Heat Engine

Heat engine is a device that converts heat energy into mechanical energy or more exactly a system which operates continuously and only heat and work may cross its boundaries. Heat engine forms the very crux of internal combustion engine. A firm understanding of Internal Combustion Engines cannot be possible without understanding working principle of Heat engines and concepts of Energy.

Heat engines are classified into two broad types:

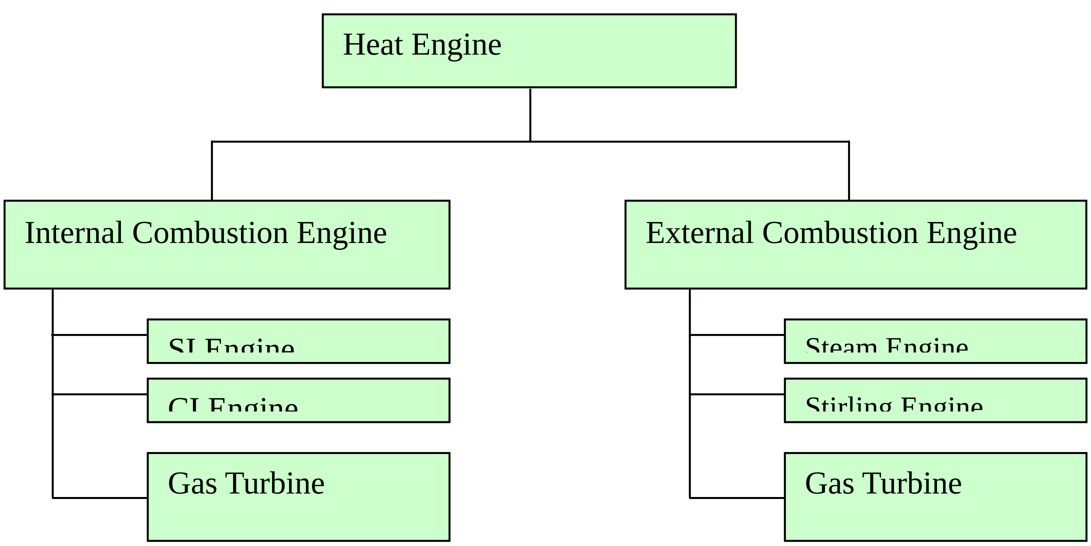
- External combustion engine
- Internal combustion engine

An external combustion engine is a heat engine where an (internal) working fluid is heated by combustion of an external source, through the engine wall or a heat exchanger. The fluid then, by expanding and acting on the mechanism of the engine produces motion and usable work. The fluid is then cooled, compressed and reused (closed cycle). For example (like water is for a steam engine, where the heat is used to generate steam from water, which in turn is used to power the piston or a turbine).

In an Internal Combustion Engine, the products of combustion would directly move the piston of the engine. Gasoline, Diesel, Wankel engines and open gas turbines are all examples of an Internal Combustion Engine.

Internal combustion engines are most commonly used for mobile propulsion in vehicles and portable machinery. In mobile equipment, internal combustion is advantageous since it can provide high power-to-weight ratios together with excellent fuel energy density.

If the combustion of the air-fuel mixture is initiated by spark plug then engine is called spark ignition (SI) engine. If air-fuel mixture is initiated by itself, the engine is called the compression ignition (CI) engine.



Otto cycle:

Otto cycle is ideal cycle for SI engines, named after Nikolaus A. Otto. In most SI engines, piston executes four complete strokes and crankshaft complete two revolutions for each thermodynamic cycle. These engines are called four-stroke(IC) engine.

The schematic diagrams of the strokes and P-v diagrams for both actual and ideal 4 stroke engines are shown in fig below.

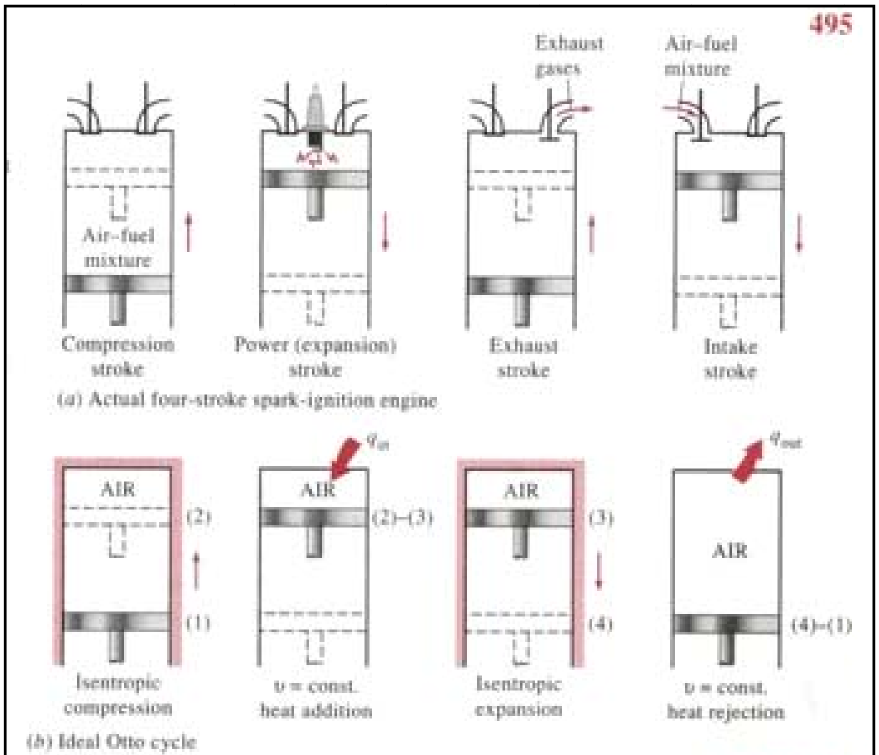
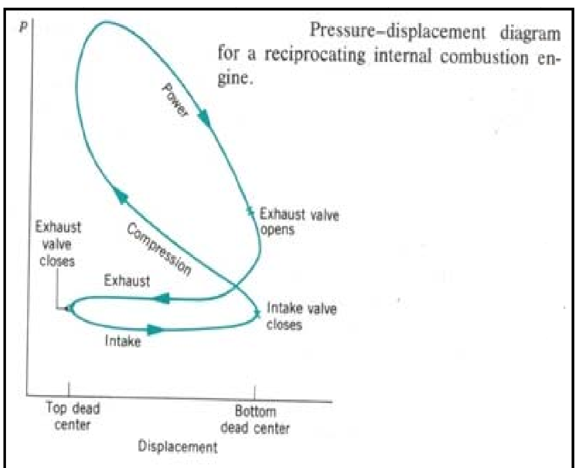


FIGURE 8-13
Actual and ideal cycles in spark-ignition engines and their P-v diagrams.



Pressure–displacement diagram for a reciprocating internal combustion engine.

Initially, both the intake and the exhaust valves are closed and the piston is at the lowest position (BDC).

Compression stroke: The piston moves upward, compressing the air-fuel mixture. Shortly before the piston reaches its highest point (TDC), the spark plug fires and the mixture ignites, increasing the pressure and temperature of the system.

Expansion or power stroke: The high-pressure gases force the piston down. The piston in turn forces the crankshaft to rotate, producing a useful work output.

Exhaust stroke: At the end of power stroke, the piston is at its lowest position and the cylinder is filled with combustion products. During the exhaust stroke the piston moves up, purging the exhaust products through the exhaust valve.

Intake stroke: The piston moves down a second time, drawing in fresh air-fuel mixture through the intake valve.

In two stroke engines, all the four functions described are executed in just two strokes, namely power stroke and compression stroke.

It may seem that two stroke engine will put out twice as much power as comparable four stroke cycle engine because there are twice as many power strokes. However this is not the case. Because to get rid of the burnt gases in the cylinder from last power stroke, it must be relied upon the force of air and fuel mixture entering the cylinder, there is some dilution of the mixture. The mixing of the intake mixture with the exhaust gases reduces the potential power output.

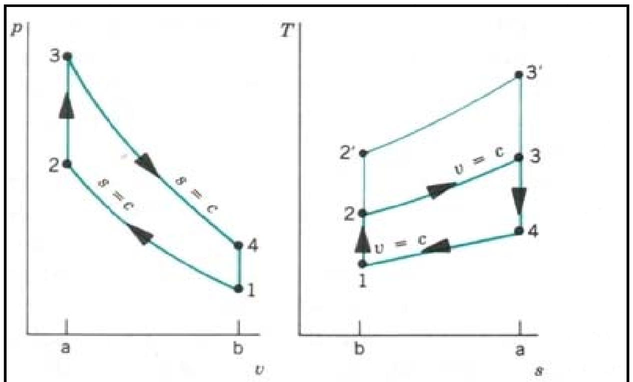
Also with inlet and exhaust port opened together, a certain amount of fuel and air mixture is lost. There is also much shorter period in which inlet port is open. These factors reduce the amount of power from each power stroke.

However they have the advantages of being simple and inexpensive, and have high power to weight and power to volume ratio. These features make them suitable for applications requiring small size and weight such as motor cycle.

Analysis of Otto cycle

The actual cycle is pretty hard to analyze. Utilizing the air-standard assumptions, the analysis can be simplified. Otto cycle is the ideal cycle for spark ignition engines. It consists of the following processes:

1. Isentropic compression
2. Constant volume heat addition
3. Isentropic expansion
4. Constant volume heat rejection



p–v and T–s diagrams of the air-standard Otto cycle.

Heat transfer to the working fluid:

$$q_{in} = u_3 - u_2$$

Heat transferred from the working fluid:

$$q_{out} = u_4 - u_1$$

Net work done

$$w_{net} = q_{in} - q_{out}$$

Thermal efficiency:

$$\eta = \frac{w_{net}}{q_{in}}$$

Relationships for the isentropic processes 1-2 and 3-4:

$$v_{r2} = v_{r1}(\frac{V_2}{V_1}) = \frac{V_{r1}}{\gamma}$$

$$v_{r2} = v_{r1}\left(\frac{V_4}{V_3}\right) = \gamma v_{r3}$$

γ being compression ratio, γ = $\frac{V_{max}}{V_{min}} = \frac{V_1}{V_2} = \frac{V_4}{V_3}$

If analysis is done on a cold air-standard basis, following expressions may be used:

$$q_{in} = u_3 - u_2 = C_v(T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = C_v(T_4 - T_1)$$

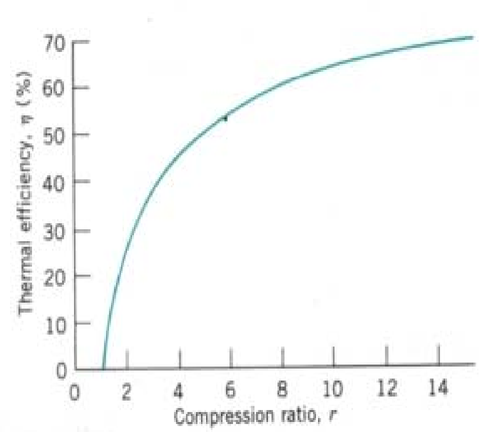
$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = \gamma^{k-1}$$

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1} = \left(\frac{1}{\gamma^{k-1}}\right)$$

$$\eta = 1 - \left(\frac{1}{\gamma^{k-1}}\right)$$

Effect of compression ratio on performance

Otto cycle thermal efficiency increases as the compression ratio increases. But the possibility of premature ignition of the fuel (known as auto ignition, which produces an audible noise called engine knock), puts an upper limit on the compression ratios that can be used in spark-ignition internal combustion engines. Engine knock affects performance and damages the engine. Fuels formulated with tetraethyl lead have good antiknock characteristics, i.e. they allow higher compression ratios. But leaded gasoline forms compounds during the combustion process that are hazardous to health and pollute the environment.



Thermal efficiency of the cold air-standard Otto cycle, k = 1.4

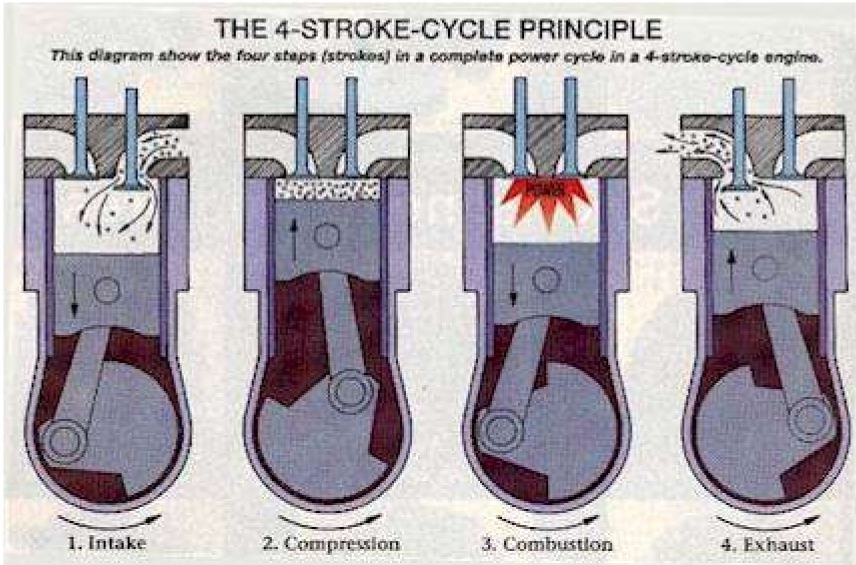
Working principle of diesel engine: model

This cycle is also known as constant pressure cycle. Diesel engine is mostly employed in Stationary Power plants, Ships, Heavy Motor Vehicles.

In Petrol Engine, the air-fuel mixture is compressed in the engine cylinder to a high pressure, and then it is ignited by an electric spark from a spark plug.

In diesel engine, diesel oil is used as fuel. This fuel is ignited by injecting it into the engine cylinder containing air compressed to a very high pressure. The temperature of this air is sufficiently high to ignite the fuel. That is why there is no spark plug used in diesel engine. This high temperature compressed air is injected at a controlled rate in the form of very fine spray so that the combustion of fuel proceeds at constant pressure.

Diesel Engine is mainly worked on below strokes.



01) Intake Stroke:-

In this stroke, the piston moves down from the top dead centre. As a result, inlet valve opens and air is drawn into the cylinder. After sufficient quantity of air with pressure is drawn, suction valve closes at the end of the stroke. The exhaust valve remains closed during this stroke.

02) Compression Stroke:-

In this stroke, piston moves up from the bottom dead centre. During this stroke both inlet and exhaust valve are closed. The air drawn into the cylinder during intake stroke is entrapped inside the cylinder and compressed due to upward movement of the piston. In diesel engine, the compression ratio used is very high. The air is compressed to a very high pressure up-to 40 kilogram per centimeter square. At this pressure, the temperature of the air is reached to 1000 degree centigrade which is enough to ignite the fuel.

03) Power Stroke:-

In this stroke, the fuel is injected into the hot compressed air where it starts burning, maintaining the pressure constant. When the piston moves to its top dead center, the supply of fuel is cut-off. It is to be said that the fuel is injected at the end of compression stroke and injection continues till the point of cut-off, but in actual practice, the ignition starts before the end of compression stroke to take care of ignition tag.

04) Working or Power Stroke:-

In this stroke, both inlet and exhaust valve remain closed. The hot gases (which are produced due to ignition of fuel during compression stroke) and compressed air now expand adiabatically, in the cylinder pushing the piston down and hence work is done. At the end of stroke, the piston finally reaches the bottom dead center.

05) Exhaust Stroke:-

In this stroke, the piston again moves upward. The exhaust valve opens, while inlet and fuel valve are closed. A greater part of the burnt fuel gases escape due to their own expansion. The upward movement of the piston pushes the remaining gases out through the open exhaust valve. Only a small quantity of exhaust gases stay in the combustion chamber. At the end of exhaust stroke, the exhaust valve closes and the cycle is thus completed.

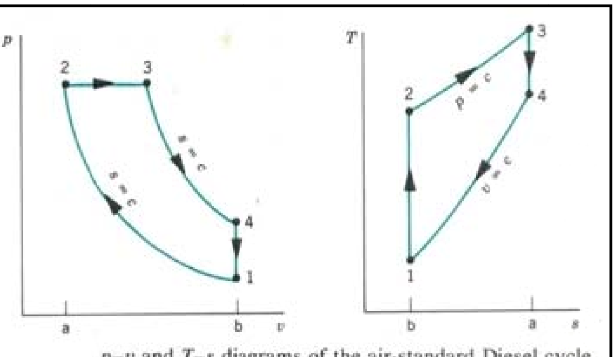
As there is some resistance while operating in inlet and exhaust valve and the some portion of burnt gases remains inside the cylinder during the cycle, resulting the pumping losses. These pumping losses are treated as negative work and therefore subtracted from actual work done during the cycle. This will give us net work done from the cycle.

Air standard diesel cycle

The diesel cycle is the ideal cycle for compression ignition engines, named after it's proposer Rudolph Diesel. The spark plug is replaced by fuel injector in diesel engines. In diesel engine it is assumed that the heat addition occurs during a constant pressure process that starts with the piston at top dead center.

The air standard diesel cycle consists of the following internally reversible processes in series:

1. Isentropic compression
2. Constant pressure heat addition
3. Isentropic expansion
4. Constant volume heat rejection



p–v and T–s diagrams of the air-standard Diesel cycle.

In diesel engine,

$$q_{in} = q_{23} = (P_2(V_3 - V_2) - (u_3 - u_2))$$

$$= h_3 - h_2$$

$$= C_p(T_3 - T_2)$$

$$q_{out} = -q_{41} = u_4 - u_1 = C_v(T_4 - T_1)$$

$$\eta = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{\gamma(T_3 - T_2)}$$

$$\eta = 1 - (\frac{T_1\left[\left(\frac{T_4}{T_1}\right) - 1\right]}{\gamma T_2\left[\left(\frac{T_3}{T_2}\right) - 1\right]})$$

Comparing η of Otto cycle and η of diesel cycle when both cycle operate at the same compression ratio,

$$\eta_{Otto} > \eta_{diesel}$$

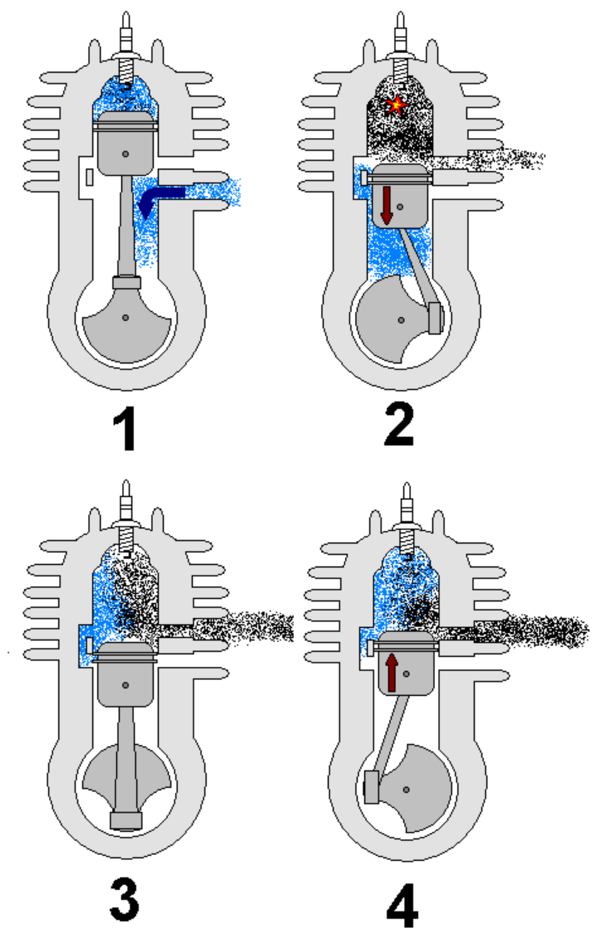
η_{diesel} ranges from 35 – 40 percentages.

Two stroke engine

Two-stroke engine is an internal combustion engine which completes the thermodynamic cycle in two movements of the piston. This increased efficiency is accomplished by using the beginning of the compression stroke and the end of the combustion stroke to perform simultaneously the intake and exhaust functions. In this way two-stroke engines often provide strikingly high specific power. Petrol (spark ignition) versions are particularly useful in lightweight (portable) applications such as chainsaws and the concept is also used in diesel compression ignition engines in large and non-weight sensitive applications such as ships and locomotives.

Instead of placing the intake and exhaust ports in the combustion chamber, they are placed in the cylinder wall. In this engine piston goes through a power stroke every time it moves from top dead center to bottom dead center. The downward stroke is also an intake and exhaust stroke. As the piston moves from bottom dead center to the top dead center, it is going through compression stroke.

Working of two stroke engine



It is easier to understand if you look at what is happening in the crankcase, then consider what is occurring above the piston in the cylinder.

Two things are always happening at the same time in the two stroke cycle.

Upward stroke:

During upward stroke, there is compression on the top of the piston and induction of the mixture below the piston.

<u>In crankcase</u>

- As the piston rises the volume increases and pressure drops below atmospheric pressure.
- The inlet port is uncovered by the skirt of the piston.
- Atmospheric pressure forces air through carburetor where it is mixed with fuel and enters the crankshaft.

<u>In the combustion chamber</u>

- as the piston rises all ports are closed off.
- Mixture previously transferred from the crankcase into the cylinder is compressed.

Downward stroke:

During downward stroke there is pressure due to combustion above the piston and fuel/air mixture is being compressed below the piston in the crankcase.

<u>In crankcase</u>

- As the piston rises the volume increases and pressure drops below atmospheric pressure.
- The inlet port is uncovered by the skirt of the piston.
- Atmospheric pressure forces air through carburetor where it is mixed with fuel and enters the crankshaft.

<u>In the combustion chamber</u>

- as the piston rises all ports are closed off.
- Mixture previously transferred from the crankcase into the cylinder is compressed.

Advantages and usage:

Two stroke engine is most extensively used in very small equipment. It is lightweight and able to run at very high speed due to the absence of mechanical valve train.

Comparison of 4-stroke and 2-stroke cycle engines

S.N	Aspects	Four stroke cycle engine	Two stroke cycle engine
1	**Completion of cycle**	The cycle is completed in 4 –strokes of the piston or in 2 revolution of the crankshaft. Thus one power stroke is obtained in every 2 revolutions of the crankshaft.	The cycle is completed in 2 strokes of the piston or in one revolution of the crankshaft. Thus one power stroke is obtained in each revolution of the crankshaft.
2	**Flywheel required heavier or lighter**	Because of the above turnin – movement is not so uniform and hence heavier flywheel is needed	More uniform turning movement and hence lighter flywheel is needed.
3	**Power produced for same size of engine**	Because of one power stroke for 2 revolutions, power produced for same size of engine is small or for the same power the engine is heavy and bulky.	Because of one power stroke for one revolution, power produced for same size of engine is more (theoretically twice, actually about 1.3 times) or for the same power the engine is light and compact.
4	**Cooling and lubrication requirements**	Because of one power stroke in two revolutions lesser cooling and lubrication requirements. Lesser rate of wear and tear.	Because of one power stroke in one revolution greater cooling and lubrication requirement. Great rate of wear and tear.
5	**Valve and valve mechanism**	The four stroke engine contains valve and valve mechanism.	Two stroke engines have no valves but only ports.
6	**Initial cost**	Because of heavy weight and complication of valve mechanism, higher is the initial cost.	Because of light weight and simplicity due to absence of valve mechanism, cheaper in initial cost.
7	**Volumetric Efficiency**	Volumetric efficiency more due to more time of induction.	Volumetric efficiency less due to lesser time for induction.
8	**Thermal and part-load efficiencies**	Thermal efficiency higher, part load efficiency better than two stroke engine.	Thermal efficiency lower, part load efficiency lesser than four stroke cycle engine.
9	**Applications**	Used where efficiency is important, in cars, buses, trucks, tractors, industrial engines, airplane, power generators etc.	In two stroke petrol engine some fuel is exhausted during scavenging. Used where (a)low cost, and (b) compactness and light weight important.

Comparison of spark ignition (SI) and combustion ignition (CI) engines

S.N	Aspect	S.I. Engine	C.I. Engine
1	**Thermodynamic Cycle**	Otto Cycle	Diesel cycle: for slow speed engines. Dual cycle: for high speed engines.
2	**Fuel used**	Petrol	Diesel
3	**Air-Fuel ratio**	10:1 to 20:1	18:1 to 100:1
4	**Compression ratio**	Up to 11; Average value 7 to 9 Upper limit of compression ratio fixed by anti-knock quality of fuel	12 to 24; Average value 15 to 18 Upper limit of compression ratio is limited by thermal and mechanical stresses.
5	**Combustion**	Spark ignition	Compression ignition
6	**Fuel supply**	By carburetor: cheap method	By injection: expensive method
7	**Operation pressure** **i.compression** **ii.Max pressure**	 7 bar to 15 bar 45 bar to 60 bar	 30 bar to 50 bar 60 bar to 120 bar
8	**Operating speed**	High speed: 2000 to 6000 rpm	Low speed: 400 rpm; Medium speed: 400-1200 rpm; High speed: 1200- 3500 rpm
9	**Control of power**	Quantity of fuel: governed by throttle	Quantity of fuel: governed by rack
10	**Heating value of fuel**	44 MJ/kg	42 MJ/Kg
11	**Running cost**	High	Low
12	**Maintenance cost**	Minor maintenance required	Major overall required by less frequently.
13	**Supercharging**	Limited by detonation. Used only in aircraft engines	Limited by blower power and mechanical and thermal stress. Widely used.
14	**Two stroke operation**	Less suitable, fuel loss in scavenging. But small two stroke engines are used in mopeds, scooters and motorcycles due to their simplicity and low cost.	No fuel loss in scavenging. More suitable.
15	**High powers**	No	Yes
16	**Uses**	Mopeds, scooter, motorcycles, simple engine passenger cars, aircrafts etc.	Buses, trucks, locomotives, tractors, earth moving machinery and stationary generating plants.

Comparison between a petrol engine and a diesel engine

S.N	Aspects	Petrol Engine	Diesel Engine
1	**Suction stroke**	Air petrol mixture is sucked in the engine cylinder	Only air is sucked during suction stroke
2	**Fuel ignition device**	Spark plug is used	Employs an injector
3	**Power stroke**	Power is produced b spark ignition	Power is produced by compression ignition
4	**Thermal efficiency**	Up to 25%	Up to 40%
5	**Size**	Occupies less space	Occupies more space
6	**Running cost**	High running cost	Low running cost
7	**Weight**	Light	Heavy
8	**Fuel cost**	Fuel(Petrol) costlier	Fuel(diesel) cheaper
9	**Volatility of fuel**	Petrol being volatile is dangerous	Diesel is no-dangerous as it is non-volatile
10	**Pre-ignition**	Pre-ignition possible	Pre-ignition not possible
11	**Working cycle**	Works on Otto cycle	Works on Diesel cycle
12	**Dependency**	Less dependable	More dependable
13	**Applications**	Used in cars and motor cycles	Used in heavy duty vehicles like trucks, buses and heavy machinery

Comparison between a gas turbine and IC engine

S.N	Aspects	Gas Turbine	IC Engine
1	**Balancing of components**	Perfect balancing of rotating parts	Difficult to balance perfectly
2	**Mech. efficiency**	Mech. Efficiency is high(95%)	Mech. Efficiency is lower(85%)
3	**Flywheel**	Torque on the turbine shaft is continuous(no need of flywheel)	Needs flywheel
4	**Weight to power ratio**	The weight of gas turbine is 0.15 kg/kW	The weight of IC engine is 2.5 kg/kW
5	**Engine rpm**	High rpm(40,000 rpm)	It works on low rpm compared to gas turbine
6	**Max pressure**	Is low (5 bar)	Is 60 bar or more
7	**Weight of components**	Components are lighter	Components are heavier
8	**Fuel**	Can use cheaper fuel(paraffin type, residue oils)	Higher grade fuels are used to avoid knocking
9	**Thermal efficiency**	Low (15-20%)	Around 25- 30%
10	**Part load efficiency**	Poor thermal efficiency at par loads(air quantity remains same)	Comparatively better thermal efficiency at part load
11	**Max gas temp**	Temp. of gases supplied to the turbine is limited to 1100K	Gas temperature can be higher
12	**Cost**	Blades(Ni-Cr alloy) are difficult to manufacture and costly	Piston assembly is cheaper
13	**Cooling system**	Special cooling system is required for the turbine blades	No need of special cooling
14	**Engine starting**	The starting of gas turbine is difficult	Easy to start IC engine
15	**Exhaust gas**	The exhaust gas less polluting but produced in large quantity	The exhaust gas is polluting and needs treatment

Merits of two stroke cycle

1. A two stroke engine has twice as many power strokes as a four stroke cycle engine, at the same engine speed. Theoretically, therefore a two-stroke engine should develop twice the power of four stroke engine of the same dimensions. However, the extra power developed is only 70 to 90%(greater value applicable in slow speed engines) due to the power absorbed in compressing the charge, reduction in the effective stroke and the compression ratio due to the valve ports and due to short time available for the exhaust of gases, in high speed engines.
2. For the same power a two stroke cycle engine is lighter and occupies less floor area. This makes it more suitable for use in marine engines.
3. As the number of working strokes are double than in four stroke engine, the turning moment is more uniform and hence a lighter flywheel is required.
4. The more uniform turning moment results in lighter foundation of the engine.
5. The mechanism is very simple, as there are no valves. In some cases mechanically operated valves may be provided.
6. In the absence of valves, a simple arrangement can be used for reversing the engine.

Demerits of two stroke cycle

1. In two stroke engines, particularly high speed ones scavenging (driving out of exhaust gases from engine cylinder) is not complete due to short time available for exhaust and hence the fresh charge is polluted. This pollution of the charge has been reduced in opposed piston tow stroke diesel engines by uni-directional scavenging.
2. As inlet and exhaust ports open simultaneously some fresh, charge containing fuel in the case of petrol and gas engines and compressed air in the case of diesel engines is lost.
   The thermal efficiency of the two strokes engines is likely to be lower than four stroke engine due to above reasons and due to lower effective compression ratio.
3. As the number of power stroke is double than four stroke cycle, cooling system presents difficulty.
4. Consumption of lubricating oil is greater.
5. As the number of power stroke is twice, there is more wear and tear.
6. The exhaust is noisy due to short time available.