4.5 EXTERNAL COMBUSTION ENGINES

The difference between internal and external combustion engines, as their names suggest, is that the former burn their fuel within the power cylinder, but the latter use their fuel to heat a gas or a vapour through the walls of an external chamber, and the heated gas or vapour is then transferred to the power cylinder. External combustion engines therefore require a heat exchanger, or boiler to take in heat, and as their fuels are burnt externally under steady conditions, they can in principle use any fuel that can burn, including agricultural residues or waste materials

There are two main families of external combustion engines; steam engines which rely on expanding steam (or occasionally some other vapour) to drive a mechanism; or Stirling engines which use hot air (or some other hot gas). The use of both technologies reached their zeniths around 1900 and have declined almost to extinction since. However a brief description is worthwhile, since:

i. they were successfully and widely used in the past for pumping water;
ii. they both have the merit of being well suited to the use of low cost fuels such as coal, peat and biomass;
iii. attempts to update and revive them are taking place.

and therefore they may re-appear as viable options in the longer term future.

The primary disadvantage of e.c. engines is that a large area of heat exchanger is necessary to transmit heat into the working cylinder(s) and also to reject heat at the end of the cycle. As a result, e.c. engines are generally bulky and expensive to construct compared with i.c. engines. Also, since they are no longer generally manufactured they do not enjoy the economies of mass-production available to i.e. engines. They also will not start so quickly or conveniently as an i.c. engine; because it takes time to light the fire and heat the machine to its working temperature.

Due to their relatively poor power/weight ratio and also the worse energy/weight ratio of solid fuels, the kinds of applications where steam or Stirling engines are most likely to be acceptable are for static applications such as as irrigation water pumping in areas where petroleum fuels are not readily available but low cost solid fuels are. On the positive side, e.c. engines have the advantage of having the potential to be much longer-lasting than i.c. engines (100 year old steam railway locomotives are relatively easy to keep in working order, but it is rare for i.c. engines to be used more than 20 years or so. E.c. engines are also significantly quieter and free of vibrations than i.c. engines. The level of skill needed for maintenance may also be lower, although the amount of time spent will be higher, particularly due to the need for cleaning out the furnace.

Modern engineering techniques promise that any future steam or Stirling engines could benefit from features not available over 60 years ago when they were last in general use. Products incorporating these new developments are not yet on the market, but R&D is in hand in various countries on a limited scale; however it will probably be some years before a new generation of multi-fuel Stirling or steam powered pumps become generally available.

4.5.1 Steam Engines

Only a limited number of small steam engines are available commercially at present; most are for general use or for powering small pleasure boats. A serious attempt to develop a 2kW steam engine for use in remote areas was made by the engine designers, Ricardos, in the UK during the 1950s (see Fig. 157). That development was possibly premature and failed, but there is currently a revival of interest in developing power sources that can run on biomass-based fuels (as discussed more fully in Section 4.10). However, small steam engines have always suffered from their need to meet quite stringent safety requirements to avoid accidents due to boiler explosions, and most countries have regulations requiring the certification of steam engine boilers, which is a serious, but necessary, inhibiting factor.

The principle of the steam engine is illustrated in Fig. 102. Fuel is burnt in a furnace and the hot gases usually pass through tubes surrounded by water (fire tube boilers). Steam is generated under pressure; typically 5 to 10 atmospheres (or 5-10bar). A safety valve is provided to release steam when the pressure becomes too high so as to avoid the risk of an explosion. High pressure steam is admitted to a power cylinder through a valve, where it expands against a moving piston to do work while its pressure drops. The inlet valve closes at a certain point, but the steam usually continues expanding until it is close to atmospheric pressure, when the exhaust valve opens to allow the piston to push the cooled and expanded steam out to make way for a new intake of high pressure steam. The valves are linked to the drive mechanism so as to open or close automatically at the correct moment. The period of opening of the inlet valve can be adjusted by the operator to vary the speed and power of the engine.

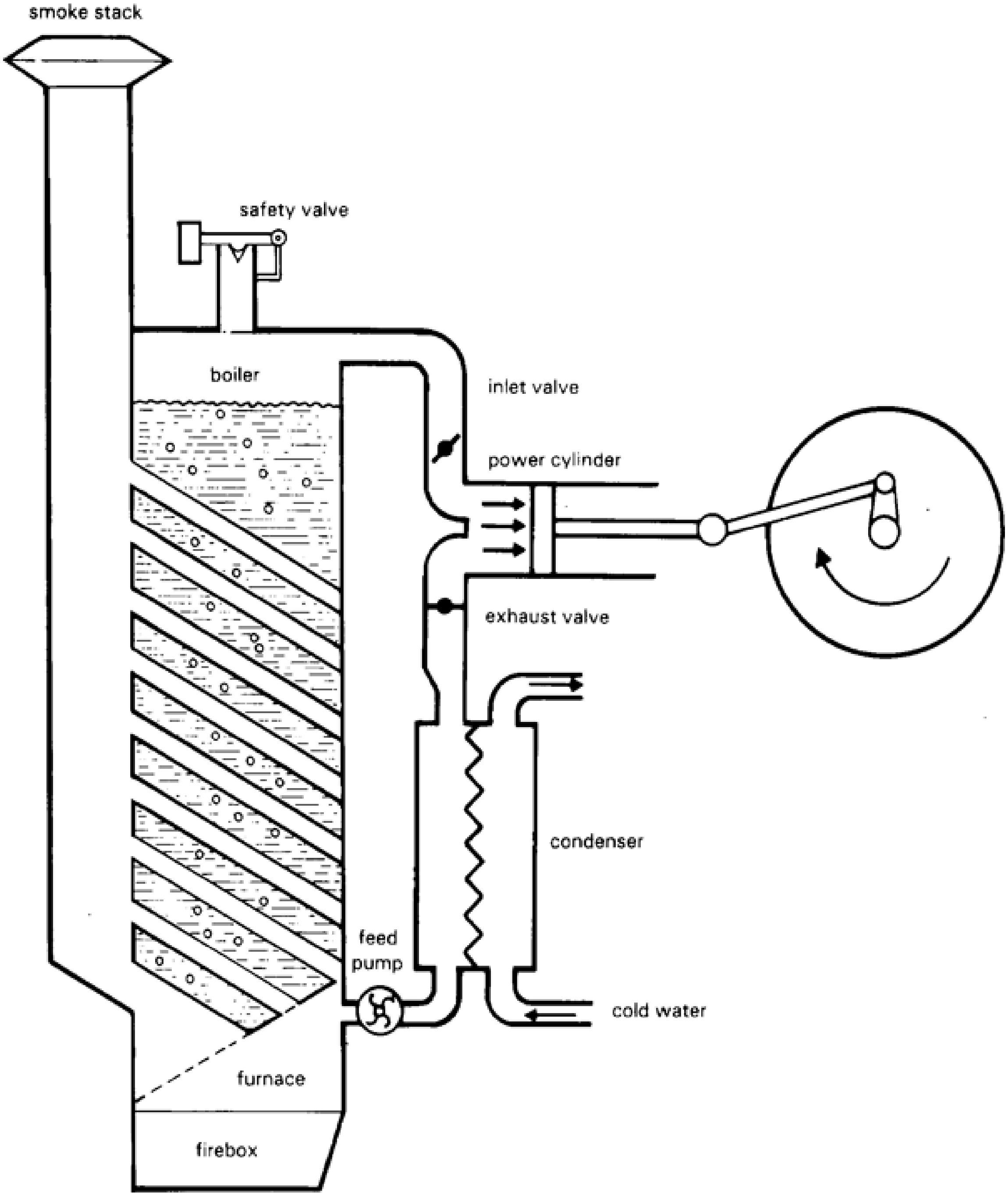


Fig. 102 Schematic arrangement of a condensing steam engine

In the simplest types of engine the steam is exhausted to the atmosphere. This however is wasteful of energy, because by cooling and condensing the exhausted steam the pressure can be reduced to a semi-vacuum and this allows more energy to be extracted from a given throughput of steam and thereby significantly improves the efficiency. When a condenser is not used, such as with steam railway locomotives, the jet of exhaust steam is utilised to create a good draught for the furnace by drawing the hot gases up the necessarily short smoke stack. Condensing steam engines, on the other hand, either need a high stack to create a draught by natural convection, or they need fans or blowers.

Steam pumps can easily include a condenser, since the pumped water can serve to cool the condenser. According to Mead [13], (and others) the typical gain in overall efficiency from using a condenser can exceed 30% extra output per unit of fuel used. Condensed steam collects as water at the bottom of the condenser and is then pumped at sufficient pressure to inject it back into the boiler by a small water feed pump, which is normally driven off the engine. A further important advantage of a condensing steam engine is that recirculating the same water reduces the problems of scaling and corrosion that commonly occur when a continuous throughput of fresh water is used. A clean and mineral-free water supply is normally necessary for non-condensing steam engines to prolong the life of the boiler.

The most basic steam engine is about 5% efficient (steam energy to mechanical shaft energy - the furnace and boiler efficiency of probably between 30 and 60% needs to be compounded with this to give an overall efficiency as a prime-mover in the 1.5 to 3% range). More sophisticated engines are around 10% efficient, while the very best reach 15%. When the boiler and furnace efficiencies (30-60%) plus the pump (40-80%) and pipework (40-90%) are compounded, we obtain system efficiencies for steam piston engine powered pumps in the 0.5 to 4.5% range, which is worse, but not a lot worse than for small s.i. internal combustion engines pumping systems, but allows the use of non-petroleum fuels and offers greater durability.

4.5.2 Stirling Engines

This type of engine was originally developed by the Rev. Robert Stirling in 1816. Tens of thousands of small Stirling engines were used in the late nineteenth and early twentieth century, mainly in the USA but also in Europe. They were applied to all manner of small scale power purposes, including water pumping. In North America they particularly saw service on the "new frontier"; which at that time suffered all the problems of a developing country in terms of lack of energy resources, etc.

Rural electrification and the rise of the small petrol engine during and after the 1920s overtook the Stirling engine, but their inherent multi-fuel capability, robustness and durability make them an attractive concept for re-development for use in remote areas in the future and certain projects are being initiated to this end. Various types of direct-action Stirling-piston water pumps have been developed since the 1970s by Beale and Sunpower Inc. in the USA, and some limited development of new engines, for example by IT Power in the UK with finance from GTZ of West Germany is continuing.

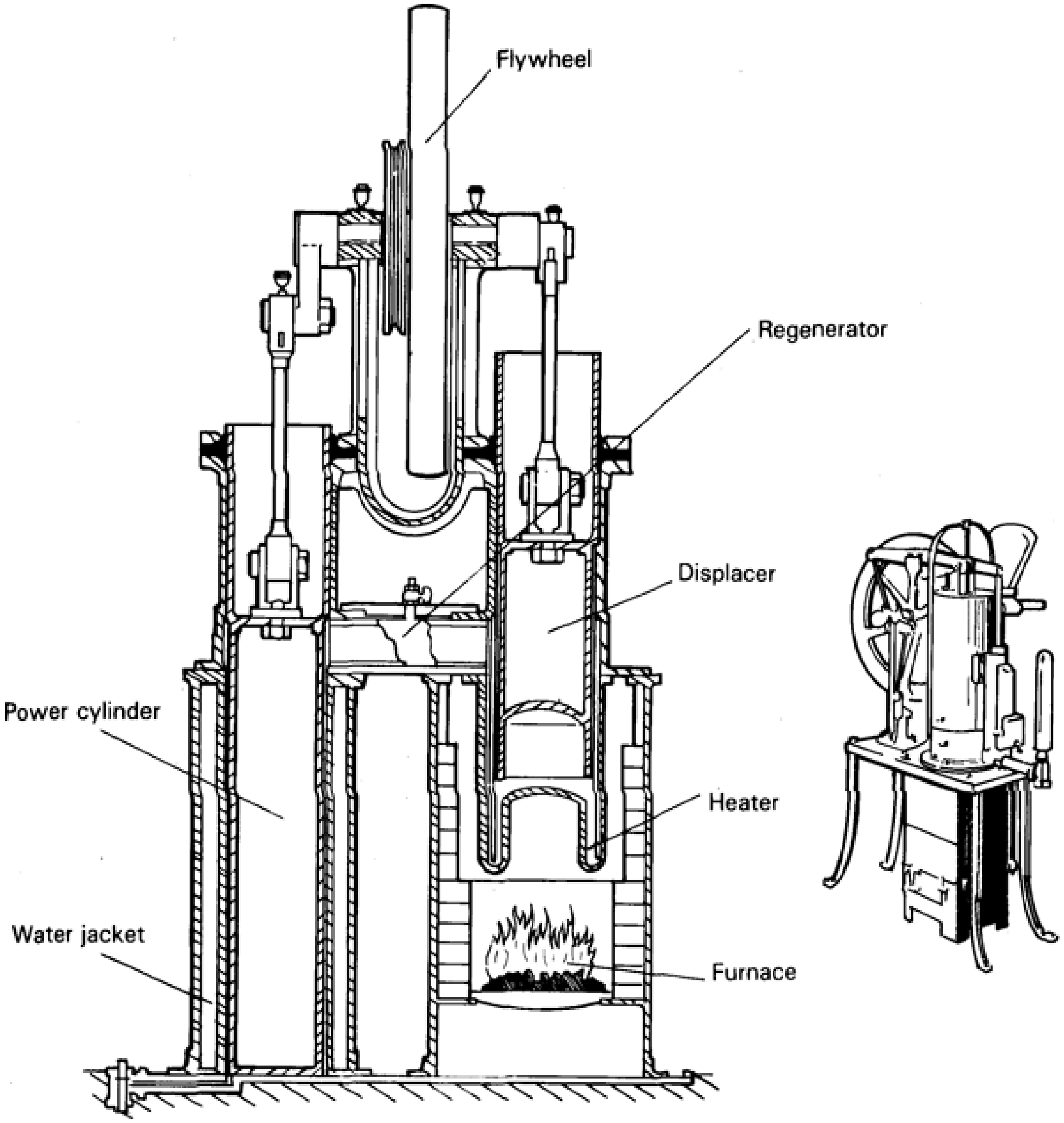


Fig. 103 Rider-Ericsson hot air pumping engine (Stirling cycle) circa 1900

Stirling engines use pressure changes caused by alternately heating and cooling an enclosed mass of air (or other gas). The Stirling engine has the potential to be more efficient than the steam engine, and also it avoids the boiler explosion and scaling hazards of steam engines. An important attribute is that the Stirling engine is almost unique as a heat engine in that it can be made to work quite well at fractional horsepower sizes where both i.c. engines and steam engines are relatively inefficient. This of course makes it of potential interest for small scale irrigation, although at present it is not a commercially available option.

To explain the Stirling cycle rigorously is a complex task. But in simple terms, a displacer is used to move the enclosed supply of air from a hot chamber to a cold chamber via a regenerator. When most of the air is in the hot end of the enclosed system, the internal pressure will be high and the gas is allowed to expand against a power piston, and conversely, when the displacer moves the air to the cool end, the pressure drops and the power piston returns. The gas moves from the hot end to the cold end through a regenerator which has a high thermal capacity combined with a lot of surface area, so that the hot air being drawn from the power cylinder cools progressively on its way through the regenerator, giving up its heat in the process; then when cool air travels back to the power cylinder ready for the next power stroke the heat is returned from the regenerator matrix to preheat the air prior to reaching the power cylinder. The regenerator is vital to achieving good efficiency from a Stirling engine. It often consists of a mass of metal gauze through which air can readily pass, [33], [34].

Some insight into the mechanics of a ' small Stirling engine can be gained from Fig. 103, which shows a 1900 vintage Rider-Ericsson engine. The displacer cylinder projects at its lower end into a small furnace. When the displacer descends it pushes all the air through the regenerator into the water cooled volume near the power cylinder and the pressure in the system drops, then as the displacer rises and pulls air back into the hot space, the pressure rises and is used to push the power piston upwards on the working stroke. The displacer is driven off the drive shaft and runs 90° out.of phase with the power piston. An idea of the potential value of engines such as this can be gained from records of their performance; for example, the half horsepower Rider-Ericsson engine could raise 2.7m^3/hr of water through 20m; it ran at about 140 rpm (only) and consumed about 2kg of coke fuel per hour. All that was needed to keep it going was for the fire to be occasionally stoked, rather like a domestic stove, and for a drop of oil to be dispensed onto the plain bearings every hour or so.

4.6 ELECTRICAL POWER

If a connection is available to a reliable mains electricity supply, nothing else is either as convenient or more cost-effective for powering an irrigation pump. Unfortunately, the majority of farmers in developing countries do not have mains electricity close at hand, and even those that do often find that the supply is unreliable. Electricity supply problems tend to be particularly prevalent during the irrigation season, because irrigation pumping tends to be practised simultaneously by all farmers in a particular district and can therefore easily overload an inadequate rural network and cause "brownouts" (voltage reductions) or even "blackouts" (complete power cuts). Therefore there is a major inhibition for many electricity utilities in encouraging any further use of electricity for irrigation pumping in developing countries where the electrical supply network is already under strain.

The real cost of extending the grid is very high, typically in the order of $5 000-10 000 per kilometer,of spur. Although connections in many countries have in the past been subsidised, whatever the pricing policy of the utility, someone has to pay for it and the tendency today is to withdraw subsidies. Therefore, although an electric motor considered in isolation is an extremely inexpensive and convenient prime-mover, it is only useful when conbnnected to a lot of capital-intensive infrastructure which needs to carry a substantial electrical load in order to be self-financing from revenue.

A further problem for developing countries in considering the mains electricity option is the high foreign exchange component in the investment; this is typically from 50-80%, according to Fluitman, [35] (quoting a World Bank source). Electricity generation in rural areas of developing countries tends to be by petroleum-fuelled plant (usually diesel generators) so this also is a burden on the economy. In fact a large fraction of many developing countries' oil imports goes to electrical power generation. The attractiveness of rural electrification as an investment for development is therefore being questioned much more now then it used to be; (eg. [35]). However it is not proposed here to deal with policy implications or macro-economic effects of the widespread use of electricity for irrigation pumping, other then to point out that it cannot be seen as a universally applicable solution to the world's irrigation pumping needs, because most countries will not be able to afford to extend a grid to all their rural areas in the forseeable future. Even where such an option can be afforded, it is still necessary to question whether it is the most cost-effective solution for irrigation pumping bearing in mind the high infrastructural costs.

4.6.1 Sources and Types of Electricity

Batteries produce a steady flow of electricity known as "direct current" or DC. Photovoltaic (solar) cells also produce DC. Electrical generators to produce DC are sometimes known as "dynamos"; they require commutators consisting of rotating brass segments with fixed carbon brushes. Alternators are almost universally used today for the generation of electricity from shaft power. Alternators are simpler and less expensive than DC generators, but they produce a voltage which reverses completely several times per revolution. This type of electrical output, which is almost universally used for mains supplies, is known as "alternating current" or AC.

AC mains voltage normally fluctuates from full positive to full negative and back 50 times per second (50Hz or 50 cycles/sec) or in some cases at 60Hz. The current fluctuates similarly. Sometimes the current and voltage can be "out of step", i.e. their peaks do not coincide. This discrepency (or phase difference) is quantified by the "power factor"; the output of an AC system is the product of the amps, volts and the power factor. When the amps and volts are in perfect phase with each other, the power factor is numerically 1. When the power factor is less than one (it frequently is 0.9 and sometimes less) then the power available is reduced proportionately for a given system rating. The rating of AC equipment is therefore generally given not in watts or kilowatts (kW), but in volt-amps or kilovolt-amps (kVA). The actual power in kW will therefore be the kVA rating multiplied by the power factor.

Another important principle to be aware of is that it is considerably more economic to transmit electricity any distance at high voltages rather than low. A smaller cross-section of conductor is needed for a given transmission efficiency. This is analagous to water transmission, where higher pressures and smaller flow rates allow smaller pipes to be used for equal hydraulic power. However, electricity is potentially lethal at AC voltages much above 240V and at DC voltages much above 100V (it can of course kill at considerably lower voltages depending on the circumstances and state of health of the victim) and insulation becomes more difficult. Therefore, for safety reasons, 240V AC or about 110V DC are usually the maximum voltages used at the end-users' supplies and for electrical appliances.

The reason AC is generally used for mains applications rather than DC are that it has a number of important advantages:

a. AC generators and motors are much simpler, less expensive and less troublesome, since they do not require commutators;
b. AC voltages can be changed efficiently and with a high degree of reliability, using transformers, but it is a technically much more difficult problem to change DC voltages; therefore AC can easily be transmitted efficiently at high voltages and then transformed to low, safer voltages close to the point of use;
c. as a result of the advantages of AC, it has become the internationally used standard for mains supplies and virtually all mass-produced electrical applicances are designed for AC use.

It is sometimes necessary to convert AC to DC or vice-versa, for example to charge batteries (which are DC) from the AC mains or to run an AC appliance designed for the mains from a DC source such as a battery or a solar photovoltaic array. AC can quite readily be converted to DC by using a rectifier; these (like transformers) are solid-state devices which require no maintenance and are relatively efficient. A battery charger usually consists of a combination of a transformer (to step mains voltage down to battery voltage) and a rectifier to convert the low voltage AC to DC. Converting DC to AC is more difficult; traditionally an inefficient electro-mechanical device called a rotary converter was used; this is a DC motor direct coupled to an AC alternator. The modern alternative is an electronic, solid state device called an inverter. Inverters are relatively inexpensive for low power applications (such as powering small fluorescent lights from low voltage batteries), but they become expensive for such higher powered applications such as electric motors for pumping. The quality and price of inverters also varies a lot; if a good quality AC output is essential (and high efficiency of conversion) a more complicated and expensive device is needed. Cheap inverters often produce a crude AC output and are relatively inefficient; they can also seriously interfere with radio and TV reception in the vicinity.

4.6.2 AC Mains Power

Mains electricity is generally supplied as alternating current (AC) either at 220 to 240V and 50Hz frequency or at 110V and 60Hz frequency for low power connections, (including domestic ones) of up to about 10kW. The 220-240V 50Hz standard is normal in Europe while the 110V 60Hz standard is in use in the USA; either might be used in other parts of the world, although 220-240V is more common, especially in Asia and Africa.

When AC is supplied through two wires, it is known as single-phase. The two wires are not "positive" and "negative" but are "live" and "neutral"; there should always also be a third wire included for safety - the "earth" or "ground". The latter is normally connected to the casing of any appliance or motor so that if any internal fault causes the casing to come into contact with the live supply, the leakage current will flow to earth (ground) and trip out the system or blow a fuse. Therefore if an electric pump keeps tripping or blowing fuses it is as well to have it checked to see if there is a short-circuit.

Mains power is normally generated as "three-phase", in which the alternator transmits three "single phase" AC outputs down three wires. Each phase is shifted by one third of a revolution of the alternator, so the voltage peaks in the three conductors do not coincide, but are evenly spaced out. The three phases, if equally balanced, will cancel each other out if fed through three equal loads, but in practice they are not usually perfectly balanced so there is normally a fourth return conductor called the neutral. A single phase AC supply is simply a connection to one of the three "lives" of a three-phase source with a return to its neutral. For this reason it is important in many cases not to confuse the live and neutral; also it is the live which should be protected by fuses or contact breakers.

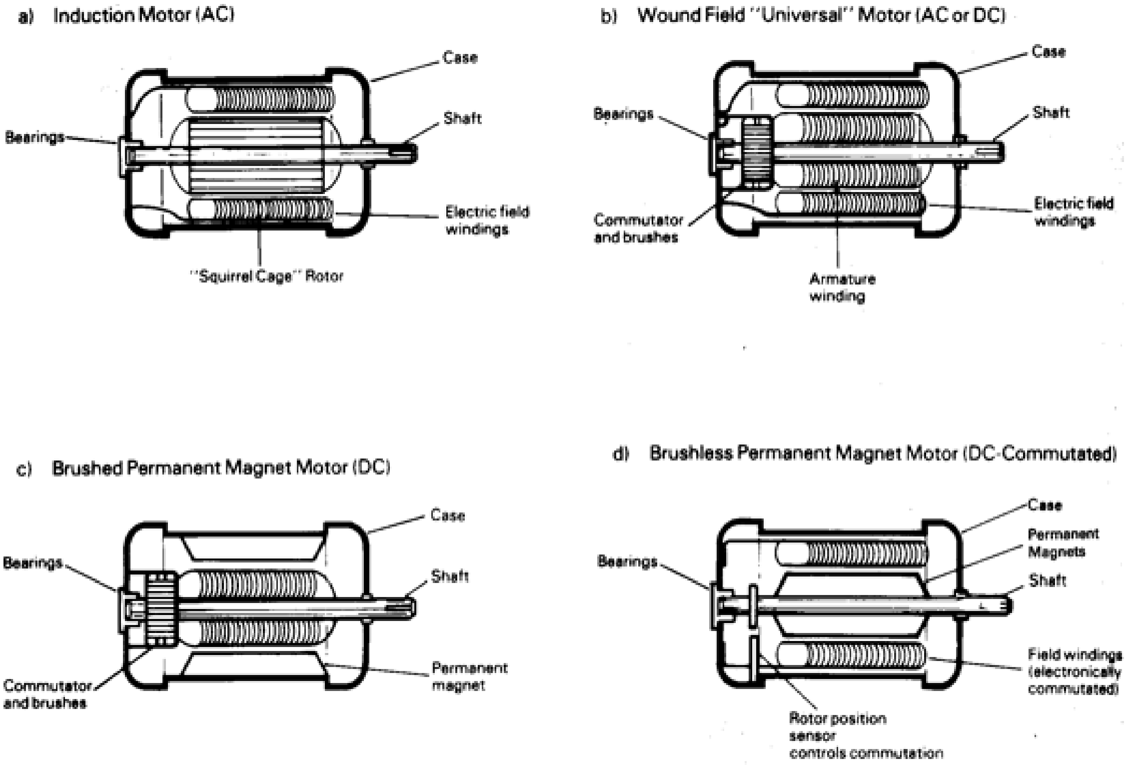
At higher power levels, usually above 5kW, and always above about 25kW, it is normal to use three-phase AC. This is supplied mostly at 415V line to line (Europe) or 190 or 440V (USA).

4.6.3 Electric Motors

An electric motor seems almost the ideal prime mover for a water pump. Power is supplied "at the flick of a switch", and water is produced at a constant rate until the motor is turned off. Electric motors have relatively long service lives and generally need little or no servicing.

The cheapest and simplest type of electric motor is the squirrel cage induction motor which is almost universally used for mains electric power applications; see Fig. 104 (a) and Fig. 105. Here there are no electrical connections to the rotating "squirrel cage", so there are no brushes or slip rings to wear or need adjustment. Motors of this kind are available in either three-phase or single-phase versions. They run at a fixed speed depending on the frequency of the power supply and the number of poles in their stator windings. The most general type (which is usually the cheapest) runs at a nominal 1 500rpm at 50Hz (1 800 at 60Hz), but other speeds are available. It is normal to direct-couple a motor to a centrifugal pump where possible (eg. Fig. 105). Non-standard speed motors may be used where this does not suit the pump, or alternatively a belt speed reduction arrangement may be used, such as in Fig. 106.

A problem with induction motors is that they normally need over three times as much current to start as they do once running at rated speed and power. This means that the peak current that can be supplied must be significantly higher than that needed for operation, which often causes not just technical but also financial problems, as some electricity tariffs are determined by the maximum current rating on a circuit. Recently electronic starting devices have become available which limit the starting current while the motor runs up to speed and which in some cases also improve the overall efficiency of an electric motor.


a) Induction Motor (AC)

b) Wound Field "Universal" Motor (AC or DC)

c) Brushed Permanent Magnet Motor (DC)

d) Brushless Permanent Magnet Motor (DC-Commutated)

Fig. 104 The four main types of electric motors

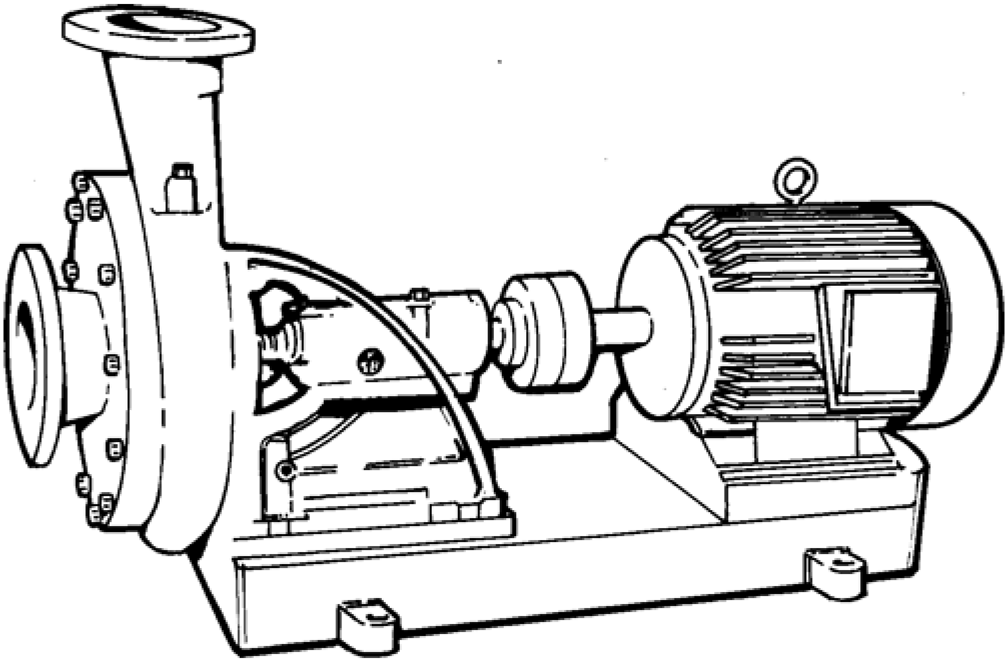


Fig. 105 Direct coupled electric motor and centrifugal pump

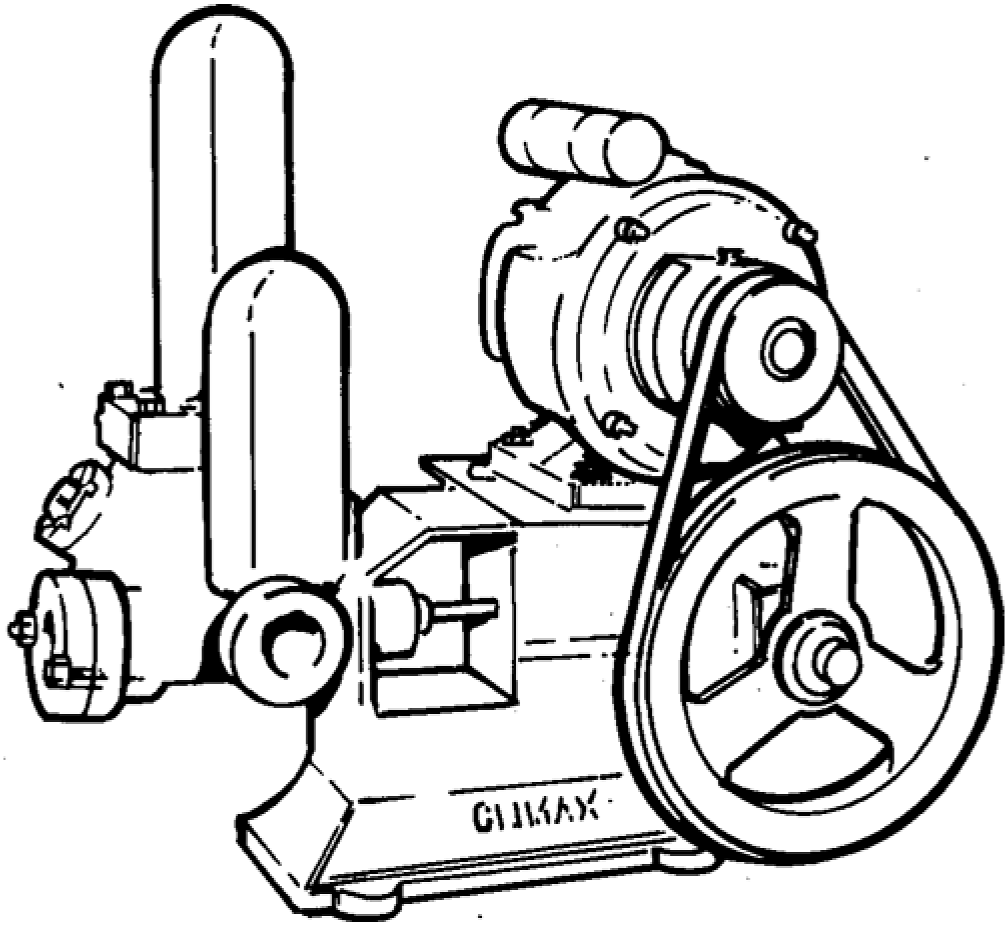


Fig. 106 Electric motor powered, belt driven piston pump (Climax) (note air chambers provided to prevent water hammer)

Induction motors are typically 75% efficient for a 300W (0.5 hp) size and may be around 85% efficient at 10kW size (subject to having a unity power factor). They are not generally made in sizes significantly smaller than 100-200W.

For very small scale applications, the so-called "universal motor" is most commonly used. The universal motor (Fig. 104 (b)) is the "classic" electric motor with a brushed commutator and wound armature. Fixed field coils produce the magnetic flux to run the motor. Motors of this kind can use either an AC or a DC supply and they are typically used for very small-scale power applications (such as in power tools, and domestic appliances, for example). They are more efficient than would be possible with a very small induction motor and their starting current is smaller in relation to their running current. They suffer however from needing periodic replacement of brushes when used intensively, as for pumping duties.

There are small-scale electrical power applications independent of a mains supply, which use a DC source such as a photovoltaic array, or batteries charged from a wind-generator. In these applications a permanent magnet DC motor is the most efficient option (Fig. 104 (c)). In these, permanent magnets replace the field coils; this offers higher efficiency, particularly at part-load, when field windings would absorb a significant proportion of the power being drawn. Permanent magnet DC motors can be 75-85% efficient even at such low power ratings as 100-200W, needed for the smallest solar pumping systems. Most permanent magnet motors have brushed/commutated armatures exactly like a universal motor, which in the pumping context is a major drawback particularly for submersible sealed in motors. However brushless permanent magnet motors have recently become available (Fig. 104 (d)). Here the magnets are fixed to the rotor and the stator windings are fed a commutated AC current at variable frequency to suit the speed of rotation; this is done by sending a signal from a rotor position-sensor which measures the speed and position of the shaft and controls electronic circuitry which performs the commutation function on a DC supply. Motors of this kind are mechanically on a par with an induction motor, and can be sealed for life in a submersible pump if required, but they are still produced in limited numbers and involve a sophisticated electronic commutator which makes them relatively expensive at the time of writing. With the increasing use of solar pumps they are likely to become more widely used and their price may fall.

Submersible pump motors, whether AC induction motors or DC brushless permanent magnet motors, are commonly filled with (clean and corrosion inhibited) water as this equalises the pressure on the seals and makes it easier to prevent ingress of well water than if the motor contained only air at atmospheric pressure. Filling motors with water is obviously only possible with brushless motors, or short-circuits would occur. Another advantage of water filled motors is that they are better-protected from overheating.

4.6.4 Electrical Safety

AC electrical voltages over about 110V and DC over 80V are potentially lethal, especially if the contact is enhanced through the presence of water. Therefore, electricity and water need to be combined with caution, and anyone using electricity for irrigation pumping should ensure that all necessary protection equipment is provided; i.e. effective trips or fuses, plus suitable armoured cables, earthed and splashproof enclosures, etc. Also all major components, the motor, pump and supporting structure should be properly earthed (or grounded) with all earth connections electrically bonded together. It is vital that electrical installations should either be completed by trained electricians or if the farmer carries it out, he should have it inspected and checked by a properly qualified person before ever attempting to use it; (in some countries this is in any case a legal requirement). It is also prudent to have some prior knowledge what action to take for treating electric shock; most electrical utilities can provide posters or notices giving details of precautions with recommendations on treatment should such an unfortunate event occur.