3 Thermal physics

3.1 Thermal concepts

Assessment statements

3.1.1 State that temperature determines the direction of thermal energy transfer between two objects.
3.1.2 State the relation between the Kelvin and Celsius scales of temperature.
3.1.3 State that the internal energy of a substance is the total potential energy and random kinetic energy of the molecules of the substance.
3.1.4 Explain and distinguish between the macroscopic concepts of temperature, internal energy and thermal energy (heat).
3.1.5 Define the mole and molar mass.
3.1.6 Define the Avogadro constant.

The role of the physicist is to observe our physical surroundings, take measurements and think of ways to explain what we see. Up to this point in the course we have been dealing with the motion of bodies. We can describe bodies in terms of their mass and volume, and if we know their speed and the forces that act on them, we can calculate where they will be at any given time. We even know what happens if two hit each other. However, this is not enough to describe all the differences between objects. For example, by simply holding different objects, we can feel that some are hot and some are cold.

In this chapter we will develop a model to explain these differences, but first of all we need to know what is inside matter.

The particle model of matter

Ancient Greek philosophers spent a lot of time thinking about what would happen if they took a piece of cheese and kept cutting it in half.

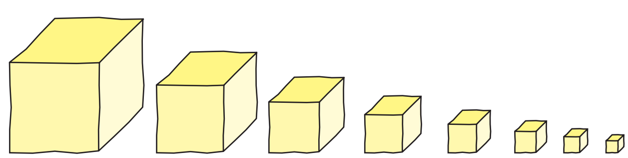


Figure 3.1 Can we keep cutting the cheese for ever?

They didn't think it was possible to keep halving it for ever, so they suggested that there must exist a smallest part – this they called the *atom*.

Atoms are too small to see (about 10^{-10} m in diameter) but we can think of them as very small perfectly elastic balls. This means that when they collide, both momentum and kinetic energy are conserved.

Elements and compounds

We might ask: 'If everything is made of atoms, why isn't everything the same?' The answer is that there are many different types of atom.

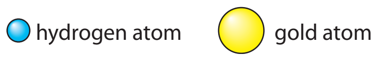


Figure 3.2 Gold is made of gold atoms and hydrogen is made of hydrogen atoms.

There are 117 different types of atom, and a material made of just one type of atom is called an *element*. There are, however, many more than 117 different types of material. The other types of matter are made of atoms that have joined together to form molecules. Materials made from molecules that contain more than one type of atom are called *compounds*.

This is a good example of how models are used in physics. Here we are modelling something that we can't see, the atom, using a familiar object, a rubber ball.

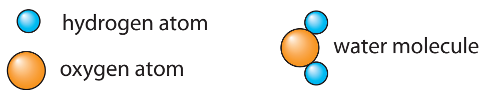


Figure 3.3 Water is an example of a compound.

The mole

When buying apples, you can ask for 5 kg of apples, or, say, 10 apples – both are a measure of amount. It's the same with matter – you can express amount in terms of either mass or number of particles.

A mole of any material contains 6.022×10^{23} atoms or molecules; this number is known as *Avogadro's number*.

Although all moles have the same number of particles, they don't all have the same mass. A mole of carbon has a mass of 12 g and a mole of neon has a mass of 20 g – this is because a neon atom has more mass than a carbon atom.

Moles of different compounds.

The three states of matter

From observations we know that there are three types, or *states* of matter: *solid*, *liquid* and *gas*. If the particle model is correct, then we can use it to explain why the three states are different.

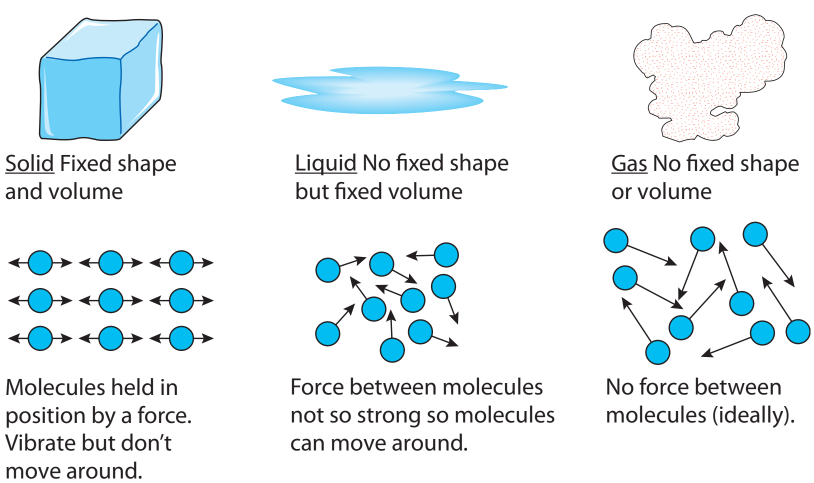


Figure 3.4 The particle model explains the differences between solids, liquids and gases. (The arrows represent velocity vectors.)

We can't prove that this model is true – we can only provide evidence that supports it.

Ice, water and steam.

Worked example

1 If a mole of carbon has a mass of 12 g, how many atoms of carbon are there in 2 g?

2 The density of iron is 7874 kg m^{-3} and the mass of a mole of iron is 55.85 g. What is the volume of 1 mole of iron?

Solution

1 One mole contains 6.022×10^{23} atoms.

2 g is $\frac{1}{6}$ of a mole so contains $\frac{1}{6} \times 6.022 \times 10^{23}$ atoms $=$ **1.004×10^{23} atoms**

2

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

$$\text{volume} = \frac{\text{mass}}{\text{density}}$$

$$\text{Volume of 1 mole} = \frac{0.05585}{7874}\,\text{m}^3$$

$$= 7.093 \times 10^{-6}\,\text{m}^3$$

$$= \mathbf{7.09\,cm^3}$$

● **Examiner's hint:** Be careful with the units. Do all calculations using m^3.

Exercises

1 The mass of 1 mole of copper is 63.54 g and its density 8920 kg m^{-3}

(a) What is the volume of one mole of copper?

(b) How many atoms does one mole of copper contain?

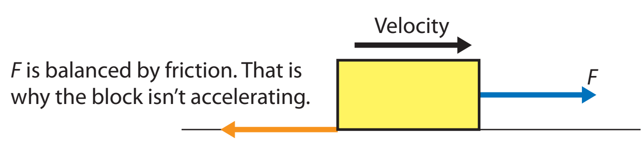
(c) How much volume does one atom of copper occupy?

2 If the density of aluminium is 2700 kg m^{-3} and the volume of 1 mole is 10 cm^3, what is the mass of one mole of aluminium?

Internal energy

In Chapter 2, Mechanics, you met the concepts of energy and work. Use these concepts to consider the following:

Figure 3.5 A wooden block is pulled along a rough horizontal surface at a constant velocity.



Is any work being done on the block by force F?

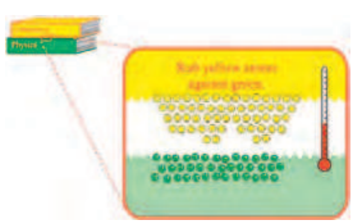
Is energy being transferred to the block?

Is the KE of the block increasing?

Is the PE of the block increasing?

Where is the energy going?

You will have realised that since work is done, energy is given to the block, but its PE and KE are not increasing. Since energy is conserved, the energy must be going somewhere. It is going inside the block as internal energy**.** We can explain what is happening using the particle model.



To a view a simulation showing how friction can increase temperature, visit heinemann.co.uk/hotlinks, enter the express code 4426P and click on Weblink 3.1.

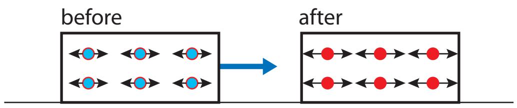


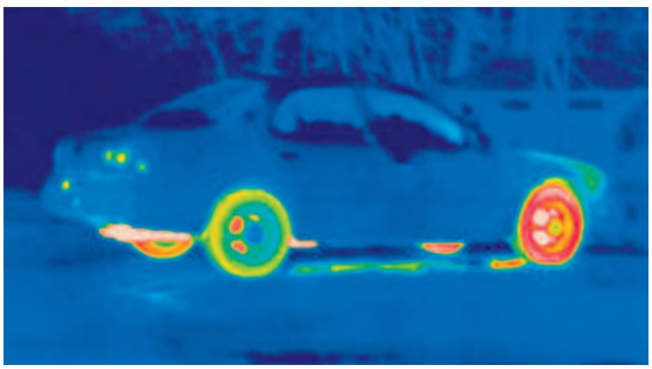
Figure 3.6 Molecules gain internal energy.

When we do work on an object, it enables the molecules to move faster (increasing KE) and move apart (increasing PE). We say that the *internal energy* of the object has increased.

In a solid, this means increasing the KE and PE of the molecules; in a gas it is just the KE. This is because there are no forces between the molecules of a gas, so it doesn't require any work to pull them apart.

Worked example

1 A car of mass 1000 kg is travelling at 30 m s^{-1}. If the brakes are applied, how much heat energy is transferred to the brakes?



This thermogram of a car shows how the wheels have become hot owing to friction between the road and the tyres, and the brakes pads and discs.

Solution

When the car is moving it has kinetic energy. This must be transferred to the brakes when the car stops.

$$\begin{aligned} \text{KE} &= \tfrac{1}{2}mv^2 \\ &= \tfrac{1}{2} \times 1000 \times 30^2\,\text{J} \\ &= 450\,\text{kJ} \end{aligned}$$

So thermal energy transferred to the brakes = 450 kJ

Exercises

3 A block of metal, mass 10 kg, is dropped from a height of 40 m.

(a) How much energy does the block have before it is dropped?

(b) How much heat energy do the block and floor gain when it hits the floor?

4 If the car in Example 1 was travelling at 60 m s^{-1}, how much heat energy would the brakes receive?

Temperature

If we now pick a block up, after dragging it, we will notice something has changed. It has got hot; doing work on the block has made it hot. *Hotness* and *coldness* are the ways we perceive differences between objects. In physics, we use temperature to measure this difference more precisely.

It is important to realise the difference between perception and physical measurement.

Temperature (T) is a measure of how hot or cold an object is, and it is temperature that determines the direction of heat flow.

Temperature is a *scalar* quantity, and is measured in degrees Celsius (°C) or kelvin (K).

0 °C is equivalent to 273 K.
100 °C is equivalent to 373 K.

At normal atmospheric pressure, pure water boils at 100 °C and freezes at 0 °C. Room temperature is about 20 °C.

During the first part of this chapter, we will measure temperature in Celsius. However when dealing with gases, we will use kelvin – this is because the Kelvin scale is based on the properties of a gas.

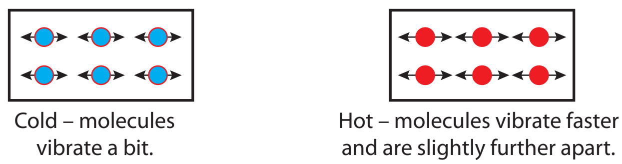
To convert from degrees Celsius to kelvin, simply add 273.

Thermometers

Temperature cannot be measured directly, so we have to find something that changes when the temperature changes. The most common thermometer consists of a small amount of alcohol in a thin glass tube. As temperature increases, the volume of the alcohol increases, so it rises up the tube. When we measure temperature, we are really measuring the length of the alcohol column, but the scale is calibrated to give the temperature in °C.

Temperature and the particle model

Figure 3.7 Temperature is related to kinetic energy.



From the previous model, we can see that the particles in a hot body move faster than those in a cold one. The temperature is related to the average KE of the particles.

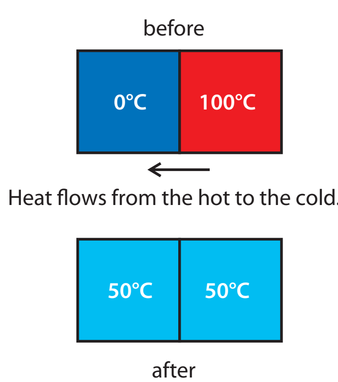
Heat transfer

Pulling a block of wood along a rough surface is not the only way to increase its temperature. We can make a cold body hot by placing it next to a hot body. We know that if the cold body gets hot, then it must have received energy – this is heat or *thermal* energy.

We are often more interested in preventing heat flow than causing it. Placing an insulating layer (e.g. woollen cloth) between the hot and cold bodies will reduce the rate of heat flow.

Thermal equilibrium

Figure 3.8 Heat flows from the hot body to the cold body until they are at the same temperature.



At this point no more heat will flow – this is called *thermal equilibrium*.

3.2 Thermal properties of matter

Assessment statements

3.2.1 Define *specific heat capacity* and *thermal capacity*.
3.2.2 Solve problems involving specific heat capacities and thermal capacities.
3.2.3 Explain the physical differences between the solid, liquid and gaseous phases in terms of molecular structure and particle motion.
3.2.4 Describe and explain the process of phase changes in terms of molecular behaviour.
3.2.5 Explain in terms of molecular behaviour why temperature does not change during a phase change.
3.2.6 Distinguish between evaporation and boiling.
3.2.7 Define *specific latent heat*.
3.2.8 Solve problems involving specific latent heats.

Thermal capacity (*C*)

If heat is added to a body, its temperature rises, but the actual increase in temperature depends on the body.

The *thermal capacity* (C) of a body is the amount of heat needed to raise its temperature by 1°C. Unit: J °C^{-1}

If the temperature of a body increases by an amount ΔT when quantity of heat Q is added, then the thermal capacity is given by the equation:

$$C = \frac{Q}{\Delta T}$$

This applies not only when things are given heat, but also when they lose heat.

Worked example

1 If the thermal capacity of a quantity of water is 5000 J °C^{-1}, how much heat is required to raise its temperature from 20 °C to 100 °C?

2 How much heat is lost from a block of metal of thermal capacity 800 J °C^{-1} when it cools down from 60 °C to 20 °C?

Solution

1	Thermal capacity	$Q = \frac{Q}{\Delta T}$	From definition
	So	$Q = C\Delta T$	Rearranging
	Therefore	$Q = 5000 \times (100 - 20)$ J	
	So the heat required	$Q =$ **400 kJ**	
2	Thermal capacity	$C = \frac{Q}{\Delta T}$	From definition
	So	$Q = C\Delta T$	Rearranging
	Therefore	$Q = 800 \times (60 - 20)$ J	
	So the heat lost	$Q =$ **32 kJ**	

Exercises

5 The thermal capacity of a 60 kg human is 210 kJ °C^{-1}. How much heat is lost from a body if its temperature drops by 2 °C?

6 The temperature of a room is 10 °C. In 1hour the room is heated to 20 °C by a 1 kW electric heater.

(a) How much heat is delivered to the room?

(b) What is the thermal capacity of the room?

(c) Does all this heat go to heat the room?

● **Examiner's hint:** Remember, power is energy per unit time.

Specific heat capacity (*c*)

The thermal capacity depends on the size of the object and what it is made of. The *specific heat capacity* depends only on the material. Raising the temperature of 1 kg of water requires more heat than raising 1kg of steel by the same amount, so the specific heat capacity of water is higher than that of steel.

The specific heat capacity of a material is the amount of heat required to raise the temperature of 1kg of the material by 1°C. Unit: J kg^{-1} °C^{-1}

If a quantity of heat Q is required to raise the temperature of a mass m of material by ΔT then the specific heat capacity (c) of that material is given by the following equation:

$$c = \frac{Q}{m\Delta T}$$

The specific heat capacity of water is quite high, so it takes a lot of energy to heat up the water for a shower.

Worked example

1 The specific heat capacity of water is 4200 J kg^{-1} °C^{-1}. How much heat will be required to heat 300 g of water from 20 °C to 60 °C?

2 A metal block of mass 1.5 kg loses 20 kJ of heat. As this happens, its temperature drops from 60 °C to 45 °C. What is the specific heat capacity of the metal?

Solution

1 Specific heat capacity $c = \frac{Q}{m\Delta T}$ From definition

So $Q = cm\Delta T$ Rearranging

Therefore $Q = 4200 \times 0.3 \times 40$ Note: Convert g to kg

$Q = \mathbf{50.4\,kJ}$

2 Specific heat capacity $c = \frac{Q}{m\Delta T}$ From definition

So $c = 20\,000/1.5(60-45)$ Rearranging

$c = \mathbf{888.9\,J\,kg^{-1}\,°C^{-1}}$

Exercises

Use the data in the table to solve the problems:

Substance	Specific heat capacity ($J\,kg^{-1}\,°C^{-1}$)
Water	4200
Copper	380
Aluminium	900
Steel	440

7 How much heat is required to raise the temperature of 250 g of copper from 20 °C to 160 °C?

8 The density of water is $1000\,kg\,m^{-3}$.
(a) What is the mass of 1 litre of water?
(b) How much energy will it take to raise the temperature of 1litre of water from 20 °C to 100 °C?
(c) A water heater has a power rating of 1 kW. How many seconds will this heater take to boil 1 litre of water?

9 A 500 g piece of aluminium is heated with a 500 W heater for 10 minutes.
(a) How much energy will be given to the aluminium in this time?
(b) If the temperature of the aluminium was 20°C at the beginning, what will its temperature be after 10 minutes?

10 A car of mass 1500 kg travelling at $20\,m\,s^{-1}$ brakes suddenly and comes to a stop.
(a) How much KE does the car lose?
(b) If 75% of the energy is given to the front brakes, how much energy will they receive?
(c) The brakes are made out of steel and have a total mass of 10 kg. By how much will their temperature rise?

11 The water comes out of a showerhead at a temperature of 50 °C at a rate of 8 litres per minute.
(a) If you take a shower lasting 10 minutes, how many kg of water have you used?
(b) If the water must be heated from 10 °C, how much energy is needed to heat the water?

Change of state

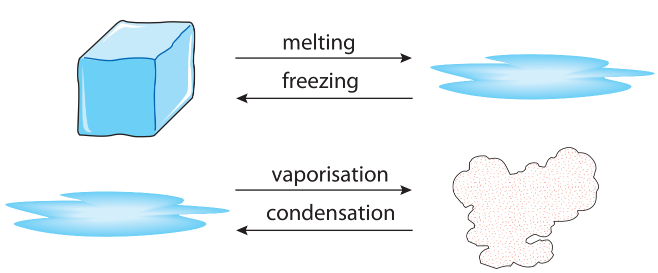
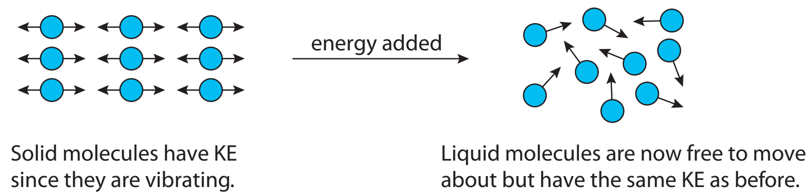


Figure 3.9 When matter changes from liquid to gas, or solid to liquid, it is changing state.

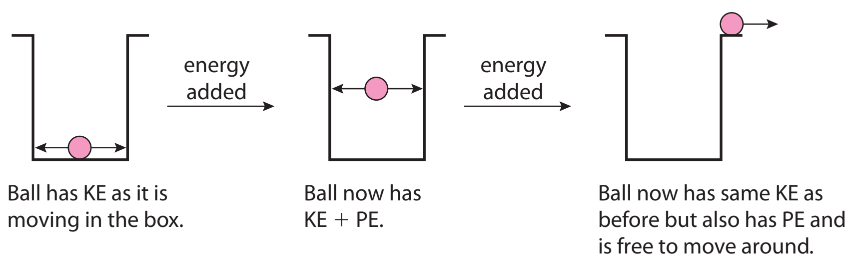
When water boils, this is called a *change of state* (or *change of phase*). As this happens, the temperature of the water doesn't change – it stays at 100 °C. In fact, we find that whenever the state of a material changes, the temperature stays the same. We can explain this in terms of the particle model.

Figure 3.10 Molecules gain PE when the state changes.



When matter changes state, the energy is needed to enable the molecules to move more freely. To understand this, consider the example below.

Figure 3.11 A ball-in-a-box model of change of state.



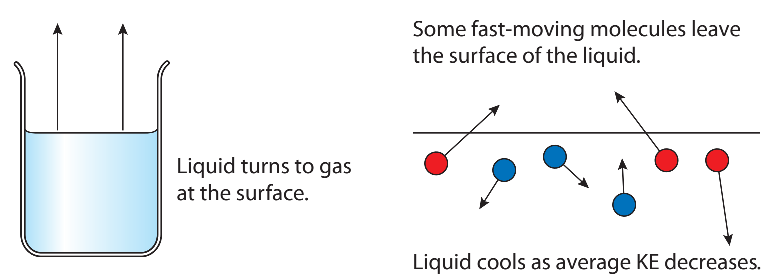
An iceberg melts as it floats into warmer water.

Boiling and evaporation

These are two different processes by which liquids can change to gases.

Boiling takes place throughout the liquid and always at the same temperature. *Evaporation* takes place only at the surface of the liquid and can happen at all temperatures.

Figure 3.12 A microscopic model of evaporation.



When a liquid evaporates, the fastest-moving particles leave the surface. This means that the average kinetic energy of the remaining particles is lower, resulting in a drop in temperature.

The rate of evaporation can be increased by:

- Increasing the surface area; this increases the number of molecules near the surface, giving more of them a chance to escape.
- Blowing across the surface. After molecules have left the surface they form a small 'vapour cloud' above the liquid. If this is blown away, it allows further molecules to leave the surface more easily.
- Raising the temperature; this increases the kinetic energy of the liquid molecules, enabling more to escape.

People sweat to increase the rate at which they lose heat. When you get hot, sweat comes out of your skin onto the surface of your body. When the sweat evaporates, it cools you down. In a sauna there is so much water vapour in the air that the sweat doesn't evaporate.

Specific latent heat (L)

The *specific latent heat* of a material is the amount of heat required to change the state of 1kg of the material without change of temperature.

Unit: $\mathrm{J\,kg^{-1}}$

Latent means *hidden*. This name is used because when matter changes state, the heat added does not cause the temperature to rise, but seems to disappear.

If it takes an amount of energy Q to change the state of a mass m of a substance, then the specific latent heat of that substance is given by the equation:

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

Solid→liquid
Specific latent heat of fusion

Liquid→gas
Specific latent heat of vaporization

Worked example

1 The specific latent heat of fusion of water is $3.35 \times 10^5\ \mathrm{J\,kg^{-1}}$. How much energy is required to change 500 g of ice into water?

2 The amount of heat released when 100 g of steam turns to water is 2.27×10^5 J. What is the specific latent heat of vaporization of water?

Solution

1 The latent heat of fusion $L_f = \frac{Q}{m}$ From definition

So $Q = mL$ Rearranging

Therefore $Q = 0.5 \times 3.35 \times 10^5$ J

So the heat required $Q = \mathbf{1.675 \times 10^5 J}$

2 The specific latent heat of vaporization $L = \frac{Q}{m}$ From definition

Therefore $L = 2.27 \times 10^5/0.1\ \mathrm{J\,kg^{-1}}$

So the specific latent heat of vaporization $L = \mathbf{2.27 \times 10^6\ J\,kg^{-1}}$

This equation $\left(L = \frac{Q}{m}\right)$ can also be used to calculate the heat lost when a substance changes from gas to liquid, or liquid to solid.

Exercises

Latent heats of water

Latent heat of vaporization	$2.27 \times 10^6\ \mathrm{J\,kg^{-1}}$
Latent heat of fusion	$3.35 \times 10^5\ \mathrm{J\,kg^{-1}}$

Use the data about water in the table to solve the following problems.

12 If the mass of water in a cloud is 1million kg, how much energy will be released if the cloud turns from water to ice?

13 A water boiler has a power rating of 800W. How long will it take to turn 400 g of boiling water into steam?

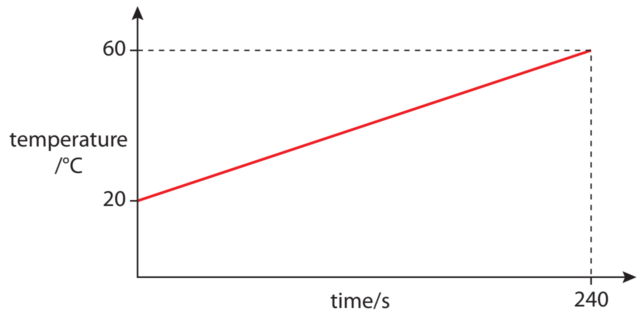
14 The ice covering a 1000 m^2 lake is 2 cm thick.

(a) If the density of ice is 920 $\mathrm{kg\,m^{-3}}$, what is the mass of the ice on the lake?
(b) How much energy is required to melt the ice?
(c) If the sun melts the ice in 5 hours, what is the power delivered to the lake?
(d) How much power does the Sun deliver per m^2?

Graphical representation of heating

The increase of the temperature of a body can be represented by a temperature–time graph. Observing this graph can give us a lot of information about the heating process.

Figure 3.13 Temperature–time graph for 1 kg of water being heated in an electric kettle.



In this example, we are ignoring the heat given to the kettle and the heat lost.

From this graph we can calculate the amount of heat given to the water per unit time (power).

The gradient of the graph $= \dfrac{\text{temperature rise}}{\text{time}} = \dfrac{\Delta T}{t}$

We know from the definition of specific heat capacity that

$$\text{heat added} = mc\Delta T$$

The rate of adding heat $= P = \dfrac{mc\Delta T}{t}$

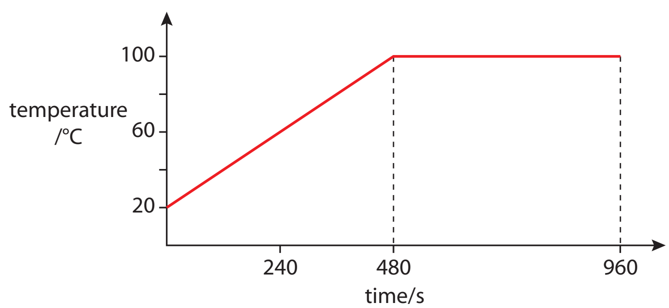
So $P = mc \times \text{gradient}$

The gradient of this line $= \dfrac{(60 - 20)}{240}\ {}^\circ\text{C s}^{-1} = 0.167\ {}^\circ\text{C s}^{-1}$

So the power delivered $= 4200 \times 0.167\ \text{W} = 700\ \text{W}$

If we continue to heat this water it will begin to boil.

Figure 3.14 A graph of temperature vs time for boiling water. When the water is boiling, the temperature does not increase any more.



If we assume that the heater is giving heat to the water at the same rate, then we can calculate how much heat was given to the water whilst it was boiling.

Power of the heater $= 700\ \text{W}$

Time of boiling $= 480\ \text{s}$

Energy supplied $= \text{power} \times \text{time} = 700 \times 480\ \text{J} = 3.36 \times 10^5\ \text{J}$

From this we can calculate how much water must have turned to steam.

Heat added to change state = mass × latent heat of vaporization,

where latent heat of vaporization of water $= 2.27 \times 10^6\ \text{J kg}^{-1}$.

Mass changed to steam $= \dfrac{3.36 \times 10^5}{2.27 \times 10^6} = 0.15\ \text{kg}$

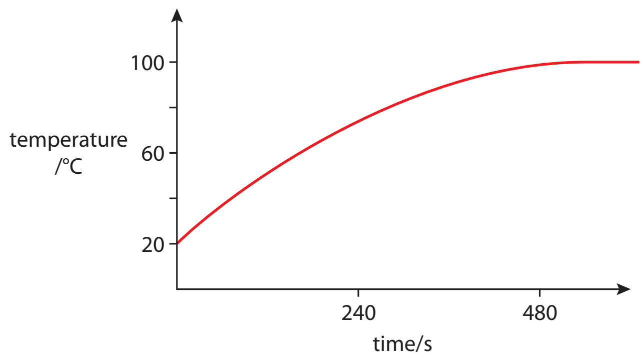


Figure 3.15 Heat loss.

When boiling a kettle, heat is continually being lost to the room. The amount of heat loss is proportional to the temperature of the kettle. For this reason, a graph of temperature against time is actually a curve, as shown in Figure 3.15.

The fact that the gradient decreases, tells us that the amount of heat given to the water gets less with time. This is because as it gets hotter, more and more of the heat is lost to the room.

Measuring thermal quantities by the method of mixtures

The method of mixtures can be used to measure the specific heat capacity and specific latent heat of substances.

Specific heat capacity of a metal

A metal sample is first heated to a known temperature. The most convenient way of doing this is to place it in boiling water for a few minutes; after this time it will be at 100 °C. The hot metal is then quickly moved to an insulated cup containing a known mass of cold water. The hot metal will cause the temperature of the cold water to rise; the rise in temperature is measured with a thermometer. Some example temperatures and masses are given in Figure 3.16.

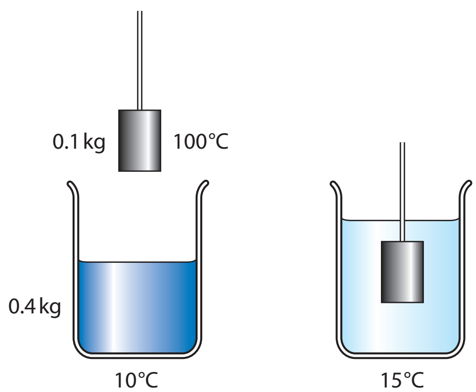


Figure 3.16 Measuring the specific heat capacity of a metal.

As the specific heat capacity of water is 4180 J kg^{-1} °C^{-1}, we can calculate the specific heat capacity of the metal.

ΔT for the metal $= 100 - 15 = 85$ °C

and ΔT for the water $= 15 - 10 = 5$ °C

Applying the formula $Q = mc\Delta T$ we get

$(mc\Delta T)_{\text{metal}} = 0.1 \times c \times 85 = 8.5c$

$(mc\Delta T)_{\text{water}} = 0.4 \times 4180 \times 5 = 8360$

If no heat is lost, then the heat transferred from the metal = heat transferred to the water

$8.5c = 8360$

$c_{\text{metal}} = 983$ J kg^{-1} °C^{-1}

Latent heat of vaporization of water

To measure the latent heat of vaporization, steam is passed into cold water. Some of the steam condenses in the water, causing the water temperature to rise.
The heat from the steam = the heat to the water.

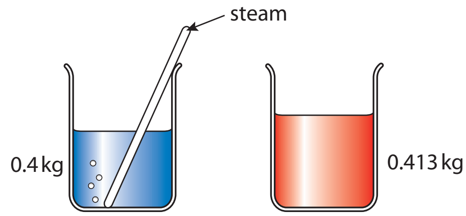


Figure 3.17 By measuring the rise in temperature, the specific latent heat can be calculated.

In Figure 3.17, 13 g of steam have condensed in the water, raising its temperature by 20 °C. The steam condenses then cools down from 100 °C to 30 °C.

Heat from steam $= ml_{steam} + mc\Delta T_{water}$

$0.013 \times L + 0.013 \times 4.18 \times 10^3 \times 70 = 0.013L + 3803.8$

Heat transferred to cold water $= mc\Delta T_{water} = 0.4 \times 4.18 \times 10^3 \times 20$

$= 33\,440$ J

Since heat from steam = heat to water

$0.013L + 3803.8 = 33\,440$

So $L = \dfrac{33\,440 - 3803.8}{0.013}$

$L = 2.28 \times 10^6\ \mathrm{J\,kg^{-1}}$

Heat loss

In both of these experiments, some of the heat coming from the hot source can be lost to the surroundings. To reduce heat loss, the temperatures can be adjusted, so you could start the experiment below room temperature and end the same amount above (e.g. if room temperature is 20 °C, then you can start at 10 °C and end at 30 °C).

Transfer of water

In the specific heat capacity experiment, droplets of hot water may be transferred with the metal block. This would add extra energy to the water, causing the temperature to rise a little bit too high. In the latent heat experiment, droplets of water sometimes condense in the tube – since they have already condensed, they don't give so much heat to the water.

3.3 Kinetic model of an ideal gas

Assessment statements
- 3.2.9 Define *pressure*.
- 3.2.10 State the assumptions of the kinetic model of an ideal gas.
- 3.2.11 State that temperature is a measure of the average random kinetic energy of the molecules of an ideal gas.
- 3.2.12 Explain the macroscopic behaviour of an ideal gas in terms of a molecular model.

The ideal gas

Of the three states of matter, the gaseous state has the simplest model; this is because the forces between the molecules of a gas are very small, so they are able to move freely. We can therefore use what we know about the motion of particles learnt in the mechanics section to study gases in more detail.

According to our simple model, a gas is made up of a large number of perfectly elastic, tiny spheres moving in random motion.

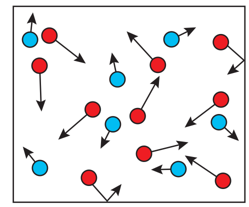


Figure 3.18 Simple model of a gas in a box. In reality the molecules have a range of velocities, not just two.

This model makes some assumptions:

- The molecules are perfectly elastic.
- The molecules are spheres.
- The molecules are identical.
- There are no forces between the molecules (except when they collide) – this means that the molecules move with constant velocity between collisions.
- The molecules are very small, that is, their total volume is much smaller than the volume of the gas.

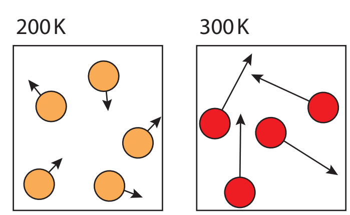
Some of these assumptions are not true for all gases, especially when the gas is compressed (when the molecules are so close together that they experience a force between them). The gas then behaves as a liquid. However, to keep things simple, we will only consider gases that behave like our model. We call these gases ideal gases.

Nitrogen becomes a liquid at low temperatures.

Temperature of a gas

From our general particle model of matter, we know that the temperature of a gas is directly related to the average KE of the molecules. If the temperature increases, then the speed of the particles will increase.

Figure 3.19 The molecules in a hot gas have a higher average KE.



Pressure of a gas

Let us apply what we know about particles to one molecule of a gas. Consider a single gas molecule in a box. According to the model, this is like a perfectly elastic sphere bouncing off the sides

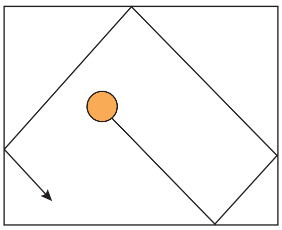


Figure 3.20 A rubber ball bouncing around a box.

We can see that this particle keeps hitting the walls of the container. Each time it does this, its direction, and therefore its velocity, changes.

Newton's first law of motion says that if a particle isn't at rest or moving with a constant velocity then it must be experiencing an unbalanced force. The particle is therefore experiencing an unbalanced force.

Newton's second law says that the size of this force is equal to the rate of change of momentum, so the force will be greater if the particle travels with a greater speed, or hits the sides more often.

Newton's third law says that if body A exerts a force on body B, then body B will exert an equal and opposite force on A. The wall exerts a force on the particle, so the particle must exert a force on the wall.

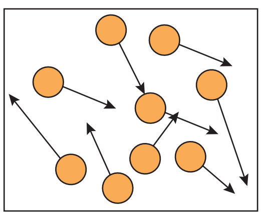


Figure 3.21 Many rubber balls bouncing around a box.

If we now add more molecules (as in Figure 3.21) then the particles exert a continuous force, F, on the walls of the container. If the walls have a total area A, then since

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

we can say that the pressure exerted on the walls is F/A – in other words, the particles exert a pressure on the container.

It is important to realise that we have been talking about the gas model, not the actual gas. The model predicts that the gas should exert a pressure on the walls of its container and it does.

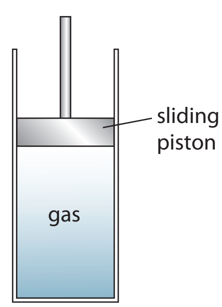
The atmosphere also exerts a pressure; this changes from day to day but is approximately 100 kPa.

1 pascal = 1 Pa = 1 N m^{-2}

Properties of a gas

We can now use the particle model to explain why a gas behaves as it does.

Figure 3.22 A gas in a piston can be used to vary the properties of a gas.



If you push on the piston you can feel the gas push back.

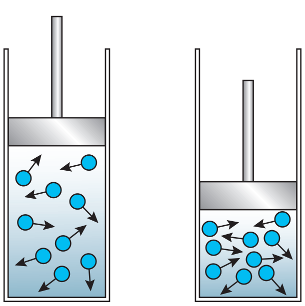


Figure 3.23 The volume of a gas is reduced.

Pressure and volume

If the volume is reduced, the particles hit the walls more often, since the walls are closer together. The force exerted by the molecules is equal to the rate of change of momentum; this will increase if the hits are more frequent, resulting in an increased pressure.

Pressure and temperature

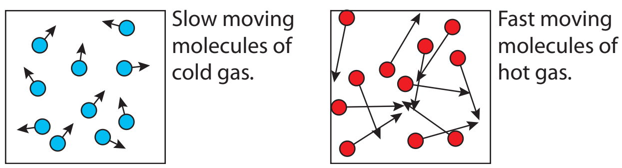
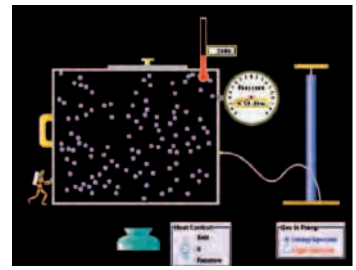


Figure 3.24 The temperature of a gas is increased.

Increase in temperature increases the speed of the molecules. When the molecules hit the walls, their change of momentum will be greater and they will hit the walls more often. The result is a greater rate of change of momentum and hence a larger force. This results in an increase in pressure.



W To understand how pressure, temperature and volume of a gas are related, visit heinemann.co.uk/hotlinks, enter the express code 4426P and click on Weblink 3.2.

Doing work on a gas

When you push the piston of a pump, it collides with the molecules, giving them energy (rather like a tennis racket hitting a ball). You are doing work on the gas. The increase in kinetic energy results in an increase in temperature and pressure. This is why the temperature of a bicycle pump increases when you pump up the tyres.

Gas does work

When a gas expands, it has to push away the surrounding air. In pushing the air away, the gas does work, and doing this work requires energy. This energy comes from the kinetic energy of the molecules, resulting in a reduction in temperature. This is why an aerosol feels cold when you spray it; the gas expands as it comes out of the canister.

3.4 Thermodynamics

Assessment statements

10.1.3 Describe the concept of the absolute zero of temperature and the Kelvin scale of temperature
10.1.1 State the equation of state for an ideal gas.
10.1.4 Solve problems using the equation of state of an ideal gas.
10.1.2 Describe the difference between an ideal gas and a real gas.

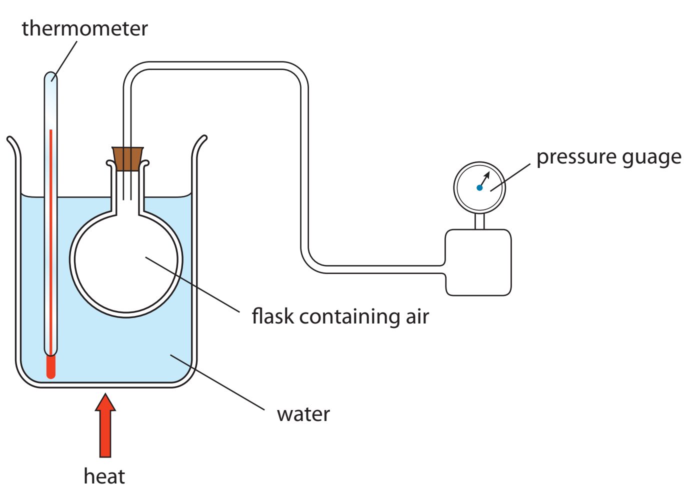


Figure 3.25 The pressure of a fixed volume of gas can be measured as the temperature is changed.