Teaching guide: Engineering physics

This teaching guide provides background material for teaching the Engineering Physics option of our A-level Physics specification (7408). The guide gives teachers more detail on topics they may not be familiar with and is designed to be used alongside the specification. We have not designed it to be used as a comprehensive set of teaching notes.

Some material has been included with the intention of putting flesh on the bones of the specification. This guide should help teachers answer questions in class and extend brighter students. Sometimes this has meant going beyond the specification. Anything that is not explicitly mentioned in the specification is printed on a light background tone.

The section on heat engine cycles is intentionally long, not to reflect the amount of time that should be spent on it, but because this is a topic that has not been covered in depth in traditional A-level physics text books. Its treatment in undergraduate level engineering textbooks goes well beyond the AQA A-level Physics specification.

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Introduction

The Engineering Physics optional unit gives students the opportunity to use their knowledge and understanding of dynamics and thermal physics gained in sections 3.4.1 and 3.6.2. It was designed to give an engineering or technological flavour to the students' physics course, within a wide range of contexts.

In the rotational dynamics section the students again meet many of the concepts covered in linear dynamics, but now applied to rotation. They are reminded of concepts of energy conversion, equations of motion, work, torque, power and momentum and then apply these ideas to rotating machines and objects, which may include the human body.

The thermodynamics section breaks down into the First Law of Thermodynamics and processes, heat engines and efficiency, and refrigerators and heat pumps. The Second Law of Thermodynamics is essential for any true understanding of topical issues of:

- power generation
- 'alternative energy'
- the limitations of internal combustion engines
- combined heat and power schemes
- use of heat pumps to reduce fuel consumption in buildings.

The order in which topics are dealt with in section 2 is slightly different from that of the specification. The Second Law and engines has been put before Engine cycles, whereas in the specification it comes after. The only reason for this is so that the importance of efficiency is dealt with first.

This option may at first glance be considered more mathematical than other options (teachers may remember having to integrate to find moments of inertia, or juggle with complex equations involving p, V, T and γ in thermodynamics) but students following this option should find it no more mathematically demanding than other A-level Physics options, and the examination will test underlying concepts and their application rather than pure mathematical manipulation. As with the other options students are expected to use their knowledge and understanding from the core sections of the specification.

Engineering courses in higher education are heavy in dynamics and thermodynamics, and the Engineering Physics option should give any student going on to study engineering something of a head start.

Chapter 1 Rotational dynamics

a) Concept of moment of inertia

For an isolated mass m at a radius r from the axis of rotation the moment of inertia I is $I = m\,r^2$

The moment of inertia I of an extended object about an axis is defined as the summation of the *mass × radius*^{2} for all the particles that make up the body.

$I = \Sigma\, m\, r^2$

I depends on both the total mass and how the mass is distributed about the axis of rotation. For example, a rod pivoted in the centre has a different moment of inertia from that which it would have when pivoted near one end.

The specification does not require students to be able to derive expressions for moments of inertia of rotating objects, but they may be required simply to add moments of inertia. For example, they would be expected to know that if a small mass m is added at radius r to a wheel of moment of inertia I the new moment of inertia is $I_{\text{new}} = I + m\,r^2$.

b) Rotational kinetic energy

The total kinetic energy of an object rotating about an axis can be found by summing the kinetic energies of all the individual particles that make up the object. This summation can be found in many older advanced-level physics textbooks, and because it explains the importance of $\Sigma\, m\, r^2$, teachers are very strongly advised to run through it. This is not, however, a requirement of the specification.

The rotational kinetic energy E_k for a body of moment of inertia I rotating at ω rad s^{-1} is given by $E_k = \frac{1}{2} I\,\omega^2$.

c) Flywheels

Flywheels are used in machines to accumulate and store energy. In some machines, the flywheel is used entirely as an energy store, for example in:

- a “push-and-go” toy car a high-revving flywheel provides the energy to move the car.
- experimental vehicles that use flywheel batteries (see below) as a source of energy. The flywheel is charged up by an electric motor at a fixed location, and is driven by flywheel power to the next location.
- regenerative braking in vehicles - where the energy absorbed by braking is used to ‘charge’ a flywheel, which then accelerates the vehicle at a later time. These systems are sometimes referred to as 'KERS' (kinetic energy recovery systems).

In other machines, flywheels **even out fluctuations in rotational speed** that would occur if the flywheel were not fitted. A flywheel is fitted to the crankshaft of an internal combustion or a reciprocating steam engine where the load torque may be fairly constant but the torque provided by the engine varies with the pressure on the piston and the crank angle. The flywheel also takes the engine over the ‘dead centres’, the positions at the top and bottom of the piston stroke at which the crank and connecting rod are in line and there is no turning effect.

In such engines, most of the time the load torque and engine torque are different. When the engine torque is greater than the load torque, the flywheel accelerates and when the engine torque is less than the load torque the engine decelerates. The flywheel accumulates energy as it speeds up and gives up the energy when the load torque falls.

The greater the moment of inertia, the smaller is the fluctuation in speed.

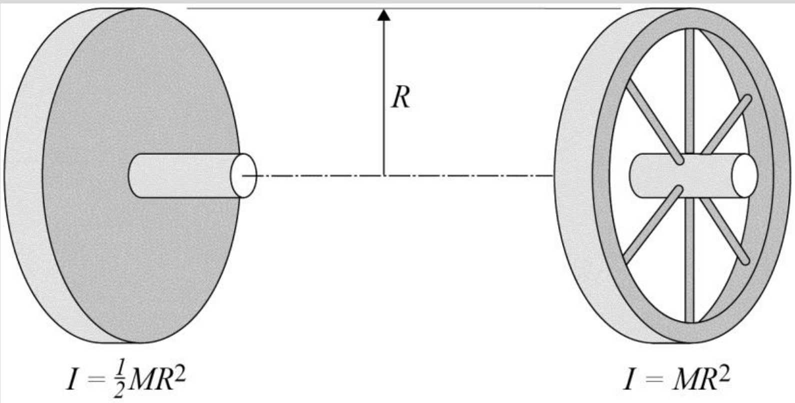
Flywheels fitted to large Victorian steam engines such as those used in pumping stations and textile mills had a massive rim fitted with spokes. This gave a greater moment of inertia than if the same mass had been used to make a solid disc flywheel of the same diameter.

Although students will be given expressions for moments of inertia in an examination, the following will be useful for discussing the shape of flywheels
Neglecting the mass of spokes and axle:

For an ideal spoked wheel with all the mass at radius R — $I = M R^2$

For a uniform solid disc of mass M and radius R — $I = \frac{1}{2} M R^2$

Figure 1



Factors affecting energy storage of a flywheel

Students should be aware that the maximum energy storage capacity depends on the mass and shape of the flywheel (hence its moment of inertia) and its maximum angular speed. The maximum allowed angular speed is governed by the breaking stress of the material of which the flywheel is made.

More able students should be able to cope with the following mathematical reasoning:

For a **solid disc** of radius R, thickness t mass M and density ρ

$M = \pi R^2 t \rho$

If I is the moment of inertia about the axis of rotation $I = \frac{1}{2} M R^2$

So $I = \frac{1}{2} (\pi R^2 t \rho) R^2$

So E_k is proportional to $R^4 \omega^2$.

Flywheel batteries

Flywheel 'batteries' are flywheels specially designed to store as much rotational energy as their size, mass and rotational speed permit. They have been incorporated in drive systems for vehicles where, for example, energy normally lost as heat when braking is stored in a rapidly spinning flywheel. Magnetic 'floating' bearings and vacuum enclosures reduce energy losses due to friction and air resistance. Research is being carried out into the design of flywheel batteries as energy stores for emergency back-up in case of power supply failure, eg in hospitals. Flywheel batteries are used in the 'Incredible Hulk' roller coaster at Universal's 'Islands of Adventure' to drive generators to provide the brief spurt of high electric current needed to accelerate the train rapidly up the track at launch.

The energy storage capacity of flywheel batteries depends on I and maximum ω. As the speed increases the centripetal stress in the material increases and eventually the flywheel will 'burst'. As a result, high-strength carbon-fibre composites and titanium are being used in the manufacture of high speed flywheel batteries with maximum speeds of above $50\,000 \text{ rev min}^{-1}$, with the flywheel encased in a strong containment system in case the wheel accidentally bursts.

Machine tools

Some machine tools, such as those used for punching holes in, or blanks from, sheet metal, or for forming shapes from sheet metal (car body parts), require a large work output in a relatively small time. They can be driven hydraulically or pneumatically, but some utilise an electric motor and flywheel. The flywheel is brought up to speed and then supplies the energy for the punching/pressing operation momentarily. If a motor on its own were used, it would simply stall.

d) Angular displacement, velocity and acceleration

$$\omega_2 = \omega_1 + \alpha t$$

$$\theta = \omega_1 t + \frac{1}{2}\alpha t^2$$

$$\omega_2^2 = \omega_1^2 + 2\alpha\theta$$

$$\theta = \frac{1}{2}(\omega_1 + \omega_2) t$$

Students should know how to use the above equations of motion as applied to rotation.

There is an opportunity here to revise equations of motion for uniformly accelerated linear motion from Section 3.4.1. They should know that angular displacement may need to be changed from revolutions or degrees to radians, and rotational speeds may have to be changed from $\mathrm{rev\ min^{-1}}$ or $\mathrm{rev\ s^{-1}}$ to $\mathrm{rad\ s^{-1}}$.

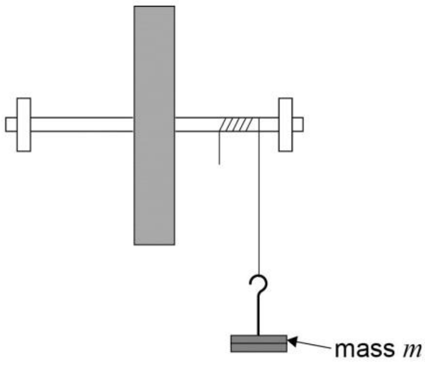
As in linear dynamics, students should be able to interpret displacement–time and velocity–time graphs for rotational motion.

e) Torque and angular acceleration

Once again there is an opportunity to reinforce ideas covered in Section 3.4.1. Students should be confident in their understanding of moments and couples from Section 3.4.1 before starting this section.

The effect of torque on angular acceleration can be demonstrated using a simple wheel and axle as shown in **Figure 2**.

Figure 2



Increasing m or changing the wheel for a lighter smaller one will increase α.

Students will need to be able to use the equation $T = I\alpha$ in a variety of familiar and unfamiliar contexts. They will **not** be asked for its derivation.

It is important to stress the use of appropriate units. Although $kg\ m^2\ rad\ s^{-2}$ or $kg\ m^2\ s^{-2}$ are *technically* correct, students should know that the newton-metre ($N\ m$) is the unit for torque.

In linear motion, we would not expect a student to write the unit of force as '$kg\ m\ s^{-2}$'.

In linear motion, the F in $F = ma$ is the unbalanced or resultant force. The same applies in rotation using $T = I\alpha$ There is usually a frictional torque which acts at the bearings of a rotating wheel or object opposing any applied torque, and this has to be taken into account. It can be found experimentally by taking the wheel or shaft or object up to speed, removing the accelerating torque, and allowing it to gradually run to a standstill. If the deceleration and moment of inertia are known, the average decelerating or frictional torque can be calculated.

f) Angular momentum

Students should know that angular momentum is defined as the product $I \times \omega$ and that the units for angular momentum are $N\ m\ s$.

They should understand that angular momentum is only conserved in cases where no external **torque** acts. A common exam error is to write '.....where no external force acts.'

The conservation of angular momentum can be demonstrated by sitting a student on a swivel chair, preferably one not fitted with castors. Ask the student to hold a $1\ kg$ mass in each hand, with the masses close to the chest. Another person spins the chair, lets it go, and asks the subject to extend their arms quickly. The speed drops suddenly. Extending the arms increases the moment of inertia and because angular momentum must be conserved, the angular speed must drop.

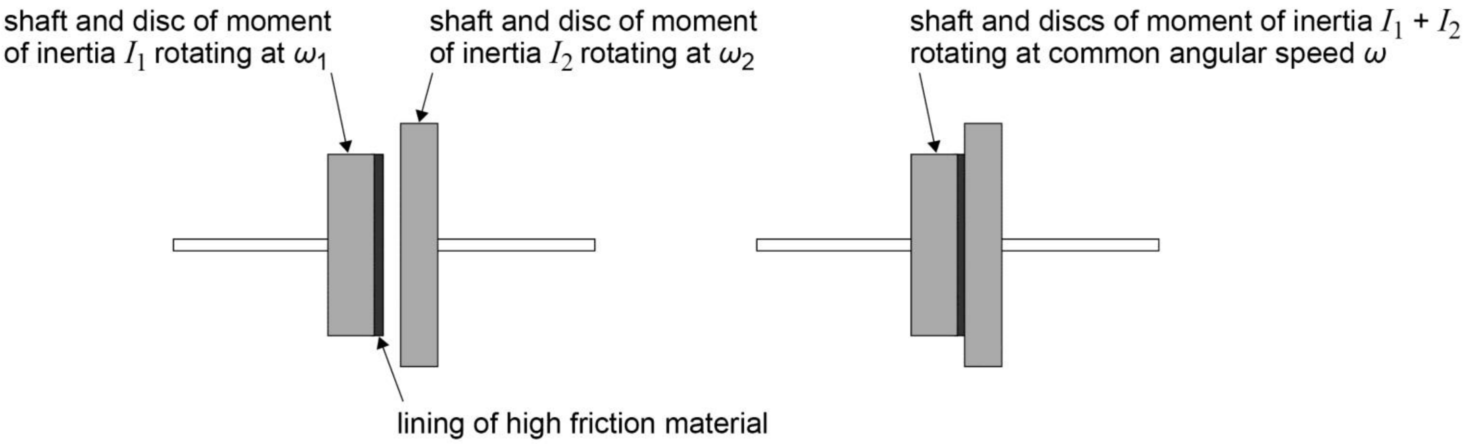
Repeat with the arms extended to start with, bringing them in close – the speed increases.

This illustrates why divers tuck themselves in to be able to perform several somersaults before reaching the surface of the water, and trampolinists, dancers or ice skaters bring their arms close to the body to spin faster. It is even better with $2\ kg$ masses, but take care!

Simple clutches

A clutch is used to bring shafts of differing moments of inertia rotating at different speeds together so they end up with a common angular speed. It is an example of a rotational dynamics 'collision', analogous to a collision in linear dynamics. See **Figure 3**.

Figure 3



Angular momentum before engagement

$= I_1 \omega_1 + I_2 \omega_2$

Angular momentum after engagement

$= (I_1 + I_2)\, \omega$

Applying the law of conservation of angular momentum:

$I_1 \omega_1 + I_2 \omega_2 = (I_1 + I_2)\, \omega$

from which the common angular speed after the clutch is engaged can be calculated.

Angular impulse

Angular impulse is the product of torque and its time of duration and is equal to the change in angular momentum in that time. Students should know that angular impulse is equal to the area under the torque-time graph, in the same way that impulse in linear dynamics is equal to the area under the force-time graph.

g) Work and power

Work has to be done on an object to cause it to rotate about an axis. Examples where large amounts of work (and correspondingly high torques) are required are swing bridges, rotating cranes and some fairground or adventure-park rides.

Students are expected to be able to apply the equations $W = T\,\theta$ and $P = T\omega$ in a wide variety of situations and should realise that in rotating machinery, power has to be expended in overcoming an opposing (frictional) torque. Students should know that the area under a T - θ graph represents work done.

> Although not explicit in the specification, a useful application of $P = T\omega$ is in measuring the output power of an engine or motor using a string, rope or band brake – see Appendix A

h) Analogy between translational and rotational motion

Students should be aware of the analogy between translational and rotational motion. They should find the analogy helpful in remembering how to apply formula, in the same way that they might be encouraged to consider the analogy between electrical and gravitational fields. This can be a useful revision tool.

feature	linear motion	rotational motion
displacement	x	θ
velocity	$v = \frac{\Delta s}{\Delta t}$	$\omega = \frac{\Delta\theta}{\Delta t}$
acceleration	$a = \frac{\Delta v}{\Delta t}$	$\alpha = \frac{\Delta\omega}{\Delta t}$
equations of motion for constant acceleration	$v = u + at$ $s = ut + \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \frac{1}{2}(u + v)t$	$\omega_2 = \omega_1 + \alpha t$ $\theta = \omega_1 t + \frac{1}{2}\alpha t^2$ $\omega_2{}^2 = \omega_1{}^2 + 2\alpha\theta$ $\theta = \frac{1}{2}(\omega_1 + \omega_2)t$
inertia	mass m	moment of inertia I
kinetic energy	$E_k = \frac{1}{2}m\,v^2$	$E_k = \frac{1}{2}I\,\omega^2$
force/torque	$F = ma$	$T = I\alpha$
momentum	mv	$I\,\omega$
impulse	$F\,\Delta t = \Delta(mv)$	$T\,\Delta t = \Delta(I\omega)$
work	$W = F\,s$	$W = T\,\theta$
power	$P = F\,v$	$P = T\,\omega$

Chapter 2 Thermodynamics and engines

a) First Law of thermodynamics

The First Law of thermodynamics is the law of conservation of energy applied to heating, cooling and working.

The First Law is expressed in different ways, according to the sign convention used. In our specification the First Law is applied to 'systems' and is written

$Q = \Delta U + W$

where

Q = energy supplied by heat transfer

If energy is **removed** by heat transfer (ie a gas is cooled) Q is **negative**.

ΔU = change in internal energy. If ΔU is **positive** there is an **increase** in internal energy, if **negative** there is a **decrease** in internal energy.

W = work done. If work is done **on** a gas, as happens when it is compressed, W is **negative**. If work is done **by** the gas, as happens when a gas expands, the work done is **positive**.

Energy supplied or removed by heat transfer = change in internal energy + work done on or by the gas.

Students should be aware of the importance of getting the sign convention correct.

The specification refers to a 'system'. In order to solve problems involving changes, being able to define the system, boundary and surroundings can be extremely useful.

A system is a region in space containing a quantity of gas or vapour. Open systems are those in which the gas or vapour flows into, out of, or through the region. The gas may pass across the boundary between the system and its surroundings.

Examples of open systems are:

- A liquid or gas expanding through a nozzle from an aerosol can.
- Steam passing through a turbine.

Closed systems are those where the gas or vapour remains within the region, although the boundary separating the closed system from its surroundings may not be fixed – it can expand or contract with changes in the volume of the gas.

Examples of closed systems are:

- A gas expanding in a cylinder by moving a piston.

- Air in a balloon being heated.

In both types of system heat and work can ‘cross’ the boundary.

b) Non-flow processes

A process is a change from one state to another, where the state of the gas is determined by its pressure (p), volume (V) and temperature (T). Because the specification is concerned with non-flow processes (where the gas does not flow across the boundary) the systems involved are closed systems.

Students and teachers need not be concerned with the intricacies of the idea of reversibility.

As a starting point, a quick revision of the ideal gas equation $pV = nRT$ would be helpful (see Section 3.6.2.2 of the specification).

The four basic changes or processes are isothermal, adiabatic, constant pressure and constant volume.

In all of these changes the application of $\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$ often provides a useful short cut.

Isothermal change

This is a change that occurs at constant temperature. If the temperature, and hence internal energy, is to remain constant, thermal energy must be supplied to the gas and the gas will expand, doing an amount of work equal to the heat supplied. Since the internal energy does not change, ΔU = zero, so $Q = W$.

Such a process is impossible, but if the container were a perfect conductor, or the process occurs infinitely slowly so that there is time for heat to transfer and the gas is always in thermal equilibrium with the surroundings, the process will be truly isothermal.

In reality, a slow process in a container which is a good conductor will be nearly isothermal.

An isothermal change obeys the law:

$pV = constant$ This is also known as Boyle’s Law.

$p_1 V_1 = p_2 V_2$

Adiabatic change

Here there is an opportunity to teach a little Greek! The word *adiabatic* comes from *a* – meaning **not** as in *a*symmetric, *dia* - meaning **through** as in *dia*meter, and *batos* - meaning **passable**, as in passing a baton in a relay race.

An adiabatic change is one in which no heat passes into or out of the gas.
Q = zero, so any work done is at the expense of the internal energy of the gas.

If the gas expands, as in a balloon bursting,

$Q = \Delta U + W$

Therefore $W = -\Delta U$. The internal energy, hence the temperature, goes down as work is done by the gas in pushing away the surrounding air.

If the gas is compressed, as in the compression stroke of an internal combustion engine,

$Q = \Delta U + W$

Therefore $-W = \Delta U$. The internal energy, and hence the temperature, goes up as work is done on the gas.

The change obeys the law:

pV^{γ} = *constant*

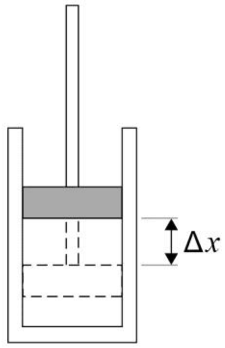
$p_1 \times V_1^{\gamma} = p_2 \times V_2^{\gamma}$

Students should be able to use their calculators to calculate pressures and volumes in adiabatic processes.

Constant pressure change

The gas in the cylinder shown in **Figure 4** is under a constant pressure due to the weight of the piston.

Figure 4



If the gas is heated, the piston moves up a distance Δx. The work done W is F Δx where

F = *pressure × area of piston*

$F = p\,A$

Therefore $W = p\,A\,\Delta x = p\,\Delta V$

Heating a gas at constant pressure causes an increase in volume (ΔV) and temperature, and external work is done owing to the increase in volume. Cooling the gas will reduce the temperature and volume.

Constant volume change

If the gas is heated in a fixed enclosed space, it remains at constant volume and the pressure and temperature, and hence internal energy both increase. Because there is no volume change (the boundary does not move) there can be no work done.

$Q = \Delta U + W$

$W = 0$ (no volume change)

so $Q = \Delta U$

The whole of the energy supplied by heating is stored in the gas in the form of increased internal energy.

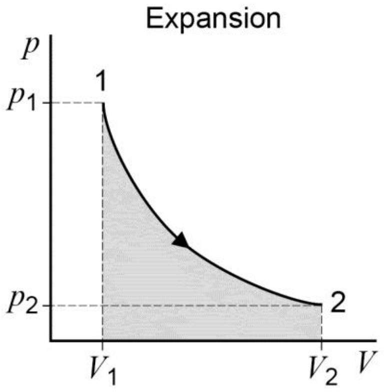
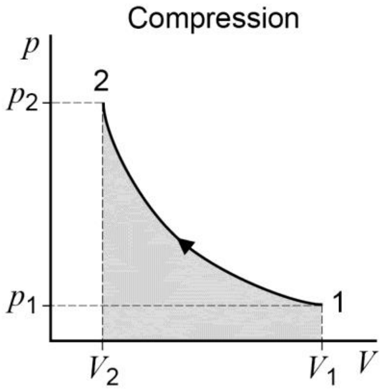
This process occurs when a camping gas bottle is warmed by the sun throughout the day. There is usually a warning not to store in direct sunlight.

c) The *p-V* diagram

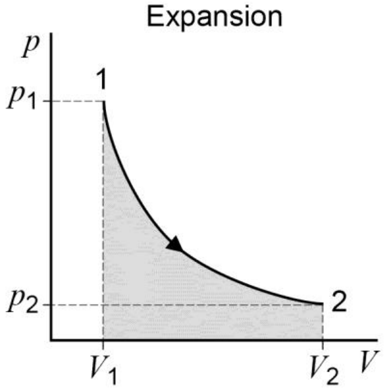
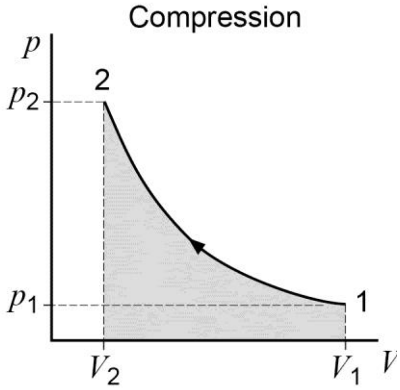
A graph of pressure against volume, or p–V diagram, is a very useful tool for visualising various processes, and is particularly important when analysing engine cycles.

Lines of constant temperature, called isotherms, can be drawn on the diagram to show temperatures. The further the isotherm is from the origin, the higher the temperature. The following p–V diagrams summarise isothermal, adiabatic, constant pressure and constant volume changes.

Isothermal change

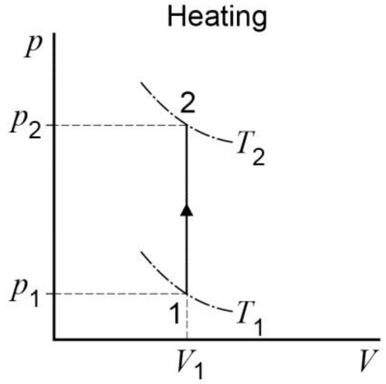
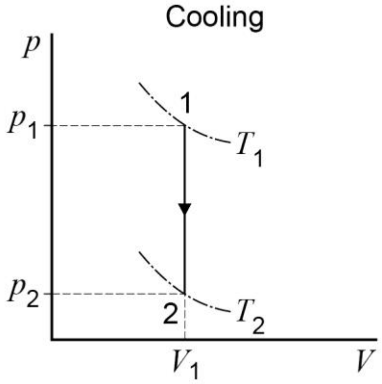
Isothermal change		
Constant temperature change from p_1, V_1, to p_2, V_2. $p_1V_1 = p_2V_2$ Work done = area shaded		
Application of First Law As there is no temperature change there is no change in internal energy.	$Q = \Delta U + W$ $\Delta U = 0$ so $Q = W$ Energy must be given to gas by heat transfer for work to be done **by** the gas.	$-Q = \Delta U - W$ $\Delta U = 0$ so $-Q = -W$ Heat transfer from gas = work done **on** gas.

Adiabatic change

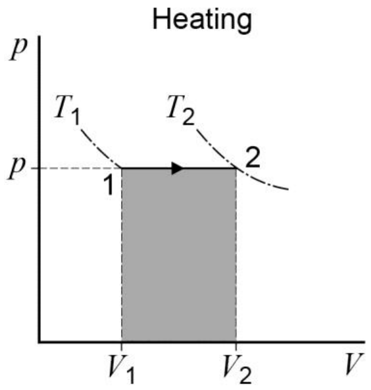
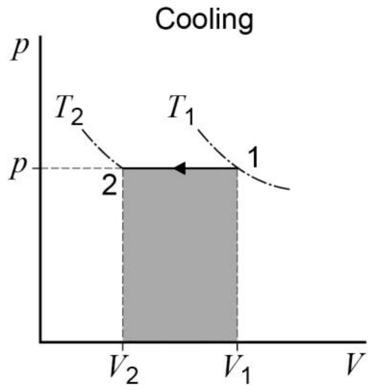
Adiabatic change		
Change from p_1, V_1, to p_2, V_2 with no heat transfer $p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$ Work done = area shaded		
Note line is steeper than isothermal	$Q = \Delta U + W$ $Q = 0$ so $W = -\Delta U$ Work is done at expense of the	$Q = \Delta U + W$ $Q = 0$ and W is negative so $\Delta U = -W$

change from same start conditions. Application of First Law	internal energy of gas. Internal energy, hence temperature, falls as work is done **by** the gas.	Work done **on** gas = increase in internal energy. Temperature increases.

Constant volume change

Constant volume change		
Constant volume change from p_1, V_1 to p_2, V_1	Heating 	Cooling 
Application of First Law Since there is no volume change, no work is done.	$Q = \Delta U + W$ $W = 0$ (no volume change) so $Q = \Delta U$ Energy must be given to the gas by heat transfer for the internal energy, hence temperature, to rise.	$Q = \Delta U + W$ $W = 0$ so $-Q = -\Delta U$ Energy leaves gas by heat transfer (gas must be cooled) and internal energy falls.

Constant pressure change

Constant pressure change		
Volume changes from V_1 to V_2. Work done = area shaded = $p(V_2 – V_1)$		
Application of First Law	$Q = \Delta U + W$ $W = p(V_2 – V_1)$ Energy must be given to gas by heat transfer for the internal energy, hence temperature, to rise and for work to be done **by** the gas.	$–Q = –\Delta U + (–W)$ $W = p(V_1 – V_2)$ Energy leaves gas by heat transfer and internal energy falls. Work is done **on** the gas.

Combining these processes into engine cycles is covered in chapter 2, section E of this booklet.

d) The Second Law and engines

An internal combustion engine is supplied with energy in the form of the chemical energy of the fuel. The chemical energy is transformed into internal energy which the engine in turn converts into mechanical energy. The overall efficiency of the engine is the ratio:

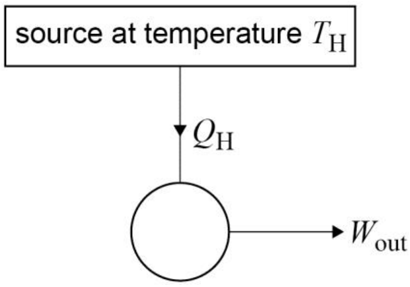
$$\frac{\text{Useful energy or work output}}{\text{energy input}} \times 100\%$$

The Law of Conservation of Energy tells us that we cannot have an engine which is greater than 100% efficient, since this would mean we had created work from nothing. We want an engine of a given size to provide as much power as possible for every kg of fuel used, so the more efficient the engine the greater the km per litre of fuel and the less the cost of running the car. Also, if less fuel is used, less CO_2 will be released into the surrounding atmosphere.

Figure 5 shows a heat engine in which there is no friction and which obeys the First Law of Thermodynamics. $W_{out} = Q_H$.

For there to be heat transfer Q_H to the engine we require a source of heating, at temperature T_H. We assume that this source remains at a constant temperature.

Figure 5



This engine is 100% efficient, all of Q_H is converted to W_{out}. Students should appreciate that no one has ever been able to make such an engine. They will probably be able to reason that in a real engine there must be frictional losses and so W_{out} is less than Q_H, but this is not enough of a reason for the very low efficiencies of heat engines.

All engines must obey the Second Law of Thermodynamics. This Law tells us that the efficiency of any process for converting heat into work cannot approach 100%. In other words an ideal engine which satisfies **both** laws of thermodynamics must have a source **and** a sink. The engine must be subjected to heating from the source and it **must** reject some energy to the sink. The source must be at a higher temperature than the sink. This as a fairly basic way of expressing the Second Law of Thermodynamics, but it is valid all the same, and to deal with the problem of low efficiency by bringing in ideas of entropy is well beyond the scope of the specification (although not beyond the capabilities of some students).

Figure 6

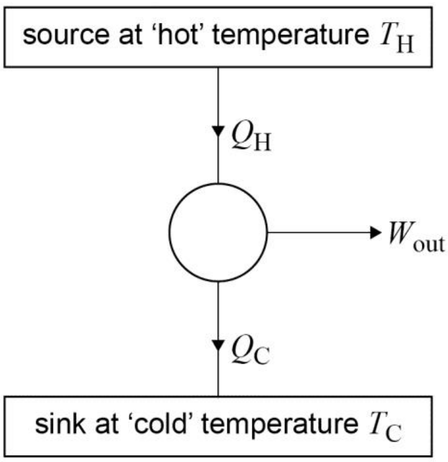


Figure 6 shows an engine which obeys the first and second laws of thermodynamics. The efficiency η of this engine is given by

$$\eta = \frac{W_{\text{out}}}{Q_{\text{H}}} = \frac{Q_{\text{H}} - Q_{\text{C}}}{Q_{\text{H}}} = 1 - \frac{Q_{\text{C}}}{Q_{\text{H}}}$$

If an ideal gas is used as the working substance in the engine, an analysis using the concept of entropy change (outside the scope of the specification) gives the following relation for the maximum possible theoretical efficiency of a heat engine operating between source and sink temperatures of T_{H} and T_{C}:

$$\eta = \frac{W_{\text{out}}}{Q_{\text{H}}} = \frac{Q_{\text{H}} - Q_{\text{C}}}{Q_{\text{H}}} = \frac{T_{\text{H}} - T_{\text{C}}}{T_{\text{H}}}$$

The engine will be 100% efficient when the sink is at a temperature of absolute zero. Real engines reject their energy by heat transfer to the atmosphere (eg car engines) or to rivers and seas (eg power stations). Therefore, to make an engine as efficient as possible whilst rejecting energy to a sink, the temperature of the source must be as high as possible. The source temperature is limited by the high-temperature properties of the materials of which the engine is made.

In the days of cheap fuel and before concerns about the limited world reserves of fossil fuels, heat engines were used exclusively for their work output. There is now an increasing move towards utilising the rejected energy Q_{C} in combined heat and power schemes (see page 31).

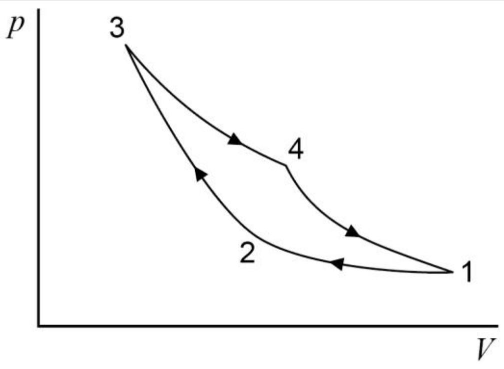
The Carnot cycle

Most heat engines contain a working 'fluid' such as gas or steam which is taken through a cycle. During each cycle a net amount of work is done. At the end of each cycle the working fluid is returned to its original pressure temperature and volume, ready to go through the next cycle. There are many different types of heat engine cycle, and only a few give the ideal efficiency

$$\frac{T_H - T_C}{T_H}$$

One cycle which does give this ideal efficiency is the Carnot cycle, (named after Sadi Carnot, 1796 – 1832, who first proposed that the maximum efficiency of a reversible engine depends on the temperatures between which it works). For this reason, the maximum possible efficiency is sometimes referred to as the Carnot efficiency.

Figure 7



In the Carnot cycle the energy input Q_H is by heat transfer during an isothermal expansion, (process 3 → 4) and the energy output Q_C to the sink is by heat transfer during an isothermal compression (1 → 2).

The rest of the cycle is made up of an adiabatic expansion (4 → 1) and an adiabatic compression (2 → 3) where $Q = 0$, so the net work out must equal to $Q_H - Q_C$.

It can be shown that the efficiency of this cycle is given by

$$\eta_{camot} = \frac{W_{out}}{Q_H} = \frac{Q_H - Q_C}{Q_H} = \frac{T_H - T_C}{T_H}$$

If it were possible to make an engine that operated on the Carnot cycle, it would have a very small power output/engine size ratio because the area of the p–V loop is very small (compare with **Figure 11**).

e) Engine cycles

The principle of the internal combustion engine is very simple. A mass of air is compressed at a low temperature and expanded at a high temperature. Because the work needed to compress the air at a low temperature is less than the work done by the air when it expands at a high temperature, there is a net output of work. The air in the engine must be heated in order to raise its temperature between the compression and the expansion. It is called an internal combustion engine because this heating is done inside the engine.

The four stroke cycle

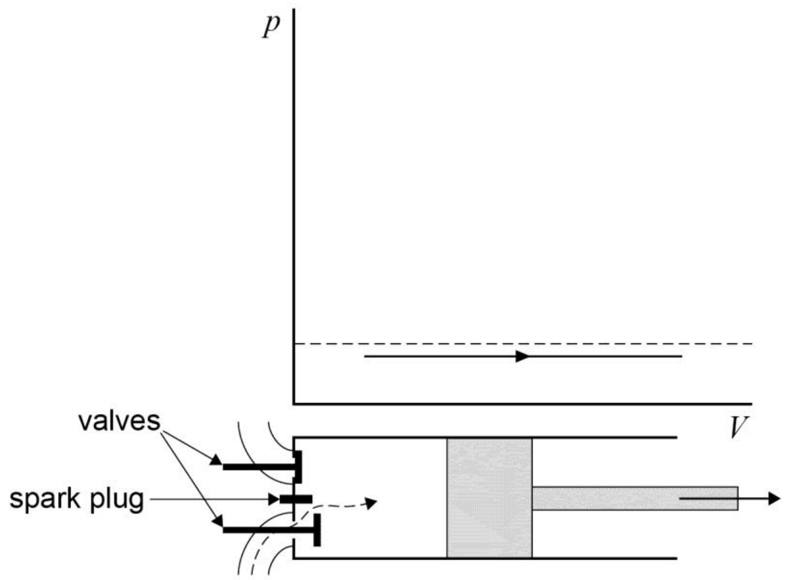
In a petrol or diesel engine a piston moves easily up and down in a cylinder with an almost gas-tight fit between the two. Each movement of the piston up or down is called a stroke. In a four-stroke engine, the fuel is burned once every four strokes, and in a two-stroke engine once every two strokes. The sequence of operations for one complete four-stroke petrol engine cycle, comprising, induction, compression and exhaust strokes is outlined in **Figure 8**.

The specifications do **not** require knowledge of the working of two-stroke or rotary (Wankel) engines.

Figure 8 The four strokes of a spark ignition petrol engine

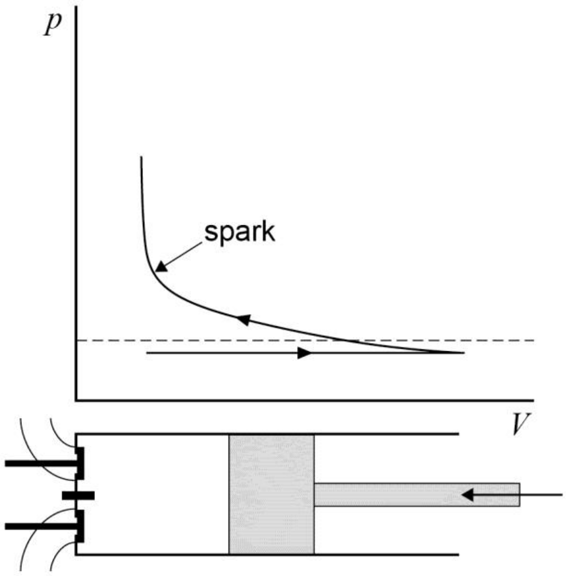
Induction

- The piston travels down the cylinder. The volume above it increases and a mixture of air and petrol vapour is drawn into the cylinder via the open inlet valve. The pressure in the cylinder remains constant, just below atmospheric pressure.



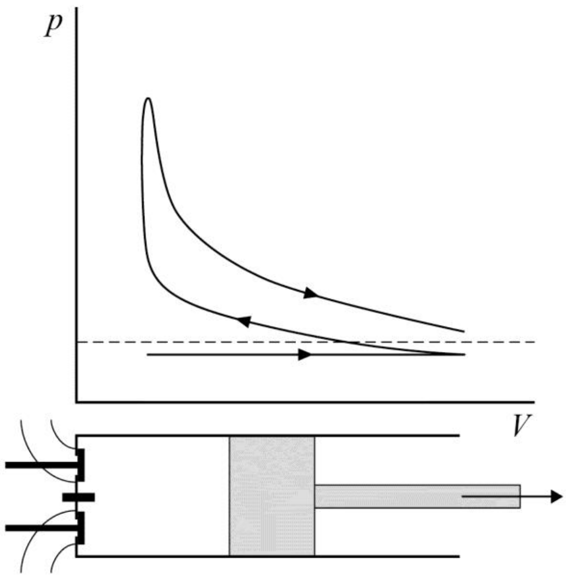
Compression

- Both valves are closed. The piston travels up the cylinder, the volume decreases and the pressure increases. Work is done on the air to compress it. Very near the end of the stroke the air/petrol mixture is ignited by a spark at the spark plug, resulting in a sudden increase in temperature and pressure at almost constant volume.



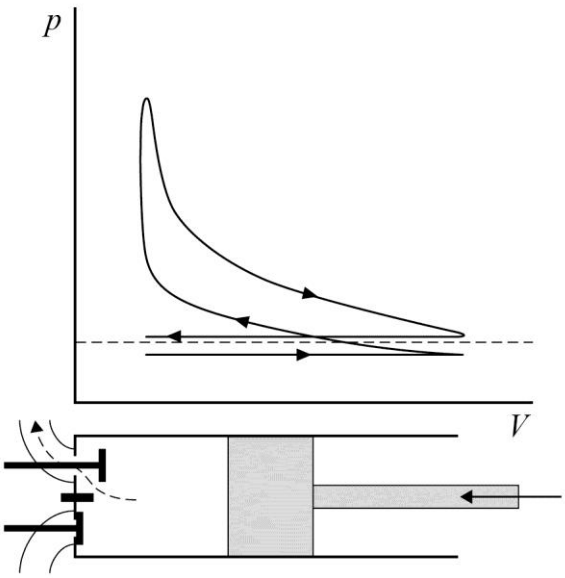
Expansion

- Both valves remain closed, and the high pressure forces the piston down the cylinder. Work is done by the expanding gas. The exhaust valve opens when the piston is very near the bottom of the stroke, and the pressure reduces to nearly atmospheric.



Exhaust

- The piston moves up the cylinder, expelling the burnt gases through the open exhaust valve. The pressure in the cylinder remains at just above atmospheric pressure.



Ignition processes

In a petrol or spark ignition engine, the fuel has to be mixed with the air before it reaches the cylinder. This used to be done in a device called a carburettor, but in modern engines a carefully metered quantity of fuel is injected into the air stream in the air inlet port just above the inlet valves. The amount of fuel injected is controlled by the electronic control unit (ecu). The resulting mixture of petrol vapour and air, in the ratio of about $1{:}15$ by weight, is ignited by a spark **just before** the end of the compression stroke. It is important that the spark occurs a little before the end of the stroke so that ignition has had time to get underway by the time the piston is at the top of its stroke, thereby allowing maximum pressure to operate on the descending piston. The fuel/air mixture burns rapidly producing a sudden rise in temperature and pressure. This type of engine is known as the Otto, petrol, or spark ignition engine.

In the diesel engine, air only is drawn into the cylinder on the induction stroke. The compression of the air produces a temperature (upwards of $550\ °C$) that is high enough to vaporise and ignite a carefully measured quantity of fuel that is pumped directly into the cylinder through an injector. The fuel enters the cylinder as a fine spray. Although both engines work on similar four – (or two–) stroke cycles, their p–V diagrams are different, and are shown in **Figure 9** and **Figure 10**.

The mechanism

The examination specification does not require students to know details of the mechanisms involved in engine operation, but here is a brief outline.

The valves are operated by a camshaft which rotates at half engine speed, so each valve opens once every two revolutions.

In a petrol engine, the spark occurs at the spark plug and is generated by an induction coil. In modern engines the timing of the spark is controlled electronically by the electronic control unit (ecu). The fuel/air mixture is also controlled by the ecu. The engine is cooled by water containing corrosion inhibitor and antifreeze which is driven by a coolant (water) pump through channels in the cylinder block and cylinder head. Oil for lubrication is stored in a tank or sump below the engine and is filtered and distributed to the bearings and cylinder wall by an oil pump.

The movement of the piston is transferred to the crankshaft via a connecting rod.

The construction of a diesel engine is similar to that of a petrol engine, but because the pressures in the cylinder are higher, it has to be stronger, so a Diesel engine tends to be heavier and costlier than a petrol engine of the same volume. Air only is drawn into the cylinder on the induction stroke, and near the end of the compression stroke, diesel fuel is injected into the cylinder as a fine spray through an injector. You can think of this as taking the place of the spark plug in a petrol engine. Obviously the fuel must be at a higher pressure than the air pressure in the cylinder, and this pressure is developed in the fuel injector pump. In modern engines an electronic control unit (ecu) determines the timing and quantity of the fuel to be injected for optimum performance.

Instead of the engine power depending only on the air drawn into the cylinder on the induction stroke, extra air can be forced into the cylinder by a turbocharger (turbo) which is simply a fan or impeller driven by the exhaust gases that leave the engine at high speed. This gives much increased power output.

More detail and an animation of the four-stroke cycle can be found in the resources listed in **Appendix A**.

Indicator diagrams

Using a suitable pressure sensor in the cylinder and a transducer whose output depends on the angular position of the crankshaft, a continuous display of the variation of pressure with volume can be obtained on a computer or cro screen. This p–V graph is called an **indicator diagram**, and it will vary with parameters such as engine load and speed, and the timing of the spark (petrol), or fuel **injection (Diesel).**

Figures 9 and **10** show typical indicator diagrams for four-stroke petrol and diesel engines for one complete mechanical cycle.

Figure 9 Petrol engine

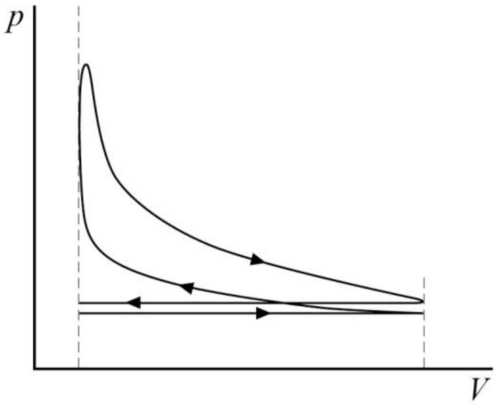
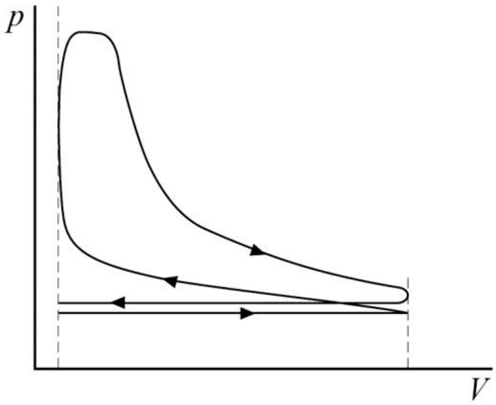


Figure 10 Diesel engine



The work done **on** the gas during the compression stroke is given by the area underneath the compression curve, and the work done **by** the gas during the expansion stroke is given by the area underneath the expansion curve. Therefore the **net work done** by the air is given by the **area enclosed by the loop** on the p-V diagram. If the net work done is divided by the time for one cycle, the indicated power is obtained.

Time for one cycle = 1/cycles per s

Therefore

indicated power = area enclosed by loop of $p - V$ diagram × number of cycles per second

If there is more than one cylinder in the engine

indicated power = area of p–V diagram × number of cycles per second × number of cylinders

Because there is one power stroke for every two revolutions of the crankshaft this can be changed to

indicated power = area enclosed by of p–V diagram × $\frac{1}{2}(\text{rev min}^{-1}/60)$ *× number of cylinders*

The area of the small loop formed between induction and exhaust strokes is negative work, and should be subtracted from the main loop area to give the true net work, but in a real indicator diagram the area is so small as to be negligible. In fact, the induction and exhaust strokes usually show up as a single horizontal line.

Some of the power developed by the air in the cylinder is expended in overcoming the frictional forces between the moving parts of the engine and the viscous resistances of the lubricating oil and cooling water. This is called the **friction power**. The output power will, therefore, be less than the indicated power by an amount equal to the friction power.

The output power is usually measured by applying an opposing torque to the output shaft by a **brake** or **dynamometer** and then using the relationship $P_{\text{out}} = T \times \omega$

Brake or output power = indicated power – friction power

See also pages 30 and 31 where the above equations are linked to efficiency.

Theoretical cycles

For the purpose of analysing engine cycles, engineers compare the actual indicator diagram with a hypothetical diagram based on an engine that uses air as the working substance, but where the compression, heating, expansion and cooling are idealised into the processes dealt with on pages 12–14. Useful deductions and comparisons concerning the performance of real engines can then be made. Engineers refer to such cycles as **air-standard cycles**.

Theoretical Otto cycle

In a theoretical Otto cycle (see **Figure 11**) air ($\gamma = 1.4$) is taken through the following cycle:

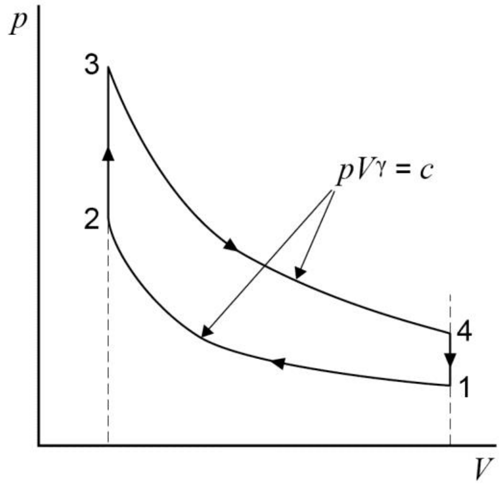
1–2 adiabatic compression

2–3 heat supplied at constant volume

3–4 adiabatic expansion

4–1 energy rejection (cooling) at constant volume

Figure 11



Note that in a theoretical 'engine' the same air is continuously taken through the cycle, with heating from an external source and cooling to an external sink, so there are no lines representing induction and compression.

It can be shown that the efficiency of this cycle is given by:

$$\eta = 1 - \frac{1}{r_v^{0.4}}$$

where r_v is the compression ratio =

$$\frac{\text{maximum volume when piston at bottom of stroke}}{\text{minimum volume when piston at top of stroke}}$$

From the equation for efficiency we see that the efficiency can be increased by raising the compression ratio, and over the years compression ratios of petrol engines have steadily increased (eg a post-war Morris Minor had a compression ratio of 6.6:1; for a Ford Focus it is 11.0:1).

A high compression ratio means a high pressure and temperature rise of the air. Two problems are encountered in petrol engines which prevent the use of compression ratios of much greater than around 10 or 11:1. These are:

If the compression ratio is too high, it is possible for the mixture to self-ignite before the spark (called pre-ignition). The same thing can happen if there has been a build-up of carbon in the cylinder (say, owing to oil that has made its way past the piston and been burnt) that glows red hot and ignites the mixture before the spark. This causes 'pinking', named from the 'pink' sound that pre-ignition causes.

The other problem is more serious. Ideally, when the mixture is sparked, a flame front should move rapidly and smoothly through the space above the piston, raising the pressure and temperature. If the compression ratio is too high (or the octane rating of the fuel too low) a rapidly moving shock wave develops in the cylinder, accelerating the rate of reaction and producing a 'knocking' noise. This is called 'detonation' and may cause:

- a considerable loss in power
- overheating and
- excess pressure on, and hence deterioration of, the bearings.

Detonation can also occur in engines in which the timing of the spark is incorrect, either too early or too late. The timing needs to be altered as the speed and load of the engine change, and electronic means of achieving this are incorporated into car engines.

Theoretical diesel engine

In the theoretical diesel cycle (see **Figure 12**) air only is taken through the following cycle:

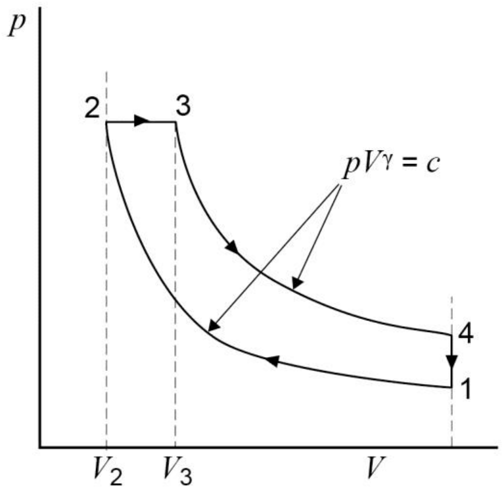
1–2 adiabatic compression

2–3 heat supplied at constant pressure

3–4 adiabatic expansion

4–1 energy rejection (cooling) at constant volume

Figure 12



Note that the only difference between this cycle and the Otto cycle is in the heating process 2–3.

The efficiency of a diesel engine depends on both the compression ratio and the ratio V_3/V_2.

For any given compression ratio the efficiency of the theoretical Diesel cycle is lower than the efficiency of the theoretical Otto cycle.

There is no chance of self ignition in a diesel engine because only air is compressed. Detonation does not occur because there is no sudden injection of fuel into the cylinder and because the rate of reaction is slow compared with the sudden reaction in a petrol engine. For these reasons, high compression ratios can be used. Diesel engines have compression ratios of between 15:1 and 25:1; giving efficiencies of modern engines in the region of 35–40% (the Diesel Ford Focus has a compression ratio of 19.4:1).

The performance of real engines

The theoretical efficiency of an Otto cycle for a compression ratio of 10:1 is 60%. The efficiency of a real engine will be about half this. Some of the reasons for the low efficiency of a real engine can be seen if you compare the theoretical and actual indicator diagrams.

- The corners of the actual indicator diagrams are rounded. This is because the valves take time to open and close.
- Heating does not take place at constant volume in a petrol engine because this would require the temperature and pressure increase to be instantaneous or for the piston to stop for a moment at the top of its stroke.
- The induction and exhaust strokes form a p–V loop that gives net work done on the gas (negative work), and although negligible it should be subtracted from the main p–V loop. There is no 'pumping' loop in the theoretical diagram.

Other reasons are:

- Between 5–20% of the indicated work is used to overcome friction between moving parts and in pumping oil and coolant around the engine.
- The temperature rise in the cylinder is not as high as it should be because the fuel is not burned completely (the calorific value of the fuel is never completely released).

- There is a reversal of the reaction of combustion at high temperatures (>1500 K) with a corresponding absorption of energy from the hot combustion space.
- Some form of cooling must be incorporated, usually in the form of a water jacket around the cylinder, in order to prevent excess temperatures; this means that some heat transfer takes place during compression and expansion, and these processes are not therefore really adiabatic.
- Also, because the working gas is not pure air (even in the diesel engine the exhaust gases are not completely scavenged out of the cylinder) and because its nature changes during combustion, the value of γ does not remain constant.

Other engine cycles

Examination questions may be set on the working or theoretical cycles of other engines. In every case it will be assumed that the student does not have a working knowledge of such engines; questions will be interpretive and all necessary information will be given by setting the scene carefully. It will be expected that students are able to make a reasonably good estimation of indicated work from the area of a p–V loop. They may also be examined on whether they have understood what is going on in the engine – a sort of technological comprehension question.

Calculations of power and efficiency

Input power = calorific value of fuel × fuel flow rate

For liquid fuel, the flow rate will be in $\mathrm{kg\ s^{-1}}$ and the calorific value in $\mathrm{MJ\ kg^{-1}}$.

For a gas, flow rate is usually in $\mathrm{m^3\ s^{-1}}$ and the calorific value in $\mathrm{MJ\ m^{-3}}$. Other units may be used.

Indicated power = power developed in the cylinders of the engine

= area of p–V diagram × number of cycles per second × number of cylinders

Students may try to use this formula when it is more appropriate to simply divide the area of the indicator diagram by the time for one cycle, particularly when the engine does not have a cylinder or cylinders.

Brake power is the power at the output shaft and is calculated using

$P_{\text{out}} = T \times \omega$

This is an application of rotational dynamics, covered in chapter 1, section A of this booklet.

Brake or output power = indicated power – friction power

$$\text{Overall efficiency} = \frac{\text{brake or output power}}{\text{input power}}$$

$$\text{Mechanical efficiency} = \frac{\text{brake or output power}}{\text{indicated power}}$$

Thermal efficiency is a measure of how well the engine transforms the chemical energy in the fuel into useful power in the engine cylinders.

$$\text{Thermal efficiency} = \frac{\text{indicated power}}{\text{input power}}$$

> For an internal combustion engine typical values are:
>
> Overall efficiency 30–35%, thermal efficiency 40–50%, mechanical efficiency 80–95%. These efficiencies vary greatly with the load on the engine.

Combined heat and power

Consider a conventional (ie coal or gas-fired or nuclear) power station that uses a heat engine, usually a steam or gas turbine, to drive an alternator to generate electricity. The engine will obey the laws of thermodynamics, and if it operates between, say, upper (source) and lower (sink) temperatures of 500 °C (773 K) and 25 °C (298 K) its maximum theoretical efficiency will be (773–298)/773 or 61%. In practice, the power station is unlikely to be more than about 35% efficient. This means that it is nearly twice as good at sending heat into the surroundings (via cooling towers and the local river or sea) than it is at generating electricity. In fact, power stations could be thought of as massive heaters with electricity generation as a by-product. In CHP plants, instead of this thermal energy going to waste, it is harnessed for other purposes, usually space heating for houses, factories, business units or horticulture, eg for heating greenhouses. Because many large power stations and nearly all nuclear power stations are sited away from centres of population, large scale CHP has not enjoyed much popularity in Britain. If smaller electrical generation schemes using heat engines (steam, gas turbine or diesel) were set up near where people live and work, and the energy rejected from the engine was used for local heating, the useful energy per kg of fuel burned would be increased enormously. CHP schemes are most likely to be of benefit to enterprises that use plenty of thermal energy, for example hospitals, schools, and chemical, brewing and paper industries.

In some of these the CHP generating plant may need to be screened for noise.

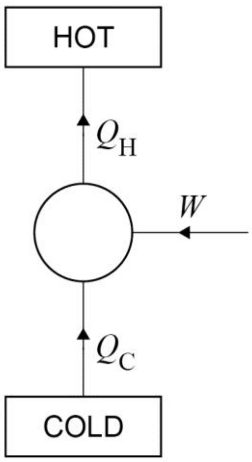
A car internal combustion engine is typically 35% efficient. It, too, is in effect a heater. A large car pulling up a hill at maximum power will be sending thermal energy to its surroundings via the exhaust and radiator at a rate equal to the heating needs of a small junior school. The move toward regenerative braking and hybrid power units goes some way to improve fuel consumption and reduce CO_2 emissions, but the basic drawback of low efficiency will not be overcome. Electric powered vehicles using electricity generated in CHP plants will, of course, not produce as much 'waste' heat overall.

f) The reversed heat engine

A reversed heat engine is one in which net work is done **on** the working fluid, ie there is a work **input.** The engine must still work between hot and cold reservoirs or spaces but the flow of energy by heat transfer is now as shown in **Figure 13**.

Energy is extracted from a cold reservoir and is supplied to a hot reservoir.

Figure 13



We cannot easily write down an expression for the efficiency because the effectiveness of such a device depends on whether its function is:

(a) to extract as much energy as possible from the cold reservoir per joule of work done or

(b) to provide as much energy as possible to the hot reservoir per joule of work done.

In case (a), the device acts as a refrigerator, and in case (b) the device acts as a heat pump.

The term coefficient of performance (or COP) is used to tell us how good the device is at converting work (W) into heat transfer (either Q_H or Q_C). We do not use the term efficiency because the COP is a ratio that is sometimes greater than one. To use the term efficiency and arrive at a value greater than one (or 100%) would give rise to confusion, as we try to drum into our students that no machine can have an efficiency greater than 100%.

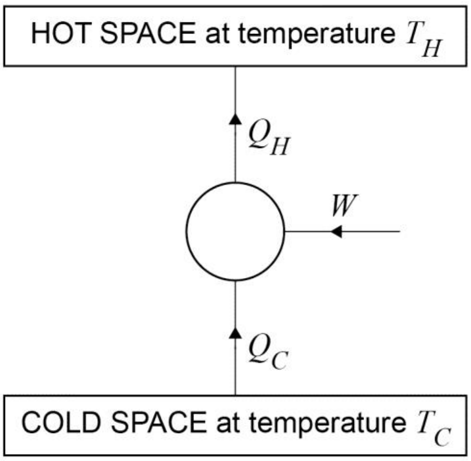
Refrigerator

The coefficient of performance of a refrigerator is defined by the ratio of the energy transfer from the cold space to the work put in. See **Figure 14**.

$$COP_{ref} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$$

$$= \frac{T_C}{T_H - T_C}$$

Figure 14



Heat pump

In a heat pump, the useful effect depends on the amount (Q_H) of energy supplied to the hot space (see **Figure 14**). The coefficient of performance of a heat pump is defined by:

$$COP_{hp} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$$

$$= \frac{T_H}{T_H - T_C}$$

Applying the First Law	$Q_H = Q_C + W$
Hence	$W\,COP_{hp} = W\,COP_{ref} + W$
So	$COP_{hp} = COP_{ref} + 1$

A heat pump and a refrigerator are identical in principle and it is possible to use one machine to fulfil the function of a refrigerator and heat pump simultaneously. As well as keeping its contents (the cold space) cool, a domestic refrigerator or freezer operates as a heater, warming up the room (hot space) in which it is placed.

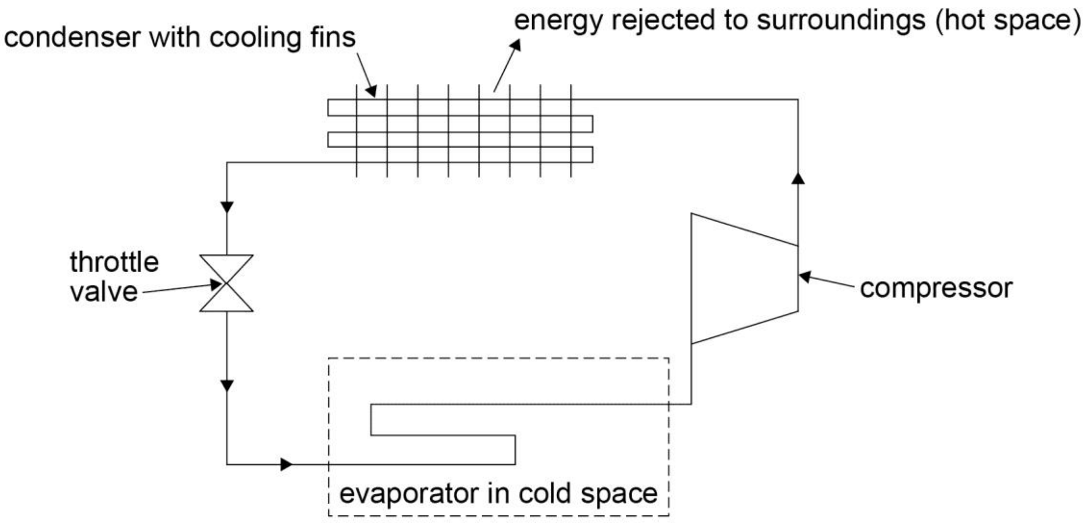
Warning!

When answering qualitative questions on refrigerators and heat pumps, students should be very careful to define terms precisely. They should be wary of using terms such as "input energy" or "output energy" without further clarification. For example, "input energy" could refer to energy input to the room or surroundings or hot space, or energy input to the device from the cold space, or even energy input in the form of input work. It is best to say where the energy is coming from or going to.

Practical refrigerator

Practical refrigerators use a vapour as the working fluid. Ideally, the vapour should be non–flammable, non–toxic, non–damaging to the environment and commercially available. The refrigerant is evaporated in the cold space, is compressed by a motor-driven compressor, and condenses by rejection of heat to the hot space. It is returned to the low pressure evaporator via a throttle valve (in its simplest form a restriction in the pipe) as shown in **Figure 15**.

Figure 15



Uses of heat pumps

More and more, heat pumps are being used for heating buildings, including domestic houses. There are two main types. Those in which the evaporating coil is put underground outside the building are called ground-source heat pumps, and those that use an external box containing the evaporator fitted to an outside wall are called air-source heat pumps.

The energy ‘pumped’ into the building is greater than the energy used to drive the compressor, so heat pumps are cheaper to run (excluding initial installation and maintenance costs) than electric or gas space heaters. This means there is also a saving of CO_2 ‘cost’.

The reversed Carnot cycle

The system shown above is a practical approximation to a reversed Carnot cycle.

In the reversed Carnot cycle (**Figure 16**) the processes are traced out in an anticlockwise sense. The area enclosed by the processes gives the work input to the machine.

Process

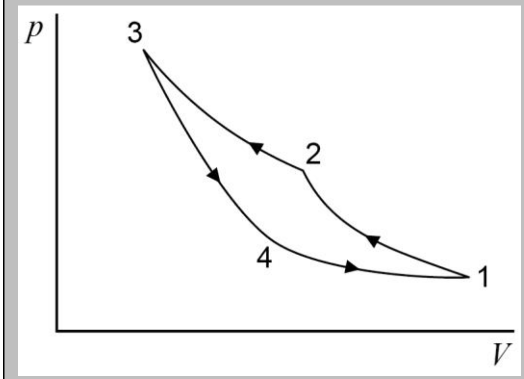
1–2 Adiabatic compression of working fluid

2–3 Isothermal heat rejection to hot space

3–4 Adiabatic expansion

4–1 Isothermal heat acceptance from cold space

Figure 16



$$COP_{\mathrm{ref}} = \frac{Q_{\mathrm{C}}}{W} = \frac{Q_{\mathrm{C}}}{Q_{\mathrm{H}} - Q_{\mathrm{C}}} = \frac{T_{\mathrm{cold}}}{T_{\mathrm{hot}} - T_{\mathrm{cold}}}$$

$$\mathrm{COP}_{\mathrm{hp}} = \frac{Q_{\mathrm{H}}}{W} = \frac{Q_{\mathrm{H}}}{Q_{\mathrm{H}} - Q_{\mathrm{C}}} = \frac{T_{\mathrm{hot}}}{T_{\mathrm{hot}} - T_{\mathrm{cold}}}$$

Note that the coefficient of performance of a heat pump is the reciprocal of the efficiency of a Carnot engine.

Appendix A Suggested experiments and demonstrations

Rotational dynamics

1. By way of introduction, it would help to demonstrate some rotating objects:

- Connect a heavy flywheel to an electric motor via a drive band. With a two-way, two pole switch the motor can be connected to a power supply, and a set of three lamp bulbs in parallel. Run the flywheel up to speed then flick the switch to connect the motor, now operating as a dynamo, to the lamps. The lamps remain lit for several seconds as the flywheel runs down, longer if only one lamp is used, showing that a rotating wheel stores energy. Flywheel, switch, motor/generator and lamp units are available from school physics equipment suppliers as Malvern energy conversion apparatus.
- Mount a wheel on a horizontal axle, tie thread to the axle, hang a weight on the thread let the weight fall accelerating the wheel. Using different wheels shows that the same weight gives different accelerations (Meccano is good for this if you can find some).
- Roll various cylinders down a slope – investigate qualitatively the factors that affect the acceleration.
- Go for the historical approach – from images of mill engines with massive spoked flywheels, ships engines with smaller solid flywheels to the latest in 'flywheel battery' design.
- There are plenty of examples of rotational (and circular) motion in fairgrounds – perhaps having something to do with the sensation of changing direction when moving.

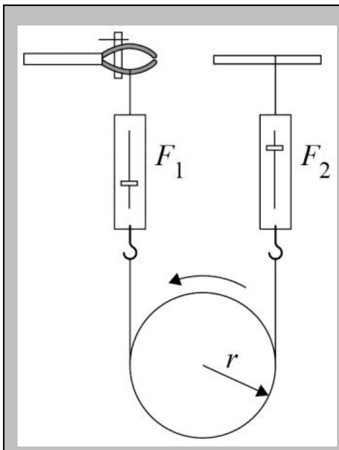
2. The moment of inertia of a flywheel can be determined using the apparatus shown in **Figure 2**. Details can be found in older (pre-2000) standard physics textbooks.

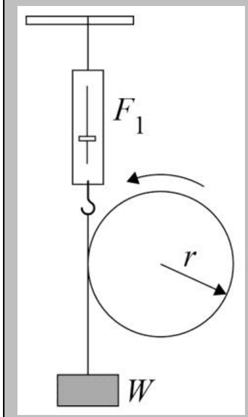
3. Conservation of angular momentum can be demonstrated as explained on page 8.

4. Measuring the power from the output shaft of a motor.

The usual technique is to use a rope brake. This method uses friction to apply a torque on the shaft.

To measure the rotational speed, use a stroboscope, or a method using a light gate and counter, or a rotational speed data logger.





A pulley is fixed to the output shaft and a string or rope is fixed to two Newton-meters to bear on the lower half of the pulley (top diagram). Alternatively, the string is fixed to one newton-meter, is wrapped around the pulley and a weight is hung on the other end (bottom diagram).

The angular speed is ω rad s^{-1}.

The torque applied is varied using the clamp or changing the weight.

The power in watts is P, and the torque provided by the string or rope is T (in N m).

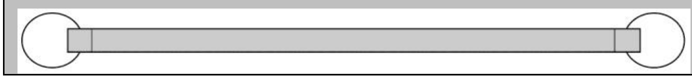
The radius of the pulley is r (in m).

The formula for the torque is $T = (F_1 - F_2)\, r$

The formula for power is $P = T\omega$. So $P = (F_1 - F_2)\, r\, \omega$

For the method shown in the bottom diagram, $P = (W - F_1)\, r\, \omega$

For large motors/pulleys an improvement is to use a band instead of string. Sew two curtain rings into the ends of a strip of canvas and hook the ends of this band to the newton-meters.



5. More on flywheel batteries in wikipedia.org (search: flywheel battery - but remember entries may not be verified).

Thermodynamics

1 Practical demonstration of an isothermal change.

Some schools and colleges may have a Boyles' law apparatus which can be used to show an isothermal change. rapidonline.com have a pump operated version, but cheaper syringe based versions are available from sci-mart.com and www.scichem.com

2 Practical demonstration of an adiabatic change.

An adiabatic change can be demonstrated quite dramatically using a 'fire piston' or 'fire syringe' especially in a darkened room. A small pad of cotton wool is placed at the bottom of a long transparent plastic tube fitted with a plunger. When the plunger is pushed quickly down the tube the air is compressed and the rapid increase in temperature causes the cotton wool to ignite.

Suppliers

- Fire syringe from scichem.com catalogue number XPG180010 (works well, not very robust so take care).
- Air compression fire generator (Hyman Fire Piston) from www.sci-mart.com code number 0107

Reasonably priced demonstration model four-stroke engines.

- scichem.com Diesel 4 stroke engine model: catalogue no. XWV900020, Petrol 4 stroke engine model: catalogue no. XWV900010
- sci-mart.com Diesel engine four stroke: code no. PH0492, Petrol engine four stroke: code no. 99-7800

For an animation of the four-stroke cycle:

- auto.howstuffworks.com/engine1.htm
- auto.howstuffworks.com/diesel.htm
- science.howstuffworks.com
- answers.com/topic/internal-combustion-engine#Principles_of_operation

Two-stroke and rotary (Wankel) engines can also be found by using the search function in howstuffworks.com