14.4 Specific heat capacity

Specification reference: 5.1.3

Learning outcomes

Demonstrate knowledge, understanding, and application of:

- ➔ the specific heat capacity of a substance – $E = mc\Delta\theta$
- ➔ an electrical experiment to determine the specific heat capacity of a metal or a liquid.

▲ **Figure 1** *Modern synthetic fluids are used to lubricate car engines and transfer force through hydraulic braking systems, yet ordinary water is used as the coolant to prevent the engine overheating*

Study tip

The term 'specific' in specific heat capacity refers to unit (1 kg) mass.

▼ **Table 1** *Some substances and their specific heat capacities*

Substance	c / J kg^{-1} K^{-1}
lead	129
silver	233
iron	449
aluminium	904
air*	1005
sodium	1230
paraffin wax	2200
water	4200
hydrogen*	14 300

*At constant pressure of 101 kPa

The wonders of water

Not only does solid water float on liquid water, but water has another unusual property that makes it an excellent coolant for everything from car engines (Figure 1), to supercomputers and even nuclear reactors – its exceptionally high **specific heat capacity**. It can absorb a large amount of energy without a significant change in its temperature.

Specific heat capacity

The specific heat capacity of a substance is defined as the energy required per unit mass to change the temperature by 1 K (or 1°C), and has units of J kg^{-1} K^{-1}.

Water has a specific heat capacity of 4200 J kg^{-1} K^{-1}, that is, 4200 J are needed to increase the temperature of 1 kg of water by 1 K.

The specific heat capacity, c, of a substance is determined using the equation below:

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

where E is the energy supplies to the substance in joules (J), m is the mass of the substance in kilograms (kg) and $\Delta\theta$ is the change in temperature of the substance. The change in temperature $\Delta\theta$ can be measured in K or °C, since both give the same numerical value for change.

This equation is normally written as

$$E = mc\Delta\theta$$

Different substances can have very different specific heat capacities. As you can see from Table 1, metals tend to have low values, and water has an exceptionally high value.

Worked example: Determining the mass of an aluminium tube

It takes 34.2 kJ to heat an aluminium tube from 20°C to 400°C. Assuming all the energy is transferred to the tube, calculate the mass of the tube.

Step 1: Select the equation and rearrange it to make mass the subject.

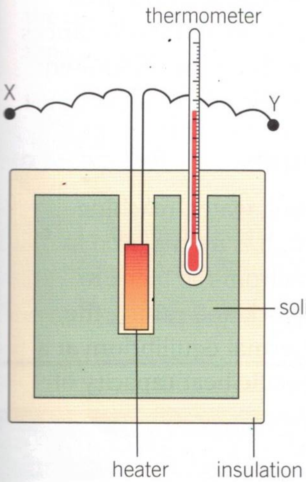
$E = mc\Delta\theta$ rearranged gives $m = \frac{E}{c\Delta\theta}$

Step 2: Substitute in known values in SI units, including a temperature change of 380°C, and calculate the mass.

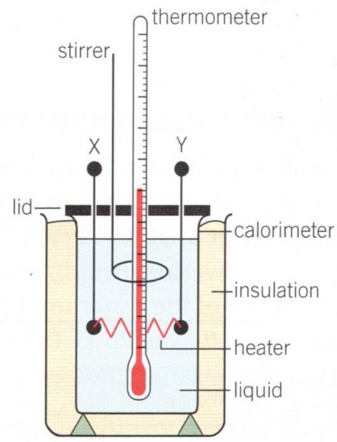
$$m = \frac{3.42 \times 10^4}{904 \times 380} = 0.10\,\text{kg (2 s.f.)}$$

Determining specific heat capacity

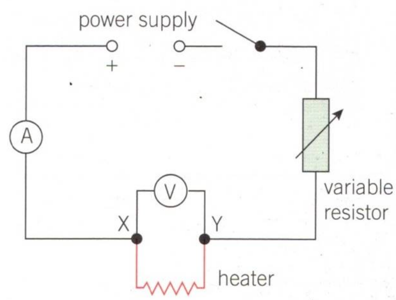
A simple experiment using an electrical heater can be used to determine the specific heat capacity of a solid or liquid (Figures 2 and 3).



▲ **Figure 2** *When determining the specific heat capacity of a substance it is important to minimise the energy transferred from the substance to the surroundings by carefully insulating the substance*



▲ **Figure 3** *When determining specific heat capacity of a liquid, the liquid must be carefully stirred to ensure it has uniform temperature throughout*



▲ **Figure 4** *Electrical circuit for the heater connected between terminals X and Y*

In both cases, the energy transferred from the heater to the substance is given by $E = IVt$, where I is the current in the heater, V is the potential difference across the heater, and t is the time taken to increase the temperature. Therefore the specific heat capacity of the substance can be determined using the equation

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

Temperature–time graphs

Plotting a graph of temperature of the substance against time allows for a more accurate determination of the specific heat capacity (Figure 5).

For a time Δt, the equation $E = mc\Delta\theta$ can be written as:

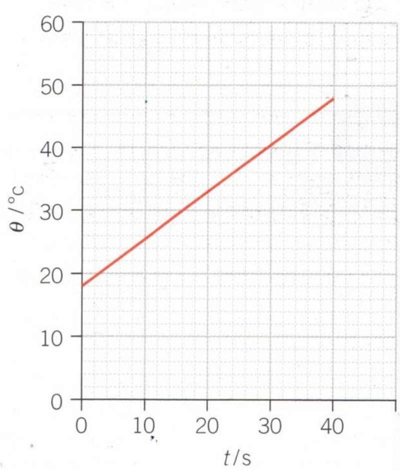
$$\frac{E}{\Delta t} = mc\frac{\Delta\theta}{\Delta t}$$

In Figure 5, $\frac{\Delta\theta}{\Delta t}$ is the gradient of the graph. $\frac{E}{\Delta t}$ is the constant power supplied, P, giving

$$P = mc\frac{\Delta\theta}{\Delta t} = mc \times \text{gradient}$$

Therefore the specific heat capacity of a substance can be determined using

$$c = \frac{P}{m \times \text{gradient}}$$



▲ **Figure 5** *A graph of temperature against time for a substance heated at a constant rate shows a linear relationship*

Method of mixtures

The method of mixtures is another way to determine specific heat capacity. Known masses of two substances at different temperatures are mixed together. Recording their final temperature at thermal equilibrium allows the specific heat capacity of one of the substances to be determined if the specific heat capacity of the other is known.

Worked example: Method of mixtures

A metal block of mass 100 g is heated in boiling water, reaching thermal equilibrium with the water at 100°C. It is then placed in 200 g of water at 20°C. Thermal energy flows from the block to the water, lowering the temperature of the block and raising the temperature of the water until they reach thermal equilibrium at a temperature θ_{final} of 26°C. Determine the specific heat capacity of the metal.

Step 1: Write down the values you know and select the equation you need to calculate the amount of energy transferred.

$m_{metal} = 0.100\,kg$, $\Delta\theta_{metal} = 74\,K$, $m_{water} = 0.200\,kg$, $\Delta\theta_{water} = 6\,K$

$E = mc\Delta\theta$

Step 2: Since thermal energy is transferred from the block to the water, energy transferred from metal block = energy transferred to water

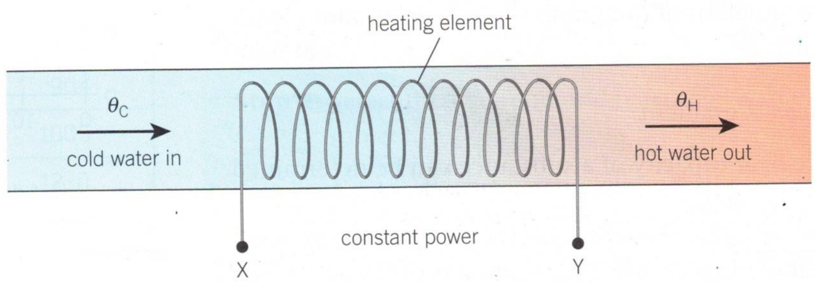
$$m_{metal}c_{metal}\Delta\theta_{metal} = m_{water}c_{water}\Delta\theta_{water}$$

Step 3: Rearrange the equation and calculate c_{metal}.

$$c_{metal} = \frac{m_{water}c_{water}\Delta\theta_{water}}{m_{metal}\Delta\theta_{metal}} = \frac{0.200 \times 4200 \times 6}{0.100 \times 74} = 680\,J\,kg^{-1}\,K^{-1} \text{ (2 s.f.)}$$

Constant-volume-flow heating

Constant-volume-flow heating is a technique used to heat a fluid passing over a heated filament. It is used to heat water in some showers and dishwashers and to transfer energy away from heat sources like car engines or nuclear reactors.



▲ **Figure 6** *The energy is supplied at a constant rate as the fluid passes over the heating element at a constant flow rate*

Because liquids are incompressible, a given volume of liquid in a pipe is equivalent to a given mass. The flow rate can therefore be regarded as the mass flowing through the pipe and passing over the heating element per unit time, in kg s^{-1}.

For constant-volume-flow heating, $E = mc\Delta\theta$ becomes

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

1 Calculate the power of an industrial heater with a flow rate of 1.20 kg s^{-1} that heats water from 10°C to 80°C.

2 Calculate the energy supplied from a power shower with a flow rate of 0.050 kg s^{-1}, heating water from 20°C to 60°C, used for 15 minutes.

3 Energy is transferred from a small water-cooled nuclear reactor at a rate of 250 MW. Assuming all the energy is transferred to the water as thermal energy and the water increases in temperature by 80°C, calculate the diameter of the pipe needed to transfer water from the reactor with a maximum velocity of 3.0 m s^{-1} (density of water = 1000 kg m^{-3}).

Summary questions

1 Calculate the energy required to raise the temperature of the following substances by 20°C.
a 1.0 kg of water **b** 600 g of aluminium **c** 4.2 μg of lead. *(4 marks)*

2 Describe an experiment that can be used to determine the specific heat capacity of a block of metal using an electrical heater, stating all the measurements that need to be taken. *(7 marks)*

3 This question is about a waterfall. Consider a 1 kg mass of water falling through a vertical drop of 450 m. Assuming all the energy is converted into thermal energy, calculate the difference in temperature between water at the top and bottom of the waterfall. *(3 marks)*

4 A 500 g mass of metal is heated using an electrical heater. The current in the heater and the potential difference across it are 2.0 A and 12 V. After 5.0 minutes the temperature of the metal has risen by 32°C. Calculate the specific heat capacity of the metal and identify the metal from Table 1. *(3 marks)*

5 A 60 W heater is used to heat a substance of mass 30 g. The graph in Figure 5 shows the change in temperature of the substance against time. Use the graph to determine the specific heat capacity of the substance. *(5 marks)*

6 A car of mass 1500 kg has two disc brakes of mass 8.0 kg. The material of the disc has a specific heat capacity of 500 J kg^{-1} K^{-1}. Assuming the kinetic energy of the car is transferred into thermal energy in the discs, calculate the increase in temperature of the brake discs when the car quickly decelerates from 20 m s^{-1} to rest. *(3 marks)*

14.5 Specific latent heat

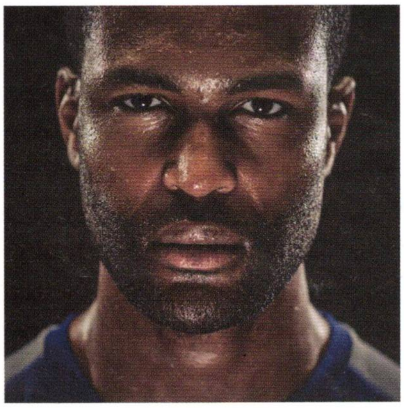
Specification reference: 5.1.3

Learning outcomes

Demonstrate knowledge, understanding, and application of:

→ specific latent heat of fusion and specific latent heat of vaporisation – $E = mL$

→ an electrical experiment to determine the specific latent heat of fusion and vaporisation.



▲ **Figure 1** *Most mammals sweat, but only humans, other primates, and horses produce large volumes of sweat to keep cool (other mammals, like dogs, control their temperature by panting)*

Study tip

As with specific heat capacity, the term 'specific' refers to unit mass, 1 kg, and the term 'latent' comes from the Latin for hidden – although energy is being transferred, the temperature of the substance does not change. The energy is 'hidden' while it is changing phase.

Keeping cool

Humans sweat to keep cool. When sweat evaporates it requires energy to change from liquid to gas, so energy transfers from the skin to the sweat, cooling the skin and preventing us from getting dangerously hot.

The amount of energy needed to turn 1 kg of liquid into gas depends on a property of the liquid called the **specific latent heat**. This varies from substance to substance.

Specific latent heat

The specific latent heat of a substance, L, is defined as the energy required to change the phase per unit mass while at constant temperature. Therefore

$$L = \frac{E}{m}$$

where E is energy supplied to change the phase of mass m of the substance. There are two forms for the specific latent heat of a substance depending on the phase change.

- When the substance changes from solid to liquid phase we refer to the **specific latent heat of fusion**, L_f.
- When the substance changes from liquid to gas, we refer to the **specific latent heat of vaporisation**, L_v.

$$E = mL_f \qquad E = mL_v$$

Water has a specific latent heat of vaporisation of $2.26 \times 10^6\,\mathrm{J\,kg^{-1}}$, so it takes 2.26×10^6 J to change 1 kg of liquid water into water vapour at constant temperature of 100 °C.

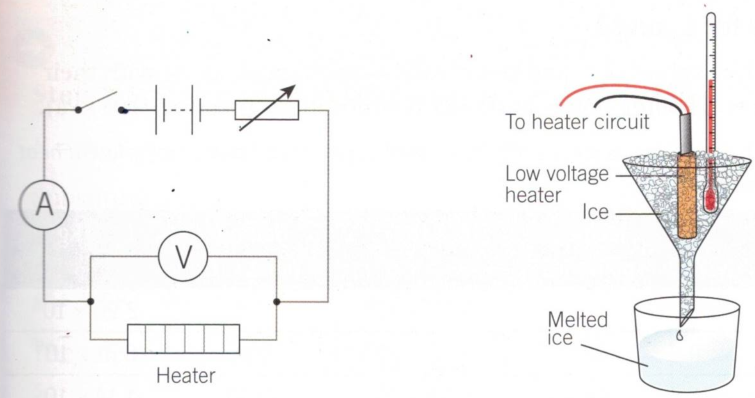
The specific latent heat of fusion L_f

When a substance is at its melting point it requires energy to change phase from solid to liquid. The energy transferred to the substance increases the internal energy of the substance without increasing its temperature.

To determine the specific latent heat of fusion, a heating circuit can be used, like the one used to determine the specific heat capacity of a substance in Topic 14.4 (Figure 4). A thermometer should be used to ensure the ice is at its melting point, not at a lower temperature, and the ice should be seen to be just starting to melt before the heater is switched on.

By measuring the potential difference V across the heater, the current I in the heater, and the time t during which the heater is used, the energy transferred to the ice can be determined using

$$E = IVt$$



a Heater circuit *b Collecting melting ice*

▲ **Figure 2** *Determining the specific latent heat of fusion of water using an electrical heater*

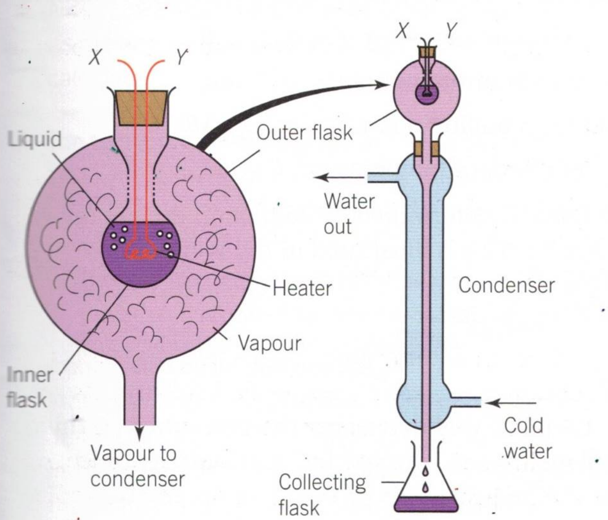
It is important to accurately measure the mass m of the substance (the ice in this example) that changes phase from solid to liquid. The specific latent heat of fusion can then be determined using

$$L_f = \frac{IVt}{m}$$

The specific latent heat of vaporisation L_v

The energy required to change 1 kg of substance from its liquid phase to its gaseous phase at its boiling point is often considerably more than its specific latent heat of fusion, because there is a much larger difference between the internal energy of a gas and a liquid than between a liquid and solid. Consequently L_v is greater than L_f for most substances.

To determine L_v an electrical heater can be used with a condenser to collect and then measure the mass of liquid that changes phase (Figure 3).



▲ **Figure 3** *Determining the specific latent heat of vaporisation requires a more complex arrangement to accurately measure the mass of liquid that changes phase*

As with the specific latent heat of fusion, the specific latent heat of vaporisation can be found using

$$L_v = \frac{IVt}{m}$$

where m is the mass of the substance that changed phase during heating.

Values for L_f and L_v

Table 1 lists values of L_f and L_v for various substances, along with their melting and boiling points at standard atmospheric pressure (101 kPa).

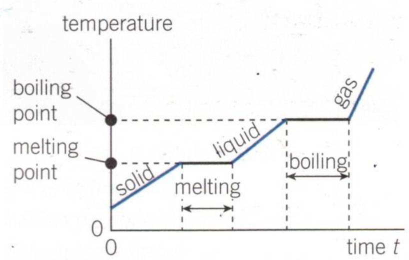
▼ **Table 1** *Some values for specific latent heat of fusion (L_f) and specific latent heat of vaporisation (L_v)*

	Melting point / °C	L_f / J kg^{-1}	Boiling point / °C	L_v / J kg^{-1}
water	0	3.30×10^4	100	2.26×10^6
lead	327	2.30×10^4	1750	8.71×10^5
aluminium	660	3.98×10^5	2450	1.14×10^7
silver	960	8.80×10^4	2190	2.33×10^6

In all cases it is important to remember that change of phase can occur the other way. When 1 kg of water freezes it transfers 330 000 J to its surroundings, as water in its solid phase has less internal energy than when in its liquid phase.

Combining specific latent heat and specific heat capacity

By considering the specific heat capacity and specific latent heat of a substance it is possible to determine the total energy required to heat and then change the phase of a substance. The graph in Figure 4 shows temperature plotted against time for a solid heated until it has completely turned into gas.



▲ **Figure 4** *A graph of temperature against time for a heated substance has several distinct sections*

This graph has four distinct sections before turning into a gas. The energy transferred to the substance in each section can be calculated using either the specific heat capacity or specific latent heat equation:

1. heating the solid to its melting point, $E = mc_{solid}\Delta\theta$
2. melting the solid at constant temperature, $E = mL_f$
3. heating the liquid to its boiling point, $E = mc_{liquid}\Delta\theta$
4. boiling the liquid at constant temperature, $E = mL_v$.

The total energy can then be determined by adding up the energy transferred in each section. This is illustrated in the worked example below.

Worked example: Turning ice into water vapour

Calculate the energy required to boil 2.0 kg ice initially at −40°C, and determine the percentage of this energy required to change the phase of the water from liquid to gas. The specific heat capacity of ice, c_{ice}, is 2.0×10^3 J kg^{-1} K^{-1}.

Step 1: By considering the energy transfers we can determine that the total energy.

total energy required = energy required to heat ice from −40°C to 0°C + energy required to melt ice + energy required to heat water from 0°C to 100°C + energy required to boil water

Step 2: Select the appropriate equations for each sections.

$$E = m_{ice} c_{ice} \Delta\theta_{(-40\rightarrow 0)} + m_{ice} L_{f\,ice} + m_{water} c_{water} \Delta\theta_{(0\rightarrow 100)} + m_{water} L_{v\,water}.$$

Substituting in known values and calculating the total energy required gives

$$E = (2.0 \times 2.0 \times 10^3 \times 40) + (2.0 \times 3.30 \times 10^4) + (2.0 \times 4200 \times 100) + (2.0 \times 2.26 \times 10^6)$$

$$E = 5.58\ldots\,\text{MJ}$$

The energy required to completely boil the water $E = 2.0 \times 2.26 \times 10^6 = 4.52\,\text{MJ}$.

Step 3: Convert the latent heat of vaporisation into a percentage of the total.

$$\frac{4.52 \times 10^6}{5.58\ldots \times 10^6} \times 100 = 81\%\ \text{(2 s.f.)}$$

About four-fifths of the energy was required to change the liquid into gas.

Summary questions

1 Calculate the energy required to change 2.5 kg of silver at its melting point from solid to liquid. *(2 marks)*

2 Describe why the specific latent heat of vaporisation is normally greater than the specific latent heat of fusion for a particular substance. *(1 mark)*

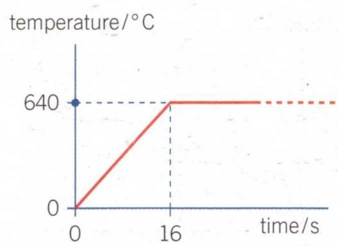
3 Calculate the energy transferred to the surroundings when 50 g of aluminium changes phase from liquid to solid. *(2 marks)*

4 A 24 W electrical heater is used to melt solid water already at its melting point. If the heater is left running for 20 minutes, calculate the mass of ice melted in that time. *(3 marks)*

5 The temperature–time graph in Figure 5 was obtained by heating a small piece of metal of mass 60 g. The specific heat capacity of the metal is 904 J kg^{-1} K^{-1} and the specific latent heat of fusion is 398 kJ kg^{1}. Calculate:

  a the rate of energy transfer to the metal from the heater *(3 marks)*

  b the energy required to melt the metal. *(2 marks)*



▲ **Figure 5** *A graph of temperature against time obtained when heating a small piece of metal*

6 A small lead bullet of mass 8.0 g travels at 400 m s^{-1}. The bullet strikes a concrete wall and melts on impact. Assuming the bullet is at 40°C on impact and that all the kinetic energy of the bullet is used to heat and then melt the bullet, calculate the temperature of the molten lead left on the wall. The specific heat capacity of lead is 129 J kg^{-1} K^{-1} (assume this is unchanged for molten lead). *(6 marks)*