1 SIMPLE KINETIC MOLECULAR MODEL OF MATTER

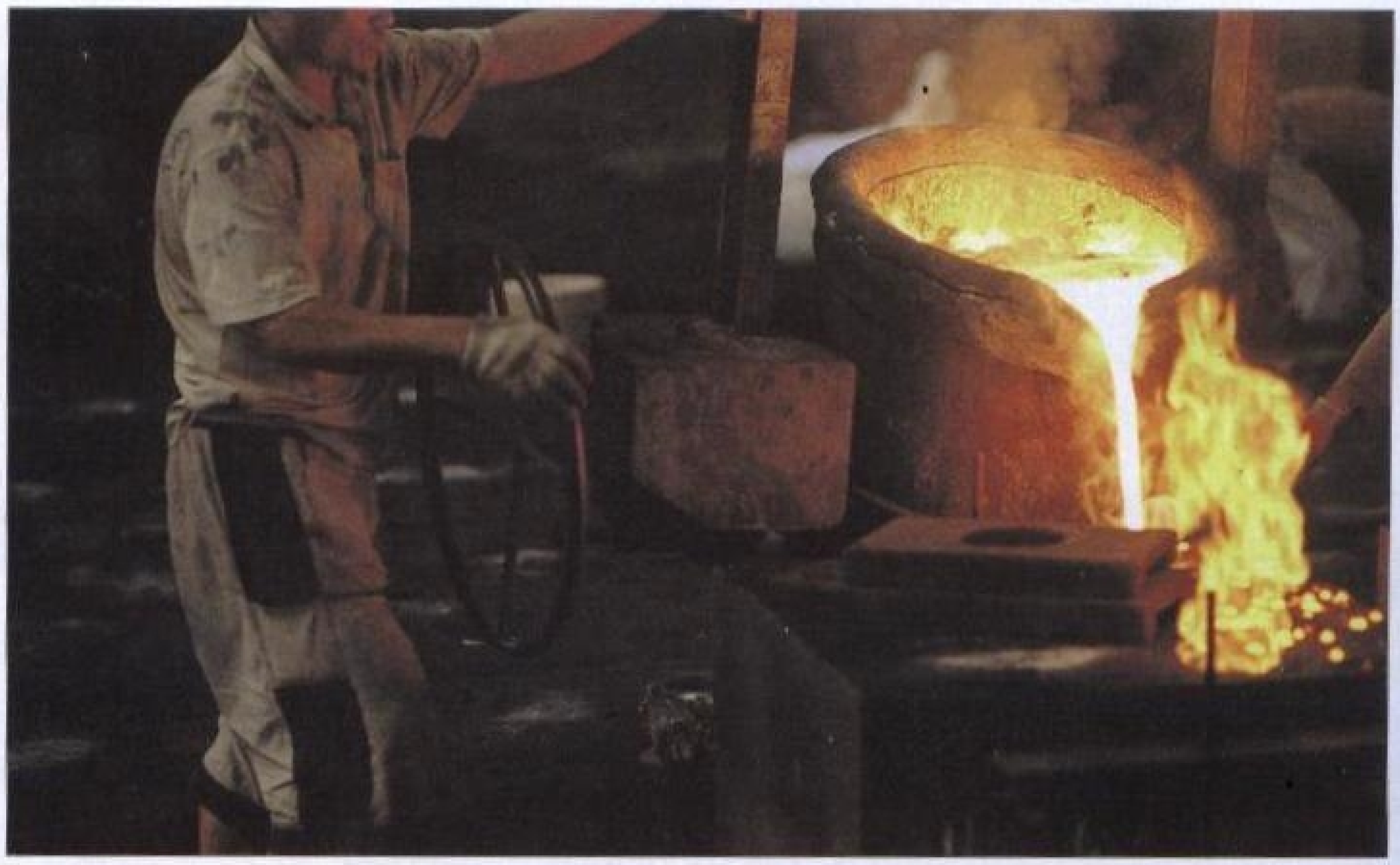
States of matter

Almost all matter can be classified as a solid, a liquid or a gas. These are called the three states of matter.

(The fourth state of matter is called 'plasma'. It only exists at high temperatures seldom seen on Earth, and so we won't consider it further here, even though most of the matter in the universe and most stars are made of plasma.)

As you will know, in general solids can be turned into liquids by heating, and with more heating liquids can be turned into gas. We are all familiar with water in all three states, but less so with other materials. Solid air is uncommon simply because it exists only at extremely low temperatures, and iron in the form of a gas only exists at very high temperatures.

The main body of this rocket is filled with liquid oxygen and liquid hydrogen, which have to be kept at extremely low temperatures to prevent them from heating up and turning back into gas. If the fuel were made colder it would turn into a solid.

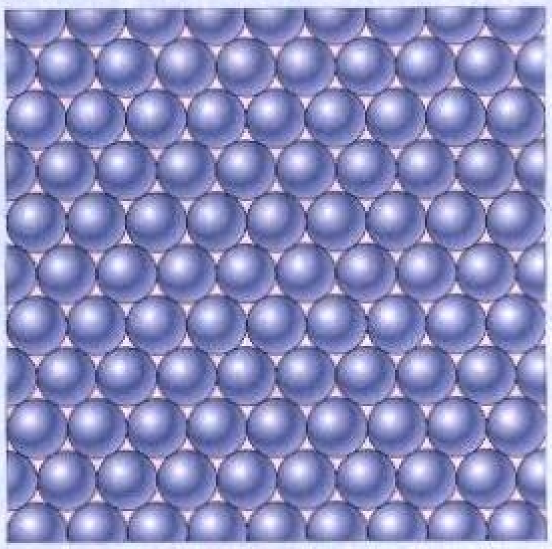
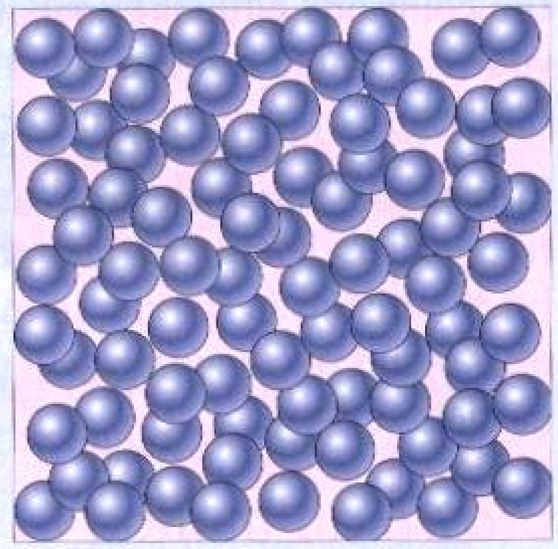
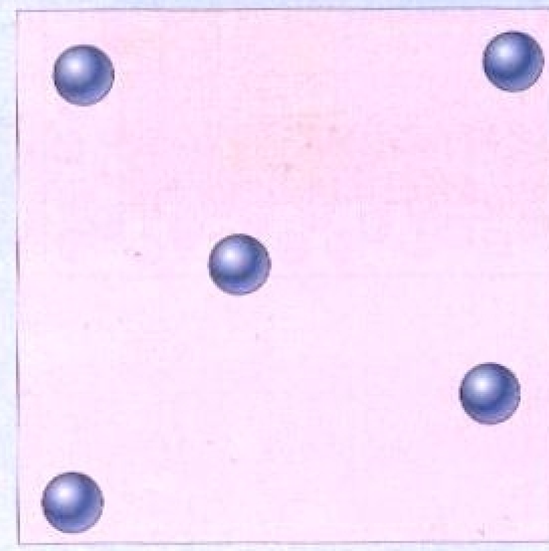


The molten iron can be poured into a mould before it cools down and turns back into a solid.

All materials are made of tiny particles called atoms. The atoms attract each other, and the particles in a solid are locked together by the forces between them. But even in a solid the particles are not completely still. They vibrate constantly about their fixed positions. If the material is heated, it is given more internal energy, and the particles vibrate faster and further.

If the temperature is increased more, the vibrations of the particles increase to the point where the forces are no longer strong enough to hold the structure together. The forces are no longer enough to prevent the particles moving around, but they do prevent the particles from flying apart from each other. This is the liquid state. A liquid can flow and takes the shape of whatever container it is in. Its volume does not change much.

If the temperature is increased even more, then the particles do indeed fly apart. They now form a gas. The particles fly around at high speed (several hundred kilometres per hour) and if they are in a container, they travel all over the container, bouncing off the walls. The volume of a gas is not fixed, it just depends on the size of the container that the gas is put in.

	Solid	**Liquid**	**Gas**
Arrangement of particles	Regular pattern, closely packed together, particles held in place	Irregularly packed together, particles able to move past each other	Irregular, widely spaced, particles able to move freely
Diagram			
Motion of particles	Vibrate in place within the structure	'Slide' over each other in a random motion	Random motion, faster movement than the other states

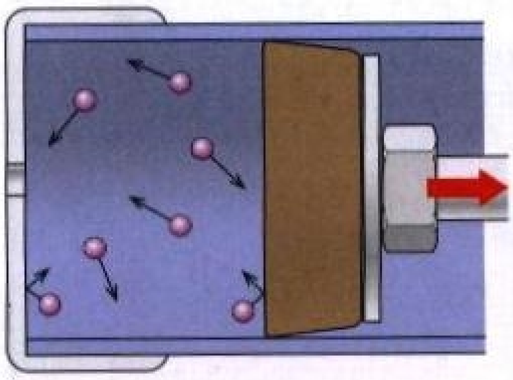
Molecular model

The kinetic molecular model uses this idea that all materials are made up of atoms that behave rather like tiny balls. And with this idea we try to build up a simple explanation (a 'model') of as much as possible.

When the model is used to try to explain the behaviour of gases it is often called the kinetic theory of gases.

In the above diagram, you can see that the particles in the liquid and the gas consist of separate atoms. There are materials that behave like this, elements such as helium and neon. In most materials, though, the particles that move around in the liquid or the gas are groups of atoms called molecules. The water molecule is H_2O, and the nitrogen molecule is N_2. This means that the particles moving around in liquid or gaseous water each consist of two hydrogen atoms and one oxygen atom. And in liquid nitrogen or in nitrogen gas, the particles each consist of two nitrogen atoms.

Observed feature of a gas	Related ideas from the kinetic theory
Gases have a mass that can be measured.	The total mass of a gas is the sum of the masses of the individual molecules.
Gases have a temperature that can be measured.	The individual molecules are always moving. The faster they move (the more **kinetic energy** they have), the higher the temperature of the gas.
Gases have a pressure that can be measured.	When the molecules hit the walls of the container they exert a force on it. It is this force, divided by the surface area of the container, that we observe when measuring pressure.
Gases fill the volume of whatever container they are put in.	Although the volume of each molecule is only tiny, they are always moving about and spread out throughout the container.
Temperature has an absolute zero.	As temperature falls lower, the speed of the molecules (and their kinetic energy) becomes less. At absolute zero the molecules would have stopped moving.



Let us see how these ideas can be used to explain the behaviour of gases.

THE EFFECT OF TEMPERATURE ON A GAS

The model says that the pressure on the walls of a container is caused by the collisions with the speeding molecules. You can feel this pressure if you try to hold a bicycle pump in the pushed-in position. (If the pump is faulty and allows the air to escape, this does not work.)

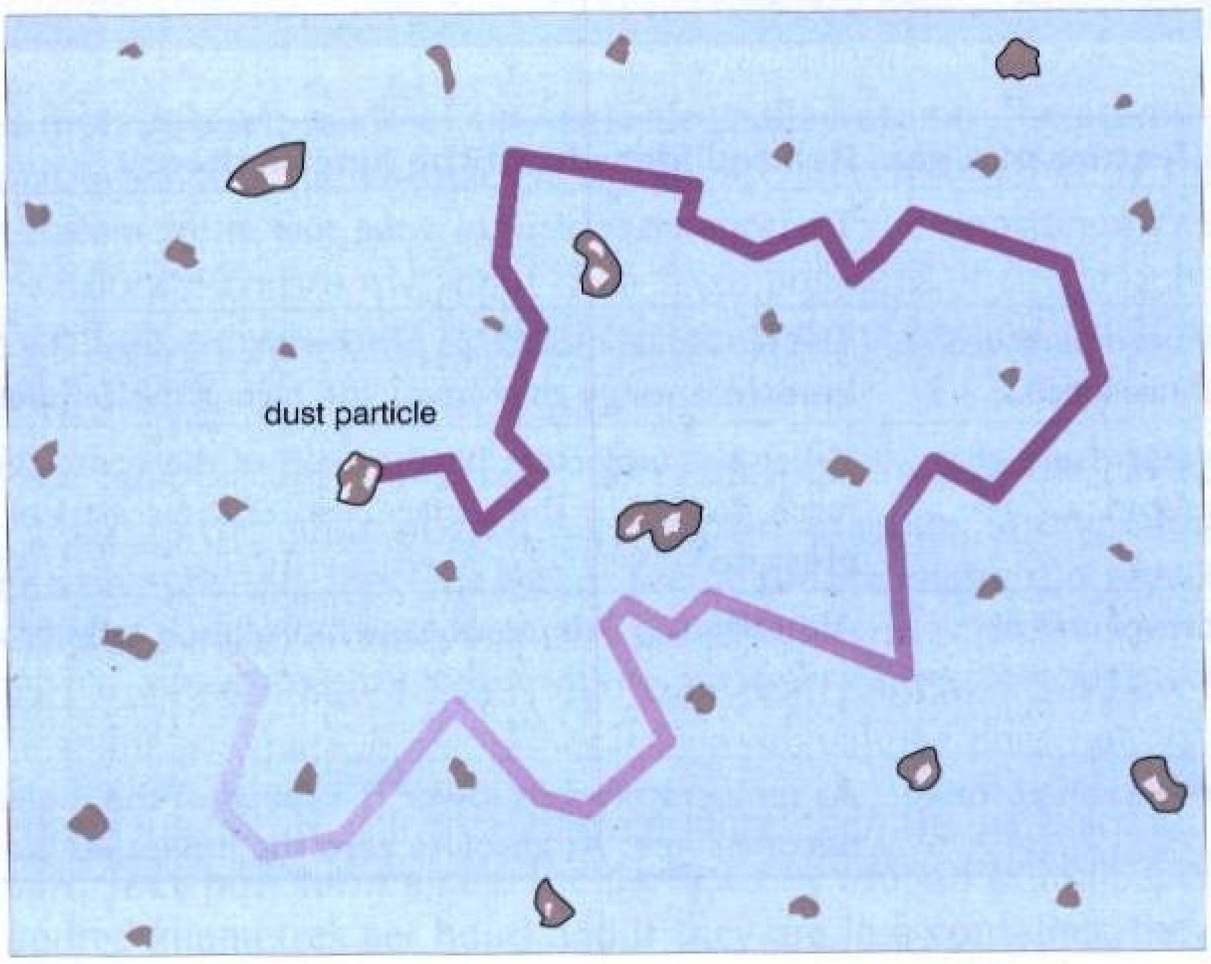
In the diagram, the piston is *not* moving. However, there is a force trying to push it out. It is clear that if the molecules travel faster then they will hit the piston in the pump more often and harder. The pressure on the piston and on the walls will go up. This is exactly what will happen if the air gets hotter.

Brownian motion

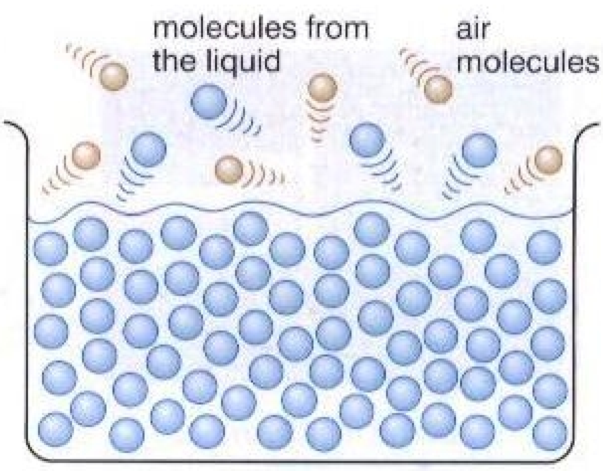
Evidence for the molecular model came from observations by Robert Brown in the early nineteenth century. When he looked through a high-magnification microscope at fine dust or pollen particles in water, he saw that the particles were all constantly moving in a jittery way, even though the water itself was stationary. Fine particles in the air do the same thing, even if the air is completely still.

The first full explanation was given by Einstein in 1905. As he explained, the movement is caused by these visible particles being hit from all sides by particles of water that are far smaller, and so are completely invisible. Each second, all sides of a dust particle are hit by millions of water particles. In general, opposite sides of the dust are hit by about the same number of water particles, so it does not move. But because the water particles are moving randomly, it is obviously possible that one side of the dust will suddenly be hit by a few more water particles than the other side. The resulting momentary force would have no detectable effect on a large object floating in the water, but it is enough to make the small dust particle move slightly. These tiny 'kicks' to the dust will come at random times and will move it in random directions.

The inner tube from a tyre has been pumped up with air before use as a toboggan. It is the pressure caused by the movement of the air molecules that keeps it inflated. Because the temperature is low, the inner tube will have needed more air. On a hot day this tube could burst.



Evaporation



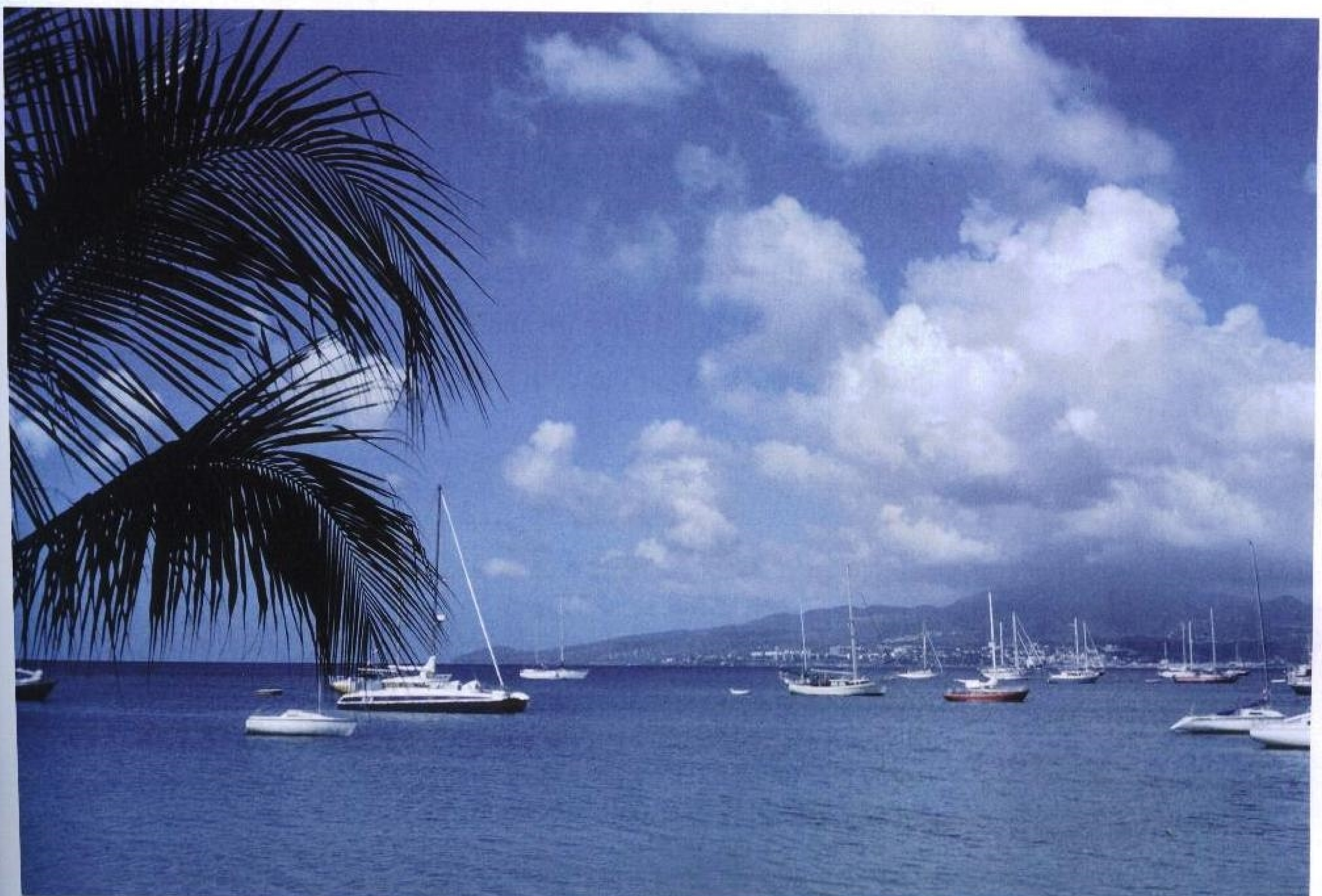
When particles break away from the surface of a liquid and form a vapour, the process is known as evaporation. The more energetic molecules of the liquid escape from the surface. This reduces the average energy of the molecules remaining in the liquid and so the liquid cools down.

Evaporation causes cooling. The evaporation of sweat helps to keep a body cool in hot weather. The cooling obtained in a refrigerator is also due to evaporation of a special liquid inside the cooling panel at the back of the compartment.

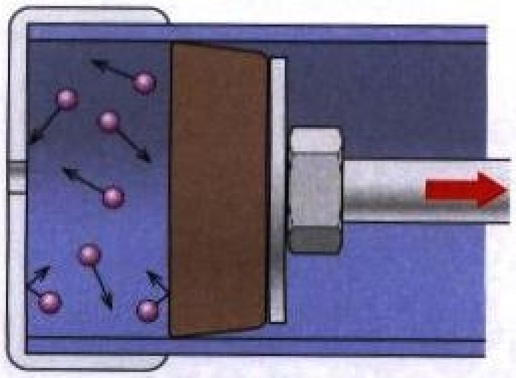
Evaporation is increased at higher temperatures and it is also increased by a strong flow of air across the surface of the liquid, as in this way the evaporating molecules are carried away quickly. A certain amount of water will also evaporate more quickly if you increase its surface area. A bowl of soup will cool down much more quickly than a mug of soup, because the large surface area of the bowl allows more evaporation.

Clouds are formed from invisible water vapour that evaporates from the sea and is carried away by the wind. When the water vapour cools at high altitude, it turns back into the small droplets of water that you can see as these clouds.

As water vapour cools, it forms clouds as seen here.



Pressure changes


piston moved in

If the piston of the bicycle pump is pushed in, then the more that you push it in, the harder and harder it gets to push it further.

This is because the pressure in the container goes up. The molecular model says there are the same number of molecules in the container travelling at the same speed. However, because the molecules are now packed in more densely, there will be more collisions with the walls and with the piston per second. If the volume is halved, then the number of collisions with the walls and with the piston will double, and the pressure on the piston will double. This relationship between pressure and volume was discovered by Robert Boyle in 1662, and is often referred to as Boyle's law. It applies to any gas, but only if the temperature of the gas does not change during the measurements.

A fixed amount of gas in a sealed container at constant temperature obeys the following equation:

pressure × volume = constant

pV = constant

p = pressure in Pa (or N/m^2 or millibar)

V = volume in m^3 (or cm^3)

Pascals and newtons per square metre are the same thing. Apart from them, you can use whichever units you like so long as you stick with them.

The constant will be a constant for a particular sample of gas in a particular container. So, in an experiment (or an exam question) you can write that the initial values of pressure and volume, $p_1 \times V_1$ = constant

And the final values of pressure and volume, $p_2 \times V_2$ = constant.

This is the same constant in both cases.

Hence p_1V_1 = constant = p_2V_2

or

$p_1V_1 = p_2V_2$

This equation, Boyle's law, only applies if the temperature stays constant.

It is important to emphasise that the temperature must remain constant. This is because the temperature of a gas will tend to go up if you compress it quickly. You may have noticed this: a bicycle pump gets very hot if you pump up a tyre quickly. So the law only applies if you measure the final pressure after the gas has cooled down again, or if you compress it very slowly so that its temperature does not change. By the same token, if you allow the gas to expand quickly, it cools down, so you have to take precautions here as well.

WORKED EXAMPLE

A bicycle pump contains 400 cm^3 of air at atmospheric pressure. If the air is compressed slowly, what is the pressure when the volume of the air is compressed to 125 cm^3? What happens to the pressure if the air is compressed quickly? (Remember that atmospheric pressure = 100 kPa.)

Write down the equation: $p_1V_1 = p_2V_2$

Substitute values into the equation: $100 \times 400 = p_2 \times 125$

$p_2 \times 125 = 40\,000$

Rearrange the equation to find p_2: $p_2 = \dfrac{40\,000}{125}$

Work out the answer and write down the unit: $= 320$ kPa

If the air is compressed quickly, it will also heat up to a higher temperature. This will mean that the final pressure will be greater than 320 kPa.

REVIEW QUESTIONS

Q1 Use ideas about particles to explain why:

- **a** solids keep their shape, but liquids and gases don't
- **b** solids and liquids have a fixed volume, but gases fill their container.

Q2 Use the kinetic molecular model to explain the following observations in detail:

- **a** It is possible to keep a bottle of drink cold by standing it in a bowl and covering it with a wet cloth.
- **b** The drink gets even colder if you place the bowl in a strong draught.
- **c** If two identical metal cylinders have most of the air removed from them, then they will balance when placed on a pair of scales. If one of the cylinders has air let back in, the scales will no longer balance.
- **d** An aerosol can of window cleaner has a large label on the side that says 'Danger. Do not dispose of the can by throwing it into a fire.'

Q3 A scuba diver has a 12 litre cylinder of air at 200 bar pressure. She is breathing the air at a depth of 20 m.

- **a** Calculate the volume of air available to this diver to breathe at this depth.
- **b** If each breath is 6 litres, and the diver is breathing 8 times per minute, how long can she stay at this depth? (In fact she would have to start ascending well before this time, as the ascent must be slow.)

More questions on the CD ROM

Examination questions are on page 82.