Fluid statics

Unit 6

Contents

Section	Learning competencies
6.1 Air pressure (page 141)	• Define the term air pressure and use the definition to solve related problems. • Describe atmospheric pressure and explain its variation with altitude. • Explain how to measure atmospheric pressure and show that 760 mmHg is equal to one atmosphere.
6.2 Fluid pressure (page 151)	• Define the term fluid and state the similarities and differences between liquids and gases. • Define the term density and relative density and determine each for a given body. • Explain how the pressure in a liquid at rest varies. • Apply the formula $p = h\rho g$ and use it to solve problems (including determining the pressure inside a fluid taking into account atmospheric pressure). • State Pascal's principle, and apply it to solve problems and explain applications (such as the hydraulic lift). • Explain the use of a manometer. • Demonstrate an understanding of, distinguish between and calculate atmospheric, gauge and absolute pressure. • State Archimedes's principle and the principle of flotation. • Distinguish between true weight and apparent weight of a body. • Calculate the buoyant force acting on the body in a fluid and explain why bodies float or sink. • Calculate the density of a floating body or density of a fluid using the flotation principle.

How does a massive ocean liner, made of steel, float on the water, yet a tiny penny sinks? Why is it when you go swimming you can feel the water pushing up on you, yet you can't feel the massive weight of the column of air on top of your head? This is all down to fluid statics, the study of the density and pressure in stationary liquids and gases.

From simply breathing in and out, to the blood pumping through your veins, pressure in liquids and gases plays an important role in our lives. Without atmospheric pressure our blood would simply boil and life on Earth would not even be possible.

In this unit we will investigate atmospheric pressure, look into what causes pressure in liquids and gases, explore the factors that affect it and learn how to use a range of simple pieces of equipment to measure pressure.

6.1 Air pressure

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

- Define the term air pressure and use the definition to solve related problems.
- Describe atmospheric pressure and explain its variation with altitude.
- Explain how to measure atmospheric pressure and show that 760 mmHg is equal to one atmosphere.

Under pressure

If you've ever had an injection you will have noticed how easy it is for the doctor to push the needle through your skin. This is because the needle has a very sharp point and so when the doctor exerts a relatively small force the needle creates a great deal of pressure on the skin.

Figure 6.1 *Injections don't hurt much because the needle exerts a very high pressure on the skin.*

Pressure is defined as the amount of *force acting per unit area*.

- **Pressure is equal to force per unit area.**

If a large force acts on a small area it creates a greater pressure. For example, most animal predators have pointed teeth. When a crocodile or shark bites into its prey, the pressure is very large and so the teeth sink in!

The reverse is also true. A large vehicle like a tractor or truck may have some very large tyres. These increase the area over which the force is acting and so reduce the pressure. This means it is less likely for the tractor to sink into the mud and get stuck.

Figure 6.2 *The area over which the force is acting affects the pressure it exerts.*

The pressure exerted by a force may be calculated using the equation below:

- pressure = force / area
- $p = F / A$

p = pressure in Pa.

F = force in N.

A = area in m^2.

Pressure is measured in pascals. One pascal is equal to a pressure of 1 N per square metre (1 N/m^2). The pascal is the SI derived unit of pressure (this includes all forms of pressure).

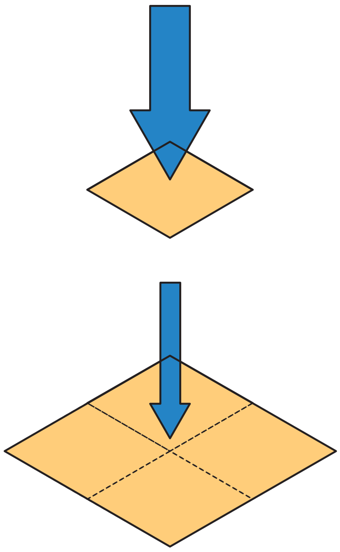


Figure 6.3 *A large force pressing on a small area creates greater pressure than a smaller force on a larger area.*

Worked example

A boy weighs 500 N and the soles of his feet have an area of 0.05 m^2. Determine the pressure he exerts when he stands a) on both feet and b) on one foot.

DID YOU KNOW?

The pascal is named after Blaise Pascal. He was a French physicist most noted for his experiments with barometers in the mid-17th century (a barometer is an instrument to measure air pressure; more on this later).

Activity 6.1: Pressure

Complete the table below:

Force	Area	Pressure
720 N	4.0 m^2	
	0.02 m^2	240 kPa
5.0 N		1.0 Pa

Activity 6.2: Your own pressure

Stand on a piece of squared paper. Carefully draw around your feet (or get a partner to do this for you).

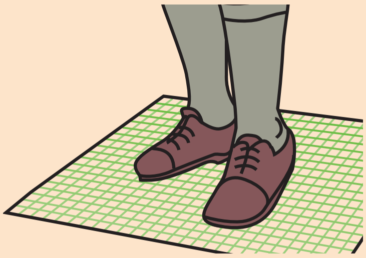


Figure 6.4 In order to determine the pressure you exert you need to measure the area of your feet!

Use this to work out the area of your feet (to do this count the number of squares and multiply by the area of each square).

Measure your weight in N (or your mass in kg and multiply by 10 N/kg), then use the equation $p = F / A$ to determine your pressure.

On both feet:

$p = F / A$ *State principle or equation to be used (definition of pressure)*

$p = 500\ N / 0.05\ m^2$ *Substitute in known values and complete calculation*

$p = 10\ 000$ Pa or 10 kPa *Clearly state the answer with unit*

If he stands on one foot his weight will be the same but the area will be halved to 0.025 m^2:

$p = F / A$ *State principle or equation to be used (definition of pressure)*

$p = 500\ N / 0.025\ m^2$ *Substitute in known values and complete calculation*

$p = 20\ 000$ Pa or 20 kPa *Clearly state the answer with unit*

We didn't really need to do that last calculation. We can see that if the area halves and the force stays the same then the pressure doubles (pressure is inversely proportional to area).

Worked example

A book rests on a desk. Its covers measures 20 cm by 25 cm. It exerts a pressure of 100 Pa. Determine the mass of the book.

$p = F / A$ *State principle or equation to be used (definition of pressure)*

$F = p \times A$ *Rearrange equation to make F the subject*

In order to find the mass we first need to find the weight of the book. This is the force the book exerts on the desk. The area of the book is 0.20 m × 0.25 m = 0.05 m^2.

$F = 100\ Pa \times 0.05\ m^2$ *Substitute in known values and complete calculation*

$F = 5$ N *Clearly state the answer with unit*

This is the weight of the book so to find its mass we use $w = mg$.

$w = mg$ so $m = w / g$ *State equation and rearrange equation to make m the subject and solve*

$m = 5\ N / 10\ N/kg$ *Substitute in known values and complete calculation*

$m = 0.5$ kg or 500 g *Clearly state the answer with unit (ideally kg)*

What causes air pressure?

Although we can't feel it in our day to day lives, air has mass. This means it also has a weight. One cubic metre of air has a mass of about 1 kg and so a weight of 10 N. The simplest way to think about air pressure is to treat it as the pressure due to the weight of the air above pushing down on a certain area. This may seem like a silly idea but actually it is pretty close to the truth.

A more complete picture involves thinking about the actual air particles. These are in constant motion, they are travelling in different directions and some travel faster than others. When the air particles are near a surface some will bounce into it and so exert a force on the surface. It is this force that gives rise to a pressure.

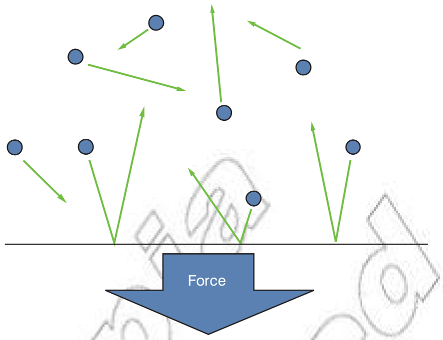


Figure 6.5 *Air particles crashing into a surface apply a force to that surface.*

Atmospheric pressure

The **atmosphere** is the layer of air that surrounds the Earth. Above your head right now there is a column of air about 40 km tall. The exact height is quite hard to determine due to the fact that as the height above the ground increases the air gets thinner and thinner until there is practically no air.

This column of air has a weight, which presses down on you and it is this that gives rise to atmospheric pressure.

We don't normally notice atmospheric pressure. If you move your hands up and down you can't really feel it, but it is definitely there! The reason we don't feel it is because not only does it push on you equally from all directions (left, right, front and back) but our bodies push back out.

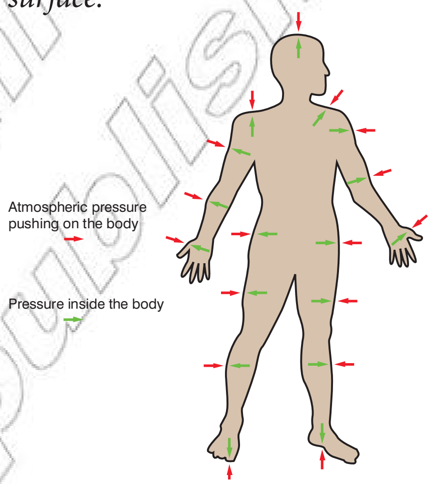


Figure 6.6 *The pressure in our bodies pushes back against atmospheric pressure.*

There is a kind of **equilibrium** between the pressure in our bodies and the surrounding atmosphere. If you went somewhere where the pressure was much greater than atmospheric pressure our bodies would be crushed. For example, deep-sea submarines have to be very strong to withstand the crushing effect caused by the pressure of the water.

Figure 6.7 *A deep-sea submarine has to withstand very high pressures.*

The reverse is also true. If you went somewhere where the pressure was very low (e.g. into space without a pressurised space suit) the pressure inside our bodies would push outwards with some very nasty effects!

Figure 6.8 *Without a pressurised space suit this astronaut would experience severe difficulties.*

How big is atmospheric pressure?

The weight of the column of air above 1 m^2 at ground level is around 101 000 N! This means atmospheric pressure at ground level is around 101 kPa. This is often referred to as 1 atmosphere or 1 atm:

- **1 atm = 101 kPa**

Think about this…

In fact the pressure inside our bodies is generally a bit higher than atmospheric pressure. Think about how you already know this and why do you think this is important?

DID YOU KNOW?

The planet Venus has a much denser atmosphere that we do on Earth. The pressure on the surface is around 90 atm! That is 9 MPa or 9 million N per square metre. That is the same pressure you would experience if diving to a depth of nearly 1 km under water.

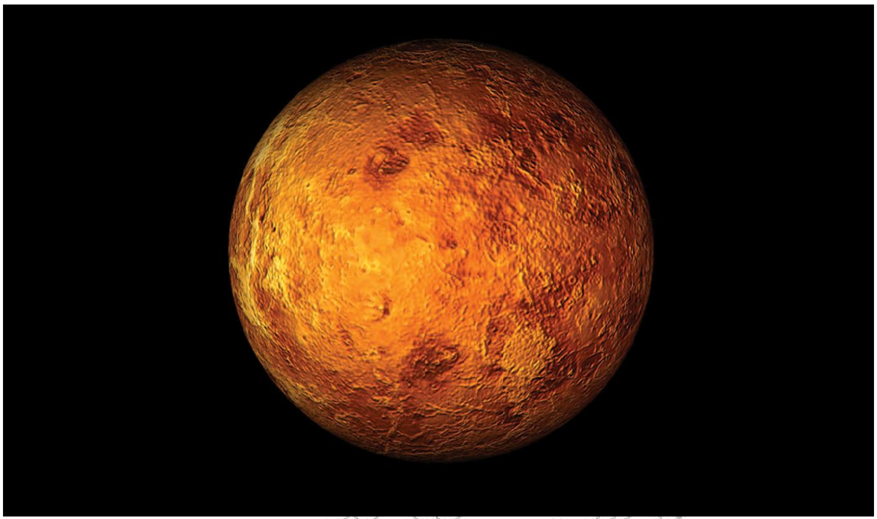


Figure 6.9 *Venus has a much greater atmospheric pressure than the Earth.*

101 000 Pa is a very large pressure, but we rarely notice it in our day to day lives. It is about the same as having a medium-sized elephant balance on the top of your head!

In the mid-17th century a German named Otto Von Guericke (who was mayor of Magdeburg) invented a **vacuum pump**. This clever machine removed the air from inside a chamber and so the force due to atmospheric pressure could really be seen.

Von Guericke used his pump to removed air from inside two brass hemispheres touching each other. With the air removed the pressure from the atmosphere squeezed the two hemispheres together. With no counter pressure from the air inside, the hemispheres were locked tightly together. In 1654, in front of Emperor Ferdinand III, he demonstrated how tightly by using thirty horses in two teams of 15 to try to separate the hemispheres. They couldn't do it!

Figure 6.10 *Magdeburg hemispheres*

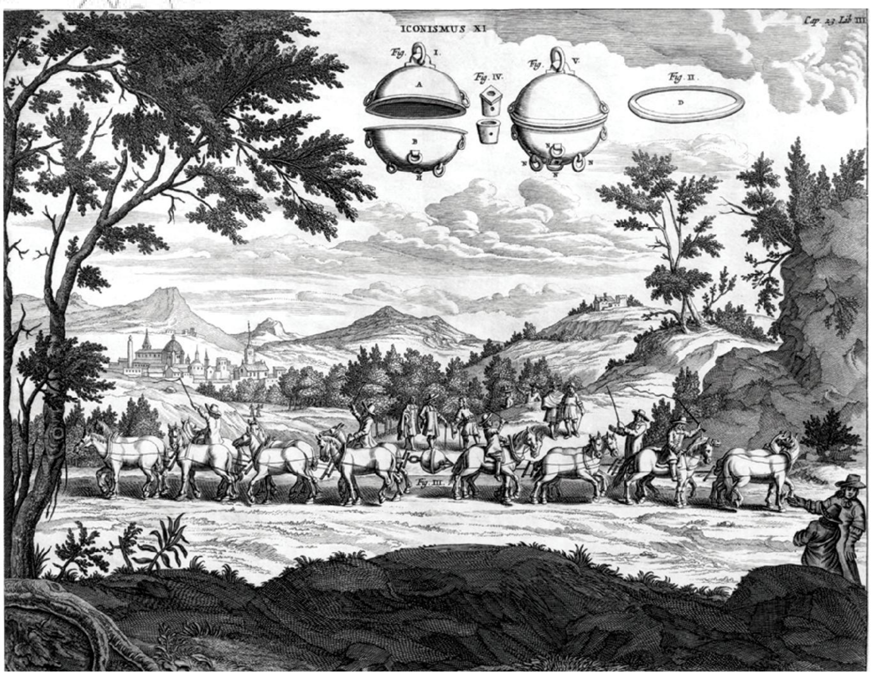


Figure 6.11 *Teams of horses could not pull the hemispheres apart.*

KEY WORDS

atmosphere *the layer of air surrounding the Earth*

vacuum pump *a machine for removing the air from inside a chamber*

The atmospheric pressure pushing the two hemispheres together was too strong. the hemispheres could not be separated. It was not until air was allowed back inside the hemispheres that the difference in pressure was small enough to allow them to be pulled apart.

What effect does altitude have on atmospheric pressure?

The actual atmospheric pressure in the room today might be a bit higher or lower than 1 atm. The heating effect from the Sun causes small changes in pressure due to the uneven heating of the Earth's surface. This leads to high or low pressure weather systems. You can think of a high pressure system as meaning there is a slightly greater mass of air above your head than on an average day.

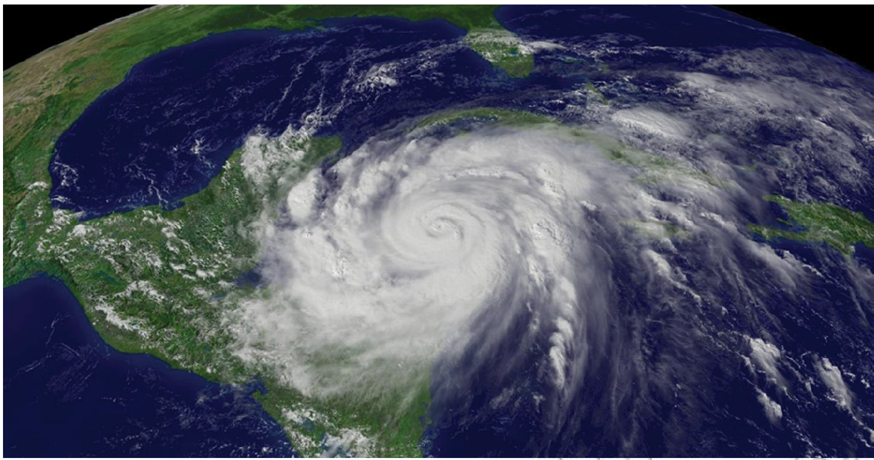


Figure 6.12 *Differences in atmospheric pressure can lead to powerful storms.*

The height above sea level, or altitude, also has a significant effect on atmospheric pressure. Imagine climbing a tall mountain; the higher you get, the smaller the column of air above you. This means there is a smaller mass of air above you and so less weight pushing down.

As altitude increases the atmospheric pressure decreases.

Table 6.1 shows how the pressure varies with altitude. You can see that it is not a simple relationship and it depends on temperature changes and position on the Earth.

Table 6.1 *Pressure at different altitudes*

Altitude (m)	Approx. pressure (Pa)
0	101 000
1000	90 000
2000	79 000
5000	54 000
10 000	26 000
15 000	12 000
20 000	6000
25 000	1300
30 000	270

Figure 6.13 *As you climb a mountain the surrounding atmospheric pressure drops.*

Activity 6.3: Atmospheric pressure

Fill a glass to the very top and then place a card on top of it. Make sure there is no air trapped between the glass the card.

While holding the card carefully turn the glass over and then let go of the card.

It should stay in place! Atmospheric pressure is pushing the card up and preventing the water from rushing out.

Activity 6.4: The effect of altitude

Plot a graph of altitude against atmospheric pressure using the information in Table 6.1.

DID YOU KNOW?

At 1 atm, water boils at 100 °C. However, if the atmospheric pressure drops so does the boiling point. At the top of tall mountains the pressure is so low water will boil at 75 °C! In the mid-19th century explorers used this fact to determine their altitude.

Figure 6.14 *A barometer*

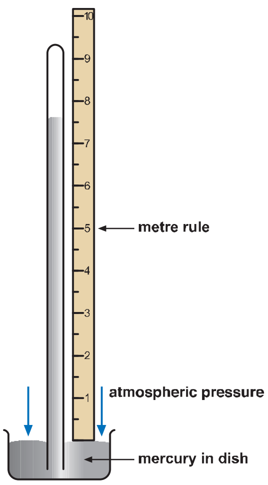


Figure 6.15 *A diagram of a simple barometer*

> ### DID YOU KNOW?
> The volume of an object is affected by the temperature and the surrounding pressure. Chemical reactions also depend on pressure and temperature. In order to ensure experiments are conducted under the same conditions across the globe the International Union of Pure and Applied Chemistry (IUPAC) define standard temperature and pressure as a temperature of 0 °C and a pressure of 100 kPa. However, several different organisations use slightly different values!

Measuring atmospheric pressure

There are several instruments used to measure atmospheric pressure. The most common is a **barometer**.

Think about the mercury in the dish. On the outside, air pressure is pressing down on the mercury. On the inside, the column of mercury in the tube is pressing down with an equal pressure. If these pressures were not equal, the level of mercury in the tube would alter until the pressures were balanced.

Until about 1650 the rise of liquid up a tube was explained by saying that the vacuum 'sucks up' the liquid. This is not so – a vacuum cannot suck, because there is nothing there to do the sucking! The rise is due to air pressure on the surface of the liquid outside.

A mercury barometer is long and inconvenient, heavy, and contains a liquid that is hazardous and easily spilt. Therefore, an **aneroid barometer** is commonly used. (*Aneroid* means *without liquid*.) It is compact and portable. A flat circular metal box, with only a little air inside, is the important part (Figure 6.16). A spring prevents its sides from being pushed in. The box is corrugated to make it strong, so that it does not collapse under air pressure. When the pressure changes, the upper face of the box moves. The movement is magnified several hundred times by a system of levers, which move a pointer over a circular scale, graduated in centimetres. It is graduated by comparing its readings with those of a mercury barometer.

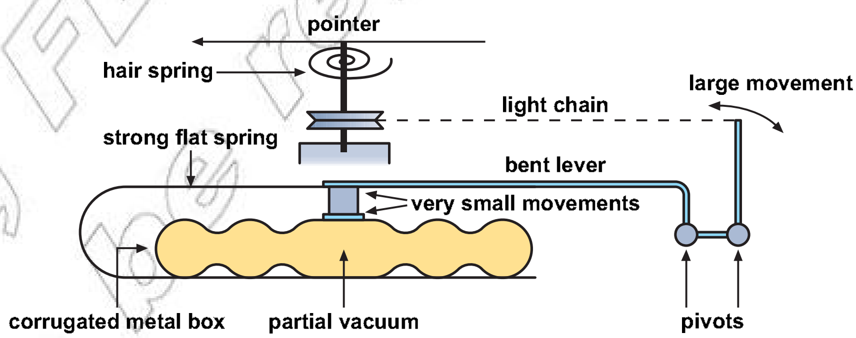


Figure 6.16 *The construction of an aneroid barometer*

Why 760 mmHg?

Pressure is often expressed in the units of mmHg. If the atmospheric pressure is equal to 1 atm then the height of the column of mercury in a barometer is 760 mm. We can prove this mathematically.

The column of mercury will have a weight and the weight must equal the force due to the atmospheric pressure pushing up on the bottom of the column. Let's imagine a column of mercury 760 mm tall with a radius of 5 mm. This exerts a force equal to its weight. The weight is given by $w = mg$ and we can determine the mass of the column from its density and volume ($\rho = m / V$ and so $m = \rho V$ and $V = \pi r^2 h$ as this is the volume of a cylinder). So:

- $V = \pi r^2 h$

- $V = \pi(0.005\ \text{m})^2 \times (0.76)$ m
- $V = 5.97 \times 10^{-5}\ \text{m}^3$

The density of mercury is 13 570 kg/m^3 so its mass is:

- $m = \rho V$
- $m = 13\,570\ \text{kg/m}^3 \times 5.97 \times 10^{-5}\ \text{m}^3$
- $m = 0.81$ kg

Therefore the weight of the column can be found:

- $w = mg$
- $w = 0.81\ \text{kg} \times 9.81\ \text{N/kg}$
- $w = 7.9$ N

This weight must equal the force due to the pressure on the bottom of the column. So we can use the pressure equation to determine the pressure required to support of column of this height.

- $p = F / A$

As it is a cylinder the area of the base of the column is given by $A = \pi r^2$ so:

- $p = F / \pi r^2$
- $p = 7.9\ \text{N} / \pi \times (0.005\ \text{m})^2$
- $p = 101\,000$ Pa or 101 kPa

You can repeat the calculation above for columns with different radii; the answers are always the same! You can combine all the steps into one big equation:

- $p = \rho\, \pi r^2 h\, g / \pi r^2$

The areas cancel, which shows that the area of the column does not matter. Any column will reach the same height. This gives us:

- $p = \rho\, h\, g$ (more on this equation later).

You might ask, why use mercury? Mercury is quite toxic and needs to be handled very carefully; why not use water instead? This is because water has a much lower density than mercury (around 1000 kg/m^3 vs. 13 600 kg/m^3). This means for that atmospheric pressure can support a column of water around 10 m tall! This would make our barometer far too large to be practical.

Some uses of air pressure

There are several uses for air pressure. Most rely on creating a **pressure difference** by pumping air into or out of a chamber. Pumping air into a chamber creates a greater pressure and pumping air out of a chamber creates a lower pressure.

If you create an area of lower pressure then the atmospheric pressure is larger in relative terms. As a result air is *pushed* in due to the greater force from the atmospheric pressure. Notice that there is no such thing as sucking to pull air into a machine.

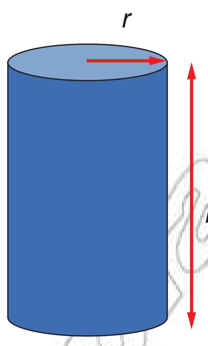


Figure 6.17 *The volume of a cylinder*

Think about this…

As atmospheric pressure can support a column of water 10 m high this is also the maximum height to which a column of water can be drawn up by a vacuum pump (i.e. by creating a pressure difference). For any higher, water pumps must be used.

KEY WORDS

aneroid barometer *a device for measuring atmospheric pressure that uses a corrugated metal box rather than liquid*

barometer *a device for measuring atmospheric pressure*

pressure difference *the relative value of the pressure of gas in different chambers*

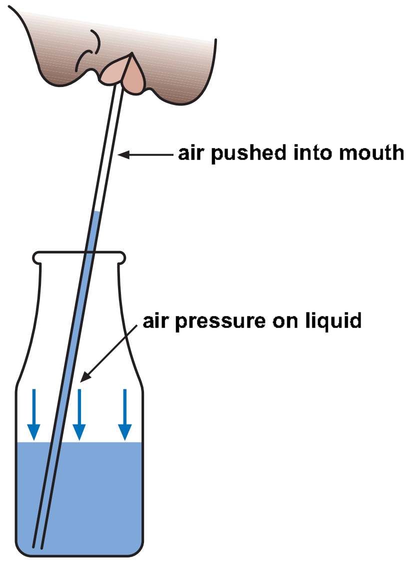


Figure 6.18 *Atmospheric pressure pushes the drink up the straw*

KEY WORDS

common pump *a pump that relies on atmospheric pressure to move water*

drinking straw a *thin tube used to suck liquids into the mouth*

force pump *a pump that relies on atmospheric pressure and compressed air to move water, often to a great height*

lift pump *a pump that relies on atmospheric pressure to move water*

suction pad *a round rubber pad that relies on atmospheric pressure to stick to smooth surfaces*

Uses of air pressure

A **suction pad** is a round rubber pad, perfectly flat on one side. Wet this side and press the pad against a window or smooth wall, pushing out all the air from under it. The pad sticks firmly. Atmospheric pressure holds it in place. The pads are used to lift and move large sheets of plate glass, metal and plastics, to put notices on windows, and on many toys, e.g. arrows, that stick to walls.

If you drink through a **drinking straw**, you are making use of atmospheric pressure. You suck on the air inside the straw. Therefore the atmospheric pressure outside is greater than the pressure inside, and liquid is pushed up (Figure 6.18).

A **lift pump (common pump)** is often used to raise water from wells. A piston moves up and down a tube (Figure 6.19). There is a valve in the piston and also one at the end of the tube. A valve is usually made of leather, and has brass on it to make it heavy. The valves are normally shut. They let water pass upwards but not downwards.

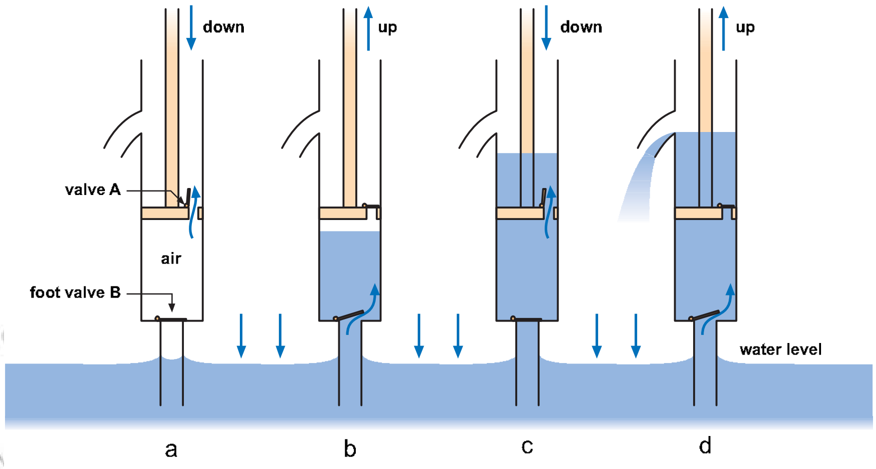


Figure 6.19 *The four stages in the operation of a lift pump*

- *Downstroke:* Foot valve B closes under its own weight. Valve A opens and lets air pass through it into the space above the piston.
- *Upstroke:* Valve A closes under its own weight. The pressure under the piston is less than atmospheric. Atmospheric pressure forces water into the tube through B.
- *Downstroke:* Valve B closes and A opens. Water passes through A into the space above the piston.
- *Upstroke:* Valve A closes and water is lifted up the tube and out of the spout. More water passes through B to keep the pump filled.

Atmospheric pressure determines the height to which water can be pumped. Even a perfect pump can raise water only 10.4 m. In practice, because of leaks at the valves and piston and of dissolved gases from the water, most pumps raise water about 7 m only. Delivery of water is not continuous.

A **force pump** can pump water to a great height. Some, used by firemen, can force water hundreds of metres high.

There is a foot valve B (see Figure 6.20), as in the lift pump, but it has a solid piston and a delivery tube at the bottom of the pump. There is a valve A in the delivery tube where it joins a chamber.

- *Upstroke:* The pressure in the tube under the piston becomes less. Valve A closes and foot valve B opens. Water is forced through B into the tube by atmospheric pressure.
- *Downstroke:* B closes. Valve A opens; water is forced through it and the delivery pipe into chamber C. The pressure on the piston (and not atmospheric pressure) determines the height to which the water is pumped.

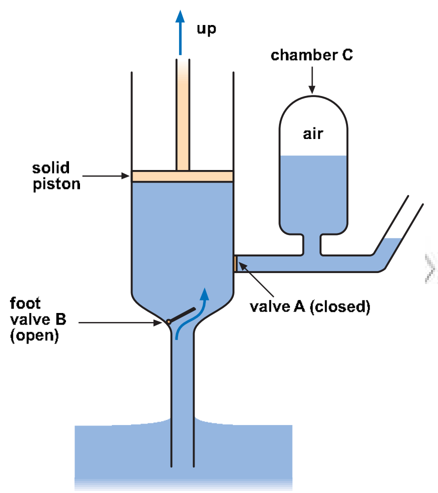


Figure 6.20 *A force pump*

The force pump itself delivers water only on the downstroke; the flow of water stops on the upstroke. However, the air trapped in chamber C is compressed during every downstroke. The pressure of this air continues to force out water during the upstroke, and therefore the pump delivers a steady stream of water.

Bicycle pump

The handle moves a piston in a metal cylinder (Figure 6.21). There is a cup-shaped leather or rubber washer on the end of the piston. This acts as a valve and lets air move in one direction only. The soft edge of the washer fits closely to the sides of the cylinder.

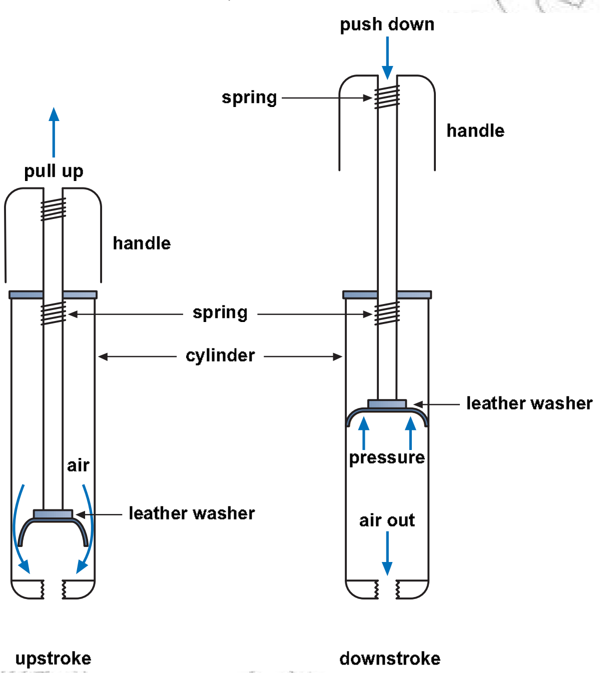


Figure 6.21 *How a bicycle pump works*

- *Upstroke:* The pressure below the piston is reduced. Atmospheric pressure forces air between the washer and the wall of the cylinder.
- *Downstroke:* The pressure below the piston is increased. The washer is pressed tightly against the walls of the cylinder, making it airtight. When the pressure rises above the pressure inside the tyre, the tyre valve opens and air is forced into the tyre.

KEY WORDS

siphon *a tube which can move liquid using the difference between the pressure of the liquid and atmospheric pressure*

A bicycle pump with the washer reversed acts as a vacuum pump or suction pump.

Siphon

A **siphon** is a convenient way of removing liquid from a container such as an aquarium or petrol tank.

Activity 6.5: To show the action of a siphon

- Fill a tall jar with water. Submerge a long rubber tube so that it fills with water.
- Leave one end in the water, close the other end with the fingers (to prevent the water running back), and lift it out of the jar. Lower this end until it is below the water level in the jar. Open it and let water flow out into a second jar (Figure 6.22).

The water flows so long as the end C is below water level A. The further C is below A, the faster is the flow of water.

- Now raise the second jar until it is higher than the first. Water flows in the other direction. (The tubing must always be full of water and its ends must be under the water.)

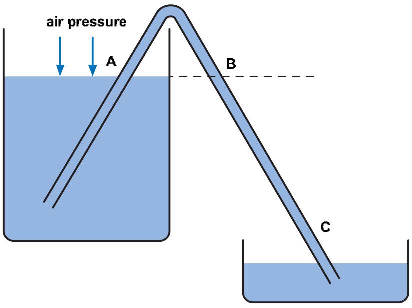


Figure 6.22 *A siphon*

Activity 6.6: Vacuum cleaner

Can you explain how a simple vacuum cleaner works? Remember that it does not suck up the dust.

How a siphon works

The pressure at A and B is atmospheric. Therefore the pressure at C is atmospheric pressure plus the pressure due to the column of water BC. Hence, the pressure at C is greater than atmospheric and the water can push its way out against the atmosphere.

Summary

In this section you have learnt that:

- Pressure is defined as the force acting per unit area. It can be calculated using the equation $p = F/A$.
- Pressure is measured in pascals (Pa), where 1 Pa equals a pressure of 1 newton per square metre.
- Atmospheric pressure is caused by the weight of the column of air above you pushing down on you. On a typical day this is equal to 101 kPa.
- As your altitude increases the atmospheric pressure decreases.
- A barometer is a simple instrument used to measure atmospheric pressure. The pressure from the atmosphere pushes the fluid up the tube.
- 1 atm is equal to 760 mmHg.

Review questions

1. Define pressure and states its units.
2. A wooden block of mass 2.0 kg is 20 cm thick, by 10 cm wide by 30 cm tall. Calculate the minimum and maximum pressure this block could exert on a surface.
3. Explain the causes of atmospheric pressure and why it changes with altitude.
4. Describe how a barometer works and show that at 1 atm the height of a column of mercury would equal 760 mm.
5. Calculate the pressure in Pa if the reading from a barometer is 820 mmHg.

6.2 Fluid pressure

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

- Define the term fluid and state the similarities and differences between liquids and gases.
- Define the term density and relative density and determine each for a given body.
- Explain how the pressure in a liquid at rest varies.
- Apply the formula $P = h\rho g$ and use it to solve problems (including determining the pressure inside a fluid taking into account atmospheric pressure).
- State Pascal's principle, and apply it to solve problems and explain applications (such as the hydraulic lift).
- Explain the use of a manometer.
- Demonstrate an understanding of, distinguish between and calculate atmospheric, gauge and absolute pressure.
- State Archimedes's principle and the principle of flotation.
- Distinguish between true weight and apparent weight of a body.
- Calculate the buoyant force acting on the body in a fluid and explain why bodies float or sink.
- Calculate the density of a floating body or density of a fluid using the flotation principle.

What are fluids?

Can you name a **fluid**? I suspect you came up with either water, an oil of some sort, petrol or maybe something like milk. However, I doubt many, if any, of you came up with air. In physics a fluid refers to a substance that will **flow** along a pipe. In common use fluids tend to mean just liquids. However, in science fluids include all **gases** as well as **liquids**

KEY WORDS

flow *smooth unbroken movement of a substance*

fluid *a substance that will flow e.g. gases, liquids*

gases *substances in a state of matter where particles can move about randomly and are widely spaced, with no bonds between them*

liquids *substances in a state of matter where there are weak bonds between the particles which are close together but can still move*

Figure 6.23 Natural gas is a fluid.

KEY WORDS

incompressible *where the volume of a substance stays the same when force is applied*

density *the mass per unit volume of a substance*

Another characteristic of fluids is that they can change their shape. This means they always take the shape of the container they are put in. For example, consider a rectangular glass box. A liquid and gas will both fill the bottom of the container; however, a solid will not.

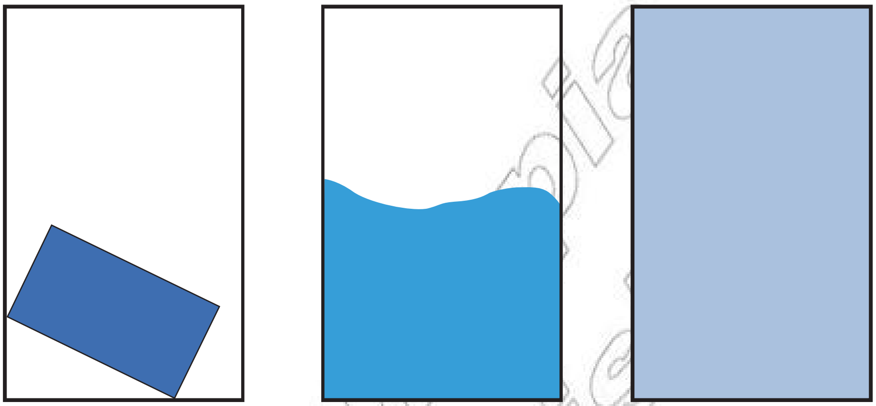


***Figure 6.24** Fluids take the shape of their container.*

There are still some very important differences between liquids and gases. Perhaps the most important is the fact that gases can be compressed by forces. You can squeeze a balloon filled with air and its volume will go down. However, liquids are **incompressible**; effectively this means the volume of a liquid stays the same when force is applied.

Table 6.2 summarises the key properties of liquids and gases.

***Table 6.2** Liquids and gases*

	Liquid	**Gas**
Particles	Quite close together, with no set pattern; particles can move past each other.	Far apart with no set pattern; particles can move past each other.
Bonding	Weak bonds between the particles	No bonding between the particles
Can flow / change their shape to match a container	Yes	Yes
Compressible	No; the particles are already close together.	Yes; there is lots of space between the particles.

Fluid density

The **density** of any fluid may be calculated using the standard equation for density:

- density = mass / volume
- $\rho = m / V$
- **Density is defined as mass per unit volume**.

As the particles are closer together in a liquid, liquids have higher densities than gases. Table 6.3 includes some typical densities of fluids.

Table 6.3 *Densities of fluids*

Fluid	Density (kg/m^3)
Mercury	13 600
Honey	1400
Water	1000
Sea water	1020
Diesel	950
Alcohol	800
Petrol	740
Air	1.20
Carbon dioxide	1.98
Nitrogen gas	1.25

Both temperature and pressure have an effect on the volume of a fluid. Therefore the densities in Table 6.3 are at standard atmospheric pressure (101 kPa) and a temperature of 20 °C.

For liquids it is fair to assume that the density is uniform throughout the liquid (as they are incompressible). However, for large volumes of gas the density increases as the gas gets closer to the surface of the Earth (due to gravity). This is most noticeable in the Earth's atmosphere. As the altitude increases the air gets less dense; the air is described as getting thinner.

Think about this...

Density is also often measured in g/cm^3. 1 g/cm^3 is equal to 1000 kg/m^3. How would convert from g/cm^3 to kg/m^3 and vice versa?

KEY WORDS

relative density *the ratio between the density of two substances*

What's relative density?

The term **relative density** is often used to compare the density between two fluids. In most cases this involves comparing the density of a fluid to that of water; however, it could be any other substance.

The relative density of a substance is the ratio between its density and the density of water. For example, if something has a relative density of two it means it is twice as dense as water. A relative density of 0.25 means it has ¼ of the density of water. You can calculate relative density using:

- relative density = density of substance / density of water.

The relative density of alcohol would be:

- relative density = density of substance / density of water
- relative density = 800 kg/m^3 / 1000 kg/m^3
- relative density = 0.8.

Notice relative density has no units since it is a ratio.

If we are comparing two identical volumes of fluids then the relative density can be calculated as the ratio of the masses of the same volume of fluid:

- relative density = mass of substance / mass of equal volume of water

Activity 6.7: Relative density

Determine the relative density of:

1. mercury
2. carbon dioxide
3. petrol
4. honey.

Activity 6.8: Measuring relative density

This method uses a density bottle (Figure 6.25) to find the relative density of a liquid. A density bottle has a ground-glass stopper, which fits exactly. There is a small hole in the stopper through which liquid and air can flow out when the stopper is put in the neck of the bottle. (This means that no air bubbles can be trapped under the stopper, which would give a false result.)

- Weigh a clean, dry density bottle with its stopper (mass = A).
- Fill with water and put in the stopper. Water should come out of the hole in the stopper. Dry the outside of the bottle and weigh it again (mass = B).
- Pour out the water, rinse with some of the liquid whose relative density is to be found. Fill with the liquid, put in the stopper, dry carefully and weigh (mass = C).

$$\text{Relative density} = \frac{\text{mass of liquid}}{\text{mass of water}} = \frac{(C - A)}{(B - A)}$$

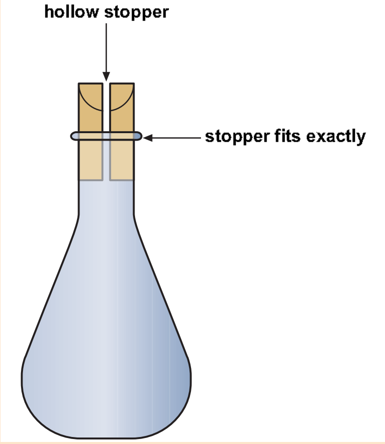


Figure 6.25 *A density bottle*

DID YOU KNOW?

If the relative density of a substance is relative to the density of water it is often called specific gravity. If the object has a specific gravity greater than 1, it will sink in water (more on this later).

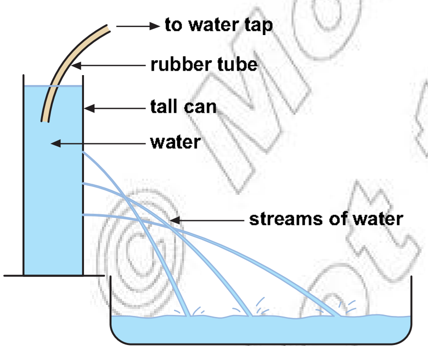


Figure 6.26 *The effect of depth on pressure*

Pressure in fluids

We've already discussed atmospheric pressure but if we investigate pressure in fluids in general we find there are two key points to consider:

- **Pressure increases with depth.**
- **At any given depth the pressure is equal in all directions.**

Pressure and depth

In any fluid the pressure increases with depth. The taller the column of the fluid above you, the greater the pressure it exerts. You can see this by conducting a very simple experiment.

Activity 6.9: Pressure and depth

Take a tall tin can and carefully make several holes going up one side (three or four should do it).

Quickly fill the tin with water and observe how the water squirts out of the holes.

You will notice that the stream from the bottom hole travels further. This is because the water is under more pressure at the bottom of the can.

We have already derived an equation for pressure in fluids in Section 6.1:

- $p = h\rho g$
- p = pressure in Pa
- h = depth of fluid in m
- ρ = density of fluid in kg/m^3
- g = gravitational field strength (9.81 N/kg)

Be careful not to mix up p and ρ (the Greek letter rho); make sure you look carefully before completing any calculations.

To recap:

Figure 6.28 shows a tank, filled with water of density ρ to a depth h. The base of the tank has area A. What is the pressure on the bottom of the tank?

The pressure is caused by the weight of the water in the tank, pressing down on the bottom.

- Volume of water = $h \times A$
- Mass of water = volume × density = $\rho \times h \times A$
- Weight of water = mass × g = $\rho \times h \times A \times g$
- Pressure = weight / area = $\rho \times h \times A \times g / A = \rho \times h \times g$.

This equation shows that the pressure increases with depth (h); in fact the pressure exerted by the fluid is directly proportional to the depth of fluid. Dive twice as deep and the pressure exerted by the water above you is doubled.

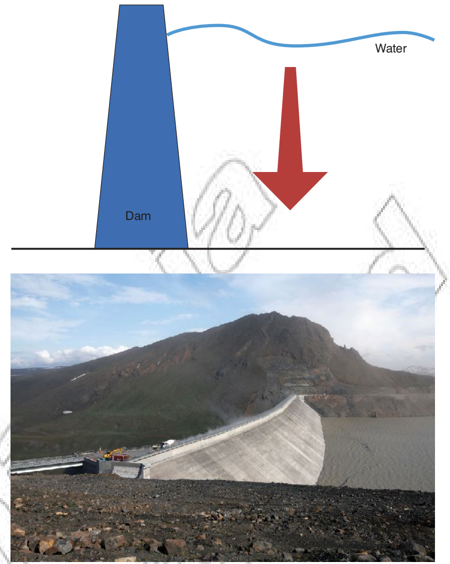


Figure 6.27 *Dams have to be thicker at the bottom in order to withstand the greater pressure.*

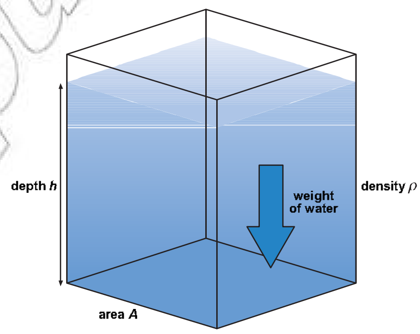


Figure 6.28 *The pressure on the bottom of the tank is caused by the weight of the water above it.*

Worked example

Calculate the pressure exerted by the water at the bottom of a swimming pool 6 m deep.

$p = h\rho g$ *State principle or equation to be used (pressure in fluids)*

$p = 6\ m \times 1000\ kg/m^3 \times 10\ N/kg$ *Substitute in known values and complete calculation*

$p = 60\ 000\ Pa$ *Clearly state the answer with unit*

Calculate the force this pressure would exert on a concrete block with an area of $3\ m^2$

$p = F / A$ *State principle or equation to be used (definition of pressure)*

$F = p \times A$ *Rearrange equation to make F the subject*

$F = 60\ 000\ Pa \times 3\ m^2$ *Substitute in known values and complete calculation*

$F = 180\ kN$ *Clearly state the answer with unit*

Activity 6.10: Pressure calculations

Using information in the density table (Table 6.3) calculate the pressure exerted by the fluid in the following situations:

1. Diving in sea water to a depth of 15 m.
2. The base of a column of mercury 760 mm tall.

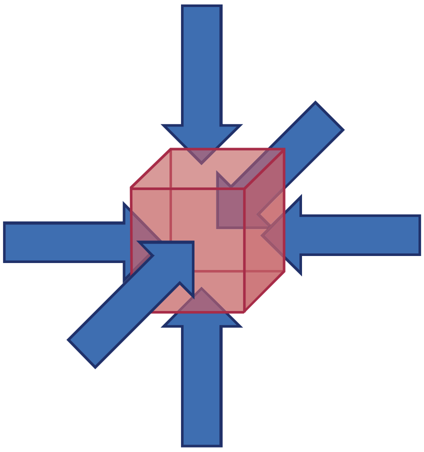


Figure 6.29 *Pressure is the same in all directions on a small cube.*

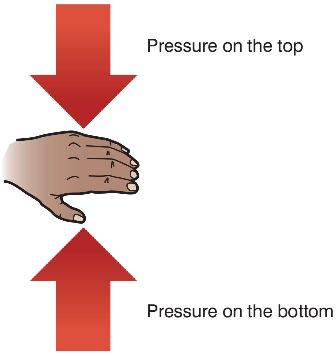


Figure 6.30 *The pressure on the top and on the bottom of your hand is essentially the same.*

DID YOU KNOW?

This topic is called fluid statics (or hydrostatics), meaning we are dealing with stationary fluids. A moving fluid exerts less pressure on its surroundings. This is studied in hydrodynamics and is very important when it comes to keeping aircraft in the air.

Pressure acts equally in all directions

In fluids, despite the pressure being caused by the column of fluid above you, the pressure acts equally in *all directions*. If you imagine a very small cube placed under water, the pressure on each cube face would be same.

If you hold your hand up horizontally in front of you the pressure on the top is the same as the pressure on the bottom.

Technically there is a very small difference in the height of the column of air on the top compared to the bottom (the thickness of your hand) but essentially the pressure is the same.

Activity 6.11: Pressure in a can

You can show this using another tin can. This time make four or five holes at the same depth around the bottom of the can.

Again quickly fill it with water and you can see all the streams of water are the same. In other words the pressure is the same in all directions inside the can.

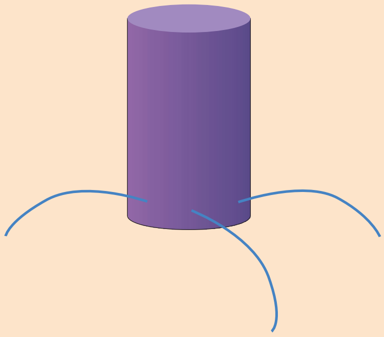
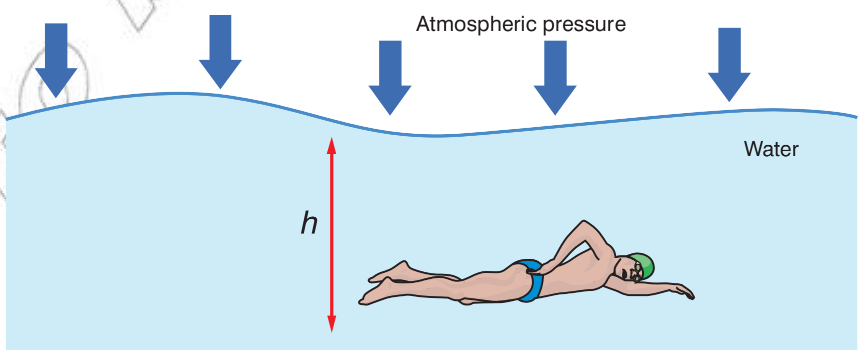


Figure 6.31 *Pressure is the same in all directions.*

What about the effect of atmospheric pressure?

If you go swimming the pressure acting on you is not just due to the water above you. You must not forget to include atmospheric pressure.



$$p = p_{atm} + p_{fluid}$$

Figure 6.32 *The total pressure on a swimmer*

The pressure on the swimmer would be the sum of the pressure due to the fluid and the atmospheric pressure. In terms of an equation this could be written as:

- $p = p_{atm} + h\rho_{fluid}g$

Pascal's principle

Activity 6.12: Water transmits pressure

- Take two syringes of different sizes. Connect them with plastic or rubber tubing. Fill the syringes and the tube with water (Figure 6.33).
- Press one syringe with one hand, and the other with the other hand. Feel how their forces differ.

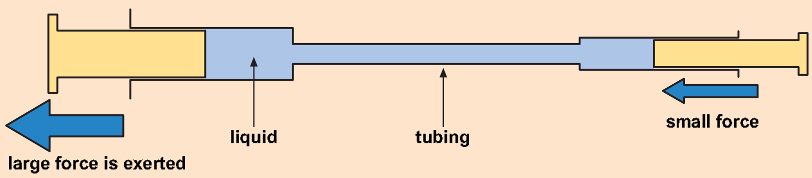


Figure 6.33 *Using water pressure to magnify a force.*

If you conduct the experiment above the difference in the forces is clear.

This difference comes down to the fact that liquids are incompressible; this means they can transfer pressure from one place to another. The force applied to the smaller syringe creates a pressure inside the liquid. This pressure is transferred throughout the liquid and is the same value everywhere. This pressure acts on the larger syringe and because the area of the syringe is larger the force exerted is also greater. Remember, from Unit 4, energy cannot be created or destroyed. Just like the simple machines studied in unit 5, if the output force gets bigger it must move through a smaller distance.

This phenomenon is referred to as **Pascal's principle** and it states:

- **The pressure applied to an enclosed fluid is transmitted to every part of the fluid, as well as to the walls of the container without reducing in value.**

Pascal's principle is used in the design and construction of simple **hydraulic machines**. Figure 6.34 shows two different sized pistons, which form part of a hydraulic system.

If a force is applied to the left hand piston it will create a pressure inside the fluid.

- $p = F_1 / A_1$

This pressure is transferred throughout the liquid. It is the same everywhere.

- p on the left = p on the right.

The piston on the right has a much larger area. The force from this piston is equal to:

- $F_2 = p \times A_2$

Worked example

Determine the pressure acting on a diver 20 m below the surface.

$p = p_{atm} + h\rho_{fluid}g$ *Express total pressure in terms of atmospheric pressure and pressure from fluid*

- In this case, h = 20 m and ρ_{fluid} = 1000 kg/m^3

p = 101 000 Pa + (20 m × 1000 kg/m^3 × 10 N/kg) *Substitute in known values and complete calculation*

p = 301 000 Pa or 301 kPa *Clearly state the answer with unit*

Think about this...

Discuss with a partner why this effect does not happen in gases.

KEY WORDS

hydraulic machines *machines that rely on the incompressibility of liquids to do work*

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

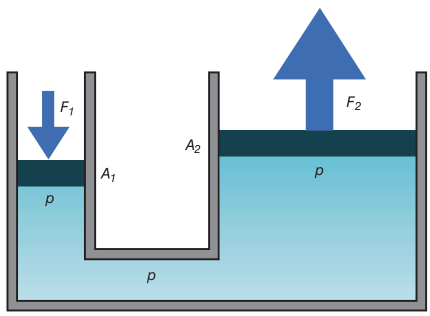


Figure 6.34 *Pascal's principle*

KEY WORDS

hydraulic lift *a hydraulic machine used to raise heavy objects*

hydraulics presses *a hydraulic machine used to shape metal or compress materials into smaller volumes*

hydraulic brakes *a mechanism which uses fluid to transfer pressure from a foot pedal to push brake pads onto brake discs*

As A_2 is much bigger than A_1, F_2 will also be bigger than F_1. In fact if the piston has double the area the force will be doubled. If the piston has ten times the area the force will be 10 times greater!

For example, let's imagine the areas are:

$A_1 = 2 \text{ m}^2 \quad A_2 = 6 \text{ m}^2$

If a force of 100 N is applied on A_1 then the force at A_2 will be 300 N (three times bigger). Let's prove it though calculation:

$p = F / A$ *State principle or equation to be used (definition of pressure)*

$p = F_1 / A_1$ *Relate to this context*

$p = 100 \text{ N} / 2 \text{ m}^2$ *Substitute in known values and complete calculation*

$p = 50 \text{ N/m}^2$ *Clearly state the answer with unit*

From Pascal's principle the pressure is the same throughout the liquid so:

$p = F_2 / A_2$ *State principle or equation to be used (definition of pressure expressed in this context)*

$F_2 = p \times A_2$ *Rearrange equation to make F_2 the subject*

$F_2 = 50 \text{ N/m}^2 \times 6 \text{ m}^2$ *Substitute in known values and complete calculation*

$F_2 = 300 \text{ N}$ *Clearly state the answer with unit*

As the pressure is same throughout the fluid we can summarise the relationship between the forces and areas in the following equation:

- $F_1 / A_1 = F_2 / A_2$

Hydraulic machines

Pascal's principle has many applications; one of the simplest is the **hydraulic lift**. This is used to lift a heavy object (such as a car) off the ground. Just like our example, a small force is applied to a smaller area piston. This creates a pressure inside a hydraulic fluid, which is transferred to a larger area piston. This piston creates a much larger force and, if the object to be lifted sits on top of the large piston, it can be easily lifted by the smaller force at the smaller area piston.

Other examples include hydraulic presses and hydraulic brakes (in cars).

Hydraulic presses are used to shape metal (e.g. make motor-car bodies), to press waste paper or cotton wool into bales of small size, to press oil from oil seeds, and to lift cars so that work can be done easily underneath.

Activity 6.13: A hydraulic lift

- **Inner tube method:**

  Use the inner tube of a bus or lorry tyre. Take out the valve, and fit about 1.5 metres of rubber tubing to the tube over the metal valve. Put a funnel into the other end of the rubber tubing. Place a large wooden board on the flat inner tube, and stand on the board. Pour water into the funnel. The inner tube fills with water and lifts you.

- **Polythene bag method:**

  Connect some rubber tubing to a closed polythene bag. Place a brick with its largest surface on the bag. Blow into the tubing. The brick is lifted.

  Turn the brick so that a smaller surface is on the bag. A larger pressure is needed to lift the brick as much as before.

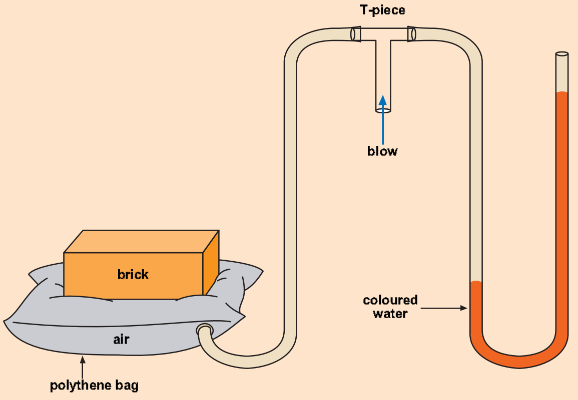


Figure 6.35 *A hydraulic lift operated by air pressure*

The hydraulic press (Figure 6.36) changes a small force into a large one. It consists of a cylinder and a piston, of large diameter, joined by a pipe to a second cylinder and a piston of small diameter. Water or oil is pumped into the small cylinder, and it lifts the large piston with an enormous force. A release valve lets the liquid run away after the piston has done its work.

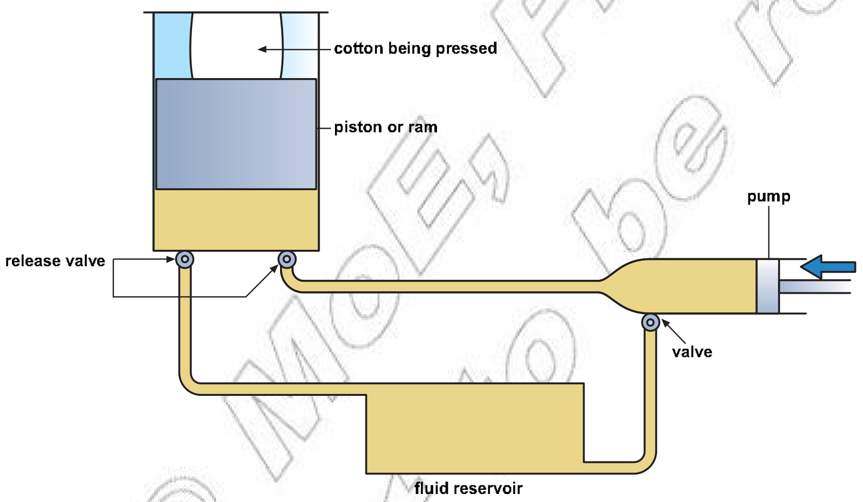


Figure 6.36 *A hydraulic press, used to compress a bale of cotton*

A car's **hydraulic brakes** work in a similar way. By pressing the foot on the brake pedal, a small force is applied to a piston with a small diameter. The pressure is transmitted through oil pipes to pistons of large diameter on the car wheels. These push the brake pads against the brake discs to stop the wheels.

Think about this...

Why is it a serious problem if air bubbles get into the hydraulic brake lines of a car?

Figure 6.37 *Pressure gauges may read absolute pressure or gauge pressure.*

KEY WORDS

absolute pressure *the actual pressure at a given point*

gauge pressure *the difference between absolute pressure and atmospheric pressure*

What is the difference between atmospheric, gauge and absolute pressure?

When it comes to measuring the pressure of a fluid there are several different terms you may come across. These include atmospheric pressure, gauge pressure and absolute pressure.

Absolute pressure

The **absolute pressure** is the actual pressure at a given point. It is the true pressure of a system if all of the factors are taken into account (including atmospheric pressure).

Atmospheric pressure

Atmospheric pressure has already been discussed. It is the pressure of the surrounding air when measured at the surface of the Earth. It has a value of 101 kPa. Atmospheric pressure varies depending on the temperature, the altitude above sea level and the impact of weather systems.

Gauge pressure

Pressure gauges often give readings of **gauge pressure** rather than absolute pressure. Gauge pressure is the pressure difference between a system and atmospheric pressure.

If the pressure gauge reads 25 kPa it would mean 25 kPa *above* atmospheric pressure (giving 126 kPa in total). If the gauge was disconnected it would read 0 Pa even though the absolute pressure is still 101 kPa.

Gauge pressure can be calculated using the equation below:

- $p_g = p_s - p_{atm}$
- p_g = gauge pressure
- p_s = system pressure (the absolute pressure of the system being measured)
- p_{atm} = atmospheric pressure

This is often used to determine the absolute pressure of the system. For example, if a compressed gas was measured and the gauge pressure of the system was 49 kPa then the absolute pressure would be:

- $p_g = p_s - p_{atm}$ so $p_s = p_g + p_{atm}$
- p_s = 49 000 Pa + 101 000 Pa
- p_s = 150 000 Pa

As gauge pressure is relative to atmospheric pressure it is possible to obtain negative readings. A reading of –10 kPa would mean 10 kPa *below* atmospheric pressure.

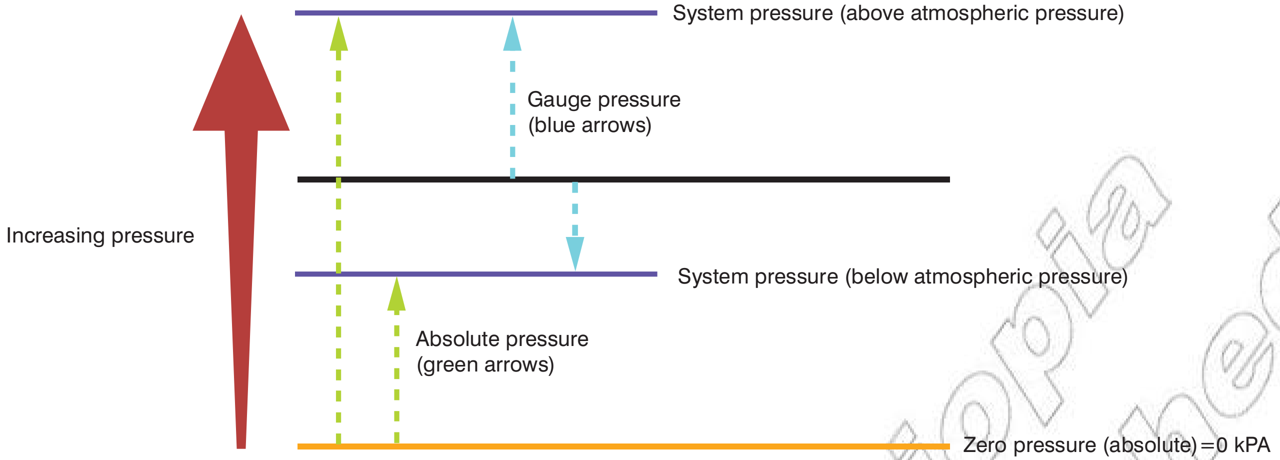


Figure 6.38 *The relationship between gauge pressure, absolute pressure and atmospheric pressure*

Measuring pressure

We have already looked at simple and aneroid barometers. However, there are a number of other ways to measure the pressure of a fluid. Most modern techniques use electronic pressure sensors. However, there are two other common mechanical techniques.

> **KEY WORDS**
>
> **Bourdon gauge** *an instrument for measuring the pressure of a gas*
>
> **manometer** *a U-shaped tube filled with liquid which is used to measure pressure*

Bourdon gauge

A **Bourdon gauge** is a more practical instrument for measuring the pressure of a gas (Figure 6.39). Inside the gauge is a flattened tube with one end sealed. The tube is coiled round in a spiral. The open end is connected to, say, the gas supply. As the gas presses in, it causes the spiral tube to uncurl slightly. This makes the needle move round the dial, indicating the pressure.

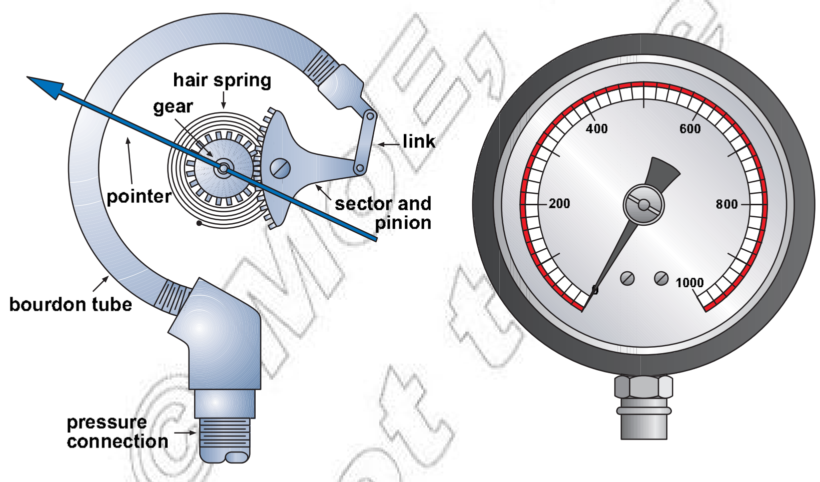


Figure 6.39 *A Bourdon gauge*

Manometer

A **manometer** is a simple instrument often used to measure the pressure of a gas supply. It comprises a U-shaped tube open at both ends. The tube is filled with a liquid (this is often coloured to make it easier to see).

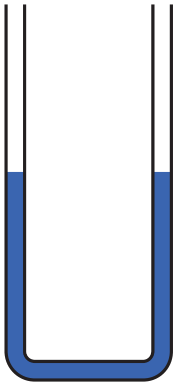


Figure 6.40 A simple manometer

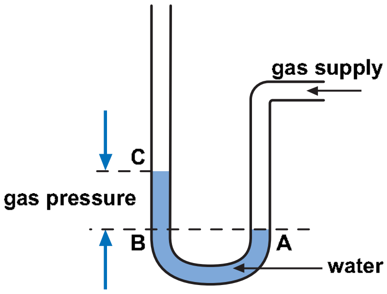


Figure 6.41 Using a manometer to measure the pressure of the gas supply

Figure 6.42 A manometer being used

Think about this...

If using a manometer to measure the pressure of higher pressure gases why is it a good idea to use mercury? Why is water usually used for gas supplies?

If one side of the manometer is connected to a system under pressure, the liquid will move. For example, if one end was connected to a gas supply the liquid would be pushed down as the supply is at a greater pressure than the surrounding atmosphere.

The height difference between B and C can then be used to determine the pressure of the gas supply.

- pressure of gas = atmospheric pressure + pressure due to the column of liquid BC
- pressure of gas = $p_{atm} + h_{BC}\rho g$

For example, if a water-filled manometer was connected to a gas supply and the height difference (BC) was 9 cm the pressure of the gas would be:

- pressure of gas = $p_{atm} + h_{BC}\rho g$
- pressure of gas = 101 000 Pa + 0.09 m × 1000 kg/m^3 × 10 N/kg
- pressure of gas = 101 900 Pa

This would most likely be expressed as a gauge pressure of 900 Pa.

Forces in fluids

Objects seem less heavy in water. For example, it is easy to hold up a friend horizontally in a swimming pool. Try doing this in air!

Figure 6.43 Despite their large mass elephants appear to be lighter underwater.

There is a force from the water that pushes you up, acting against gravity. This force is called a **buoyant force** (or sometimes **upthrust**). It arises due to the fact that as pressure increases with depth if you immerse an object in a fluid the pressure on the bottom will be greater than the pressure on the top.

This can be shown by considering the equation, $p = h\rho g$. The difference in pressure can be found by using:

- $\Delta p = \Delta h\rho g$

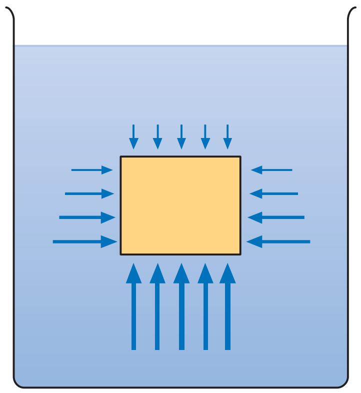


Figure 6.44 *The pressure is greater at a greater depth in water, so there is a bigger force on the lower surface of the block than on the upper surface.*

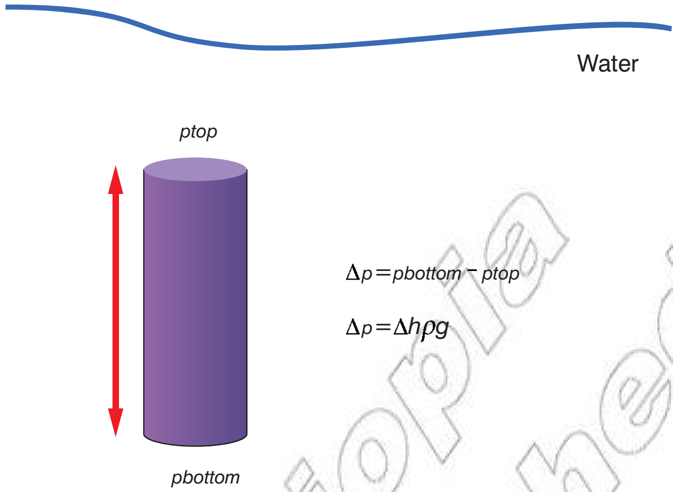


Figure 6.45 *The pressure difference = Δhρg*

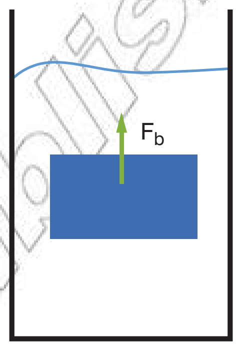


Figure 6.46 *The pressure difference leads to a force acting vertically upwards.*

This difference in pressure means there is a difference in force acting on the top and bottom of the object. The force on the bottom is greater and so there is net force upwards.

If you hold a cork underwater and then release it the buoyant force accelerates it towards the surface of the water. Equally if you drop a stone in the water it accelerates through the water much more slowly than it did through the air as the buoyant force means the net force acting on the stone is reduced.

The size of the buoyant force (F_b) depends on a number of factors including the *density of the fluid* and the *volume of the object.*

Buoyant forces are not just limited to liquids. Air also provides a buoyant force but it is very small (as the density of air is much less than that of water). In order for it to have a significant effect the volume of the object must be huge. Hot air balloons 'float' in the air due to the buoyant force of the air pushing them up, acting against their weight.

Figure 6.47 *The buoyant force from the air keeps the hot balloon in the air.*

Apparent weight

As we mentioned earlier, objects immersed in water (or any liquid) appear to weigh less. Obviously their weight has not changed ($w = mg$) but they now have an apparent weight. The buoyant force pushes upwards, acting against the objects weight and so the weight appears to drop.

The apparent weight may be calculated using the equation below:

- apparent weight = weight – buoyant force

Gases (like air) also provide a buoyant force but it is usually too small to need thinking about.

This equation is more commonly used to determine the buoyant force acting on an object:

- buoyant force = weight – apparent weight

KEY WORDS

buoyant force *a force from the water which pushes a body upwards against gravity*

upthrust *a force from the water which pushes a body upwards against gravity*

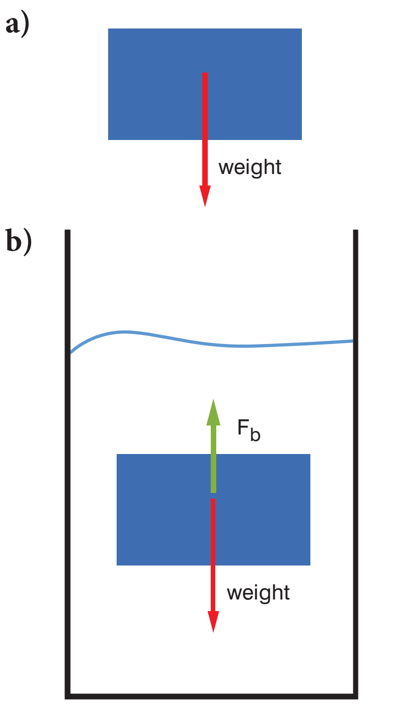


Figure 6.48 *The forces acting on an object a) in air b) in water*

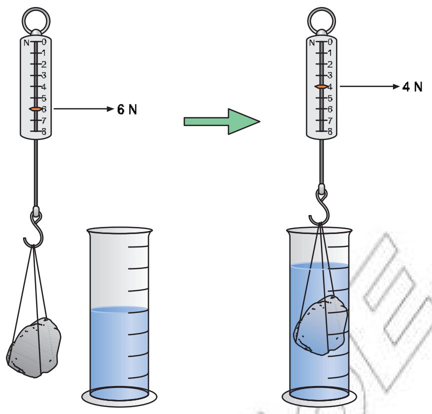


Figure 6.49 *Measuring the buoyant force acting on a stone*

KEY WORDS

Archimedes's principle *principle stating that the weight of the fluid displaced by an object is equal to the buoyant force acting on it*

Using a forcemeter we can easily determine the buoyant force acting on a stone (see Figure 6.49).

Here the buoyant force is equal to:

buoyant force = weight – apparent weight *State principle or equation to be used*

buoyant force = 6.0 N – 4.0 N *Substitute in known values and complete calculation*

buoyant force = 2.0 N *Clearly state the answer with unit*

Archimedes's principle

You probably know the story of Archimedes in his bath. King Hiero had ordered a new gold crown, in the shape of a wreath of leaves. The crown was the correct weight, but he suspected that the jeweller had cheated him by mixing silver with the gold. Could Archimedes find a way of checking the crown without damaging it?

Archimedes was in his bath when he thought of the solution. As everyone knows, when you get in the bath, the water level rises because your body displaces some of the water. Archimedes, seeing how he could put this to use, leapt from the bath and ran down the street shouting 'Eureka!' which means 'I have it!'

Here is how Archimedes tested the crown. He put a weight of gold equal to the crown, and known to be pure, into a bowl which was filled with water to the brim. Then the gold was removed and the king's crown put in, in its place. This caused the bowl to overflow.

Archimedes was using the fact that gold is denser than silver, so it takes up less space. He found that the new crown had a greater volume than one made of pure gold. It was indeed a cheat, and the jeweller was punished.

Archimedes realised that when an object is immersed in a liquid it displaces a certain volume of the liquid.

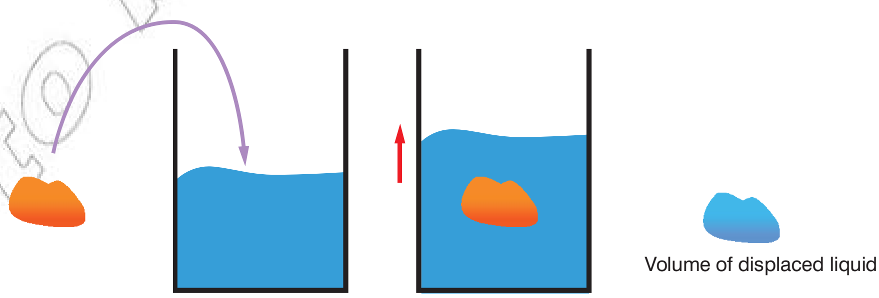


Figure 6.50 *A stone placed in a beaker of water will cause the level of water to rise as it displaces its own volume.*

He determined that the weight of the displaced fluid was equal to the buoyant force. Or in his own words:

- **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.**

In other words, the buoyant force acting on an object is equal to the weight of the displaced liquid.

- buoyant force = weight of displaced fluid

The greater the volume of liquid displaced the greater the buoyant force.

Activity 6.14: Testing Archimedes's principle

Use thin thread to tie an object (a stone, metal weight or glass stopper is suitable) to the hook of a newtonmeter (a spring balance). Note its weight.

- Weigh a beaker.
- Place an overflow can on the bench and fill it with water. When no more water drips out of the can, place the weighed beaker under its spout (see Figure 6.51).
- Lower the object carefully into the water until it is partially immersed. Note the apparent weight of the object.
- Weigh the beaker with the displaced water in it.
- Replace the beaker and water under the spout. Lower the object into the can until it is totally immersed but not touching the bottom of the can. Note the apparent weight of the object.
- Weigh the beaker and the displaced water.

You have to find the buoyant force on the object, and compare it with the weight of water displaced.

Upthrust = weight of object in air – weight of object in water

Weight of displaced water = weight of beaker with water – weight of empty beaker

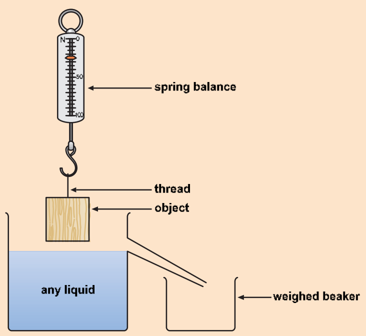


Figure 6.51 *Testing Archimedes's principle*

We can modify our equation for apparent weight in light of Archimedes' principle:

- apparent weight = weight – buoyant force
- buoyant force = weight of displaced fluid
- apparent weight = weight – weight of displaced fluid

KEY WORDS

law of flotation *law stating that if the buoyant force is equal to the weight of the object then the object will float*

Floating and sinking

Whether or not an object floats or sinks depends on the weight of the object and the size of the buoyant force acting on the object.

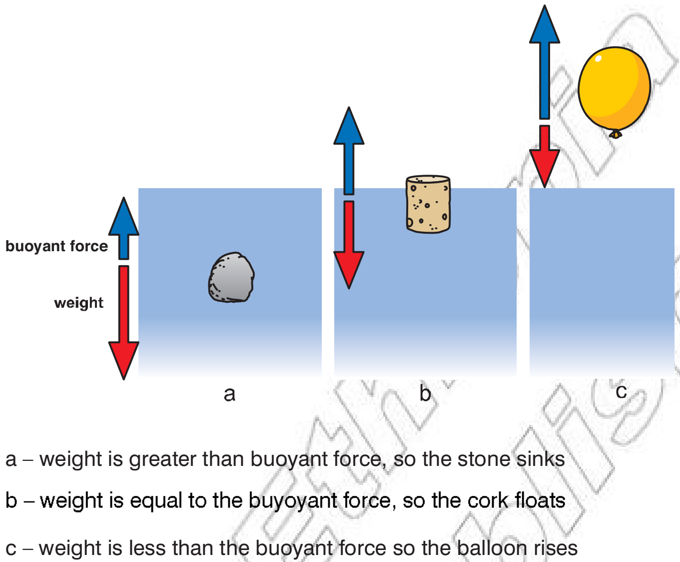


Figure 6.52 *The relative sizes of the buoyant force and the weight determine whether an object will float or sink.*

Figure 6.53 *The ship floats due to the law of flotation.*

In order to float an object must displace a volume of fluid (liquid or gas) equal to its own weight. This is called the **law of flotation**.

If the weight of the volume of fluid displaced is equal to the weight of the object then the object will float.

A large steel ship is able to float because it displaces such a large volume of water. This volume of water has the same weight as the ship.

When you step into a small boat you might notice the boat sinks down a little in the water. This is because as the weight of the boat increases it needs to displace a greater volume of liquid in order to float, and so it sinks down lower in the water. A heavily loaded boat sits much lower in the water than a lightly loaded boat.

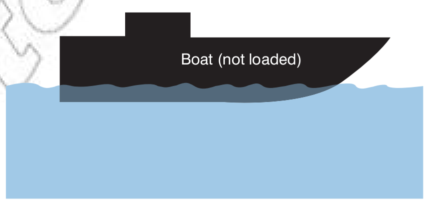


Figure 6.54 *A boat that is not heavily loaded displaces a smaller volume of liquid in order to float.*

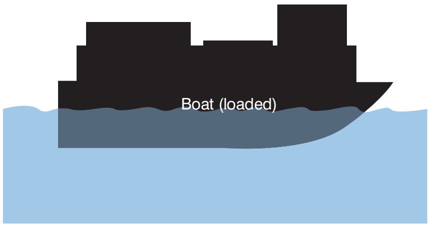


Figure 6.55 *A boat that is heavily loaded needs to displace a much larger volume of water in order to float.*

In the late 19th century greedy ship owners were overloading their ships and several ships sank as a result. The Englishman Samuel Plimsoll developed the waterline (or more commonly the Plimsoll line). This was a line that by law must be painted on all large ships. For safety reasons, when the ship is fully loaded the level of the water must not be above the Plimsoll line.

Figure 6.56 The Plimsoll line on a ship

Worked example

A toy submarine has a weight of 6.2 N in air. When immersed in water it has a weight of 4.6 N. Determine the buoyant force and the weight of water displaced

buoyant force = weight – apparent weight *State principle or equation to be used*

buoyant force = 6.2 N – 4.6 N *Substitute in known values and complete calculation*

buoyant force = 1.6 N *Clearly state the answer with unit*

weight of displaced fluid = buoyant force *Make it clear the two quantities are equal from Archimedes's principle*

- weight of displaced fluid = 1.6 N *Clearly state the answer with unit*

Think about this...

If you look carefully at the image of the Plimsoll line you can see that there are several different lines depending on whether the ship is in fresh water, salt water, cold water (North Atlantic) or warm water (tropical). Why is this?

What about density?

If, even when fully immersed, the weight of the volume of liquid displaced is less than the weight of the object, then the object will sink. A small cube of steel does not displace enough water to float. However, if you hammer out the steel into a bowl shape it displaces a greater volume of water and so will float.

***Figure 6.57** The same mass of steel will sink or float depending on its shape and so the amount of fluid it displaces.*

In other words, if the density of the object is greater than the density of the fluid it will sink.

This means we need to consider the relative density between the object and the liquid. If the relative density is less than one the object will float (as the weight of the object will be less than the weight of the volume of liquid it displaces). If the relative density is more than one the object will sink (as the weight of the object will be more than the weight of the volume of liquid it displaces). We can modify our previous equations to include the density of the object and the density of the fluid.

Worked example

A floating wooden block has a volume of 0.4 m³ and displaces 0.3 m³ of water. Determine the density of the block.

$\rho_{object} V_{object} = \rho_{fluid} V_{fluid}$ *State principle or equation to be used (a version of Archimedes's principle)*

$\rho_{object} = \rho_{fluid} V_{fluid} / V_{object}$ *Rearrange equation to give ρ_{object}*

$\rho_{object} = (1000 \text{ kg/m}^3 \times 0.3 \text{ m}^3) / 0.4 \text{ m}^3$ *Substitute in known values and complete calculation*

$\rho_{object} = 750 \text{ kg/m}^3$ (or a relative density of 0.75) *Clearly state the answer with unit*

- $w = mg$ and $\rho = m / V$
- weight of object = $m_{object} g$ and so weight of object = $\rho_{object} V_{object} g$
- weight of displaced liquid = $m_{fluid} g$ and so weight of displaced fluid = $\rho_{fluid} V_{fluid} g$

If the object is floating then:

- buoyant force = weight of displaced liquid = weight of object

So:

- $\rho_{object} V_{object} g = \rho_{fluid} V_{fluid} g$

The g's cancel, giving:

- $\rho_{object} V_{object} = \rho_{fluid} V_{fluid}$

This equation only applies if the object is floating.

Summary

In this section you have learnt that:

- A fluid is any substance that can flow. This includes gases as well as liquids.
- Gases may be compressed but liquids are incompressible.
- Density is defined as the mass per unit volume and it may be calculated using the equation $\rho = m / V$. Density is measured in kg/m^3.
- The relative density of a substance is the density of the substance compared to another (e.g. compared to water).
- In fluids the pressure increases with depth and is the same in all directions.
- In fluids the pressure due to the fluid is equal to $p = h\rho g$. The total pressure is equal to the pressure due to the fluid plus atmospheric pressure.
- Pascal's principle states that liquids transfer pressure from one place to another without any reduction in pressure.
- Gauge pressure is the difference between absolute pressure and atmospheric pressure.
- A manometer is a simple U-shaped tube filled with liquid used to measure pressure.
- The apparent weight of a body is equal to the weight of the object minus the buoyant force acting on it.
- Archimedes's principle states that the weight of the displaced fluid is equal to the buoyant force acting on the object.
- The principle of flotation states if the buoyant force (or weight of displaced fluid) is equal to the weight of the object then the object will float.
- If the object is floating then the density of the floating object can be calculated from: $\rho_{object}V_{object} = \rho_{fluid}V_{fluid}$ where V_{fluid} is the volume of the displaced fluid.

Review questions

1. Explain what is meant by the term fluid and give three examples.
2. Calculate the pressure caused by sea water when diving to a depth of 100 m. What is the total pressure acting on the diver?
3. State Pascal's principle and describe one of its applications.

4. Two pistons are connected together to make a hydraulic lift. The smaller piston has an area of 0.05 m^2 and the larger piston has an area of 2 m^2. Calculate the following:
   a) The pressure in the fluid and the force at the larger piston if the force on the smaller piston is 50 N.
   b) The pressure in the fluid and the force from the smaller piston required to lift a car of mass 1200 kg.
5. Describe the relationship between the buoyant force and the weight of an object if the object:
   a) is floating
   b) is sinking
   c) is rising up through the water.

End of unit questions

1. An elephant has a mass of 3200 kg. Each of its feet covers an area equal to 0.08 m^2. Calculate the pressure from each foot.
2. Describe what causes pressure in gases in terms of the particles in the gas.
3. Describe some similarities and difference between liquids and gases.
4. How deep under water would you need to be in order to be at double atmospheric pressure?
5. Explain the meaning of the terms atmospheric pressure, absolute pressure and gauge pressure.
6. Describe the use of a manometer and calculate the pressure of a gas supply that causes a column of water 15 cm high.
7. State Archimedes's principle and explain how this leads to the law of flotation.
8. Explain why a heavily loaded boat sinks lower in the water.
9. The weight of an object is measured in air to be 7.0 N. The object is then immersed in water and its apparent weight is measured to be 4.0 N. Determine the buoyant force and state whether or not the object floats.
10. A large ocean liner floating in the sea has a volume of 375 000 m^2 and displaces 50 000 m^2 of sea water. Determine the density and mass of the ship. Explain why, despite being made of metal, the ship is able to float.