INTERNAL COMBUSTION (IC) ENGINES

An IC engine is one in which the heat transfer to the working fluid occurs within the engine itself, usually by the combustion of fuel with the oxygen of air.

In *external* combustion engines heat is transferred to the working fluid from the combustion gases via a heat exchanger. e.g. steam engines; Stirling engines.

IC engines include spark ignition (SI) engines using petrol as a fuel, and compression ignition (CI) engines (usually referred to as Diesel engines) using fuel oil, DERV, etc as a fuel.

In these engines there is a sequence of processes:

- compression
- combustion
- expansion
- exhaust / induction

There are two basic mechanical designs to achieve these four processes in either:-

four strokes of the piston - hence the 4-stroke engine, or
two strokes of the piston - hence 2-stroke engines.

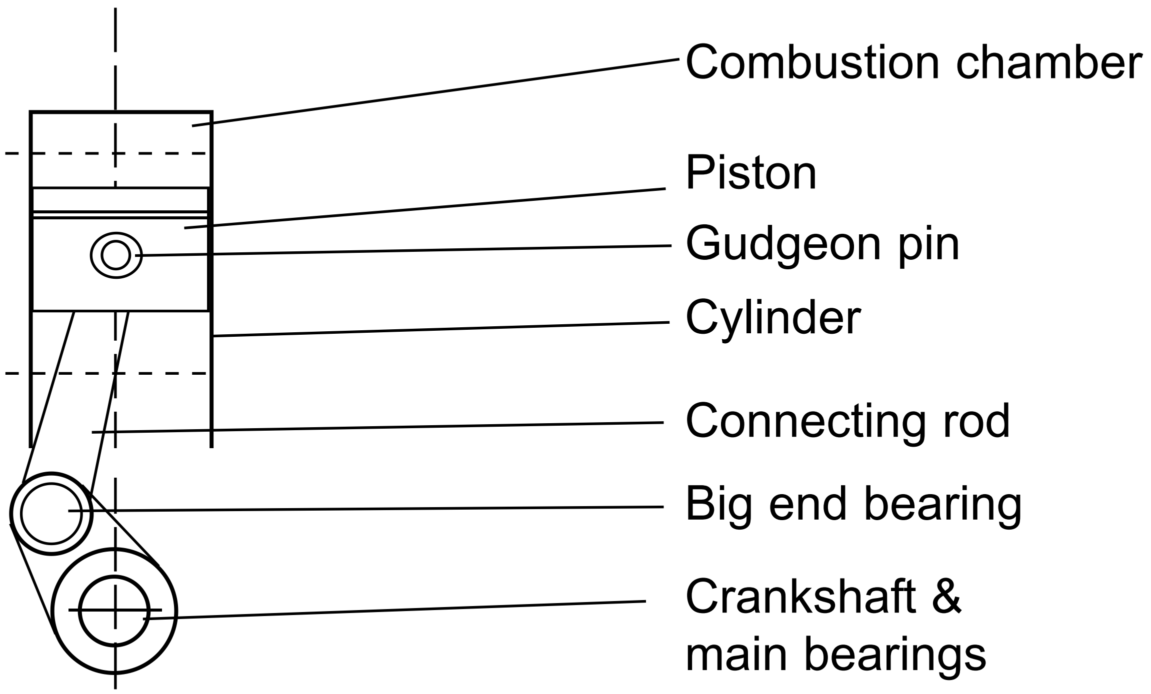
The basic difference between the petrol engine and the diesel engine is in the method of ignition and the combustion process, both of which will be discussed later.

The main types of IC engine are:

Gas Turbines	Rotary	Reciprocating

Various cylinder arrangements (in-line, Vee, radial, flat, etc.) are used but we shall analyse the simple in-line arrangement.

BASIC CON-ROD CRANK MECHANISM



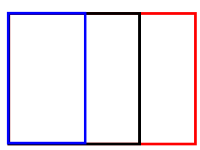
Bore = cylinder diameter

Stroke = piston movement (BDC to TDC) = 2 x crank radius

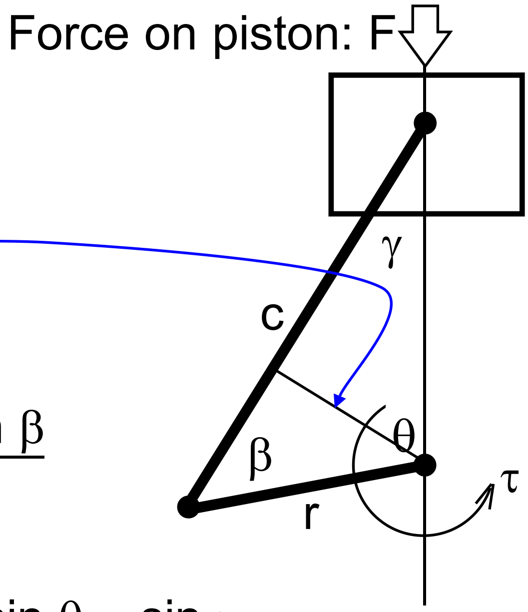
$$\frac{\text{Bore}}{\text{Stroke}} = \text{‘squareness’}$$

>1 is ‘over square’

<1 is ‘under square’



MECHANICAL ACTION
(static, frictionless)



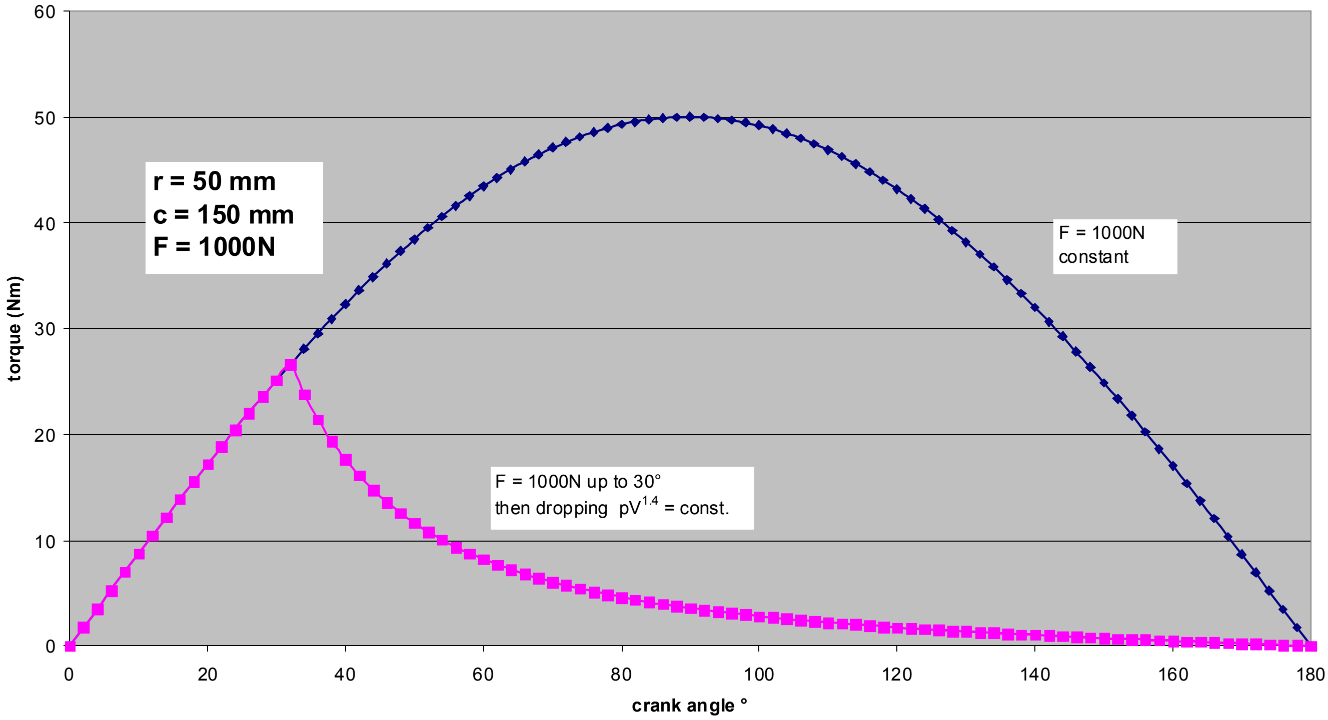
Force in con-rod = $\dfrac{F}{\cos\gamma}$

Perpendicular distance from crank axis = $r \sin\beta$

Therefore:
Instantaneous torque (τ) = $\dfrac{F\, r \sin\beta}{\cos\gamma}$

For any value of θ, γ & β are defined by $\theta + \beta + \gamma = \pi$ and $\dfrac{\sin\theta}{c} = \dfrac{\sin\gamma}{r}$

F normally varies with cylinder volume:



The force on the piston is affected by the quantity of air induced. It is therefore affected by the gas dynamics (breathing) of the engine, which is mainly determined by engine speed.

The mechanical losses (friction) depend on the piston forces and RPM. Friction power loss $\propto$ RPM^3 (approx.)

Thus the fundamental output of a reciprocating IC engine can be considered to be <u>torque</u> - it is theoretically produced even when engine speed (RPM) is zero.

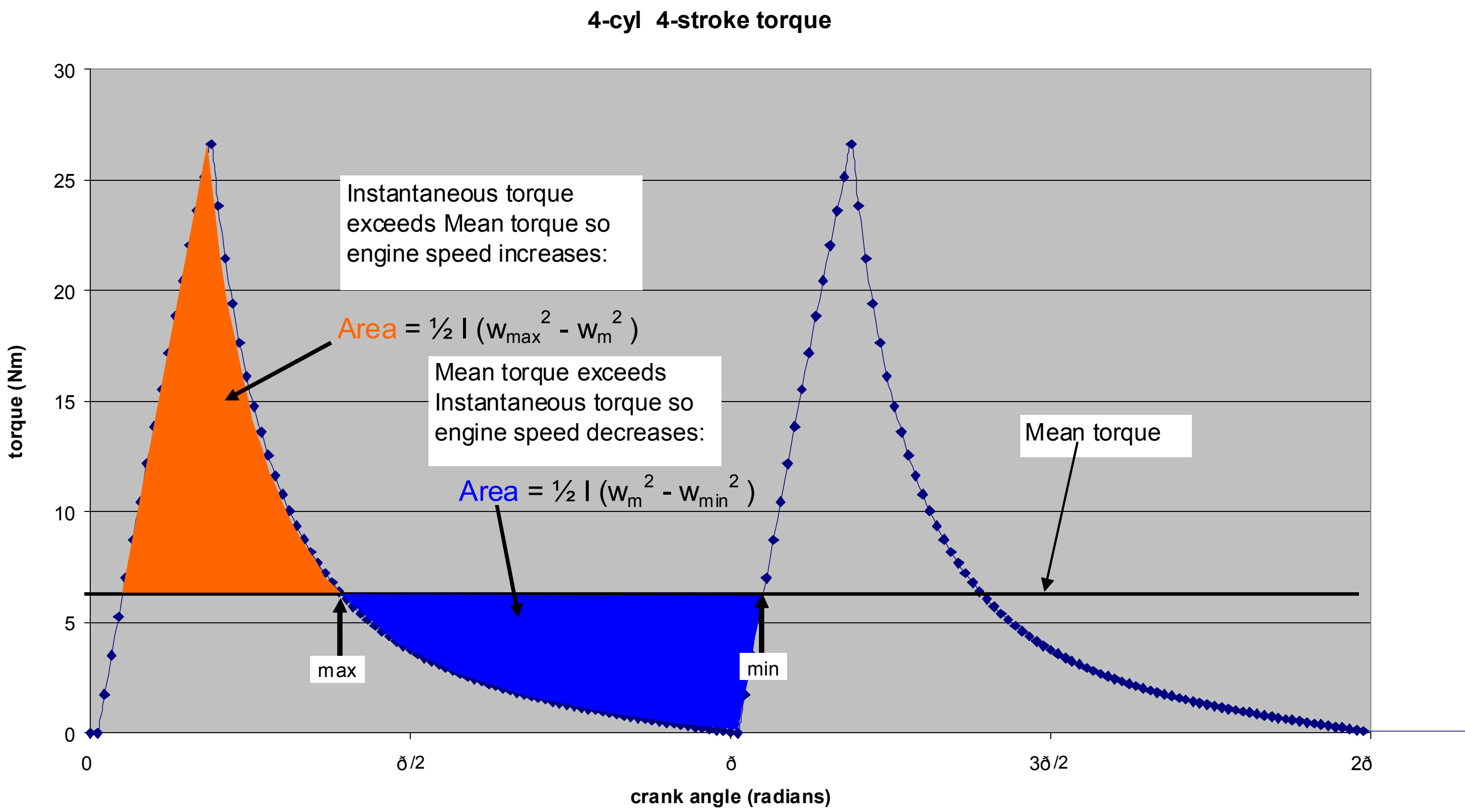
The torque fluctuations are smoothed out by:-

(i) multi-cylinder arrangement

(ii) the use of a flywheel

so that the torque output from the engine's drive shaft is 'smooth' at any given condition of speed and load.

In the graph below: **w** = engine speed in **radians/sec**



$$\text{Coefficient of speed fluctuation} = \frac{w_{max} - w_{min}}{2\,w_m}$$

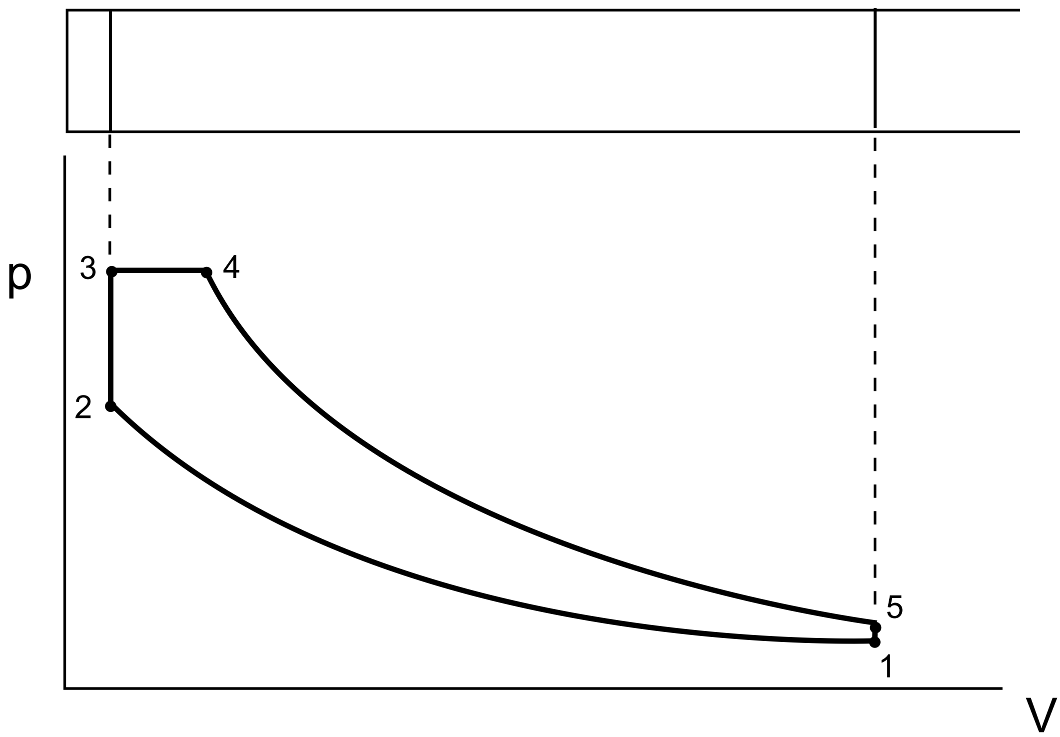
This coefficient is decreased by increasing the moment of inertia (I) of the flywheel.

AIR STANDARD CYCLES

Because the products of combustion are not too different from air (in terms of thermodynamic properties) we can analyse the engine cycle as a series of reversible non-flow processes using air as the working fluid *throughout* the cycle.
This is known as an air-standard cycle.

DUAL CYCLE

The heat transfer to the gas is assumed to occur partially at constant volume (2→3) and partially at constant pressure (3→4), i.e. a **dual** heat transfer process.



Volume **c**ompression **r**atio : $\frac{V_1}{V_2} = r_c$

Pressure 'rise' ratio : $\frac{p_3}{p_2} = \alpha$

Volume ratio : $\frac{V_4}{V_3} = \beta$ also known as the 'cut-off' ratio

Dual Cycle Thermal Efficiency

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{[c_v(T_3-T_2)+c_p(T_4-T_3)]-c_v(T_5-T_1)}{[c_v(T_3-T_2)+c_p(T_4-T_3)]}$$

$$\eta_{th} = 1 - \frac{T_5 - T_1}{(T_3-T_2) + \gamma\,(T_4-T_3)} \qquad \frac{c_p}{c_v} = \gamma$$

$$\eta_{th} = 1 - \frac{\frac{T_5}{T_1} - 1}{\frac{T_3}{T_1} - \frac{T_2}{T_1} + \gamma\left(\frac{T_4}{T_1} - \frac{T_3}{T_1}\right)}$$

$$\boxed{\frac{T_2}{T_1}} = \left(\frac{V_2}{V_1}\right)^{1-\gamma} = \left(\frac{1}{r_c}\right)^{1-\gamma} = \boxed{r_c^{\gamma-1}}$$

$$\frac{T_3}{T_2} = \frac{p_3}{p_2} = \alpha \qquad \boxed{\frac{T_3}{T_1}} = \frac{T_3}{T_2} x \frac{T_2}{T_1} = \boxed{\alpha\, r_c^{\gamma-1}}$$

$$\frac{T_4}{T_3} = \frac{V_4}{V_3} = \beta \qquad \boxed{\frac{T_4}{T_1}} = \frac{T_4}{T_3} x \frac{T_3}{T_1} = \boxed{\beta\,\alpha\, r_c^{\gamma-1}}$$

$$\frac{T_5}{T_4} = \left(\frac{V_5}{V_4}\right)^{1-\gamma} = \left(\frac{V_5}{V_3} x \frac{V_3}{V_4}\right)^{1-\gamma} = \left(\frac{V_1}{V_2} x \frac{V_3}{V_4}\right)^{1-\gamma} = \left(\frac{r_c}{\beta}\right)^{1-\gamma} = \left(\frac{\beta}{r_c}\right)^{\gamma-1}$$

$$\boxed{\frac{T_5}{T_1}} = \frac{T_5}{T_4} x \frac{T_4}{T_1} = \left(\frac{\beta}{r_c}\right)^{\gamma-1} x\ \beta\,\alpha\, r_c^{\gamma-1} = \boxed{\alpha\,\beta^{\gamma}}$$

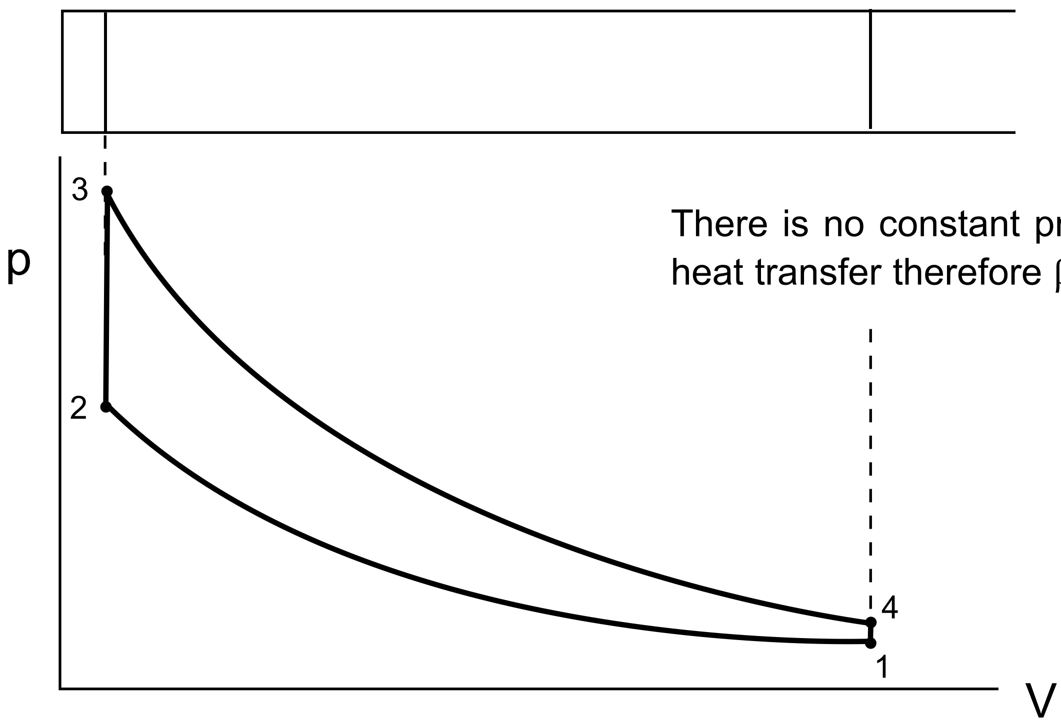
If we substitute the above in the expression for η_{th} we obtain:-

$$\boxed{\eta_{th} = 1 - \frac{1}{r_c^{\gamma-1}}\left[\frac{\alpha\,\beta^{\gamma} - 1}{(\alpha-1) + \gamma\,\alpha\,(\beta-1)}\right]}$$

The DUAL cycle approximates to the processes within a modern high speed diesel engine.

In petrol engines, and large slow speed (< 500 RPM) diesels, the pressure rise because of combustion is comparatively rapid (relative to piston speed) and the cycle can be reasonably approximated by the constant volume or OTTO cycle.

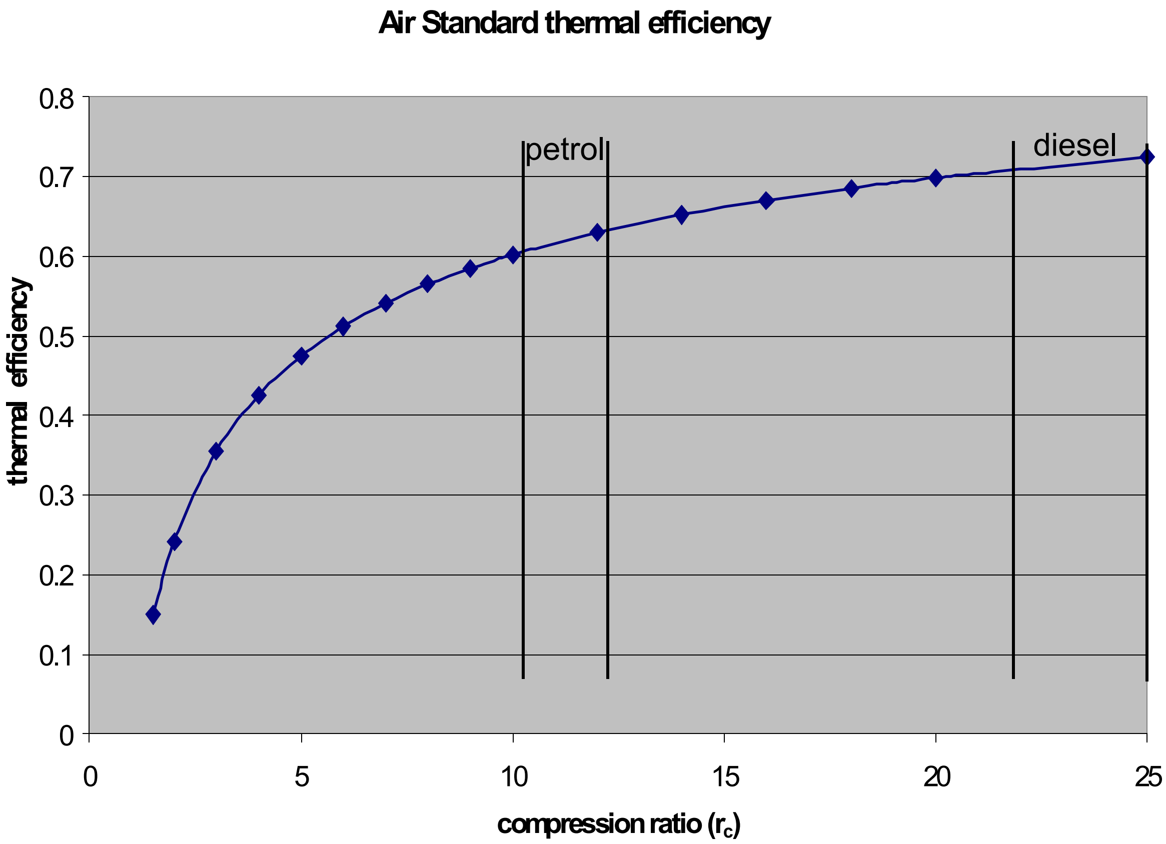
OTTO CYCLE



There is no constant pressure heat transfer therefore $\beta = 1$

$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma-1}}$$

We can plot the way thermal efficiency varies with volume compression ratio (r_c).



The actual measured values of thermal efficiencies for each of these types of engines is approximately *half* of the values indicated above. The above analysis does not take into account the effects of heat losses, frictional losses and gas dynamics.

PETROL ENGINES

In petrol engines the air-fuel ratio (AFR) is maintained at an approximately constant value of 14-16:1 by the carburettor or fuel injection system. The top temperature (T_3) and the torque is determined by the ***amount*** of air-fuel mixture admitted by the throttle. Hence petrol engines are described as being QUANTITY governed.

In normal running - the flame front advances through the mixture at flame propagation speed after a short delay from spark ignition.

Under certain conditions detonation - combustion / shock waves form (often referred to as ‘pinking’ or ‘knocking’). The Octane rating of a fuel - is a measure of it's tendency to resist detonation (from a mixture of iso-octane & n-heptane).

In petrol engines air and fuel are pre-mixed and ignited by an electric spark and the combustion process proceeds as a flame front across the combustion chamber. If the design and mixture is correct then there are no problems but if $r_c > 9$ the mixture tends to explode prematurely.
Also, fuel will not ignite and burn except between air-fuel ratios of between 10 and 20 to 1.
An air-fuel ratio of 14.7 to 1 is the chemically ideal ratio (known as the stoichiometric ratio) and the carburettor or fuel injection system attempts to provide this.

DIESEL ENGINES

In diesel engines *varying* amounts of fuel, in the form of very fine droplets, are injected into approximately the *same* amount of air, irrespective of the engine’s speed, to control the top temperature and the torque. The ***AFR therefore varies*** (typically between 20 - 100:1), hence Diesel engines are described as being QUALITY governed.
Fuel burns (after a slight delay) on injection.
Compression ratios (r_c, typically 18 - 22:1] are limited more by engine component strength than thermodynamics.

Fuel ignitability is measured by 'CETANE' rating.

Diesel knock can also occur (initial rapid combustion).

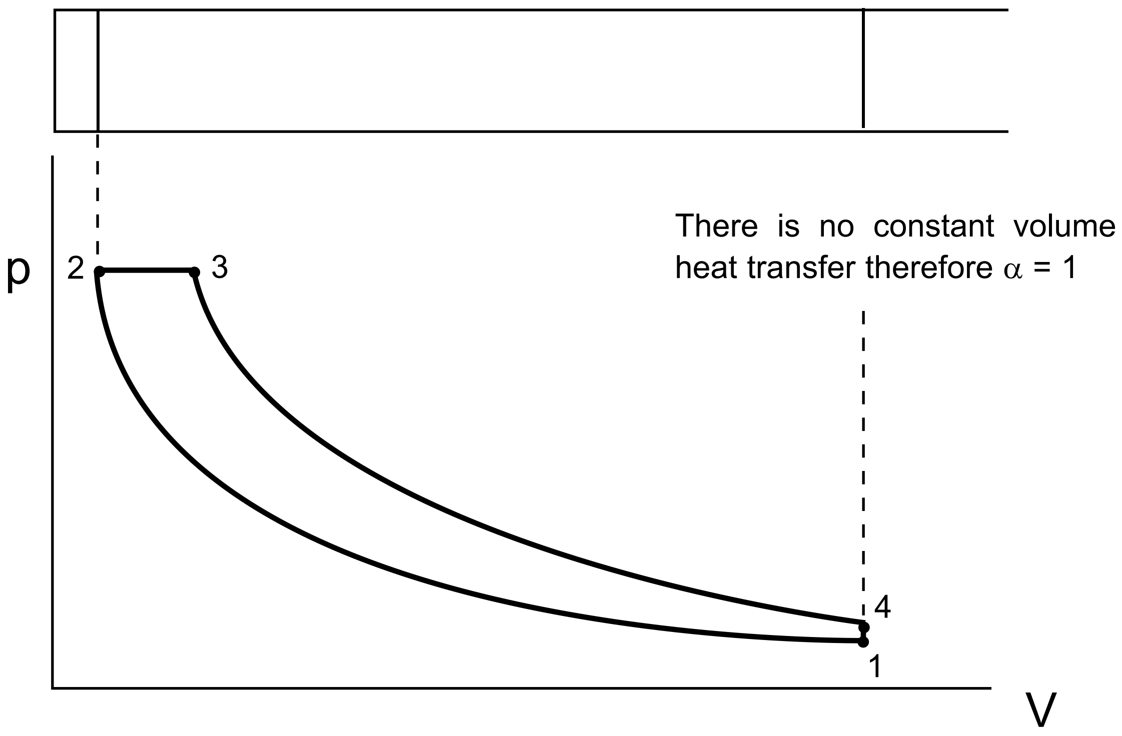
On the compression stroke air is compressed adiabatically to a temperature such that when liquid fuel is sprayed into the combustion space in droplet form it self-ignites. This is why the compression ratios of diesel engines are typically about twice those of petrol engines. The droplets move around in the combustion space seeking oxygen and burning takes place on the droplet surface at a local AFR of about 15 to 1.

To promote finding oxygen turbulence is induced in the combustion space. In a diesel engine only enough fuel is injected to produce the torque required at any given engine speed. It is not possible to use the stoichiometric AFR because the fuel will never find enough oxygen quickly enough - and unburned fuel in the form of black smoke (carbon particles) will be emitted.

At 300 RPM the time for combustion is about 8 milliseconds!

Early diesel engines used constant pressure heat transfer rather than constant volume heat transfer as in the Otto cycle.
In practice this can be achieved by a relatively short air blast fuel injection process.
The ideal (or 'true') diesel cycle is shown below in which the process 2→3 is constant pressure heat transfer to the cycle.

DIESEL CYCLE



$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma-1}}\left[\frac{\beta^{\gamma} - 1}{\gamma\,(\beta-1)}\right]$$

The effect of the term in [ ] is to reduce the thermal efficiency as β increases but this effect is offset by the higher value of r_c of a diesel engine.

REFERENCES :- Rogers & Mayhew; Eastop & McConkey; Richard Stone.