# 1 Some basic mechanics

## 1.1 Introduction

This is a reference chapter rather than one for general reading. It is useful as a reminder about the physical properties of water and for those who want to re-visit some basic physics which is directly relevant to the behaviour of water.

## 1.2 Units and dimensions

To understand hydraulics properly it is essential to be able to put numerical values on such things as pressure, velocity and discharge in order for them to have meaning. It is not enough to say the pressure is high or the discharge is large; some specific value needs to be given to quantify it. Also, just providing a number is quite meaningless. To say a pipeline is 6 long is not enough. It might be 6 centimetres, 6 metres or 6 kilometres. So the numbers must have dimensions to give them some useful meaning.

Different units of measurement are used in different parts of the world. The foot, pounds and second system (known as fps) is still used extensively in the USA and to some extent in the UK. The metric system, which relies on centimetres, grammes and seconds (known as cgs), is widely used in continental Europe. But in engineering and hydraulics the most common units are those in the SI system and it is this system which is used throughout this book.

### *1.2.1 SI units*

The Systeme International d'Unites, usually abbreviated to SI, is not difficult to grasp and it has many advantages over the other systems. It is based on metric measurement and is slowly replacing the old fps system and the European cgs system. All length measurements are in metres, mass is in kilograms and time is in seconds (Table 1.1). SI units are simple to use and their big advantage is they can help to avoid much of the confusion which surrounds the use of other units. For example, it is quite easy to confuse mass and weight in both fps and cgs units as they are both measured in pounds in fps and in kilograms in cgs. Any mix-up between them can have serious consequences for the design of engineering works. In the SI system the difference is clear because they have different dimensions – mass is in kilograms whereas weight is in Newtons. This is discussed later in Section 1.7.

Table 1.1 Basic SI units of measurement.

| *Measurement* | *Unit* | *Symbol* |
|---|---|---|
| Length | Metre | m |
| Mass | Kilogram | kg |
| Time | Second | s |

Table 1.2 Some useful derived units.

| *Measurement* | *Dimension* | *Measurement* | *Dimension* |
|---|---|---|---|
| Area | $m^2$ | Force | N |
| Volume | $m^3$ | Mass density | $kg/m^3$ |
| Velocity | m/s | Specific weight | $N/m^3$ |
| Acceleration | $m/s^2$ | Pressure | $N/m^2$ |
| Viscosity | kg/ms | Momentum | kgm/s |
| Kinematic viscosity | $m^2/s$ | Energy for solids | Nm/N |
| | | Energy for fluids | Nm/N |

Note there is no mention of centimetres in Table 1.1. Centimetres are part of the cgs units and not SI and so play no part in hydraulics or in this text. Millimetres are acceptable for very small measurements and kilometres for long lengths – but *not* centimetres.

### *1.2.2 Dimensions*

Every measurement must have a dimension so that it has meaning. The units chosen for measurement do not affect the quantities measured and so, for example, 1.0 metre is exactly the same as 3.28 feet. However, when solving problems, all the measurements used must be in the same system of units. If they are mixed up (e.g. centimetres or inches instead of metres, or minutes instead of seconds) and added together, the answer will be meaningless. Some useful dimensions which come from the SI system of units in Table 1.1 are included in Table 1.2.

## 1.3 Velocity and acceleration

In everyday language *velocity* is often used in place of *speed*. But they are different. Speed is the rate at which some object is travelling and is measured in metres/second (m/s) but there is no indication of the direction of travel. Velocity is speed plus direction. It defines movement in a particular direction and is also measured in metres/second (m/s). In hydraulics, it is useful to know which direction water is moving and so the term velocity is used instead of speed. When an object travels a known distance and the time taken to do this is also known, then the velocity can be calculated as follows:

$$\text{velocity (m/s)} = \frac{\text{distance (m)}}{\text{time (s)}}$$

*Acceleration* describes change in velocity. When an object's velocity is increasing then it is *accelerating*; when it is slowing down it is *decelerating.* Acceleration is measured in metres/second/

second (m/s$^2$). If the initial and final velocities are known as well as the time taken for the velocity to change then the acceleration can be calculated as follows:

$$\text{acceleration (m/s}^2) = \frac{\text{change in velocity (m/s)}}{\text{time (s)}}$$

**EXAMPLE: CALCULATING VELOCITY AND ACCELERATION**

An object is moving along at a steady velocity and it takes 150 s to travel 100 m. Calculate the velocity.

$$\text{velocity} = \frac{\text{distance (m)}}{\text{time (s)}} = \frac{100}{150} = 0.67 \text{ m/s}$$

If the object starts from rest, calculate the acceleration if its final velocity of 1.5 m/s is reached in 50 s:

$$\text{acceleration} = \frac{\text{change in velocity (m/s)}}{\text{time (s)}} = \frac{1.5-0}{50} = 0.03 \text{ m/s}^2$$

## 1.4 Forces

Force is not a word that can be easily described in the same way as some material object. It is commonly used and understood to mean a pushing or a pulling action and so it is only possible to say what a force will do and not what it is. Using this idea, if a force is applied to some stationary object then, if the force is large enough, the object will begin to move. If the force is applied for long enough then the object will begin to move faster, that is, it will accelerate. The same applies to water and to other fluids as well. It may be difficult to think of pushing water, but, if it is to flow along a pipeline or a channel, a force will be needed to move it. So one way of describing force is to say that *a force causes movement.*

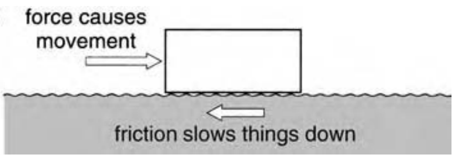
## 1.5 Friction

Friction is the name given to the force which resists movement and so causes objects to slow down (Figure 1.1a). It is an important aspect of all our daily lives. Without friction between our feet and the ground surface it would be difficult to walk and we are reminded of this each time we step onto ice or some smooth oily surface. We would not be able to swim if water was frictionless. Our arms would just slide through the water and we would not make any headway – just like children trying to 'swim' in a sea of plastic balls in the playground (Figure 1.1b).

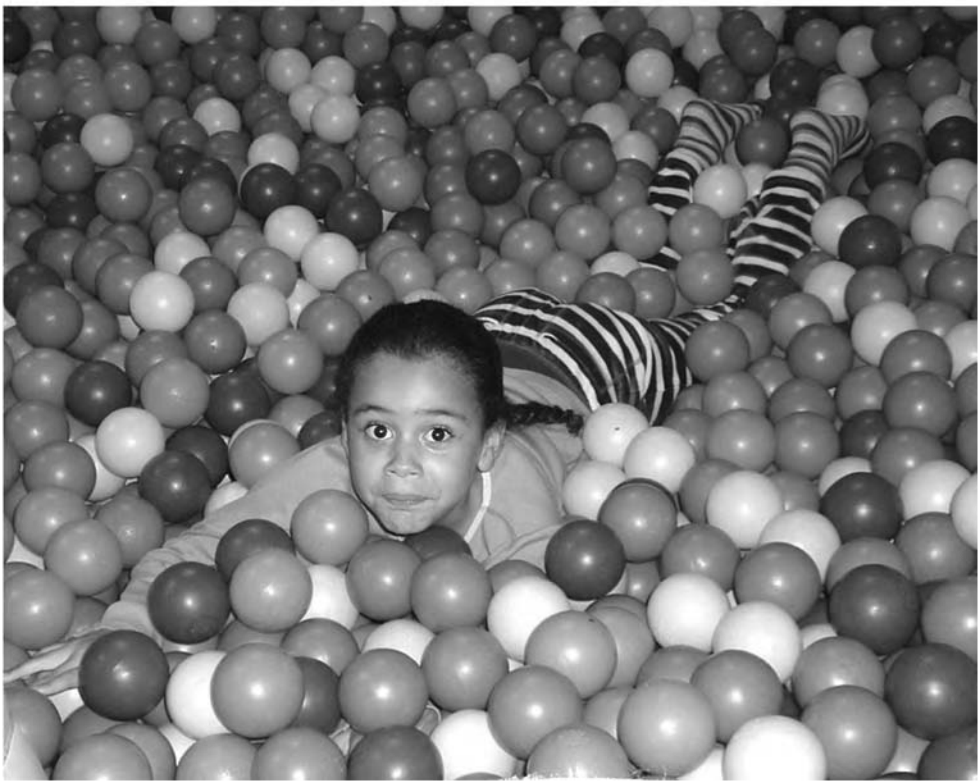
Friction is an essential part of our existence but sometimes it can be a nuisance. In car engines, for example, friction between the moving parts would cause them to quickly heat up and the engine would seize up. But oil lubricates the surfaces and reduces the friction.

Friction also occurs in pipes and channels between flowing water and the internal surface of a pipe or the bed and sides of a channel. Indeed, much of pipe and channel hydraulics is concerned with predicting this friction force so that the right size of pipe or channel can be chosen to carry a given flow (see Chapter 4 Pipes and Chapter 5 Channels).

(a)




(b)



1.1 (a) Friction resists movement and (b) Trying to 'swim in a frictionless fluid'.

Friction is not only confined to boundaries, there is also friction inside fluids (internal friction) which makes some fluids flow more easily than others. The term *viscosity* is used to describe this internal friction (see Section 1.13.3).

## 1.6 Newton's laws of motion

Sir Isaac Newton (1642–1728) was one of the first to begin the study of forces and how they cause movement. His work is now enshrined in three basic rules known as *Newton's laws of motion.* They are very simple laws and at first sight they appear so obvious, they seem hardly worth writing down. But they form the basis of all our understanding of hydraulics (and movement of solid objects as well) and it took the genius of Newton to recognise their importance.

### *Law 1: forces cause movement*

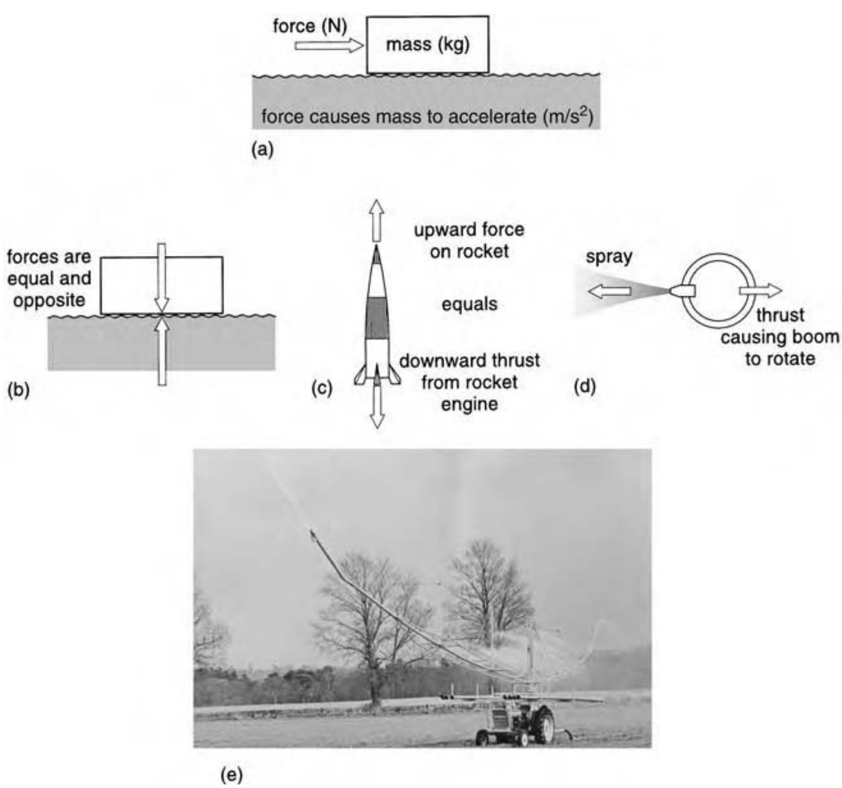
First imagine this in terms of solid objects. A block of wood placed on a table will stay there unless it is pushed (i.e. a force is applied to it). Equally, if it is moving, it will continue to move unless some force (e.g. friction) causes it to slow down or to change direction. So forces are needed to make objects move or to stop them. This same law also applies to water.

### *Law 2: forces cause objects to accelerate*

This law builds on the first and provides the link between force, mass and acceleration (Figure 1.2a). Again think in solid material terms first. If the block of wood is to move it will need a force to do it. The size of this force depends on the size of the block (its mass) and how fast it needs to go (its acceleration). The larger the block and the faster it must go, the larger must be the force. Water behaves in the same way. If water is to be moved along a pipeline then some force will be needed to do it. Newton linked these three together in mathematical terms to calculate the force required:

force (N) = mass (kg) $\times$ acceleration (m/s$^2$)

The dimension of force can be derived from multiplying mass and acceleration, that is, kgm/s$^2$. But this is a complicated dimension and so in the SI system it is simplified and called the




1.2 Newton's laws of motion.

*Newton* (N) in recognition of Sir Isaac Newton's contribution to our understanding of mechanics. A force of 1 Newton is defined as the force needed to cause a mass of 1 kg to accelerate at 1 m/s$^2$. This is not a large force. An apple held in the palm of your hand weighs approximately 1 Newton – an interesting point, since it was supposed to have been an apple falling on Newton's head, which set off his thoughts on forces, gravity and motion.

Using Newtons in hydraulics will produce some very large numbers and so to overcome this, forces are measured in kilo Newtons (kN).

1 kN = 1000 N

**EXAMPLE: CALCULATING FORCE USING NEWTON'S SECOND LAW**

A mass of 3 kg is to be moved from rest to reach a speed of 6 m/s and this must be done in 10 s. Calculate the force needed.
First calculate acceleration:

$$\text{acceleration (m/s}^2\text{)} = \frac{\text{change in velocity (m/s)}}{\text{time (s)}}$$

$$\text{acceleration} = \frac{6}{10} = 0.6 \text{ m/s}^2$$

Using Newton's second law:

force = mass × acceleration
force = 3 × 0.6 = 1.8 N

So a force of 1.8 N is needed to move a mass of 3 kg to a velocity of 6 m/s in 10 s.

### *Law 3: for every force there is always an equal and opposite force*

To understand this simple but vitally important law, again think of the block of wood sitting on a table (Figure 1.2b). The block exerts a force (its weight) downwards on the table; but the table also exerts an equal but opposite upward force on the block. If it did not, the block would drop down through the table under the influence of gravity. So there are two forces, exactly equal in magnitude but in opposite directions and so the block does not move.

The same idea can be applied to moving objects as well. In earlier times it was thought that objects were propelled forward by the air rushing in behind them. This idea was put forward by the Greeks but it failed to show how an object could be propelled in a vacuum as is the case when a rocket travels into space. What in fact happens is the downward thrust of the burning fuel creates an equal and opposite thrust which pushes the rocket upwards (Figure 1.2c). Newton helped to discredit the Greek idea by setting up an experiment which showed that rather than encourage an object to move faster, the air (or water) flow around it slowed it down because of the friction between the object and the air.

Another example of Newton's third law occurs in irrigation where rotating booms spray water over crops (Figure 1.2d). The booms are not powered by a motor but by the reaction of the water jets. As water is forced out of the nozzles along the boom it creates an equal and opposite force on the boom itself which causes it to rotate. The same principle is used to drive the water distrubutors on the circular water-cleaning filters at the sewage works.

## 1.7 Mass and weight

There is often confusion between mass and weight and this has not been helped by the system of units used in the past. It is also not helped by our common use of the terms in everyday language. Mass and weight have very specific scientific meanings and for any study of water it is essential to have a clear understanding of the difference between them.

*Mass refers to an amount of matter or material.* It is a constant value and is measured in kilograms (kg). A specific quantity of matter is often referred to as an *object*. Hence the use of this term in the earlier description of Newton's laws.

*Weight is a force.* Weight is a measure of the force of gravity on an object and this will be different from place to place depending on the gravity. On the earth there are only slight variations in gravity, but the gravity on the moon is much less than it is on the earth. So the mass of an object on the moon would be the same as it is on the earth but its weight would be much less. As weight is a force, it is measured in Newtons. This clearly distinguishes it from mass which is measured in kilograms.

Newton's second law also links mass and weight and in this case the acceleration term is the acceleration resulting from gravity. This is the acceleration that any object experiences when dropped and allowed to fall to the earth's surface. Objects dropped in the atmosphere do, in fact, experience different rates of acceleration because of the resistance of the air – hence the reason why a feather falls more slowly than a coin. But if both were dropped at the same time in a vacuum they would fall (accelerate) at the same rate. There are also minor variations over the earth's surface and this is the reason why athletes can sometimes run faster or throw the javelin further in some parts of the world. However, for engineering purposes, acceleration due to gravity is assumed to have a constant value of 9.81 $m/s^2$ – usually called the *gravity constant* and denoted by the letter *g*. The following equation based on Newton's second law provides the link between weight and mass:

$$\text{weight (N)} = \text{mass (kg)} \times \text{gravity constant } (m/s^2)$$

**EXAMPLE: CALCULATING THE WEIGHT OF AN OBJECT**

Calculate the weight of an object when its mass is 5 kg.
Using Newton's second law:

$$\text{weight} = \text{mass} \times \text{gravity constant}$$
$$\text{weight} = 5 \times 9.81 = 49.05 \text{ N}$$

Sometimes engineers assume that the gravity constant is 10 $m/s^2$ because it is easier to multiply by 10 and the error involved in this is not significant in engineering terms.
In this case:

$$\text{weight} = 5 \times 10 = 50 \text{ N}$$

Confusion between mass and weight occurs in our everyday lives. When visiting a shop and asking for 5 kg of potatoes these are duly weighed out on a weigh balance. To be strictly correct we should ask for 50 N of potatoes, as the balance is measuring the *weight* of the potatoes (i.e. the force of gravity) and not their mass. But because gravity acceleration is constant all over the world (or nearly so for most engineering purposes) the conversion factor between mass and weight is a constant value. So the shopkeeper's balance will most likely show kilograms and not Newtons. If shopkeepers were to change their balances to read in Newtons to resolve a scientific confusion, engineers and scientists might be happy but no doubt a lot of shoppers would not be so happy!

## 1.8 Scalar and vector quantities

Measurements in hydraulics are either called *scalar* or *vector* quantities. Scalar measurements only indicate magnitude. Examples of this are mass, volume, area and length. So if there are 120 boxes in a room and they each have a volume of 2 $m^3$ both the number of boxes and the volume of each are scalar quantities.

Vectors have direction as well as magnitude. Examples of vectors include force and velocity. It is just as important to know which direction forces are pushing and water is moving as well as their magnitude.

## 1.9 Dealing with vectors

Scalar quantities can be added together by following the rules of arithmetic. Thus, 5 boxes and 4 boxes can be added to make 9 boxes and 3 m and 7 m can be added to make 10 m.

Vectors can also be added together provided their direction is taken into account. The addition (or subtraction) of two or more vectors results in another single vector called the *resultant* and the vectors that make up the resultant are called the *components*. If two forces, 25 N and 15 N, are pushing in the same direction then their resultant is found simply by adding the two together, that is, 40 N (Figure 1.3a). If they are pushing in opposite directions then their resultant is found by subtracting them, that is, 10 N. So one direction is considered positive and the opposite direction negative for the purposes of combining vectors.

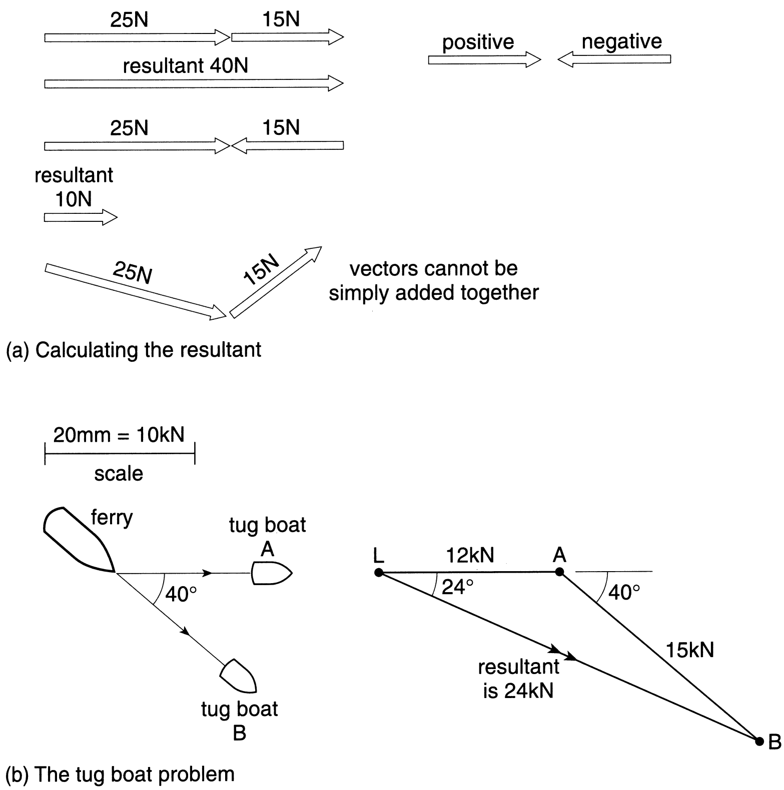
But forces can also be at an angle to each other and in such cases a different way of adding or subtracting them is needed – a *vector diagram* is used for this purpose. This is a diagram drawn to a chosen scale to show both the magnitude and the direction of the vectors and hence the magnitude of the resultant vector. An example of how this is done is shown in the box.

Vectors can also be added and subtracted mathematically but a knowledge of trigonometry is needed. For those interested in this approach, it is described in most basic books on maths and mechanics.

**EXAMPLE: CALCULATING THE RESULTANT FORCE USING A VECTOR DIAGRAM**

Two tug boats A and B are pulling a large ferry boat into a harbour. Tug A is pulling with a force of 12 kN, tug B with a force of 15 kN and the angle between the two tow ropes is 40° (Figure 1.3b). Calculate the resultant force and show the direction in which the ferry boat will move.

First draw a diagram of the ferry and the two tugs. Then, assuming a scale of 40 mm equals 10 kN (this is chosen so that the diagram fits conveniently onto a sheet of paper)




1.3 Adding and subtracting vectors.

draw the 12 kN force to scale, that is, the line LA. Next, draw the second force, 15 kN, to the same scale but starting the line at A and drawing it at an angle of 40° to the first line. This 'adds' the second force to the first one. The resultant force is found by joining the points L and B, measuring this in mm and converting this to a value in kN using the scale. Its value is 24 kN. The line of the resultant is shown by the positioning of the line LB in the diagram.

To summarise, the ferry boat will move in a direction LB as a result of the pull exerted by the two tugs and the resultant force pulling on the ferry in that direction is 24 kN. The triangle drawn in Figure 1.3b is the *vector diagram* and shows how two forces can be added. As there are three forces in this problem it is sometimes called a *triangle of forces.* It is possible to add together many forces using the same technique. In such cases the diagram is referred to as a *polygon of forces.*

## 1.10 Work, energy and power

Work, energy and power are all words commonly used in everyday language, but in engineering and hydraulics they have very specific meanings and so it is important to clarify what each means.

### *1.10.1 Work*

Work refers to almost any kind of physical activity but in engineering it has a very specific meaning. Work is done when a force produces movement. A crane does work when it lifts a load against the force of gravity and a train does work when it pulls trucks. But if you hold a large weight for a long period of time you will undoubtedly get very tired and feel that you have done a lot of work but you will not have done any work at all in an engineering sense because nothing moved.

Work done on an object can be calculated as follows:

work done (Nm) = force (N) × distance moved by the object (m)

Work done is the product of force (N) and distance (m) so it is measured in Newton-metres (Nm).

### *1.10.2 Energy*

Energy enables useful work to be done. People and animals require energy to do work. They get this by eating food and converting it into useful energy for work through the muscles of the body. Energy is also needed to make water flow and this is why reservoirs are built in mountainous areas so that the natural energy of water can be used to make it flow downhill to a town or to a hydro-electric power station. In many cases energy must be added to water to lift it from a well or a river. This can be supplied by a pumping device driven by a motor using energy from fossil fuels such as diesel or petrol. Solar and wind energy are alternatives and so is energy provided by human hands or animals.

The amount of energy needed to do a job is determined by the amount of work to be done. So that:

energy required = work done

so

energy required (Nm) = force (N) × distance (m)

Energy, like work, is measured in Newton-metres (Nm) but the more conventional measurement of energy is *watt-seconds* (Ws) where:

1 Ws = 1 Nm

But this is a very small quantity for engineers to use and so rather than calculate energy in large numbers of Newton-metres or watt-seconds they prefer to use *watt-hours* (Wh) or *kilowatt-hours* (kWh). So multiply both sides of this equation by 3600 to change seconds to hours:

1 Wh = 3600 Nm

Now multiply both sides by 1000 to change watts-hours to kilowatt-hours (Wh to kWh):

1 kWh = 3 600 000 Nm
= 3600 kNm

Just to add to the confusion some scientists measure energy in *joules* (J). This is in recognition of the contribution made by the English physicist, James Joule (1818–1889) to our understanding of energy, in particular, the conversion of mechanical energy to heat energy (see next section).

So for the record:

1 joule = 1 Nm

To avoid confusion the term joule is not used in this text. Some everyday examples of energy use include:

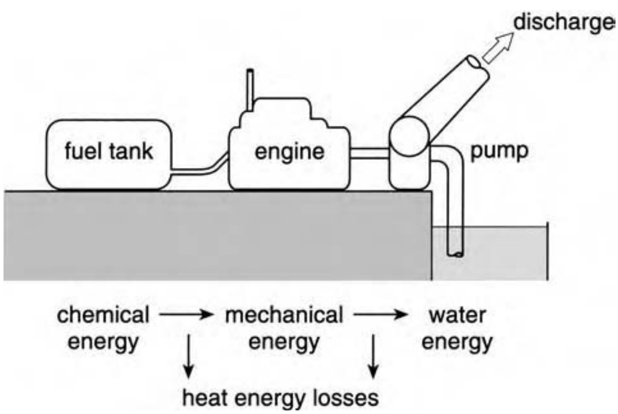
- A farmer working in the field uses 0.2–0.3 kWh every day.
- An electric desk fan uses 0.3 kWh every hour.
- An air-conditioner uses 1 kWh every hour.

Notice how it is important to specify the time period (e.g. every hour, every day) over which the energy is used. Energy used for pumping water is discussed more fully in Chapter 8.

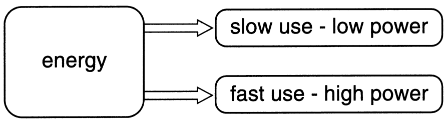
### *1.10.2.1 Changing energy*

An important aspect of energy is that it can be changed from one form to another. People and animals are able to convert food into useful energy to drive their muscles. The farmer using 0.2 kWh every day, for example, must eat enough food each day to supply this energy need otherwise the farmer would not be able to work properly. In a typical diesel engine pumping system, the energy is changed several times before it gets to the water. Chemical energy contained within the fuel (e.g. diesel oil) is burnt in a diesel engine to produce mechanical energy. This is converted to useful water energy via the drive shaft and pump (Figure 1.4). So a pumping unit is both an energy converter as well as a device for adding energy into a water system.

The system of energy transfer is not perfect and energy losses occur through friction between the moving parts and is usually lost as heat energy. These losses can be significant and costly in terms of fuel use. For this reason it is important to match a pump and its power unit with the job to be done to maximise the efficiency of energy use (see Chapter 8).




1.4 Changing energy from one form to another.




1.5 Power is the rate of energy use.

### *1.10.3 Power*

Power is often confused with the term energy. They are related but they have different meanings. Whilst energy is the capacity to do useful work, power is the rate at which the energy is used (Figure 1.5).
And so:

$$\text{power (kW)} = \frac{\text{energy (kWh)}}{\text{time (h)}}$$

Examples of power requirements, a typical room air-conditioner has a power rating of 3 kW. This means that it consumes 3 kWh of energy every hour it is working. A small electric radiator has a rating of 1–2 kW and the average person walking up and down stairs has a power requirement of about 70 W.

Energy requirements are sometimes calculated from knowing the equipment power rating and the time over which it is used rather than trying to calculate it from the work done. In this case:

$$\text{energy (kWh)} = \text{power (kW)} \times \text{time (h)}$$

*Horse Power* (HP) is still a very commonly used measure of power but it is not used in this book, as it is not an SI unit. However, for the record:

$$1 \text{ kW} = 1.36 \text{ HP}$$

Power used for pumping water is discussed more fully in Chapter 8.

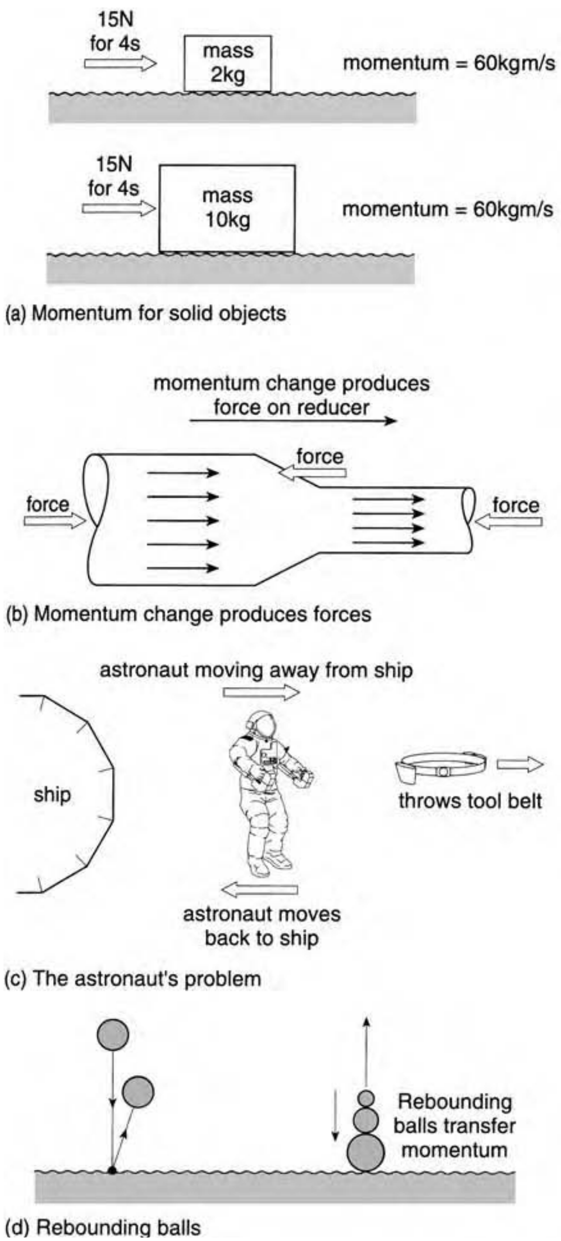
## 1.11 Momentum

Applying a force to a mass causes it to accelerate (Newton's second law) and the effect of this is to cause a change in velocity. This means there is a link between mass and velocity and this is called *momentum*. Momentum is another scientific term that is used in everyday language to describe something that is moving – we say that some object or a football game has momentum if it is moving along and making good progress. In engineering terms it has a specific meaning and it can be calculated by multiplying the mass and the velocity together:

$$\text{momentum (kgm/s)} = \text{mass (kg)} \times \text{velocity (m/s)}$$

Note the dimensions of momentum are a combination of those of velocity and mass.

The following example demonstrates the links between force, mass and velocity. Figure 1.6 shows two blocks that are to be pushed along by applying a force to them. Imagine that the sliding surface is very smooth and so there is no friction.




1.6 Understanding momentum.

The first block of mass 2 kg is pushed by a force of 15 N for 4 s. Using Newton's second law the acceleration and the resulting velocity after a period of 4 s can be calculated:

$$\text{force} = \text{mass} \times \text{acceleration}$$
$$15 = 2 \times f$$
$$f = 7.5 \text{ m/s}^2$$

So for every second the force is applied the block will move faster by 7.5 m/s. After 4 s it will have reached a velocity of:

$$4 \times 7.5 = 30 \text{ m/s}$$

Calculate the momentum of the block:

$$\begin{aligned} \text{momentum} &= \text{mass} \times \text{velocity} \\ &= 2 \times 30 \\ &= 60 \text{ kgm/s} \end{aligned}$$

Now hold this information for a moment. Suppose a larger block of mass 10 kg is pushed by the same force of 15 N for the same time of 4 s. Use the same calculations as before to calculate the acceleration and the velocity of the block after 4 s:

$$15 = 10 \times f$$

And so:

$$f = 1.5 \text{ m/s}^2$$

So when the same force is applied to this larger block it accelerates more slowly at 1.5 m/s for every second the force is applied. After 4 s it will have a velocity of:

$$4 \times 1.5 = 6 \text{ m/s}$$

Now calculate momentum of this block:

$$\begin{aligned} \text{momentum} &= 10 \times 6 \\ &= 60 \text{ kgm/s} \end{aligned}$$

Although the masses and the resulting accelerations are very different the momentum produced in each case when the same force is applied for the same time period is the same.

Now multiply the force by the time:

$$\begin{aligned} \text{force} \times \text{time} &= 15 \times 4 \\ &= 60 \text{ Ns} \end{aligned}$$

But the dimension for Newtons can also be written as kgm/s$^2$. And so:

$$\text{force} \times \text{time} = 60 \text{ kgm/s}$$

This is equal to the momentum and has the same dimensions. It is called the *impulse* and it is equal to the momentum it creates. So:

$$\text{impulse} = \text{momentum}$$

And:

$$\text{force} \times \text{time} = \text{mass} \times \text{velocity}$$

This is more commonly written as:

impulse = change of momentum

Writing 'change in momentum' is more appropriate because an object need not be starting from rest – it may already be moving. In such cases the object will have some momentum and an impulse would be increasing (changing) it. A momentum change need not be just a change in velocity but also a change in mass. If a lorry loses some of its load when travelling at speed its mass will change. In this case the lorry would gain speed as a result of being smaller in mass, the momentum before being equal to the momentum after the loss of load.

The equation for momentum change becomes:

force × time = mass × change in velocity

This equation works well for solid blocks which are forced to move but it is not easily applied to flowing water in its present form. For water it is better to look at the rate at which the water mass is flowing rather than thinking of the flow as a series of discrete solid blocks of water. This is done by dividing both sides of the equation by time:

$$\text{force} = \frac{\text{mass}}{\text{time}} \times \text{change in velocity}$$

Mass divided by time is the mass flow in kg/s and so the equation becomes:

force (N) = mass flow (kg/s) × change in velocity (m/s)

So when flowing water undergoes a change of momentum either by a change in velocity or a change in mass flow (e.g. water flowing around a pipe bend or through a reducer) then a force is produced by that change (Figure 1.6b). Equally if a force is applied to water (e.g. in a pump or turbine) then the water will experience a change in momentum.

As momentum is about forces and velocities the direction in which momentum changes is also important. In the simple force example, the forces are pushing from left to right and so the movement is from left to right. This is assumed to be the positive direction. Any force or movement from right to left would be considered negative. So if several forces are involved they can be added or subtracted to find a single resultant force. Another important point to note is that Newton's third law also applies to momentum. The force on the reducer (Figure 1.6b) could be drawn in either direction. In the diagram the force is shown in the negative direction (right to left) and this is the force that the reducer exerts on the water. Equally it could be drawn in the opposite direction, that is, the positive direction (left to right) when it would be the force of the water on the reducer. Either way the two forces are equal and opposite as Newton’s third law states.

The application of this idea to water flow is developed further in Section 4.1.3.

Those not so familiar with Newton's laws might find momentum more difficult to deal with than other aspects of hydraulics. To help understand the concept here are two interesting examples of momentum change which may help.

### *1.11.1 The astronaut's problem*

An astronaut has just completed a repair job on his space ship and secures his tools on his belt. He then pushes off from the ship to drift in space only to find that his life-line has come undone and he is drifting further and further away from his ship (Figure 1.6c). How can he get back? He could radio for help, but another solution would be to take off his tool belt and throw it as hard as he can in the direction he is travelling. The reaction from this will be to propel him in the opposite direction and back to his space ship. The momentum created by throwing the tool belt in one direction (i.e. mass of tool belt multiplied by velocity of tool belt) will be matched by momentum in the opposite direction (i.e. mass of spaceman multiplied by velocity of spaceman). His mass will be much larger than the tool belt and so his velocity will be smaller but at least it will be in the right direction!

### *1.11.2 Rebounding balls*

Another interesting example of momentum change occurs when several balls are dropped onto the ground together (Figure 1.6d). If dropped individually they rebound to a modest height – less than the height from which they were dropped. If several balls, each one slightly smaller than the previous one, are now dropped together, one on top of the other, the top one will shoot upwards at an alarming velocity to a height far greater than any of the individual balls. The reason for this is the first ball rebounds on impact with the ground and hits the second ball and the second ball hits the third and so on. Each ball transfers its momentum to the next one. If it was possible to drop eight balls onto each other in this way the top ball would reach a velocity of 10 000 m/s. This would be fast enough to put it into orbit if it did not vaporise from the heat created by friction as it went through in the earth's atmosphere! Eight balls may be difficult to manage but even with two or three the effect is quite dramatic. Try it with just two and see for yourself.

## 1.12 Properties of water

The following are some of the physical properties of water. This will be a useful reference for work in later chapters.

### *1.12.1 Density*

When dealing with solid objects their mass and weight are important, but when dealing with fluids it is much more useful to know about their *density.* There are two ways of expressing density; *mass density* and *weight density*. Mass density of any material is the mass of one cubic metre of the material and is a fixed value for the material concerned. For example, the mass density of air is 1.29 kg/m$^3$, steel is 7800 kg/m$^3$ and gold is 19 300 kg/m$^3$.

Mass density is determined by dividing the mass of some object by its volume:

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

Mass density is usually denoted by the Greek letter $\rho$ (rho).

For water the mass of one cubic metre of water is 1000 kg and so:

$$\rho = 1000 \text{ kg/m}^3$$

Density can also be written in terms of weight as well as mass. This is referred to as *weight density* but engineers often use the term *specific weight* ($w$). This is the weight of one cubic metre of water.

Newton's second law is used to link mass and weight:

weight density ($kN/m^3$) = mass density ($kg/m^3$) $\times$ gravity constant ($m/s^2$)

For water:

$$\begin{aligned}\text{weight density} &= 1000 \times 9.81\\ &= 9810\ \text{N/m}^3\ (\text{or } 9.81\ \text{kN/m}^3)\\ &= 10\ \text{kN/m}^3\ (\text{approximately})\end{aligned}$$

Sometimes weight density for water is rounded off by engineers to 10 $kN/m^3$. Usually this makes very little difference to the design of most hydraulic works. Note the equation for weight density is applicable to all fluids and not just water. It can be used to find the weight density of any fluid provided the mass density is known.

Engineers generally use the term specific weight in their calculations whereas scientists tend to use the term $\rho g$ to describe the weight density. They are in effect the same but for clarity, $\rho g$ is used throughout this book.

### 1.12.2 Relative density or specific gravity

Sometimes it is more convenient to use *relative density* rather than just density. It is more commonly referred to as *specific gravity* and is the ratio of the density of a material or fluid to that of some standard density – usually water. It can be written both in terms of the mass density and the weight density.

$$\text{specific gravity (SG)} = \frac{\text{density of an object (kg/m}^3)}{\text{density of water (kg/m}^3)}$$

Note that specific gravity has no dimensions. As the volume is the same for both the object and the water, another way of writing this formula is in terms of weight:

$$\text{specific gravity} = \frac{\text{weight of an object}}{\text{weight of an equal volume of water}}$$

Some useful specific gravity values are included in Table 1.3.

The density of any other fluid (or any solid object) can be calculated by knowing the specific gravity. The mass density of mercury, for example, can be calculated from its specific gravity:

$$\text{specific gravity of mercury (SG)} = \frac{\text{mass density of mercury (kg/m}^3)}{\text{mass density of water (kg/m}^3)}$$

Table 1.3 Some values of specific gravity.

| *Material/fluid* | *Specific gravity* | *Comments* |
|---|---|---|
| Water | 1 | All other specific gravity measurements are made relative to that of water |
| Oil | 0.9 | Less than 1.0 and so it floats on water |
| Sand/silt | 2.65 | Important in sediment transport problems |
| Mercury | 13.6 | Fluid used in manometers for measuring pressure |

So:

$$\text{mass density of mercury} = \text{SG of mercury} \times \text{mass density of water}$$
$$= 13.6 \times 1000$$
$$= 13\,600 \text{ kg/m}^3$$

The mass density of mercury is 13.6 times greater than that of water.

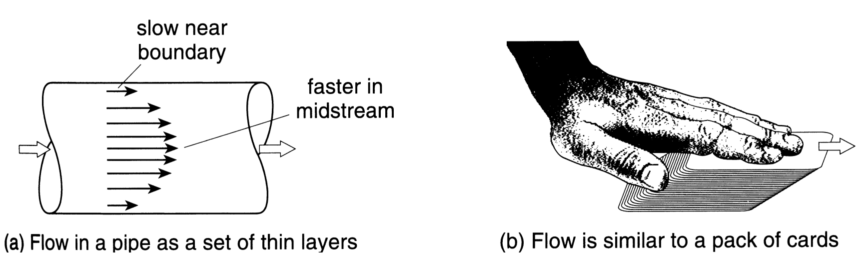
Archimedes used this concept of specific gravity in his famous principle (Table 1.3), which is discussed in Section 2.12.

### *1.12.3 Viscosity*

This is the friction force which exists inside a fluid as it flows. It is sometimes referred to as the *dynamic viscosity*. To understand the influence of viscosity imagine a fluid flowing along a pipe as a set of thin layers (Figure 1.7a). Although it cannot be seen and it is not very obvious, the layer nearest to the boundary actually sticks to it and does not slide along as the other layers do. The next layer away from the boundary is moving but is slowed down by friction between it and the first layer. The third layer moves faster but is slowed by the second. This effect continues until the entire flow is affected. It is similar to the sliding effect of a pack of playing cards (Figure 1.7b). This internal friction between the layers of fluid is known as the *viscosity*. Some fluids, such as water, have a low viscosity and this means the friction between the layers of fluid is low and its influence is not so evident when water is flowing. In contrast engine oils have a much higher viscosity and they seem to flow more slowly. This is because the internal friction is much greater.

One way to see viscosity at work is to try and pull out a spoon from a jar of honey. Some of the honey sticks to the spoon and some sticks to the jar, demonstrating that fluid sticks to the boundaries as referred to above. There is also a resistance to pulling out the spoon and this is the influence of viscosity. This effect is the same for all fluids including water but it cannot be so clearly demonstrated as in the honey jar. In fact, viscous resistance in water is ignored in many hydraulic designs. To take account of it not only complicates the problem but also has little or no effect on the outcome because the forces of viscosity are usually very small relative to other forces involved. When forces of viscosity are ignored the fluid is described as an *ideal fluid*.

Another interesting feature of the honey jar is that the resistance changes depending on how quickly the spoon is pulled out. The faster it is pulled the more resistance there is to the pulling. Newton related this rate of movement (the velocity) to the resistance and found they were proportional. This means the resistance increases directly as the velocity of the fluid increases. In other words the faster you try to pull the spoon out of the honey jar the greater will be the force required to do it. Most common fluids conform to this relationship and are still known today as *Newtonian fluids*.




1.7 Understanding viscosity.

Some modern fluids however, have different viscous properties and are called *non-Newtonian fluids*. One good example is tomato ketchup. When left on the shelf it is a highly viscous fluid which does not flow easily from the bottle. Sometimes you can turn a full bottle upside down and nothing comes out. But shake it vigorously (in scientific terms this means applying a shear force) its viscosity suddenly changes and the ketchup flows easily from the bottle. In other words, applying a force to a fluid can change its viscous properties often to our advantage.

Although viscosity is often ignored in hydraulics, life would be difficult without it. The spoon in the honey jar would come out clean and it would be difficult to get the honey out of the jar. Rivers rely on viscosity to slow down flows otherwise they would continue to accelerate to very high speeds. The Mississippi river would reach a speed of over 300 km/h as its flow gradually descends 450 m towards the sea if water had no viscosity. Pumps would not work because impellers would not be able to grip the water and swimmers would not be able to propel themselves through the water for the same reason.

Viscosity is usually denoted by the Greek letter (mu).

For water:

$$\mu = 0.00114 \text{ kg/ms at a temperature of } 15°\text{C}$$
$$= 1.14 \times 10^{3} \text{ kg/ms}$$

The viscosity of all fluids is influenced by temperature. Viscosity decreases with increasing temperature.

### 1.12.4 Kinematic viscosity

In many hydraulic calculations viscosity and mass density go together and so they are often combined into a term known as the *kinematic viscosity*. It is denoted by the Greek letter (nu) and is calculated as follows:

$$\text{kinematic viscosity } (\nu) = \frac{\text{viscosity } (\mu)}{\text{density } (\rho)}$$

For water:

$$\nu = 1.14 \times 10^{-2} \text{ m}^2\text{/s at a temperature of } 15°\text{C}$$

Sometimes kinematic viscosity is measured in Stokes in recognition of the work of Sir George Stokes who helped to develop a fuller understanding of the role of viscosity in fluids.

$$10^4 \text{ Stokes} = 1 \text{ m}^2\text{/s}$$

For water:

$$\nu = 1.14 \times 10^{-2} \text{ Stokes}$$

### 1.12.5 Surface tension

An ordinary steel sewing needle can be made to float on water if it is placed there very carefully. A close examination of the water surface around the needle shows that it appears to be sitting in a slight depression and the water behaves as if it is covered with an elastic skin. This property is known as *surface tension.* The force of surface tension is very small and is normally expressed in terms of force per unit length.

For water:

surface tension = 0.51 N/m at a temperature of 20°C

This force is ignored in most hydraulic calculations but in hydraulic modelling, where small-scale models are constructed in a laboratory to try and work out forces and flows in large, complex problems, surface tension may influence the outcome because of the small water depths and flows involved.

### *1.12.6 Compressibility*

It is easy to imagine a gas being compressible and to some extent some solid materials such as rubber. In fact all materials are compressible to some degree including water which is 100 times more compressible than steel! The compressibility of water is important in many aspects of hydraulics. Take for example the task of closing a sluice valve to stop water flowing along a pipeline. If the water was incompressible it would be like trying to stop a solid 40 ton truck. The water column would be a solid mass running into the valve and the force of impact could be significant. Fortunately water is compressible and as it impacts on the valve it compresses like a spring and this absorbs the energy of the impact. Returning to the road analogy, it is similar to what happens when cars crash on the road because of some sudden stoppage. Each car collapses on impact and this absorbs much of the energy of the collision. However, this is not the end of the story. As the water compresses the energy that is absorbed causes the water pressure to suddenly rise and this leads to another problem known as water hammer. This is discussed more fully in Section 4.16.