2.2 Thermal properties and temperature

2.2.1 Thermal expansion of solids, liquids and gases

FOCUS POINTS

- ★ Describe thermal expansion in solids, liquids and gases and know some everyday applications of thermal expansion.
- ★ Use the motion and arrangement of particles in solids, liquids and gases to explain the relative order of magnitudes of their expansion as temperature increases.

As thermal energy is transferred to a material, the particles tend to move further apart. As you saw in Topic 2.1, the effect on heating a gas is large because the particles are free to move and expansion can easily occur. Expansion is much smaller in solids but thermal effects in a solid can still be important in conditions where there are wide temperature variations. Special features to absorb expansion need to be included in railway tracks and engineered structures such as bridges so that they do not distort on very hot days. In this topic you will encounter some everyday applications and consequences of expansion in solids and liquids.

When solids, liquids and gases are heated, the magnitude of the expansion for a given temperature rise is less for a liquid than a gas and even less for a solid where the particles are close together and the force of attraction between them is high.

Thermal expansion

According to the kinetic particle model (Topic 2.1.2) the particles of solids and liquids are in constant vibration. When heated they vibrate faster, so force each other a little further apart and **expansion** results.

The particles in a gas are free to move about rapidly and fill the entire volume of the container. When a gas is heated and its temperature rises, the average speed of its particles increases and there are more frequent collisions with the surfaces of the container. If the pressure of the gas is to remain constant, the volume of the container must increase so that the frequency of collisions does not increase; that means expansion of the gas must occur.

Relative expansion of solids, liquids and gases

The linear (length) expansion of solids is small and for the effect to be noticed, the solid must be long and/or the temperature change must be large. For a 1 m length of steel it is 0.012 mm for a 1°C rise in temperature.

The particles in a liquid are further apart, less ordered and are more mobile than in a solid so the interaction between the particles is less and expansion is easier for liquids than for solids. Liquids typically expand about five times more than solids for a given temperature rise. In gases, the interactions between particles are few because they are far apart and move about very quickly; this means they are able to expand much more easily than liquids. Typically, gases expand about 20 times more than liquids for a given temperature rise. These figures indicate that gases expand much more readily than liquids, and liquids expand more readily than solids.

Uses of expansion

Axles and gear wheels are major components of clocks on the small scale and wheeled vehicles from cars to trains on the large scale.

In Figure 2.2.1 the axles have been shrunk by cooling in liquid nitrogen at −196°C until the gear wheels can be slipped on to them. On regaining normal temperature, the axles expand to give a very tight fit.

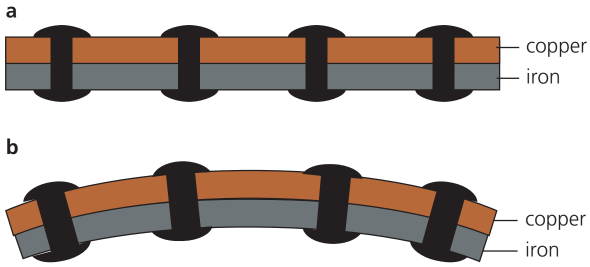
▲ **Figure 2.2.1** 'Shrink-fitting' of axles into gear wheels

In the kitchen, a tight metal lid can be removed from a glass jar by immersing the lid in hot water so that it expands and loosens. The expansion of a liquid or a gas can be used in thermometers to measure temperature (see p. 103). An expanding gas drives the pistons in the engine of a motor car.

Bimetallic strip

If equal lengths of two different metals, such as copper and iron, are riveted together so that they cannot move separately, they form a **bimetallic strip** (Figure 2.2.2a). When heated, copper expands more than iron and to allow this the strip bends with copper on the outside (Figure 2.2.2b). If they had expanded equally, the strip would have stayed straight.

Bimetallic strips have many uses.

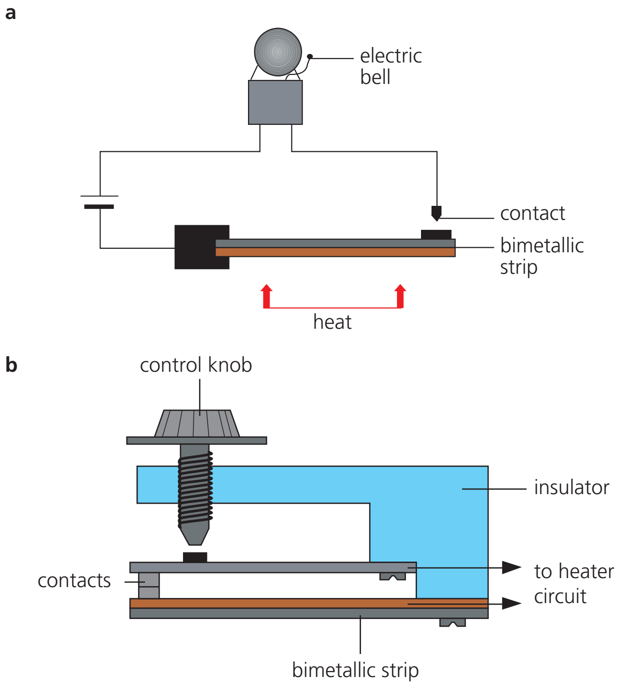


▲ **Figure 2.2.2** A bimetallic strip: **a** before heating; **b** after heating

Fire alarm

Heat from the fire makes the bimetallic strip bend and complete the electrical circuit, so ringing the alarm bell (Figure 2.2.3a).

A bimetallic strip is also used in this way to work the flashing direction indicator lamps in a car, being warmed by an electric heating coil wound round it.



▲ **Figure 2.2.3** Uses of a bimetallic strip: **a** fire alarm; **b** a thermostat in an iron

Thermostat

A **thermostat** keeps the temperature of a room or an appliance constant. The one in Figure 2.2.3b uses a bimetallic strip in the electrical heating circuit of, for example, an iron.

When the iron reaches the required temperature the strip bends down, breaks the circuit at the contacts and switches off the heater. After cooling a little, the strip remakes contact and turns the heater on again. A near-steady temperature results.

If the control knob is screwed down, the strip has to bend more to break the heating circuit and this requires a higher temperature.

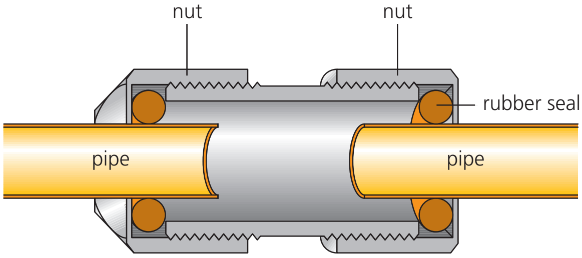
Precautions against expansion

In general, when matter is heated it expands and when cooled it contracts. If the changes are resisted large forces are created, which are sometimes useful but at other times are a nuisance.

Gaps used to be left between lengths of railway lines to allow for expansion in summer. They caused a familiar 'clickety-click' sound as the train passed over them. These days rails are welded into lengths of about 1 km and are held by concrete 'sleepers' that can withstand the large forces created without buckling. Also, at the joints the ends are tapered and overlap (Figure 2.2.4a). This gives a smoother journey and allows some expansion near the ends of each length of rail.

For similar reasons slight gaps are left between lengths of aluminium guttering. In central heating pipes 'expansion joints' are used to join lengths of pipe (Figure 2.2.4b); these allow the copper pipes to expand in length inside the joints when carrying very hot water.

▲ **Figure 2.2.4a** Tapered overlap of rails

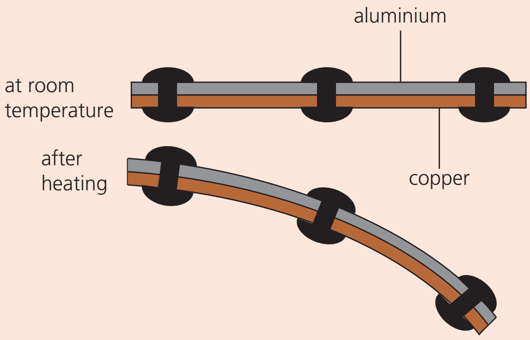


▲ **Figure 2.2.4b** Expansion joint

Test yourself

1 Explain why
  a the metal lid on a glass jam jar can be unscrewed easily if the jar is inverted for a few seconds with the *lid* in very hot water
  b furniture may creak at night after a warm day
  c concrete roads are laid in sections with pitch (a compressible filling) between them.

2 A bimetallic strip is made from aluminium and copper. When heated it bends in the direction shown in Figure 2.2.5.
  a Which metal expands more for the same rise in temperature, aluminium or copper?
  b Draw a diagram to show how the bimetallic strip would appear if it were cooled to below room temperature.



▲ **Figure 2.2.5**

Going further

Linear expansivity

An engineer has to allow for the linear expansion of a bridge when designing it. The expansion can be calculated if all the following are known:

- the length of the bridge,
- the range of temperature it will experience, and
- the linear expansivity of the material to be used.

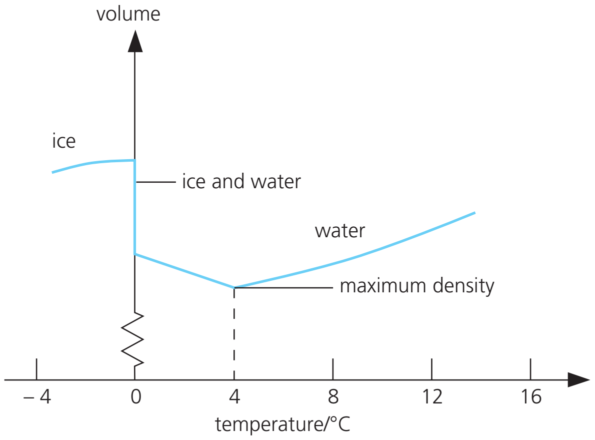
The linear expansivity of a substance is the increase in length of 1 m for a 1°C rise in temperature.

The linear expansivity of a material is found by experiment. For steel it is 0.000012 per °C. This means that 1 m will become 1.000012 m for a temperature rise of 1°C. A steel bridge 100 m long will expand by 0.000012 × 100 m for each 1°C rise in temperature. If the maximum temperature change expected is 60°C (e.g. from −15°C to +45°C), the expansion will be 0.000012 per °C × 100 m × 60°C = 0.072 m, or 7.2 cm. In general,

$$\text{expansion} = \text{linear expansivity} \times \text{original length} \times \text{temperature rise}$$

Unusual expansion of water

As water is cooled to 4°C it contracts, as we would expect. However, between 4°C and 0°C it expands, surprisingly. Water has a *maximum density* at 4°C (Figure 2.2.6).

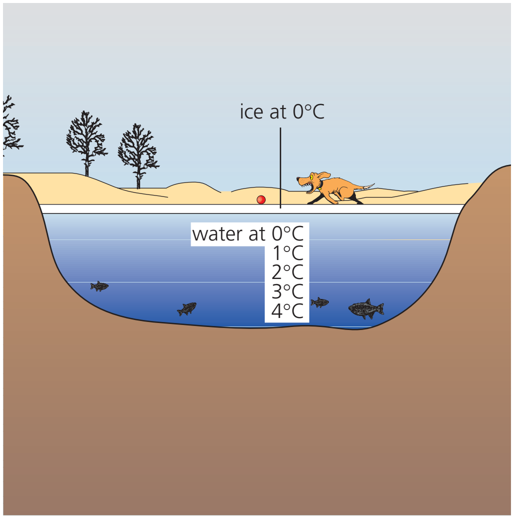


▲ **Figure 2.2.6** Water expands on cooling below 4°C.

At 0°C, when it freezes, a considerable volume expansion occurs and every 100 cm^3 of water becomes 109 cm^3 of ice. This accounts for the bursting of unlagged water pipes in very cold weather and for the fact that ice is less dense than cold water and so floats. Figure 2.2.7 shows a bottle of frozen milk, the main constituent of which is water.

▲ **Figure 2.2.7** Result of the expansion of water on freezing

The unusual (anomalous) expansion of water between 4°C and 0°C explains why fish survive in a frozen pond. The water at the top of the pond cools first, contracts and being denser sinks to the bottom. Warmer, less dense water rises to the surface to be cooled. When all the water is at 4°C the circulation stops. If the temperature of the surface water falls below 4°C, it becomes less dense and remains at the top, eventually forming a layer of ice at 0°C. Temperatures in the pond are then as in Figure 2.2.8.



▲ **Figure 2.2.8** Fish can survive in a frozen pond.

The volume expansion of water between 4°C and 0°C is due to the breaking up of the groups that water particles form above 4°C. The new arrangement requires a larger volume and more than cancels out the contraction due to the fall in temperature.

Liquid-in-glass thermometer

The temperature of a body tells us how hot the body is. It is measured using a thermometer usually in degrees Celsius (0°C).

In the liquid-in-glass thermometer the liquid in a glass bulb expands up a capillary tube when the bulb is heated. The liquid must be easily seen and must expand (or contract) rapidly and by a large amount over a wide range of temperature. It must not stick to the inside of the tube or the reading will be too high when the temperature is falling.

Mercury and coloured alcohol are commonly used liquids in this type of thermometer. Mercury freezes at –39°C and boils at 357°C but is a toxic material. A non-toxic metal alloy substitute for mercury, such as Galinstan, is often used nowadays; it melts at –19°C and boils at 1300°C. Alcohol freezes at –115°C and boils at 78°C and is therefore more suitable for low temperatures.

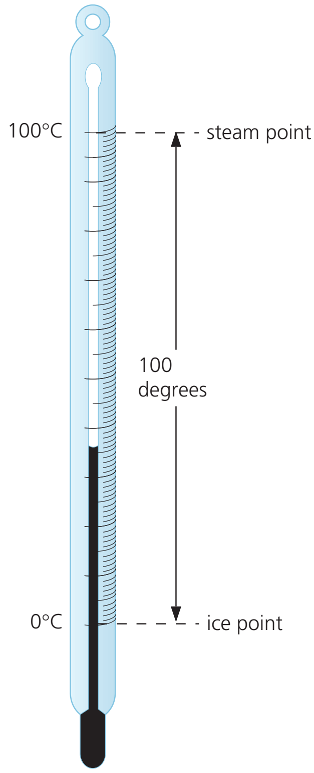
Going further

Scale of temperature

A scale and unit of temperature are obtained by choosing two temperatures, called the fixed points, and dividing the range between them into a number of equal divisions or degrees.

On the Celsius scale (named after the Swedish scientist Anders Celsius who suggested it), the lower fixed point is the temperature of pure melting ice and is taken as 0°C. The upper fixed point is the temperature of the steam above water boiling at normal atmospheric pressure, 10^5 Pa (or N/m^2), and is taken as 100°C.

When the fixed points have been marked on the thermometer, the distance between them is divided into 100 equal degrees (Figure 2.2.9). The thermometer now has a linear scale, in other words it has been *calibrated* or *graduated*.



▲ **Figure 2.2.9** A temperature scale in degrees Celsius

Test yourself

3 Explain the relative order of magnitude of the expansion of solids, liquids and gases.

4 a What is meant by the anomalous expansion of water?
  b Name two consequences of the unusual expansion of water.

5 Discuss the action of a liquid-in-glass thermometer.

2.2.2 Specific heat capacity

FOCUS POINTS

★ Know that an object's internal energy is increased when its temperature rises.

★ Explain a change in an object's temperature in terms of the change in kinetic energy of all its particles.
★ Define specific heat capacity, use the correct equation in calculations and describe experiments to measure it.

Some materials require more heat than others to raise their temperature. As discussed in the previous topic, when the temperature of an object rises, its particles move more rapidly.
The increase in the kinetic energy associated with this motion raises the internal energy of the object.

The extent of the increase in kinetic energy of the particles in a material when it is heated depends on the nature of the material and its state, and is measured in terms of specific heat capacity.
The specific heat capacity of aluminium is higher than that of copper, so copper is a more energy efficient material to use for saucepans. In this topic you will find out how to measure and calculate the specific heat capacity of some solids and liquids.

The **internal energy** of an object is the energy associated with the motion of its particles.

When an object is heated and its temperature rises, there is an increase in the internal energy of the object.

Internal energy

The kinetic particle theory (Topic 2.1.2) regards temperature as a measure of the average kinetic energy (E_k) of the particles of the body. The greater this is, the faster the particles move and the higher the temperature of the body. Increasing the temperature of an object increases its internal energy because the kinetic energy of all the particles increases.

Thermal energy and temperature

It is important not to confuse the temperature of a body with the thermal energy that can be obtained from it. For example, a red-hot spark from a fire is at a higher temperature than the boiling water in a saucepan. In the boiling water the average kinetic energy of the particles is lower than in the spark; but since there are many more water particles, their total energy is greater, and therefore more thermal energy can be supplied by the water than by the spark.

Thermal energy is transferred from a body at a higher temperature to one at a lower temperature.

This is because the average kinetic energy (and speed) of the particles in the hot body falls as a result of the collisions with particles of the cold body whose average kinetic energy, and therefore temperature, increases. When the average kinetic energy of the particles is the same in both bodies, they are at the same temperature. For example, if the red-hot spark landed in the boiling water, thermal energy would be transferred from it to the water even though much more thermal energy could be obtained from the water.

Specific heat capacity

If 1 kg of water and 1 kg of paraffin are heated in turn for the same time by the same heater, the temperature rise of the paraffin is about *twice* that of the water. Since the heater gives equal amounts of thermal energy to each liquid, it seems that different substances require different amounts of energy to cause the same temperature rise in the same mass, say 1°C in 1 kg.

The amount of heat required to raise the temperature of a particular substance by one degree is measured by its **specific heat capacity** (symbol c).

The specific heat capacity of a substance is defined as the energy required per unit mass per unit temperature increase.

In physics, the word 'specific' means that unit mass is being considered.

In general, for a mass m, receiving energy ΔE which results in a temperature rise $\Delta\theta$, this can be written in equation form as

$$c = \frac{\Delta E}{m\Delta\theta}$$

where c is the specific heat capacity of a material of mass m whose temperature rises by $\Delta\theta$ when its internal energy increases by ΔE.

Internal energy is measured in joules (J) and the unit of specific heat capacity is the joule per kilogram per °C, i.e. J/(kg °C).

The equation for specific heat can be rearranged to give the equation:

$$\Delta E = mc\Delta\theta = \text{mass} \times \text{specific heat capacity} \times \text{temperature rise}$$

Key definition

Specific heat capacity the energy required per unit mass per unit temperature increase

Worked example

If 20 000 J is supplied to a mass of 5 kg and its temperature rises from 15°C to 25°C, calculate the specific heat capacity of the mass.

Using $c = \dfrac{\Delta E}{m\Delta\theta}$

$$c = \frac{20000\ \text{J}}{(5\,\text{kg} \times (25-15)\,°\text{C})} = \frac{20000\ \text{J}}{50\ \text{kg}\,°\text{C}} = \frac{400\,\text{J}}{\text{kg}\,°\text{C}}$$

Now put this into practice

1 If 25 000 J of energy is supplied to a mass of 2 kg and its temperature rises from 10°C to 35°C, calculate the specific heat capacity of the mass.
2 How much energy must be supplied to a mass of 3 kg of material of specific heat capacity = 500 J/(kg °C) to raise its temperature by 10°C?

Practical work

Finding specific heat capacities

For safe experiments/demonstrations related to this topic, please refer to the *Cambridge IGCSE Physics Practical Skills Workbook* that is also part of this series.

Safety

- Eye protection must be worn.
- Take care as the pan and water and aluminium block may become hot.

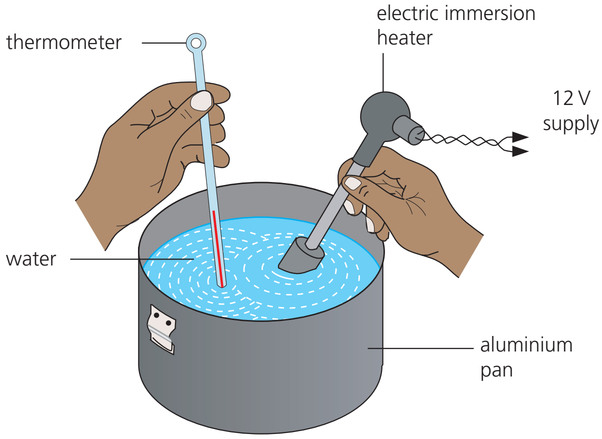
You need to know the power of the 12 V electric immersion heater to be used.

Precaution: Do not use one with a cracked seal.

A 40 W heater transfers 40 joules of energy to thermal energy per second. If the power is not marked on the heater, ask about it.

Water

Weigh out 1 kg of water into a container, such as an aluminium saucepan. Note the temperature of the water, insert the heater (Figure 2.2.10), switch on the 12 V supply and start timing. Stir the water and after 5 minutes switch off but continue stirring and note the *highest* temperature reached.



▲ **Figure 2.2.10**

Assuming that the energy supplied by the heater equals the heat received by the water, work out the specific heat capacity of water in J/(kg °C), as shown below:

$$\text{heat received by water (J)} = \text{power of heater (J/s)} \times \text{time heater on (s)}$$

then the

$$\text{specific heat capacity of water} = \frac{\text{heat received by water (J)}}{\text{mass (kg)} \times \text{temp. rise (°C)}}$$

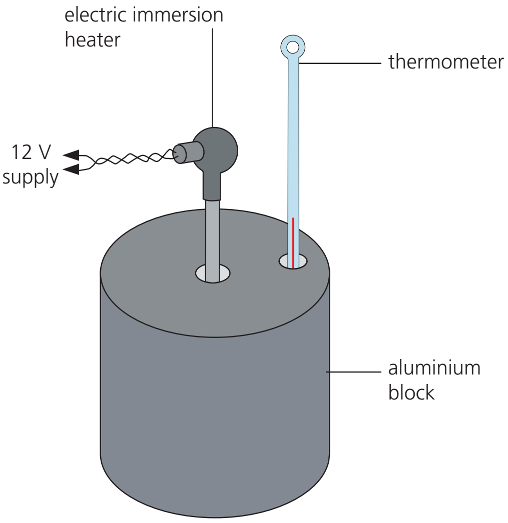
1 Suggest sources of error in the experiment described above to find the specific heat capacity of water.
2 In an experiment to determine the specific heat capacity of water, the temperature rise of 1 kg of water is found to be 2.5°C when the water is heated by a 40 W heater for 5 minutes. Calculate the specific heat capacity of water.

Aluminium

An aluminium cylinder weighing 1 kg and having two holes drilled in it is used. Place the immersion heater in the central hole and a thermometer in the other hole (Figure 2.2.11).

Note the temperature, connect the heater to a 12 V supply and switch it on for 5 minutes. When the temperature stops rising, record its highest value.

Calculate the specific heat capacity as before.



▲ **Figure 2.2.11**

3 Suggest a source of error in the experiment to measure the specific heat capacity of aluminium and suggest how the experiment could be improved.

4 In an experiment to determine the specific heat capacity of aluminium, the temperature rise of an aluminium cylinder weighing 1 kg is found to be 12.5°C when the cylinder is heated by a 40 W heater for 5 minutes. Calculate the specific heat capacity of aluminium.

Importance of the high specific heat capacity of water

The specific heat capacity of water is 4200 J/(kg °C) and that of soil is about 800 J/(kg °C). As a result, the temperature of the sea rises and falls more slowly than that of the land. A certain mass of water needs five times more energy than the same mass of soil for its temperature to rise by 1°C. Water also has to give out more energy to fall 1°C. Since islands are surrounded by water, they experience much smaller changes of temperature from summer to winter than large land masses such as Central Asia.

The high specific heat capacity of water (as well as its cheapness and availability) accounts for its use in cooling engines and in the radiators of central heating systems.

Worked example

a A tank holding 60 kg of water is heated by a 3 kW electric immersion heater. If the specific heat capacity of water is 4200 J/(kg °C), estimate the time for the temperature to rise from 10°C to 60°C.

Rearranging $c = \frac{\Delta E}{m\Delta\theta}$ gives $\Delta E = mc\Delta\theta$

Energy supplied to water = 3000 J/s × t, where t is the time of heating in seconds.

Assuming energy supplied = energy received by water

$$3000\,\text{J/s} \times t = \Delta E = mc\Delta\theta$$

$$\therefore t = \frac{(60 \times 4200 \times 50)\,\text{J}}{3000\ \text{J/s}} = 4200\ \text{s}\ (70\ \text{min})$$

b A piece of aluminium of mass 0.5 kg is heated to 100°C and then placed in 0.4 kg of water at 10°C. If the resulting temperature of the mixture is 30°C, what is the specific heat capacity of aluminium if that of water is 4200 J/(kg °C)?

When two substances at different temperatures are mixed, energy flows from the one at the higher temperature to the one at the lower temperature until both are at the same temperature – the temperature of the mixture. If there is no loss of energy, then in this case:

energy given out by aluminium = energy taken in by water

Using the heat equation $\Delta E = mc\Delta\theta$ and letting c be the specific heat capacity of aluminium in J/(kg °C), we have

$$\text{energy given out} = 0.5\,\text{kg} \times c \times (100 - 30)\,^\circ\text{C}$$

$$\text{energy taken in} = 0.4\,\text{kg} \times 4200\,\text{J/(kg}\,^\circ\text{C)} \times (30 - 10)\,^\circ\text{C}$$

$$\therefore\ 0.5\,\text{kg} \times c \times 70\,^\circ\text{C} = 0.4\,\text{kg} \times 4200\,\text{J/(kg}\,^\circ\text{C)} \times 20\,^\circ\text{C}$$

$$c = \frac{(4200 \times 8)\,\text{J}}{35\ \text{kg}\,^\circ\text{C}} = 960\ \text{J/kg}\,^\circ\text{C}$$

Now put this into practice

1. An electric kettle rated at 3 kW containing 1 kg of water is switched on. If the specific heat capacity of water is 4200 J/(kg °C), estimate the time for the water temperature to rise from 30°C to 100°C.
2. A metal sphere of mass 100 g is heated to 100°C and then placed in 200 g of water at 20°C. If the resulting temperature of the mixture is 25°C, what is the specific heat capacity of the metal if that of water is 4200 J/(kg °C)?

Test yourself

6 Which one of the following statements is *not* true?
 A Temperature tells us how hot an object is.
 B When the temperature of an object rises so does its internal energy.
 C Heat flows naturally from an object at a lower temperature to one at a higher temperature.
 D The particles of an object move faster when its temperature rises.

7 How much thermal energy is needed to raise the temperature by 10°C of 5 kg of a substance of specific heat capacity 300 J/(kg °C)?

8 How long will it take a 3 kW immersion heater to raise the temperature of 5 kg of water from 30°C to 50°C?

2.2.3 Melting, boiling and evaporation

FOCUS POINTS

★ Describe melting and boiling, including the temperatures for both for water.
★ Describe condensation, solidification and evaporation in terms of particles.

★ Understand the differences between boiling and evaporation.
★ Describe the factors that affect evaporation.

To melt a bar of chocolate you will need to heat it. Melting and boiling require the input of energy to change the state of matter from solid to liquid or from liquid to gas. In the reverse changes, heat is released. During a change of state there is no change in temperature until the process is complete. The kinetic particle model can help us to understand the processes which occur during a change of state. In this section you will also learn how the model explains evaporation and cooling in terms of the escape of energetic particles from the surface of a liquid.

You will learn the differences between the processes of evaporation and boiling and the factors which affect the rate of cooling of an object.

When a solid is heated, it may melt and *change its state* from solid to liquid. If ice is heated it becomes water. The opposite process, freezing, occurs when a liquid solidifies.

A pure substance melts at a definite temperature, called the **melting temperature**; it solidifies at the same temperature – sometimes then called the **freezing temperature**. At standard atmospheric pressure, the melting temperature of water is 0°C.

Practical work

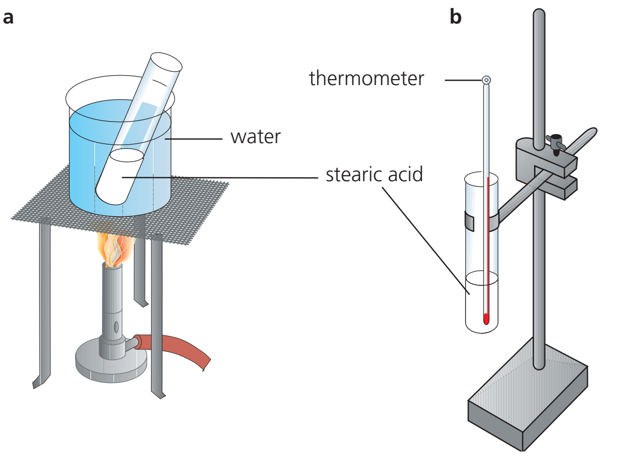
Cooling curve of stearic acid

Safety

- Eye protection must be worn.

Half fill a test tube with stearic acid and place it in a beaker of water (Figure 2.2.12a). Heat the water until all the stearic acid has melted and its temperature reaches about 80°C.

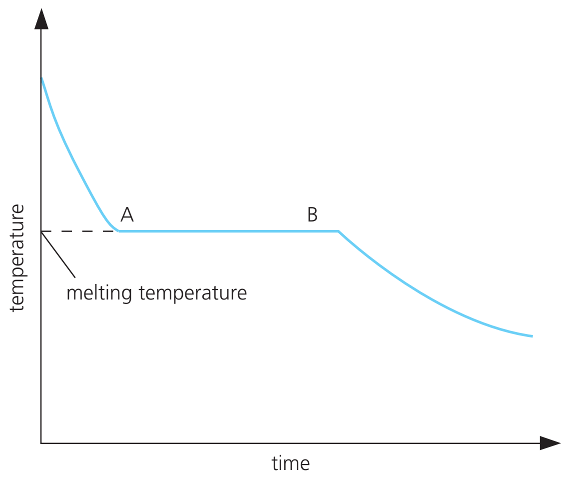
Remove the test tube and arrange it as in Figure 2.2.12b, with a thermometer in the liquid stearic acid. Record the temperature every minute until it has fallen to 60°C.



▲ **Figure 2.2.12**

5 Plot a graph of temperature against time (a cooling curve) and identify the freezing temperature of stearic acid.

6 The cooling curve (a plot of temperature against time) for a pure substance is shown in Figure 2.2.13. Why is the cooling curve flat in the region AB?



▲ **Figure 2.2.13** Cooling curve

7 What is happening to the liquid over region AB in Figure 2.2.13?

8 Is the rate of cooling faster or slower at higher temperatures in Figure 2.2.13?

Solidifying, melting and boiling

The previous experiment shows that the temperature of liquid stearic acid falls until it starts to solidify (at 69°C) and remains constant until it has all solidified. The cooling curve in Figure 2.2.13 is for a pure substance; the flat part AB occurs at the melting temperature when the substance is solidifying.

During *solidification* a substance transfers thermal energy to its surroundings but its temperature does not fall. Conversely when a solid is *melting*, the energy supplied does not cause a temperature rise; energy is transferred but the substance does not get hotter. For example, the temperature of a well-stirred ice–water mixture remains at 0°C until all the ice is melted. Similarly when energy is supplied to a boiling liquid, the temperature of the liquid does not change. The temperature of pure water boiling at standard atmospheric pressure is 100°C.

Going further

Latent heat of fusion

Energy that is transferred to a solid during melting or given out by a liquid during solidification is called latent heat of fusion. Latent means hidden and fusion means melting. Latent heat does not cause a temperature change; it seems to disappear.

Specific latent heat of fusion

The specific latent heat of fusion (l_f) of a substance is the quantity of heat needed to change *unit mass* from solid to liquid without temperature change.

Specific latent heat is measured in J/kg or J/g.
In general, the quantity of heat ΔE needed to change a mass m from solid to liquid is given by

$$\Delta E = m \times l_f$$

Practical work

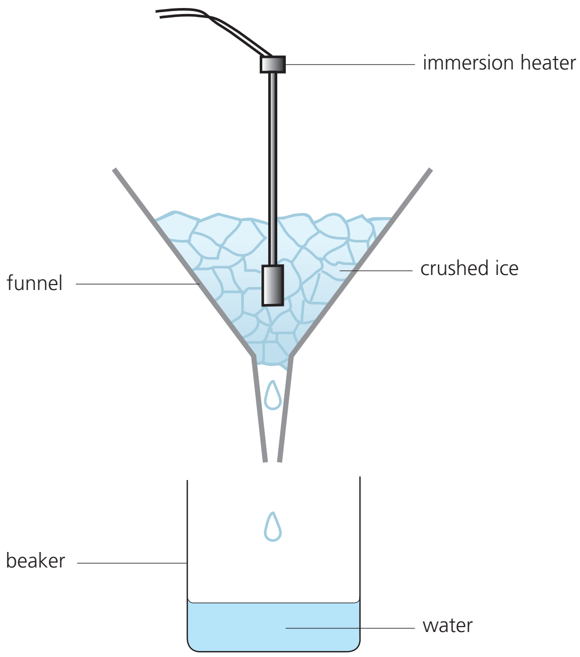
Specific latent heat of fusion for ice

Safety

- Eye protection must be worn.

Through measurement of the mass of water m produced when energy ΔE is transferred to melting ice, the specific latent heat of fusion for ice can be calculated.

Insert a 12 V electric immersion heater of known power P into a funnel, and pack crushed ice around it as shown in Figure 2.2.14.



▲ **Figure 2.2.14**

To correct for heat transferred from the surroundings, collect the melted ice in a beaker for time t (e.g. 4 minutes); weigh the beaker plus the melted ice, m_1. Empty the beaker, switch on the heater, and collect the melted ice for the same time t; re-weigh the beaker plus the melted ice, m_2. The mass of ice melted by the heater is then

$$m = m_2 - m_1$$

The energy supplied by the heater is given by $\Delta E = P \times t$, where P is in J/s and t is in seconds; ΔE will be in joules. Alternatively, a joulemeter can be used to record ΔE directly.

9 Use your data to calculate the specific latent heat of fusion, l_f, for ice from the equation $\Delta E = m \times l_f$.

10 What correction is made in the above experiment to measure the specific latent heat of fusion of ice to compensate for heat gained from the surroundings?

11 How could you reduce heat loss to the surroundings in this experiment?

Going further

Latent heat of vaporisation

Latent heat is also needed to change a liquid into a vapour. The reading of a thermometer placed in water that is boiling remains constant at 100°C even though heat, called *latent heat of vaporisation*, is still being transferred to the water from whatever is heating it. When steam condenses to form water, latent heat is given out. A scald from steam is often more serious than one from boiling water (Figure 2.2.15).

▲ **Figure 2.2.15** Steam from boiling water; invisible steam near the spout condenses into visible water droplets higher up.

Specific latent heat of vaporisation

The specific latent heat of vaporisation (l_v) of a substance is the quantity of heat needed to change unit mass from liquid to vapour without change of temperature.

Again, the specific latent heat is measured in J/kg or J/g. In general, the quantity of heat ΔE to change a mass m from liquid to vapour is given by

$$\Delta E = m \times l_v$$

To change 1 kg of water at 100°C to steam at 100°C needs over *five* times as much heat as is needed to raise the temperature of 1 kg of water at 0°C to water at 100°C.

Test yourself

9 1530°C 100°C 55°C 37°C 19°C 0°C −12°C −50°C

From the above list of temperatures choose the most likely value for *each* of the following:

- **a** the melting temperature of iron
- **b** the temperature of a room that is comfortably warm
- **c** the melting temperature of pure ice at normal pressure
- **d** the boiling temperature of water
- **e** the normal body temperature of a healthy person.

10 **a** Why is ice good for cooling drinks?

b Why do engineers often use superheated steam (steam above 100°C) to transfer heat?

Change of state and the kinetic particle model

Melting and solidification

The kinetic particle model explains the energy absorbed in melting as being the energy that enables the particles of a solid to overcome the intermolecular forces that hold them in place, and when it exceeds a certain value, they break free. Their vibratory motion about fixed positions changes to the slightly greater range of movement they have as liquid particles, and the solid melts. In the reverse process of solidification in which the liquid returns to the solid state, where the range of movement of the particles is less, potential energy is transferred from the particles to thermal energy in the surroundings.

The energy input in melting is used to increase the potential energy (ΔE_p) of the particles, but not their average kinetic energy (E_k) as happens when the energy input causes a temperature rise.

Vaporisation and condensation

If liquid particles are to overcome the forces holding them together and gain the freedom to move around independently as gas particles, they need a large amount of energy. This energy increases the potential energy of the particles but not their kinetic energy. Energy is also required to push back the surrounding atmosphere in the large expansion that occurs when a liquid vaporises. In the reverse process of condensation, in which a vapour returns to the liquid state, where the particles are closer together, potential energy is transferred from the particles to thermal energy in the surroundings.

Boiling and evaporation

At standard atmospheric pressure, the boiling temperature of water is 100°C.

Boiling

For a pure liquid, boiling occurs at a definite temperature called its *boiling temperature* and is accompanied by bubbles that form within the liquid, containing the gaseous or vapour form of the particular substance.

Energy is needed in both evaporation and boiling and is stored in the vapour, from which it is released when the vapour is cooled or compressed and changes to liquid again.

Evaporation

A few energetic particles close to the surface of a liquid may escape and become gas particles. This process of **evaporation** occurs at all temperatures.

Conditions affecting evaporation

Evaporation happens more rapidly when

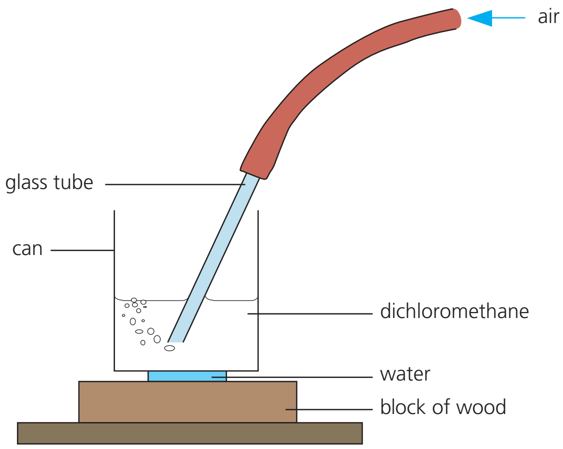
- the *temperature is higher*, since then more particles in the liquid are moving fast enough to escape from the surface
- the *surface area of the liquid is large*, so giving more particles a chance to escape because more are near the surface
- a *wind* or *draught* is blowing over the surface carrying vapour particles away from the surface, thus stopping them from returning to the liquid and making it easier for more liquid particles to break free. (Evaporation into a vacuum occurs much more rapidly than into a region where there are gas particles.)

Cooling by evaporation

In evaporation, energy is transferred to the liquid from its surroundings, as may be shown by the following demonstration, *done in a fume cupboard*.

Demonstration

Dichloromethane is a volatile liquid, i.e. it has a low boiling temperature and evaporates readily at room temperature, especially when air is blown through it (Figure 2.2.16). Energy is transferred first from the liquid itself and then from the water below the can. The water soon freezes causing the block and can to stick together.



▲ **Figure 2.2.16** Demonstrating cooling by evaporation

Explanation

Evaporation occurs when faster-moving particles escape from the surface of the liquid. The average speed and therefore the average kinetic energy of the particles left behind decreases, i.e. the temperature of the liquid falls.

Cooling by contact

When evaporation occurs from a liquid and the average kinetic energy of the remaining particles decreases, the liquid cools. In Topic 2.3.1 we will see that thermal energy flows from a hotter to a colder object by conduction. If an object is in contact with the liquid during evaporation, thermal energy will flow from the object to the liquid. The object will cool until its temperature equals that of the liquid.

Uses

Water evaporates from the skin when we sweat. This is the body's way of losing unwanted heat and keeping a constant temperature. After vigorous exercise there is a risk of the body being overcooled, especially in a draught; it is then less able to resist infection.

Ether acts as a local anaesthetic by chilling (as well as cleaning) your arm when you are having an injection. Refrigerators, freezers and air-conditioning systems use cooling by evaporation on a large scale.

Volatile liquids are used in perfumes.

Test yourself

11 a When a solid is melting
- **i** does its temperature increase, decrease or remain constant
- **ii** is energy absorbed or released or neither?

b When a liquid is boiling does its temperature increase, decrease or remain constant?

12 a Describe the process of evaporation in particle terms.

b How does the temperature of a liquid change during evaporation?

13 Some water is stored in a bag of porous material, such as canvas, which is hung where it is exposed to a draught of air. Explain why the temperature of the water is lower than that of the air.

Revision checklist

After studying Topic 2.2 you should know and understand:

✔ that a rise in the temperature of an object increases its internal energy

✔ the relation between an object's temperature and the kinetic energy of the particles

✔ that melting and boiling occur without a change in temperature and recall those temperatures for water.

After studying Topic 2.2 you should be able to:

✔ describe the thermal expansion of solids and liquids

✔ describe precautions taken against expansion and uses of expansion

✔ explain the relative order of magnitude of the expansion of solids, liquids and gases

✔ distinguish between evaporation and boiling

✔ define specific heat capacity, c, and solve problems using the equation $c = \frac{\Delta E}{m\Delta\theta}$

✔ describe experiments to measure the specific heat capacity of metals and liquids by electrical heating

✔ describe condensation, solidification and evaporation processes in terms of the kinetic particle model

✔ explain cooling by evaporation

✔ recall the factors which affect evaporation.

Exam-style questions

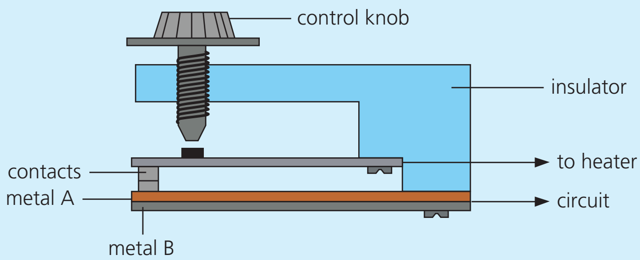
1

a A gas expands more easily than a liquid. Explain in terms of the motion and arrangement of particles. [3]

b Explain why water pipes may burst in cold weather. [2]

[Total: 5]

2 A bimetallic thermostat for use in an iron is shown in Figure 2.2.17.



▲ **Figure 2.2.17**

State if the following statements are *correct* or *incorrect*.

A It operates by the bimetallic strip bending away from the contact. [1]

B Metal A has a greater expansivity than metal B. [1]

C Screwing in the control knob raises the temperature at which the contacts open. [1]

[Total: 3]

3 The same quantity of heat was given to different masses of three substances A, B and C. The temperature rise in each case is shown in the table. Calculate the specific heat capacities of A, B and C.

Material	Mass/kg	Heat given/J	Temp. rise/°C
A	1.0	2000	1.0
B	2.0	2000	5.0
C	0.5	2000	4.0

[3 marks for each of A, B, C]

[Total: 9]

4 a The jam in a hot jam tart always seems hotter than the pastry. Why? [2]

b Calculate the temperature rise of 3 kg of a material of specific heat capacity 500 J/(kg °C) when it is heated with 15 000 J of energy. [3]

[Total: 5]

5 a A certain liquid has a specific heat capacity of 4.0 J/(g °C). How much energy must be supplied to raise the temperature of 10 g of the liquid from 20°C to 50°C? [3]

b Explain why a bottle of milk keeps better when it stands in water in a porous pot in a draught. [3]

[Total: 6]

6 a Define

i melting temperature

ii boiling temperature

iii freezing temperature. [3]

b State

i the melting temperature of ice

ii the boiling temperature of water

at standard atmospheric pressure. [2]

c State if energy is absorbed or released when

i a liquid solidifies

ii a gas condenses. [2]

[Total: 7]

7 A drink is cooled more by ice at 0°C than by the same mass of water at 0°C.
This is because ice

A floats on the drink [1]

B has a smaller specific heat capacity [1]

C gives out heat to the drink as it melts [1]

D absorbs heat from the drink to melt [1]

E is a solid. [1]

State whether each of the above statements is *correct* or *incorrect*.

[Total: 5]

Alternative to Practical

8 In an experiment to investigate the cooling of a liquid to a solid, a test tube containing a pure solid is warmed in a beaker of hot water until it has completely melted to a liquid and has reached a temperature of 90°C. The tube is then removed from the hot water and the temperature recorded every 2 minutes while the liquid cools to a solid. The results are given in the following table.

Time/minutes	0	2	4	6	8	10	12	14	16	18
Temperature/°C	90	86	82	81	80	80	79	76	73	72

a Plot a graph of temperature versus time. [4]

b Estimate the melting temperature of the solid and explain your choice. [2]

c Explain what happens to the arrangement of the particles in the liquid during solidification. [2]

[Total: 8]