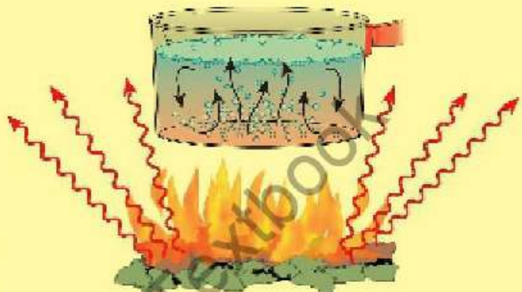
Chapter 7 Thermal Properties of Matter

Student Learning Outcomes

After completing this chapter, students will be able to:



- Describe, qualitatively, the particle structure of solids, liquids and gasses [Including and relating their properties to the forces and distances between particles and to the motion of the particles (atoms, molecules, ions and electrons)].
- Describe plasma as a fourth state of matter [In which a significant portion of the material is made up of ions or electrons e.g. in stars, neon lights and lightning streamers].
- Describe the relationship between the motion of particles and temperature [including the idea that there is a lowest possible temperature (approx.-273°C), known as absolute zero, where the particles have least kinetic energy]
- State that an increase in the temperature of an object increases its internal energy
- Explain, with examples, how a physical property which varies with temperature may be used for the measurement of temperature
- Justify the need for fixed points in the calibration of thermometers [including what is meant by the ice point and steam point.]
- Illustrate what is meant by the sensitivity, range and linearity of thermometers.
- Differentiate between the structure and function of liquid-in-glass and of thermocouple thermometers
- Discuss how the structure of a liquid in-glass thermometer affects its sensitivity, range and linearity

Heat or thermal energy has always been the necessity of human beings, animals and plants in this world. Without heat, their existence would not have been possible. In the beginning, the Sun was the only source of light and heat. With the discovery of fire, a new era was started. The uses of heat produced from fire were increased day by day and contributed greatly to the comforts and facilities for the human being. Initially, the hot and cold objects were sensed by touching which was not a good standard to measure the degree of hotness of an object. So, man evolved different methods to measure it. After the invention of standard measuring devices, the temperature was also included in the list of basic physical quantities like mass, length and time.

This chapter begins with the introduction of kinetic molecular theory of particles of matter. It is due to the fact that temperature and heat or internal energy are associated with the motion of particles in the matter.

7.1 Kinetic Molecular Theory of Matter

According to this theory, matter is composed of very small particles called molecules which are always in motion. Their motion may be vibrational, rotational or linear. There exists a mutual force of attraction between the molecules known as intermolecular force. This force depends upon the distance between the molecules. It decreases with increasing distance between them.

The molecules possess kinetic energy due to motion and potential energy due to force of attraction. When a substance is heated, its temperature rises and its molecular motion becomes more vigorous which increases the kinetic energy of the molecules. Thus, the temperature of the substance depends upon the average kinetic energy of its molecules. In general, matter exists in three states solids, liquids and gases as shown in Fig. 7.1.

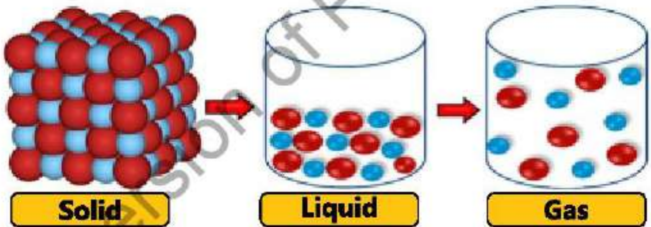


Fig. 7.1

Most of the properties of solids, liquids and gases can be explained on the basis of kinetic molecular theory of matter. In case of solids, the intermolecular forces are so strong that they keep the molecules bound. So, the molecules are held at fixed positions but still they show vibrational motion about their fixed points (Fig. 7.2). This is why, the solids have a definite shape and a definite volume.

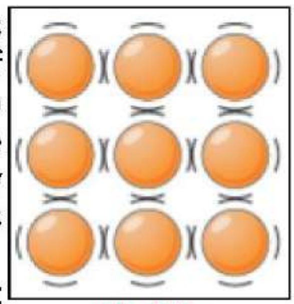


Fig. 7.2

In case of liquids, intermolecular force is so weak that it cannot hold the molecules at fixed positions and the molecules can slide over each other in random directions. A liquid, therefore, possesses a definite volume but has no definite shape. Due to flow of the molecules, it acquires the shape of the containing vessel.

Gas molecules are relatively far away from one and another. Due to which, gas neither posseses a definite volume nor a definite shape.

Plasma

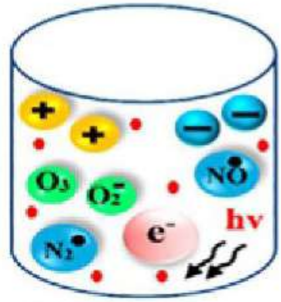


Fig. 7.3(a) Plasma

The plasma is a gas in which most of the atoms are ionized containing positive ions and electrons (Fig. 7.3-a). They are freely moving in the volume of the gas. Due to presence of positive ions and free electrons, plasma is the conducting state of matter. It allows electric current to pass through it. Since the gas in plasma state has properties which are quite different from ordinary gas, therefore, plasma is known as fourth state of matter. The Sun and the most of other stars are in plasma state. Plasma is also found in plasma TV and in gas discharge tubes (Fig. 7.3-b) when electric current passes through them. The plasma state also occurs during the early stages of lightning formation known as lightning streamers which are the conducting paths through the atmosphere due to ionized air molecules.


Fig. 7.3(b) Gas discharge tube

7.2 Temperature and Heat

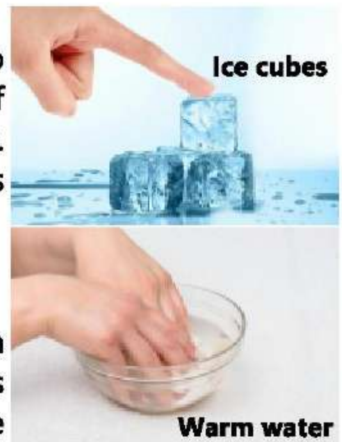


Fig. 7.4

When we touch ice, we feel cold. When we dip our fingers in warm water, we feel hot. Thus, by sense of touch we can tell which of the bodies is colder or hotter. A hotter body is said to be at higher temperature as compared to a colder body.

Temperature of a body is defined as degree of its hotness or coldness.

It is our common experience that when we heat a body, its temperature rises. Process of heating provides heat or **thermal energy** to the body which is the cause of the rise in temperature.

The following activity will help to define temperature.

Activity 7.1

The teacher should arrange hot water in some tea cups, thermometers and metal spoons. Make groups of the students. Each group will put the spoon in the hot water and stir it. Ask them what do they feel. Does the other end of the spoon also become hot?

Do they observe that the spoon also gets hotter? It means heat is being transferred from the hot water to the spoon because the temperature of the water was higher than that of the spoon.

Thus

Temperature can be defined as a physical quantity which determines the direction of flow of thermal energy.

This means that thermal energy is transferred from one object to another due to temperature difference of the two bodies. Therefore, we can define heat as follows:

Heat is the energy which is transferred from one object to another due to difference of temperature between the two bodies.

Temperature and Internal Energy

We know that matter is composed of molecules which are always in motion. Molecules of a solid are vibrating about their fixed positions. The molecules of a liquid are sliding one over the other and those of gases are randomly moving. The molecules possess kinetic energy on account of their motion. Potential energy is also associated with molecules because of their attractive forces.

Fig. 7.5 The internal energy of air inside a hot-air balloon increases as the temperature increases.

The sum of kinetic and potential energies of the molecules of an object is called its internal energy.

When we heat a substance, its molecular motion becomes more vigorous which means an increase in its internal energy. As a result, temperature of the substance rises. The heat energy transferred to a body increases the internal energy of its molecules due to which its temperature rises.

Remember that, it is not true to say that a substance contains heat. The substance contains internal energy. The word heat is used only when referring to the energy actually in transit from hot to cold body.

7.3 Thermometers

Our sense of touch can tell us whether an object is hot or cold. It gives an idea about the object's temperature but we cannot measure the actual temperature of the body just by touching it. For the exact measurement of the hotness of a substance, we require an instrument called a thermometer.

Thermometers use some property of a substance, which changes appreciably with the change of temperature.

Basic Thermometric Properties

Some basic thermometric properties for a material suitable to construct a thermometer are the following:

1. It is a good conductor of heat.
2. It gives quick response to temperature changes.
3. It has uniform thermal expansion.
4. It has high boiling point.
5. It has low freezing point.
6. It has large expansivity (low specific heat capacity).
7. It does not wet glass.
8. It does not vapourize.
9. It is visible.

Liquid-in-Glass Thermometer

We know that liquids expand on heating. So, expansion in the volume of a liquid can be used for the measurement of temperature. This is known as liquid-in-glass thermometer. One such liquid which is commonly used in thermometers is mercury. Figure 7.6 shows a mercury thermometer. It is made of glass. It has a bulb at one end filled with mercury.

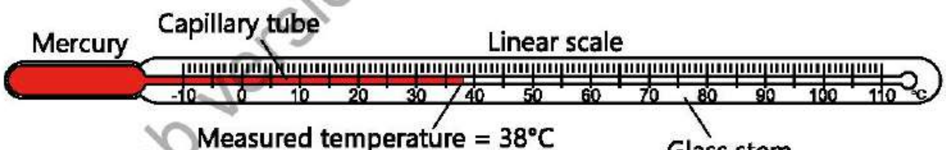


Fig. 7.6

When the temperature rises, the mercury expands and moves up through the narrow capillary tube in the form of a mercury thread. As shown in Fig. 7.6, the position of the end of thread reads the temperature. Mercury is opaque and can be easily seen due to its silvery colour. Alcohol is also a choice for the thermometric liquid, but it must be coloured to make it visible.

Point to Ponder!
Could we make mercury thermometer if expansion of glass would have been greater than mercury?

Brain Teaser!
(a) Why the walls of the thermometer bulb are thin? (b) Why the inner bore must be narrow?

Temperature Scales

For the measurement of temperature, a scale is to be constructed which requires two reference temperatures called two fixed points. One is the steam point slightly above the boiling of water at standard atmospheric pressure. This corresponds to upper fixed point of the scale. The second fixed point is the melting point of pure ice or simply ice point. It is called the lower fixed point. Different scales of temperature have been constructed by assigning different numerical values to these fixed points. Three different scales are:

(i) Celsius or centigrade scale
(ii) Fahrenheit scale
(iii) Kelvin scale

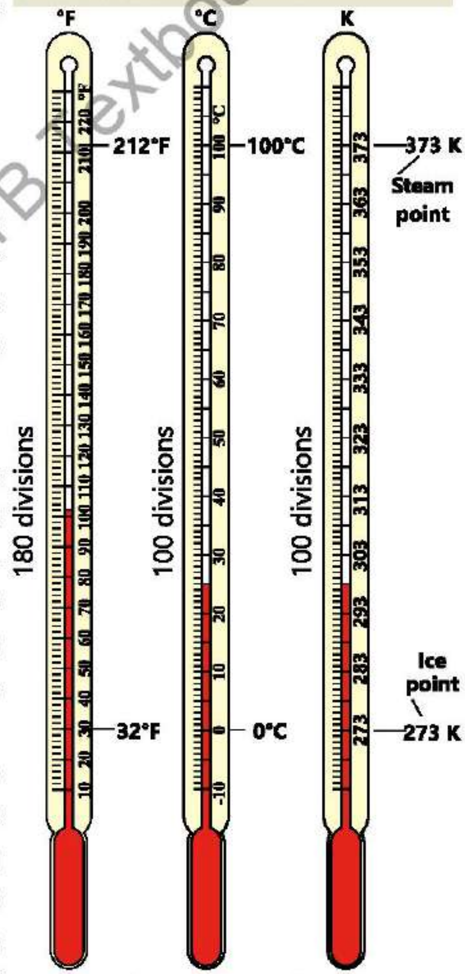
In Celsius or centigrade scale, the numerical values assigned to lower and upper fixed points are 0 and 100. As the difference between these values is 100, so the space between these points is divided into 100 equal parts. Each part is known as 1°C.

In Fahrenheit scale, the lower fixed point is labelled as 32 and upper as 212. As the difference between these two numbers is 180, so in this scale the space between these points is divided into 180 equal parts. Each part is known as 1°F. Celsius and Fahrenheit scales are generally used in ordinary life.

There is a third scale of temperature known as Kelvin scale or Absolute temperature scale. It is used in scientific measurements. In Kelvin scale, the lower and upper fixed points are labelled as 273 and 373. As the difference between these values is 100, so the width of 1 K is the same as that of 1°C. The zero point of this scale is the temperature at which the molecules

For Your Information!

The pressure of a given mass of gas increases with temperature. So, pressure of a gas is also a thermometric property which is used in gas thermometers. The resistance of a given length of wire also depends upon temperature. It increases with the increase in temperature. So, the resistance of a wire is also a thermometric substance and is used in platinum resistance thermometer.



Comparison of three scales of temperature
Fig. 7.7

of a substance cease to move. Their average kinetic energy becomes zero. This is known as absolute zero. Its value is -273.15 °C. For calculations, it is simply taken as -273 °C. Absolute zero is the lowest possible temperature ever to be in the whole universe. The matter does not exist below absolute zero temperature.

Conversion of Temperature from One Scale to Another

If the temperature of a body is T_c on Celsius scale, T_F on Fahrenheit scale and T_k on Kelvin scale, then these readings are related by the following formulae:

(I) Conversion of Celsius (centigrade) to Fahrenheit scale:

$$T_F = \frac{9}{5} \times T_C + 32 \quad \text{....... (7.1)}$$

(ii) Conversion of Fahrenheit to Celsius scale:

$$T_C = \frac{5}{9}(T_F - 32) \quad \text{....... (7.2)}$$

(iii) Relationship between Kelvin and Celsius scales:

$$T_k = T_C + 273 \quad \text{....... (7.3)}$$

Example 7.1

How much 30°C temperature would be on Fahrenheit and Kelvin scales?

Solution

Temperature $T_C = 30°C$

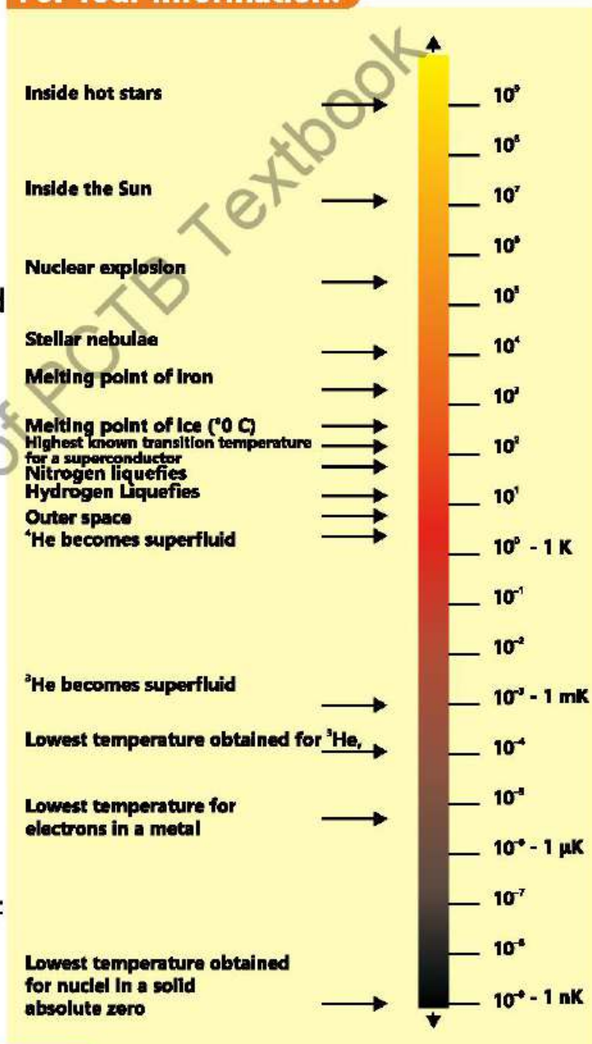
Using $T_F = \frac{9}{5} \times T_C + 32°$

$= \frac{9}{5} \times 30°C + 32° = 86°F$

Using $T_k = T_C + 273$

$= 30°C + 273 = 303K$

For Your Information!



Thermocouple Thermometer

This type of thermometer consists of two wires of different materials such as copper and iron. Their ends are joined together to form two junctions. If the two junctions are at different temperatures, a small current flows across them. This current is due to the potential difference produced across the two junctions as the two wires have different resistance to the flow of current. The greater is the difference of temperatures, the greater is the potential difference or voltage produced across the junctions. If one end of the junction is kept at a fixed lower temperature, say by placing it in an ice bath at $0^{o}C$ for reference, the temperature of other junction at a higher temperature can be measured using a millivolt meter by a calibrated scale on it (Fig. 7.8).

For Your Information!
Thermo-electric current is a thermometric property in a thermocouple

Thermocouple

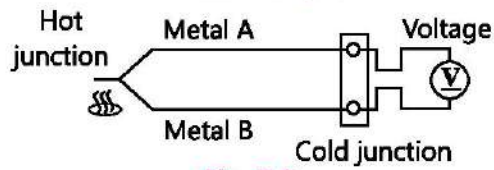


Fig. 7.8

This type of thermometer is particularly useful for very high temperatures and also rapidly changing temperature as there is only a small mass of metal (the junction) to heat up.

7.4 Sensitivity, Range and Linearity of Thermometers

A thermometer is evaluated by its three key characteristics that are sensitivity, range and linearity. They help determine the suitability of the thermometer for specific use ensuring accurate and reliable measurement of temperature.

Sensitivity

Sensitivity of a thermometer refers to its ability to detect small changes in the temperature of an object. For example, the minimum division on the scale of a thermometer is 1°C. The accuracy of its temperature measurement will be 1°C. On another thermometer the marks are 0.1°C apart. Hence, its accuracy will be up to 0.1°C and said to be more sensitive. Its measurement will be more precise than the measurement by a thermometer with an accuracy of 1°C.

Range

This refers to the span of temperature, from low to high, over which the thermometer can measure accurately. For example, a clinical thermometer designed for human body temperature has a narrow or short range, say from 35°C to 45°C. A long-range thermometer is usually used for science experiments in the laboratory with markings from −10°C to 110°C. The choice of liquid for thermometers put a lower and upper limit for the range of a thermometer. For example, Mercury freezes at -39°C and boils at 357°C. Hence, we can construct mercury in glass thermometers within this range. The marking scale depends on desired range of measurement. For extremely low temperatures, alcohol is used. Alcohol has a much lower freezing point about -112°C which increases its lower limit for the range but it has lower upper limit as it boils at 78 °C.

Linearity

This refers to a direct proportional relationship between the temperature and scale reading across entire range of measurement. A good linear thermometer should measure equal increments on the scale corresponding to equal change in the temperature. It means that marking on the scale should be evenly spaced over the whole range. High linearity means more consistent and proportional scale readings over the entire range to ensure accuracy of measurement.

7.5 Structure of a Liquid-in-Glass Thermometer

A liquid-in-glass thermometer has a narrow and uniform capillary tube having a small bulb filled with mercury or alcohol at its lower end. The thin wall of the glass bulb allows quick conduction through glass to the liquid from a hot object whose temperature is to be measured. Mercury being metal is a good conductor and hence responds quickly to the change in temperature. The small amount of liquid also responds more quickly to a change in temperature. The quick response makes the device sensitive. Use of mercury is quite sensitive for normal measurements. For greater accuracy, alcohol can be used as its expansivity is six times more than mercury but it has range limitation to higher temperature measurements due to its low boiling point (78°C).

The uniformity of the narrow tube or bore ensures even expansion of the liquid required to make the linear measuring scale. The choice of mercury allows to use it over a long-range temperature due to its low freezing point and high boiling point. It provides a fairly long range of measurement of temperature.

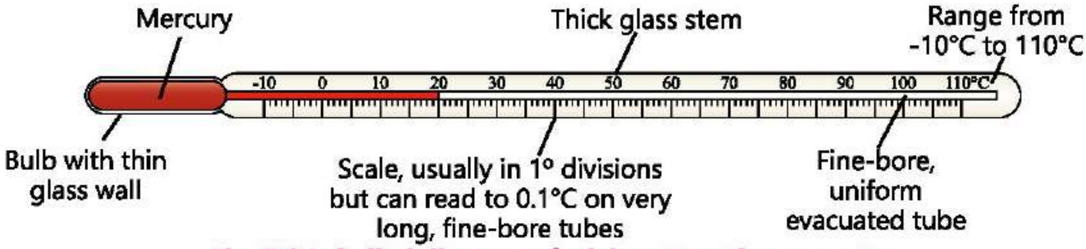


Fig. 7.9 Labelled diagram of a laboratory thermometer

KEY POINTS

- According to kinetic molecular theory of matter, the matter is composed of molecules which are in motion. The molecules possess a mutual force of attraction. The molecules have kinetic energy due to their motion and potential energy due to the force of attraction.
- Plasma consists of ionized atoms of a gas containing equal amount of positive and negative charges.
- Temperature is the degree of hotness or coldness of a body and it determines the direction of flow of heat when two bodies are brought in thermal contact.
- Heat is the form of energy which is transferred from one body to the other due to the difference in temperature.
- A body does not contain heat. It contains internal energy which is the sum of kinetic and potential energy of the total molecules of an object.
- Temperature is the degree of hotness of an object. According to molecular theory of matter, it is a measure of the average kinetic energy of the molecules of an object.
- Thermometer is a device used to measure the temperature of a body.
- Conversion of temperature from one scale to the other:
  (a) Relationship between Kelvin (T_K) and Celsius (T_C) temperature $T_K = T_C + 273$
  (b) Relationship between Celsius (T_C) also known as centigrade to Fahrenheit temperature (T_F)
  $$T_F = \frac{9}{5} \times T_C + 32$$
  (c) Relationship between Fahrenheit (T_F) to Celsius (T_C) $T_C = \frac{5}{9}(T_F - 32)$
- Thermocouple thermometer is based on the flow of electric current between two junctions of two wires of different materials due to difference of temperatures at the junctions.

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

7.1. How do the molecules in a solid behave?

(a) Move randomly
(b) Vibrate about their mean positions
(c) Rotate and vibrate randomly at their own positions
(d) Move in a straight line from hot to cold ends.

7.2. What type of motion is of the molecules in a gas?

(a) Linear motion (b) Random motion
(c) Vibratory motion (d) Rotatory motion

7.3. Temperature of a substance is:
(a) the total amount of heat contained in it
(b) the total number of molecules in it
(c) degree of hotness or coldness
(d) dependent upon the intermolecular distance

7.4. Heat is the:
(a) total kinetic energy of the molecules
(b) the internal energy
(c) work done by the molecules
(d) the energy in transit

7.5. In Kelvin scale, the temperature corresponding to melting point of ice is:
(a) zero (b) 32 (c) -273 (d) +273

7.6. The temperature which has the same value on Celsius and Fahrenheit scale is:
(a) -40 (b) +40 (c) +45 (d) -45

7.7. Which one is a better choice for a liquid-in-glass thermometer?
(a) Is colourless (b) Is a bad conductor
(c) Expand linearly (d) Wets glass

7.8. One disadvantage of using alcohol in a liquid-in-glass thermometer:
(a) it has large expansivity (b) it has low freezing point (-112°C)
(c) it wets the glass tube (d) its expansion is linear

7.9. Water is not used as a thermometric liquid mainly due to:
(a) colourless (b) a bad conductor of heat
(c) non-linear expansion (d) a low boiling point (100°C)

7.10. A thermometer has a narrow capillary tube so that it:
(a) quickly responds to temperature changes
(b) can read the maximum temperature
(c) gives a large change for a given temperature rise
(d) can measure a large range of temperature

7.11. Which thermometer is most suitable for recording rapidly varying temperature?
(a) Thermocouple thermometer
(b) Mercury-in-glass laboratory thermometer
(c) Alcohol-in-glass thermometer
(d) Mercury-in-glass clinical thermometer

B Short Answer Questions

7.1. Why solids have a fixed volume and shape according to particle theory of matter?

7.2. What are the reasons that gases have neither a fixed volume nor a fixed shape?

7.3. Compare the spacing of molecules in the solid, liquid and gaseous state.

7.4. What is the effect of raising the temperature of a liquid?

7.5. What is meant by temperature of a body?

7.6. Define heat as 'energy in transit'.

7.7. What is meant by thermometric property of a substance? Enlist some thermometric properties.

7.8. State the main scales used for the measurement of temperature.

7.9. What is meant by sensitivity of a thermometer?

7.10. What do you mean by the linearity of a thermometer?

7.11. What makes the scale reading of a thermometer accurate?

7.12. What does determine the direction of heat flow?

7.13. Distinguish between the heat and internal energy.

7.14. When you touch a cold surface, does cold travel from the surface to your hand or does energy travel from your hand to cold surface?

7.15. Can you feel your fever by touching your own forehead? Explain.

C Constructed Response Questions

7.1. Is kinetic molecular theory of matter applicable to the plasma state of matter? Describe briefly.

7.2. Why is mercury usually preferred to alcohol as a thermometric liquid?

7.3. Why is water not suitable for use in thermometers? Without calculations, guess what is equivalent temperature of 373 K on Celsius and Fahrenheit scales?

7.4. Mention two ways in which the design of a liquid-in-glass thermometer may be altered to increase its sensitivity.

7.5. One litre of water is heated by a stove and its temperature rises by 2°C. If two litres of water is heated on the same stove for the same time, what will be then rise in temperature?

7.6. Why are there no negative numbers on the Kelvin scale?

7.7. Comment on the statement. "A thermometer measures its own temperature."

7.8. There are various objects made of cotton, wood, plastic, metals, etc. In a winter night, compare their temperatures with the air temperature by touching them with your hand.

7.9. Which is greater: an increase in temperature 1°C or one 1°F?

7.10. Why would not you expect all the molecules in a gas to have the same speed?

7.11. Does it make sense to talk about the temperature of a vacuum?

7.12. Comment on the statement: "A hot body does not contain heat".

7.13. Discuss whether the Sun is matter.

D Comprehensive Questions

7.1. Describe the main points of particle theory of matter which differentiate solids, liquids and gases.

7.2. What is temperature? How is it measured? Describe briefly the construction of a mercury-in-glass thermometer.

7.3. Compare the three scales used for measuring temperature.

7.4. What is meant by sensitive, range and linearity of thermometers? Explain with examples.

7.5. Explain, how the parameters mentioned in question 7.4 are improved in the structure of liquid-in-glass thermometer.

E Numerical Problems

7.1 The temperature of a normal human body on Fahrenheit scale is 98.6°F. Convert it into Celsius scale and Kelvin scale.

(37°C, 310 K)

7.2 At what temperature Celsius and Fahrenheit thermometer reading would be the same? (-40°)

7.3 Convert 5°F to Celsius and Kelvin scale. (-15°C, 258 K)

7.4 What is equivalent temperature of 25°C on Fahrenheit and Kelvin scales?

(77°F, 298 K)

7.5 The ice and steam points on an ungraduated thermometer are found to be 192 mm apart. What temperature will be on Celsius scale if the length of mercury thread is at 67.2 mm above the ice point mark?

(35°C)

7.6 The length between the fixed point of liquid-in-glass thermometer is 20 cm. If the mercury level is 4.5 cm above the lower mark, what is the temperature on the Fahrenheit scale? (72.5°F)