Edexcel

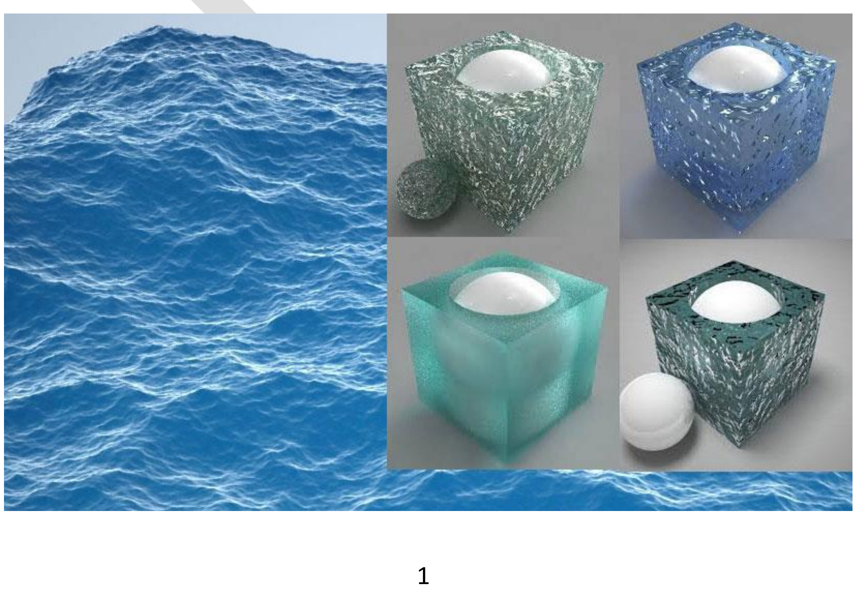
AS level

Physics

CODE: (4BI1)

Topic 2-Materials

2A-Fluids



2A.1 – Fluids, Density and Upthrust

Fluids

Fluids, such as gas or liquid, can flow, but they can also behave as solids made up of tiny particles. Manufacturers intentionally make thick sauces to satisfy consumer preferences, as thick sauces make sauce flow slowly. Understanding fluid properties is crucial for effective product development.

Density

One of the key properties of a fluid is its density. Density is a measure of the mass per unit volume of a substance - this is technically called 'volumic mass'. Its value depends on the mass of the particles from which the substance is made, and how closely those particles are packed:

$$\text{density (kg m}^{-3}\text{)} = \frac{\text{mass (kg)}}{\text{volume (m}^3\text{)}}$$

$$\rho = \frac{m}{V}$$

Here is a table showing densities for different materials.

MATERIAL	STATE	DENSITY / kg m^{-3}
air	gas (sea level, 20 °C)	1.2
pure water	liquid (4 °C)	1000
sulfuric acid (95% conc)	liquid (20 °C)	1839
cork	solid	240
ice	solid	919
window glass	solid	2579
iron	solid	7850
gold	solid	19 320

table A Examples of density values for solids, liquids and gases.

Upthrust

When an object is submerged in a fluid, it feels an upwards force caused by the fluid pressure - the upthrust. It turns out that the size of this force is equal to the weight of the fluid that has been displaced by the object. This is known as Archimedes' principle. If the object is completely submerged, the mass of fluid displaced is equal to the volume of the object multiplied by the density of the fluid:

m = Vp

The weight of fluid displaced (i.e. upthrust) is then found using the relationship:
W = mg

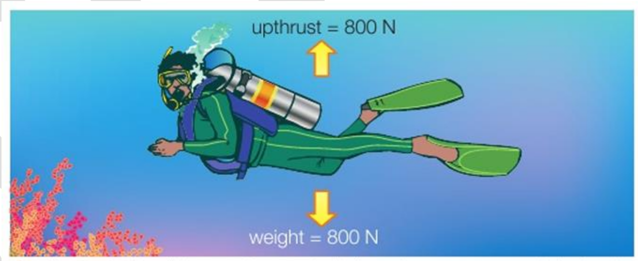


fig B Scuba diving equipment includes a buoyancy control device that can change volume to displace more or less water. This varies the upthrust and so helps the diver move up or down.

WHY DOES A BRICK SINK?

If the house brick from the example calculation of density above were dropped in a pond, it would experience an upthrust equal to the weight of water it displaced. This is simply the weight of an equal volume of water. As the density of water is 1000 kg m-3, the mass of water displaced by the brick would be:

m = 1000 kg m^{-3} x 1.61 x 10^{-3} m^3 = 1.61 kg

The water has a weight of:

W = 1.61 x 9.81 = 15.8 N

so there is an upward force on the brick of 15.8 N.

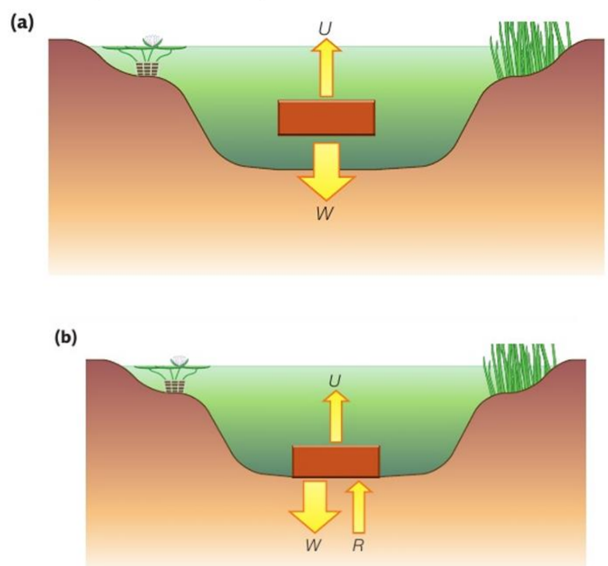


fig C **(a)** If the upthrust on an object is less than its weight, then the object will sink through a fluid; **(b)** an object will remain at rest when balanced forces act on it.

If we compare the weight of the brick with the upthrust when it is submerged, the resultant force will be downwards:

weight = 3.38 x 9.81 = 33.2 N downwards upthrust = 15.8 N upwards
resultant force = 33.2 15.8 17.6 N downwards

, the brick will accelerate downwards within the water until it reaches the bottom of the pond, which then exerts an extra upwards force to balance the weight so the brick rests stationary on the bottom with zero resultant force.

SUBJECT VOCABULARY

laminar flow/streamline flow a fluid moves with uniform lines in which the velocity is constant over time
turbulent flow fluid velocity in a particular place changes over time, often in an unpredictable manner
streamlines lines of laminar flow in which the velocity is constant over time

Floating

An object sinks into a fluid, causing no upthrust as it touches the surface. As it sinks deeper, it displaces fluid, increasing upthrust. A point where upthrust and weight are balanced stops sinking, allowing the object to float.

The hydrometer

A hydrometer is an instrument used to determine fluid density by floating at different depths. Its constant weight sinks lower in less-dense fluids, requiring greater volume displacement. Scale markings indicate liquid density. Car batteries' sulfuric acid solution density indicates battery charge level.

SUBJECT VOCABULARY

fluid any substance that can flow
density a measure of the mass per unit volume of a substance
upthrust an upwards force on an object caused by the object displacing fluid
Archimedes' principle the upthrust on an object is equal to the weight of fluid displaced
hydrometer an instrument used to determine the density of a fluid

HYDROMETER READING (DENSITY COMPARED TO WATER)	STATE OF CHARGE
1.255–1.275	100%
1.215–1.235	75%
1.180–1.200	50%
1.155–1.165	25%
1.110–1.130	0%

table B For a particular car battery, the hydrometer readings can be compared to a table to tell us how charged the battery is.

2A.2 – Fluid movement

Laminar flow

When a fluid moves, there are two ways this can happen: **laminar flow** (also called **streamline flow**) and turbulent flow. In general, laminar flow occurs at lower speeds, and will change to **turbulent flow** as the fluid velocity increases past a certain value.

Fluid flow velocity varies based on the fluid and its shape.

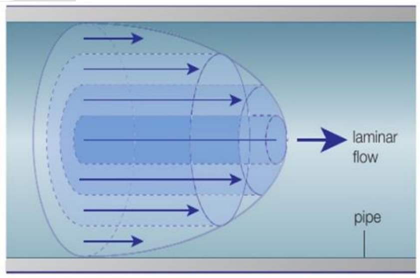


fig B Laminar flow in a pipe shows streamlines of different but unchanging velocities

Streamline

Laminar fluid flow is represented by **streamlines**, which maintain constant velocity over time. These streamlines, which are vectors, ensure water moves in the same direction and speed at any point. Designers can test the behavior of prototypes at faster speeds by changing airflow speed and determining when laminar flow transitions to turbulent flow.

fig D Increased speeds change streamline flow to turbulent flow.

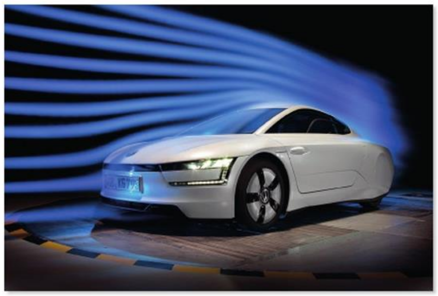


fig C Smoke streamlines show laminar flow of air over a well-designed car.

2A.3 – Viscosity

Viscosity is a crucial factor in determining the frictional force in fluids, such as water, which makes walking through a swimming pool harder than in air. Newton's formula for friction in liquids includes factors related to the specific liquid, such as the **coefficient of viscosity** (eta) – η. Viscosity directly affects the rate of flow of the fluid, as seen in the flow of lava in a river compared to its viscosity.

FLUID	TEMPERATURE / °C	VISCOSITY / Pa S
air	0	0.000017
air	20	0.000018
air	100	0.000022
water	0	0.0018
water	20	0.0010
water	100	0.0003
glycerine	−40	6700
glycerine	20	1.5
glycerine	30	0.63
chocolate	30	100
chocolate	50	60

table B The viscosities of different fluids at different temperatures.

LAVA TYPE	SILICA CONTENT	VISCOSITY	APPROXIMATE FLOW RATE / km h^{-1}
basaltic	least	least	30–60
andesitic	in between	in between	10
rhyolitic	most	most	1

table A How is the rate of flow related to the viscosity of the fluid?

2A.4 – Terminal velocity

The equation for a falling object like a skydiver involves weight, upthrust, and viscous drag force. The difficulty lies in balancing these forces, ensuring constant **terminal velocity,** which is determined by the equilibrium situation of weight and upthrust.

Stoker's law

In the mid-nineteenth century, Sir George Gabriel Stokes, an Irish mathematician and physicist at Cambridge University, investigated fluid dynamics and came up with an equation for the viscous drag (F) on a small sphere at low speeds. This formula is now called Stokes' law:

F = 6 πτηv

where r is the radius of sphere (m), v is the velocity of sphere (ms¯1), and ’n is the coefficient of viscosity of the fluid (Pas).

For simplicity, we will only consider simple situations, such as a solid sphere moving slowly in a fluid. Imagine a ball bearing dropping through a column of oil, for example. If you consider the terminal velocity of the sphere in terms of the forces in detail, then:

weight = upthrust + Stokes' force

$$m_s g = \text{weight of fluid displaced} + 6\pi r\eta v_{\text{term}}$$

where m_s is the mass of the sphere and v_{term} is its terminal velocity.

For the sphere, the mass m_s is given by:

$$m_s = \text{volume} \times \text{density of sphere} = \frac{4}{3}\pi r^3 \times \rho_s$$

so the weight of the sphere W_s is given by:

$$W_s = m_s g = \frac{4}{3}\pi r^3 \rho_s g$$

For the sphere, the upthrust is equal to the weight of fluid displaced. The mass m_f of fluid displaced is given by:

$$m_f = \text{volume} \times \text{density of fluid} = \frac{4}{3}\pi r^3 \times \rho_f$$

so the weight of fluid displaced W_f is given by:

$$W_f = m_f g = \frac{4}{3}\pi r^3 \rho_f g$$

Overall then:

$$\frac{4}{3}\pi r^3 \rho_s g = \frac{4}{3}\pi r^3 \rho_f g + 6\pi r\eta v_{\text{term}}$$

We can rearrange the equation to find the terminal velocity:

$$v_{\text{term}} = \frac{\frac{4}{3}\pi r^3 g(\rho_s - \rho_f)}{6\pi r\eta}$$

Cancelling the π and the radius term:

$$v_{\text{term}} = \frac{2r^2 g(\rho_s - \rho_f)}{9\eta}$$

▲ **fig B** Along with Lord Kelvin and James Clerk Maxwell, Sir George Gabriel Stokes helped to build the reputation of Cambridge University in many areas of mathematical physics.

Viscous drag

Viscous drag, the friction force between a solid and fluid, can be complex for large, fast, and irregularly shaped objects. Stokes' law, which states that larger objects generally fall faster, is not a common situation and terminal velocity values are often determined through complex calculations.

FALLING OBJECT	TERMINAL VELOCITY / m s^{-1}
skydiver	60
golf ball	32
hail stone (0.5 cm radius)	14
raindrop (0.2 cm radius)	9

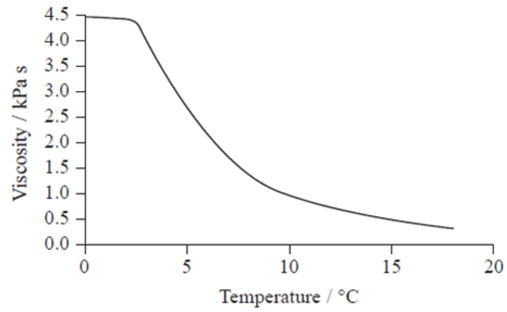
table A The terminal velocities of various objects falling in air. Note that the skydiver value varies greatly with the shape in which the body is held when falling.

Revision questions

(1) A small helium balloon is released into the air. The balloon initially accelerates upwards. The resultant force F on the balloon is given by
F = upthrust − weight − viscous drag

The viscosity of the air decreases as the balloon rises. On a warmer day a balloon of the same total mass and radius rises at a lower constant upwards speed. Give a reason why.

(2) The graph shows the effect of temperature on viscosity for butter. Explain why it is easier to use butter at room temperature than straight from the fridge.



(3) Car engines use motor oil as a lubricant. Motor oils need to operate over a range of temperatures because they may be at 0ºC or below when the engine is started but be up to 160ºC when the engine is running. At all times motor oils need to be thin enough to allow the parts to move smoothly but thick enough to remain on the moving parts.

Explain why the engine may experience difficulties if the temperature becomes too hot or cold.

(4) A student carries out an experiment to determine the viscosity of glycerol. She does this by determining the terminal velocity of a steel sphere falling through glycerol. The equation shows how the terminal velocity of a solid sphere falling through a liquid depends on the density of both the solid and the liquid.

$$v = \frac{Vg(\rho_s - \rho_l)}{6\pi r\eta}$$

where

ρ_l = density of liquid
ρ_s = density of solid
r = radius of sphere
V = volume of sphere
η = viscosity of liquid
v = terminal velocity

The derivation of the equation for terminal velocity has been started below. Complete the derivation.

At terminal velocity: weight of solid sphere = drag + upthrust

(5) A small helium balloon is released into the air. The balloon initially accelerates upwards. The resultant force F on the balloon is given by

F = upthrust − weight − viscous drag

density of air = 1.2 kg m^{-3}
mass of unfilled balloon = 4.0 g
mass of helium in balloon = 1.2 g

Eventually the balloon reaches a constant upwards speed. Calculate a value for the viscous drag force acting on the balloon at this speed. The balloon may be considered as a sphere with radius 12 cm.

(6) An exhibit in a science museum requires the observer to use a pump to create air bubbles in a column of liquid. The bubbles then rise through the liquid. A student wishes to determine the total drag force acting on a bubble.

(i) Explain why it might not be possible to use Stokes' law to calculate the drag force acting on a bubble
(ii) Describe an additional measurement that would need to be taken from the photograph and how it could be used to determine the drag force, assuming that the bubble has reached its terminal velocity.

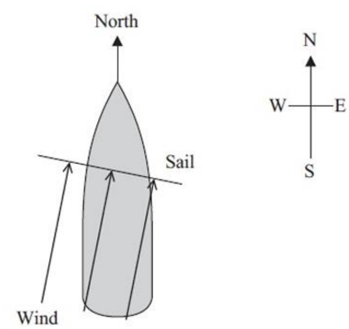
(7) (a) The force required to launch 'Stealth' is not always the same. The ride is monitored and the data from preceding launches is used to calculate the required force.

If the mass of the passengers for a particular ride is significantly more than for preceding launches, this can lead to 'rollback'. This is when the carriages do not quite reach the top of the first slope and return backwards to the start.

Explain why 'rollback' would occur in this situation

(b) Suggest why roller coasters may have a greater acceleration when the lubricating oil between the moving parts has had time to warm up.

(8) A stationary boat is pointing north as shown in the diagram. A wind starts blowing at 10 m s^{-1} in a direction 20º east of north against the sail. The boat starts to move northwards.



(a) (i) The wind exerts a force per unit area of 84 N m^{-2} on the sail, which is at right angles to the wind direction. Show that the component of force in a northerly direction is about 1400 N.

area of sail = 18 m^2

(ii) When the wind starts to blow the water exerts a force on the boat to the west. Explain why
(iii) Draw a vector diagram showing the forces exerted on the boat by the wind and the water and the resultant force calculated in part (a)(i).
(iv) Assuming the boat is starting from rest in still water, calculate the initial acceleration of the boat. mass of boat = 400 kg