THERMODYNAMICS
TUTORIAL 6

RECIPROCATING INTERNAL COMBUSTION ENGINES

This tutorial is set at QCF Level 3 and 4

On completion of this tutorial you should be able to

- Explain the basic working principles of compression and spark ignition internal combustion engines.
- Define the various parameters needed to define their performance
- Calculate the various parameters defining engine performance.

Contents

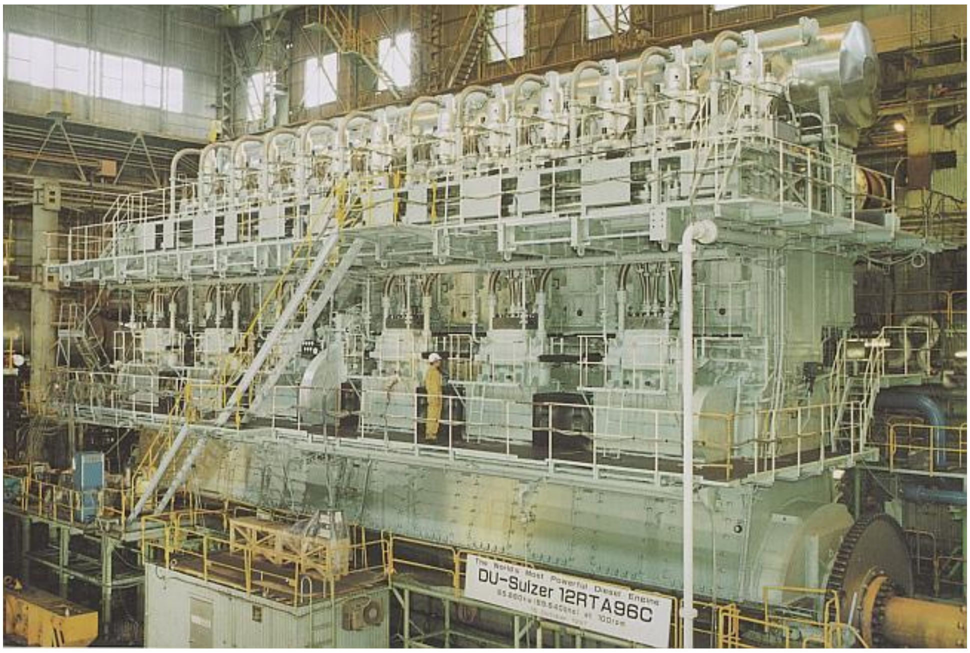
1. Introduction

Internal combustion engines have two main groups, Spark Ignition Engines and Compression Ignition Engines. In this tutorial we look at the general principles of real engines and how the performance of these engines is measured.

2. *Compression Ignition Engines*

The invention of compression ignition engines, commonly known as diesel engines, was credited to Rudolf Diesel.

A Typical Diesel Generator Set



The most powerful diesel engine in the world produces 81 MW at 102 rev/min.
(http://www.ultimatestupidity.com/pics/1/diesel/)

Diesel engines have long been the main power source for railway locomotives. Now they have become the main power source for ships and all marine application. Similarly large road vehicles and mobile plant machinery almost entirely use diesel engines. Increasingly large diesels are also being used for electric generation and the exhaust gas is used to generate hot water or process steam. With their high thermal efficiencies of 50% or better, Diesel engines have become the engine of choice for all mobile plant.

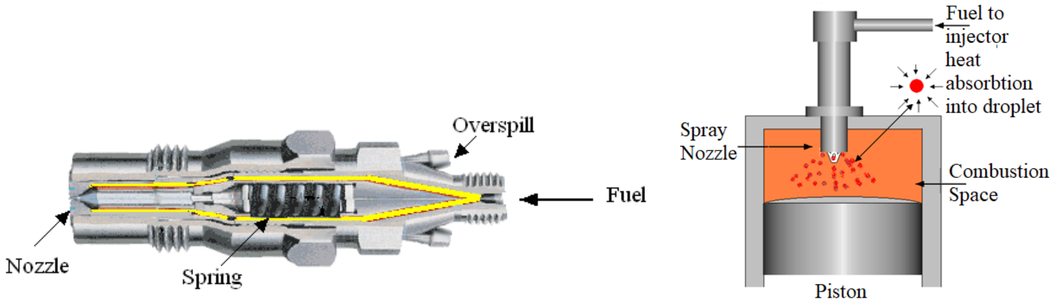
The basic principle is that when high compression ratios are used, the air becomes hot enough to make the fuel ignite without a spark. In modern engines the fuel oil is injected directly into the cylinder as fine droplets. The details of the combustion process depend on the size of the engine. Large engines run slowly and at constant speed so the fuel injection and burning is highly controllable. Smaller engines (typically car engines) run at fast and variable speeds so controlling the fuel injection is more difficult.

2.1. Injection and Combustion

The injector sprays fine droplets of oil into the combustions space. You will find a demonstration of fuel injection at http://auto.howstuffworks.com/fuel-injection3.htm.

On electronic systems the nozzle is opened by an electro-magnet and this is switched by the engine management computer which is capable of controlling the duration and timing of the injection.

Purely mechanical systems use nozzles that open against a spring when pressure is applied and the duration is controlled by the mechanics of the pump.



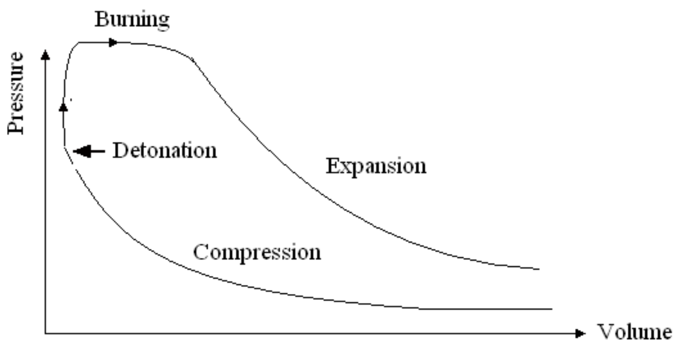
Injector Nozzle

A fixed time is required for the droplets to absorb heat from the surrounding air and ignite. If the engine is running fast, this time delay covers a larger part of the cycle time than when the engine is running slow.

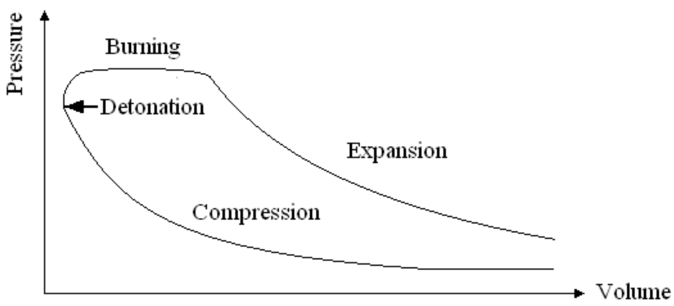
Depending on the speed and injector characteristic, an accumulation of fuel occurs in the combustion space during the time delay. When the droplets ignite, heat is released and radiated to all the accumulated fuel and this detonates spontaneously causing the characteristic diesel knock. The injection timing must be advanced for higher speeds if the detonation is to occur at the right moment.

On large slow running engines such as ship engines, the time delay period occupies a much shorter part of the cycle and the accumulation of fuel is relatively small. Consequently the detonation is less obvious.

Once ignition has occurred the fuel will burn as it is injected so combustion can be maintained during the power stroke thus raising the average pressure on the piston. Once the fuel injection is cut off, the hot gasses in the cylinder will expand naturally with pressure falling as the volume increases. The plots of pressure against volume of gas show the effect of detonation of accumulated fuel. When the speed is fast the detonation produces a sharp rise in pressure followed by burning. The slow running engine has a smaller rise due to the smaller detonation.



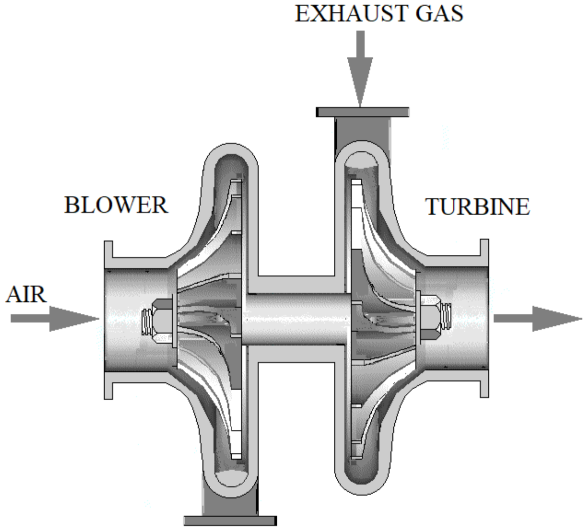
Fast Running



Slow Running

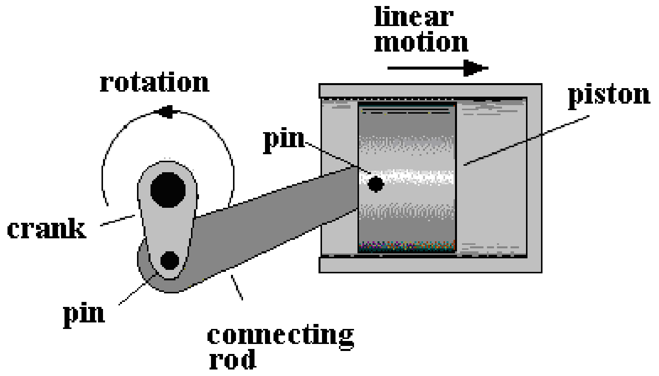
2.2. Turbochargers and Superchargers

A turbocharger typically consists of a compressor or blower fan driven by a turbine. The turbine is driven by the exhaust gas and the blower blows air into the engine. This means that a greater mass of air is supplied to the combustion space so more fuel can be injected and more power produced. A supercharger serves the same function but the compressor is mechanically driven by a belt connected to the engine crank shaft



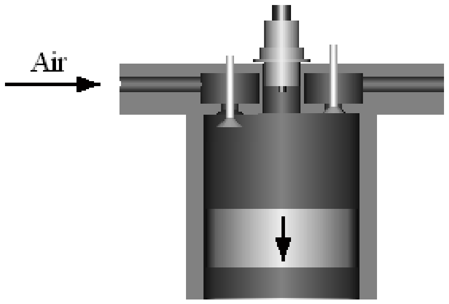
2.3. The 4 Stroke Cycle

There are two basic mechanical designs – 4 stroke and 2 stroke. In both cases a crank and connecting rod is used to convert the reciprocating motion of the piston into rotation of the crank shaft.

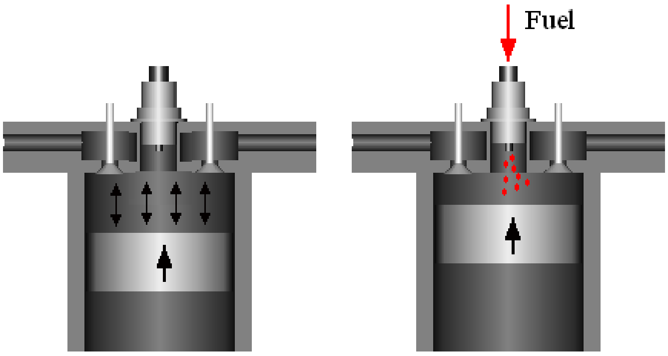


Engines using the four stroke cycle produce one power stroke every second revolution of the crank shaft. One revolution is used to efficiently clear out the exhaust gas and refill the cylinder with air. The following explanation of the 4 stroke cycle does not show the crank shaft and connecting rod and it is assumed that the student is already familiar with the basic mechanics of a reciprocating engine.

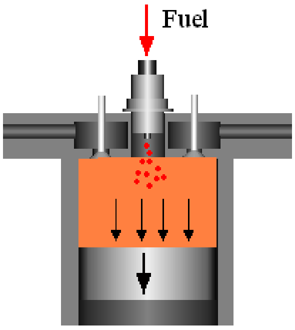
A - **Induction Stroke.** The piston moves away from the cylinder head and draws in air through the inlet valve. On turbocharged engines, the air is blown in by a compressor or turbocharger. This means that more air and oxygen will be present in the cylinder so more fuel can be burned in it than would otherwise be possible thus increasing the power of the engine.



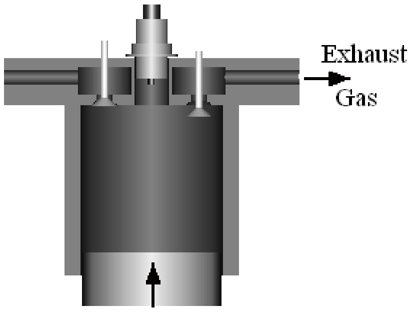
B - **The Compression Stroke.** The piston moves towards the cylinder head and compresses the air making it hot. Work is needed to compress the air. Fuel is then injected into the space above the piston. The timing of the injection is important because of the time delay before the fuel detonates. This produces a sharp rise in pressure.



C - **Expansion Stroke.** The pressure forces the piston away from the cylinder head and powers the engine. Work is extracted from the system. The way the pressure varies as the piston moves is controlled by the continued injection of fuel. At some point the fuel injection is cut off and the pressure falls as the piston moves towards the extreme position.

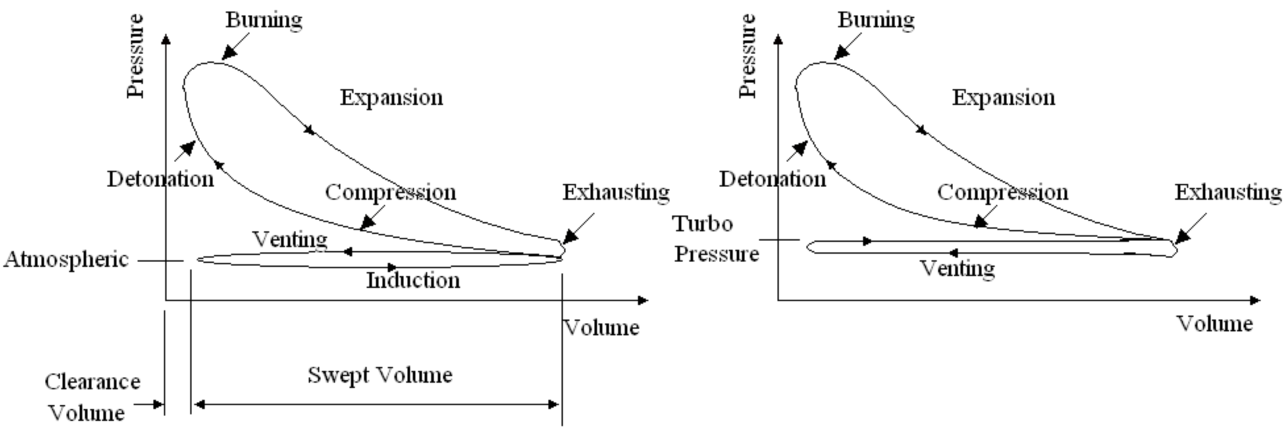


D – **Exhaust Stroke**. When the piston starts to move back towards the cylinder head, the exhaust valve opens and the exhaust gas is pushed out. The whole cycle is then repeated. On very large engines, the gas can be used to drive the turbocharger by forcing it through a turbine connected to it.



2.4. Pressure – Volume Diagram

The resulting trace of pressure and volume is shown for the 4 stroke cycle. The induction cycle is greatly exaggerated to show that when the exhaust is venting the pressure is slightly above atmospheric pressure and when inducting without a turbocharger, it is slightly below. With a turbocharger, the pressure rises to the turbo pressure as soon as the exhaust is vented.



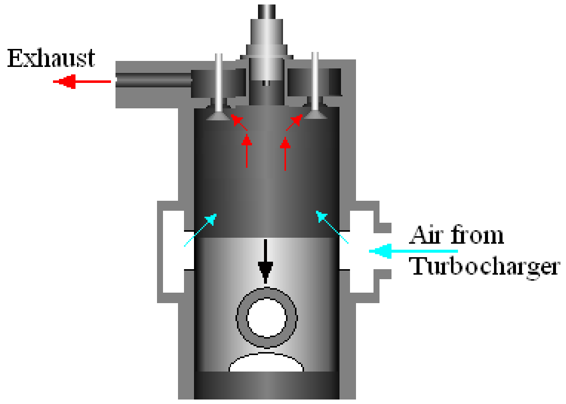
The clearance volume is the volume in the combustion chamber when the piston is closest to the cylinder head. The clearance volume + the swept volume is the volume when the piston is furthest from the cylinder head. The swept volume is the change in volume. The compression ratio is defined as:

$$r_v = \frac{\text{swept volume} + \text{clearance volume}}{\text{clearance volume}}$$

2.5. *The Two Stroke Cycle*

The 2 stroke engine produces a power stroke every revolution of the crank so they are twice as powerful as the same size 4 stroke engine at the same speed. For this reason 2 stroke engines have become very popular for large engines although for small engines 4 strokes are more efficient because of the efficient way they replace the burned gas with fresh air.

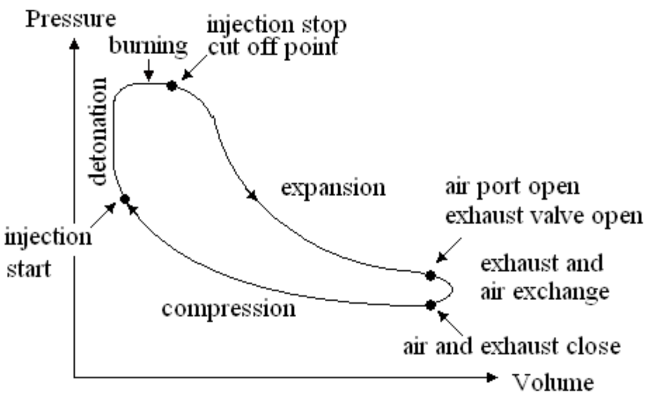
The 2 stroke engine has ports in the side of the cylinder as shown and when the piston is close to the bottom, they are exposed and air from the turbocharger is blown into the cylinder. At the same time the exhaust valve opens and the exhaust gas still under pressure is vented and blown out by the incoming air. Some designs use no valves at all and has exhaust ports instead.



2.6. Pressure – Volume Diagrams

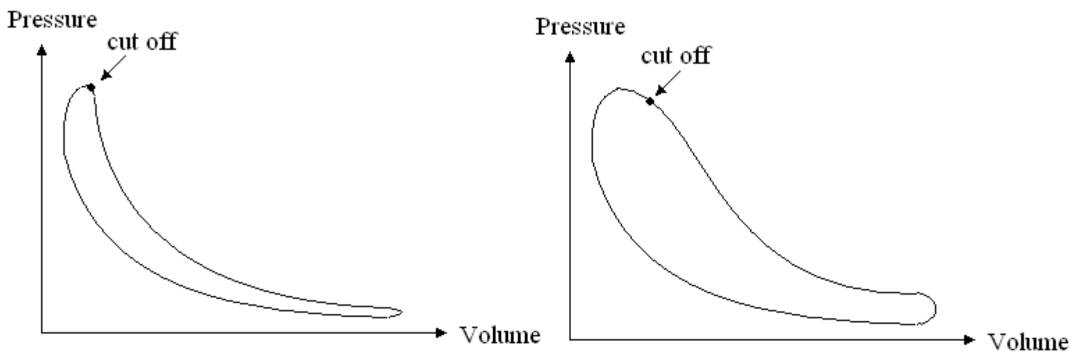
Real engines can be fitted with pressure transducers and position transducers so that the way the pressure changes with movement of the piston and hence volume of gas, can be traced out. The diagram shows a typical result.

The injection starts just before the point of maximum compression. The detonation produces a sharp rise in pressure then the fuel burns keeping the pressure high as the piston moves down the cylinder. The cut off point is where injection stops and no further burning takes place. The pressure then falls as the volume expands further. When the exhaust port opens the pressure drops to the turbocharger pressure



The area enclosed by the diagram represents the work output produced each cycle or revolution in the case of a 2 stroke engine.

Varying the cut off point reduces or increases the work output and this is how the power of the engine is controlled. The diagram shows how varying the cut off point changes the area and hence power of the engine.



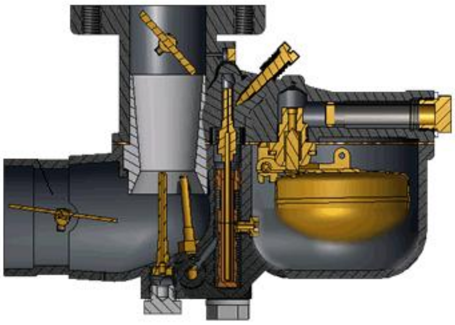
The ***Thermal Efficiency*** of the engine is based on the net work output W_{net} and the amount of heat released by combustion Q_{in}. The thermal efficiency is defined as:

$$\eta_{th} = \frac{W_{net}}{Q_{in}}$$

2. *Spark Ignition Engines*

Spark ignition engines use a gaseous fuel or a liquid volatile fuel that vapourises easily. The fuel may be mixed with the incoming air prior to entering the combustion chamber and this is controlled with a carburettor or by injecting the fuel. Engines with carburettors work by restricting the air flow with a butterfly valve. This reduces the pressure to less than atmospheric at inlet to the cylinder and the restriction of the inlet valve adds to the affect.

Engine



Carburettor

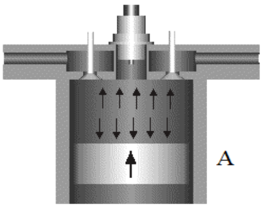
Engines with turbo charging use a compressor to deliver air to the cylinders at pressures higher than atmospheric pressure.

There are 4 stroke and 2 stroke versions much the same as described above for compression ignition engines.

The four processes used in a complete cycle are as before.

A - Compression Stroke

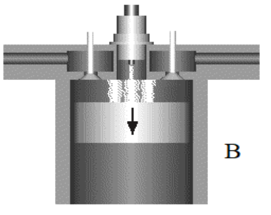
Air and fuel are mixed and compressed so rapidly that there is no time for heat to be lost. (Figure A) In other words the compression is adiabatic. Work must be done to compress the gas.



A

B - Ignition

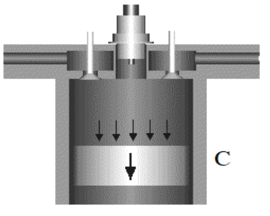
Just before the point of maximum compression, the air is hot and a spark ignites the mixture causing an explosion (Figure B). This produces a rapid rise in the pressure and temperature. The process is idealised as a constant volume process in the Otto cycle.



B

C - Expansion or Working Stroke

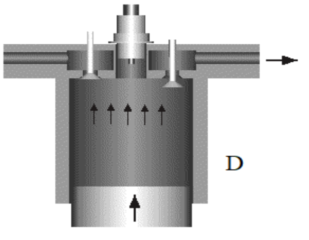
The explosion is followed by an adiabatic expansion pushing the piston and giving out work. (Figure C)



C

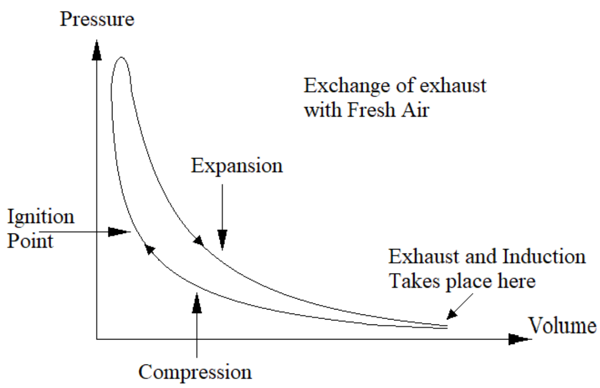
D - Exhaust

At the end of the working stroke, there is still some pressure in the cylinder. This is released suddenly by the opening of an exhaust valve. (Figure D) This is idealised by a constant volume drop in pressure in the Otto cycle. In 4 stroke engines a second cycle is performed to push out the products of combustion and draw in fresh air and fuel. It is only the power cycle that we are concerned with.



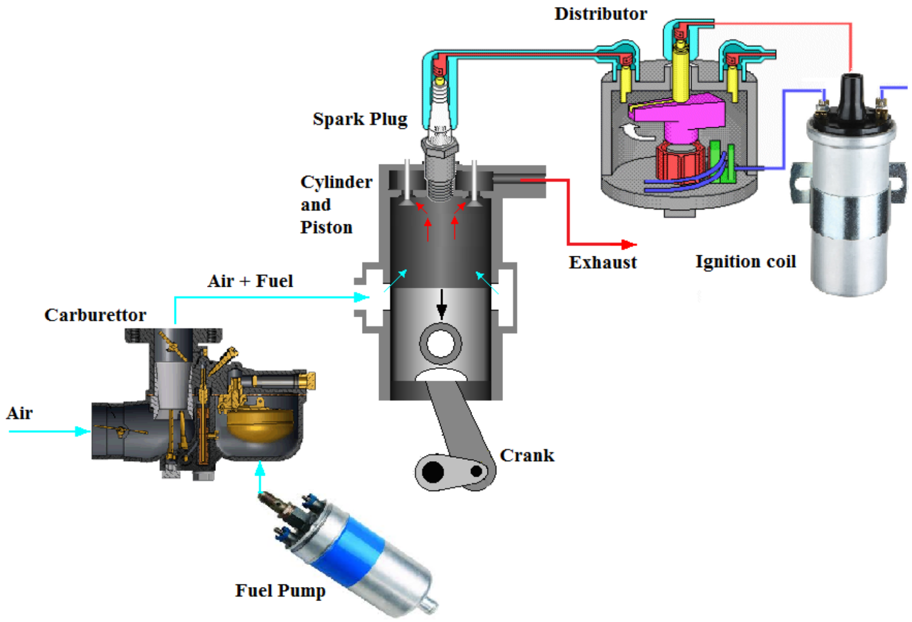
D

__The pressure – Volume diagram__ for a spark ignition engine shows the compression process. Just before the compression is completed the spark initiates an explosion that causes a rapid rise in pressure followed by the expansion stroke. At the end of the expansion the exhaust gas is exchanged with fresh air either by completing and extra exhaust and induction cycle (4 stroke) or by the method used in a 2 stroke engine.



2.1 Traditional Engine

Consider how a typical traditional internal combustion engine burning a volatile fuel like petrol or gas functions.



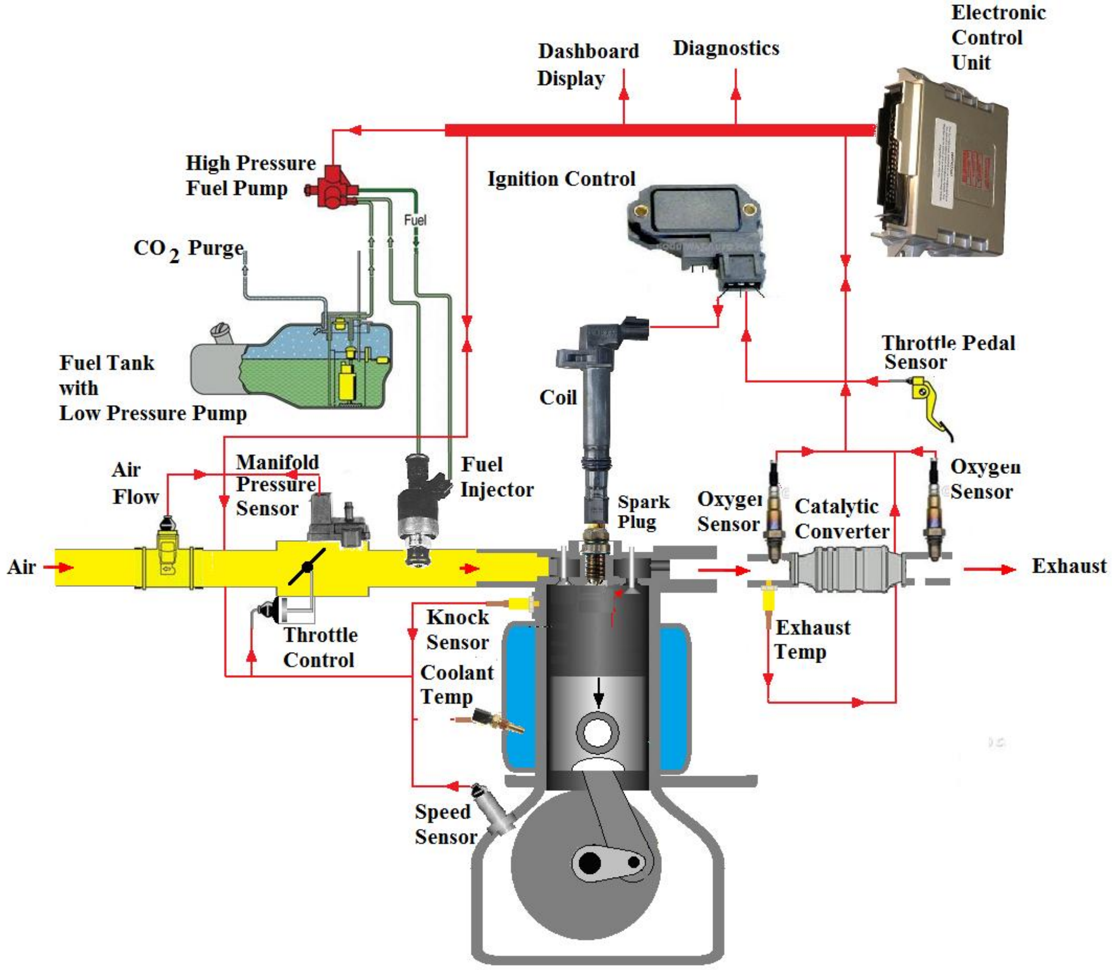
Fuel is pumped (electric or mechanical drive) to the carburettor where it is vapourised and mixed with the air as the air is sucked or blown into the combustion chamber inside the cylinder. The mixture is ignited by a spark plug at the right moment to detonate it. The spark is generated by an ignition coil and point breaker built into the distributor. If the engine has more than one cylinder then the sparking voltage has to be sent to the correct spark plug at the correct moment.

In order to function correctly the distributor and spark has to be timed by being mechanically driven from the engine crank shaft. The power and speed is controlled by controlling the fuel and this is done in the carburettor. A butterfly valve at the exit point is opened or closed by rotating it with the throttle (accelerator or gas pedal). This restricts the air flow and causes suction in the carburettor that sucks the fuel from the float chamber and mixes the resulting spray with the air. For efficient operation the engine needs to have the correct ratio of fuel and air. Ideally this ratio needs to be adjusted to suit the speed and power requirements so that combustion is efficient. Inefficient combustion shows up in the exhaust gas as unbalanced products such as carbon dioxide, carbon monoxide, nitrogen and oxygen. The combustion efficiency also depends on the correct timing of the spark and this in turn depends on the air fuel ratio and speed. The distributor changes the timing by a mechanical actuator responding to the vacuum in the carburettor to rotate the plate with the contact breaker. Another thing that affects the efficiency is the opening of the inlet and exhaust valves on the cylinder and these were fixed by the mechanics of the engine on traditional designs.

There are many variations of the above description but it is given to show how engines developed without the use of computers or electronics. Let's now see how a modern engine works thanks to the mechatronic approach using new technologies.

The traditional engine was improved by the introduction of electronic ignition triggered by an optical sensor mounted close to a rotating part of the engine. It was then realised that the timing could also be adjusted to suit conditions and with the development of other sensors such as exhaust gas analysers, manifold pressure sensors and fuel flow rate it became obvious that a computer could control all of it to give optimal performance. Add to this all the other electronics in a modern car controlling lights, dashboard instruments and diagnostics on board entertainment and so on, the mechatronic approach became a clear choice. Another development with this was the electrically controlled fuel injection system to replace the carburettor and in the case of volatile fuel this could be into the inlet manifold or into the combustion chamber similar to how it is done on a diesel engine. Here is brief description of a modern engine.

2.2 Modern Engine



At the heart of the electronic system is the **ECU** (Engine Control Unit) also known now as the **PCM** (Powertrain Control Module). This controls a series of actuators to ensure optimal engine performance. It takes the readings from a multitude of sensors, interpreting the data using multidimensional performance maps (called lookup tables), and adjusting the engine actuators accordingly.

It controls the following features:

Air/Fuel ratio

The ECU controls the quantity of fuel being injected based on the throttle setting and the air flow rate. It follows that a sensor for the throttle position and an air flow sensor is part of the system. It is also linked to a temperature sensor and takes into account if the engine is hot or cold making it run rich when cold (similar to the choke on carburetted engine).

The ECU can be used with carburetted engines controlling the mixture with a control solenoid or stepper motor incorporated in the float bowl.

Control of ignition timing

The ECU can adjust the exact timing of the spark. The spark is triggered from the ignition control unit. The ignition system still needs a high voltage coil to produce the spark. Modern engine designs have abandoned the high-voltage distributor and coil, instead performing the distribution function in the primary circuit

If the spark is too early the resulting detonation produces a shock (called knocking) due to the excess and sudden pressure on the piston. This is detected and the timing delayed or retarded. Since knock tends to occur more easily at lower rpm, the ECU may send a signal for the automatic transmission to downshift as a first attempt to alleviate knock.

Control of idle speed

The idle speed of the engine is the speed it runs at when the throttle is at minimum setting and the engine is driving no load. Older engines had carburettor adjustment for setting this to the recommended speed but with an ECU it is in the software. Engine speed is sensed by a crank shaft position sensor that is essential for timing of the spark and valve movement.

A full authority throttle control system may be used to control idle speed, provide cruise control functions and top speed limitation.

Control of variable valve timing

Some engines have Variable Valve Timing. In such an engine, the ECU controls the time in the engine cycle at which the valves open. The valves are usually opened sooner at higher speed than at lower speed. This can optimize the flow of air into the cylinder, increasing power and fuel economy.

Information for Diagnostics and Display

The digital signals are fed by a data bus to the ECU and this can be used to provide information on the engine status for display on the dashboard instruments and to indicate faults.

3. *Engine Performance Testing*

In order to evaluate the performance of an engine we need to know the parameters and how to measure them. The following gives the definitions of the various parameters.

3.1 Calorific Value

This is the heat released by burning 1 kg of fuel. There is a higher and lower value for fuels containing hydrogen. The lower value is normally used because water vapour formed during combustion passes out of the system and takes with it the latent energy. We can now define the fuel power.

Fuel Power = Mass of fuel/s × Calorific Value

3.2 Fuel Power (F. P.)

Fuel power is the thermal power released by burning fuel inside the engine.

F.P. = mass of fuel burned per second × calorific value of the fuel. **F.P. = m_f × C.V.**

All engines burn fuel to produce heat that is then partially converted into mechanical power. The chemistry of combustion is covered in another tutorial.

3.3 Air Fuel Ratio

This is the ratio of the mass of air used to the mass of fuel burned.

$$\textbf{Air Fuel Ratio} = \frac{\mathbf{m_a}}{\mathbf{m_f}}$$

Stoichiometric Ratio

This is the theoretical air/fuel ratio which is required to exactly burn the fuel.

True Ratio

In reality, the air needed to ensure complete combustion is greater than the ideal ratio. This depends on how efficient the engine is at getting all the oxygen to meet the combustible elements.

The volume of air drawn into the engine is theoretically equal to the capacity of the engine (the swept volumes of the cylinders). The mass contained in this volume depends upon the pressure and temperature of the air. The pressure in particular, depends upon the nature of any restrictions placed in the inlet flow path.

Engines with carburettors work by restricting the air flow with a butterfly valve. This reduces the pressure to less than atmospheric at inlet to the cylinder and the restriction of the inlet valve adds to the affect.

Engines with turbo charging use a compressor to deliver air to the cylinders at pressures higher than atmospheric.

The actual mass of air which enters the cylinder is less than the theoretical value for various reasons such as warming from the cylinder walls, residual gas left inside and leaks from the valves and around the piston. To deal with this we use the concept of ***Efficiency Ratio.***

$$\textbf{Efficiency Ratio} = \frac{\textbf{actual mass}}{\textbf{theoretical mass}}$$

Dissociation

At the high temperatures and pressures experienced in combustion, dissociation occurs. This is a process where the vibrating molecules of different gases make violent encounters resulting in combustion products reforming into smaller molecules of unburned fuel. Even though there is plenty of oxygen to completely burn the fuel, combustible products such as carbon monoxide (CO) and hydrogen (H_2) appear in the exhaust gas. The reasons for this will not be covered here other than to say it is predicted by the 2nd law of thermodynamics and involves equilibrium in the chemical process. Dissociation reduces the thermal efficiencies of any engine.

Variable Specific Heats

The specific heat ratio used in heat release calculations plays a crucial role in the determination of parameters used in combustion and engine cycle processes (e.g. the adiabatic index). Consequently accurate predictions of thermal efficiencies are made more complex.

3.4 Volume Flow Rate

A two stroke engine induces the volume of air once every revolution of the crank. A 4 stroke engine does so once every two revolutions.

Induced Volume = Capacity × speed   for a 2 stroke engine

Induced volume = Capacity × speed ÷ 2 for a 4 stroke engine.

WORKED EXAMPLE No. 1

A 4 stroke carburetted engine runs at 2 500 rev/min. The engine capacity is 3 litres. The air is supplied at 0.52 bar and 15°C with an efficiency ratio of 0.4. The air fuel ratio is 12/1.
The calorific value is 46 MJ/kg. Calculate the heat released by combustion.

SOLUTION

Capacity = 0.003 m^3

$$\text{Volume Induced} = 0.003 \times \frac{2\,500}{60 \times 2} = 0.0625\ \text{m}^3/\text{s}$$

Using the gas law pV = mRT we have
Ideal air

$$\dot{m} = \frac{pV}{RT} = \frac{0.52 \times 10^5 \times 0.0625}{287 \times 288} = 0.03932\ \text{kg/s}$$

Actual air $\dot{m} = 0.03932 \times 0.4 = 0.01573$ kg/s.

Mass of fuel
$\dot{m}_f = 0.01573/12 = 0.00131$ kg/s

Heat released

Φ = calorific value × $\dot{m}_f$ = 46 000 kJ/kg × 0.00131 kg/s = 60.3 KW

SELF ASSESSMENT EXERCISE No. 1

1. A 4 stroke carburetted engine runs at 3 000 rev/min. The engine capacity is 4 litres. The air is supplied at 0.7 bar and 10^oC with an efficiency ratio of 0.5. The air fuel ratio is 13/1. The calorific value is 45 MJ/kg. Calculate the heat released by combustion.

   (Answer 149 KW)

2. An engine requires 120 kW of fuel power by burning fuel with a calorific value of 37 MJ/kg. The air fuel/ratio required is 14/1. Calculate the mass flow rate of air required.
   (Answer 45.4 g/s)

3.5 Brake Power (B. P.)

This is also called ***Shaft Power*** and it is the power transmitted by the shaft of the engine. Smaller engines can be tested on a test bed by connecting them to a ***Brake Dynamometer***. The shaft power is absorbed by the brake hence the name ***Brake Power***. Dynamometers measure the speed and the Torque of the shaft. The output power of an engine is normally absorbed by the load such as a generator, compressor, hydraulic pump or simple friction brake. Very large engines such as ships engines cannot be tested with a dynamometer. With modern technology it is possible to monitor the torque and speed of the output shaft when it is driving its intended load and obtain a direct reading of shaft or brake power during normal operation. Modern test beds have full electronic monitoring to give instant recordings of all parameters.

Typical Test Bed

The Brake Power is calculated with the formula **B.P. = 2πNT**

N is the shaft speed in rev/s and T is the torque in N m

You may need to know how to work out the torque for different types of dynamometers. In all cases the torque is:

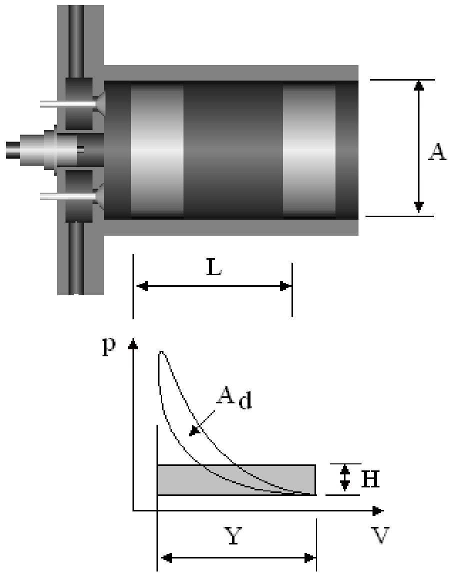
$$\mathbf{T = net\ brake\ force \times radius}$$

3.6 Indicated Power and Mean Effective Pressure

This is the power developed by the pressure of the gas acting on the pistons. The difference between this and the Brake Power is energy lost between the pistons and the output shaft. This will be due to friction in the bearings and transmission system. It also includes energy absorbed by the ancillary equipment vital to the engine such as the fuel pump, coolant pump, injectors, and electrical systems and so on.

Indicated Power is found by recording the pressure and volume of the gas in the cylinder. This involves fitting a pressure transducer to the cylinder and another transducer to measure the volume but this is related to crank angle so ways of calculating the volume values from the measured crank angle are possible.

On multi – cylinder engines it is possible to measure the IP of each cylinder separately by simply cutting off the fuel or ignition to each cylinder in turn and measuring the drop in the brake power (Morse Test).



Pressure – Volume graphs are called indicator diagrams. The name is taken from early mechanical equipment used on engines called engine indicators. (Historians might look up the Farnborough Indicator and Dobbie Mc.Innes Indicator). These produced physical traces on paper but now it is all done electronically with computers linked to the transducers.

The diagram shows a typical indicator diagram for an internal combustion engine. The average force on the piston throughout one cycle is F where

$$F = \text{MEP} \times \text{Area of piston} = pA$$

The Mean Effective Pressure p is the mean pressure during the cycle. The work done during one cycle is $W = F\,L = pAL$

The number of cycles per second is N. The Indicated Power is then

I.P. = pLAN per cylinder. (Note for a 4 stroke engine N = ½ the shaft speed).

The mean effective pressure is found from the indicator diagram as follows. The area enclosed by the indicator diagram represents the work done per cycle per cylinder. Let this area be A_d mm^2. The average height of the graph is H mm. The length of the diagram is Y mm.

The shaded area is equal to A_d and so $A_d = Y \times H$ $H = A_d/Y$

In order to convert H into pressure units, the pressure scale (or spring rate) of the indicator measuring system must be known. Let this be S_p with typical units of kPa/mm. The MEP is then found from

$$\textbf{M. E. P.} = S_p\ H$$

This is also known as the Indicated Mean Effective Pressure because it is used to calculate the Indicated Power. There is also a Brake Mean Effective Pressure (BMEP) which is the mean pressure which would produce the brake power.

$$\text{B. P.} = (\text{B. M. E. P.}) \times L \times A \times N$$

The BMEP may be defined from this as

$$\textbf{B.M.E.P.} = \frac{\textbf{B.P.}}{\textbf{L} \times \textbf{A} \times \textbf{N}}$$

4 *Efficiencies*

4.1 Brake Thermal Efficiency

This tells us how much of the fuel power is converted into brake power.

$$\eta_{BTh} = \frac{\mathbf{B.P.}}{\mathbf{F.P.}}$$

4.2 Indicated Thermal Efficiency

This tells us how much of the fuel power is converted into brake power.

$$\eta_{ITh} = \frac{\mathbf{I.P.}}{\mathbf{F.P.}}$$

4.3 Mechanical Efficiency

This tells us how much of the indicated power is converted into brake power. The difference between them is due to frictional losses between the moving parts and the energy taken to run the auxiliary equipment such as the fuel pump, water pump, oil pump and alternator.

$$\eta_{mech} = \frac{\mathbf{B.P.}}{\mathbf{I.P.}}$$

4.4 Specific Fuel Consumption

$$\mathbf{S.F.C.} = \frac{\textbf{mass of fuel burned.}}{\textbf{energy obtained from the shaft}} (\textbf{in the same time period})$$

This is often stated in kg per kilowatt-hour but g/MJ is also used. The conversion factor is 1000/3.6
These figures will vary with throttle setting and speed but for engines designed to run at optimal speed such as a large marine engine, these figures are very useful for comparison.

Over a period of 1 second SFC is the same as:- fuel flow consumption rate/Brake Power.

$$\text{S.F.C.} = \frac{m_f}{\text{B.P.} \times \text{Calorific Value}} = \frac{1}{\eta_{BTh} \times \text{Calorific Value}}$$

$$\eta_{BTh} = \frac{1}{\text{S.F.C} \times \text{Calorific Value}}$$

WORKED EXAMPLE No. 2

A very efficient marine diesel has a SFC of 0.163 kg/kW-h. The calorific value is 38 MJ/kg. What is the energy efficiency?

SOLUTION

This converts to 0.163/3.6 = 0.0453 kg/MJ

$$\eta_{BTh} = \frac{1}{0.0453 \times 38} = 0.58 \text{ or } 58\%$$

WORKED EXAMPLE No. 3

A 4 cylinder, 4 stroke engine gave the following results on a test bed.

Shaft Speed	N = 2 500 rev/min
Torque arm	R = 0.4 m
Net Brake Load	F = 200 N
Fuel consumption	m_f = 2 g/s
Calorific value	42 MJ/kg
Area of indicator diagram	A_d = 300 mm^2
Pressure scale	S_p = 80 kPa/mm
Stroke	L = 100 mm
Bore	D = 100 mm
Base length of diagram	Y = 60 mm.

Calculate the B. P., F. P., I. P., MEP, η_{BTh}, η_{ITh}, and η_{mech},

SOLUTION

$$BP = 2\pi NT = 2\pi \times (2\,500/60) \times (200 \times 0.4) = 20.94 \text{ kW}$$

$$FP = \text{mass/s} \times C.V. = 0.002 \text{ kg/s} \times 42\,000 \text{ kJ/kg} = 84 \text{ kW}$$

$$IP = pLAN$$

$$p = MEP = \frac{A_d}{Y} \times S_p = \frac{300}{60} \times 80 = 400 \text{ kPa}$$

$$IP = 400 \times 0.1 \times \frac{\pi \times 0.1^2}{4} \times \frac{2\,500}{60} \times \frac{1}{2} = 6.54 \text{ kW per cylinder}$$

For 4 cylinders

$$IP = 6.54 \times 4 = 26.18 \text{ kW}$$

$$\eta_{BTh} = 20.94/84 = 24.9\%$$

$$\eta_{ITh} = 26.18/84 = 31.1\ \%$$

$$\eta_{mech} = 20.94/26.18 = 80\%$$

SELF ASSESSMENT EXERCISE No. 2

1. A 4 stroke engine gave the following results during a test.

Number of cylinders	6
Bore of cylinders	90 mm
Stroke	80 mm
Speed	5 000 rev/min
Fuel consumption rate	0.225 kg/min
Calorific value	44 MJ/kg
Net brake load	180 N
Torque arm	0.5 m
Net indicated area	720 mm^2
Base length of indicator diagram	60 mm
Pressure scale	40 kPa/mm

Calculate the following.

i. The Brake Power. (47.12 kW)
ii. The Mean effective Pressure. (480 kPa)
iii. The Indicated Power. (61 kW)
iv. The Mechanical Efficiency. (77.2%)
v. The Brake Thermal efficiency. (28.6%)
vi. The Specific Fuel Consumption (0.0795 kg/MJ)

2. A two stroke engine gave the following results during a test.

Number of cylinders	4
Bore of cylinders	100 mm
Stroke	100 mm
Speed	2 000 rev/min
Fuel consumption rate	5 g/s
Calorific value	46 MJ/kg
Net brake load	500 N
Torque arm	0.5 m
Net indicated area	1 500 mm^2
Base length of indicator diagram	66 mm
Pressure scale	25 kPa/mm

Calculate the following.

i. The Indicated thermal efficiency. (25.9%)
ii. The Mechanical Efficiency. (88%)
iii. The Brake Thermal efficiency. (22.8%)
iv. The Specific Fuel Consumption (0.0953 kg/MJ)

3. A two stroke diesel engine gave the following results during a test.

Number of cylinders	4
Bore of cylinders	80 mm
Stroke	80 mm
Speed	2 200 rev/min
Fuel consumption rate	1.6 cm^3/s
Fuel density	750 kg/m^3
Calorific value	60 MJ/kg
Nett brake load	195 N
Torque arm	0.4 m
Nett indicated area	300 mm^2
Base length of indicator diagram	40.2 mm
Pressure scale	50 kPa/mm

Calculate

i. The Indicated thermal efficiency. (30.5%)
ii. The Mechanical Efficiency. (81.7%)
iii. The Brake Thermal efficiency. (25%)
iv. The Specific Fuel Consumption. (0.0667 kg/MJ))

4. A four stroke diesel engine gave the following results during a test.

Number of cylinders	4
Bore of cylinders	90 mm
Stroke	80 mm
Speed	5 000 rev/min
Fuel consumption rate	0.09 kg/min
Calorific value	44 MJ/kg
Nett brake load	60 N
Torque arm	0.5 m
MEP	280 kPa

Calculate the following.

i. The Mechanical Efficiency. (66.1%)
ii. The Brake Thermal efficiency. (23.8%)
iii. The Indicated Thermal Efficiency. (36%)
iv. The Specific Fuel Consumption (0.0955 kg/MJ)

5. Define Indicated Mean Effective Pressure and Brake Mean Effective Pressure.

The BMEP for a 4 cylinder, 4 stroke spark ignition engine is 8.4 bar. The total capacity is 1.3 dm^3 (litres). The engine is run at 4 200 rev/min.
Calculate the Brake Power. (38.22 kW)

There are 10 kW of mechanical losses in the engine.
Calculate the Indicated Mean effective Pressure. (10.6 bar).

The Volumetric Efficiency is 85% and the Brake Thermal Efficiency of the engine is 28%. The air drawn in to the engine is at 5^oC and 1.01 bar. The fuel has a calorific value of 43.5 MJ/kg.
Calculate the air/fuel ratio. (Answer 12.3/1).