Properties of bulk matter Unit 8

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8.1 Elastic behaviour

By the end of this section you should be able to:

- Define the terms elastic limit, stress, strain, Young's modulus, shear modulus.
- State Hooke's law.
- Carry out calculations involving stress, strain, Young's modulus and the energy stored in a stretched material.

You have already learnt about forces. Sometimes forces can deform a body (push it out of shape). You need two equal but opposite forces to cause a body to deform. A single force would merely cause it to start moving with increasing speed.

Stress–strain relation

You need to know about four main types of deformation – tensile deformation, torsional deformation, shear deformation and compressional deformation. Notice that a single force acting on its own will accelerate a body, not deform it.

Any deformation may be elastic, or it may be plastic. With **elastic deformations**, when you remove the forces that caused the deformation, the body goes back to its original dimensions.

With **plastic deformations**, irreversible changes occurred while the body was being deformed. In a metal, layers of atoms may have slipped over one another, for example. It no longer returns to its original dimensions when the forces are removed. Note that there is a difference in elasticity between metallic and non-metallic solids. For all materials there is an **elastic limit** – beyond this limit the material will be permanently deformed. The elastic limit

KEY WORDS

elastic deformations *deformations where, when forces that caused deformation are removed, body goes back to its original dimensions*

plastic deformations *deformations where irreversible changes occur when the body is being deformed*

elastic limit *point beyond which all materials are permanently deformed*

Worked example 8.1

Find the tensile stress when a force of 4.9 N acts over a cross-sectional area of 2×10^{-3} m².

Tensile stress (N/m²)	Force (N)	Cross-sectional area (m²)
?	4.9	2×10^{-3}

Use tensile stress = $\frac{F}{A}$

$= 4.9/2 \times 10^{-3}$ m $= 2450$ N m^{-2}

Activity 8.1: Experiencing deforming forces

Lay a 1 m length of rubber on a bench: try stretching it using first one hand then two. Describe the difference between the two situations.

Different types of deformation can be produced, depending on how these forces are applied. Figure 8.1 shows some examples.

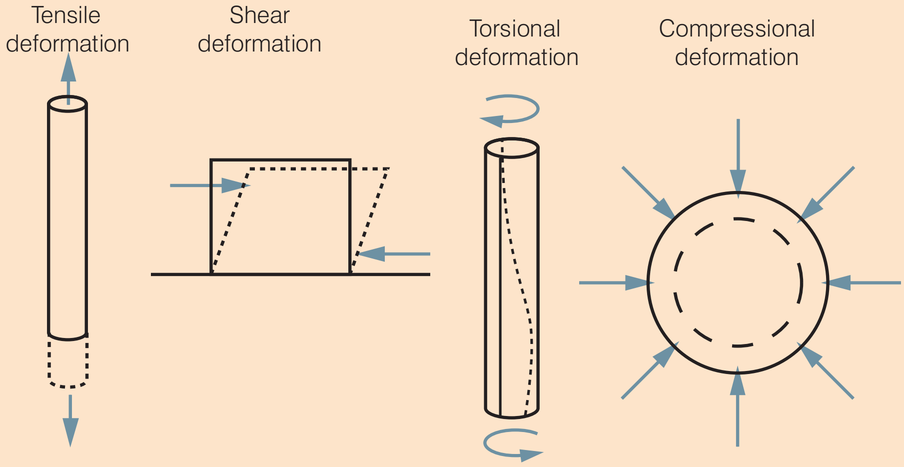

Figure 8.1 Different types of deformation

KEY WORDS

tensile stress *tensile force F divided by the cross-section area A of the wire*

tensile stress = $\frac{F}{A}$

depends on the internal structure of the material. Steel (a metal), for example, has a low elastic limit, whereas rubber (a non-metal) has a very much higher limit.

Activity 8.2 shows us what force was needed to stretch the particular wire we tested. In general, how easily does copper stretch?

To take the applied force alone as a measure of how much we are *trying* to deform it is not sufficient. A force of 100 N would have hardly any effect on a thick copper bar, but that same force might break a thin wire. To compare like with like, we use as the measure the **tensile stress** being applied. This is defined to be the tensile force F divided by the area of cross-section A of the wire.

$$\text{Tensile stress} = \frac{F}{A}$$

The units of tensile stress will be N/m^2.

For the measure of how much the copper has deformed as a result, it is not enough to consider just the wire's extension x. To cause

Activity 8.2: Exploring tensile deformation

Tensile deformation involves putting a load on a wire to stretch it. The easiest way to stretch it is to fix the wire securely near the ceiling, let it hang down and place weights on the free end. The extension is not likely to be great, but you can make sure that it is as large as possible by choosing a wire which is both long and thin. Even so you will need something more precise than a metre ruler to measure how far it extends when you load it.

A vernier scale is one way to do it, and Figure 8.2 shows how you might arrange it. The complete apparatus reaches from the ceiling almost to the floor.

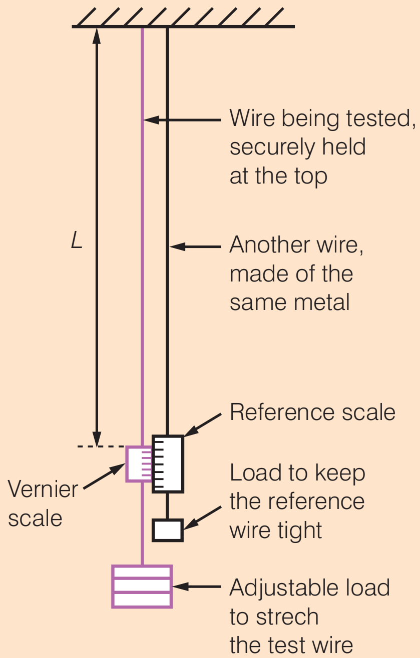

Figure 8.2 *Vernier scale*

Set up the apparatus as shown: use around 2 m of copper wire. It is essential that the clamp near the ceiling is absolutely secure – because the extension is so small, a slip of only a millimetre would completely invalidate the readings. The length marked L represents the length of wire being tested, so the vernier scale should be near its lower end. Notice that the reference scale is attached to a similar wire, suspended from the same clamp. If the support at the top sags due to the heavy load being placed on it, both scales will descend by the same amount so it does not matter. Also, though less likely to be a problem, if the room warmed up considerably during the course of the experiment, both wires would have the same expansion so again the vernier reading would not be affected.

Increase the load by 0.5 kg at a time. Each time take the reading of the vernier scale and subtract it from its reading at the start to find the extension.

Record readings of the values of extension and applied load. Draw a graph with extension on the vertical axis and applied load on the horizontal axis. Write a report of your experiment. Use the writing frame in Section 1.4, pages 19–20.

a copper wire of 10 m length to extend by 1 mm is a far different outcome from causing a 10 cm wire to extend by that amount. Therefore we measure the deformation by the **tensile strain**, which is the extension, x, divided by the wire's original length, L.

$$\text{Tensile strain} = \frac{x}{L}$$

The tensile strain is just a number with no units. In effect it is the fractional extension of the wire. To calculate it, the extension and the length must, of course, both be expressed in the same units – usually metres.

Hooke's law

A graph of the extension plotted against the applied load in Activity 8.2 (see Figure 8.3) shows the sort of results that may be obtained for the copper wire.

The graph starts as a straight line. Over this range the extension will be proportional to the applied force – this is known as **Hooke's law**.

As the load increases, the line begins to curve. This point is marked A on the graph, and is known as the **limit of proportionality.**

At B, the **yield point** is reached, where there is a sudden increase in the extension. At C, the wire breaks.

Elastic limit

For small loads the extension is elastic, but for large loads the copper suffers plastic deformation. In Activity 8.2, you cannot know the exact load for which elastic behaviour ceases (we call it the elastic limit) – the only way of telling that is to remove the load each time and see if the wire recovers fully.

Nevertheless, you can be sure that over the Hooke's law region the behaviour is elastic. When the yield point is reached, it may be assumed that layers of atoms have slipped over one another within the metal and the wire will suffer a permanent extension. The graph does not indicate just where the elastic limit lies, but it is bound to be after A and near B.

The final part of the graph shows the copper deforming in a plastic manner, with ever increasing extensions until the wire breaks at point C.

Activity 8.3: Finding the elastic limit

Use the same apparatus as in Activity 8.2. Add a load until the extension starts to increase dramatically. Record the load required to reach this point – this will be the elastic limit of the wire.

Worked example 8.2

Find the tensile strain when a wire of length 2 m is extended by 5 cm.

Tensile strain	Extension (m)	Original length (m)
?	0.05	2

Use tensile strain $= \frac{0.05}{2}$

$= 0.025$

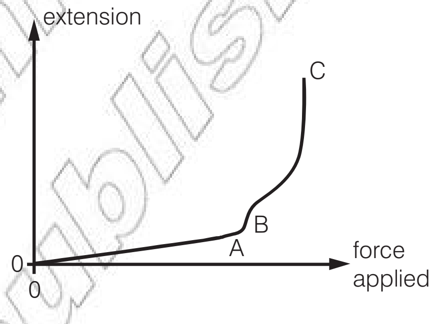

Figure 8.3 *Hooke's law*

KEY WORDS

tensile strain *extension x divided by the wire's original length, L*

tensile strain $= \frac{x}{L}$

Hooke's law *the force applied to a material is directly proportional to its extension, up to the elastic limit*

limit of proportionality *point at which extension and applied force are no longer proportional*

yield point *point where there is a sudden increase in extension*

Ductile materials and brittle materials

Because copper has a large plastic stage it is not difficult to deform it by drawing it out into a wire. Such material is described as being ductile.

At the other extreme there are some materials that have no plastic stage at all. These are described as being brittle.

If you stretch a glass fibre, for example, the extension–force graph would look like the one in Figure 8.4.

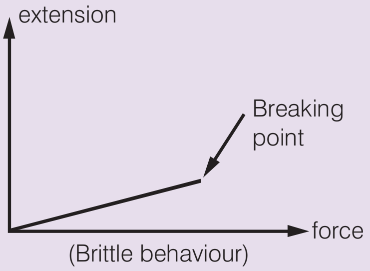

Figure 8.4 *Brittle materials*

The behaviour remains elastic all the way up to the breaking point, when it suddenly and unexpectedly snaps.

Not all metals are ductile. Cast iron is brittle, for instance. So too is tungsten – the metal used to make the filament in a light bulb – because of its extremely high melting point. The only way of making the filament is to take some of the powdered metal and compress it into the required shape.

KEY WORDS

Young's modulus *the ratio of tensile stress to tensile strain up to the material's limit of proportionality*

Young's modulus

We know that stress applied to a copper wire produces strain in it. For a measure of how readily copper stretches, we take the ratio tensile stress divided by tensile strain – the stress we would have to apply for each unit strain caused. This is **Young's modulus**, y, of the material, sometimes called the Young modulus and named after an English physicist.

The ratio will be a constant only over the straight line part of the extension–force graph, so Young's modulus describes behaviour over the range for which Hooke's law applies.

Therefore, Young's modulus is defined as:

the ratio of tensile stress to tensile strain up to the material's limit of proportionality.

In symbols:

$$E = \frac{\frac{F}{A}}{\frac{x}{L}}$$

Rearranging, this gives $E = \frac{FL}{xA}$.

The units of Young's modulus will be those of stress (N/m^2) divided by those of strain. Strain is just a number, so Young's modulus will be measured in N/m^2.

This unit does have a name – the pascal (Pa), used especially for pressures. Sometimes Young's modulus will be expressed in Pa, but remember that is just N/m^2 by another name.

Worked example 8.3

A steel wire of length 3.0 m has a cross-sectional area of 4.1 mm^2. It hangs from a tall support, and a load of 500 g is attached to its end. By how much will it extend? Take Young's modulus of steel to be 2.0×10^{11} Pa.

Here F = the weight of the 500 g load, which is 0.5 kg × 9.8 N/kg^1 = 4.9 N

L = 3.0 m

$A = 4.1\ mm^2 = 4.1 \times 10^{-6}\ m^2$

(If you are not confident about doing this conversion, do not just ignore it. Be sure to ask your teacher for help.)

$E = 2.0 \times 10^{11}$ Pa (that is, N m^{-2})

E (N/m^2)	F (N)	L (m)	x (m)	A (m)
2×10^{11}	4.9	3.0	?	4.1×10^{-6}

Starting with $E = \frac{FL}{xA}$ and rearranging, we get

$$x = \frac{FL}{EA}$$

Putting in the values, x

$$= \frac{4.9 \times 3.0}{2.0 \times 10^{11} \times 4.1 \times 10^{-6}} = \frac{14.7}{820\,000} = 1.79 \times 10^{-5}\ m$$

Activity 8.4: Measuring Young's modulus

You can use the apparatus from Activity 8.2 here. The one difference is that you need to investigate only the elastic part of the graph this time.

Add loads one at a time, and for each one record from the vernier scale the extension x it has produced. If the loads are standard masses m, you can work out the force they cause by mg.

You must record the original length L of the wire. A metre ruler is sufficiently accurate for finding this.

You also require the cross-sectional area A of the wire. Measure the wire's average diameter d with a micrometer screw gauge at a few different points along the wire (including some at right angles to others), divide it by 2 to get the wire's radius r, then use $A = \pi r^2$.

Because Young's modulus $E = \frac{FL}{xA}$

just one set of readings would suffice to give a value.

However, it is better to plot a graph of x against F and draw a best straight line through your readings. The gradient of the line is $\frac{x}{F}$, so 1 over the gradient gives your best estimate of $\frac{F}{x}$ obtained from all your readings. Multiply that by $\frac{L}{A}$ and you have Young's modulus.

KEY WORDS

bulk modulus *a measure of the ability of a substance to resist changes in volume when under increasing pressure from all sides*

shear modulus *a measure of the ability of a substance to resist deformation caused by a force parallel to one of its surfaces*

shear stress *the force divided by the cross-sectional area which is being sheared*

shear strain $\frac{\Delta x}{L}$ *(see Figure 8.1)*

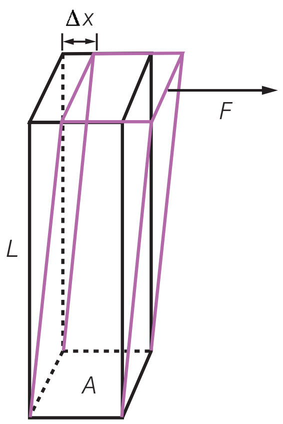

Figure 8.5 *Bar under shear force*

Bulk modulus and shear modulus

Each sort of deformation will have its own modulus of elasticity, and each one is defined as the ratio of stress over strain in the Hooke's law region – how much deforming stress is required to cause unit strain. All have the units N m^{-2}.

The difference lies in how each one defines the applied stress and the resulting strain.

The **bulk modulus** relates to a gas or a liquid which is subjected to an increased pressure acting on it. The pressure in N m^{-2} is the stress in this case. The deformation is a reduction in its volume as the substance gets squashed, so the strain is taken to be the ratio

$$\frac{\text{change in volume}}{\text{original volume}}$$

This corresponds exactly to the strain in a tensile deformation being taken as $\frac{\text{extension}}{\text{original length}}$

Shear will occur if the base of the body is fixed and the deforming force causes it to tilt out of shape as shown in Figure 8.5.

The **shear modulus** is $\frac{\text{the shear stress}}{\text{the shear strain}}$

Shear stress is defined to be the force divided by the cross-sectional area which is being sheared ($\frac{F}{A}$), and the **shear strain** is $\frac{\Delta x}{L}$.

Strain energy

If you stretch a wire, you have to exert a force and move a distance. You have done work, and the chemical energy from your food has thereby been converted into strain energy in the wire.

Suppose you are exerting a force F on the wire, and this has caused it to extend by a distance x. You reached this situation by taking the unstretched wire and providing a steadily increasing force as it extended further and further, until by the end your force had risen to F.

Your force was not a constant one as you moved through the distance x. It built up steadily from 0 to F, so its average value was $\frac{1}{2}F$ – half way between the two extremes. The work you did may be calculated by that average force multiplied by the distance you moved it through, so it will be $\frac{1}{2}Fx$.

Strain energy in a stretched wire = $\frac{1}{2}Fx$

Worked example 8.4

Consider a long steel wire where a tension of 4.9 N causes an extension of 18 mm. Find the strain energy.

F (N)	x (m)
4.9	18×10^{-3}

The strain energy in it $= \frac{1}{2}Fx = \frac{1}{2} \times 4.9\ \text{N} \times 1.8 \times 10^{-3}\ \text{m}$
$= 4.4 \times 10^{-2}$ J.

Notice how small it is – only 44 millijoules (mJ). The large forces that have to be exerted are more than offset by the tiny distances moved.

Summary

In this section you have learnt that:

- The elastic limit is the point beyond which all materials are permanently deformed.
- Tensile stress is tensile force divided by cross-sectional area A of the wire.
- Tensile strain is the extension x divided by the wire's original length, L.
- Shear stress is the force divided by the cross-sectional area being sheared.
- Shear strain $= \frac{\Delta x}{L}$
- Young's modulus is the ratio of tensile stress to tensile strain over the range for which Hooke's law applies.
- Hooke's law states that the extension is proportional to the applied force.
- Shear modulus is shear stress $(\frac{F}{A})$ divided by shear strain $(\frac{\Delta x}{L})$.
- The energy stored in a stretched wire is $\frac{1}{2}Fx$ where F is the force applied and x is the extension.

Review questions

1. Define the terms a) elastic limit, b) stress, c) strain, d) Young's modulus, e) shear modulus.
2. A load of 2.0 kg is applied to the ends of a wire 4.0 m long, and produces an extension of 0.24 mm. If the diameter of the wire is 2.0 mm, find:
   a) the stress on the wire
   b) the strain it produces

c) the value of Young's modulus of the material from which it is made

d) the strain energy.

3. a) What load in kilograms must be hung from a steel wire 6.0 m long and radius 0.80 mm to produce an extension of 1.0 mm? Young's modulus for steel is 2.0×10^{11} Pa.

b) What is the strain energy?

8.2 Fluid statics

By the end of this section you should be able to:

- Define the terms density, atmospheric pressure, absolute pressure, pressure, volume.
- Describe the concepts related to hydraulic and pneumatic systems.
- State and apply Archimedes's principle.
- Define surface tension and surface energy.
- Define the angle of contact and account for the shapes of the surfaces of liquids.
- Determine the relationship for capillary rise and use it to solve problems.

KEY WORDS

atmospheric pressure *the pressure exerted by weight of air against a surface*

density *the mass per unit volume of a substance*

pressure *the amount of force acting per unit area*

volume *the amount of space filled by an object or substance*

absolute pressure *the actual pressure at a given point*

Pressure due to a fluid column

The **pressure** (the force per unit area) at any point in a liquid depends on the depth and **density** (mass per unit **volume**) of the liquid. For example, the pressure at a depth of 10 m under the sea will be greater than the pressure at a depth of 5 m under the sea. This is why divers have to be particularly careful when they return to the surface, otherwise they can suffer from the effects of the pressure difference in the form of 'bends'. When we are on the surface of the earth, going about everyday business, we are subject to **atmospheric pressure**. This is the pressure exerted by the air around us and varies a little according to atmospheric conditions. Atmospheric pressure is used by weather forecasters to predict weather changes and is measured using an instrument called a barometer.

Pressure gauges measure pressure relative to atmospheric pressure but **absolute pressure** is defined as force applied perpendicular to a particular area.

Consider Figure 8.6.

At depth h in the liquid, the pressure is force per unit area at that point. If we look at a horizontal area A at depth h, then

$$\text{pressure} = \frac{\text{weight of liquid of volume } (A \times h)}{\text{area}}$$

If the liquid has density ρ, then since density $= \frac{\text{mass}}{\text{volume}}$

mass (m) = volume × density = $Ah\rho$

and weight of liquid = $mg = Ah\rho g$

So pressure $p = \frac{\text{weight}}{A} = Ah\rho g/A = h\rho g$

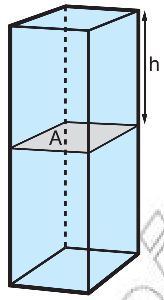

Figure 8.6 *At depth h, the pressure is force per unit area at that point*

Activity 8.5: Demonstrating the transmission of pressure by fluids (Cartesian diver)

Take a small test tube, partially filled with water, and cover the open end with part of a balloon, securely fastened with a rubber band, as shown in Figure 8.7.

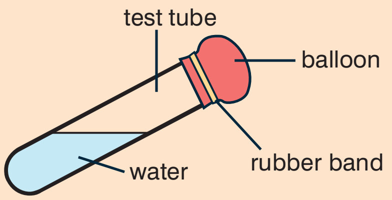

Figure 8.7 *How to prepare the apparatus*

Place the tube in a clear plastic squeezy bottle that is completely filled with water. Cap the squeezy bottle securely, squeeze it and observe what happens. (You may have to experiment with the amount of water in the tube that is needed to produce this dramatic effect.)

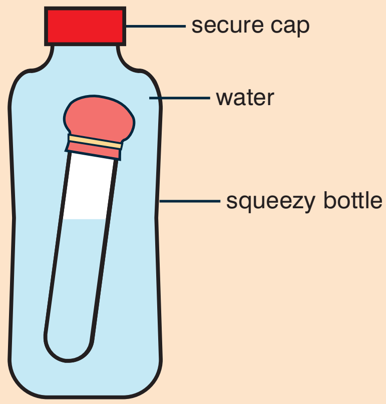

Figure 8.8 *The Cartesian diver apparatus*

Pascal's law and its applications

Activity 8.5 shows that fluids transmit pressure equally and are less compressible than gases. Pascal's law states that:

> **Pressure exerted anywhere in a confined liquid is transmitted equally and undiminished in all directions throughout the liquid.**

The transmission of pressure in liquids is used in hydraulic brakes for vehicles. In this case the liquid is oil and it connects the master piston (which is operated by the brake pedal) to the slave piston, which is connected to the brake drums on the wheels of the car as shown in Figure 8.9.

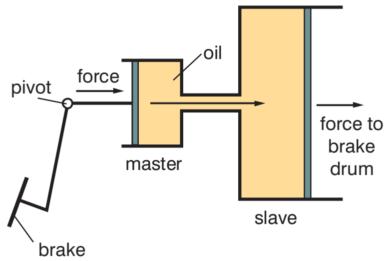

Figure 8.9 *Oil connects the master piston to the slave piston and transmits the pressure on the brake to the brake drum*

KEY WORDS

Pascal's law *the pressure applied to an enclosed fluid is transmitted to every part of the fluid without reducing in value*

Activity 8.6: What happens to water when it is under pressure?

This activity allows you to see what happens to the flow of water when it is under pressure. You will need two empty cans, nails and adhesive tape.

- Punch three holes horizontally at the bottom of one can, about 1.5 cm to 2 cm apart. Cover the holes with adhesive tape. What do you think will happen when you fill the can with water and remove the tape? Will any of the streams be longer than the others?
- Punch three holes diagonally in the side of another can. Cover the holes with adhesive tape. What do you think will happen when you fill the can with water and remove the tape? Will any of the streams be longer than the others?
- Fill both cans with water, and then tear off the tape on the can with the horizontal holes. Observe what happens.
- Now tear off the tape on the can with the diagonal holes. Observe what happens. Discuss your results with other students and try and explain them using Pascal's law.

Worked example 8.5

The force on a brake pedal is 2 N. The cross-sectional area of the pedal is 0.05 m^2. If the area of the brake drum is 0.045 m^2, what is the force on the brake drum?

F_{bp} (N)	A_{bp} (m^2)	F_{bd} (N)	A_{bd} (m^2)
2	0.05	?	0.045

Use $\frac{F_{bp}}{A_{bp}} = \frac{F_{bd}}{A_{bd}}$

Rearrange $F_{bd} = \frac{F_{bp}}{A_{bp}} \times A_{bd}$

$= \frac{2}{0.05} \times 0.045$

$= 1.8$ N

Activity 8.7: Other applications of hydraulics

In a small group, research other applications of hydraulics. (You could also research applications of pneumatics, which is where air is used as the medium for transmission of pressure rather than a liquid.) Present your findings to the rest of your class in a form of your choice.

Archimedes's principle and its applications

Archimedes's principle states that:

> **Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.**

The weight of the displaced fluid is directly proportional to the volume of the displaced fluid (if the surrounding fluid is of uniform density). Thus, among completely submerged objects with equal masses, objects with greater volume have greater buoyancy.

Buoyancy reduces the apparent weight of objects that have sunk completely to the sea floor.

Suppose a rock's weight is measured as 10 N when suspended by a string in a vacuum. Suppose that when the rock is lowered by the string into water, it displaces water of weight 3 N. The force it then exerts on the string from which it hangs would be 10 N minus the 3 N of buoyant force: 10 – 3 = 7 N.

Activity 8.8: Finding the density of an object using Archimedes's principle

Use the relation density $= \dfrac{\text{mass}}{\text{volume}}$

to design a way of finding the density of an object by applying Archimedes's principle. Write a report on your method, explaining the steps and the theory behind them. Carry out your investigation on a selection of objects.

You learnt about equilibrium in Grade 10. A floating object is stable if it tends to restore itself to an equilibrium position after a small displacement. For example, floating objects will generally have vertical stability, as if the object is pushed down slightly, this will create a greater buoyant force, which, unbalanced against the weight force, will push the object back up.

Rotational stability is of great importance to floating vessels. Given a small angular displacement, which you learnt about in Grade 10, the vessel may return to its original position (stable), move away from its original position (unstable), or remain where it is (neutral). An object will be stable if an angular displacement moves the line of action of the forces acting on it to set up a 'righting moment'.

The atmosphere's density depends upon height above the surface of the earth (altitude). As an airship rises in the atmosphere, its buoyancy decreases as the density of the surrounding air decreases. As a submarine expels water from its buoyancy tanks (by pumping them full of air), it rises because its volume is constant (the volume of water it displaces if it is fully submerged) as its weight is decreased.

Submarines rise and dive by filling large tanks with seawater. To dive, the tanks are opened to allow air to exhaust out the top of the

KEY WORDS

Archimedes's principle *the buoyant force on an object wholly or partially immersed in a fluid is equal to the weight of the fluid displaced by the object*

DID YOU KNOW?

RMS Titanic sank in 1912 after it hit an iceberg. Before the collision, the average density of the ship was less than that of water but, after the collision left a hole in the structure, water poured in and the average density was then less than that of water and it sank.

tanks, while the water flows in from the bottom. Once the weight has been balanced so the overall density of the submarine is equal to the water around it, it has neutral buoyancy and will remain at that depth. Normally, precautions are taken to ensure that no air has been left in the tanks. If air were left in the tanks and the submarine were to descend even slightly, the increased pressure of the water would compress the remaining air in the tanks, reducing its volume. Since buoyancy is a function of volume, this would cause a decrease in buoyancy, and the submarine would continue to descend.

Activity 8.9: Exploring Archimedes's principle

In a small group, design an investigation to explore Archimedes's principle. You could start by testing whether objects float or sink in water, and measuring the volume of water each displaces, then move on to making model boats in various shapes to test their stability. Record the steps in your investigation and the observations carefully, then try to explain them using Archimedes's principle.

Worked example 8.6

The density of ice is 0.92 and the density of water is 1.00.

What percentage of an iceberg will be above sea level?

Since the iceberg is ice, and the relative denisty of ice is 0.92, the iceberg will 'sink' until it has displaced 0.92 of its volume. This means that 8% of the iceberg will be above sea level.

KEY WORDS

surface tension *a property of a liquid's surface that causes it to act like a stretched elastic skin; it is caused by the forces of attraction between the particles of the liquid and the other substances with which it comes into contact*

Surface tension and surface energy

Surface tension makes itself known when the surface of a liquid gives the appearance of being covered by a stretched elastic skin, which pulls small drops into a spherical shape.

There are two ways to reduce surface tension – warm the water, or add detergent to it.

Activity 8.10: Exploring the effects of surface tension

Try laying a needle very carefully on to the surface of some water, as shown in Figure 8.10. What happens?

Now dip a rectangular wire frame with a piece of cotton tied loosely across it in soap solution to produce a liquid film, as shown in Figure 8.11.

Burst the film one side and describe what happens.

Try to explain your observations in terms of the surface tension of water.

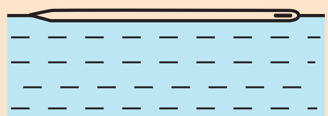

***Figure 8.10** Effect of surface tension: steel needle on water surface*

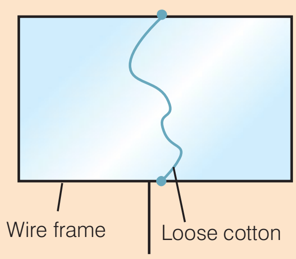

***Figure 8.11** Effect of surface tension in a film of soap*

The temptation is to think of the water as if it were being covered by a stretched rubber skin, but this does not fit everything that can be observed. With a rubber film, if the surface is stretched more, the tension will increase. With water, if the surface is stretched further, the tension stays exactly the same.

How can we explain this? What is the cause of surface tension?

Think of the liquid at a molecular level. For it to clump together and not split up into a gas, there must be forces of attraction between its molecules, which hold the liquid together. Figure 8.12 is an attempt to show these forces.

The molecules in the bulk of the liquid are surrounded by other molecules and so all the pulls cancel, but you can see that the ones at the surface seem to be tugged inwards. This disruption is measured by **surface energy**.

Figure 8.13 shows a very trivial sort of experiment and the outcome is exaggerated, but it is surprisingly revealing. A glass block is dipped into some water, and when you lift it up it comes out wet.

Stage 2 shows that you pull the water up with the block – as well as forces between neighbouring water molecules holding the water column together, there is also a cohesive force between the molecules in water and those in glass, so the water stays attached to the glass.

Stage 3 shows that the break, when it eventually occurs, happens within the water – the forces between glass and water are the stronger ones.

Surface tension is defined as:

> **a cohesive effect at the surface of the liquid due to the forces between the liquid's atoms or molecules.**

$$f = \frac{F}{l} = \frac{\text{force}}{\text{length}}$$

Pressure difference across a surface film

In Activity 8.10, you will have observed that the surface of a liquid will tend to take on a curved shape. This observation tells us that there must be a pressure difference between the sides of the surface to cause the curvature. There is an equation which can be used to calculate the pressure difference called the Young–Laplace equation.

pressure difference = surface tension × $\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$, where R_1 and R_2 are the radii of curvature of each of the axes that are parallel to the surface.

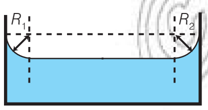

Figure 8.14 *The radii of curvature*

In symbols $\Delta p = f\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$, where p is pressure, f is surface tension.

If you solve this equation, you can find the shape of water drops, puddles, menisci, soap bubbles, and all other shapes determined by surface tension (such as the shape of the impressions that a water strider's feet make on the surface of a pond).

KEY WORDS

surface energy *a measure of the disruption of intermolecular bonds caused by a surface*

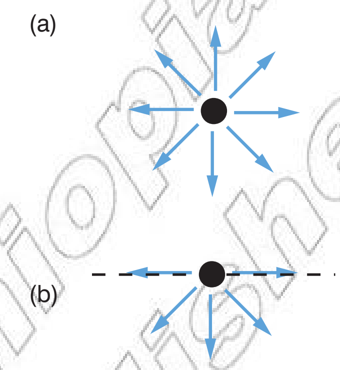

Figure 8.12 *The forces on a molecule (a) in the bulk of a liquid and (b) at the surface*

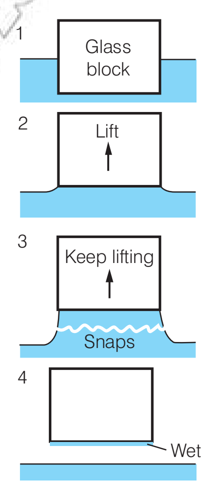

Figure 8.13 *The effect of surface tension on a glass block lifted out of water*

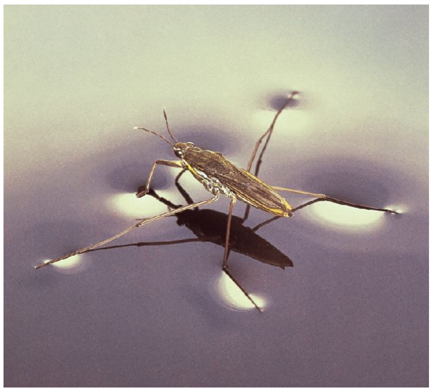

Figure 8.15 *Water strider*

KEY WORDS

contact angle *the angle at which a liquid surface meets a solid surface*

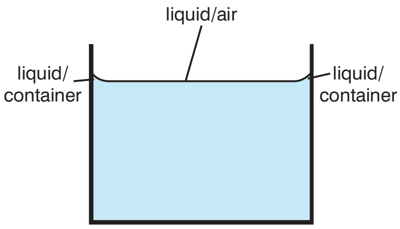

Figure 8.16 *Interfaces between a liquid, its container and air*

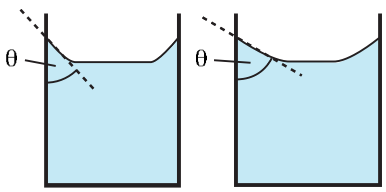

Figure 8.17 *Examples of contact angles*

Activity 8.11: Applications of surface tension ideas

In a small group, use the information given on pages 170–171 and your own research to write a presentation on the applications of surface tension ideas. Present your findings to the rest of your class.

Angle of contact and capillary action

No liquid can exist in a perfect vacuum for very long, so the surface of any liquid is an interface between that liquid and some other medium. For example, the top surface of a puddle is an interface between the water in the puddle and the air. This means that surface tension is not just a property of the liquid, but a property of the liquid's interface with another medium. If a liquid is in a container, then besides the liquid/air interface at its top surface, there is also an interface between the liquid and the walls of the container (see Figure 8.16).

Usually, the surface tension between the liquid and air is greater than its surface tension with the walls of a container. Where the two surfaces meet, their geometry must be such that all forces balance.

Where the two surfaces meet, they form a **contact angle**, which is the angle the tangent to the surface makes with the solid surface. Figure 8.17 shows two examples.

The contact angle for various liquid/solid interfaces has been measured and Table 8.1 shows these results.

Table 8.1 *Contact angles for different liquid/solid interfaces*

Liquid	Solid	Contact angle
water	soda-lime glass lead glass fused quartz	0°
ethanol		
diethyl ether		
carbon tetrachloride		
glycerol		
acetic acid		
water	paraffin wax	107°
	silver	90°
methyl iodide	soda–lime glass	29°
	lead glass	30°
	fused quartz	33°
mercury	soda-lime glass	140°

Where a water surface meets the glass wall of its container, the glass pulls some of the water molecules to it and a **meniscus** forms (see Figure 8.18). The forces are sufficiently strong to pull a column of water some distance up a narrow tube, until eventually the weight of the water prevents it from being pulled further – this is capillary action.

Capillary action explains two phenomena:

1. the movement of liquids in thin tubes
2. the flow of liquids through porous materials, such as the flow of water through soil.

KEY WORDS

capillary action *the movement of a liquid along the surface of a solid caused by the attraction of molecules of the liquid to molecules of the solid*

meniscus *a curve in the surface of a liquid caused by the relative attraction of the liquid molecules to the solid surfaces of the container*

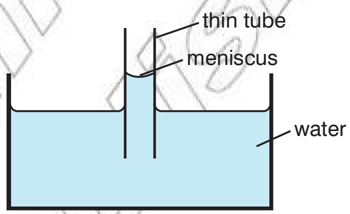

Figure 8.18 *Capillary action*

Activity 8.12: Demonstrating capillary action in thin tubes

The movement of liquids through tubes can be demonstrated using a capillary tube (a glass tube with a narrow diameter).

Place the end of a capillary tube in a liquid such as water.

Describe what you see. Now use a tube with a wider diameter. Describe the differences in the results. Try to explain your observation in terms of surface tension before reading on.

Explaining capillary action in thin tubes

Surface tension pulls the liquid column up until there is a sufficient mass of liquid for gravitational forces to overcome the intermolecular forces. The contact length (around the edge) between the top of the liquid column and the tube is proportional to the diameter of the tube, while the weight of the liquid column is proportional to the square of the tube's diameter, so a narrow tube will draw a liquid column higher than a wide tube. Different liquids will also have different capillary action, as shown in Figure 8.19, which compares the capillary action of water with the capillary action of mercury.

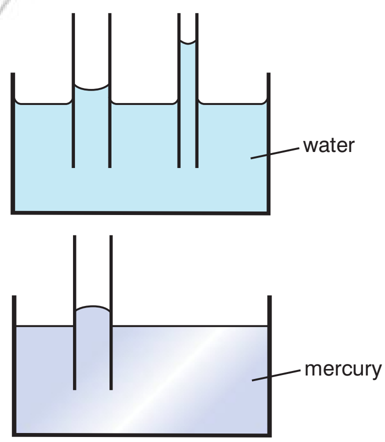

Figure 8.19 *Comparing the capillary action of water with that of mercury*

You can use this equation to find the height h of a liquid column caused as a result of capillary action $h = \dfrac{2f\cos\theta}{\rho g \times r}$ where:

- f is the liquid–air surface tension
- θ is the contact angle
- ρ is the density of liquid
- g is acceleration due to gravity
- r is radius of tube (length).

Activity 8.13: Exploring capillary action

Work in a small group. Moisten the lips of two styrofoam cups with water and press the cups firmly against opposite sides of a partially inflated balloon. Inflate the balloon further. What happens? Try to explain your observation in your small group.

Activity 8.14: Exploring applications of capillary action

Research some applications of capillary action. Present your findings to your class in a form of your own choice.

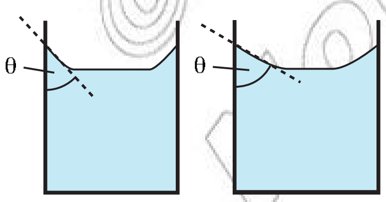

Figure 8.20 Contact angles

Worked example 8.7

Find the height of a column of methyl iodide in a soda–lime glass tube of radius 10 mm. The surface tension is 0.26, the contact angle is 29°, the density is 2.28.

h (m)	f	θ (°)	ρ (kg/m³)	g (m/s²)	r (m)
?	0.26	29	2.28	9.81	10×10^{-3}

Use $h = \dfrac{2\,f\cos\theta}{\rho\,g\,r}$

$= \dfrac{2 \times 0.26 \times \cos 29}{(2.28 \times 9.81 \times 10 \times 10^{-3})} = 0.455/0.224 = 2$ m

Summary

In this section you have learnt that:

- Density $= \dfrac{\text{mass}}{\text{volume}}$
- Volume = length × breadth × height
- Pressure $= \dfrac{\text{force}}{\text{perpendicular area}}$
- Atmospheric pressure is the pressure exerted by the air around us.
- Absolute pressure is the force applied perpendicular to a particular area.
- Hydraulic and pneumatic systems rely on Parcal's law: pressure exerted anywhere in a confined liquid is transmitted equally and undiminished in all directions throughout the liquid.
- Liquid (or air) is used in hydraulic (or pneumatic) systems to transmit pressure from one place (such as a brake pedal) to another (such as a brake drum).
- Archimedes's prinicple states thate any object, wholly or partly immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.
- Surface tension is defined as a cohesive effect at the surface of the liquid due to the forces between the liquids atoms or molecules $f = \dfrac{F}{l} = \dfrac{\text{force}}{\text{length}}$
- Surface energy measures the disruption to the forces a the molecules at the surface of the liquid, which seem to be tugged inwards.
- The contact angle is the angle the tanget in to the surface makes with the solid surface, as shown in Figure 8.20.
- For capillary rise, $h = \dfrac{2\,f\cos\theta}{\rho\,g\,r}$

Review questions

1. Define the terms a) density, b) atmospheric pressure, c) absolute pressure, d) pressure, e) volume.
2. a) State Archimedes's principle.
   b) Explain some applications of Archimedes's principle.
3. Define a) surface tension and b) surface energy.
4. a) Define the angle of contact.
   b) Use the angle of contact to account for the shapes of the surfaces of liquids.
5. State the relationship for capillary rise.

8.3 Fluid dynamics

By the end of this section you should be able to:

- Define the terms laminar and turbulent flow, flow rate.
- Identify factors affecting and give examples of laminar flow.
- Identify factors that affect the streamlining of cars, boats and planes.
- Define the Reynolds number.
- State Bernoulli's principle.
- Explain applications of Bernoulli's principle.
- Use Bernoulli's equation to solve problems.
- State Stoke's law and use it to solve problems.
- Use equation of continuity to solve problems.

KEY WORDS

Bernoulli's principle *principle stating that as the velocity of a fluid increases, the pressure exerted by that fluid decreases*

streamline/laminar flow *type of fluid flow where the fluid travels smoothly in regular layers; the velocity and pressure remain constant at every point in the fluid*

turbulent flow *type of fluid flow where there is disruption to the layers of fluid; the speed of the fluid at any point is continuously changing both in magnitude and direction*

Streamline and turbulent flow

When a liquid flows in parallel layers, with no disruption between the layers as shown in Figure 8.21, the flow is known as **streamline** or **laminar** flow.

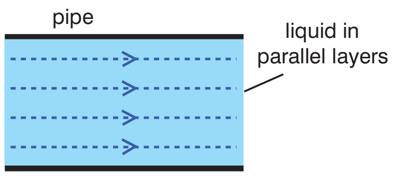

Figure 8.21 *Streamline flow*

In this type of flow, air moves with the same speed in the same direction at all times and the flow appears to be smooth and regular. **Bernoulli's principle**, which states that a fluid (such as air) travelling over the surface of an object exerts less pressure than if the fluid were still, applies during laminar flow. Aeroplanes fly because of Bernoulli's principle. When an aeroplane takes off, air rushes over the top surface of its wing, reducing pressure on the upper surface of the wing. Normal pressure below the wing pushes the wing upward, carrying the airplane upward along with it. You will explore this principle in more detail on page 179.

In contrast, in **turbulent flow** there is disruption between the layers of fluid as shown in Figure 8.22.

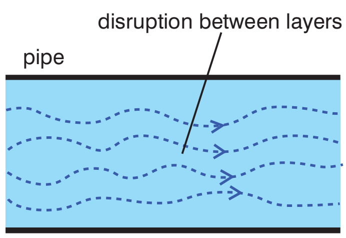

Figure 8.22 *Turbulent flow*

KEY WORDS

flow rate *the volume of liquid flowing past a given point per unit time*

This type of flow is chaotic and unpredictable. It consists of irregular eddies (circular currents) of air that push on a surface in unexpected ways. You may have experienced turbulence on a commercial aeroplane flight – your bumpy ride could have resulted from the development of turbulent flow over the aeroplane's wings.

The **flow rate** is the volume of liquid flowing past a given point per unit time.

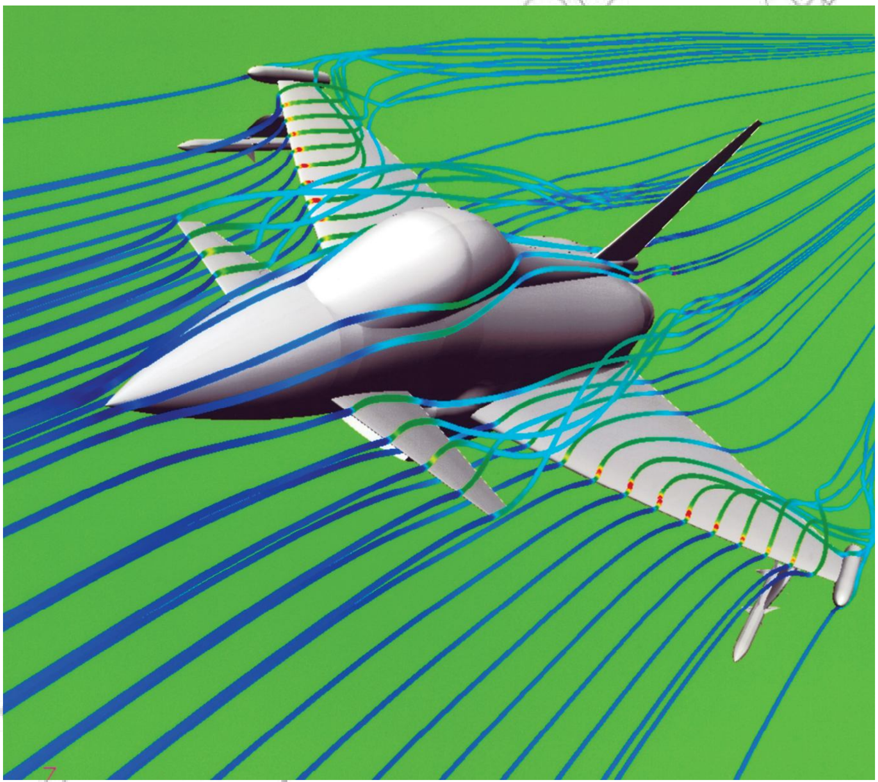

Figure 8.23 *Turbulent flow over an aeroplane's wings*

Factors affecting laminar flow

There are four properties of air that affect the way it flows past an object: density, compressibility (how much its volume can be reduced), temperature and viscosity. (You will learn more about viscosity on page 180–181.)

The density and compressibility of air are important factors at high speeds. As an object travels rapidly through air, it causes air to become compressed and more dense. As a result, other properties of air then change.

The effects of temperature change on air flow also become important at high speeds. A regular commercial airplane, after landing, will feel cool to the touch.

Factors affecting streamlining of cars, boats and planes

Unless you keep pushing an object, as it moves through the air it will slow down because of air resistance acting to oppose the motion, as shown in Figure 8.24.

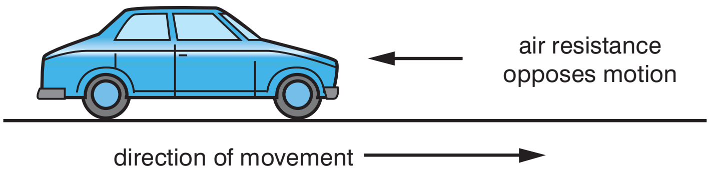

Figure 8.24 Ai resistance opposes motion

In general, objects with larger surface areas will travel slower through the air (or any other fluid). There are certain shapes which help objects to speed up and travel faster through the air or other fluid than others – this is called streamlining. An application of streamlining is in motorsport, where the vehicles are designed so that their shape is streamlined to help their performance.

Activity 8.15: Identifying streamlining features on motorsport vehicles

Compare the photographs of the ordinary car and Formula 1 car here. What differences can you see?

Figure 8.25 a) Typical Ethiopian car, b) Formula 1 car

Activity 8.16: Exploring streamlining

Obtain a long see-through tube which you can fill with a liquid such as water. In a small group, make various objects out of modelling clay, some of which should have features which make them more streamlined than others (e.g. lower surface area at front, etc.). Drop the objects into the top of the tube of liquid and time how long they take to reach the bottom. Do the ones that you thought you had designed to be more streamlined travel more quickly through the liquid?

KEY WORDS

equation of continuity *the mass flow rate of fluid flowing into a system is equal to the mass flow rate of fluid leaving the system*

Equation of continuity

The **equation of continuity** in fluid dynamics states that the volume flow rate of an ideal fluid flowing through a closed system is the same at every point.

In Figure 8.26, the system is closed and so $V_{in} = V_{out}$, where V_{in} is the volume flow rate of liquid in, V_{out} is the volume flow rate of liquid out.

$V_{in} = v_1$

$v_2 = V_{out}$

where v_1 is the volume flow rate of section 1, v_2 is the volume flow rate of section 2.

Since $V_{in} = V_{out}$

$v_1 = v_2$

$$\text{Flow rate} = \frac{\text{volume}}{\text{time}}$$

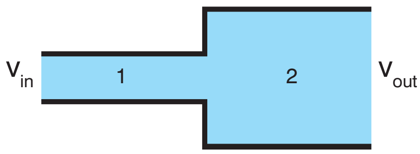

Figure 8.26 An ideal fluid flowing through a closed system

Worked example 8.8

Water flows at 10 m^3/h through a pipe connected to a tap. At what rate will the water leave the tap?

Use the equation of continuity.

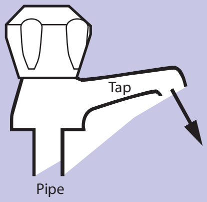

Figure 8.27

The volume flow rate is the same at every point.

Volume flow rate = volume flow rate of tap

10 m^3/h = 10 m^3/h

Water will leave the tap at 10 m^3/h

$$\theta = \frac{V_{in}}{\text{time}} = \frac{v_1}{\text{time}} = \frac{v_2}{\text{time}} = \frac{V_{out}}{\text{time}}$$

Since $V_{in} = v_1 = v_2 = V_{out}$ θ is the same at all points in the system.

$$m = \rho_{i1} v_{i1} A_{i1} + \rho_{i2} v_{i2} A_{i2} + \ldots + \rho_{in} v_{in} A_{in}$$
$$= \rho_{o1} v_{o1} A_{o1} + \rho_{o2} v_{o2} A_{o2} + \ldots + \rho_{om} v_{om} A_{om} \quad (1)$$

where

m = mass flow rate (kg/s)

ρ = density (kg/m^3)

v = speed (m/s)

A = area (m^2)

With uniform density, equation (1) can be modified to

$$q = v_{i1} A_{i1} + v_{i2} A_{i2} + \ldots + v_{in} A_{in}$$
$$= v_{o1} A_{o1} + v_{o2} A_{o2} + \ldots + v_{on} A_{on} \quad (2)$$

where

q = flow rate (m^3/s)

$\rho_{i1} = \rho_{i2} = \ldots = \rho_{in} = \rho_{o1} = \rho_{o2} = \ldots = \rho_{on}$

Worked example 8.9

Water flows at 10 m^3/h through a pipe with 100 mm inside diameter. The pipe is reduced to an inside dimension of 80 mm. Find the velocity of the water in each part of the pipe.

Using equation (2)

$$q = v_{i1} A_{i1} + v_{i2} A_{i2} + \ldots + v_{in} A_{in}$$
$$= v_{o1} A_{o1} + v_{o2} A_{o2} + \ldots + v_{on} A_{on}$$

the velocity in the 100 mm pipe can be calculated as

$(10\ m^3/h)(1 / 3600\ h/s) = v_{100}\ (3.14\ (0.1\ m)^2 / 4)$

or

$v_{100} = (10\ m^3/h)(1 / 3600\ h/s) / (3.14\ (0.1\ m)^2 / 4)$

= 0.35 m/s

Using equation (2), the velocity in the 80 mm pipe can be calculated

$(10\ m^3/h)(1 / 3600\ h/s) = v_{80}\ (3.14\ (0.08\ m)^2 / 4)$

or

$v_{80} = (10\ m^3/h)(1 / 3600\ h/s) / (3.14\ (0.08\ m)^2 / 4)$

= 0.55 m/s

Activity 8.17: Application of the equation of continuity

You can demonstrate the equation of continuity by taking a hose, watching the water flow out and then half covering the exit point with your thumb. What happens to the speed of the water coming out of the hose? Try to explain the observation using the equation of continuity before reading on.

Common applications of the equation of continuity are pipes, tubes and ducts with flowing fluids or gases, rivers, overall processes as power plants, roads, computer networks and semiconductor technology.

Explaining the results of Activity 8.17

The rate of flow stays constant in a closed system. The decrease of the cross-section of the opening is balanced by the increased speed of the water. Note that you cannot apply the equation to the water once it has left the system as it is no longer in a closed system!

Bernoulli's equation

We discussed Bernoulli's principle briefly on page 175. In most examples of liquid flow, we can consider that the fluid in the flow can be described as incompressible flow. Bernoulli performed his experiments on liquids and his equation in its original form is valid only for incompressible flow.

A common form of Bernoulli's equation, which is valid at any arbitrary point along a streamline where gravity is constant, is:

$$\frac{p}{\rho} + gh + \frac{v^2}{2} = \text{constant}$$

where:

- v is the fluid flow speed at a point on a streamline
- g is the acceleration due to gravity
- h is the elevation of the point above a reference plane, with the positive z-direction pointing upward — so in the direction opposite to the gravitational acceleration
- p is the pressure at the point
- ρ is the density of the fluid at all points in the fluid.

In many applications of Bernoulli's equation, we can use the following simplified form:

$$p + q = p_0$$

where p_0 is called total pressure, and q is dynamic pressure. The pressure p is often referred to as static pressure to distinguish it from total pressure p_0 and dynamic pressure q.

The simplified form of Bernoulli's equation can be summarised as:

static pressure + dynamic pressure = total pressure

Every point in a steadily flowing fluid, regardless of the fluid speed at that point, has its own unique static pressure p and dynamic pressure q. Their sum $p + q$ is defined to be the total pressure p_0. The significance of Bernoulli's principle can now be summarised as:

Total pressure is constant along a streamline.

Activity 8.19: Demonstrating Bernoulli's principle 2

Suspend two light bulbs from a table rod in the field of an overhead projector turned on its side so that you can see the magnified image on the ceiling. Blow sharply between the bulbs so that they clank together.

As an alternative, you could blow sharply between two pieces of paper or ping-pong balls.

Activity 8.18: Demonstrating Bernoulli's principle 1

Take a ping-pong ball and a hairdryer. Use the flow of air from the hair-dryer to hold the ping-pong ball in the air. How long can you support the ball with the air flow? Try other light objects such as feathers and pieces of paper (take care not to put the heat source too close to them though!). Make a table of results to compare the mass of the object and how long it can be held up in the airflow.

Worked example 8.10

Use the simplified version of Bernoulli's equation to find the total pressure when the static pressure is 5 Pa and the dynamic pressure is 7 Pa.

static pressure + dynamic pressure = total pressure

5 Pa + 7 Pa = 12 Pa

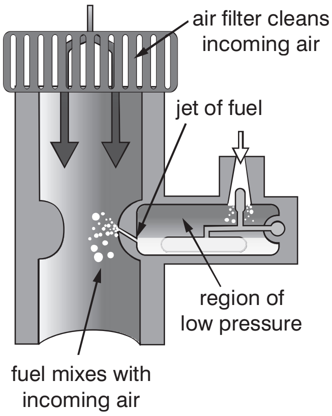

Figure 8.28 *In the narrow throat, the air is moving at its fastest speed and is therefore at its lowest pressure*

Figure 8.29 *The wind passing in front of the sail is fast enough to experience a significant reduction in pressure and the sail is pulled forward*

Further applications of Bernoulli's principle

We have already learnt (on page 175) that Bernoulli's principle can be used to calculate the lift force on an aeroplane if you know the behaviour of the fluid flow in the vicinity of the wing. Other applications of the principle include:

- The carburettor in engines contains a device to create a region of low pressure to draw fuel into the carburettor and mix it thoroughly with the incoming air. The low pressure in the device can be explained by Bernoulli's principle; in the narrow throat, the air is moving at its fastest speed and therefore it is at its lowest pressure.
- The pitot tube and static port on an aircraft are used to determine the airspeed of the aircraft. These two devices are connected to the airspeed indicator which determines the dynamic pressure of the airflow past the aircraft. Dynamic pressure is the difference between stagnation pressure and static pressure. Bernoulli's principle is used to calibrate the airspeed indicator so that it displays the indicated airspeed appropriate to the dynamic pressure.
- The flow speed of a fluid can be measured using a device placed into a pipeline to reduce the diameter of the flow. For a horizontal device, the continuity equation shows that for an incompressible fluid, the reduction in diameter will cause an increase in the fluid flow speed. Subsequently Bernoulli's principle then shows that there must be a decrease in the pressure in the reduced diameter region.
- The maximum possible drain rate for a tank with a hole or tap at the base can be calculated directly from Bernoulli's equation, and is found to be proportional to the square root of the height of the fluid in the tank.
- The principle also makes it possible for sail-powered craft to travel faster than the wind that propels them (if friction can be sufficiently reduced). If the wind passing in front of the sail is fast enough to experience a significant reduction in pressure, the sail is pulled forward, in addition to being pushed from behind. Although boats in water must contend with the friction of the water along the hull, ice sailing and land sailing vehicles can travel faster than the wind.

Viscosity

If water flows through a pipe, smooth streamline motion can ensue. The layer of water touching the walls is at rest, the water in the centre is moving fastest. The layers of water are travelling at an increasing speed as we go from the walls to the centre, and this means that each layer is being dragged forward by the faster layer one side but held back by the slower one on the other side. The overall outcome turns out to be a resultant drag force (Figure 8.30).

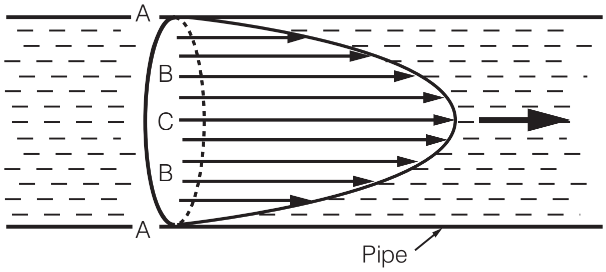

Figure 8.30 *Velocity of layers of liquid in a pipe*

The force required to drive the layers

$$F = \eta A \frac{\Delta v}{\Delta y}$$

where v = speed of flow

y = distance from container wall

A = cross-sectional area

η = viscosity

Some liquids flow move readily through pipes, or move out of the way more freely to allow a body to move through them. These are the liquids that have a low **viscosity** – to put it simply, they are very runny.

The coefficient of viscosity

Thick oils and the like are quite the opposite. They are very viscous, and large drag forces appear when layers have to slide over one another. The viscosity of a liquid may be measured by a quantity called its coefficient of viscosity, given the Greek letter η ('eta'). Its units are kg/m/s, and a large number indicates a viscous liquid. It is not essential that you remember those units – so long as you put all the values into an equation in their basic SI units it is bound to work out. As a liquid warms up, its viscosity falls considerably.

The viscous force between layers is determined in part by how rapidly the velocity is changing as you go from layer to layer. This is specified by what is known as the velocity gradient. It is the change in velocity (in m/s^1) per metre as you move in from the wall of the pipe. It is measured in m/s per metre, and m/s/m reduces to just /s.

The second factor is just the area of contact A between the two layers. In a given liquid at a given temperature, the viscous drag force F acting between the layers is given by

F = (a constant) × A × the velocity gradient.

The constant is defined to be the viscosity η of the liquid.

Stokes's law and terminal velocity

Consider a body moving through a fluid (or the fluid moving past the body, which is the same thing). The viscous drag force on the moving body (the 'head wind' effect) may be worked out. For simplicity we imagine the body is a sphere, of radius r.

Activity 8.20: Comparing viscosity of various liquids

In a small group, devise an investigation to find out which of a selection of liquids is the most viscous. You could compare water and cooking oil, for example. Think carefully about your method and check it with your teacher before you begin. How will you record your observations so that you can draw conclusions? What measurements will you need to take?

KEY WORDS

viscosity *the internal resistance of a fluid to flow and a measure of 'thickness' of a fluid*

Poiseuille's Law

Poiseuille's law states that

$$\text{Volume flowrate} = \frac{\pi \times \Delta p\, r^4}{8\,\eta L}$$

Where Δp is the difference in pressure between the ends of a pipe

r is the radius of the pipe

η is the coeficient of viscosity

L is the length of the pipe

KEY WORDS

terminal velocity *the maximum constant velocity reached by a falling body when the drag force acting on it is equal to the force of gravity acting on it*

Worked example 8.11

Find the force on a ball bearing of radius 4×10^{-3} m falling through a liquid of viscosity 0.985 at a velocity of 0.5 m/s.

F (N)	η $(kg/m/s^{-1}5^{-1})$	r (M)	v (m/s)
?	0.985	4×10^{-3}	0.5

$F = 6\pi\eta rv = 6\pi \times 0.985 \times 4 \times 10^{-3} \times 0.5 = 0.01182\pi$ N

Activity 8.21: Measuring terminal velocities

If you have available a long transparent tube, you may be able to fill it full of a liquid and measure terminal speeds through it to find the liquid's viscosity at room temperature. Steel ball bearings through an oil may be suitable, perhaps.

The details, and the theory behind it, are up to you.

Start with just one ball. How will you measure its terminal velocity v? What other quantities will you have to measure, and how? How could you take a check reading?

There are three factors that affect the magnitude of the drag force F:

1. There is the size of the body. A reasonable guess might be that what matters is the area which the shape presents to the fluid, but this turns out not to be the case. The force is proportional to the radius r.
2. The force is also proportional to the velocity v at which the sphere moves through the air: double that velocity and the drag force doubles.
3. The third factor is the viscosity of the fluid, which is η.

Put them all together and we get

$$F = (\text{some constant}) \times \eta \times r \times v.$$

A full theoretical treatment tells us that the constant is 6π, and the result is Stokes's law – the viscous drag force F that acts on a sphere of radius r travelling at a velocity v through a fluid of viscosity η is given by:

$$F = 6\pi\eta rv$$

If a ball is dropped through a fluid, the force of gravity causes it to go faster and faster. As its velocity increases, the drag force becomes bigger too. Eventually it is going so fast that the drag force is as large as its weight and therefore cancels it out. The ball no longer accelerates. Instead it goes at a constant velocity – its **terminal velocity** through that fluid.

If you have spheres that are similar except that they are of, say, five different sizes, how could you improve the method? Could you plot a graph of your results and deduce the viscosity from that?

Reynolds numbers

The Reynolds number, which does not have any units, is an important variable in equations that describe whether flow conditions lead to laminar or turbulent flow. In the case of flow through a straight pipe with a circular cross-section, Reynolds numbers of less than 2300 are generally considered to be of a laminar type. However, the Reynolds number at which laminar flows become turbulent is dependent upon the flow geometry.

Summary

In this section you have learnt that:

- Laminar flow occurs when liquids flow in parallel layers and there is no disruption between the layers.
- Turbulent flow occurs when there is disruption between the layer of fluid.
- The flow rate is the volume of liquid flowing past a given point per unit time.
- Factors that affect laminar flow are density, compressibility (how much the volume of the liquid can be reduced), temperature and viscosity.
- Density, compressibility and temperature of air become important at high speeds: on landing, a commercial aeroplane will feel cool to the touch.
- The Reynolds number is available in equations that describe whether conditions lead to laminar or turbulent flow.
- Bernovilli's principle states that a fluid travelling over the surface of an object exerts less pressure that if the fluid were still, for example, when aeroplanes fly.
- Bernovilli's equation is $\frac{p}{\rho} + gh + \frac{v^2}{2}$ = constant.
- A simplified form is

  static pressure + dynamic pressure = constant
- Stoke's law is

  the viscous drag force F that acts on a sphere of radius r travelling at a velocity v through a fluid of viscosity η is given by $F = 6\pi\eta rv$.
- The equation of continuity states that the volume flow rate of an ideal fluid flowing through a closed system is the same at every point.

Review questions

1. Give examples of laminar flow.
2. Identify factors that affect the streamlining of cars, boats and planes.
3. Define the Reynolds number.
4. State Bernoulli's principle.
5. Use the simplified version of Bernoulli's equation to find the total pressure when the static pressure is 9 Pa and the dynamic pressure is 3 Pa.
6. State Stokes's law.
7. State the equation of continuity.

8.4 Heat, temperature and thermal expansion

By the end of this section you should be able to:

- Define the terms calorimetry, phase, phase change, phase diagram, state variable, critical point, triple point, latent heat, heat capacity, specific heat capacity.
- Distinguish between heat, temperature, internal energy and work.
- Describe the units for heat, heat capacity, specific heat capacity and latent heat.
- Explain the factors that determine the rate of heat flow through a material.
- Describe the thermal expansion of solids in terms of the molecular theory of matter.
- Carry out calculations involving expansivity.
- Solve problems involving thermal conductivity.
- Describe experiments to measure latent heat.

KEY WORDS

specific heat capacity *the heat energy required to raise the temperature of 1 kg of a given substance by 1 K*

heat capacity *the heat capacity,* C, *of a body of mass* m *is given by heat capacity +* m × *specifc heat capacity*

Specific heat capacity

You learnt about **specific heat capacity** in Grade 9, Section 7.3, so this section should be revision.

Accurate measurements suggest that for every gram of water we are heating and for every 1 K we are raising its temperature, we have to supply about 4.2 J of energy. If we took a thousand times as much water, that is, a kilogram, we would have to provide a thousand times as much energy (4200 J) to raise the temperature of this larger mass of water by 1 K.

Other substances vary. Kerosene, for instance, is found to need only 2200 J of energy to warm 1 kg of it by 1 K. Thus a kettle containing a kilogram of kerosene instead of water would heat up nearly twice as fast, but as the heat escaped again it would cool down more quickly.

The **specific heat capacity** of a substance is defined as:

> **The number of joules of heat energy required to raise the temperature of 1 kg of it by 1 K.**

(Sometimes the specific heat capacity is defined as the amount of energy needed to raise the temperature of 1 gram of a substance by 1 K, but the definition using 1 kg is more correct.)

Specific heat capacity is represented by the symbol *c*. If you had got not 1 kg but *m* kg to warm up, you would have to supply *m* times as much heat energy. Likewise if you raised its temperature through not 1 K but through a temperature rise of $\Delta\theta$, then $\Delta\theta$ times as many joules of energy are needed. (The symbol Δ is the capital form of the Greek letter delta, and should be understood as the difference in θ).

Therefore, to find the number of joules of energy needed:

1. Take the specific heat capacity *c* in J/kg/K or in J/g/K.
2. Multiply it by the number of kilograms (or grams) you are heating.
3. Multiply it again by the change in temperature in kelvin.

This process can be summed up by the formula: $E_H = mc\,\Delta\theta$

where E_H is the number of joules of energy to be supplied (if you are heating the substance), or the number of joules of thermal energy released (if it is cooling down).

Worked example 8.12

The specific heat capacity of water is 4200 J/kg/K.
How much energy will be needed to warm 800 g of water from 17°C to 27°C?

E_h	m	c	$\Delta\theta$
J	kg	J kg^{-1}	K^{-1}
?	0.8	4200	10

The change in temperature $\Delta\theta = 27 - 17 = 10$ K

Because the specific heat capacity has been given in J/kg/K, we must take '*m*' to be not 800 g but 0.8 kg.

$E_H = mc\Delta\theta = 0.8 \times 4200 \times 10 = 33\,600$ J

Notice carefully in the above example that a rise in temperature from 17°C to 27°C is a gain of 10 K. Degrees Celsius and the kelvin are the same-sized interval of temperature. You do not need to add 273 to the 17°C and 27°C; you would still end up with a 10 degree rise in temperature.

Worked example 8.13

Using a current of 1.5 A, a 12 V, 1.5 A heater was used to heat 100g of water for 15 minutes. The temperature rose from 21°C to 52°C. Based on these results, how much energy would be required to warm 1 kg of water by 1°C?

Power of heater (W)	Energy supplied (J)	Δθ (°C)
12 × 1.5 = 18	15 × 60 × 18 = 16 200	52 – 21 = 31

Use $E = mc\Delta\theta$

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

$$= \frac{16\,200}{0.1 \times 31}$$

$$= \frac{16\,200}{3.1}$$

$$= 5226 \text{ J/kg/K}$$

Activity 8.22: Measuring the specific heat capacity of a liquid by electrical heating

To find the specific heat capacity of water you need to supply a measured number of joules of heat energy to a known number of kilograms of water, and see what temperature rise results.

If you use an electric heater submerged under the water (an immersion heater), you can measure accurately its wattage. You work out the power of the heater in watts by multiplying the voltage drop across the heating coil by the current in amperes which is passing through it ($P = VI$). This works because the voltage tells you how many joules of heat energy will be produced for each coulomb of charge that passes, and the current is the number of coulombs which pass every second.

All this energy goes into the water, so we simply have to insulate the water's container in order to keep it there. Figure 8.31 shows the electrical circuit. Do not switch on until the heater is covered by water or you may burn it out.

The rest of the apparatus is shown in Figure 8.32. A suitable container is an insulated cup of the sort drinks are sometimes sold in. The lid can be made from a small piece of plastic or hardboard. The thermometer can be supported by a tight-fitting collar cut from a length of rubber tubing. The stirrer must be made from a piece of insulated wire so that it does not short out the heater.

What we are trying to find out, remember, is how many joules of energy are needed to raise the temperature of 1 kg of water by 1°C. A kilogram is a lot of water to heat, however, so it makes sense to take 100 g and scale the final answer up. A convenient way to measure the water out is to pour 100 cm^3 into the cup from a measuring cylinder, since the density of water is 1 g/cm^3.

You are now ready to start. Record the temperature of the cold water, then start a stopwatch and switch on the heater.

A temperature rise of 1°C is too small to measure accurately, so aim for a temperature rise somewhere between 10 and 30°C. When you have finished, switch off, note the time, stir thoroughly and take the final temperature of the water.

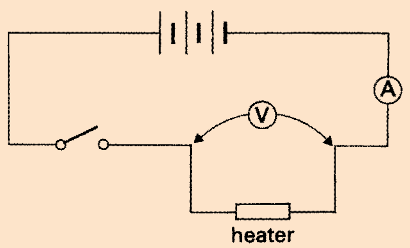

Figure 8.31 *The circuit used to find the specific heat capacity of a liquid*

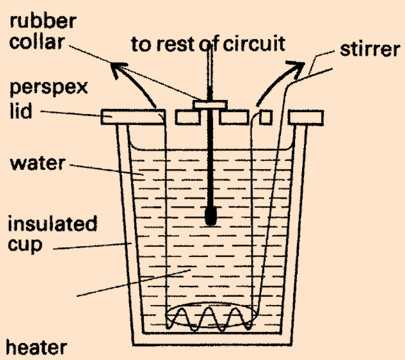

Figure 8.32 *The rest of the apparatus used to find the specific heat capacity of a liquid*

Sample readings

Use your own results if possible, but if not make use of these sample readings:

Mass of water being heated = 100 g

Starting temperature of cold water = 22°C

Steady current I through heater = 1.5 A

Steady p.d. V across heater = 12.0 V

Total time t of heating = 10 min = 600 s

Final temperature of warm water = 47°C

Analysing the readings

1. What is the power of the heater (in watts)?
2. How many joules of heat energy did the heater supply in total?
3. Through how many degrees C did this energy warm the 100 g of water?
4. How much energy, therefore, was needed to warm 1 kg of water by 1°C?

Calorimetry

Calorimetry is the science of measuring the heat of chemical reactions or physical changes. Calorimetry involves the use of a calorimeter. The word calorimetry is derived from the Latin word calor, meaning heat. Scottish physician and scientist Joseph Black, who was the first to recognise the distinction between heat and temperature, is said to be the founder of calorimetry.

Change of state

In Grade 9, you learnt about changes of state in Section 7.4. The three states of matter that you have considered are solid, liquid and gas. Each of these states of matter can be considered as a **phase**. A **phase change** occurs when a substance changes state – for example, when ice (solid) turns to water (liquid) which then turns to vapour. These changes of state happen when the kinetic energy of the molecules in the substance increases (which we usually record as an increase in temperature, because the kinetic energy of the molecules in a substance, *internal energy*, is related to the temperature of the substance) or decreases (which we usually record as a decrease in temperature). A **phase change diagram** such as the one in Figure 8.33 shows the three phases of a substance.

The diagram shows the **triple point** for the substance, which is the point where all three states coexist together. This occurs at 0°C for water. At the **critical point** the liquid and gas phases become indistinguishable.

KEY WORDS

calorimetry *the experimental approach to measuring heat capacities and heat changes during chemical and physical processes*

critical point *the temperature and pressure at which the liquid and gas phases of a substance become identical*

phase *the distinct form of a substance under different conditions, e.g. solid, liquid, gas*

phase change *a change from one state of matter to another without a change in chemical composition*

phase change diagram *a graph of pressure against temperature which can be used to show the conditions under which each phase of a substance exists*

state variable *a variable that describes the state of a dynamic system. In thermodynamics, this may include properties such as temperature, pressure or internal energy*

triple point *the temperature and pressure at which the three phases of a substance coexist*

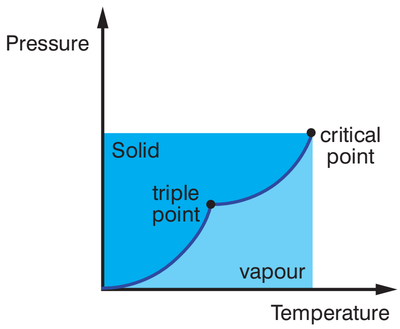

Figure 8.33 *Phase change diagram*

Activity 8.23: The phase diagram

In a small group, discuss the phase diagram in Figure 8.33 and try to explain what it shows in your own words.

KEY WORDS

latent heat *the amount of energy released or absorbed by a substance during a change of state that occurs without a change in temperature*

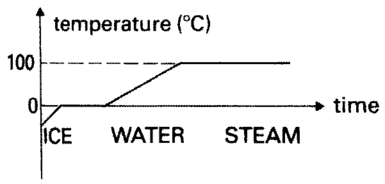

Figure 8.34 *Why does the temperature stop rising at 0°C and 100°C?*

Latent heat

If you heat a body, it will get hotter. That seems pretty obvious, so it may come as a surprise to discover that it is not necessarily true.

If you imagine being given a beaker containing water at 100°C and a Bunsen burner, you will begin to see why. You can continue to feed thermal energy into that water, but a thermometer would persist in reading 100°C. The extra energy you are supplying does not show itself as a rise in temperature, and it is given the name **latent heat**. 'Latent' means hidden.

The water of course is boiling away and turning to steam. The energy goes not into making the molecules move faster, but instead it is used to separate the molecules from each other. Work has to be done in moving them apart against the attractive forces which hold them together as a liquid.

Something similar happens as ice melts. All that time the heat energy it is gaining makes it no hotter, but instead it goes into breaking down the rigid structure of the solid.

Figure 8.34 shows what should happen if heat energy is fed into a block of ice in a steady and even way. Despite this constant input of heat energy the temperature twice stays fixed: once at 0°C as it melts and once at 100°C as it boils.

Melting and boiling are, of course, examples of changes of state, from the solid state to the liquid state or from liquid to gas. Whenever a substance changes state, latent heat is involved.

When steam condenses or water freezes, this latent heat is given out again. A scald from steam at 100°C can prove much worse than a scald from water at that temperature. The steam condenses on the cool skin, giving out its considerable latent heat as it turns to water still at 100°C, and then the hot water gives out its heat in turn as it cools down.

Activity 8.24: Determining the amount of heat necessary to convert a known quantity of ice at 0°C to water at 0°C

In a small group, use the experience you have gained from the activities so far in this section to devise and carry out an investigation into the amount of heat necessary to convert a known quantity of ice to water at 0°C. Show your plans to your teacher before you begin the investigation. How will you measure how much heat is supplied? What measurements will you need to take?

Specific latent heat of fusion

The process of melting is sometimes called fusion (which is how an electrical fuse got its name). Likewise changing from a liquid to a gas is called vaporisation, and includes evaporation as well as boiling.

To turn a 1 kg block of ice at 0°C into water still at 0°C needs about 340 000 J of energy (which may be expressed as 340 kilojoules, 340 kJ). It is a very large figure, partly because the joule is quite a small unit but mainly because it does take a lot of energy to melt 1 kg of ice.

The figure is referred to as the specific latent heat of fusion (symbol 'L_f') of ice. The units are joules per kilogram (J/kg).

The specific latent heat of fusion of a substance is

the thermal energy required to change 1 kg of the solid at its melting point into 1 kg of liquid at the same temperature.

If you tried to melt not 1 kg but 2 kg of ice, you would have to supply twice as much energy (i.e., 2 × 340 000 J).

In order to melt *m* kg of ice, the energy E_H needed is given by:

$$E_H = mL_f$$

Activity 8.25: Measuring the specific latent heat of fusion of ice

The question you want to answer here is: how many joules of heat energy are needed to change 1 g (or 1 kg) of ice at 0°C into water still at 0°C?

If ice cubes on the point of melting are added to a drink, then it becomes chilled. The heat energy removed from your drink has gone first into melting the ice and then into warming that 'molten ice' up from 0°C to the temperature of the rest of the chilled drink.

An experiment to discover how effective ice cubes are at cooling a drink should help us to find an answer to the question.

Figure 8.35 shows the idea. We assume the ice is at its melting point, but it is important to make sure the ice cubes are carefully dried with filter paper before they are added. It is therefore not feasible to weigh them before putting them in, so we find the number of grams of ice added by seeing at the end how much heavier the cup of water has become.

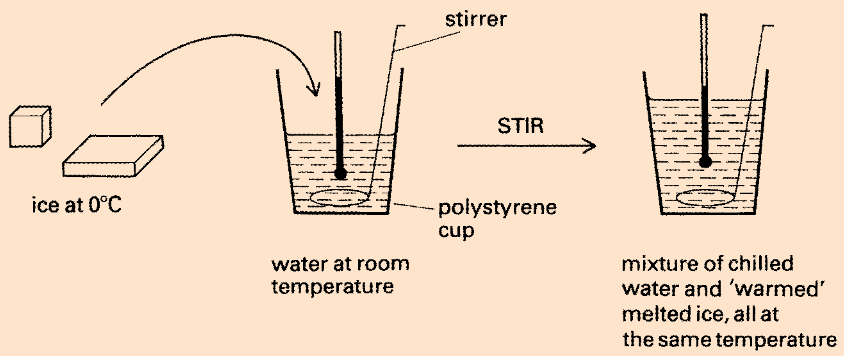

Figure 8.35 *How much energy is needed to change the ice into water?*

Finding the specific latent heat of fusion ice

Sample data:

Mass of cup empty = 23 g

Mass of cup + 'room temperature' water = 123 g

Initial temperature of 'room temperature' water = 17°C

Final temperature of chilled water + 'molten ice' = 5°C

Total mass of cup, water + 'molten ice' at end = 139 g

Your calculations:

1. How many grams of 'room temperature' water were there at the start?
2. By how many degrees was this water eventually chilled?
3. How much energy must have been removed from this water? Take the specific heat capacity of water to be 4.2 J g^{-1} K^{-1}.
4. How many grams of ice at 0°C must there have been originally?
5. When, having melted, it warmed up from 0°C to the final temperature of the chilled mixture, how many joules of energy did it gain?
6. By comparing your answers to questions 3 and 5, how many joules of energy must the ice have taken in melting?
7. How much energy therefore was required to change 1 g of ice at 0°C into 1 g of water at 0°C?
8. Give your value for the specific latent heat of fusion of ice in both J/g and J/kg.

Specific latent heat of vaporisation

The specific latent heat of vaporisation ('L_v') of water is about 2 300 000 J/kg. In other words, if you are trying to turn 1 kg of water into steam, even when its temperature has reached 100°C, you still have a long way to go: another 2.3 million joules of energy have yet to be supplied just to separate the molecules and so change the liquid to a gas.

The specific latent heat of vaporisation of a liquid is the thermal energy required to change 1 kg of the liquid at the boiling point into 1 kg of gas at the same temperature.

Again, to vaporise *m* kg the energy required is given by:

$$E_H = mL_v$$

Activity 8.26: Measuring the specific latent heat of vaporisation of water

In this activity you are trying to answer the following question: if we take 1 kg (or 1 g) of water which is already at 100°C, how many joules of heat energy must we supply to change it all into steam at 100°C? The answer will be expressed in J/kg (or J/g). In principle the method is straightforward. You must take some water at its boiling point, and find out how much energy has to be supplied so that 1 kg (or 1 g) shall be boiled away. In practice, how can this be done?

A method using a Bunsen burner is depicted in Figure 8.36.

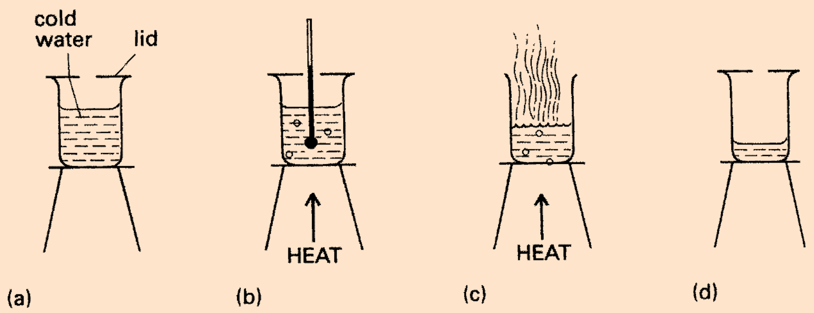

Figure 8.36 *a) The mass of the cold water is known. b) The water is brought to the boil, using a Bunsen burner whose flame is not altered. Readings of temperature and time are taken. c) Still keeping the flame constant, the water is boiled for 10 minutes. d) The lid is replaced and the apparatus weighted to find out how much water has been boiled away.*

Set up the apparatus as shown. The thermometer is there to measure how quickly the Bunsen burner heats the water. This enables you to work out how many joules of heat energy the Bunsen burner is supplying every second, so the flame must not be altered throughout the experiment.

Take readings and work out how much energy is needed to turn 1 g of water to steam.

Heat, temperature, internal energy and work

It is important that you are clear about the difference between heat and temperature. An example will show you that there is a difference. Suppose you have a race with a friend to see who can raise the temperature of some water from room temperature to 100°C the faster. To be fair, you each have an identical electric heater. There is just one point to mention, however: to be unselfish you give your friend a whole bucketful of water to warm up, and keep only a little in a cup for yourself.

You know the result, of course. Both of you are doing the same thing: raising the temperature of some water by about 80 K. To do this you need to do work (feed in energy). One person has far

KEY WORDS

internal energy *energy possessed by the molecules of a substance*

conduction *the transfer of heat energy through a material from molecule to molecule without any movement of the material itself*

insulation *use of a material that does not conduct heat energy and hence can prevent heat gain or loss*

more water than the other though, and she will have to feed in far more heat energy to do the job. Her heater must be switched on for a longer time, and her bill from the electricity company for energy supplied will be more.

Heat is a form of energy, measured in joules. When the water was heated and warmed up, the molecules of water moved faster. Thus the energy is stored in the hot water in the form of kinetic energy, the energy of motion of its molecules.

This energy is the **internal energy** of the water.

The word 'heat' is often used misleadingly in daily life. For example, some thermometers have 37°C marked as 'body heat'; what they should say is body temperature. When the weather is hot, this means that the temperature of the air outside is high.

Temperature, you may recall, may be described as the degree of hotness of a body, although that is rather a vague description. It is that which a thermometer records. A difference in temperature between two places can lead to a flow of heat energy between them, from the high temperature place to the lower temperature place. Thus the hot body will cool down and the cold one will warm up, the exchange of energy stopping when they have both reached the same temperature.

Heat transfer: conduction

If a bowl of hot soup is left standing on a table, it will get cold. Evaporation must be one cause of this, but it is not the only one. The table under the bowl becomes warm, and this is because heat has been conducted through the bowl.

Conduction is the passage of heat through a material from molecule to molecule, without any movement of the material as a whole.

If a spoon is left in a cup of coffee, the handle gets warm. A hot drink served in a metal mug is good for warming your hands, though the drink is not going to stay hot for long. These are examples of the **conduction** of heat through a metal.

Gases are even poorer conductors of heat than liquids. Air is thus a very good insulator, and commercial insulating materials are effective because they have many tiny pockets of still air trapped in them. An example is expanded polystyrene, used in coolers to keep your food and drink chilled. A refrigerator is lined between its inner and outer surfaces with a kind of woolly mat made from glass fibres loosely packed together.

Sometimes the purpose of the **insulation** is to keep things hot, rather than to protect cool things from the heat of the day. An oven needs to have lining similar to that in a refrigerator. Hot water pipes and steam pipes should be covered with a jacket made of expanded polystyrene or something similar to prevent a wasteful loss of heat.

Activity 8.27: Conduction in copper

Copper is a particularly good conductor of heat, and Figure 8.37 shows a demonstration of this.

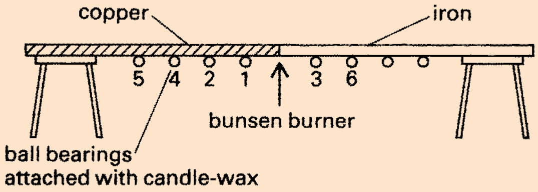

Figure 8.37 *How to show that copper is a better conductor of heat than iron*

Take a long bar made of copper at one end and iron at the other, joined together with a rivet. At regular intervals along it attach ball bearings with candle wax. Heat the bar strongly at its midpoint with a Bunsen burner. Record your observations. Try to explain them before reading on.

As heat is conducted along the bar in both directions, the wax melts and the ball bearings drop off. The iron conducts the heat, but not as well as the copper: the numbers on Figure 8.37 indicate a likely order in which the balls will fall.

Activity 8.28: Heat transfer in insulators

Metals generally are good conductors of heat, but most other substances are far poorer conductors (or, to look at it another way, are far better insulators).

A small electric heater used to warm a beaker of water can demonstrate this vividly. Use a low-value electrical resistor (perhaps 5 or 6 ohms if run off a 12-volt supply) as the heater, and arrange it so it is well clear of the bottom of the beaker (see Figure 8.38).

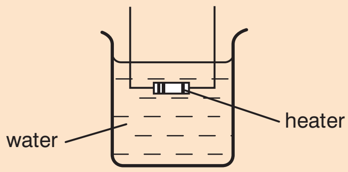

Figure 8.38 *Showing that water is a poor conductor of heat*

Do not switch on until the resistor is in the water or it will almost instantly burn out. Once in place, turn it on and leave it until the water has heated up.

Now feel the outside of the beaker high up, just below the water line. It will be hot, maybe uncomfortably so. Run a finger down the beaker, and you will find that there is a sudden change in temperature as you go below the heater. From that level downwards the water seems cold. Hot water is sitting on the top of cold water, yet hardly any conduction takes place.

Heat transfer: convection

If water is such a poor conductor, how is it that a kettle manages to heat its water up to boiling point? Why in Activity 8.28 was it only the water below the heater which was still cold?

The answer lies in thermal expansion. When water is heated it expands. This means that, comparing the same volumes, hot water is lighter than cold water. In other words, it is less dense.

In liquids and gases less dense substances are forced upwards. Oil floats on the top of water, for example, and hydrogen balloons rise when released in air. Therefore if some water is heated it expands, becomes less dense and so rises up to the surface. So long as the heating is being done at the bottom, this means that the water has a kind on inbuilt self-stirring mechanism. This is known as convection.

Activity 8.29: Observing convection

Convection can be observed in Figure 8.39 by taking a larger beaker of water and dropping in just one small crystal of potassium permanganate (a chemical that dissolves in water to give an amazingly deep purple colouring).

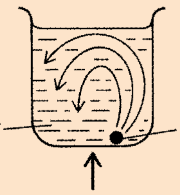

Figure 8.39 *Convection currents in water*

Heat the beaker gently under the crystal and watch how the coloured water rises to the surface in quite a fast and narrow stream. Cold water sinks in a wider and gentler downdraught to take its place.

The water in direct contact with the hot base gets heated by conduction. This water then rises, cold water replaces it and becomes warmed in its turn. These circulating currents are known as convection currents.

Convection is the transfer of heat throughout a fluid (that is, a liquid or a gas) by means of bulk movement of the hot fluid.

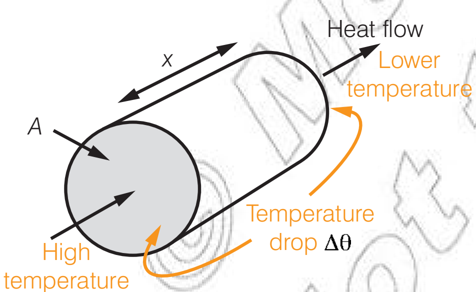

Figure 8.40 *Thermal conductivity*

Thermal conductivity

The rate at which heat energy will be conducted through a lagged bar is found to depend on three things:

- The material from which the bar is made.
- The area A of cross-section of the bar. Double the area, and heat is conducted through the bar at twice the rate.
- The temperature gradient along the bar – that is, how rapidly the temperature drops as you go along it. For a given conductor this takes into account both the temperature drop between its two ends and its total length. Using the notation in Figure 8.40, the temperature gradient will be $\Delta\theta / x$ (in Km^{-1}).

This means that the rate of flow of heat energy $\frac{Q}{t}$ in watts (J/s) along the bar will be given by:

$$\frac{Q}{t} = k\,A\,\frac{\Delta\theta}{x}$$

The constant k depends on which material the bar is made from. It is known as the material's **thermal conductivity**. The units of k work out to be W/m/K. Be sure you understand why.

KEY WORDS

thermal conductivity *a measurement of the ability of a material to conduct heat*

Worked example 8.14

The thermal conductivity of copper is 390 W/m/K. Calculate the rate of heat flow through a copper bar whose area is 4.0 cm^2 and whose length is 0.50 m, if a there is a temperature difference of 30°C maintained between its ends.

Start by putting down what you know. Here:

K (W/m/K)	A (m^2)	$\Delta\theta$ (K)	x (m)	Q/t (W)
390	4.0×10^{-4}	30	0.5	?

$$\frac{Q}{t} = kA\frac{\Delta\theta}{x} = \frac{390 \times 4.0 \times 10^{-4} \times 30}{0.5} = 2.3 \text{ W}$$

Worked example 8.15

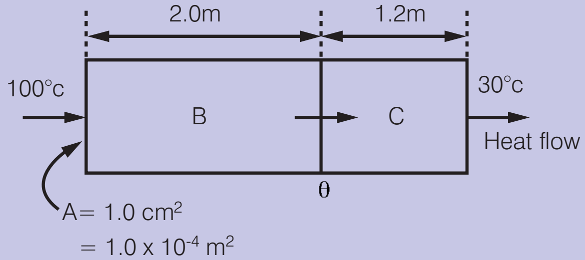

Figure 8.41 *Thermal conductivity of copper*

Suppose you had to work out the rate of flow of heat through a bar made of two materials in contact, as shown in the drawing. Let the thermal conductivity of B be 400 W/m/K while that for C is 50 W/m/K.

Start by finding the temperature at the interface, θ say. This rate must be the same through B and through C.

Equating them, $\dfrac{400 \times A \times (100 - \theta)}{2.0} = \dfrac{50 \times A \times (\theta - 30)}{1.2.}$

The As cancel, and solving we get θ = 88°C.

You can then go back and substitute θ = 88°C into the flow equation for either bar.

Thus, considering bar B,

$$\text{rate of flow of heat} = \frac{400 \times 1.0 \times 10^{-4} \times (100 - 88)}{2.0} = 0.24 \text{ W}$$

If you had chosen to substitute θ = 88°C for bar C instead, check that the result would have been the same.

KEY WORDS

black body *a theoretical object that absorbs all electromagnetic radiation that hits it*

Stefan–Boltzmann law

If you have the opportunity, look at the bare element of an electric heater or something else that is red hot. There are likely to be some spots on the surface which are glowing more brightly than others. If so, remember where they are.

Let the body cool down and look again. You should find that the spots which glowed brightest are now the darkest parts of the surface – good emitters are good absorbers.

If we want to make a surface which will radiate freely to emit the maximum possible radiation at any given temperature, it will be a perfect absorber too. It will look matt black because no light will reflect from it: all is absorbed. We call this a **black body**.

The radiation a black body gives off depends on its temperature, and on nothing else. Figure 8.42 shows what will be emitted at a range of temperatures from 3500 K rising to 5500 K.

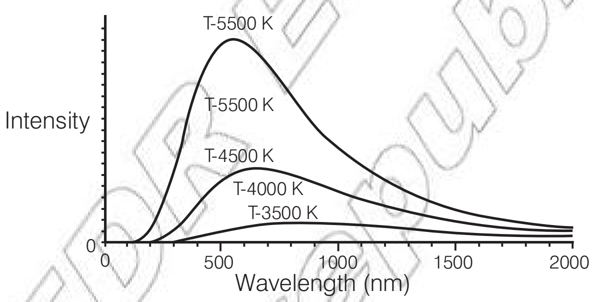

Figure 8.42 *Black body radiation curve.*

In Grade 10, you learnt that the wavelength of visible light ranges from about 750 nm (nanometres, $\times 10^{-9}$ m) at the red end of the spectrum down to 400 nm for the blue.

At 3500 K most of the radiation is in the infrared region, but just a little is visible light (mainly red). The surface is glowing red hot.

As it heats up further, two things happen: a greater amount of radiation is emitted in total, and the peak wavelength becomes smaller, so by 5500 K it is white hot. A pyrometer to measure temperatures might use either of those changes to estimate the temperature of the emitting surface.

The Stefan–Boltzmann law describes the total energy radiated by a black body. Consider a surface of area A at a temperature T (which must be its absolute temperature in kelvin). The radiated power P in watts (J/s) is given by:

$$P = \sigma A T^4$$

The constant σ (the Greek letter sigma) is a universal constant that does not depend on the material of the surface. All that is necessary is that it is behaving as a black body and so is radiating freely. Its value has been measured to be 5.67×10^{-8} W/m^2/K^4.

Thus all surfaces above absolute zero emit radiation, though at low temperatures this is very feeble and none is in the visible range. Because it depends on T^4, however, at very high temperatures radiation becomes a major source of energy loss. If the absolute temperature doubles, the radiated power increases sixteen fold; at ten times the temperature the power increases by a factor of 10^4 – 10 000 times!

Newton's law of cooling

If some hot water is contained in a beaker, the presence of a lid should reduce the rate of cooling. This stops continual evaporation from the water's surface. To change from a liquid to a vapour needs energy (which you know is called latent heat), and this is obtained from the water that remains. Evaporation causes cooling.

The cooling may be reduced further by lagging the beaker. What this means is that we put an insulating jacket round it to reduce the rate at which heat is being conducted to the outside world.

The rate of cooling of a hot body was one of the many topics which Newton investigated. His experimental result is known as **Newton's law of cooling**. It states that:

> **The rate of loss of heat from a body is proportional to its excess temperature above its surroundings.**

Mathematically, this is written as $\frac{dH}{dt} = K \times A \times (\theta_{sum} - \theta_{obj})$

H is heat energy

t is time

K is heat transfer coefficient (a constant)

A is surface area of heat being transferred

θ_{sum} is temperature of surroundings

θ_{obj} is temperature of body

If the body is 20 K warmer that the room, it will lose heat twice as fast than if it was only 10 K above its surroundings. It is approximately true for a body in air for excess temperatures up to a few tens of kelvin. The actual rate of that loss of heat may be increased if we subject the body to what we call forced convection – such as blowing cold air from a fan over it.

Global warming and the greenhouse effect

The greenhouse effect was first proposed in 1824. It is the process by which absorption and emission of infrared radiation by gases in the atmosphere cause a rise in temperature of the Earth's lower atmosphere and surface, The increase in the average temperature of the Earth's near-surface air and oceans since the mid-2oth century is called global warming.

KEY WORDS

Newton's law of cooling *the rate of change of the temperature of an object is proportional to the difference between its own temperature and the temperature of its surroundings*

Activity 8.30: Investigating cooling

Plan and, if you can, carry out an investigation into one of these topics:

1. How much difference does the lid make to how quickly a beaker of hot water cools?
2. Compare the effectiveness of different materials in providing insulation.

In either case, ask yourself what will have to be kept the same every time and what should be varied. What measurements will you take, and how? How will you analyse those readings to get as much information as possible from them? How will you present your conclusions so other people may follow them clearly?

Activity 8.31: Research global warming

In a small group, research global warming. Present your research in a format of your choice.

Summary

In this section you have learnt that:

- Calorimetry is the science of measuring the heat of chemical reactions or physical changes.
- A phase is a state of matter, e.g. solid, liquid, gas.
- A phase change occurs when a substance changes state.
- A phase diagram shows the three phases of a substance.
- State variables are properties such as temperature, pressure and internal energy.
- The critical point is where the liquid and gas phases become indistinguishable.
- The triple point is where all three states coexist together.
- Latent heat is energy that is supplied to a substance but does not result in a rise in temperature but does result in a change of phase (measured in J/kg).
- Specific heat capacity is the number of joules of heat energy required to raise the temperature of 1 kg of a substance by 1 K (measured J/kg/K).
- Heat capacity = mass specific $\times$ heat capacity (measured J/K)
- Heat is a form of energy (measured in J).
- Temperature is the quantity a thermometer records
- Internal energy is the energy possessed by the molecules of a substance.
- The rate at which heat energy will be conducted through a lagged bar of length x depends on: the material the bar is made from, the area of cross-section, A, of the bar, the temperature gradient along the bar, $\frac{\Delta\theta}{x}$

Review questions

1. Define the terms a) calorimetry, b) phase, c) phase change, d) phase diagram, e) state variable, f) latent heat, g) heat capacity, h) specific heat capacity.
2. Distinguish between heat, temperature, internal energy and work.
3. Give the units for heat, heat capacity, specific heat capacity and latent heat.
4. Explain the factors that determine the rate of heat flow through a material.
5. Work out the rate of flow of heat through the bar shown in Figure 8.43. Let the thermal conductivity of B be 450 W/m/K while that for C is 150 W/m/K.
6. Describe experiments to measure latent heat.

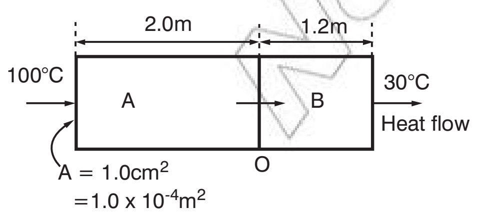

Figure 8.43

End of unit questions

1. Construct a glossary of all the key terms in this unit. You could add it to the one you made for Units 1–7.
2. State Hooke's law.
3. A 0.50 kg mass is hung from the end of a wire 1.5 m long of diameter 0.30 mm. If Young's modulus for its material is 1.0×10^{11} Pa,
   a) calculate the extension produced
   b) hence find the strain energy.
4. Describe the concepts related to hydraulic and pneumatic systems.
5. Find the height of a column of methyl iodide in a soda-lime glass tube of radius 20 mm. The surface tension is 0.26, the contact angle is 29°, the density is 2.28.
6. Identify factors affecting laminar flow.
7. Explain applications of Bernoulli's principle.
8. A healthy section of artery of length 10 cm and radius *r* has a pressure difference of 120 mmHg. The volume flow rate of the blood in the artery is 100 cm^3 the viscosity of blood is η. A diseased artery of the same length has a radius which is half that of the healthy artery. The volume flow rate of the blood in this artery is 6.3 cm^3/min. What pressure difference is needed to bring the volume flow rate up to 100 cm^3/min? (Assume the viscosity of the blood is the same as the healthy artery.)
9. Find the force on a ball bearing of radius 5×10^{-3} m falling through a liquid of viscosity 0.985 at a velocity of 0.35 m/s.
10. Water flows at 20 m^3/h of through a pipe with 150 mm inside diameter. The pipe is reduced to an inside dimension of 120 mm. Find the velocity of the water in each part of the pipe.
11. a) Draw a phase diagram for water
    b) Explain what is meant by i) critical point, ii) triple point.
12. The diagram shows two slabs of material in contact. A is 2.0 cm thick and its thermal conductivity is 3.0 W/m/K. B is 4.0 cm thick and of conductivity 1.5 W/m/K. The left hand face of A is kept at 0°C and the right hand face of B at 100ºC.
    a) The slabs have been in place long enough for the temperatures within them to become steady. Which of the following quantities will have the same value in A and in B:
       i) temperature gradient
       ii) temperature difference between opposite faces
       iii) rate of flow of heat?
    b) Find the temperature at the junction of A and B.
    c) What is the rate of flow of heat through the slabs?
13. Describe an experiment to demonstrate conduction in copper.