	25.5	200
Oxygen	-219	-183	13.8	210
Water	0	100	336.0	2260

EXPERIMENT 8.2

At the end of experiment 8.1, the beaker contains boiling water. Continue heating water till all the water changes into steam. Note the time which the water in the beaker takes to change completely into steam at its boiling point 100°C.

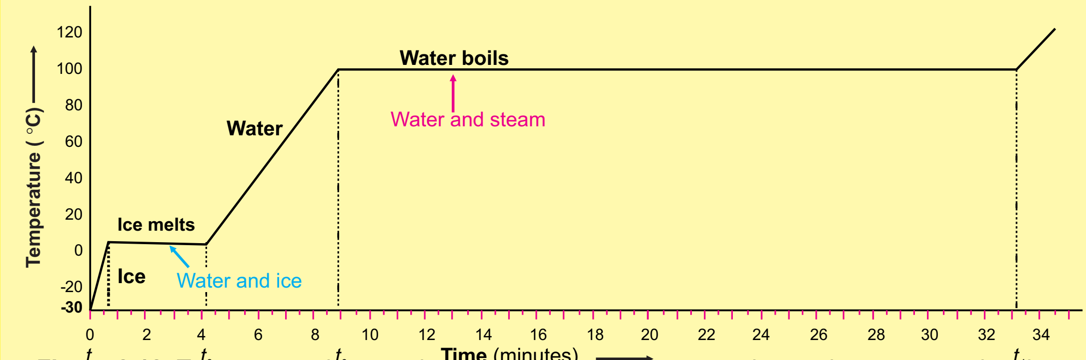


Figure 8.12: Temperature-time graph as ice changes into water and water into steam on heating.

Extend the temperature-time graph such as shown in figure 8.12. Calculate the latent heat of fusion of ice from the data as follows:

Let Mass of ice = m

Time t0 taken to heat water from 0°C to 100°C (melt) $= t_o = t_3 - t_2 = 4.6$ min.

Time taken by water at 100°C to change it into steam $= t_v = t_4 - t_3 = 24.4$ min.

Specific heat of water c $= 4200 \text{ Jkg}^{-1}\text{K}^{-1}$

Increase in the temperature of water $= \Delta T = 100^{\circ}\text{C} = 100 \text{ K}$

Heat required to heat water from 0°C to 100°C $= \Delta Q = m c \Delta T$

$= m \times 4200 \text{ Jkg}^{-1}\text{K}^{-1} \times 100 \text{ K}$

$= m \times 420\,000 \text{ Jkg}^{-1}$

$= m \times 4.2 \times 10^5 \text{ Jkg}^{-1}$

As burner supplies heat Δ Q to water in time t_o to raise its temperature from 0°C to 100°C. Hence, the rate at which heat is absorbed by the beaker is given by

Rate of absorbing heat $= \dfrac{\Delta Q}{t_o}$

$\therefore$ Heat absorbed in time t_v $= \Delta Q_v = \dfrac{\Delta Q \times t_v}{t_o}$

$$= \Delta Q \times \frac{t_v}{t_o}$$

Since $\Delta Q_v = m \times H_v$ (from eq.8.8)

Putting the values, we get

$$m \times H_v = m \times 4.2\times10^5\ \text{Jkg}^{-1} \times \frac{t_v}{t_o}$$

or

$$H_v = 4.2\times10^5\ \text{Jkg}^{-1} \times \frac{t_v}{t_o}$$

Putting the values of t_v and t_o from the graph, we get

$$H_v = 4.2\times10^5\ \text{Jkg}^{-1} \times \frac{24.4\ \text{min.}}{4.6\ \text{min.}}$$

$$= 2.23\times10^6\ \text{Jkg}^{-1}$$

The latent heat of vaporization of water found by the above experiment is $2.23\text{x}10^6$ Jkg^{-1} while its actual value is $2.26\text{x}10^6$ Jkg^{-1}.

8.7 THE EVAPORATION

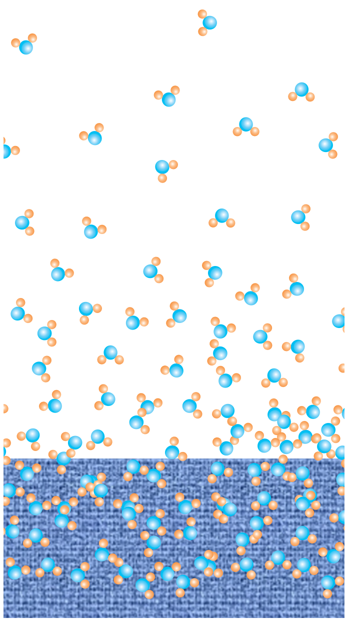


Figure 8.13: Evaporation is escaping out of fast moving water molecules from the surface of a liquid without heating.

Take some water in a dish. The water in the dish will disappear after sometime. It is because the molecules of water are in constant motion and possess kinetic energy. Fast moving molecules escape out from the surface of water and goes into the atmosphere. This is called **evaporation.** Thus

Evaporation is the changing of a liquid into vapours (gaseous state) from the surface of the liquid without heating it.

Unlike boiling, evaporation takes place at all temperatures but only from the surface of a liquid. The process of boiling takes place at a certain fixed temperature which is the boiling point of that liquid. At boiling point, a liquid is changing into vapours not only from the surface but also within the liquid. These vapours come out of the boiling liquid as bubbles which breakdown on reaching the surface.

Mini Exercise

1. How specific heat differs from heat capacity?
2. Give two uses of cooling effect by evaporation.
3. How evaporation differs from vaporization?

Evaporation plays an important role in our daily life. Wet clothes dry up rapidly when spread. Evaporation causes cooling. Why? During evaporation fast moving molecules escape out from the surface of the liquid. Molecules that have lower kinetic energies are left behind. This lowers the average kinetic energy of the liquid molecules and the temperature of the liquid. Since temperature of a substance depends on the average kinetic energy of its molecules. Evaporation of perspiration helps to cool our bodies.

Evaporation takes place at all temperature from the surface of a liquid. The rate of evaporation is affected by various factors.

TEMPERATURE

Why wet clothes dry up more quickly in summer than in winter? At higher temperature, more molecules of a liquid are moving with high velocities. Thus, more molecules escape from its surface. Thus, evaporation is faster at high temperature than at low temperature.

SURFACE AREA

Why water evaporates faster when spread over large area? Larger is the surface area of a liquid, greater number of molecules has the chance to escape from its surface.

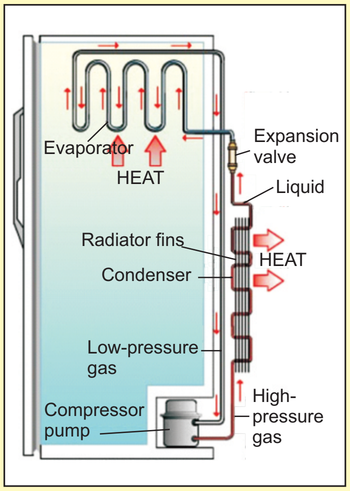
WIND

Wind blowing over the surface of a liquid sweeps away the liquid molecules that have just escaped out. This increases the chance for more liquid molecules to escape out.

NATURE OF THE LIQUID

Does spirit and water evaporate at the same rate? Liquids differ in the rate at which they evaporate. Spread a few drops of ether or spirit on your palm. You feel cold, why?

COOLING IN REFRIGERATORS



Cooling is produced in refrigerators by evaporation of a liquified gas. This produces cooling effect. Freon, a CFC, was used as a refrigerant gas. But its use has been forbidden when it was known that CFC is the cause of ozone depletion in the upper atmosphere which results increase in amount of UV rays from the Sun. The rays are harmful to all living matter. Freon gas is now replaced by Ammonia and other substances which are not harmful to the environment.

8.8 THERMAL EXPANSION

Most of the substances solids, liquids and gases expand on heating and contract on cooling. Their thermal expansions and contractions are usually small and are not noticeable. However, these expansions and contractions are important in our daily life.

The kinetic energy of the molecules of an object depends on its temperature. The molecules of a solid vibrate with larger amplitude at high temperature than

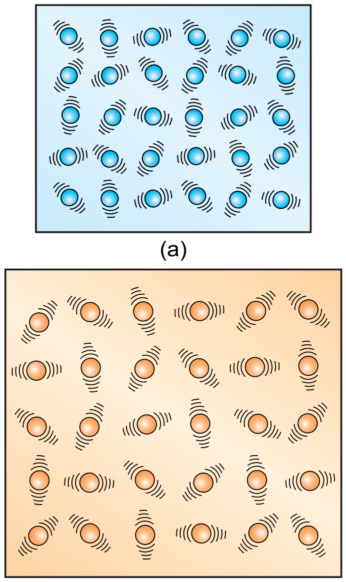


Figure 8.14: Molecules of an object moving with **(a)** smaller amplitude at low temperature **(b)** larger amplitude at high temperature.

at low temperature. Thus, on heating, the amplitude of vibration of the atoms or molecules of an object increases. They push one another farther away as the amplitude of vibration increases. Thermal expansion results an increase in length, breadth and thickness of a substance.

LINEAR THERMAL EXPANSION IN SOLIDS

It has been observed that solids expand on heating and their expansion is nearly uniform over a wide range of temperature. Consider a metal rod of length L_o at certain temperature T_o. Let its length on heating to a temperature T becomes L Thus

Increase in length of the rod $= \Delta L = L - L_o$

Increase in temperature $= \Delta T = T - T_o$

It is found that change in length AL of a solid is directly proportional to its original length L_o, and the change in temperature ΔT. That is;

$$\Delta L \propto L_o \Delta T$$

or $$\Delta L = \alpha L_o \Delta T \quad \dots \dots \dots \quad (8.9)$$

or $$L - L_o = \alpha L_o \Delta T$$

or $$L = L_o (1 + \alpha \Delta T) \quad \dots \dots \quad (8.10)$$

where α is called the **coefficient of linear thermal expansion of the substance.**

From equation (8.9), we get

$$\alpha = \frac{\Delta L}{L_o \Delta T} \quad \dots \dots \dots \quad (8.11)$$

Thus, we can define the coefficient of linear expansion α of a substance as the fractional increase in its length per kelvin rise in temperature. Table 8.3 gives coefficient of linear thermal expansion of some common solids.

Table 8.3: Coefficient of linear thermal expansion (α) of some common solids.

Substance	α (K^{-1})
Aluminium	2.4×10^{-5}
Brass	1.9×10^{-5}
Copper	1.7×10^{-5}
Steel	1.2×10^{-5}
Silver	1.93×10^{-5}
Gold	1.3×10^{-5}
Platinum	8.6×10^{-5}
Tungsten	0.4×10^{-5}
Glass (pyrex)	0.4×10^{-5}
Glass(ordinary)	0.9×10^{-5}
Concrete	1.2×10^{-5}

EXAMPLE 8.6

A brass rod is 1 m long at 0°C. Find its length at 30°C. (Coefficient of linear expansion of brass $=1.9 \times 10^{-5} K^{-1}$)

SOLUTION

$L_o = 1\text{m}$

$t = 30^oC$

$t_o = 0^oC$

$T_o = 0+273 = 273K$

$T = 30 + 273 = 303K$

$\Delta T = T - T_o$

$= 303\ K - 273\ K$

$= 30\ K$

$\alpha = 1.9 \times 10^{-5} K^{-1}$

since $L = L_o(1 + \alpha\ \Delta T)$

$L = 1m \times (1 + 1.9 \times 10^{-5} K^{-1} \times 30K)$

$L = 1.00057\ m$

Hence, the length of the brass bar at 30°C will be 1.00057 m.

VOLUME THERMAL EXPANSION

The volume of a solid also changes with the change in temperature and is called volume thermal expansion or cubical thermal expansion. Consider a solid of initial volume V_0 at certain temperature T_0. On heating the solid to a temperature T, let its volume becomes V, then

Change in the volume of a solid $\Delta V = V - V_o$

and Change in temperature $\Delta T = T - T_o$

Like linear expansion, the change in volume ΔV is found to be proportional to its original volume V_0 and change in temperature ΔT. Thus

$$\Delta V \propto V_o \Delta T$$

or $$\Delta V = \beta V_o \Delta T \quad \ldots \ldots \ldots \ldots (8.12)$$

$$V - V_o = \beta V_o \Delta T$$

$$\therefore \quad V = V_o (1 + \beta \Delta T) \ldots \ldots \ldots \ldots (8.13)$$

where β is the temperature coefficient of volume expansion. Using equation 8.12, we get

Table 8.4: Coefficient of volume expansion of various substances.

Substance	$\beta\ (K^{-1})$
Aluminium	7.2×10^{-5}
Brass	6.0×10^{-5}
Copper	5.1×10^{-5}
Steel	3.6×10^{-5}
Platinum	27.0×10^{-5}
Glass(ordinary)	2.7×10^{-5}
Glass(pyrex)	1.2×10^{-5}
Glycerine	53×10^{-5}
Mercury	18×10^{-5}
Water	21×10^{-5}
Air	3.67×10^{-3}
Carbon dioxide	3.72×10^{-3}
Hydrogen	3.66×10^{-3}

$$\beta = \frac{\Delta V}{V_o \Delta T} \qquad \ldots\ \ldots\ \ldots\ \ldots\ \ldots (8.14)$$

Thus, we can define the temperature coefficient of volume expansion β as the fractional change in its volume per kelvin change in temperature. The coefficients of linear expansion and volume expansion are related by the equation:

$$\beta = 3\,\alpha \qquad \ldots\ \ldots\ \ldots\ \ldots\ \ldots (8.15)$$

Values of β for different substances are given in Table 8.4.

EXAMPLE 8.7

Find the volume of a brass cube at 100°C whose side is 10 cm at 0°C. (coefficient of linear thermal expansion of brass = 1.9x 10^{-5} $K^{-}1$).

SOLUTION

L_o = 10cm = 0.1 m

T_o = 0^o C = (0 + 273) K = 273 K

T = 100^o C = (100 + 273) K = 373 K

ΔT = $T - T_o$

= 373 K – 273 K = 100 K

$\alpha = 1.9 \times 10^{-5}\,K^{-1}$

as $\beta = 3\,\alpha$

Therefore $\beta = 3 \times 1.9 \times 10^{-5}\,K^{-1}$

$= 5.7 \times 10^{-5}\,K^{-1}$

initial volume $V_o = L_o^3 = (0.1\ m)^3$

$= 0.001\ m^3 = 10^{-3}\ m^3$

Since $V = V_o\,(1 + \beta \Delta T)$

Hence $V = 10^{-3}\,m^3 \times (1 + 5.7 \times 10^{-5}\,K^{-1} \times 100\ K)$

or $V = 10^{-3}\,m^3 \times (1 + 5.7 \times 10^{-3})$

$= 10^{-3}\,m^3 \times (1 + 0.0057)$

$= 1.0057 \times 10^{-3}\,m^3$

Hence, the volume of brass cube at 100 °C will be $1.0057 \times 10^{-3} m^3$.

CONSEQUENCES OF THERMAL EXPANSION

Why gaps are left in railway tracks? The expansion of solids may damage the bridges, railway tracks and roads as they are constantly subjected to temperature changes. So provision is made during construction for expansion and contraction with temperature. For example, railway tracks buckled on a hot summer day due to expansion if gaps are not left between sections.

Figure 8.15: Gaps are left in railway tracks to compensate thermal expansion during hot season.

Bridges made of steel girders also expand during the day and contract during night. They will bend if their ends are fixed. To allow thermal expansion, one end is fixed while the other end of the girder rests on rollers in the gap left for expansion. Overhead transmission lines are also given a certain amount of sag so that they can contract in winter without snapping.

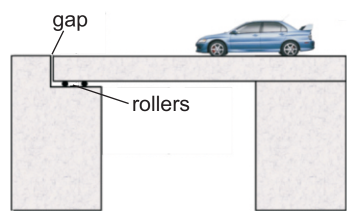


Figure 8.16: Bridges with rollers below one of their ends allow movements due to expansion and contraction.

APPLICATIONS OF THERMAL EXPANSION

Thermal expansion is used in our daily life. In thermometers, thermal expansion is used in temperature measurements. To open the cap of a bottle that is tight enough, immerse it in hot water for a minute or so. Metal cap expands and becomes loose. It would now be easy to turn it to open.

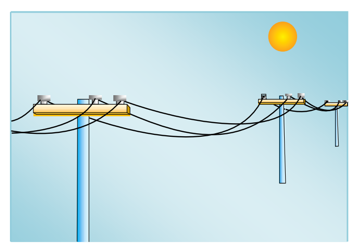


Figure 8.17: Wires on electric poles are given some sag to prevent breakina in winter.

To join steel plates tightly together, red hot rivets are forced through holes in the plates as shown in figure 8.18 (a). The end of hot rivet is then hammered. On cooling, the rivets contract and bring the plates tightly gripped.

(a)

(b)

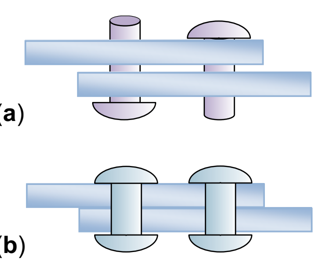


Figure 8.18 (a) Hot rivets inserted **(b)** after hammering, rivets are cold down.

Iron rims are fixed on wooden wheels of carts. Iron rims are heated. Thermal expansion allows them to slip over the wooden wheel. Water is poured on it to cool. The rim contracts and becomes tight over the wheel.

BIMETAL STRIP

A bimetal strip consists of two thin strips of different metals such as brass and iron joined together as shown in figure 8.19(a). On heating the strip, brass expands more than iron. This unequal expansion causes bending of the strip as shown in figure 8. 19(b).

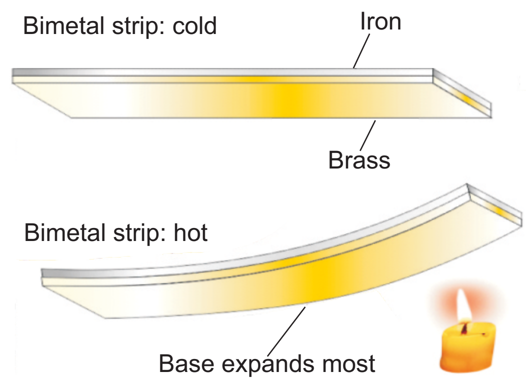


Figure 8.19 (a) A bimetal strip of brass and iron (b) Bending of brass-iron bimetal strip on heating due to the difference in their thermal expansion.

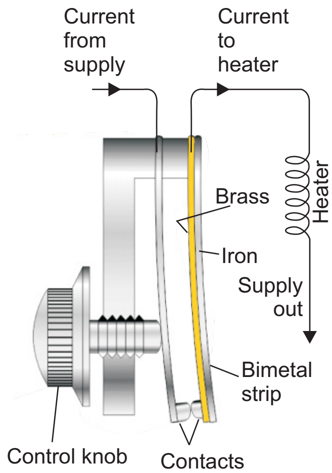


Figure 8.20: Bimetal thermostat breaks the electrical circuit at preset temperature.

Bimetal strips are used for various purposes. Bimetal thermometers are used to measure temperatures especially in furnaces and ovens. Bimetal strips are also used in thermostats. Bimetal thermostat switch such as shown in figure 8.20 is used to control the temperature of heater coil in an electric iron.

THERMAL EXPANSION OF LIQUIDS

The molecules of liquids are free to move in all directions within the liquid. On heating a liquid, the average amplitude of vibration of its molecules increases. The molecules push each other and need more space to occupy. This accounts for the expansion of the liquid when heated. The thermal expansion in liquids is greater than solids due to the weak forces between their molecules. Therefore, the coefficient of volume expansion of liquids is greater than solids.

Liquids have no definite shape of their own. A liquid always attains shape of the container in which it is poured. Therefore, when a liquid is heated, both liquid and the container undergo a change in their volume. Thus, there are two types of thermal volume expansion for liquid.

- Apparent volume expansion
- Real volume expansion

DO YOU KNOW?

Water on cooling below 4°C begins to expand until it reaches 0°C. On further cooling its volume increases suddenly as it changes into ice at 0°C. When ice is cooled below 0°C, it contracts i.e. its volume decreases like solids. This unusual expansion of water is called the **anomalous expansion of water.**

ACTIVITY

Take a long-necked flask. Fill it with some coloured liquid upto the mark A on its neck as shown in figure 8.21. Now start heating the flask from bottom. The liquid level first falls to B and then rises to C.

The heat first reaches the flask which expands and its volume increases. As a result liquid descends in the flask and its level falls to B. After sometime, the liquid begins to rise above B on getting hot. At certain temperature it reaches at C. The rise in level from A to C is due to the apparent expansion in the volume of the liquid. Actual expansion of the liquid is greater than that due to the expansion because of the expansion of the glass flask. Thus real expansion of the liquid is equal to the volume difference between A and C in addition to the volume expansion of the flask. Hence

Real expansion of the liquid = Apparent expansion of the liquid + Expansion of the flask

or BC = AC + AB ... ... (8.16)

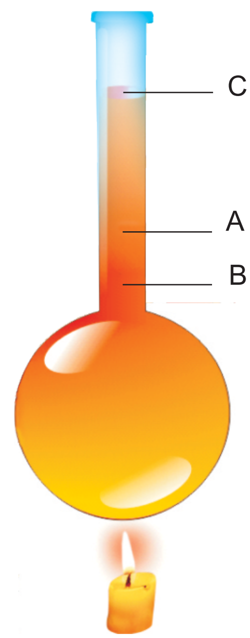


Figure 8.21: Real and apparent expansion of liquid.

The expansion of the volume of a liquid taking into consideration the expansion of the container also, is called the real volume expansion of the liquid. The real rate of volume expansion β_r of a liquid is defined as the actual change in the unit volume of a liquid for 1K (or 1°C) rise in its temperature. The real rate of volume expansion β_r is always greater than the apparent rate of volume expansion β_a by an amount equal to the rate of volume expansion of the container β_g. Thus

$$\beta_r = \beta_a + \beta_g \quad \ldots \ldots \ldots (8.17)$$

It should be noted that different liquids have different coefficients of volume expansion.

SUMMARY

- The temperature of a body is the degree of hotness or coldness of the body.
- Thermometers are made to measure the temperature of a body or places.
- The lower fixed point is the mark that gives the position of mercury in the thermometer when it is placed in ice.
- The upper fixed point is the mark that shows the position of mercury in the thermometer when it is placed in steam from boiling water at standard pressure.
- Inter-conversion between scales:
    - From Celsius To Kelvin Scale: T(K)=273 + C
    - From Kelvin to Celsius Scale:

      $$C = T\,(K) - 273$$
    - From Celsius to Fahrenheit Scale:

      $$F = 1.8\,C + 32$$
- Heat is a form of energy and this energy is called heat as long as it is in the process of transfer from one body to another body. When a body is heated, the kinetic energy of its molecules increases, the average distances between the molecules increase.
- The specific heat of a substance is defined as the amount of heat required to raise the temperature of a unit mass of that substance through one degree centigrade (1°C) or one kelvin (1K).
- The heat required by unit mass of a substance at its melting point to change it from solid state to liquid state is called the latent heat of fusion.
- The quantity of heat required by the unit mass of a liquid at a certain constant temperature to change its state completely from liquid into gas is called the latent heat of vaporization.
- It has been observed that solids expand on heating and their expansion is nearly uniform over a wide range of temperature. Mathematically,

  $$L = L_o\,(1 + \alpha\,\Delta T)$$
- The thermal coefficient of linear expansion α of a substance is defined as the fractional increase in its length per kelvin rise in temperature.
- The volume of a solid changes with the change in temperature and is called as volume or cubical expansion.

  $$V = V_o\,(1 + \beta\Delta T)$$
- The thermal coefficient of volume expansion β is defined as the fractional change in its volume per kelvin change in temperature.
- There are two types of thermal volume expansion for liquids as well as for gases. Apparent volume expansion and real volume expansion.

QUESTIONS

8.1 Encircle the correct answer from the given choices.

i. Water freezes at

(a) 0°F (b) 32 °F

(c) -273 K (d) 0 K

ii. Normal human body temperature is

(a) 15°C (b)37°C

(c) 37 °F (d)98.6°C

iii. Mercury is used as thermometric material because it has

(a) uniform thermal expansion

(b) low freezing point

(c) small heat capacity

(d) all the above properties

iv. Which of the following material has large specific heat?

(a) copper (b) ice

(c) water (d) mercury

v. Which of the following material has large value of temperature coefficient of linear expansion?

(a) aluminum (b) gold

(c) brass (d) steel

vi. What will be the value of p for a solid for which a has a value of $2x10^{-5}K^{-1}$?

(a) $2x10^{-5}$ K^{-1}

(b) $6x10^{-5}$ K^{-1}

(c) $8x10^{-15}$ K^{-1}

(d) $8x10^{-5}$ K^{-1}

vii. A large water reservoir keeps the temperature of nearby land moderate due to

(a) low temperature of water

(b) low specific heat of water

(c) less absorption of heat

(d) large specific heat of water

viii. Which of the following affects evaporation?

(a) temperature

(b) surface area of the liquid

(c) wind

(d) all of the above

8.2 Why does heat flow from hot body to cold body?

8.3 Define the terms heat and temperature.

8.4 What is meant by internal energy of a body?

8.5 How does heating affect the motion of molecules of a gas?

8.6 What is a thermometer? Why mercury is preferred as a thermometric substance?

8.7 Explain the volumetric thermal expansion.

8.8 Define specific heat. How would you find the specific heat of a solid?

8.9 Define and explain latent heat of fusion.

8.10 Define latent heat of vaporization.

8.11 What is meant by evaporation? On what factors the evaporation of a liquid depends? Explain how cooling is produced by evaporation.

PROBLEMS

8.1 Temperature of water in a beaker is 50°C. What is its value in Fahrenheit scale?
(122 °F)

8.2 Normal human body temperature is 98.6°F. Convert it into Celsius scale and Kelvin scale.
(37 °C, 310 K)

8.3 Calculate the increase in the length of an aluminum bar 2 m long when heated from 0°C to 20°C. If the thermal coefficient of linear expansion of aluminium is $2.5 \times 10^{-5} K^{-1}$. (0.1cm)

8.4 A balloon contains 1.2 m^3 air at 15 °C. Find its volume at 40 °C. Thermal coefficient of volume expansion of air is $3.67 \times 10^{3} K^{-1}$.
(1.3 m^3)

8.5 How much heat is required to increase the temperature of 0.5 kg of water from 10 °C to 65 °C?
(115500 J)

8.6 An electric heater supplies heat at the rate of 1000 joule per second. How much time is required to raise the temperature of 200 g of water from 20 °C to 90 °C? (58.8 s)

8.7 How much ice will melt by 50000 J of heat? Latent heat of fusion of ice = 336000 J kg^{-1}.
(150 g)

8.8 Find the quantity of heat needed to melt 100g of ice at -10 °C into water at 10 °C. (39900 J)

(Note: Specific heat of ice is 2100 $Jkg^{-1}K^{-1}$, specific heat of water is 4200 $Jkg^{-1}K^{-1}$, Latent heat of fusion of ice is 336000 Jkg^{-1}).

8.9 How much heat is required to change 100 g of water at 100°C into steam? (Latent heat of vaporization of water is 2.26×10^{6} Jkg^{-1}. (2.26×10^{5} J)

8.10 Find the temperature of water after passing 5 g of steam at 100 °C through 500 g of water at 10 °C. (16.2°C)

(Note: Specific heat of water is 4200 $Jkg^{-1}K^{-1}$, Latent heat of vaporization of water is 2.26×10^{6} Jkg^{-1}).