11.3 Change of state

Learning objectives:

- What is latent heat?
- How do we measure it?
- Why does the temperature of a substance remain steady when it is changing state?

Specification reference: 3.5A.3

When a solid is heated and heated, its temperature increases until it melts. If it is a pure substance, it melts at a well-defined temperature, its **melting point**. Once all the solid has melted, continued heating causes the temperature of the liquid to increase until the liquid boils. This occurs at a certain temperature, the **boiling point**. The substance turns to a vapour as it boils away.

The three physical states of a substance, solid, liquid and vapour, have different physical properties. For example:

- the density of a gas is much less than the density of the same substance in the liquid or the solid state. This is because the molecules of a liquid and of a solid are packed together in contact with each other. In contrast, the molecules of a gas are on average separated from each other by relatively large distances.
- liquids and gases can flow, but solids cannot. This is because the atoms in a solid are locked together by strong force bonds which the atoms are unable to break free from. In a liquid or a gas, the molecules are not locked together because they have too much kinetic energy and the force bonds are not strong enough to keep the molecules fixed to each other.

Latent heat

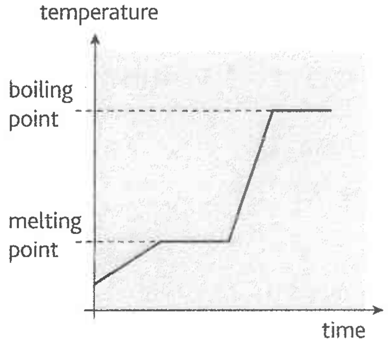

Figure 1 *Melting and boiling*

When a solid or a liquid is heated so its temperature increases, its molecules gain kinetic energy. In a solid, the atoms vibrate more about their mean positions. In a liquid, the molecules move about faster, still keeping in contact with each other but free to move about.

1 **When a solid is heated at its melting point**, its atoms vibrate so much that they break free from each other. The solid therefore becomes a liquid due to energy being supplied at the melting point. The energy needed to melt a solid at its melting point is referred to as **latent heat of fusion**.

   Latent heat is released when a liquid solidifies. This happens because the liquid molecules slow down as the liquid is cooled; at the melting point, the molecules move slowly enough for the force bonds to lock the molecules together. Some of the latent heat released keeps the temperature at the melting point until all the liquid has solidified.

   - 'Latent' means 'hidden': latent heat supplied to melt a solid may be thought of as hidden because no temperature change takes place even though the solid is being heated.
   - Fusion is a term used for the melting of a solid because the solid 'fuses' into a liquid as it melts.

2 **When a liquid is heated at its boiling point**, the molecules gain enough kinetic energy to overcome the bonds that hold them close together. The molecules therefore break away from each other to form bubbles of vapour in the liquid. The energy needed to vaporise a liquid is referred to as **latent heat of vaporisation**.

Latent heat is released when a vapour condenses. This happens because the vapour molecules slow down as the vapour is cooled; the molecules move slowly enough for the force bonds to pull the molecules together to form a liquid.

Some solids vaporise directly when heated. This process is known as **sublimation**.

In general, much more energy is needed to vaporise a substance than to melt it. For example, 2.25 MJ is needed to vaporise 1 kg of water at its boiling point. In comparison, 0.336 MJ is needed to melt 1 kg of ice at its melting point. The energy needed to change the state of unit mass (i.e. 1 kg) of a substance at its melting point (or its boiling point) is referred to as its specific latent heat of fusion (or vaporisation).

The **specific latent heat of fusion, l_f** of a substance is the energy needed to change the state of unit mass of the substance from solid to liquid without change of temperature.

The **specific latent heat of vaporisation** of a substance is the energy needed to change the state of unit mass of the substance from liquid to vapour without change of temperature.

Therefore, the energy Q needed to change the state of mass m of a substance from solid to liquid or liquid to vapour without change of temperature is given by

$$Q = ml$$

where l is the specific latent heat of fusion or vaporisation as appropriate.

The unit of specific latent heat is $\mathrm{J\,kg^{-1}}$.

Hint

Where a substance changes its state and changes its temperature, to calculate the energy transferred,

- use $Q = ml$ to calculate the energy transferred when its state changes,
- use $Q = mc(T_2 - T_1)$ when its temperature changes.

Worked example:

Calculate the energy needed to melt 5.0 kg of ice at 0 °C and heat the melted ice to 50 °C.

specific latent heat of fusion of ice = $3.36 \times 10^5\ \mathrm{J\,kg^{-1}}$

specific heat capacity of water = $4200\ \mathrm{J\,kg^{-1}\,K^{-1}}$

Solution

To melt 5.0 kg of ice, energy needed $Q_1 = ml = 5.0 \times 3.36 \times 10^5 = 1.68 \times 10^6$ J

To heat 5.0 kg of melted ice (i.e. water) from 0 °C to 50 °C, energy needed $Q_2 = mc\,(T_2 - T_1) = 5.0 \times 4200 \times (50 - 0) = 1.05 \times 10^6$ J

Therefore, the total energy needed $= Q_1 + Q_2 = 2.73 \times 10^6$ J

Link

If the volume of a substance is given, you need to know its density to find its mass. See *AS Physics* Topic 11.1.

Temperature–time graphs

If a pure solid is heated to its melting point and beyond, its temperature–time graph will be as shown in Figure 2.

Assuming no heat loss occurs during heating and energy is transferred to the substance at a constant rate P (i.e. power supplied):

- before the solid melts, $P = mc_S\left(\frac{\Delta T}{\Delta t}\right)_S$ where $\left(\frac{\Delta T}{\Delta t}\right)_S$ is the rise of temperature per second and c_S is the specific heat capacity of the solid. Therefore the rise of temperature per second of the solid, $\left(\frac{\Delta T}{\Delta t}\right)_S = \frac{P}{mc_S}$

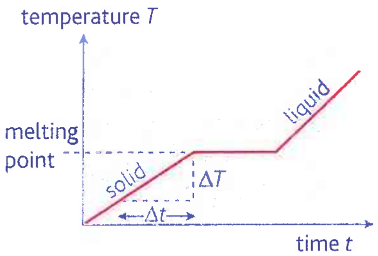

Figure 2 *Temperature against time for a solid being heated*

- after the solid melts, $P = mc_L\left(\frac{\Delta T}{\Delta t}\right)_L$ where $\left(\frac{\Delta T}{\Delta t}\right)_L$ is the rise of temperature per second and c_L is the specific heat capacity of the liquid.

  Therefore the rise of temperature per second of the liquid, $\left(\frac{\Delta T}{\Delta t}\right)_L = \frac{P}{mc_L}$

Therefore, if the solid has a larger specific heat capacity than the liquid, the rate of temperature rise of the solid is less than that of the liquid. In other words, the liquid heats up faster than the solid.

Summary questions

1 a Explain why energy is needed to melt a solid.

b Explain why the internal energy of the water in a beaker must be reduced to freeze the water.

2 Calculate the mass of water boiled away in a 3 kW electric kettle in 2 min.

The specific latent heat of vaporisation of water is $2.25\,\mathrm{MJ\,kg^{-1}}$.

3 A plastic beaker containing 0.080 kg of water at 15 °C was placed in a refrigerator and cooled to 0 °C in 1200 s.

a Calculate how much energy each second was removed from the water in this process. The specific heat capacity of water = $4200\,\mathrm{J\,kg^{-1}\,K^{-1}}$.

b Calculate how long the refrigerator would take to freeze the water in a. The specific latent heat of fusion of water = $3.4 \times 10^5\,\mathrm{J\,kg^{-1}}$.

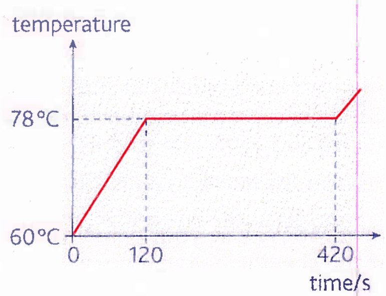

Figure 3

4 The temperature–time graph shown in Figure 3 was obtained by heating 0.12 kg of a substance in an insulated container. The specific heat capacity of the substance in the solid state is $1200\,\mathrm{J\,kg^{-1}\,K^{-1}}$.

Calculate:

a the energy per second supplied to the substance in the solid state if its temperature increased from 60 °C to its melting point at 78 °C in 120 s,

b the energy needed to melt the solid if it took 300 s to melt with energy supplied at the same rate as in a.

Hint

At the melting point, P = energy supplied per second is $\frac{ml}{t}$, where l is the specific latent heat of fusion of the substance and t is the time taken to melt mass m of the substance. Therefore, the time taken to melt the substance $t = \frac{ml}{P}$

AQA Examiner's tip

Change of state for a pure substance is at constant temperature.