3 Heat

You have learnt certain things about heat in your earlier classes. For example, you have learnt how temperature is measured. You have learnt that heat can cause (a) changes in temperature, (b) changes in state, and (c) changes in the size of solids and in the volume of liquids. You also have some idea about the ways in which heat is transferred. In this chapter, we will revise some of these ideas and discuss them in greater detail. We will also define some of the quantities involved in these processes.

HEAT IS A FORM OF ENERGY

You will recall that energy is defined as the capacity to do work. Let us see how heat satisfies this definition. In order to make a motor vehicle move, petrol is burnt inside the engine to produce heat. A set of complex processes then converts this heat to the work of moving the car. Thus, heat has the capacity to do work and is a form of energy. In this example, heat performs the work of moving the car, and as the car begins to move, this work changes to the kinetic energy of the car.

Unit of Heat

Since heat is a form of energy, it is measured in joules (J), which is the SI unit of work and energy. However, traditionally, heat is measured in calories (cal). The relation between the two quantities is

$$1 \text{ calorie} = 4.18 \text{ joules} \approx 4.2 \text{ joules}$$

The quantity 4.2 joules per calorie is called the mechanical equivalent of heat, and has the symbol *J*. This is because, under ideal conditions, 1 cal of heat can be converted into 4.2 J of (mechanical) work.

Another unit of heat called the kilocalorie (kcal) or Calorie (Cal) is still widely used, mainly in measuring the energy values of food, and the energy spent in exercise and other physical activities. As the name suggests, the kilocalorie is 1000 times the calorie. When speaking of the Calories expended in any activity, such as weightlifting or cycling, we usually say Calories 'burnt'.

Fig. 3.1 The energy value of food is measured in kilocalories or Calories.

$$1 \text{ Calorie} = 4.2 \times 10^3 \text{ joules}$$

EXAMPLE 1. A man weighing 70 kg climbs a three-storey building. Each storey has 20 steps of height 15 cm each. How many Calories of energy does he burn?

Given, mass of the man = 70 kg.

$\therefore$ weight of the man = (70×9.8) N.

This is the force the man overcomes while climbing.

Total height of stairs = $3 \times 20 \times 0.15 \text{ m} = 9 \text{ m}$.

Then work done by the man = $F \times d = 70 \times 9.8 \times 9 = 6174$ J.

Energy burnt by him = $\dfrac{6174}{4.2 \times 10^3} = 1.47$ Calories.

CALORIMETRY

The study of the heat gained or lost during physical processes and chemical reactions is called calorimetry. Temperature is of central importance in any such study since whenever a body (or a material) loses or gains heat, its temperature changes. Besides, heat flows by itself from a higher temperature to a lower temperature. You must remember that the direction in which heat flows between two bodies in contact depends only on their temperature. Thus, if a small body at a higher temperature is brought into contact with a much larger body at a lower temperature, heat will flow from the smaller to the larger body. Again, if two bodies in contact are at the same temperature, no heat will flow between them, irrespective of how hot or cold they are. This brings us to two very important points related to the flow of heat between two bodies.

Fig. 3.2 If you keep some ice cream in your mouth until it is in thermal equilibrium with your mouth, it will stop seeming cold because heat will stop flowing from your mouth to the ice cream.

- Heat flows between two bodies in contact only if they are at different temperatures.
- Heat stops flowing when the two bodies in contact reach the same temperature, or are in thermal equilibrium (equilibrium means balance).

Amount of Heat

There is a definite relation between the heat gained (or lost) by a body and the change in its temperature. The following activities will help you understand this. However, even simple experiments involving heat can be dangerous. Therefore, you must do these only in the presence of an adult.

ACTIVITY Pour a measured quantity of water into a small vessel. Record its temperature. Heat the vessel over a small flame for, say, a minute (use a watch to note the time). Then measure the temperature of the water again and find the change in temperature. Repeat the procedure, but let the water be heated for double the time. If possible, do it again and heat the water for thrice as long as the first time. You will find that the change in temperature in the second and third cases is about twice and three times the change in the first case. It should be obvious that the heat supplied in the second case and that in the third case are twice and three times as much as the heat supplied in the first case. Hence, we can conclude that the rise in temperature of a system (a solid or liquid) is proportional to the heat received by it.

Next pour a measured quantity of water into one vessel and pour double the quantity of water into another identical vessel. Measure the temperature of the water. Place both the vessels in a water bath (a large vessel of water) and heat the water for some time (Figure 3.3). (This way both the vessels of water will receive the same amount of heat.) You will find that the change in the temperature of the water in the second vessel is about half that of the water in the first vessel. Since the heat supplied in the two cases is the same, we can conclude that the rise in the temperature of a system is inversely proportional to its mass.

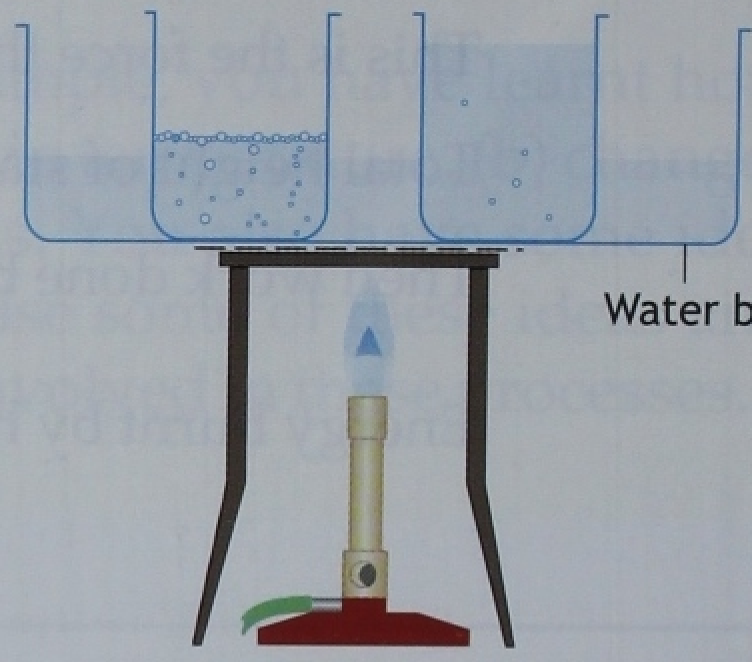


Fig. 3.3

Lastly, pour equal quantities of oil and water into two identical vessels and heat them in a water bath for the same time. You will find that the temperature of the oil rises faster than that of the water. Hence, the rise in the temperature of a substance depends on the nature of the substance.

Specific heat capacity

We can now summarise what we have learnt so far mathematically. Let Q be the heat gained by a solid or liquid of mass m. Then the rise in its temperature (θ) will be related to Q and m as follows.

$$Q = m\theta \times (\text{something related to the nature of the substance}) \quad \text{... (1)}$$

This 'something related to the nature of the substance' is called the specific heat capacity or specific heat of the substance, and has the symbol s.

Now we can write the relation (1) as

$$Q = ms\theta \quad \text{... (2)}$$

Then

$$s = \frac{Q}{m\theta} \quad \text{... (3)}$$

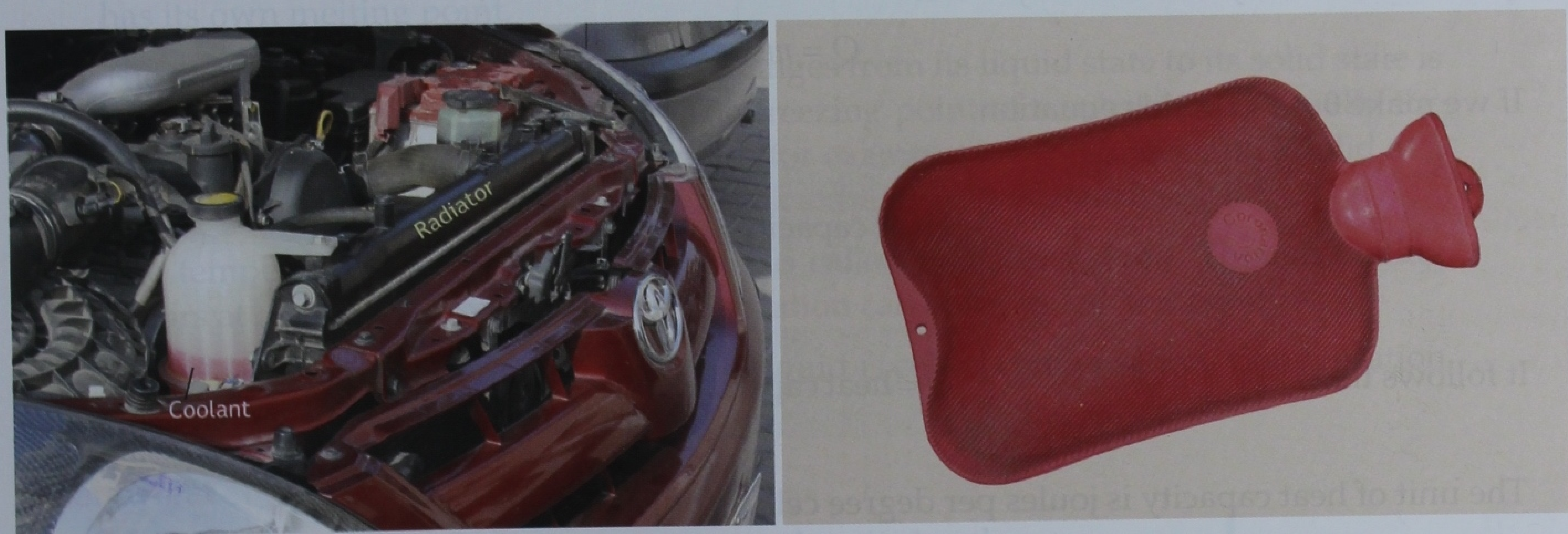
If Q is in joules (J), m in kg and θ in °C, the unit of s is J/kg °C. The relation (3) also helps us define specific heat. The specific heat of a substance is the heat required to raise the temperature of 1 kg of the substance by 1°C. The relations (2) and (3) hold for a fall in temperature as well as for a rise in temperature. Hence, s is also the amount of heat 1 kg of a substance loses when its temperature falls by 1°C.

Different materials have different specific heats. Some of these are listed in Table 3.1. Water has an unusually high specific heat. This means it has to gain (or lose) a large amount of heat for a small rise (or fall in temperature). This makes water useful in the study of heat and in many other ways, some of which are mentioned here.

Table 3.1 Specific heats of some substances

Substance	Specific heat (J/kg °C)
Water	4200
Alcohol	2400
Ice	2100
Glass	670
Iron	450
Copper	390
Lead	130
Gold	129
Silver	233

1. It is used as a coolant in car radiators, factories and power stations because it can absorb a lot of heat without becoming too hot or boiling.
2. A hot-water bottle remains hot for a long time because water has to lose a lot of heat in order to cool down.
3. The high specific heat of water causes land and sea breezes. The sea takes much longer to get heated and to cool down than the land (the specific heat of land is much lower than that of water). Hence, it is cooler than the land during the day, and warmer than the land during the night. This makes sea breezes blow in during the day and land breezes blow out during the night.



(a) (b)

Fig. 3.4 (a) Water or water-based coolants are used in car radiators. (b) A hot-water bottle works because water remains hot for a long time.

EXAMPLE 2. The temperature of a vessel weighing 250 g increases by 20°C when it absorbs 2000 J of heat. Find the specific heat capacity of the material of the vessel.

Here, $m = 250\text{ g} = 0.25\text{ kg},\ \theta = 20°\text{C},\ Q = 2000\text{ J}$.

You know that $s = \dfrac{Q}{m\theta} = \dfrac{2000\text{ J}}{0.25\text{ kg} \times 20°\text{C}} = 400\text{ J/kg °C}$.

EXAMPLE 3. How much heat would be required to raise the temperature of half a litre of water from 25°C to 35°C. The specific heat capacity of water is 4200 J/kg°C.

Here, volume of water $= 0.5\text{ L} = 500\text{ cc} = 500 \times 10^{-6}\text{ m}^3 = 5 \times 10^{-4}\text{ m}^3$.

$\therefore$ mass of water = volume × density $= 5 \times 10^{-4}\ \text{m}^3 \times 1000\ \text{kg/m}^3 = 0.5\ \text{kg}$.

Heat required $= ms\theta = 0.5\ \text{kg} \times (4200\ \text{J/kg°C}) \times 10\text{°C} = 21{,}000\ \text{J}$.

EXAMPLE 4. Find the mass of a glass bowl of specific heat capacity 600 J/kg°C if its temperature rises by 20°C when it absorbs 1200 J of heat.

$$m = \frac{Q}{s\theta} = \frac{1200\ \text{J}}{(600\ \text{J/kg°C}) \times 20\text{°C}} = 0.1\ \text{kg} = 100\ \text{g}.$$

EXAMPLE 5. A metallic cylinder of mass 100 g absorbs 1500 J of heat. Find the rise in its temperature if the specific heat capacity of the metal is 500 J/kg°C.

$$\theta = \frac{Q}{ms} = \frac{1500\ \text{J}}{0.1\ \text{kg} \times 500\ \text{J/kg°C}} = 30\text{°C}.$$

Heat capacity

The heat capacity of a body is the amount of heat required to raise its temperature by 1°C. It is also the heat lost by the body when its temperature falls by 1°C. We know that the heat required to raise the temperature of a body of mass m by θ°C is

$$Q = ms\theta.$$

If we make θ = 1°C in this equation,

$$\text{Heat capacity} = ms$$

It follows that

$$Q = \text{heat capacity} \times \theta$$

The unit of heat capacity is joules per degree celsius or J/°C.

EXAMPLE 6. Find the heat capacity of the vessel described in Example 2.

$$\text{Heat capacity} = ms = \frac{Q}{\theta} = \frac{2000\ \text{J}}{20\text{°C}} = 100\ \text{J/°C}.$$

EXAMPLE 7. Find the heat capacity of a copper vessel of mass 120 g. Take the specific heat of copper as 400 J/kg°C.

$$\text{Heat capacity} = ms = (120 \times 10^{-3})\ \text{kg} \times 400\ \text{J/kg°C} = 48\ \text{J/°C}.$$

EXAMPLE 8. A metal ball of heat capacity 50 J/°C loses 2000 J of heat. By how much will its temperature fall?

$$\text{Heat capacity} = \frac{Q}{\theta}.$$

$$\therefore\quad \theta = \frac{Q}{\text{heat capacity}} = \frac{2000\ \text{J}}{50\ \text{J/°C}} = 40\text{°C}.$$

EXAMPLE 9. A vessel of milk of heat capacity 200 J/°C was kept in a refrigerator for three hours. If its temperature fell by 15°C, how much heat did it lose per hour?

Given, heat capacity = 200 J/°C, $\theta = 15°C$.

$\therefore \quad Q = (200\ \text{J/°C}) \times 15°C = 3000\ \text{J}.$

This heat is lost in three hours.

$\therefore \quad \text{heat lost per hour} = \dfrac{3000\ \text{J}}{3} = 1000\ \text{J}.$

CHANGE OF STATE

You know that matter exists in three states, and that it changes from one state to another by gaining or losing heat. In most cases, the state in which a substance exists depends on its temperature. In general, a material will be in the solid state at lower temperatures, in the liquid state at intermediate temperatures and in the gaseous state at higher temperatures.

- The process of a solid changing into a liquid is called melting. The temperature at which this occurs is called the melting point of the substance. Every pure substance has its own melting point.
- The temperature at which a substance changes from its liquid state to its solid state is the freezing point of the substance. The freezing point of a substance is usually the same as its melting point. When a liquid (for example, lava) changes into a solid at a high temperature, we use the word solidification instead of freezing.
- The temperature at which a liquid boils is called its boiling point. Though boiling occurs at a particular temperature, evaporation can occur at any temperature.
- The process of a vapour changing into a liquid is called condensation. Condensation does not occur at a fixed temperature.

Latent Heat

When a substance changes from one state to another, it absorbs or loses a large amount of heat without any change in temperature. The following activity, which you should do only in the presence of an adult, will show you that this is true.

ACTIVITY Fill two thirds of a beaker (or any vessel) with loose wax. Heat the beaker until all the wax melts. Fix a thermometer in such a way that the bulb dips into the wax. Note the temperature at regular intervals of, say, one minute. Continue recording the temperature until a while after all the wax solidifies. Plot a graph of the temperature (y-axis) readings against time (x-axis). The curve will be similar to the one in Figure 3.6.

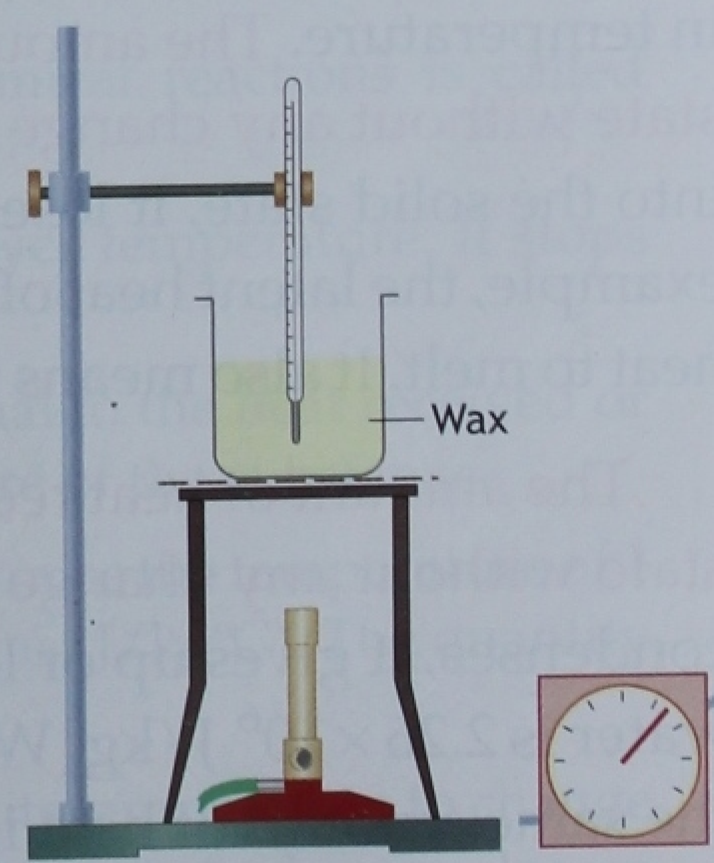


Fig. 3.5

You will notice from your readings or from the graph that the temperature of the molten wax falls until the wax starts solidifying. Then it remains steady until all the wax solidifies, and then it starts

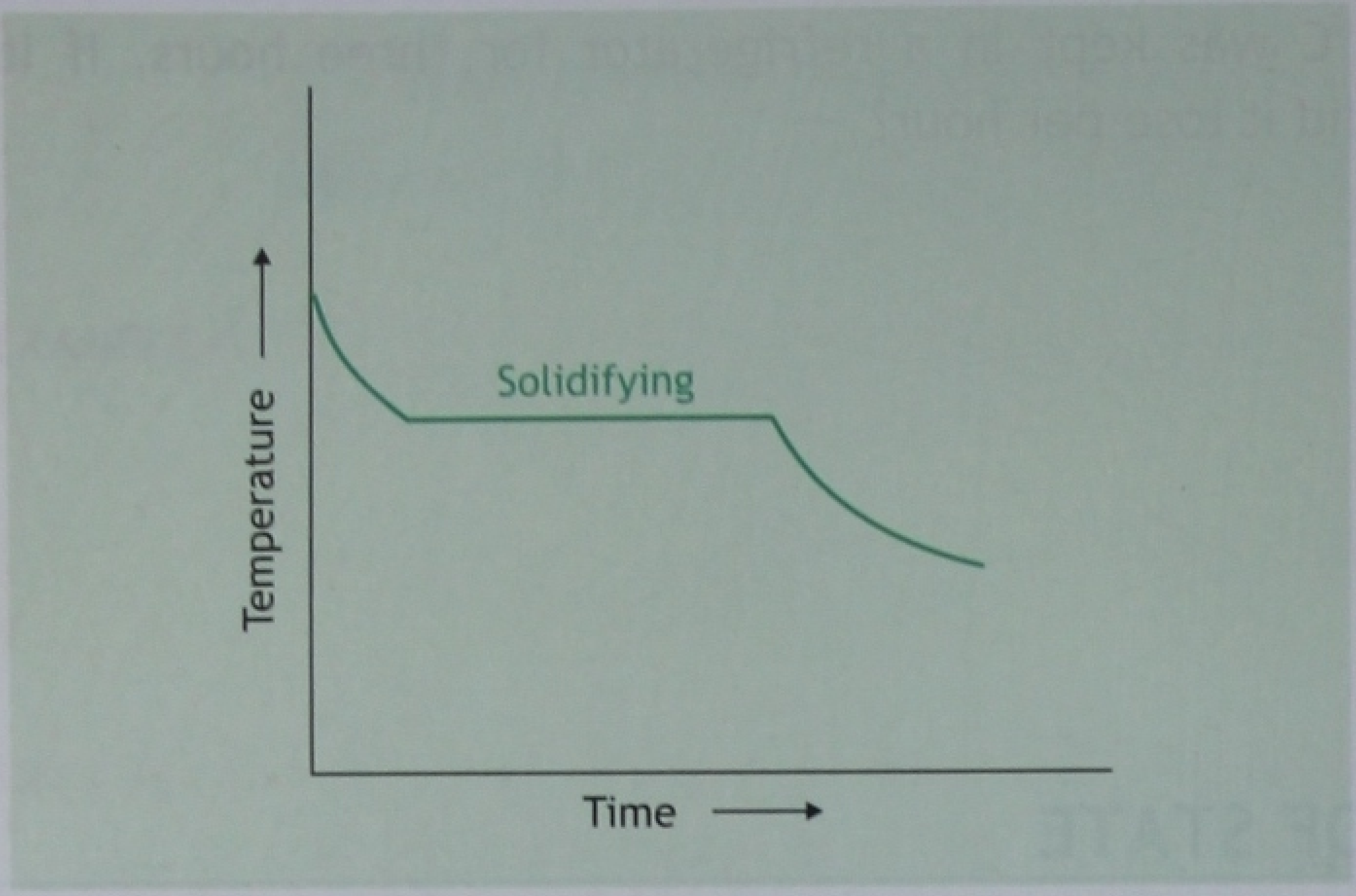


Fig. 3.6 Curve for wax

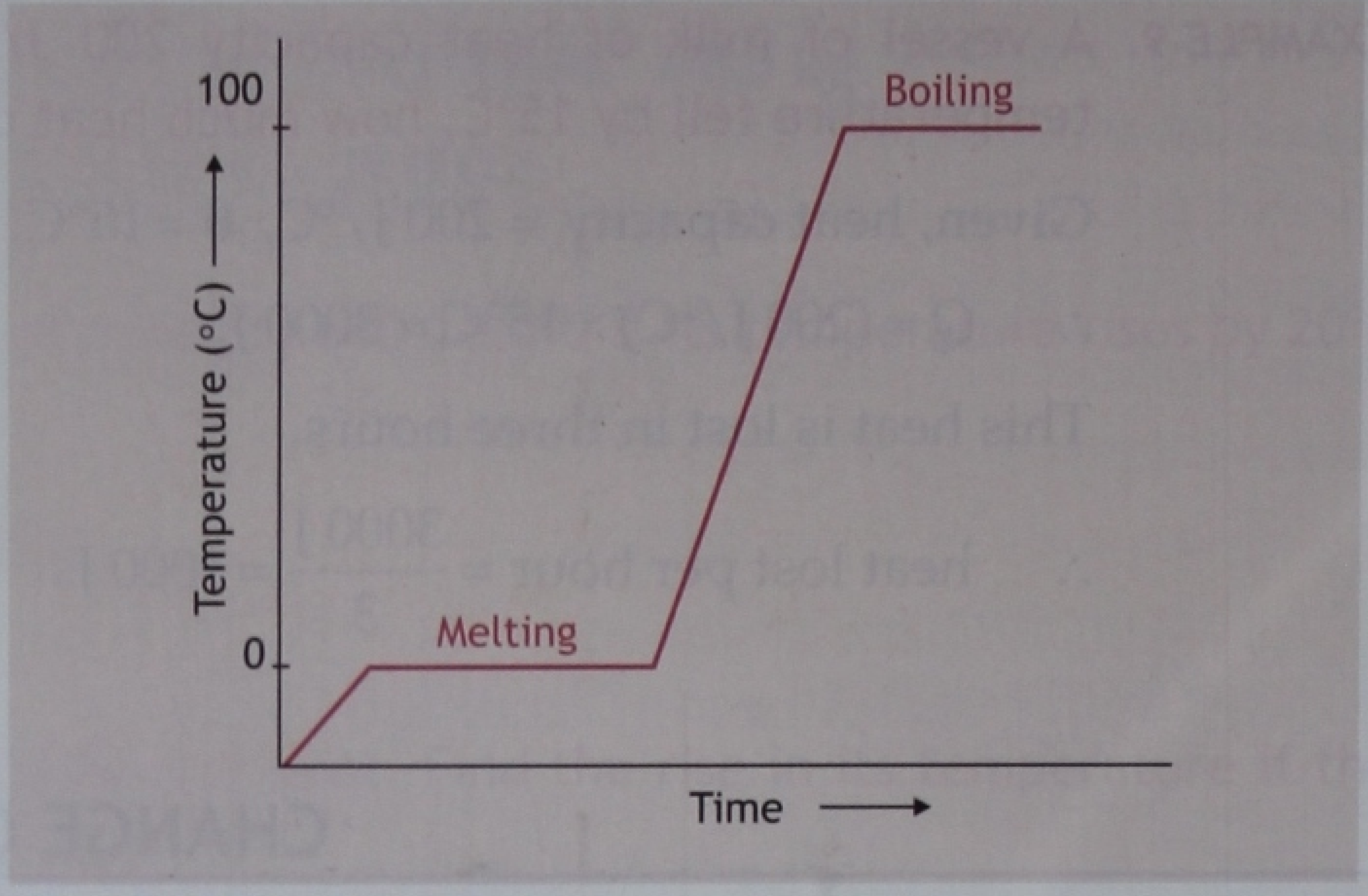


Fig. 3.7 Curve for water

falling again. You will see a similar thing if you heat some ice until it changes into water and then continue to heat the water until it starts boiling. The temperature of the ice will remain steady until all of it changes to water. Then the temperature of the water will rise until it starts boiling. After that it will become steady again though you continue to supply heat.

Why does a substance not show any change in temperature while it is changing from one state to another? Ordinarily, when a substance gains heat, its molecules gain energy and start moving faster. This shows up as a rise in temperature. However, when a solid starts changing into a liquid, all the energy absorbed by it goes into rearranging the molecules. You have learnt that the molecules of a liquid have more freedom of movement than those of a solid. Let us say that the energy absorbed during melting goes into breaking the hold of the solid molecules over each other so that they can move about with greater freedom. Similarly, when a liquid changes into a vapour, the energy absorbed by the liquid is used by its molecules to break away from the attraction of the other molecules.

A substance needs to gain a fixed amount of heat in order to change from one state to another. This fixed amount of heat is called latent heat ('latent' means hidden) because it does not show up as a rise in temperature. The amount of heat required to change 1 kg of a substance from its solid to its liquid state without any change in temperature is called its latent heat of fusion. When the liquid changes into the solid state, it loses or releases the same quantity of heat. The unit of latent heat is J/kg. For example, the latent heat of fusion of ice is 3.36×10^5 J/kg. This means 1 kg of ice requires 3.36×10^5 J of heat to melt. It also means that 3.36×10^5 J of heat is released when water freezes to form 1 kg of ice.

The amount of heat required to change 1 kg of a substance from its liquid to its vapour or gaseous state without any change in temperature is called its latent heat of vaporisation. When the vapour condenses, it gives up or loses this amount of energy. For example, the latent heat of vaporisation of water is 2.26×10^6 J/kg. Water needs to gain this amount of heat to change into the vapour state and the same amount of heat is released during condensation.

Effects of latent heat

1. Ice needs to absorb a lot of heat in order to melt. This is why just a cube or two of ice is enough to cool a drink. The ice takes the heat it needs from the drink and the drink cools.

Fig. 3.8 The melting ice takes away heat from the drink.

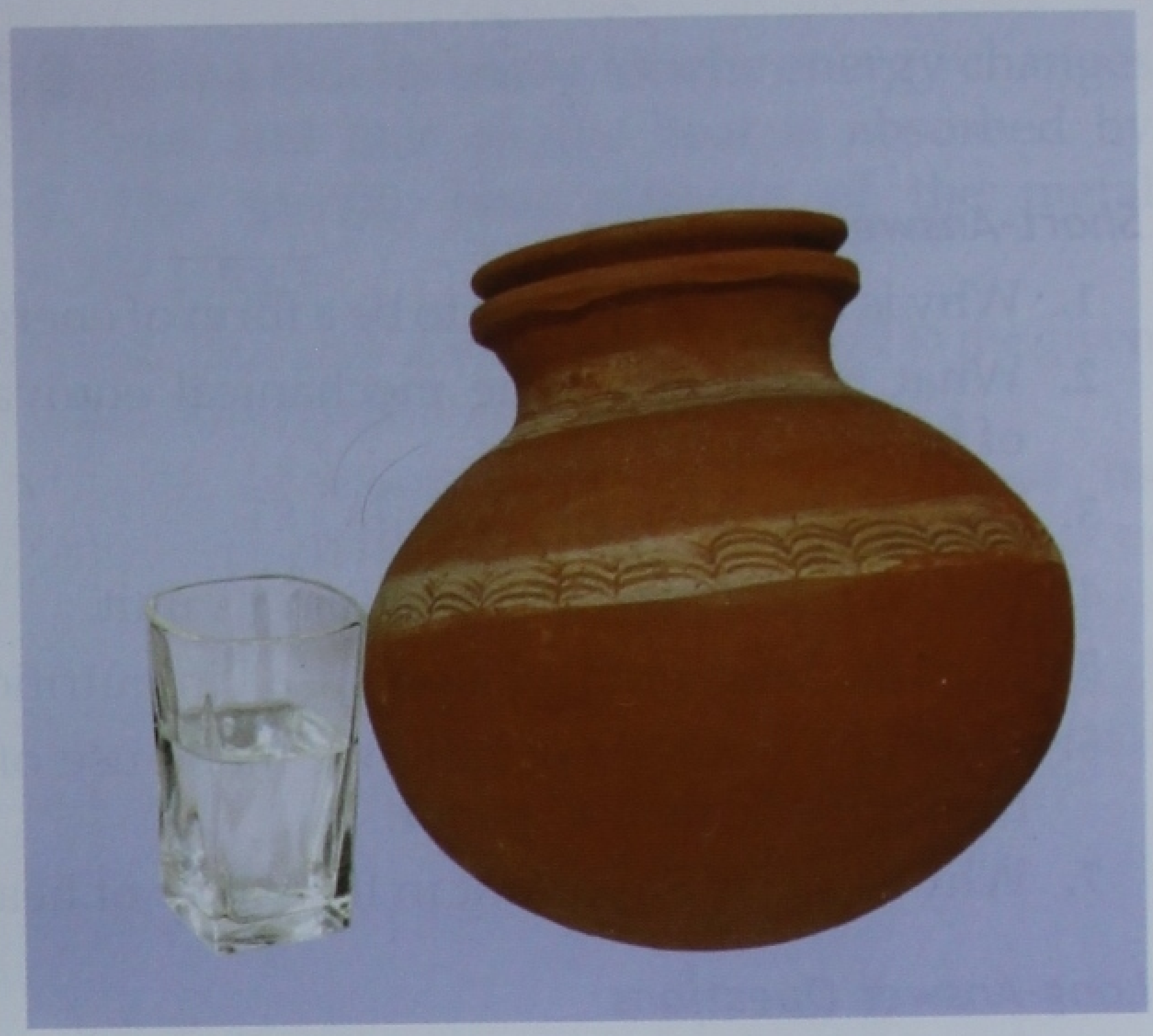


Fig. 3.9 The evaporation of water cools the water in an earthen vessel.

2. Water needs to gain a large amount of heat to change into vapour. This helps to cool the water stored in an earthen vessel. As the water seeping out of the porous vessel evaporates, it takes heat from the vessel and the water in it. In the same way, sweating helps us feel cooler. As the sweat evaporates, it takes away heat from the body. Coolers work on the same principle. The evaporating water takes away heat from the air that passes through a cooler into a room.

POINTS TO REMEMBER

- Heat has the capacity to do work. Therefore, it is a form of energy.
- The SI unit of heat is the joule. The calorie is another unit of heat. 1 cal ≈ 4.2 joules. The quantity 4.2 joules/cal is called the mechanical equivalent of heat because under ideal conditions, 1 cal of heat can be converted into 4.2 J of (mechanical) work. The kilocalorie (1000 cal) is used to measure the energy value of food and the energy spent on physical activity.
- The study of the heat gained or lost during physical processes and chemical reactions is called calorimetry.
- Heat flows by itself from a body at a higher temperature to a body at a lower temperature. It stops flowing when the two are at the same temperature.
- The change in the temperature of a system (body or substance) is proportional to the heat received or lost by it, and inversely proportional to its mass. It also depends on the nature of the substance.
- The specific heat capacity or specific heat of a substance is the heat required to raise the temperature of 1 kg of the substance by 1°C. The unit of specific heat is joules/kg degree Celsius (J/kg°C). The quantity of heat (Q) gained or lost by a system = $ms\theta$.
- The heat capacity of a system is the amount of heat it has to absorb or lose for its temperature to change by 1°C. Heat capacity = mass × specific heat capacity. The unit of heat capacity is joules per degree Celsius (J/°C).
- Changes in the state of matter usually occur at particular temperatures. The latent heat of a substance is the heat absorbed or lost by 1 kg of it to change from one state to another without any change in temperature. The unit of latent heat is J/kg.

EXERCISE

Short-Answer Questions

1. Why is heat considered to be a form of energy?
2. What is meant by the mechanical equivalent of heat?
3. Define specific heat capacity.
4. Define latent heat and mention its unit.
5. Explain the quantity Calorie used in nutrition.
6. Give one example of how we make use of the high specific heat of water.
7. Why is water important in the study of heat?

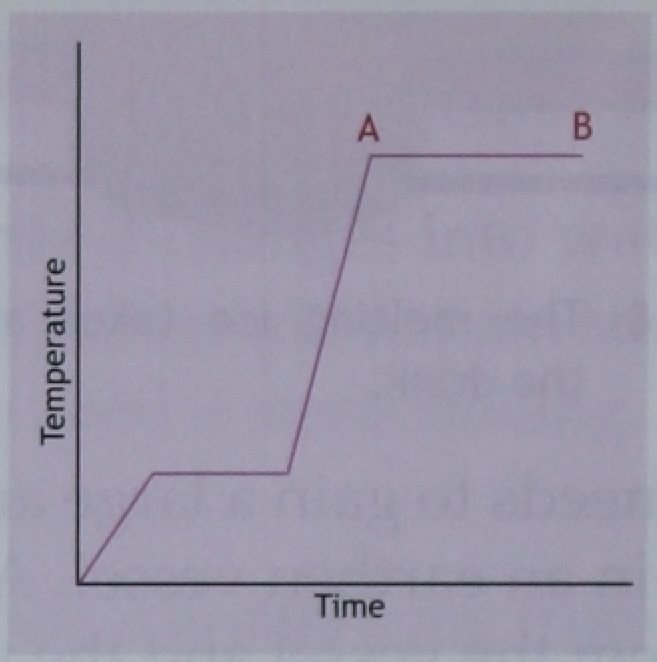
Long-Answer Questions

1. Describe an experiment to show the existence of latent heat.
2. Explain what happens during a change of state with reference to heat and temperature.
3. Distinguish clearly between heat and temperature. How do they depend on each other?
4. How are heat and work related to each other? Give examples of the two changing into each other.

Objective Questions

Choose the correct option.

1. The Calorie used to measure the energy values of foods is equal to
   (a) 4.2 J (b) 42 J
   (c) 1000 J (d) 4200 J
2. Which of the following would show a change in temperature?
   (a) A glass of water being cooled in a refrigerator
   (b) A vessel of water boiling over a flame
   (c) A bowl of ice melting slowly
   (d) Molten wax that is beginning to solidify
3. The heat capacity of a body depends
   (a) only on its temperature
   (b) only on its mass
   (c) only on its specific heat capacity
   (d) on its mass and specific heat capacity
4. Which of the following usually have the same value for most materials?
   (a) Melting point and freezing point
   (b) Latent heat and specific heat
   (c) Melting point and boiling point
   (d) None of the above
5. The unit of latent heat is
   (a) J (b) J/kg
   (c) J/℃ (d) J/kg/℃
6. The graph shows the temperature of a substance recorded at regular intervals of time. The part AB of the graph shows that the substance is



   (a) evaporating (b) boiling
   (c) condensing (d) melting
7. Sweating causes cooling because water has a
   (a) high specific heat
   (b) low specific heat
   (c) high latent heat of fusion
   (d) high latent heat of vaporisation

Fill in the blanks.

1. Heat flows by itself from a ...... to a lower ....
2. One calorie is equal to ...... joules.
3. The ratio of the heat absorbed by a body and its rise in temperature is equal to its ....
4. When a body is undergoing a change of state, there is no change in its ....
5. The state of a material usually depends on its ....

Write true or false.

1. Change of state and change of temperature usually do not take place together.
2. Water has an unusually low specific heat capacity.
3. All solids behave similarly with change of temperature.
4. Two bodies in contact must reach the same final temperature.

5. The sea is cooler than the land during the day because evaporation causes cooling.

Numericals

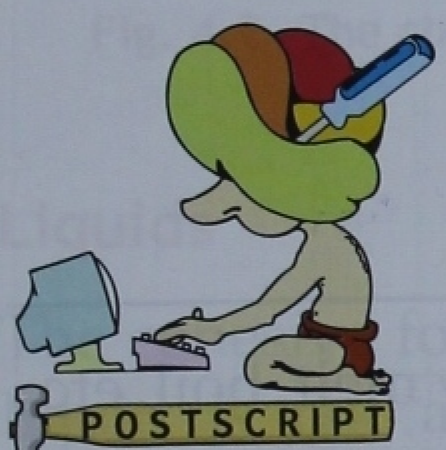
1. How much heat is required to raise the temperature of 100 g of water from 20°C to 50°C?
2. The temperature of a metal ball of mass 100 g increases by 15°C when it absorbs 600 joules of heat. Find its specific heat capacity.
3. Find the change in the temperature of a cooking utensil of heat capacity 250 J/°C, when it absorbs 500 calories of heat.
4. The temperature of a metal cylinder rises by 10°C when it absorbs 500 J of heat. If the specific heat capacity of the metal is 250 J/kg °C, what is the mass of the cylinder?
5. A metal ball falls from a height of 42 m on to the ground. Find the change in its temperature, assuming that its entire kinetic energy changes to heat and half of this heat is absorbed by it. The specific heat capacity of the metal = 420 J/kg°C.

   [**Hint:** The work done in raising the ball to the given height is converted into its kinetic energy.]
6. A piece of metal slides on a rough floor. Its speed decreases from 10 m/s to 5 m/s due to friction. Assume that half of the kinetic energy lost is absorbed by it in the form of heat. Find the increase in its temperature if the specific heat capacity of the metal = 375 J/kg°C.

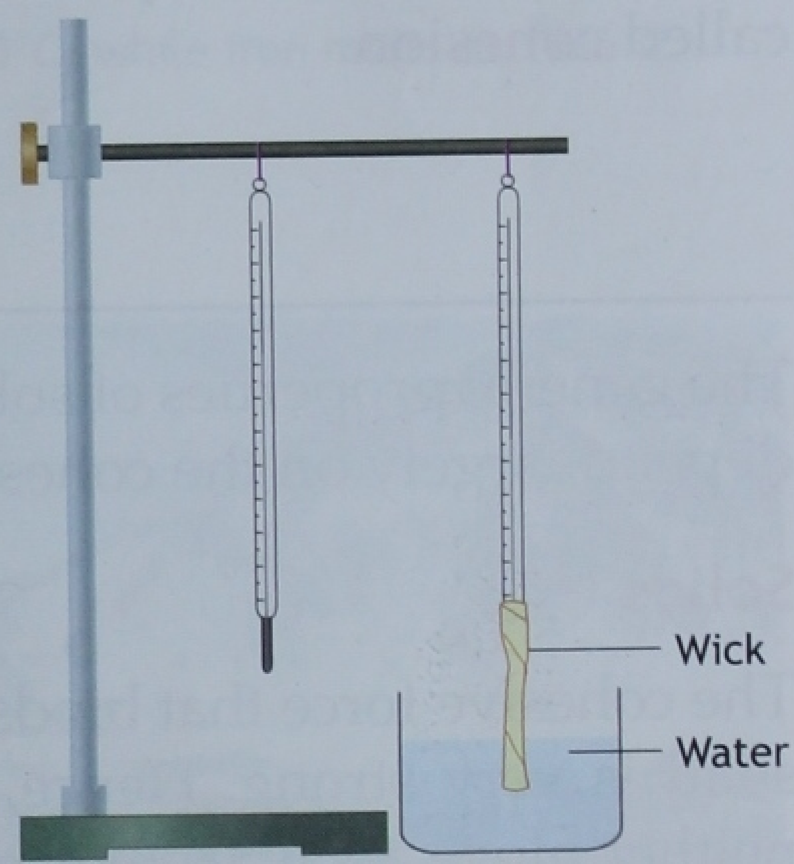
   [**Hint:** Kinetic energy $= \frac{1}{2} mv^2$.]

Answers

1. 12,600 J	**2.** 400 J/kg°C	**3.** 8.4°C
4. 200 g	**5.** 0.5°C	**6.** 0.05°C



A hygrometer is an instrument used by meteorologists to measure the humidity (wetness) of the air. You can set one up in your classroom. Suspend two thermometers from a stand. Wrap a moist wick around the bulb of one of the thermometers and let the wick dip into a bowl of water. This is to ensure that it remains moist. The temperature shown by the thermometer with the wick will fall as water evaporates from the wick (evaporation causes cooling). Let it become steady. Then record the difference between the temperatures shown by the two thermometers. This will give you an idea about the humidity of the air. When the air is dry, water will evaporate more readily and the temperature difference will be greater.



❑