

Unit 6

Fluid statics

6.1 Air pressure

- ✓ Pressure is defined as the amount of force acting 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 tires. 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.
- ✓ The pressure exerted by a force may be calculated using the equation below:

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

$$p = \frac{F}{A}$$

- ✓ Pressure is measured in Pascal. One Pascal is equal to a pressure of 1N per square meter (1 N/m²). The Pascal is the SI derived unit of pressure (this includes all forms of pressure).

For example

1. A boy weighs 500 N and the soles of his feet have an area of 0.05 m². Determine the pressure he exerts when he stands a) on both feet and b) on one foot.

Solution

$$p = \frac{F}{A}$$

$$p = 500 \text{ N} / 0.05 \text{ m}^2$$

$$p = 10000 \text{ Pa} \checkmark 10 \text{ kPa}$$

- If he stands on one foot his weight will be the same but the area will be halved to 0.025 m².

$$p = \frac{F}{A}$$

$$p = 500 \text{ N} / 0.025 \text{ m}^2$$

$$p = 20000 \text{ Pa} \checkmark 20 \text{ kPa}$$

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.

$$p = F/A$$

$$F = p \times A$$

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 m².

$$F = 100 \text{ Pa} \times 0.05 \text{ m}^2$$

$$F = 5 \text{ N}$$

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

$$w = mg \text{ so } m = w / g$$

$$m = 5 \text{ N} / 10 \text{ N/kg}$$

$$m = 0.5 \text{ kg or } 500 \text{ g}$$

6.1.1 What causes air pressure?

- ✓ The causes of air pressure are air particles exerting a force on a surface.
- ✓ As altitude increases, the atmospheric pressure decreases and vice versa.
- ✓ The atmospheric pressure depends on
 - *Altitude*
 - *Temperature changes*
 - *Position on the earth.*

Atmospheric pressure

6.1.2. Atmospheric pressure

- ✓ Atmosphere is the layer of air that surrounds the Earth.
- ✓ 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.
- ✓ 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.

6.1.3. How big is atmospheric pressure?

- ✓ The weight of the column of air above 1 m² 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:

$$1 \text{ atm} = 101 \text{ kPa}$$

- ✓ 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!

- ✓ Vacuum pump a machine for removing the air from inside a chamber.

6.1.4. Measuring atmospheric pressure

- ✓ Barometer is a device for measuring atmospheric pressure.
- ✓ There are different types of barometer.
 - I. Mercury barometer
 - II. Aneroid barometer

What is mercury barometer?

A mercury barometer is

- Long and inconvenient
- Heavy and contains liquid that is hazardous
- Easily split.

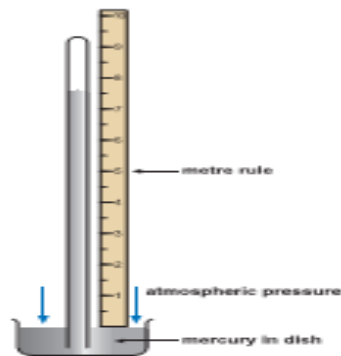


Figure 6.15 A diagram of a simple barometer

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:

$$V = \pi r^2 h$$

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

- $V = 5.97 \times 10^{-5} \text{ m}^3$

The density of mercury is $13\,570 \text{ kg/m}^3$ so its mass is:

- $m = \rho V$

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

- $m = 0.81 \text{ kg}$

Therefore the weight of the column can be found:

- $w = mg$

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

- $w = 7.9 \text{ N}$

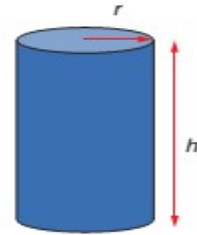


Figure 6.17 The volume of a cylinder

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:

$$p = F / \pi r^2$$

$$p = 7.9 \text{ N} / \pi \times (0.005 \text{ m})^2$$

$$p = 101\,000 \text{ Pa or } 101 \text{ kPa}$$

We 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:

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

What is Aneroid barometer?

- ✓ Aneroid barometer is a device for measuring atmospheric pressure that uses a corrugated metal box rather than liquid.
- ✓ Compact & Portable
- ✓ Flat circular metal box
- ✓ With a little air inside
- ✓ Aneroid barometer means without liquid.

Example

Calculate the pressure in Pa if the reading from a barometer is 820mm Hg.

$$1 \text{ atm} = 760 \text{ mm Hg}$$

$$? = 820 \text{ mm Hg}$$

$$P \text{ in atm} = \frac{(1 \text{ atm} \times 820 \text{ mm Hg})}{760 \text{ mm Hg}} = 1.07894737 \text{ atm}$$

Again

$$1 \text{ atm} = 101\,000 \text{ Pa}$$

$$1.07894737 \text{ atm} = ?$$

$$P \text{ in Pa} = \frac{1.07894737 \text{ atm} \times 101\,000 \text{ Pa}}{1 \text{ atm}} = 108\,973.7 \text{ Pa}$$

Some uses of air pressure

Pressure difference is the relative value of the pressure of gas in different chambers. 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.

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 we drink through a drinking straw, we are making use of atmospheric pressure. We suck on the air inside the straw. Therefore the atmospheric pressure outside is greater than the pressure inside, and liquid is pushed up.
- ✓ A lift pump (common pump) is often used to raise water from wells. A piston moves up and down a tube. 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.
- ✓ A force pump can pump water to a great height. Some, used by firemen, can force water hundreds of meters high.
- ✓ Bicycle pump is a cup-shaped leather or rubber washer on the end of the piston. This acts as a valve and let's air move in one direction only. The soft edge of the washer fits closely to the sides of the cylinder.
- ✓ A siphon is a convenient way of removing liquid from a container such as an aquarium or petrol tank.

Review questions on page 151

6.2 Fluid pressure

6.2.1. What are fluids?

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.

flow is smooth unbroken movement of a substance.

Fluid is a substance that will flow e.g. gases, liquids.

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

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

- 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.
- Incompressible where the volume of a substance stays the same when force is applied.
- Density the mass per unit volume of a substance.

Table 6.2 summarizes the key properties of 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.

6.2.2. Fluid density

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

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

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

- ✓ 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.

6.2.3. What's relative density?

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 $\frac{1}{4}$ of the density of water. You can calculate relative density using.

$$\text{relative density} = \frac{\text{density of substance}}{\text{density of water}}$$

Example

The relative density of alcohol would be:

$$\text{relative density} = \frac{\text{density of substance}}{\text{density of water}}$$

$$\text{relative density} = (800 \text{ kg/m}^3) / (1000 \text{ kg/m}^3)$$

$$\text{Relative density} = 0.8$$

6.2.4. Pressure in fluids

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

$$p = h \rho g$$

Example

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

$$p = h \rho g$$

$$p = 6 \text{ m} \times 1000 \text{ kg/m}^3 \times 10 \text{ N/kg}$$

$$p = 60\,000 \text{ Pa}$$

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

$$F = p \times A$$

$$F = 60\,000 \text{ Pa} \times 3 \text{ m}^2$$

$$F = 180 \text{ kN}$$

6.2.5. 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.
- ✓ 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:

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

Example

Calculate the pressure caused by sea water when diving to a depth of 100m. what is the total pressure acting on the diver?

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

$$P = 101\,000 \text{ Pa} + 100 \text{ m} \times 1020 \text{ Kg/m}^3 \times 10 \text{ m/s}^2$$

$$P = 1121\,000 \text{ Pa}$$

6.2.6. Pascal's principle

- ✓ Pascal's principle states that the pressure applied to an enclosed fluid is transmitted to every part of the fluid without reducing in value.

- ✓ hydraulic machines that rely on the incompressibility of liquids to do work
- ✓ 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.

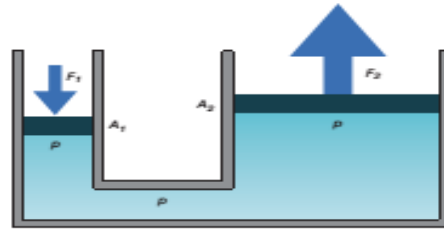


Figure 6.34 Pascal's principle

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

$$p = \frac{F_1}{A_1}$$

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:

Example

Two pistons are connected together to make a hydraulic lift. The smaller piston has an area of 0.05m^2 and larger piston has an area of 2m^2 . Calculate

- The pressure in fluid and the force at the larger piston if the force of the smaller piston is 50N .
- The pressure in fluid and the force from the smaller piston required to lift a car of mass 1200Kg .

Solution

$$\text{a. } P = \frac{F_1}{A_1} = \frac{50\text{N}}{0.05\text{m}^2} = 1000\text{Pa}$$

From Pascal's principle

$$P = \frac{F_1}{A_1} = \frac{F_2}{A_2} =$$

$$F_2 = \frac{F_1 A_2}{A_1}$$

$$F_2 = \frac{50\text{N} \times 2\text{m}^2}{0.05\text{m}^2} = 2000\text{N}$$

$$\text{b. } P = \frac{F_2}{A_2} = \frac{mg}{A_2} = \frac{1200 \times 10}{2\text{m}^2} = 6000\text{Pa}$$

From Pascal's principle

$$P = \frac{F_1}{A_1} = \frac{F_2}{A_2} =$$

$$F_1 = \frac{F_2 A_1}{A_2} = \frac{12000\text{N} \times 0.05\text{m}^2}{2\text{m}^2} = 300\text{N}$$

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.

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

- ✓ 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).
- ✓ 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

$$p_g = p_s - p_{\text{atm}}$$

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.

Example

If a compressed gas was measured and the gauge pressure of the system was 49 kPa then the absolute pressure would be:

$$p_g = p_s - p_{\text{atm}} \quad \text{so} \quad p_s = p_g + p_{\text{atm}}$$

$$p_s = 49\,000 \text{ Pa} + 101\,000 \text{ Pa}$$

$$p_s = 150\,000 \text{ Pa}$$

- 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.

6.2.8. Measuring pressure

- ✓ Bourdons gauge an instrument for measuring the pressure of a gas.
- ✓ Manometer a U-shaped tube filled with liquid which is used to measure pressure.

Pressure of gas = atmospheric pressure + pressure due to the column of liquid

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

$$\text{Pressure of gas} = p_{\text{atm}} + h\rho g$$

$$\text{Pressure of gas} = 101\,000 \text{ Pa} + 0.09\text{m} \times 1000 \text{ kg/m}^3 \times 10 \text{ N/kg}$$

$$\text{pressure of gas} = 101\,900 \text{ Pa}$$

6.2.9. Forces in fluids

There is a force from the water that pushes you up, acting against gravity. This force is called a buoyant force (or sometimes up thrust). 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:

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

Apparent weight

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
- ✓ Buoyant force is a force from the water which pushes a body upwards against gravity.
- ✓ Up thrust a force from the water which pushes a body upwards against gravity.

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.

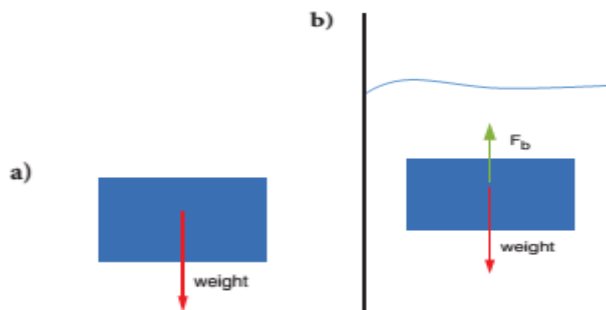


Figure 6.48 the forces acting on an object a) in air b) in water.

6.2.10. Archimedes's principle

Archimedes's principle states that the weight of the fluid displaced by an object is equal to the buoyant force acting on it. In other words, the buoyant force acting on an object is equal to the weight of the displaced liquid.

6.2.11. Floating and sinking

The law of flotation states that if the buoyant force is equal to the weight of the object then the object will float.

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.

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.

Solution

Buoyant force = weight - apparent weight

Buoyant force = 6.2 N - 4.6 N

Buoyant force = 1.6 N

Weight of displaced fluid = buoyant force from Archimedes's principle

Weight of displaced fluid = 1.6 N

What about density?

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.

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

If the object is floating then:

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

So:

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

The g's cancel, giving:

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

This equation only applies if the object is floating.

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.

$$\rho_{\text{object}} V_{\text{Object}} = \rho_{\text{fluid}} V_{\text{fluid}}$$

$$\rho_{\text{object}} = \frac{\rho_{\text{fluid}} V_{\text{fluid}}}{V_{\text{Object}}}$$

$$\rho_{\text{object}} = (1000 \text{ kg/m}^3 \times 0.3 \text{ m}^3) / 0.4 \text{ m}^3$$

$$\rho_{\text{object}} = 750 \text{ kg/m}^3 \text{ (or a relative density of 0.75)}$$

Review questions on page 169-170 & End of unit questions on page 170