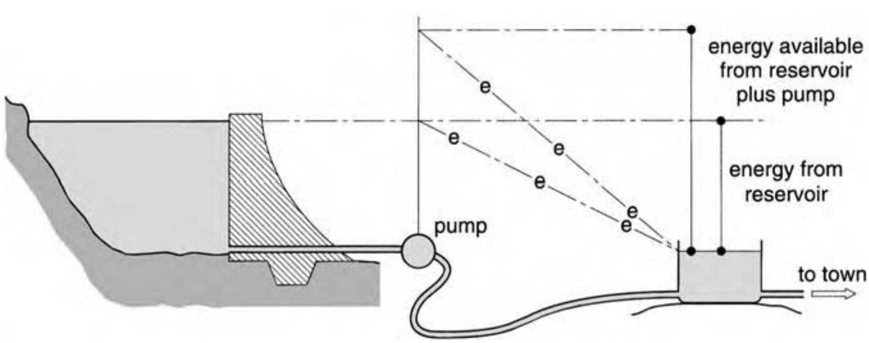
8 Pumps

8.1 Introduction

A few water supply systems have the benefit of a gravity supply but most require some kind of pumping. Pumps are a means of adding energy to water. They convert fuel energy, such as petrol or diesel, into useful water energy using combustion engines or electric motors. In the pipeline problem in Chapter 5 the energy to drive water along the pipeline to the town was obtained from a reservoir located high above the town. The energy line drawn from the reservoir to the town indicated the amount of energy available. Adding a pump to this system increases the available energy and raises the energy line so that the discharge from the reservoir to the town can be increased (Figure 8.1).

Pumps have been used for thousands of years. Early examples were largely small hand- or animal-powered pumps for lifting small quantities of water. It was not until the advent of the steam engine, only two centuries ago, that the larger rotating pumps were developed and became an important part of the study of hydraulics. Consequently there are two main types of pump:

- Positive displacement pumps – these are mainly small hand- and animal-powered pumps many of which are still used today;
- Roto-dynamic pumps – these are mainly the modern pumps driven by diesel or electric motors that are now in common use throughout the world.



8.1 Pumps add energy to pipe systems

Because of the similarities between pumps and turbines (used to generate energy) a small section is devoted to them at the end of this chapter.

8.2 Positive displacement pumps

Positive displacement pumps usually deliver small discharges over a wide range of pumping heads. Typical examples are hand-piston pumps, rotary pumps, air-lift pumps and Archimedean screws (Figure 8.2).

Hand-piston pumps are used extensively in developing countries for lifting groundwater for domestic water supplies. A pipe connects the pump to the water source – usually a well. At the end of this pipe is a non-return valve that only allows water to enter the pump and stops it from flowing back into the source. The pump itself comprises a piston and cylinder. These must have a very close fit so that when the piston is raised, it creates a vacuum in the cylinder and water is drawn up into the pump. When the piston is pushed down the water is pushed through a small valve in the piston to fill up the space above it. As the piston is raised again, it lifts the water above it so it pores out through the spout of the pump and into a tank or other water collecting device. The procedure is then repeated. The discharge from the pump depends on the energy available from those working the pump handle. You basically get out what you put in. The height to which water can be pumped in this way is fixed only by the strength of those pumping and the pump seals, which will start to leak when the pressure gets too high.

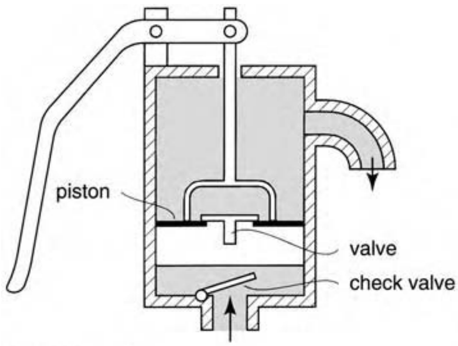
The rotary pump contains two gears that mesh together as they rotate in opposite directions. The liquid becomes trapped between the gears and is forced into the delivery pipe.

The air-lift pump uses an air compressor to force air down a pipe into the inlet of the water pipe. The mixture of air and water, which is less dense than the surrounding water in the well, then rises up above ground level. This pump is not very efficient but it will pump water that has sand and grit in it which would normally damage other pumps.

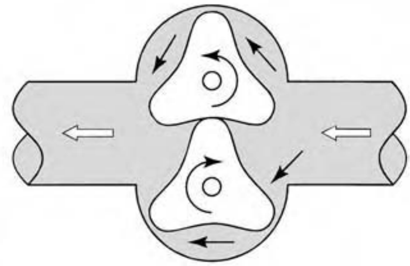
The Archimedean screw pump has been used for thousands of years and is still used today for pumping irrigation water in Egypt. It comprises a helical screw inside a casing. Water is lifted by turning the screw by hand. Some modern pumping stations also use this idea but the screws are much larger and are driven by a diesel or electric power unit.

The treadle pump is another example of positive displacement pump (Figure 8.3). It is growing in popularity in many developing countries because it enables poor farmers, who cannot afford a motor-driven pump, to use their human power to pump the large volumes of water needed for irrigating crops. It was first developed in Bangladesh in the early 1980s for irrigating flooded rice and it is now estimated that some two million pumps are in use throughout Asia. Their popularity has spread in recent years to sub-Saharan Africa. The designers of the treadle pump have skilfully adapted the principle of the hand-piston pump so that greater volumes of water can be lifted. Two pistons and cylinders are used to raise water instead of one. But the most important innovation was the change in driving power from arms and hands to legs and feet. Leg muscles are much more powerful than arm muscles and so they are capable of lifting much more water. The two cylinders 0.75 to 110 mm in diameter, are located side-by-side and a chain or rope, which passes over a pulley, connects the two pistons together so that when one piston is being pushed down, the other one is being raised. Each piston is connected to a treadle on which the operator stands and pushes them up and down in a rhythmic motion – like pushing peddles on a bicycle. This rhythmic method of driving the pump seems to have gained wide acceptance among farmers in the developing world.

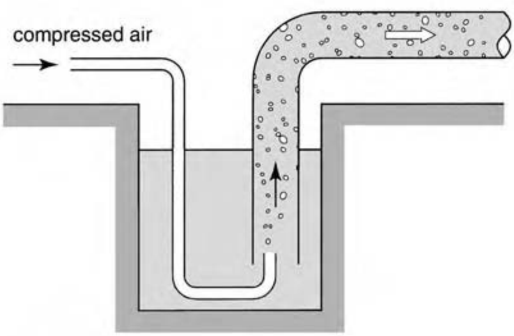
Although the pump is popular in several developing countries some exaggerated claims are often made about its physical performance, usually by those who have little knowledge of how



(a) Piston pump



(b) Rotary pump

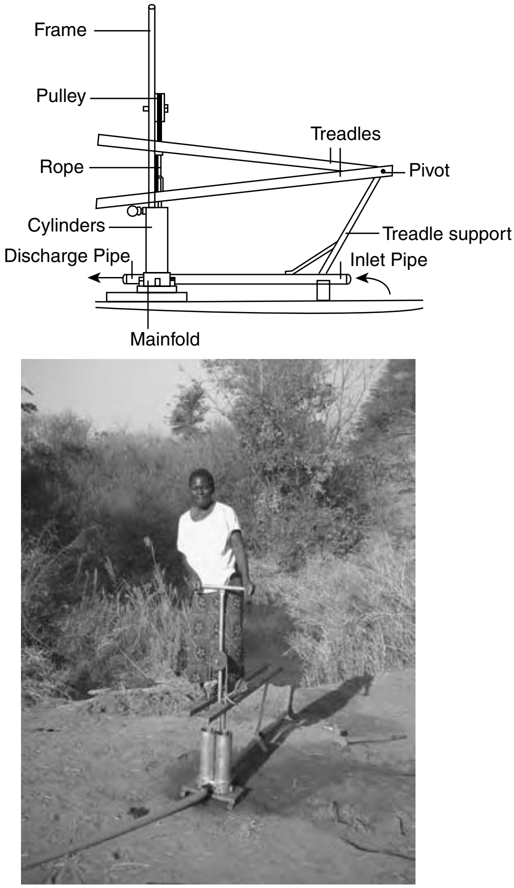


(c) Air-lift pump

(d) Archimedian screw pump in Egypt

(e) Hand pump in village in the Gambia

8.2 Positive displacement pumps.



8.3 Treadle pump.

the physical world works. Some claim it will deliver pressures up to 15 m and at the same time deliver discharges of 1–2 l/s and more as if it contains magical properties. Applying some simple hydraulic principles to this pump can dispel some of this magic and show just what it is capable of producing for a small farmer in a developing country (see box in Section 8.5). The reality is more like 0.6 l/s to 1.2 l/s with a head of 1–2 m. Like most things in life you can only get out of this pump what you are prepared to put into it in terms of power and energy – I am afraid there are no free lunches even in pumping.

Typically, one fit, male operator could irrigate up to 0.25 ha which can dramatically transform a family's livelihood from one of subsistence to one where there is a cash income from irrigated produce.

One final positive displacement pump worth mentioning is the heart which pushes blood around your body. The muscles around the heart contract and push blood into your arteries, which is your body's pipe system. It must create enough pressure to force blood to flow around your entire body with enough flow to carry all the nutrients your body needs. Problems of high blood pressure (known as hypertension) occur when the arteries (the pipe system) become restricted in some way. Your heart then increases the pressure to maintain circulation. Applying basic hydraulics to this – fatty deposits in your pipes (or arteries) increase pipe friction and can also reduce pipe diameters. Muscles surrounding the pipes are also known to contract and reduce pipe diameters. All these physical factors can push up the pumping pressure. Also the taller you are the more pressure your heart needs to produce to get blood to the top of your head and lift it back up from your feet to your heart. Flow in arteries is mostly laminar, although in the larger main artery near the heart it can be turbulent. This implies that friction loss in arteries is a function of viscosity rather than roughness and so anything that ‘thins’ blood (reduces its viscosity) should ease the flow. Some drugs are known to do this as well as others that stop blood clots and pipe blockages. Blood pressure-reducing drugs work in many different ways. Some slow down the heart rate, and others increase pipe diameters by reducing the squeezing effects of the muscles around them. But the process is not simply a physical one. It is a complex mixture of physical and biological processes and there is still a great deal not yet known about how these processes combine and work together. But basic hydraulics undoubtedly plays a part.

8.3 Roto-dynamic pumps

All roto-dynamic pumps rely on spinning an impeller or rotor for their pumping action. There are three main types that are described by the way in which water flows through them:

- centrifugal pumps
- mixed flow pumps
- axial flow pumps.

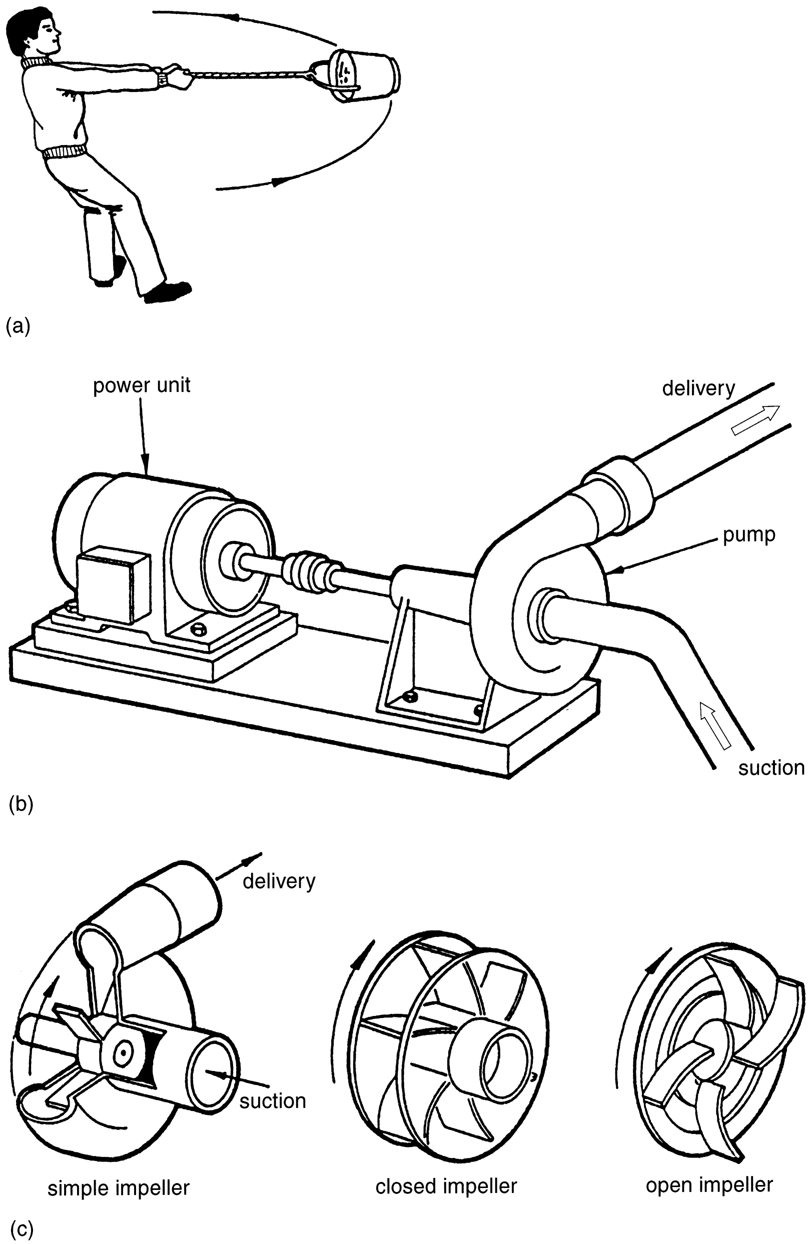
8.3.1 Centrifugal pumps

Centrifugal pumps are the most widely used of all the roto-dynamic pumps. The discharges and pressures they produce are ideally suited to water supply and irrigation schemes.

To understand how centrifugal pumps work, consider first how centrifugal forces occur. Most people will, at some time, have spun a bucket of water around at arm’s length and observed that water stays in the bucket even when it is upside down (Figure 8.4a). Water is held in the bucket by the centrifugal force created by spinning the bucket. The faster the bucket is spun the tighter the water is held. Centrifugal pumps make use of this idea (Figure 8.4b). The bucket is replaced by an *impeller* which spins at high speed inside a spiral casing. Water is drawn into the pump from the source of supply through a short length of pipe called the *suction*. As the impeller spins, water is thrown outwards and is collected by a spiral-shaped pump casing and guided towards the outlet. This is the *delivery* side of the pump.

The design of the impeller and the casing is important for efficient pump performance. As water enters the pump through the suction pipe the opening is small so velocity is high and, as a consequence of this, the pressure is low (think about the energy equation). As the flow moves through the pump and up between the blades of the impeller the flow gradually expands. This causes the velocity to fall and the pressure to rise again. It is important at this stage to recover as much pressure energy as possible and not to lose energy through friction and turbulence. This is achieved by carefully shaping the impeller blades and the spiral pump casing so that the movement of water is as ‘streamline’ as possible. Any sudden change in change in shape would create a great deal of turbulence, which would dissipate the water energy instead of increasing the pressure.

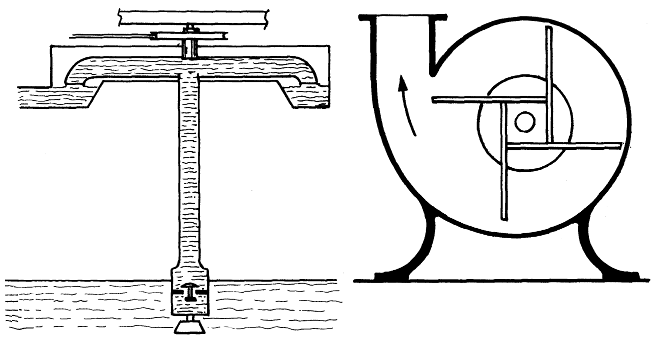
Some pumps have very simple impellers with straight blades (Figure 8.4c), but these create a lot of turbulence in the flow and so pressure recovery is not so good. Energy losses tend to be high and the efficiency is poor. From a practical point of view pumps like this are cheap to make and are used where efficiency is not so important such as in domestic washing machines.



8.4 Centrifugal pumps.

Larger pumps need more careful design and have curved vanes so that the water enters and leaves the impeller smoothly. This ensures that energy losses are kept to a minimum and a high level of efficiency of energy and power use can be achieved. Most impellers have side plates and are called *closed impellers*. When there is debris in the water *open impellers* are used to reduce the risk of blockage.

Centrifugal pumps are very versatile and can be used for a wide variety of applications. They can deliver water at low heads of just a few metres up to 100 m or more. The discharge range is



8.5 Early examples of roto-dynamic pumps.

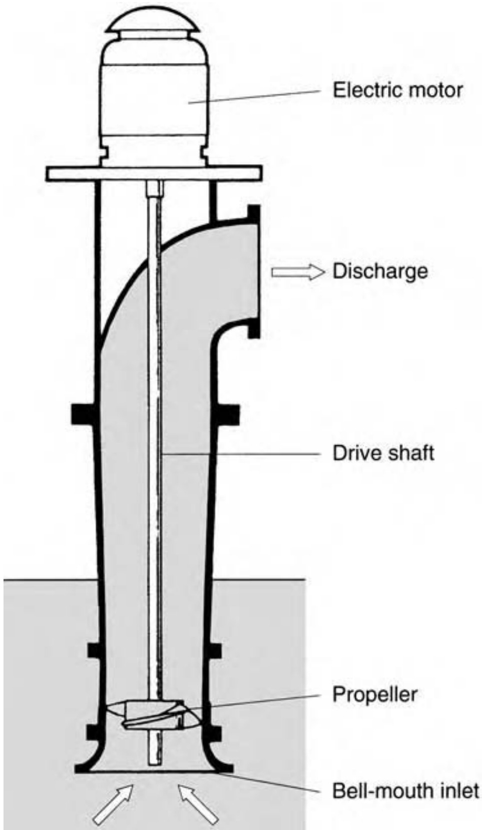
also high, from a few litres per second up to several cubic metres per second. Higher discharges and pressures are achieved by running several pumps together (see Section 8.10) or by using a multi-stage pump. This comprises several impellers on a shaft, driven by the same motor. Water is fed from the outlet of one stage into the inlet of the next impeller, increasing the pressure at each stage. Multi-stage pumps are commonly used in boreholes for lifting groundwater.

From a historical perspective one of the earliest centrifugal pumps was developed in the late 18th century and used a spinning pipe that discharged into a semi-circular collecting channel (Figure 8.5). Once the pipe was filled with water (primed) and was spinning, water was continually drawn up the tube and discharged into the collecting channel. Another, the Massachusetts pump built in 1818, comprised a set of simple straight blades mounted on a horizontal shaft surrounded by a collecting case that directed the velocity of the water up the discharge pipe. This looks similar in some respects to modern centrifugal pumps but it differs in one important aspect. In this and other earlier pumps the water leaves the pump impeller at high speed and friction is left to do the job of slowing down the water once it leaves the pump. This means that they were not very efficient at transferring energy and power to the water and so their performance was rather poor.

It was the application of the energy equation to pumps that revolutionised pump design and performance. This was the realisation that when water is flowing in a pipe, pressure can be converted to velocity and vice-versa. It is well known that pressure is needed to produce a high velocity jet of water but what was not so obvious was that the pressure can be recovered if the water jet is slowed down in a smooth manner. This was the understanding that was missing in the early pumps. Designers knew that the spinning action would speed up the water but they did not realise that pressure could be recovered again by smoothly slowing the water down. It is the recovery of pressure energy that marks out the design of modern pumps.

8.3.2 Axial flow pumps

Axial flow pumps consist of a propeller housed inside a tube that acts as a discharge pipe (Figure 8.6). The power unit turns the propeller by means of a long shaft running down the middle of the pipe and this lifts the water up the pipe. These pumps are very efficient at lifting large volumes of water at low pressure. They are ideally suited for lifting water from rivers or lakes into canals for irrigation and for land drainage where large volumes of water need to be lifted through a few metres. However, they tend to be very expensive because of the high cost of materials, particularly the drive shaft and bearings to support the shafted propeller. For this reason they tend only to be used for large pumping works.



8.6 Axial flow pump.

8.3.3 Mixed flow pumps

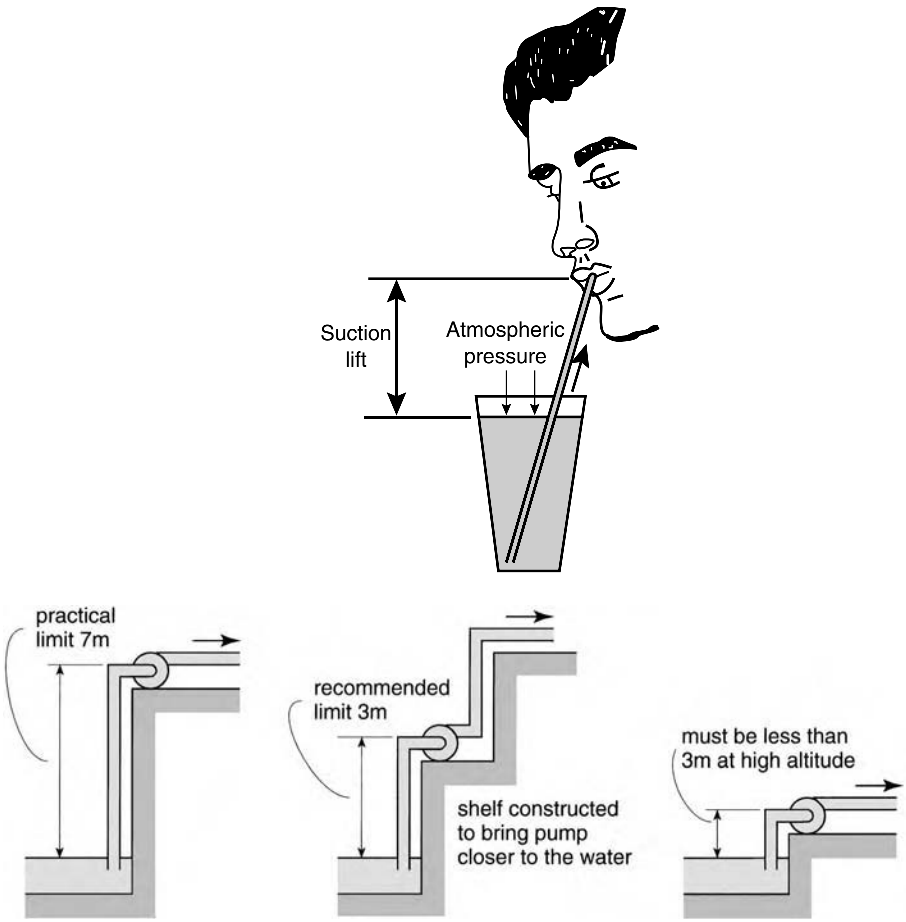
These pumps are a mixture of axial flow and centrifugal pumps and so combine the best features of both pump types. Mixed flow pumps are more efficient at pumping larger quantities of water than centrifugal pumps and are more efficient at pumping to higher pressures than axial flow pumps.

8.4 Pumping pressure

8.4.1 Suction lift

Pumps are usually located above the water source for the convenience of the users and this leads to the idea that pumps must 'suck' up water from the source before lifting it to some higher level. But this idea and the word 'sucking' can lead to misunderstandings about how pumps work (Figure 8.7).

'Sucking' water up a drinking straw is very similar to the way a pump draws water from a source. However, you do not actually suck up the water, you suck out the air from the straw and create a vacuum. Atmospheric pressure does the rest. It pushes down on the water surface in the glass and forces water up the straw to fill the vacuum. So atmospheric pressure provides the driving force but it also puts a limit on how high water can be lifted in this way. It does not depend on the ability of the sucker. At sea level, atmospheric pressure is approximately 10 m



8.7 Pump suction.

head of water and so if you were relying on a straw 10.1 m long for your water needs you would surely die of thirst! Even a straw 9 m long would cause you a lot of problems. It would be very difficult to maintain the vacuum in the straw and you would probably spend most of the day taking the small trickle of water that emerged at the top of the straw just to stay alive. The shorter the straw however, the easier drinking becomes and the more water you get.

This same principle applies to pumps. Ideally it should be possible to draw water from a source up to 10 m. But because of friction losses in the pipework an upper limit is usually set at 7 m. Even at this level there can be problems in keeping out air and maintaining a vacuum and so a more practical limit is 3 m. When water is more than 3 m below the pump a shelf can be excavated below ground level to bring the pump closer to the water. For pumps operating at high altitudes in mountainous regions where atmospheric pressure is less than 10 m the practical limit of 3 m will need to be lowered further for satisfactory pump operation.

The difference in height between the water source (usually referred to as the sump) and the pump is called the *suction lift*. It is an unfortunate name as it clearly does not describe what actually happens in practice. However, it is in common use and so we are stuck with.

Not all pumps suffer from suction problems. Some pumps are designed to work below the water level in the sump and are called *submersible pumps*. These are often used for deep boreholes and are driven by an electric motor, which is also submerged, connected directly to the pump drive shaft. The motor is well sealed from the water but being submerged helps to keep the motor from overheating.

Excessive suction lift can affect pump performance and this is demonstrated by the results of a test performed on a pump for a small rural water supply scheme. The pump delivered 6.5 l/s with a 3 m suction lift. But when the suction lift was increased to 8 m the discharge dropped to 1.2 l/s – a loss in flow of 5.3 l/s – only 15% of the original discharge! So the general rule is to keep the suction lift as short as possible.

Centrifugal pumps will not normally suck out the air from the suction and will only work when the pump and the suction pipe is full of water. If pumps are located above the sump then it will be necessary to fill the pump and the suction pipe with water before the pump is started up. This process is called *priming*. A small hand-pump, located on the pump casing is used to evacuate the air. When pumps are located below the sump they will naturally fill with water under the influence of gravity and so no additional priming is required.

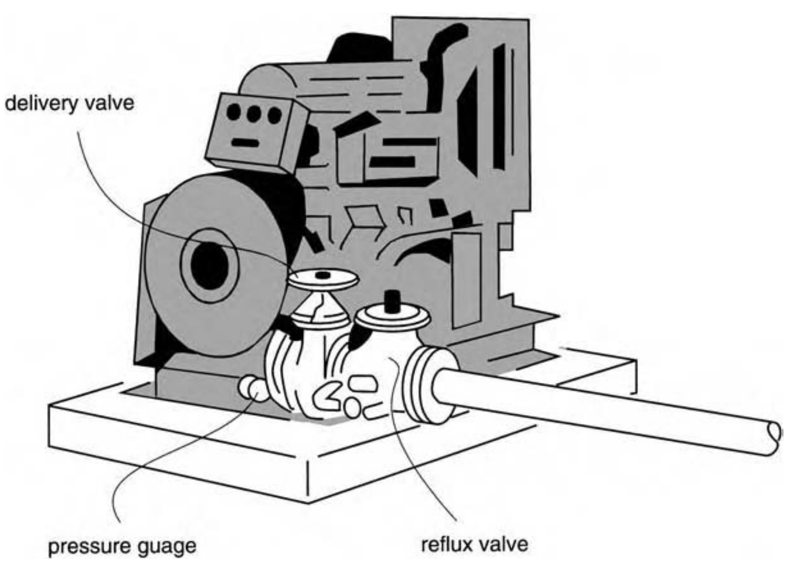
For axial flow pumps, the impeller is best located below the water level in the sump and so no priming is needed.

8.4.2 Delivery

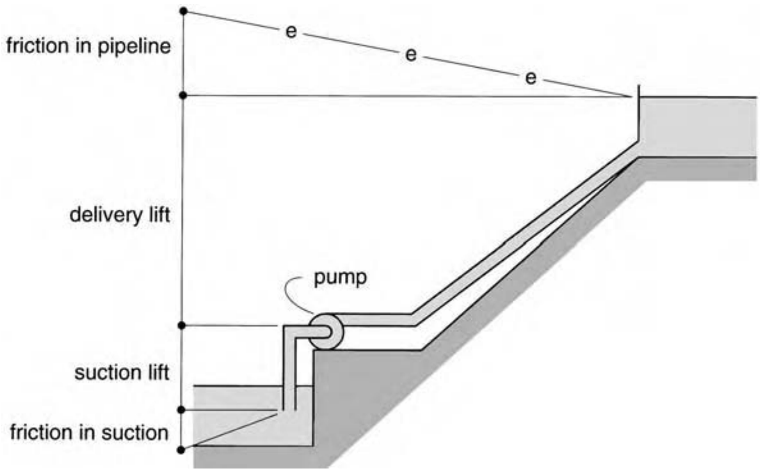
The delivery lift is the pressure created on the delivery side of the pump. The delivery side comprises pipes and fittings that connect the pump to the main pipe system and provide some control over the pressure and discharge.

For centrifugal and mixed flow pumps, a sluice valve is connected to the pump outlet to assist in controlling pressure and discharge (Figure 8.8). It is closed before starting so that the pump can be primed. Once the pump is running it is slowly opened to deliver the flow.

A reflux valve is connected downstream of the delivery valve. This allows water to flow one way only – out of the pump and into the pipeline. When a pump stops, water can flow back towards the pump and cause a rapid pressure rise which can seriously damage both the pump and the pipeline (Section 8.14). The reflux valve prevents the return flow from reaching the pump. Some reflux valves have a small by-pass valve fitted which allows water stored in the pipe to pass around the valve and to prime the pump.



8.8 Delivery side of centrifugal pump.



8.9 Pumping head.

8.4.3 Pumping head

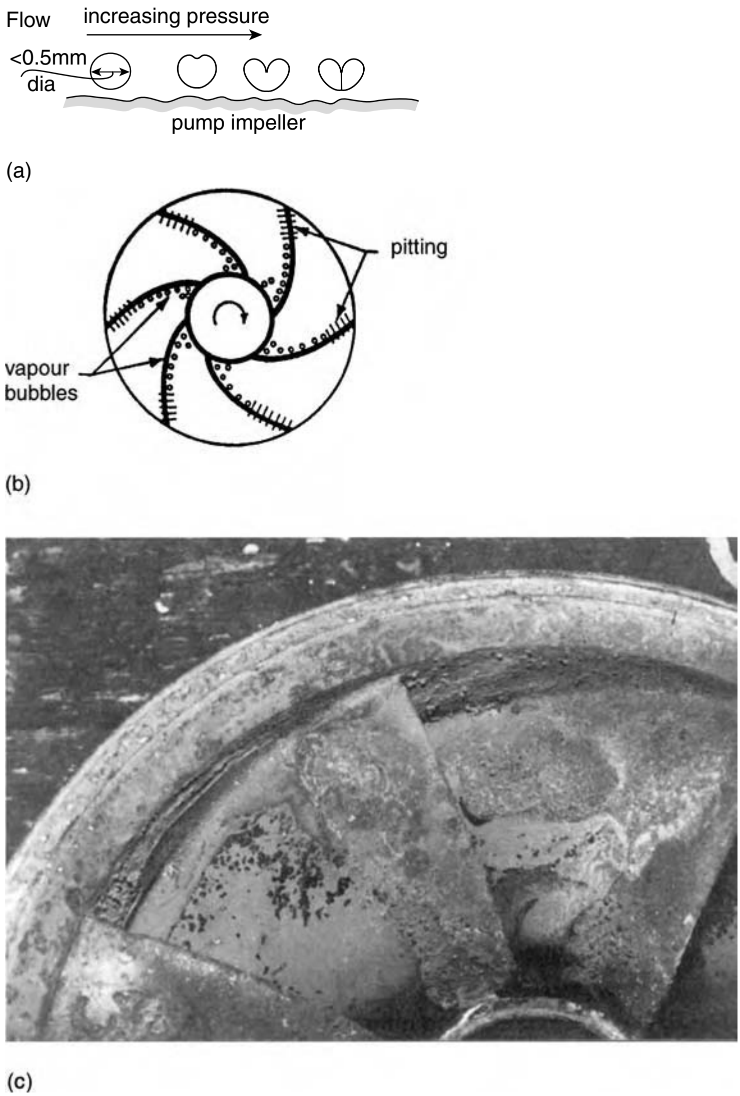
Pumping head should not be confused with the delivery head as is often the case. Pumping water requires energy not only to deliver water but also to draw it up from its source. So the pumping head is the sum of the delivery lift and suction lift and the friction losses in both suction and delivery pipes (Figure 8.9).

pumping head (m) = suction lift (m)
+ friction loss in suction (m)
+ delivery lift (m)
+ friction loss in pipeline (m)

The suction lift refers to the elevation change between the sump water level and the pump and the delivery lift is the elevation change between the pump and the point of supply, in this case it is the reservoir water level. Both are fixed values for a given installation. The friction losses in the sump and the delivery will vary depending on the discharge. There are also minor losses at the inlet and outlet to a pipeline but these tend to be very small in comparison to the main lift and other friction losses. To allow for all their minor losses it is common practice to add 10% to the pumping heads rather than try and work them out in detail.

So if the suction lift is 4 m and the pump then delivers 7 m head the pumping head would be 11 m. This represents the total height through which the water must be lifted from source to delivery point. If 11 m was the maximum that a pump can deliver then any change in the suction lift would affect the delivery lift. For example, if the suction lift increased to 6 m then the delivery lift would reduce to 5 m resulting in the same overall total pumping head of 11 m. So just quoting delivery lift without any reference to suction lift does not provide enough information about what a pump can do in pressure terms.

In many pumping installations, the pumping head also includes any losses in head resulting from friction in the suction pipes and the losses as the water flows through filters and valves and also friction and fittings losses on the delivery side.



8.10 Cavitation. (a) How cavitation bubbles collapse. (b) and (c) Cavitation damage to a pump.

8.4.4 Cavitation

A particular problem associated with excessive suction lift is a phenomenon known as *cavitation* which can not only damage the pump but also reduce its operating efficiency (Section 3.9.2). When water enters a pump near the centre of the impeller the water velocity is high and so the pressure is very low. This is exacerbated when the suction lift is high. In some cases the pressure is so low that it reaches the vapour pressure of water (approx. 0.5 m absolute) and cavities (similar to bubbles) begin to form in the flow. The cavities are very small – less than 0.5 mm diameter – but there are usually so many of them that the water looks milky in appearance. This must not be confused with air entrainment which looks similar. Rather they are 'holes' in the water that contain only water vapour. The problems occur when the cavities move through the pump into an area of higher pressure where they become unstable and begin to collapse (Figure 8.10a).

A small needle jet of water rushes across the cavity with such force that if the cavity is close to the pump impeller or casing then it can start to damage them. Each cavity collapse is not significant on its own but when many thousands of them continually collapse close to the metal surfaces then damage begins to grow. In some cases it has been known to completely wear away the impeller blades (Figure 8.10b).

Most pumps in fact cavitate but not all cavitation causes damage. Pump designers go to great lengths to ensure that the cavities collapse in the main flow, well away from the impeller blades. If this is not possible then stainless steel impellers are used as this is one of the few materials which can resist cavitation damage. But this is a very expensive option and not one to take up lightly.

Cavitation not only erodes the surfaces in contact with water but it can also be very noisy. It also causes vibration and can reduce pumping efficiency. If you have an opportunity to visit a water pumping station then place your ear against the pump casing and you will hear the cavitation. Above all the noise of the pump engines it should be possible to hear a sharp crackling sound. This is the sound of the cavities collapsing as the pressure rises in the pump. The level of the noise produced by the cavitation is a measure of how badly the pump is cavitating.

Cavitation also occurs in turbine runners which are discussed briefly later in this chapter. High velocities at the turbine inlet produce cavities which then collapse close to the runner blades near the exit.

A concept sometimes used for limiting suction lift and so avoiding cavitation is the Net Positive Suction Head (NPSH). Manufacturers normally specify a value of NPSH for each discharge to ensure a pump operates satisfactorily.

The NPSH for an installation can be calculated as follows:

$$\text{NPSH} = P_a - H_s - V_p - h_f$$

where P_a is atmospheric pressure (m); H_s is suction head (m); V_p is the vapour pressure of water (approx. 0.5 m absolute); h_f is the head loss in the suction pipe (approx. 0.75 m).

The value of NPSH calculated using this formula must be greater than that quoted by the pump manufacturer for the pump to operate satisfactorily.

8.5 Energy for pumping

Energy is needed to pump water. The amount required depends on both the volume of water pumped and the height to which it is lifted. It can be calculated using the following formula:

$$\text{water energy (kWh)} = \frac{\text{volume (m}^3\text{)} \times \text{head (m)}}{367}$$

A derivation of this formula is shown in the box for the more inquisitive reader.

DERIVATION: A FORMULA TO CALCULATE ENERGY FOR PUMPING

Derive a formula to calculate the amount of energy needed to lift a volume of water V m^3 to a height of H m.

Start with the basic equation for calculating energy from Section 1.10:

water energy = work done

So:

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

We now need to establish what the values of force and distance mean in terms of pumping water. Look first at force. This is the total weight of water to be lifted. Usually the volume is known and so we use Newton's second law to determine the weight:

force = mass (kg) × acceleration (m/s^2)

In this case acceleration is due to gravity and so:

mass of water = volume (m^3) × density (kg/m^3)

So:

force = volume (m^3) × density (kg/m^3) × gravity constant (m/s^2)

Now density $\rho = 1000\ kg/m^3$ and the gravity constant $g = 9.81\ m/s^2$ so:

force = volume (m^3) × 1000 × 9.81
= volume (m^3) × 9810

The 'distance' part of the energy equation is the pumping head and so:

distance = pumping head (m)

Putting the values for force and distance in the energy equation:

water energy (Nm) = volume (m^3) × 9810 × head (m)

But this is in Nm. We need to convert this to more useful and practical units of energy like kWh so:

1 kWh = 3 600 000 Nm (Section 1.10.2)

So:

$$\text{water energy (kWh)} = \frac{\text{volume (m}^3\text{)} \times 9810 \times \text{head (m)}}{3\,600\,000}$$

This simplifies to the formula which is most often used:

$$\text{water energy (kWh)} = \frac{\text{volume (m}^3\text{)} \times \text{head (m)}}{367}$$

An example of how to use this formula for calculating energy for pumping is shown in the next box.

8.6 Power for pumping

Remember from Chapter 1 that the terms power and energy are often used to mean the same thing. But power is the rate of energy use. So as energy is determined by volume and head, power is determined by discharge and head. Power is usually measured in Watts (W) but this is a relatively small amount of power and so it is more common to speak of pumping power in terms of kilo-Watts (kW).

One way of calculating power is to divide energy by the time taken to use the energy. So:

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

But another way of calculating power is to use the formula:

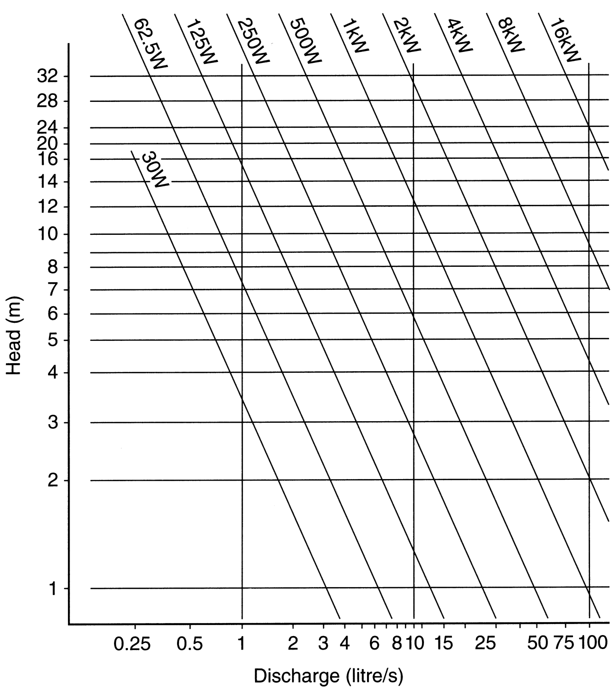
$$\text{water power (kW)} = 9.81 \times \text{discharge (m}^3\text{/s)} \times \text{pumping head (m)}$$
$$P = 9.81\ QH$$

A graph of water power and discharge for a wide range of pumping heads is a convenient way of showing the range of this formula (Figure 8.11).

Manufacturers often quote discharges in m^3/h rather than in m^3/s. In this case the formula becomes:

$$\text{water power (kW)} = \frac{\text{discharge (m}^3\text{/h} \times \text{head (m)}}{367}$$

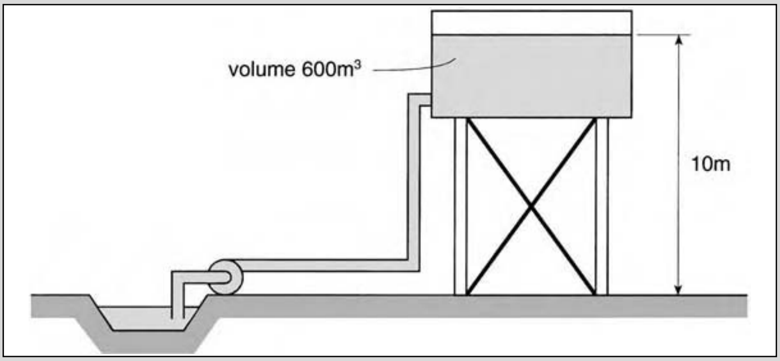
The derivation of this formula is similar to that for water energy but discharge is used instead of volume. Try to work this one out for yourself.



8.11 Power requirements for pumps.

EXAMPLE: CALCULATING THE ENERGY AND POWER REQUIRED TO FILL A TANK WITH WATER

A 600 m^3 tank 10 m high is filled with water each day. Calculate the amount of energy required to fill the tank. If the pump runs for 6 hours each day calculate the power required.



8.12 Calculating the energy and power required to fill a tank with water.

First calculate the amount of energy needed each day using the energy formula:

$$\text{energy (kWh)} = \frac{\text{volume (m}^3) \times \text{head (m)}}{367}$$

Put in values for volume and head:

$$\text{energy (kWh)} = \frac{600 \times 10}{367} = 16.3 \text{ kWh}$$

This is the energy required each day to fill the tank. Notice how the time period over which the energy is used needs to be specified.
Now calculate the water power needed. First calculate the discharge:

$$\text{discharge (m}^3\text{/h)} = \frac{\text{volume (m}^3)}{\text{time (h)}} = \frac{600}{6} = 100 \text{ m}^3\text{/h}$$

Now calculate power:

$$\text{power (kW)} = \frac{\text{discharge (m}^3\text{/h)} \times \text{head (m)}}{367} = \frac{100 \times 10}{367} = 2.7 \text{ kW}$$

The energy can also be calculated from power by multiplying power by the time over which the power is used. In this case the time is 6 hours.

$$\begin{aligned}\text{energy (kWh)} &= \text{water power (kW) x operating time (h)}\\ &= 2.7 \times 6\\ &= 16.3 \text{ kWh}\end{aligned}$$

Note the two approaches produce the same answer.

8.6.1 Efficiency

In the example in the box the 'water energy' and 'water power' are only part of what is needed to actually fill the water tank. Losses occur in the power unit that drives the pump and in the pump itself and these need to be taken into account when the total power needed for pumping is determined. Energy and power losses occur when fuel energy is converted into useful water energy and through turbulence and friction in the pump and fittings. Much of this is dissipated as heat energy. The losses that occur are expressed as an *efficiency*, which can be looked at from both a power and an energy point of view.

Energy and power efficiencies are often assumed to be the same. In practice this may not be the case. A seasonal assessment of energy use efficiency may not always give the same value as power use efficiency measured only one or two times during a lengthy period of operation.

Power efficiency is a measure of how well the power from the power unit is converted into useful water power in the pump and is calculated as follows:

$$\text{power efficiency (\%)} = \frac{\text{water power output}}{\text{actual power input}} \times 100$$

Energy use efficiency is used to judge how well a pump is performing over a longer period of time.

$$\text{energy efficiency (\%)} = \frac{\text{water energy output}}{\text{actual energy input}} \times 100$$

To calculate energy efficiency, the time over which the energy is used must be known, for example, a day, month or a season.

A system with no energy losses would have an efficiency of 100%, so all the power or energy input would be transferred to the water. But this does not happen in practice. There are always losses in the various components of the power unit and pump, as well as in the pipe system. The actual efficiency will be the product of the efficiency of each component. For example, a centrifugal pump with an efficiency of 80% being driven by an electric motor with an efficiency of 80% would have an overall efficiency of 64% ($0.8 \times 0.8 = 0.64$). The efficiency of the pipe system can be incorporated in a similar way. So it is not just the efficiency of the pump that matters – all the components of the system must be well matched to produce a high overall efficiency. Just to complicate matters, the efficiency of each component is not fixed – the values vary depending on the discharge and pressure in the system. The designer's objective is to match the various components so that together they produce the highest level of overall efficiency at the desired pressure and discharge. Usually this is not one fixed point but a range of pressures and discharges in which it is judged that the system is performing optimally with minimal energy losses.

This is true for all lifting devices and not just centrifugal pumps. Treadle pumps, for example, have an optimum treadling speed that minimises losses and power inputs from an operator and maximises pump output in terms of pressure and discharge.

EXAMPLE: ESTIMATING THE DISCHARGE AND PRESSURE THAT CAN BE ACHIEVED WITH A TREADLE PUMP

Estimate the discharge and pressures that can be expected from a treadle pump operated by a farmer in a developing country (Section 8.2). Make reasonable assumptions to complete the calculations.

The first step is to determine the power available for pumping. Once this is established it is possible to determine the pressure and discharge that could be expected from the pump.

A reasonably fit, well-fed male between 20 and 40 could produce a steady power output of 75 Watts for long periods. To give you some idea of what this means, it is like walking up and down a flight of stairs in about 20 s. Not so bad for the first few times but think about sustaining this over several hours. In a developing country where operators may not be so well fed, or operators are women and children, a more reasonable power value might be 30 Watts.

The pump unit is also not very efficient at converting human power into water power so we need to allow for an efficiency of say 40%.

So taking these figures into account assume the power input is 30 Watts (0.03 kW) and the pump efficiency is 40%:

$$\text{water power (kW)} = \frac{\text{discharge (m}^3\text{/h)} \times \text{head (m)}}{367}$$

$$0.03 \times 0.4 = \frac{\text{discharge (m}^3\text{/h)} \times \text{head (m)}}{367}$$

Power is directly related to both discharge and head so at the same power input level, if head increases then discharge will decrease and vice-versa.

So assume the suction lift is 2 m which is typical for many treadle pump applications. Now calculate the discharge using the above power formula:

$$\text{discharge} = \frac{0.03 \times 0.4 \times 367}{2} = 2.20 \text{ m}^3\text{/h}$$

$$= 0.6 \text{ l/s}$$

If the water lift is reduced to 1 m the discharge increases:

$$\text{discharge} = 1.2 \text{ l/s}$$

So when the pumping head is low the discharge ranges from 0. 6 to 1.2 l/s.

In some countries treadle pumps are used to pump water to much higher heads than this, but there is a limit to this which depends on the operator. The maximum pressure is determined by the weight of the operator who stands on the treadle and applies a downward force on the pistons.

So assume a typical 65 kg operator standing on a treadle immediately above a typical 100 mm diameter piston. Now calculate the pressure using:

$$\text{pressure (N/m}^2) = \frac{\text{force (N/m}^2)}{\text{area (m}^2)}$$

Calculate the force and the area:

$$\begin{aligned}\text{max. force from operator (N)} &= \text{mass of operator (kg)} \times \text{gravity constant (m/s}^2) \\ &= 65 \times 9.81 \\ &= 637\ \text{N} \\ \text{area of piston} &= \frac{\pi \times d^2}{4} = \frac{\pi \times 0.1^2}{4} = 0.007\ \text{m}^2\end{aligned}$$

Put values for force and area into the formula to calculate pressure:

$$\text{pressure} = \frac{637}{0.007} = 91\,000\ \text{N/m}^2$$

Calculate this in terms of head (m) using the pressure-head equation:

$$P = \rho g h$$

$$\text{head (m)} = \frac{P}{\rho g}$$

$$= \frac{91\,000}{1000 \times 9.81} = 9.27\ \text{m}$$

So the maximum head this operator can achieve pressing his full weight onto each piston is 9 m. In practice not all operators put their full weight on the treadles and so the actual pressure may be much lower than this, say 5 m. The pressure can be increased by reducing the diameter of the pistons but this will also reduce the volume of water lifted each pump stoke. Another way of course, would be to get a heavier operator or perhaps use two operators at the same time, which is often done when children are using it.

If the maximum pressure that can realistically be achieved on this pump is 5 m then in such circumstances, the water power formula shows that the discharge would be reduced to 0. 24 l/s.

Three important points to note:

First, the pumping head is the sum of the suction lift and the delivery lift and so it is the pumping head that is 5 m. Treadle pump suppliers are notorious for quoting delivery and suction lifts separately and this can confuse the buyer who is trying to compare pump performance.

Second, it is clear that you cannot have both high pressure and a large discharge. You can have one or the other and the combination depends on the power available from operator. Basically there is no 'free lunch' – you get out of the pump what you are prepared to put into it.

Finally, this is not rocket science. But it does demonstrate how basic hydraulics can be applied usefully to design what is a simple but very effective water lifting device – something that is not always done in practice.

8.7 Roto-dynamic pump performance

Small centrifugal pumps are sometimes characterised by the power of their drive motors, for example, 3 HP pump or a 5 kW pump; or by their delivery diameter, for example, 50 mm pump (Table 8.1). This provides some guidance for selection but the full performance characteristics should be used for larger pumps.

All roto-dynamic pumps are factory tested and data are published by the manufacturers on the following characteristics:

- discharge and head
- discharge and power
- discharge and efficiency.

These data are usually presented graphically; typical characteristics for all three pump types are shown in Figure 8.13. The curves shown are only for one operating speed. But as pumps can run at many different speeds, several graphs are needed to show their full performance possibilities.

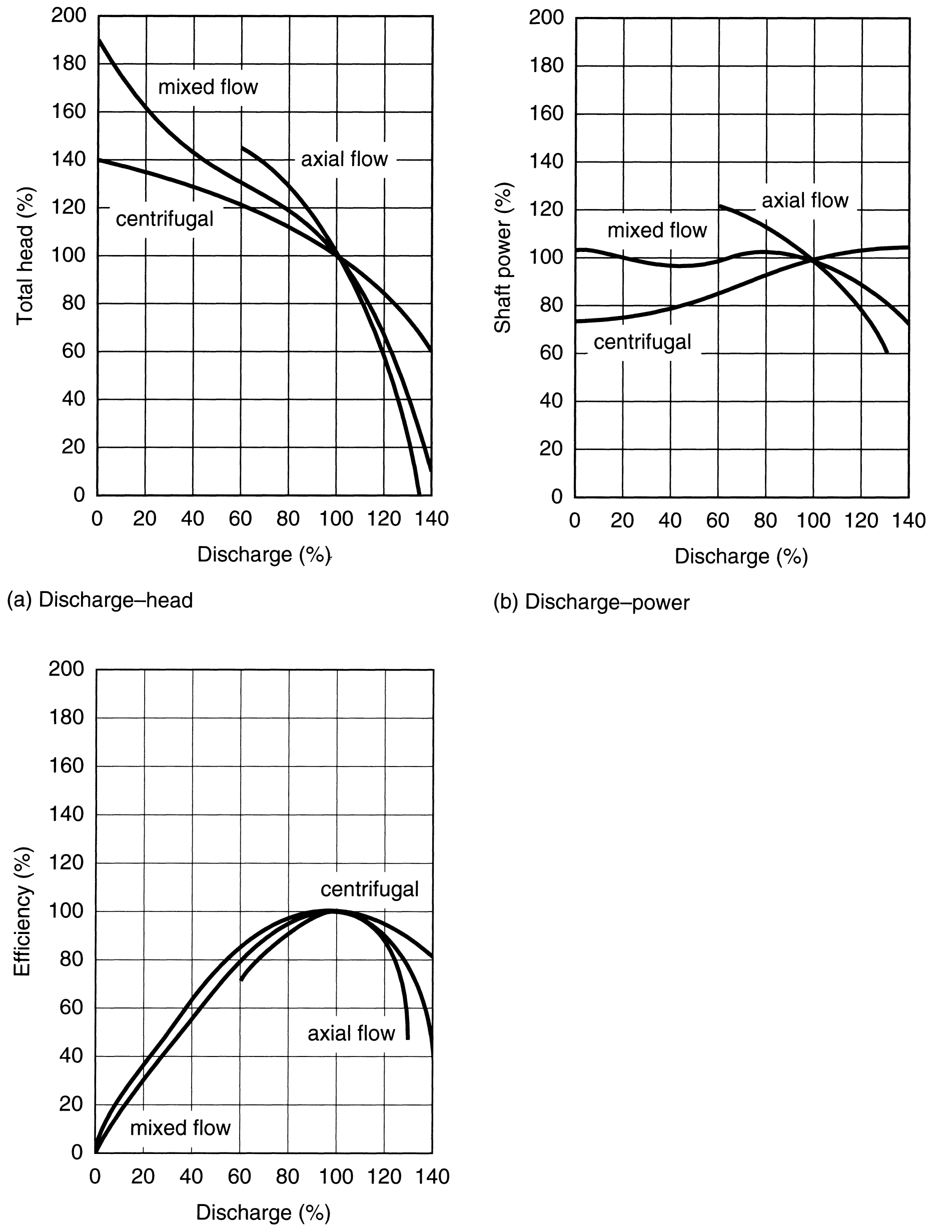
8.7.1 Discharge and head

The relationship between discharge and head is usually of most immediate concern to the user. Will the pump deliver the discharge at the required pressure? A pump can, in fact, deliver a wide range of discharges but there will be changes in pressure as the discharge changes. Pump speed can also be varied and this changes both head and discharge. The faster the speed the greater will be the head and discharge.

Figure 8.13a shows typical discharge – head curves for centrifugal, mixed flow and axial flow pumps for a given pump speed. The axes of the graph would normally show discharge (in m^3/s) and head (in m). But in order to show typical changes in performance the curves have been drawn to show the percentage changes when either the discharge or the head is changed from the normal operating condition represented by the 100% point. So for the centrifugal pump, when the discharge is reduced to 80% of its design flow the head increases to

Table 8.1 Typical discharges from small centrifugal pumps.

Pump size (mm)	*Discharge (litre/s)*
25	0–5
50	5–15
75	15–25
100	25–35
125	35–50



(a) Discharge–head

(b) Discharge–power

(c) Discharge–efficiency

8.13 Pump characteristics.

112% of its design value. Note these values of change are only representative values. They would be different for different pumps and so reference would need to be made to manufacturer's data.

Consider the centrifugal pump first. When it is started up and the delivery valve is closed, there is no discharge and the head is at its maximum. The graph shows that for this pump the head reaches 140% of its design head. As the discharge increases there is a trade-off between discharge and head. When the discharge increases then less head is available.

The discharge-head curves for both the mixed flow and axial flow pumps are similar in shape to that of the centrifugal pump. When the head is high the discharge is low and when the head is low the discharge is high.

The curves for all three pumps are for a given speed of rotation. When the speed is changed the curve will also change. The greater the speed, the greater will be the head and the discharge. So there will be several discharge-head curves for each pump; one for each speed.

8.7.2 Discharge and power

All pumps need power to rotate their impellers. The amount of power needed depends on the pump speed and the head and discharge required. For centrifugal pumps the power requirement is low when starting up but it rises steadily as the discharge increases (Figure 8.13b). For axial flow pumps the power requirement is quite different. There is a very large power demand when starting up because there is a lot of water and a heavy pump impeller to get moving. Once the pump is running the power demand drops to its normal operating level. Mixed flow pumps operate in between these two contrasting conditions and have a more uniform power demand over the discharge range.

8.7.3 Discharge and efficiency

Power efficiency is a measure of the power input to the water power output and this varies over the operating range of all three pump types. Generally, efficiency increases as the discharge increases. But it rises to some maximum value and then falls again over the remaining discharge range (Figure 8.13c). The maximum efficiency is usually between 30 and 80%, and so there is only a limited range of discharges and heads over which pumps operate at maximum efficiency. Outside this range they will still work but they will be less efficient and so more power is needed to operate the same system. Smaller pumps are usually less efficient than larger ones because there is more friction to overcome relative to their size. But inefficiency is less important for small pumps.

8.8 Choosing the right kind of pump

Specific speed (N_s) is one way of selecting the right kind of pump to use – centrifugal, mixed flow or axial. This is a number that depends on the speed of the pump, the discharge and head required for a particular installation and provides a common baseline for comparing pumps.

It is the speed at which a pump will deliver 1 m^3/s at 1.0 m head and is calculated as follows:

$$N_s = \frac{NQ^{1/2}}{H^{3/4}}$$

where N is rotational speed of the pump (rpm); Q is pump discharge (m^3/s); H is pumping head (m).

The specific speed is independent of the size of the pump and so it describes the shape of the pump rather than how big it is. But specific speed is not dimensionless. So it is important to make sure that SI units are used so that the range of specific speeds and pump types is as shown in Table 8.2.

Table 8.2 Specific speeds for different pumps.

Pump type	*Specific speed N_s*	*Comments*
Centrifugal	10–70	High head – low discharge
Mixed flow	70–170	Medium head – medium discharge
Axial flow	above 110	Low head – large discharge

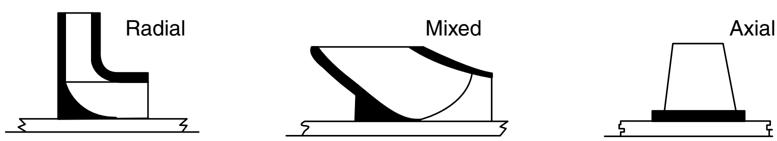
Beware of specific speeds that seem to be quite different to those used here. The main reason is likely to be the use of different units of measurement. USA still uses feet and pounds as its basic units of measurement and so any specific speed there will depend on these units.

The shape of the pump impeller also helps to define the different pump types (Figure 8.14 below). Centrifugal pumps produce high pressures using centrifugal force. To achieve this, the impeller is shaped to turn the flow from the pump inlet through a right angle so that it moves radially outwards towards the delivery pipe as the impeller spins (left-hand picture Figure 8.14). It is this radial flow and the large ratio between the pump inlet diameter and the outlet diameter that generates high velocities and hence the high pressures associated with centrifugal pumps. In contrast, axial flow pumps produce large discharges rather than high heads and so no centrifugal forces are needed. The impeller is propeller-shaped and is designed to move large volumes of water along the axis of the pump. It works in much the same way as a propeller pulls an aircraft through the air (right-hand picture Figure 8.14). Note the ratio of the inlet diameter to the outlet diameter is 1.0. In between these two extremes are mixed flow pumps. These variously have a mixture of radial flow and a larger outlet diameter – to produce some pressure, and axial flow – to produce flow.

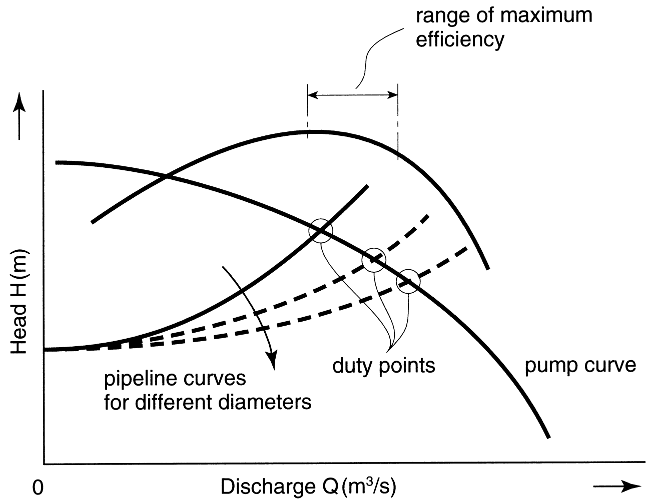
8.9 Matching a centrifugal pump with a pipeline

Selecting the right centrifugal pump and pipe system for a particular water supply installation depends both on hydraulics and cost. There is not just one unique solution to the problem. There will be several pump and pipeline combinations that will do the job from a hydraulic point of view but the final choice usually comes down to cost – which combination is the cheapest? Will a small diameter pipe with a large pump to overcome the high head losses be more or less costly than a larger and more expensive pipeline with a small pump that is less expensive to run? Working out the capital costs of each pump and pipeline together with the fuel and maintenance costs over the life time of the installation will provide the answer.

First the hydraulics. An example of matching a pump and pipeline is shown in Figure 8.15. The pump is represented by two curves – a discharge-head curve and a discharge–efficiency curve. The pipeline is represented by a head–discharge curve which shows how head losses in the pipe change when it is carrying a range of different discharges. This is constructed by putting discharge values into a head loss formula, such as the Darcy-Weisbach formula, and



8.14 Typical pump impeller shapes.



(a)

8.15 Matching a pump with a pipeline.

calculating the resulting head loss. The corresponding discharge and head loss values are then plotted onto the graph. Note the pipeline curve does not start at zero on the head axis but at some point which represents the total static head on the pump. This will be the elevation change from the water level in the sump to the point of delivery. This will be a fixed value for a given installation and not dependent on discharge. The intersection of the pump curve and the pipeline curve gives the pressure and discharge at which the combined pump and pipeline will operate. If this intersection occurs within the acceptable efficiency range for the pump then the combination is acceptable from a hydraulic point of view. A practical example of how to match a pump with a pipeline is shown in the box.

Next comes the cost bit. The hydraulic example above is for one pipeline and pump combination. But other pipe diameters could do the job just as well. Figure 8.15 above shows how several pipelines of different diameters can be assessed each producing a different duty point. More pump curves could also be introduced to see how each pipeline would interact with a range of different pumps. The end result is a wide range of possible pipeline and pump combinations that can do the job. But some will be cheaper than others and the task then is to find out which is the cheapest. This is done by comparing not just the capital costs of each pipeline and pump but a combination of both the capital costs and the running costs (energy and maintenance) over the economic life of the system. An example of how to do this is shown in a box.

EXAMPLE: MATCHING A PUMP WITH A PIPELINE

Water is pumped from a river through a 150 mm diameter pipeline 950 m long to an open storage tank with a water level 45 m above the river. A pump is available and has the discharge-head performance characteristics shown below. Calculate the duty point for the pump–when the friction factor for the pipeline $\lambda = 0.04$.

Total head (m)	30	50	65	80	87	94
Discharge (l/minute)	2000	1750	1410	800	500	0

The first step is to plot a graph of the pump discharge-head characteristic.

Next calculate the head loss in the pipeline for a range of discharge values using the Darcy–Weisbach formula:

$$h_f = \frac{\lambda l v^2}{2gd}$$

When $\lambda = 0.04$, length $l = 950$ m and diameter $d = 0.15$ m:

$$h_f = \frac{0.04 \times 950 \times v^2}{2 \times 9.81 \times 0.15} = 12.9\, v^2$$

But from the discharge equation:

$$v = \frac{Q}{a}$$

And so

$$v^2 = \frac{Q^2}{a^2}$$

Calculate area a

$$a = \frac{\pi d^2}{4} = \frac{\pi \times 0.15^2}{4} = 0.017 \text{ m}^2$$

Use these values to calculate h_f:

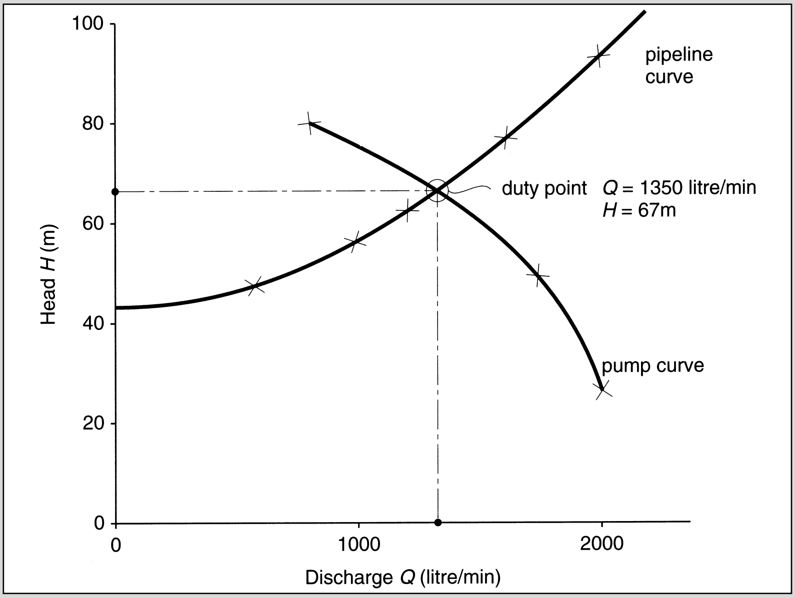
$$h_f = 12.9 \times \frac{Q^2}{0.017^2}$$

$$= 44\,636\, Q^2$$

Now calculate values of head loss for different values of Q. Remember the values of discharge need to be in SI units of m^3/s for the calculation. Also the static head of 45 m must be added to the calculated head loss to determine the total pumping head. The results are tabulated below:

Discharge (l/min)	*Discharge (m^3/s)*	*Head loss h_f (m)*	*Head loss + 45 m (m)*
2000	0.33	48.6	93.6
1600	0.027	30.17	75.15
1200	0.02	17.85	62.85
1000	0.017	12.30	57.30
500	0.006	1.60	46.60

Now construct a graph of the pump curve and the pipe curve:



8.16 Pump and pipeline characteristic curves.

From the graph the duty point is located where the two curves cross. This occurs when:

$Q = 1350$ l/min and $H = 67$ m

EXAMPLE: SELECTING THE CHEAPEST PIPELINE AND PUMP COMBINATION

A pumped water supply pipeline 1150 m long is to deliver 2700 l/min. The static lift is 20 m, the friction factor for the pipeline $\lambda = 0.03$ and the pumping plant operates at 80% efficiency. If the system runs for 17 hours each day 365 days per year, determine the cheapest combination of pipeline and pump for this installation given the following data:

Item	*Cost*	*Economic life*	*Maintenance costs*
Pumps		20 years	10% per annum
One kilowatt of installed power	£150		
Electricity	1.8 p/kWh		
Pipelines			0%
100 mm	£5.90/m	50 years	
150 mm	£8.00/m	50 years	
200 mm	£10.50/m	50 years	
250 mm	£14.80/m	50 years	
300 mm	£21/m	50 years	

Interest rate 5%

To calculate the cost of pumping first determine the power requirement of each pipe-pump combination. So use the power formula:

$$\text{power (kW)} = \frac{\text{discharge (m}^3\text{/h)} \times \text{head (m)}}{367 \times \text{efficiency}}$$

We know the discharge is 2700 l/min (162 m^3/h) and the efficiency is 80% (0.8 in the formula) but we do not know the head which is a combination of the static head and the head loss in the pipeline. So first calculate the head loss h_f using the Darcy–Weisbach formula:

$$h_f = \frac{\lambda l v^2}{2gd}$$

To calculate velocity use the discharge equation:

$$v = \frac{Q}{a}$$

Calculate area a:

$$a = \frac{\pi d^2}{4}$$

Put this into the equation for v:

$$v = \frac{4Q}{\pi d^2}$$

Now calculate the power for each of the pipe and pump combinations. The results are tabulated below.

Pipe dia (mm)	*Velocity (m/s)*	*Head loss (m)*	*Static head*	*Total pumping head (m)*	*Power (kW)*
100	5.73	577.84	20	597.84	329.89
150	2.55	76.09	20	96.09	53.03
200	1.43	18.06	20	38.06	21.00
250	0.92	5.92	20	25.92	14.30
300	0.64	2.38	20	22.38	12.35

In order to combine and compare capital costs and operating costs of the various pipeline-pump combinations calculate the equivalent annual costs for each system (if you are not familiar with discounting cash flows then please refer to any basic economics text book). First calculate the annual pump cost:

annual pump cost (£) = energy cost + annual replacement cost
+ maintenance cost + annual interest cost

Calculate each component of the annual pump cost:

energy cost (£) = operating time (h) × power (kW) × cost (£/kWh)
= 17 × 365 × power (kW) × cost (£/kWh)
= 6205 × power (kW) × cost (£/kWh)

The pump must be replaced every 20 years so the annual replacement cost is 5% of the capital cost of the pump.

$$\text{annual replacement cost} = \%\ \text{annual replacement} \times \text{capital cost (£)}$$
$$= 0.05 \times £150 \times \text{installed power (kW)}$$

$$\text{maintenance cost} = 10\%\ \text{of capital cost}$$
$$= 0.1 \times £150 \times \text{installed power (kW)}$$

$$\text{annual interest cost} = \text{pump capital cost (£)} \times \text{interest rate (\%)}$$
$$= £150 \times \text{installed power (kW)} \times \text{interest rate (\%)}$$

Add all these costs together for each pump to obtain the annual cost of pumping:

Pipe dia (mm) (1)	*Capital cost (£) (2)*	*Energy cost (£) (3)*	*Replacement cost (£) (4)*	*Maintenance cost (£) (5)*	*Interest cost (£) (6)*	*Total annual cost (£) (3)+(4)+(5)+(6)*
100	49 484	36 845	2474	4948	2474	46 741
150	7953	5922	397	795	397	7511
200	3150	2345	157	315	157	2974
250	2145	1597	107	214	107	2025
300	1852	1379	92	185	92	1748

Now calculate the annual cost of each pipeline over the economic life of the pipeline (note in this instance there is no maintenance cost):

$$\text{annual pipe cost (£)} = \text{annual replacement cost} + \text{annual interest cost}$$

Calculate each component of the annual pipeline cost:

The pipe must be replaced every 50 years so the annual replacement cost is 2% of the capital cost of the pipe.

$$\text{annual replacement cost} = \%\ \text{annual replacement} \times \text{capital cost (£)}$$
$$= 0.02 \times \text{capital cost (£)}$$
$$\text{annual interest cost} = \text{capital cost (£)} \times \text{interest rate (\%)}$$

Add all these together to determine the annual cost of the pipelines:

Pipe dia (mm)	*Capital cost (£) (1)*	*Replacement cost (£) (2)*	*Interest cost (£) (3)*	*Total annual cost (£) (2)+(3)*
100	6785	135	339	474
150	9200	184	460	644
200	12 075	241	603	845
250	17 020	340	851	1191
300	24 150	483	1207	1690

Now add the annual pumping costs to the annual pipeline costs to obtain the total cost for each pump and pipeline combination:

Pipe dia (mm)	*Pump costs (£) (1)*	*Pipeline costs (£) (2)*	*Combined cost (£) (1)+(2)*
100	46 741	474	47 215
150	7511	644	8155
200	2974	845	3819
250	2025	1191	3216
300	1748	1690	3438

The costs show that the 250 mm diameter pipe is the lowest cost solution.

8.10 Connecting centrifugal pumps in series and in parallel

There are many situations when one centrifugal pump is not enough to deliver the required head or discharge and so two or more pumps are needed. There may also be circumstances when discharge requirements vary widely, such as in meeting domestic water demand, and it is preferable to have several small pumps working together instead of one large one. Centrifugal pumps can be operated together either in *series* or in *parallel* (Figure 8.17).

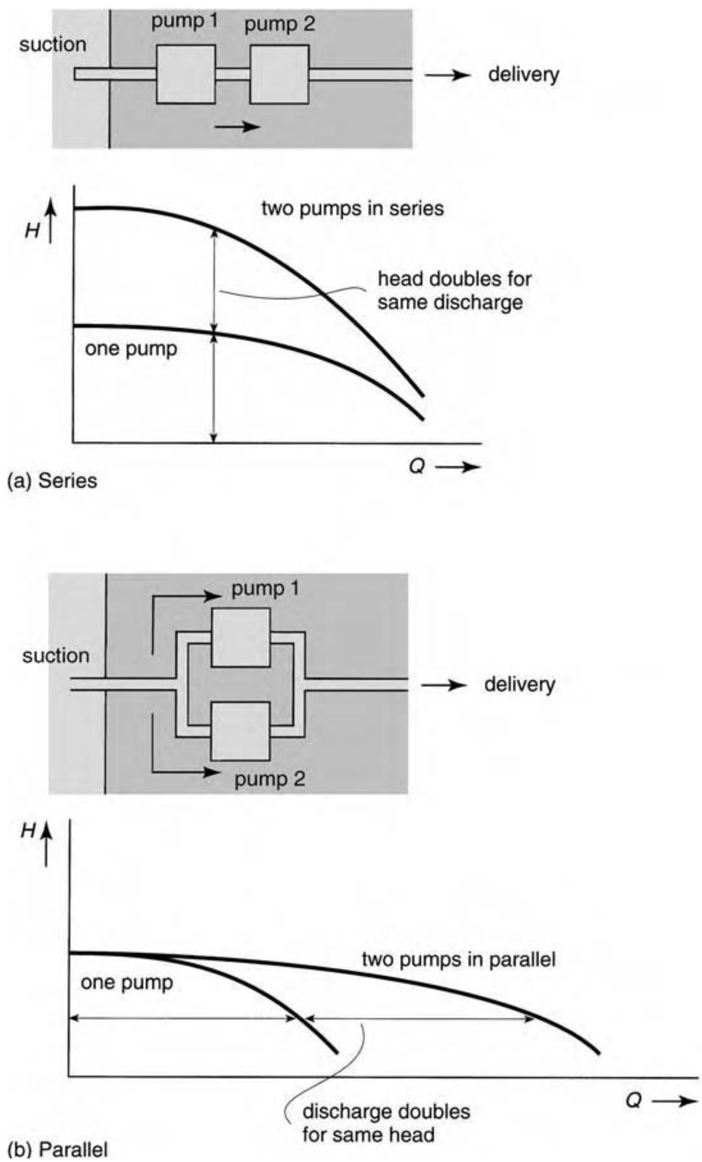
Pumps are connected in series when extra head is required. Note that the pumps need to be identical. They are connected together with the same suction and delivery pipe but are powered by different motors. The same flow passes through pump 1 and then through pump 2 and so the discharge is the same as it would be for one pump but the head is doubled. The discharge-head curve for two pumps is obtained by taking the curve for one pump and doubling the head for each value of discharge.

Pumps are operated in parallel when more discharge is required. Again the pumps must be identical. They each have separate suctions but they are connected into a common delivery pipe. With this type of connection the head is the same as for a single pump but the discharge is doubled. The discharge-head curve for the two pumps is obtained by taking the curve for one pump and doubling the discharge for each value of head.

But doubling the discharge on the pump curve does not mean that the system discharge is also doubled. The new combined pump curve must be matched with the pipe curve to determine the new discharge and pressure at which the new setup will work. The same is true when the pump head is doubled in series connections.

An example in the box illustrates how two pumps working in parallel affect the discharge and head in a pipeline.

Pumps in series work well but when one pump breaks down then the whole system is down. Pumps in parallel are useful when there are widely varying demands for water. One pump can operate to provide low flows and the second pump can be brought into operation to provide the larger flows.



8.17 Pumps in series and in parallel.

EXAMPLE: CALCULATING NEW DUTY POINT FOR PUMPS WORKING IN PARALLEL

In a previous box (Matching a pump with pipeline) the duty point – discharge 1350 l/min and head 67 m – was calculated for a centrifugal pump and a 150 mm diameter pipeline 950 m long supplying an open storage tank with a water level 45 m above the river. Determine the revised duty point when a second similar pump is connected in parallel into the system.

Characteristic of single pump:

Total head (m)	30	50	65	80	87	94
Discharge (l/minute)	2000	1750	1410	800	500	0

Determine the characteristic of two similar pumps working in parallel by doubling the discharge values for the same head. The new characteristic is:

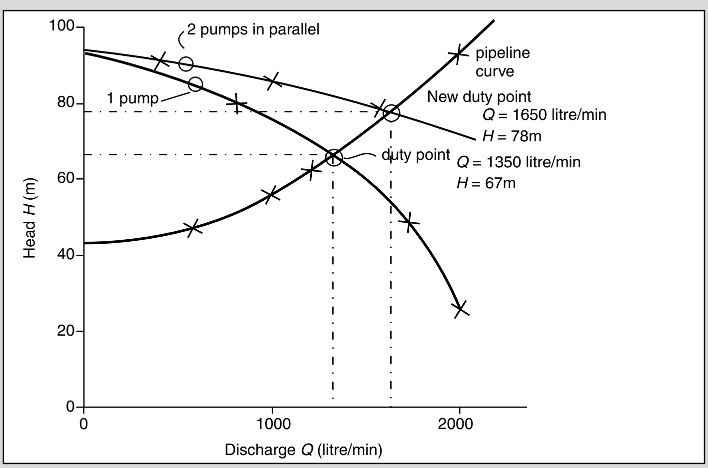
Total head (m)	30	50	65	80	87	94
Discharge (l/minute)	4000	3500	2820	1600	1000	0

The pipe curve is the same as in the previous example as this does not change. The formula for calculating the head loss is based on the Darcy-Weisbach formula:

$$h_f = 44\,636\,Q^2$$

Discharge (l/min)	*Discharge (m^3/s)*	*Head loss h_f (m)*	*Head loss + 45 mm*
2000	0.33	48.6	93.6
1600	0.027	30.17	75.15
1200	0.02	17.85	62.85
1000	0.017	12.30	57.30
500	0.006	1.60	46.60

Now construct a graph of the pipe and two pumps curves to show the effect of pumping in parallel:



8.18 Characteristic curves for pumps operating in parallel.

From the graph the new duty point is located where the new parallel pump curve intersects the pipe curve.
This occurs when Q = 1650 l/min and H = 78 m

8.11 Variable speed pumps

Centrifugal pump installations are designed to the meet the maximum discharge at a particular running speed. Lower discharges are then dealt with by throttling the flow using various types of valve installed along the pipeline. This works fine as a control mechanism but the pump is still using up energy as if it was delivering the design discharge and so a lot of energy is wasted. A typical electric motor costing some £500 could consume over £50 000 in electricity charges over its useful life and so a single percentage point increase in efficiency can save as much as the capital cost of the motor itself.

One solution to the varying flow problem is to vary the pump speed to fit with the change in demand. But this is not always convenient and easy to do. Electric motors, which are increasingly used to drive pumps, are usually ac induction motors and they run at a fixed speed which is determined by the frequency of the alternating electricity supply. In the UK this is 50 Hz (50 cycles per second) so motors (and pumps) run at 3000 rpm. In some countries the ac supply is 60 Hz and so motors there run at 3600 rpm.

It is possible to vary motor speed by setting a number of predetermined speeds using different motor wiring systems. But another way is to vary the frequency of the electricity supply. This is a recent innovation for controlling pumps. The pump motor is fitted with a frequency converter and various electronic sensors so that the pump can be set to run at a constant pressure over a wide range of discharges or at a constant discharge over a wide range of pressures (Figure 8.19). They are often referred to as inverters but this describes only part of their function. The frequency converter adjusts the motor and hence the pump speed so that the various set demands are met. This can significantly reduce energy demands and the costs of pumping.

8.12 Operating pumps

Here are some good practical guidelines for operating pumps properly.

8.12.1 Centrifugal pumps

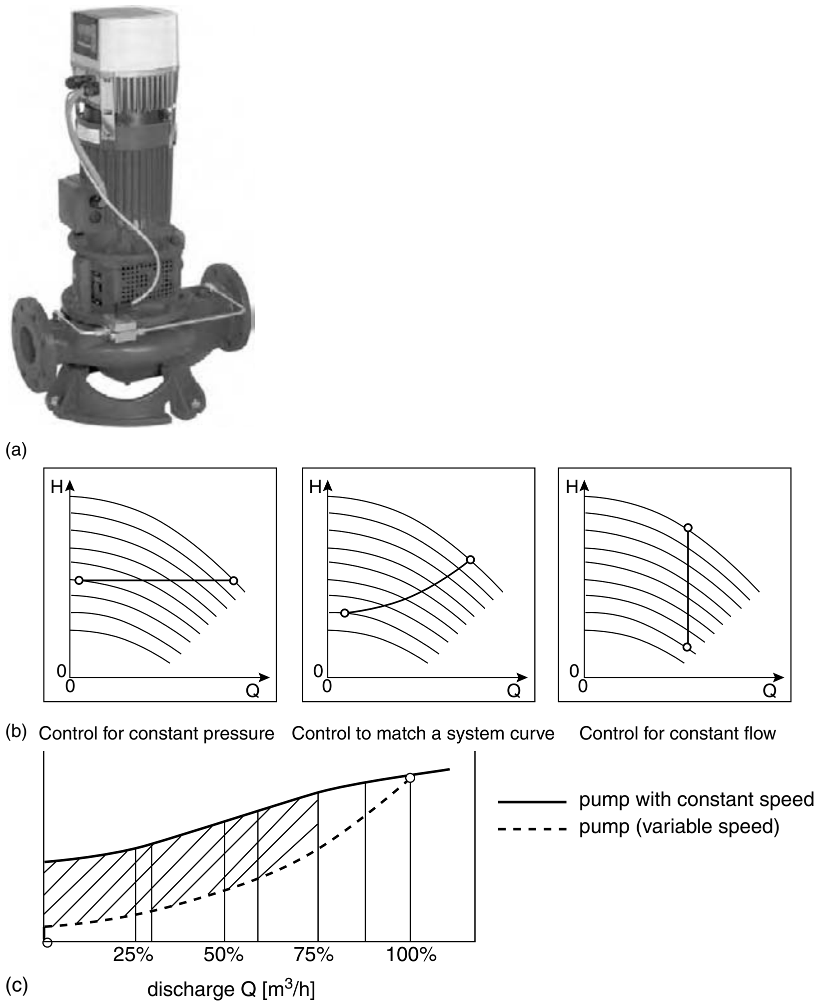
Centrifugal pumps always have control valves fitted on the suction and delivery sides of the pump. The valve on the delivery side is used to control pressure and discharge (Figure 8.8). It is closed before starting so that the pump can be primed. Once the pump is running it is slowly opened to deliver the flow.

A reflux (non-return) valve is also usually fitted after the delivery valve to stop reverse flows that can damage the pump (Section 8.14). Some reflux valves have a small by-pass valve fitted which allows water stored in the pipe to pass around the valve and be used for priming the pump.

A reflux valve is usually fitted on the end of the suction pipe. This keeps the suction pipe full of water and makes priming easier.

Before starting a pump, the delivery valve must be closed. The pump and the suction pipe are then filled with water for priming. When pumps are located below the sump water level they are primed automatically as water flows under gravity into the pump casing. Contrary to expectation starting a pump with a closed delivery valve does not cause problems. The pressure does not go on rising and damage the pump. Rather it reaches a steady speed and pressure. Remember the pressure depends only on the speed of rotation of the impeller. The faster it rotates the higher will be the pressure. The delivery valve is then slowly opened, water flows into the pipeline and as the discharge increases the pressure at the pump gradually falls. At the same time the power requirement increases. This gradual change continues until the delivery pipe is full of water and the system is operating at its design head and discharge.

These operating procedures are important for several reasons. Suppose for example, the delivery valve was left open as often happens. Not only would it be difficult to prime the pump



8.19 Variable speed pumps. (a) Pump fitted with electric motor power unit and frequency converter. (b) Pump output matched to demand by varying motor speed. (c) Difference in power consumption for fixed and variable speed pumps.

but also when it is started, water would surge along the delivery pipe. Such a sudden surge of water might damage valves and fittings along the pipeline. The rapid increase in discharge also causes a rapid increase in power demand and power units do not usually like this. It is like getting into a car when the engine is cold and suddenly trying to put it into top gear and accelerate fast. The power demand is too great and the engine will stall and stop. The most sensible way to get moving is to build up the power demand gradually through the use of the gears and clutch. The same idea applies to pumps by opening the delivery valve slowly.

8.12.2 Axial flow pumps

Axial flow pumps do not have any control valves on either the suction or the delivery. Because of the high power demand when starting up, it is not desirable to start a pump against a closed valve. What is needed, however, on some pumps is a siphon breaker. This stops water from siphoning back from the delivery side into the sump when the pump stops by allowing air into the pump casing.

8.13 Power units

There are two main types of power unit: internal combustion engines and electric motors.

8.13.1 Internal combustion engines

Many pumping installations do not have easy access to electricity and so rely on petrol (spark ignition) engines or diesel (compression ignition) engines to drive pumps. These engines have a good weight to power output ratio, and are compact in size and relatively cheap due to mass production techniques.

Diesel engines tend to be heavier and more robust than petrol engines but are more expensive to buy. However, they are also more efficient to run and if operated and maintained properly they have a longer working life and are more reliable than petrol. In some countries petrol-driven pumps have needed replacing after only three years of operation. Diesel pumps operating in similar conditions could be expected to last at least 6 years. However, it must not be forgotten that engine life is not just measured in years, it is measured in hours of operation and its useful life depends on how well it is operated and serviced. There are cases in developing countries where well maintained diesel pumps have been in continuous use for 30 years and more. A diesel pump can be up to four times as heavy as an equivalent petrol pump and so if portability is important a petrol engine may be the answer.

8.13.2 Electric motors

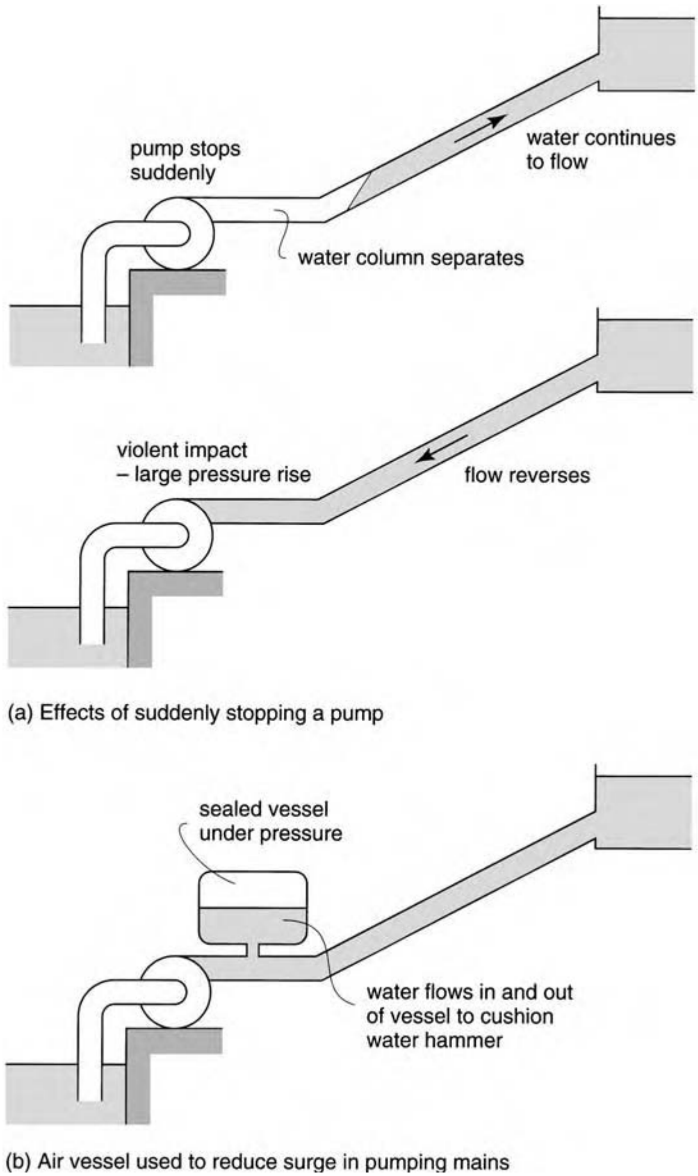
Electric motors are very efficient in energy use (75–85%) and can be used to drive all sizes and types of pumps. The main drawback is the reliance on a power supply which is outside the control of the pump operator and in some countries it is unreliable. Inevitably electrical power supplies usually fail when they are most needed and so backup generators may be needed driven by diesel engines.

8.14 Surge in pumping mains

Water hammer in pipelines has already been discussed in Section 4.14, but it can cause particular problems in pumping mains by creating *surges*. This is the slower mass movement of water often resulting from the faster moving water hammer shock waves.

In pumping mains the process is reversed and it is the surge of water that can set up the water hammer. To see how this happens imagine water being pumped along a pipeline when suddenly the pump stops (Figure 8.20). The flow in the pipe does not stop immediately but continues to move along the pipe. But as the main driving force has now gone, the flow gradually slows down because of friction. As the flow moves away from the pump and as no water enters the pipe, an empty space forms near the pump. This is called *water column separation* and the pressure in the empty space drops rapidly to the vapour pressure of water.

The flow gradually slows down through friction and stops. But there is now an empty space in the pipe and so water starts to flow back towards the pump gathering speed as it goes. It rapidly refills the void and then comes to a sudden and violent stop as it hits the pump. This is very similar to suddenly closing a valve on a pipeline and results in a high pressure shock wave



8.20 Surge and water hammer in pumping mains.

which moves up the pipe at high speed (approx. 1200 m/s). This can not only burst the pipe but it may also seriously damage the pump as well.

There are several ways of avoiding this problem:

Stop pumps slowly. When pumps stop slowly water continues to enter the pipe and so the water column does not separate and water hammer is avoided. Electric pumps are a problem because they stop very quickly when the power fails. Diesel pumps take some time to slow down when the fuel is switched off and this is usually enough time to avoid the problem.

Use a non-return valve. Using a non-return valve in the delivery pipeline will allow the flow to pass normally along the pipe but stop water from flowing back towards the pump. In this case the valve and the pipe absorb the water hammer pressures and the pump is protected.

Use an air vessel. This is similar in action to a surge tank but in reverse (Figure 8.20b). When a pump stops and the pressure starts to drop, water flows from a pressurised tank into the pipeline to fill the void and stop the water column from separating. When the flow stops and reverses, it flows back into the tank. The water then oscillates back and forth until it eventually stops through friction. Unlike a surge tank, an air vessel is sealed and the air trapped inside acts like a large coiled spring compressing and expanding to dampen the movement of the water in much the same way as a shock absorber on a car dampens the large bumps in the road. This device tends to be expensive and so would only be used on large, important pumping installations where the designers expect serious water hammer problems to occur.

8.15 Turbines

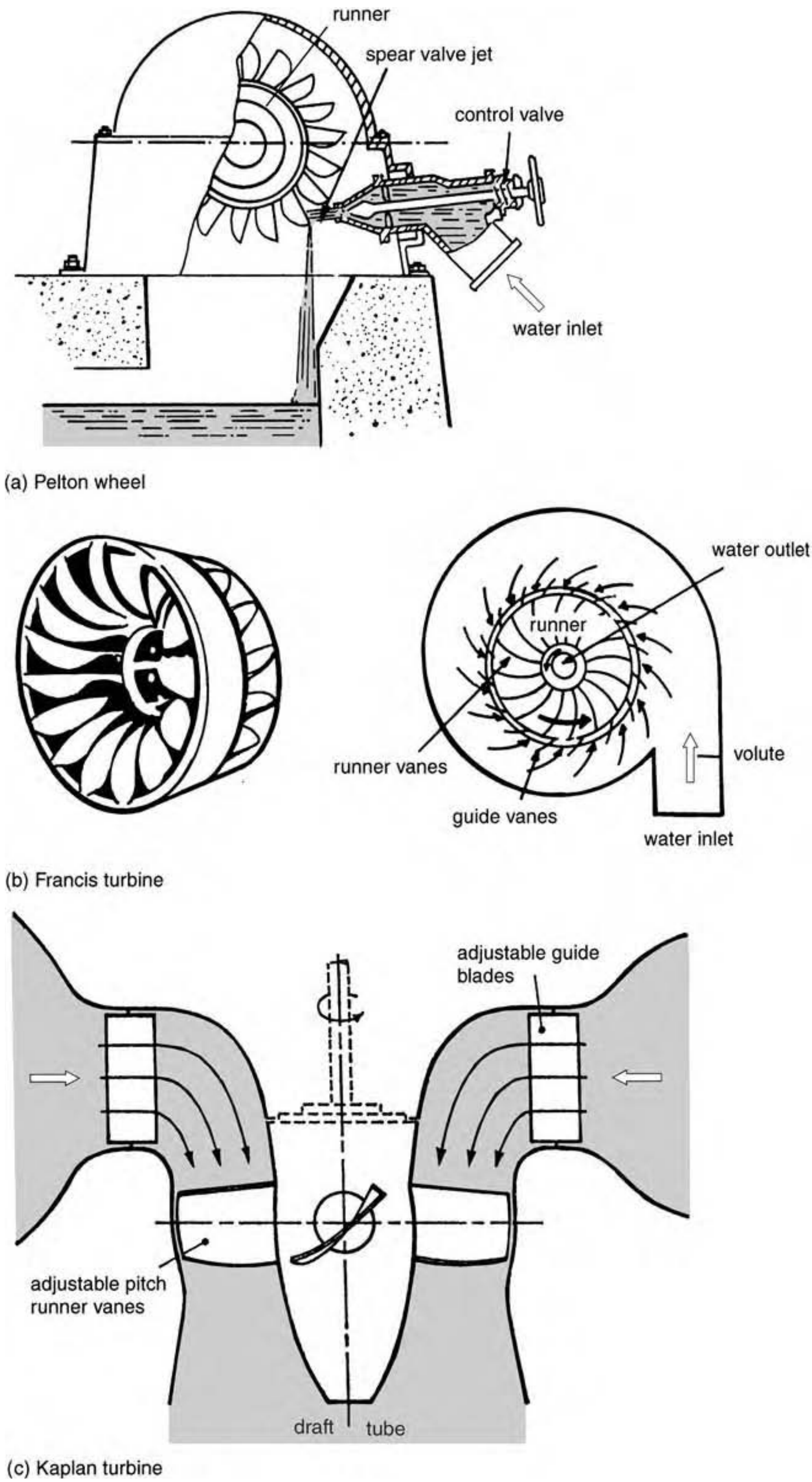
Water can also produce energy as well as absorb it. This idea has been exploited for centuries long before rotary pumps were invented. Water wheels were used by the Romans and throughout Europe to grind cereals. Today these wheels have been replaced by turbines that are connected to generators to produce electrical energy. These are used extensively in Scotland for power generation, in mountainous countries such as Switzerland and in many other countries where convenient dam sites can be located to produce the required head. Unfortunately there are not many sites around the world where there are sufficient renewable energy sources that can be exploited in this way. They are not usually the main source of electricity but provide a valuable addition to the main power source, such as coal, gas or oil-fired power stations, to meet peak demands.

Another development has been the combination of pumps and turbines in what is known as a pumped storage scheme. In Wales, for example, a small hydropower plant is used to generate electricity during the day to meet peak demands. During the night when power demand is low, surplus electricity from the main grid is used to pump water back up into the reservoir to generate electricity the next day. This is a way of 'storing' electricity by storing water.

There are three main types of turbine (Figure 8.21): impulse turbines, reaction turbines and axial flow turbines.

Impulse turbines are similar in operation to the old water wheel. The most common is the Pelton wheel, named after its American inventor, Lester Pelton (1829–1908). This comprises a wheel with specially shaped buckets around its periphery known as the runner. Water from a high level reservoir is directed along a pipe and through a nozzle to produce a high speed water jet. This is directed at the buckets and causes the runner to rotate. The momentum change of the jet as it hits the moving buckets creates the force for rotation. So by knowing the speed of the jet it is possible to work out this force and the amount of electrical energy that can be generated. Pelton wheels can be very efficient at transferring energy from water to electricity and figures as high as 90% are quoted by manufacturers. They are best suited to high heads above 150 m. Some installations run with heads in excess of 600 m.

Reaction turbines are like centrifugal pumps in reverse. The most common design is the Francis turbine. Although James Francis (1815–1892) did not invent the turbine he did a great deal to develop the inlet guide vanes and runner blades to improve turbine efficiency and so his name became associated with it. The turbine resembles a centrifugal pump but instead of the rotating impeller driving the water as in a pump, the runner is driven by the water. Water is fed



8.21 Turbines.

under pressure and at high velocity around a spiral casing onto the runner and as rotates the pressure and kinetic energy of the water is transferred to the runner. Francis turbines normally work at heads of 15–150 m.

Axial flow (or propeller) turbines are known as Kaplan turbines. They are named after Victor Kaplan (1876–1934), a German professor who developed this type of turbine with adjustable blades. Axial flow turbines operate like axial flow pumps in reverse. They operate at low heads (less than 30 m) and are used in tidal power installations. They have blades on their runners that can be twisted to different angles in order to work at high efficiency over a wide range of operating conditions. This kind of turbine is also used in pumped storage schemes. It is used as a turbine during the day when power demand is high and at night it is connected to an electric motor and used as a pump to lift water back into a high level reservoir in readiness for the next day.

8.16 Some examples to test your understanding

1 A centrifugal pump is connected to a 25 m length of 300 mm diameter suction pipe and discharges into a 500 m long pipe with a diameter of 150 mm. The water level in the river is 2 m above datum, the centre line of the pump is 3.75 m higher, and the discharge pipe enters a tank whose water level is 25 m above datum. Calculate the pressure head that the pump must produce to pump a discharge of 0.150 m^3/s. Assume a friction factor of $\lambda = 0.015$ (61.8m).

2 A pump supplies water to a large reservoir through a 2000 m long pipeline 400 mm in diameter. If the difference in water level between the sump and the reservoir is 20 m and the friction factor for the pipeline is $\lambda = 0.03$, calculate the pressure and power output required to deliver a discharge of 0.35 m^3/s (29.38 m; 101 kW).

3 A centrifugal pump lifts water from a well to a storage tank with an outlet 20 m above the water level in the well. The suction and delivery pipes are 50 mm in diameter and the total pipe length is 150 m. The friction factor for the pipeline is $\lambda = 0.035$. The pump performance at different heads is tabulated below:

Head (m)	0	12	25	30	32	33
Discharge (l/s)	9	8	6	4	2	0
Efficiency (%)	0	50	60	60	50	0

Plot the pump characteristic curves and the pipe system curve and determine the discharge, head, efficiency, and power required at the duty point (2.8 l/s; 31 m; 56%; 0.85 kW).

If a second pump is connected in series calculate the new duty point (4.8 l/s; 57 m; 60%; 2.64 kW).