

UNIT IV

INTERNAL COMBUSTION ENGINES – FEATURES AND COMBUSTION

INTRODUCTION

A heat engine is a device which converts the chemical energy of fuel into thermal energy and in turn into mechanical energy. The heat engines are classified into external combustion engines (EC Engines) and internal combustion engines (IC Engines).

In external combustion engine, the combustion of fuel takes place outside the engine cylinder and the heat produced is transferred to a second fluid which the working fluid of the cycle to produce the mechanical energy. Steam engine, steam turbine, Stirling engine and closed cycle gas turbine are the examples of external combustion engine.

In internal combustion engine, the combustion of fuel takes place inside the engine and the products of combustion is used to produce mechanical energy. Open cycle gas turbine, Wankel engine, gasoline engine and diesel engine are examples of internal combustion engines.

ENGINE COMPONENTS

A cross section of a single cylinder internal combustion engine with overhead valves is shown in figure 3.1. The major components of the engine and their functions are briefly described below.

(i) Cylinder: As the name implies it is a cylindrical vessel or space in which the piston makes a reciprocating motion. The varying volume created in the cylinder during the operations of the engine is filled with the working fluid and subjected to different thermodynamic processes. The cylinder is supported in the cylinder block.

(ii) Piston: It is a cylindrical components fitted into the cylinder forming the moving boundary of the combustion system. It fits perfectly into the cylinder providing a gas tight space with the piston rings and the lubricant. It forms the first link in transmitting the gas forces to the output shaft

(iii) Combustion chamber: The space enclosed in the upper part of the cylinder, by the cylinder head and the piston top during the combustion process is called the combustion chamber. The combustion of fuel and the consequent release of thermal energy results in the building up pressure in the part of the cylinder.

(iv) Inlet manifold: The pipe which connects the intake system to the inlet valve of the engine and through which air or air-fuel mixture is drawn into the cylinder is called the inlet manifold.

(v) Exhaust manifold: The pipe which connects the exhaust system to the exhaust valve of the engine and through which the products of the combustion escape into the atmosphere is called the exhaust manifold.

(vi) Inlet and exhaust valves: Valves are commonly mushroom shaped puppet type. They are provided either on the cylinder head or on the side of the cylinder for regulating the charge coming into the cylinder (inlet valve) and for discharging the products of combustion (exhaust valve) from the cylinder.

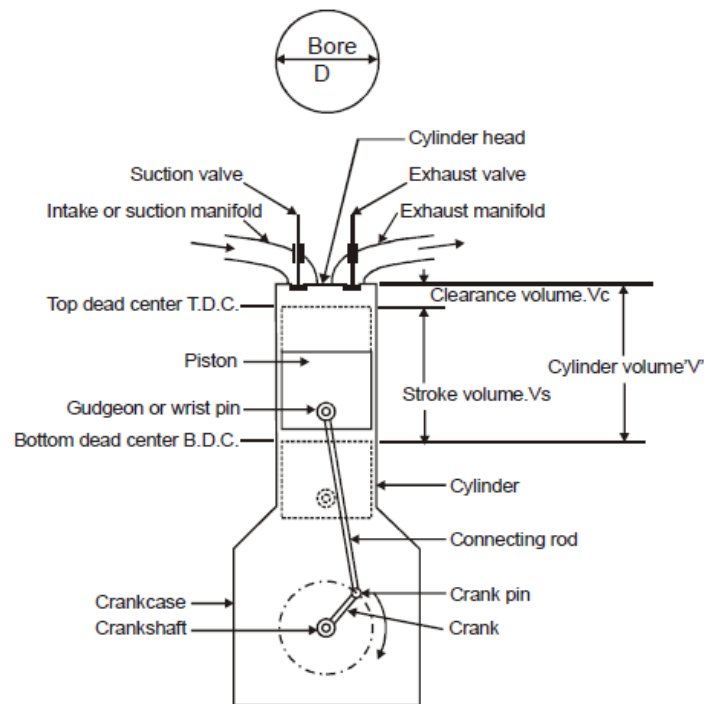


Figure 3.1 Cross section of an Internal Combustion Engine

(vii) Spark plug: It is a component initiates the combustion process in spark ignition engines and is usually located on the cylinder head.

(viii) Fuel injector: It is the component mounted on the cylinder head of compression ignition engine to inject the fuel at the end of compression stroke

(ix) Connecting rod: It interconnects the piston and the crank shaft and transmits the gas forces from the piston to the crankshaft.

(x) Crankshaft: It converts the reciprocating motion of the piston into useful rotary motion of the output shaft. In the crankshaft of a single cylinder engine there is a pair of crank arms and balance weights. The balance weights are provided for static and dynamic balancing of the rotating system. The crankshaft is enclosed in a crankcase.

(xi) Piston rings: Piston rings, fitted into the slots around the piston, provides a tight seal between the piston and the cylinder wall thus preventing leakage of combustion gases.

(xii) Gudgeon pin: It forms the link between the small end of the connecting rod and the piston.

(xiii) Cam shaft: The camshaft and its associated parts control the opening and closing of the two valves. The associated parts are push rods, rocker arms, valve springs and tappets. This shaft also provides the drive to the ignition system. The camshaft is driven by the crank shaft through timing gears.

(xiv) Cams: These are made as integral parts of the camshaft and are designed in such a way to open the valves at the correct timing and to keep them open for the necessary duration.

(xv) Flywheel: The net torque imparted to the crank shaft during one completed cycle of operation of the engine fluctuates causing a change in the angular velocity of the shaft. In order to achieve a uniform torque an inertia mass in the form of a wheel is attached to the output shaft and this wheel is called the flywheel. The variation of the net torque decreases with

increase in the number of cylinders in the engine and thereby the size of the flywheel also becomes smaller. This means that a single cylinder engine will have a larger flywheel whereas a multi cylinder engine will have a smaller flywheel.

The list of engine parts and material used are given in table 3.1

Table: The list of engine parts and material used	
Name of the part	Material used
Cylinder	Cast iron, alloy steel
Cylinder head	Cast iron, aluminium alloy
Piston	Cast iron, aluminium alloy
Piston rings	Silicon cast iron
Wrist pin	Steel
Valves	Alloy steel
Connecting rod	Steel
Crankshaft	Alloy steel, SG iron
Crankcase	Aluminium alloy, steel, cast iron
Cylinder liner	Cast iron, nickel alloy steel
Bearing	White metal, leaded bronze

ENGINE TERMINOLOGIES

The various terminologies used in an internal combustion engines are:

(i) Cylinder bore: The nominal inner diameter of the working cylinder is called the cylinder bore and is designated by the letter (d) and is usually expressed in millimeter.

(ii) Piston area: At the area of the circle of diameter equal to the cylinder bore is called the piston area and is designated by the letter (A) and usually expressed in square centimeter.

(iii) Stroke: The nominal distance through which a working piston moves between two successive reversals of its direction of motion is called the stroke and is designated by the letter L and expressed in millimeter

(iv) Dead center: The position of the working piston and the moving parts which are mechanically connected to it, at the moment when the direction of the piston motion is reversed at either end of the stroke is called the dead center. There are two dead centers in an engine, top dead center (TDC) and bottom dead center (BDC). The TDC is the dead center when the piston is farthest from the crankshaft. The BDC is the dead center when the piston is nearest to the crankshaft.

(v) Displacement or swept volume (V_s): The nominal volume swept by the piston when traveling from one dead center to the other is called the displacement volume. It is expressed in terms of the cubic centimeter

$$V_s = (\pi/4) d^2L$$

(vi) Clearance volume: The nominal volume of the combustion chamber above the piston when it is at the top dead center is the clearance volume. It is designated as V_c and expressed in cubic centimeter.

(vii) Compression ratio: It is the ratio of the total cylinder volume when the piston is at the bottom dead center to the clearance volume. It is designated by the letter r .

$$r = (V_s + V_c)/V_c$$

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES

Internal Combustion engines are classified under different headings, some of the classifications are as follows.

(i) According to number of strokes

- ✘ Four stroke cycle engine and
- ✘ Two stroke engine

(ii) According to cycle of operation

- ✘ Otto cycle engine and
- ✘ Diesel cycle engine

(iii) According to type of fuel used

- ✘ Engine using volatile liquid fuels like gasoline, alcohol, kerosene
- ✘ Engine using gaseous fuel like natural gas, petroleum gas, blast furnace gas
- ✘ Engine using solid fuel like char coal, powdered coal
- ✘ Engine using viscous fuels like diesel oil
- ✘ Engine using dual fuel

(iv) According to Method of charging

- ✘ Naturally aspirated engine and
- ✘ Supercharged engine

(v) According to type of ignition

- ✘ Spark ignition engine and
- ✘ Compression ignition engine

(vi) According to cooling method

- ✘ Air cooled engine and
- ✘ Water cooled engine

(vii) According to governing method

- ✘ Hit and miss governed engine
- ✘ Quantity governed engine
- ✘ Quality governed engine

(viii) According to speed of the engine

- ✘ Low speed engine
- ✘ High speed engine
- ✘ Medium speed engine

(ix) According to their use

- ✘ Stationary engine
- ✘ Automobile engine
- ✘ Portable engine
- ✘ Aero engine
- ✘ Marine engine

(x) According to number of cylinders

- ✘ Single cylinder engine
- ✘ Multi cylinder engine

(xi) According to Cylinder arrangement

- ✎ Inline engine
- ✎ V- Engine
- ✎ Opposed cylinder engine
- ✎ Opposed piston engine
- ✎ Radial engine etc.,

WORKING PRINCIPLE OF ENGINES

For an engine is to work successfully then it has to follow a cycle of operation in a sequential manner. This sequence is quite rigid and cannot be changed. In the following sections the working principles of both SI and CI engines is described. Even though both engines have much in common there are certain fundamental differences. The credit of inventing the spark ignition engine goes to Nicolas Otto (1876) whereas compression ignition engine was invented by Rudolf Diesel (1892). Therefore, they are often referred to as Otto engine and Diesel engine.

Working of Four Stroke Spark Ignition Engine

In a four stroke engine, the cycle of operations is completed in four strokes of the piston or two revolutions of the crankshaft. During the four strokes, there are five events to completed, viz., suction, compression, combustion, expansion and exhaust. Each stroke consists of 180 degrees of crank rotation and hence a four stroke cycle is completed through 720 degrees of crank rotation.

The cycle of operation for an ideal four stroke SI engine consists of (i) Suction stroke (ii) Compression stroke (iii) Expansion or power stroke and (iv) Exhaust stroke as shown in figure.

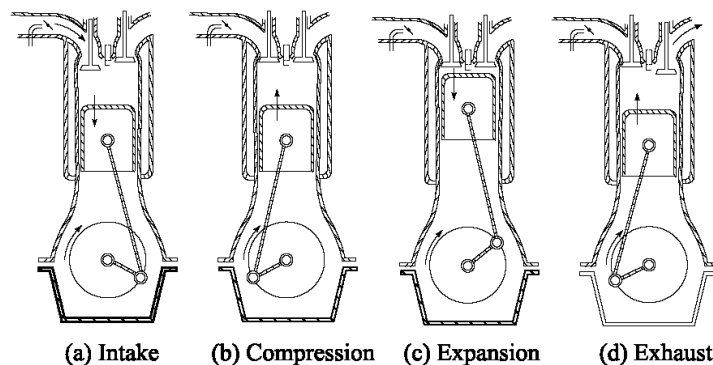


Figure Four Stroke Cycle SI Engine

(i) Suction or intake stroke: Suction stroke starts when the piston is at the top dead center and about to move downwards. The inlet valve is open at this time and the exhaust valve is closed. Due to the suction created by the motion of the piston towards the bottom dead center, the charge consisting of fuel air mixture is drawn into the cylinder. When the piston reaches the bottom dead center, the suction stroke ends and the inlet valve closes.

(ii) Compression stroke: The charge taken into the cylinder during the suction stroke is compressed by the return stroke of the piston. During this stroke both inlet and exhaust valves are in the closed position and the piston moves from BDC to TDC. The mixture which fills the entire cylinder volume is now compressed into the clearance volume. At the end of the compression stroke the mixture is ignited with the help of a spark produced by a spark plug located on the cylinder head. Burning takes place almost instantaneously when the piston is the top dead center and hence the burning process can be approximated as heat addition at constant volume. During the burning process the chemical energy of the fuel is

converted into heat energy producing a temperature rise of about 2000 °C. This pressure at the end of the combustion process is considerably increased due to the heat release.

(iii) Expansion stroke: The high pressure of the burnt gases forces the piston towards the BDC with both inlet and exhaust valves remaining closed. Thus power is obtained during this stroke. Both pressure and temperature decreases during expansion.

(iv) Exhaust stroke: At the end of the expansion stroke the exhaust valve opens and the inlet valve remains closed. The piston moves from BDC to TDC. The pressure falls to atmospheric level and the burnt gases are sent out of the cylinder. The exhaust valve is closed at the end of the stroke some residual gases are left in the clearance space of the engine cylinder. These residual gases mix with the fresh charge coming in during the following cycle, forming its working fluid. Each cylinder of a four stroke engine completes the above four operations in two engine revolutions, one revolution of the crankshaft occurs during the suction and compression strokes and the second revolution during the power and exhaust strokes. Thus, for one complete cycle there is only one power stroke while the crankshaft turns by two revolutions.

Working of Four Stroke Cycle Compression Ignition Engine

The four stroke CI engine is similar to the four stroke SI engine but it operated at a much higher compression ratio. The compression ratio of a SI engine varies from 6 to 10 while for a CI engine it is from 16 to 20. In the CI engine during suction stroke air is inducted due to the high compression ratio employed the temperature at the end of the compression stroke is sufficiently high to self-ignite the fuel which is injected into the combustion chamber.

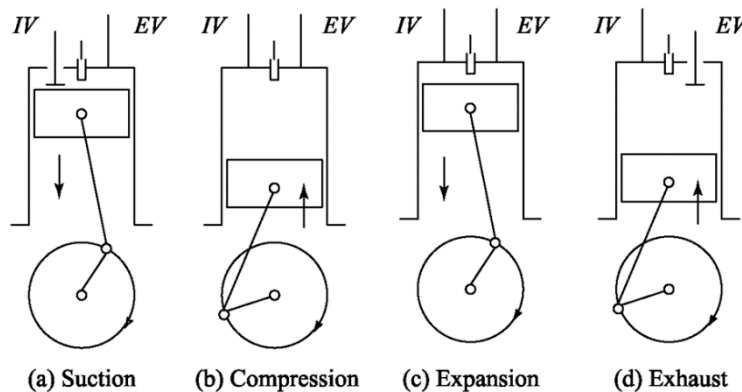


Figure Four Stroke Cycle CI Engine

Figure shows the four stroke cycle CI engine. The ideal sequence of operations for the four stroke CI engine is as follows

- (i) Suction stroke:** During this stroke intake valve is open and exhaust valve is closed. The piston moves from TDC to BDC. Air alone is inducted during the suction stroke.
- (ii) Compression stroke:** Both valves remain closed and piston moves from BDC to TDC during this stroke. Air inducted during the suction stroke is compressed into the clearance volume. The pressure and temperature at the end of compression stroke is very high.
- (iii) Expansion stroke:** Fuel injection starts nearly at the end of the compression stroke and combustion of fuel takes place. The products of combustion expand with both valves remain closed during the expansion stroke.
- (iv) Exhaust stroke:** The piston is travelling from BDC to TDC pushes out the products of combustion. The exhaust valve opens and the intake valve is closed during this stroke.

Comparison of SI and CI Engines

The detailed comparison of SI and CI engines is given in table

Table Comparison of SI and CI engines		
Description	SI engine	CI engine
Basic cycle	Otto cycle or constant volume heat addition cycle	Diesel cycle or constant pressure heat addition cycle
Fuel	Gasoline, a high volatile fuel. Self-ignition temperature is high	Diesel oil, a non-volatile fuel. Self-ignition temperature is comparatively low
Ignition	Requires an ignition system with spark plug in the combustion chamber. Primary voltage is provided by a battery or magneto	Self-ignition occurs due to high temperature of air because of the high compression. Ignition system and spark plug are not necessary
Load control	Throttle controls the quantity of mixture introduced	The quantity of fuel is regulated in the pump. Air quantity is not controlled
Speed	Due to light weight and also due to homogeneous combustion they are high speed engines	Due to heavy weight and also due to heterogeneous combustion, they are low speed engines
Compression ratio	6 to 10 upper limit is fixed by antiknock quality of the fuel	16 to 20 upper limit is limited by weight increase of the engine
Weight	Lighter due to lower peak pressures	Heavier due to higher peak pressures
Thermal efficiency	Low because of lower compression ratio	High because of the higher compression ratio
Introduction of fuel	A gaseous mixture of fuel and air is introduced during the suction stroke. A carburetor is necessary to provide the mixture	Fuel is injected directly into the combustion chamber at high pressure at the end of the compression stroke. A fuel pump and injector are necessary

Working of Two Stroke Cycle Engine

In two stroke cycle engine, the cycle is completed in one revolution of the crank shaft. The main difference between two stroke and four stroke engines is in the method of filling the fresh charge and removing the burnt gases from the cylinder. In the four stroke engine these operations are performed by the engine piston during the suction and exhaust strokes respectively. In a two stroke engine, the filling process is accomplished by the charge compressed in crankcase or by a blower. The induction of the compressed charge moves out the product of combustion through exhaust ports. Therefore, no piston strokes are required for these two operations. Two strokes are sufficient to complete the cycle, one for compressing the fresh charge and the other for expansion or power stroke.

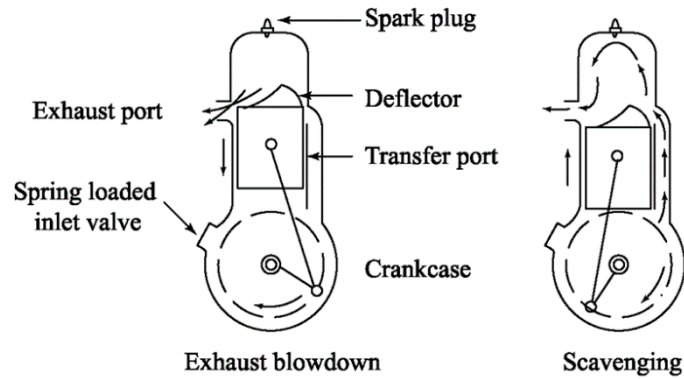


Figure Two stroke cycle engine

Figure shows the two stroke cycle engine. When the piston is in the TDC, compressed charge available at the top of the piston is ignited and combustion of the fuel takes place, the intake port is kept opened and the fresh charge is inducted into the crankcase. The fresh charge is compressed in the crank case when the piston forced towards the BDC by the expansion of the gases and power is obtained during this stroke. When the piston is nearing the BDC, first the exhaust port is opened and the pressure inside the cylinder decreased to atmospheric pressure and the burnt gases are leaving to the atmosphere. Then, the transfer port is opened and the fresh charge is sent to the cylinder. When the piston is at BDC the cylinder is completely filled with fresh charge. As the piston moves towards the TDC, the fresh charge in the engine cylinder is compressed and at the end of compression the ignition is initiated and combustion of the fuel takes place and the cycle is repeated.

Comparison of Four Stroke and Two Stroke Cycle Engines

The comparison of four stroke and two stroke cycle engines are given in table

Table Comparison of four stroke and two stroke engines	
Four stroke engine	Two stroke engine
The thermodynamic cycle is completed in four strokes of the piston or in two revolutions of the crank shaft. Thus, one power stroke is obtained in every two revolutions of the crank shaft	The thermodynamic cycle is completed in two strokes or one revolution of the crank shaft. Thus, one power stroke is obtained in every revolution of the crank shaft
Because of the above turning moment is not uniform and hence heavier flywheel is required	Turning is more uniform and hence lighter flywheel can be used
Because of one power stroke in two revolutions of the crank shaft lesser cooling and lubrication requirement. Lower rate of wear and tear	Because of one power stroke in one revolution greater cooling and lubrication requirements. Higher rate of wear and tear
Power produced by same size of the engine is less	Power produced by the same size of the engine is more
The four stroke engine contains valves and valve actuating mechanism to open and close the valves	Two stroke engines have no valves but only ports.

Initial cost of the engine is more	Initial cost of the engine is less
Volumetric efficiency is more due to more time of induction	Volumetric efficiency is low due to lesser time for induction
Thermal efficiency is higher and part load efficiency is better	Thermal efficiency is lower and part load efficiency is poor
Used where efficiency is important e.g., cars, buses, tractors, power generation	Used where low cost, compactness and light weight are important, e.g., mopeds, scooters , motor cycles , hand sprayers.

THEORITICAL AND ACTUAL P-V DIAGRAMS

3.6.1 Four stroke Otto cycle engine

The theoretical P-V diagram of a four stroke Otto cycle engine is shown in figure and the processes are given in table.

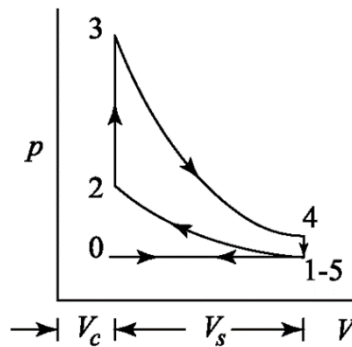


Figure Theoretical P-V diagram of four stroke Otto cycle engine

Table				
	Inlet valve	Exhaust valve	Piston movement	Process
Suction stroke (5 – 1)	Opened	Closed	TDC to BDC	The air-fuel mixture is drawn into the cylinder at constant pressure.
Compression stroke (1 – 2)	Closed	Closed	BDC to TDC	The air fuel mixture is compressed isentropically. At the end of compression process an electric spark is produced which initiate the combustion process (2 – 3). The combustion takes place at constant volume.
Expansion stroke (3 – 4)	Closed	Closed	TDC to BDC	The hot gases produced by combustion pushes the piston towards BDC and work is obtained in this stroke.
Exhaust stroke (1 – 5)	Closed	Opened	BDC to TDC	When the exhaust valve open the pressure inside the cylinder drops as shown in 4–1. Then the waste gases are exhausted to the atmosphere at constant

				pressure.
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The actual P-V diagram of four stroke Otto cycle engine is shown in figure. During the suction process the pressure inside the cylinder is lower than atmospheric pressure to enable the fresh charge enter into the cylinder effectively and during exhaust process the pressure inside the cylinder is slightly higher than the atmospheric pressure for effective exhaust of the gases. The loop 4-5-1 is called negative loop and 1-2-3-4 is called as positive loop and the net work of cycle is obtained by subtracting the area 4-5-1 from 1-2-3-4

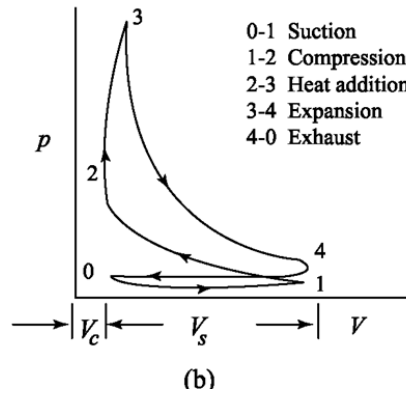


Figure Actual P-V diagram of four stroke Otto cycle engine

3.6.2 Four stroke diesel cycle engine

The theoretical P-V diagram of a four stroke Diesel cycle engine is shown in figure and the processes are given in table

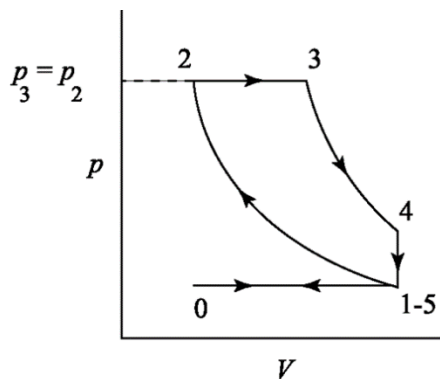


Figure Theoretical P-V diagram of four stroke Diesel cycle engine

Table				
	Inlet valve	Exhaust valve	Piston movement	Process
Suction stroke (5-1)	Opened	Closed	TDC to BDC	The air is drawn into the cylinder at constant pressure.
Compression stroke (1-2)	Closed	Closed	BDC to TDC	The air is compressed isentropically. At the end of compression process, fuel is injected and it is ignited using the high temperature at the end of compression stroke. The combustion takes place at constant pressure (2-3)

Expansion stroke (3-4)	Closed	Closed	TDC to BDC	The hot gases produced by combustion pushes the piston towards BDC and work is obtained in this stroke.
Exhaust stroke (1-5)	Closed	Opened	BDC to TDC	When the exhaust valve open the pressure inside the cylinder drops as shown in 4-1. Then the waste gases are exhausted to the atmosphere at constant pressure.

The actual P-V diagram of four stroke Diesel cycle engine is shown in figure. The actual P-V diagram of four stroke Diesel cycle engine is shown in figure 3.8. During the suction process the pressure inside the cylinder is lower than atmospheric pressure to enable the fresh charge enter into the cylinder effectively and during exhaust process the pressure inside the cylinder is slightly higher than the atmospheric pressure for effective exhaust of the gases. The loop 4-5-1 is called negative loop and 1-2-3-4 is called as positive loop and the net work of cycle is obtained by subtracting the area 4-5-1 from 1-2-3-4.

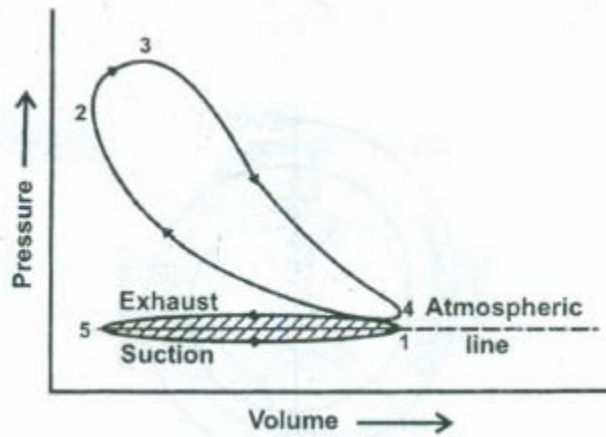


Figure Actual P-V diagram of four stroke Diesel cycle engine

3.6.3 Two stroke cycle engine

The P-V diagram of two stroke cycle engine is shown in figure for the main cylinder or top of the piston. The processes compression and expansion are shown and suction and crank case compression are not shown in the diagram.

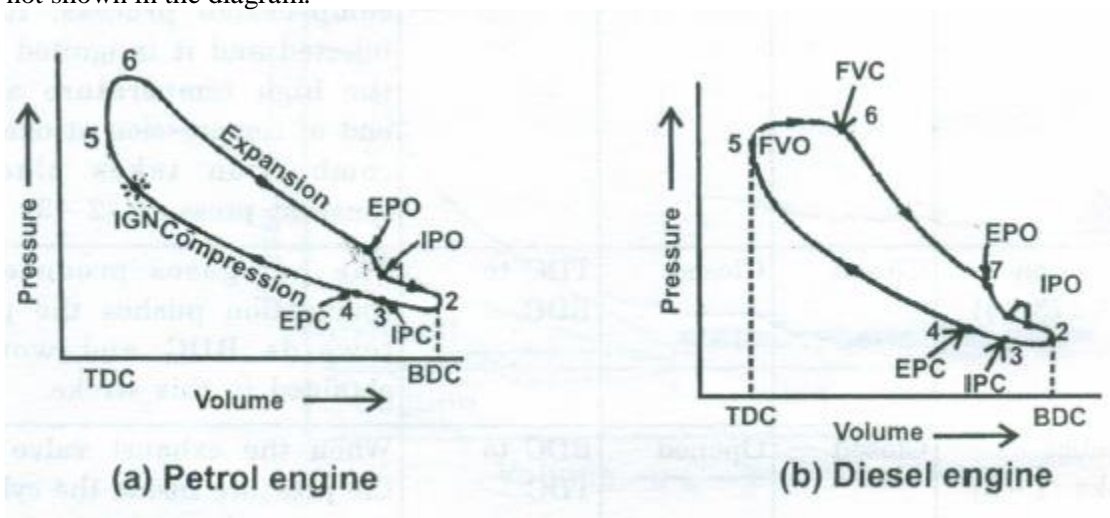
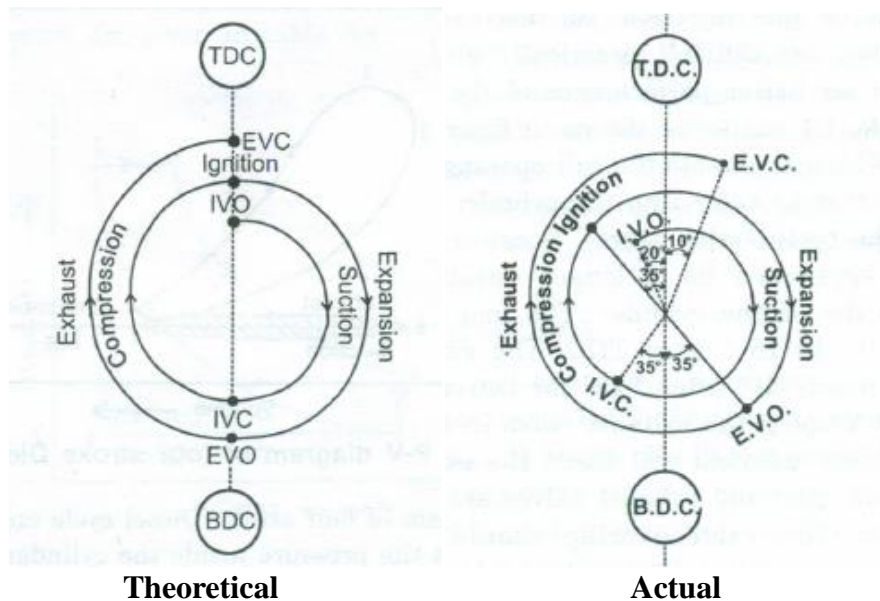


Figure P-V diagram of two stroke cycle engine

VALVE AND PORT TIMING DIAGRAMS

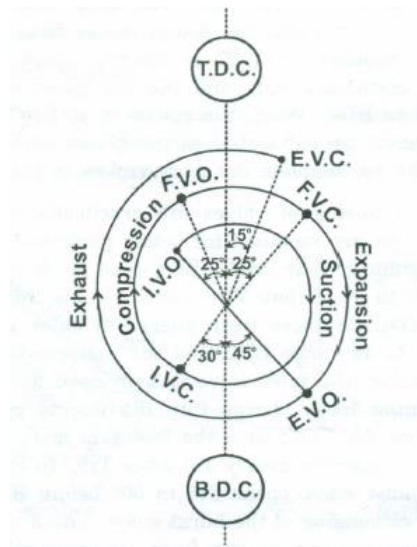
Valve timing diagram of four stroke cycle SI engine

Figure (theoretical) below shows the theoretical valve timing diagram of four stroke cycle spark ignition engine. The inlet valve opens (IVO) when the piston is at TDC and suction process occurs as piston moves towards BDC. The inlet valve closes (IVC) at BDC. The compression process occurs when the piston moves from BDC to TDC. At the end of the compression process, at TDC an electric spark is produced and the combustion takes place instantaneously and the hot gases are expanded and the piston moves from TDC to BDC. When the piston is at BDC the exhaust valve is opened and the waste gases are exhausted as the piston moves from BDC to TDC. The crank rotates by 720° to complete the four strokes in the cycle.



Instant opening and closing of valves are practically difficult and the valve opening and closing timings are modified for better performance of the engine. The actual valve timing diagram of four stroke SI engine is shown in figure (actual). The inlet valve is opened 10° to 30° before TDC which enable the full opening of valve when the piston is at TDC for more fresh charge to enter into the cylinder. The inlet valve is closed 30° to 40° after BDC and the compression starts. Because the change in inlet valve timing, the inlet valve is kept open for a longer duration for the admission of maximum fresh charge into the engine cylinder. The spark is produced 30° to 40° before the TDC; thus the fuel gets more time to burn and the cylinder pressure will be maximum nearly 10° after TDC to extract maximum work from the gases. The exhaust valve opens 30° to 50° before BDC and closed nearly 10° after TDC for better scavenging of the burnt gases. The next cycle begins keeping the exhaust valve in open position so the fresh charge coming in via the intake manifold will assist the exhaust of the burnt gases. For certain period of time both inlet and exhaust valves are kept open and the period is known as valve overlap. The valve overlap should be optimum for better performance of the engine.

Valve timing diagram of four stroke cycle CI engine

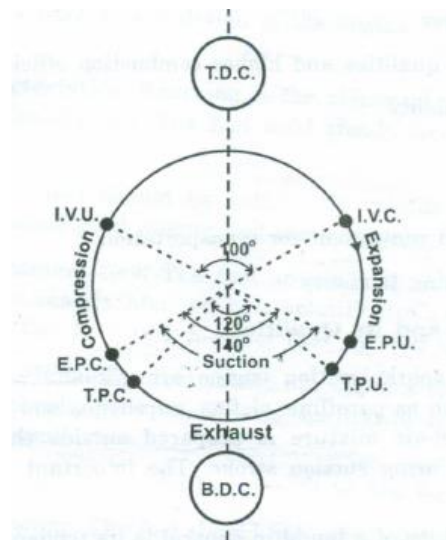


Actual valve timing diagram of CI engine

The theoretical valve timing diagram of four stroke CI engine is similar to figure petrol engine but the ignition is replaced by fuel injection. As discussed for SI engine, instant opening and closing of valves are difficult practically and the valve opening and closing timings are modified for better performance of the engine. The actual valve timing diagram of four stroke CI engine is shown in figure above. The inlet valve is opened 10° to 25° before TDC which enable the full opening of valve when the piston is at TDC for more fresh charge to enter into the cylinder. The inlet valve is closed 25° to 40° after BDC and the compression starts. Because the change in inlet valve timing, the inlet valve is kept open for a longer duration for the admission of maximum fresh charge into the engine cylinder. The fuel injection begins 5° to 10° before TDC and continues 10° to 15° after TDC. The exhaust valve opens 30° to 50° before BDC and closed nearly 10° after TDC for better scavenging of the burnt gases. The next cycle begins keeping the exhaust valve in open position so the fresh charge coming in via the intake manifold will assist the exhaust of the burnt gases. For certain period of time both inlet and exhaust valves are kept open and the period is known as valve overlap. The valve overlap should be optimum for better performance of the engine.

Port timing diagram of two stroke cycle engine

The port timing diagram of two stroke cycle engine is shown in figure below. The inlet port opens before TDC and closes after TDC and the total duration of inlet port opening is approximately 100° . The exhaust port opens before BDC and closes after BDC and the total duration of exhaust port opening is approximately 140° . The transfer port opens before BDC and closes after BDC and the total duration of opening is approximately 120° . In a two stroke cycle engine all the four operations viz., suction, compression, expansion and exhaust are taking place in one revolution of crankshaft i.e. 360° of crank rotation. The port timing diagram of petrol and diesel engines are same excepting the fuel injection in diesel engine and spark production in petrol engine. In petrol engine the spark is produced just before the TDC and in diesel engine the fuel injection valve open just prior to TDC and closes just after TDC.



Port timing diagram of two stroke cycle engine

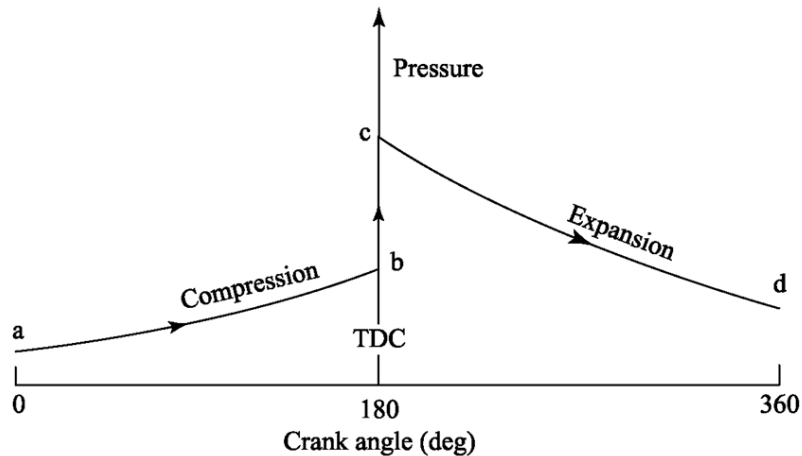
Learning Outcome Assessment Questions

1. What is meant by valve overlapping period? (AU-Nov 2014)
2. Draw the port timing diagram with fuel injection of a two stroke diesel engine and explain the salient points (AU-Nov 2009, May 2010)
3. Draw and explain the port timing diagram of two stroke cycle diesel engine (AU-May 2013)
4. Draw and describe the four stroke SI engine valve diagram (AU-May 2009)

COMBUSTION IN SI ENGINE

Combustion is a chemical reaction in which the carbon and hydrogen elements of the fuel combine with oxygen in the air liberating heat energy and causing an increase in temperature of the gases. The process of combustion in engines generally takes place either in a homogeneous or a heterogeneous fuel vapour air mixture depending of the type of the engine.

In a conventional SI engine the fuel and air are homogeneously mixed together in the intake system and inducted through the intake valve into the cylinder where it mixes with residual gases and is then compressed. Under normal operation conditions a spark is produced at the end of the compression process which initiates the combustion. Once the fuel vapour air mixture is ignited at a point, a flame front appears and rapidly spreads in the mixture. The flame propagation is caused by heat transfer and diffusion of burning fuel molecules from the combustion zone to the adjacent layer of fresh mixture. The flame front is a narrow zone separating the fresh mixture from the combustion products. The velocity with which the flame front moves with respect to the unburned mixture in a direction normal to its surface is called the normal flame velocity. In a homogeneous mixture the equivalence ratio is approximately 1.1 and the normal flame velocity is 40 cm/sec. Higher flame velocity is obtained when the mixture is slightly rich.



Stages of combustion in SI engine

The combustion in a SI engine is divided into three stages

Stage I: Ignition lag period (A – B)

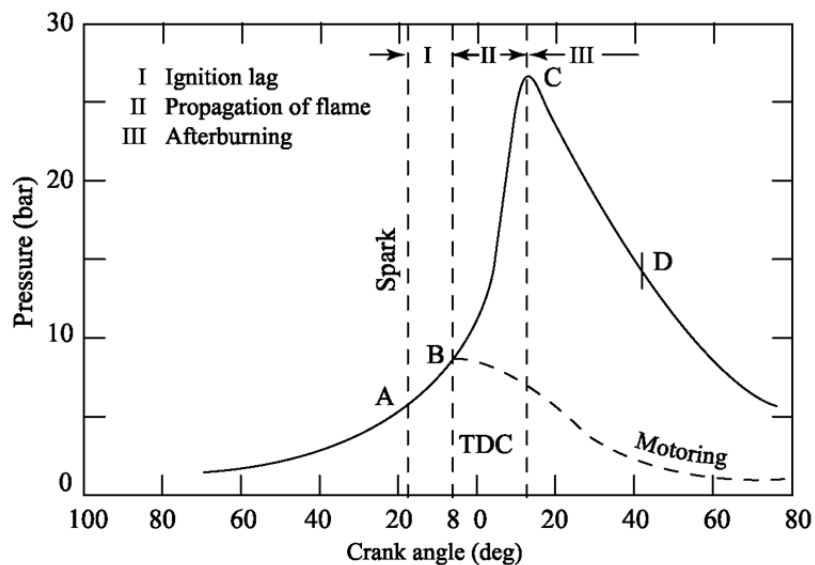
Stage II: Flame propagation period (B – C)

Stage III: After burning stage(C - D)

I stage: It is the ignition lag or preparation phase period during which growth and development of a self-propagating nucleus of flame takes place. This is a chemical process period depends on both temperature and pressure, nature of the fuel and proportion of exhaust residual gas.

II stage: It is the flame propagation period during which the flame spreads throughout the combustion chamber. The flame propagates at a constant velocity. The heat release rate depends on the intensity of turbulence and the reaction rate which depends of the mixture composition.

III stage: In the after burning stage, the flame velocity decreases. The rate of combustion becomes low due to lower flame velocity and reduced flame front surface. Since the expansion stroke starts before this stage of combustion with the piston moving away from the TDC there can be no pressure rise during this stage.



Flame front propagation:

For efficient combustion the rate of propagation of the flame front within the cylinder is quite critical. The two important factors which determine the rate of movement of the

flame front across the combustion chamber are the reaction rate and the transposition rate. The reaction rate is the result of a purely chemical combination process in which the flame eats its way into the unburned charge. The transposition rate is due to the physical movement of the flame front relative to the cylinder wall and is also the result of the pressure differential set up between the burning and unburnt gases in the combustion chamber.

Factors influencing the flame speed:

The various factors influencing the flame speed are

Turbulence: Turbulence is swirls produced in the combustion chamber which improves the proper mixing of air and fuel. In a combustion chamber, many minute swirls are preferred than larger swirls. The turbulence in the combustion chamber increases the heat flow to the cylinder wall, accelerate the chemical reaction and the combustion duration is minimized which reduces the tendency of abnormal combustion.

Fuel air ratio: The fuel air ratio has a very significant influence on the flame speed. The highest flame velocities are obtained with somewhat richer mixture. When the mixture is made leaner or richer with respect to the figure the flame speed decreases. Less thermal energy is released in the case of lean mixtures resulting in lower flame temperature. Very rich mixtures lead to incomplete combustion which result again in the release of less thermal energy.

Temperature and pressure: Flame speed increases with increase in intake pressure and temperature. This is possible because of an overall increase in density of charge.

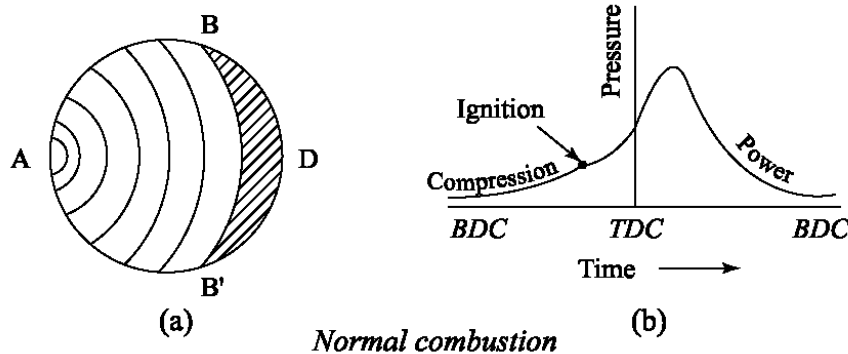
Compression ratio: Higher the compression ratio the flame speed will be high.

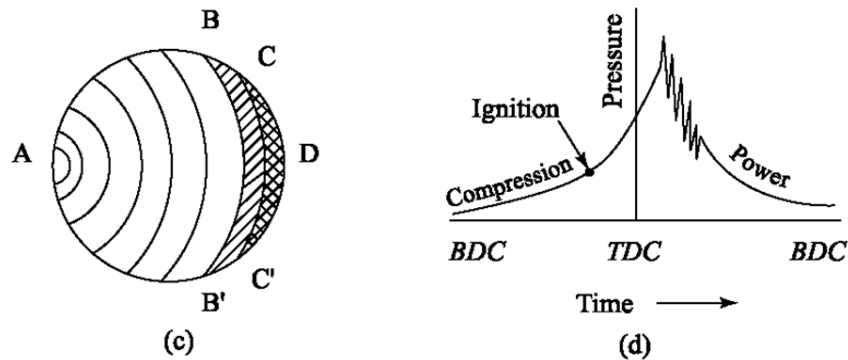
Engine output: The cycle pressure increases when the engine output is increased resulting in increased flame speed.

Engine speed: Flame speed increases almost linearly with engine speed since increase in engine speed increased the turbulence inside the cylinder

Normal and Abnormal combustion:

In a spark ignition engine combustion which is initiated between the spark plug electrodes spreads across the combustible mixture. A definite flame front which separates the fresh mixture from the products of combustion travels from the spark plug to the other end of the combustion chamber. Heat release due to combustion increases the temperature and consequently the pressure of the burned part of the mixture above those of the unburned mixture. In order to effect pressure equalization the burned part of the mixture will expand and compress the unburned mixture adiabatically thereby increasing its pressure and temperature. This process continues as the flame front advances through the mixture and the temperature and pressure of the unburned mixture are increased further.





Combustion with detonation

If the temperature of the unburnt mixture exceeds the self-ignition temperature of the fuel and remains at or above this temperature during the period of preflame reactions, spontaneous ignition or auto ignition occurs at various pin point locations. This phenomenon is called **knocking**. The process of auto ignition leads towards engine knock.

The normal and abnormal combustion are shown in the figures. In the normal combustion the flame is initiated near the spark plug and it propagates at constant velocity towards other end of the combustion chamber. In the abnormal combustion, because of the auto ignition another flame front starts traveling in the opposite direction to the main flame front. When the two flame front collides a severe pressure pulse is generated. The gas in the chamber is alternatively compressed and expanded by the pressure pulse until pressure equilibrium is restored. This disturbance can force the walls of the combustion chambers to vibrate at the same frequency as the gas. The abnormal combustion causes loss of power and mechanical damage to the engine.

Effect of engine variables on knock:

(a) Density factor: Any factor which reduces the temperature of unburned charge should reduce the possibility of knocking.

Any factor which reduces the density of unburned charge should reduce the possibility of knocking.

- ✘ Increasing the compression ratio will increase the tendency of knocking
- ✘ Reduction in mass of charge inducted will reduce the tendency of knocking
- ✘ Increasing the temperature of mixture at inlet will increase the tendency of knocking.
- ✘ Hot spots in the combustion chamber wall should be avoided to reduce the tendency of knocking
- ✘ By retarding the spark timing from the optimized timing the peak pressure are reached farther down on the power stroke and are thus of lower magnitude. This might reduce the knocking.
- ✘ A decrease in output of the engine will reduce the tendency of knocking.

(b)Time factor: Increasing the flame speed or reducing the time of exposure of the unburned mixture to auto ignition condition will tend to reduce knocking.

- ✘ Increasing the flame speed increases flame speed and reduces the tendency of knocking
- ✘ An increase in engine speed increases the turbulence of the mixture
- ✘ The knocking tendency is reduced by shortening the time required for the flame front to traverse the combustion chamber. Engine size, combustion chamber size and spark plug position are the factors governing the flame travel distance.

- ✍ Larger the engine size has greater tendency for knocking
- ✍ In order to have a minimum flame travel, the spark plug is centrally located in the combustion chamber resulting in minimum knocking tendency.

(c)Composition factor: The composition of fuel like fuel air ratio and octane value are also influences the knocking tendency of the engine. The flame speed, flame temperature and reaction time are different for different fuel air ratio.

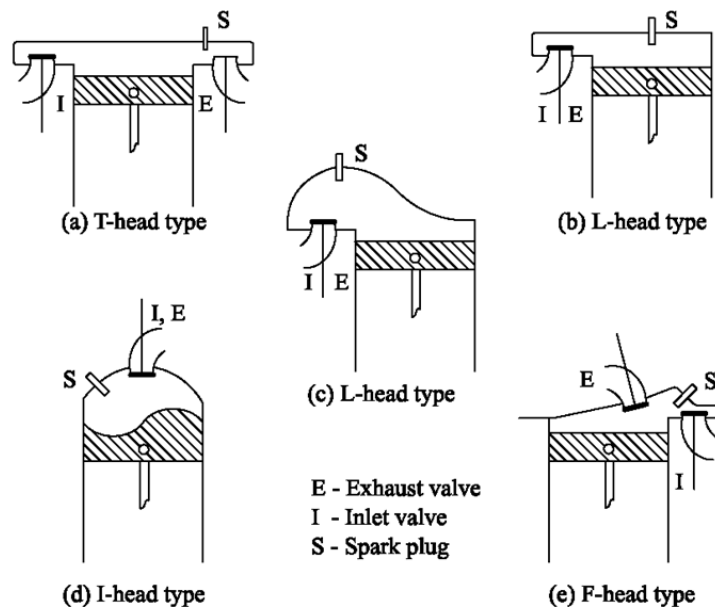
Combustion chamber for SI engine:

The design of combustion chamber for an SI engine has an important influence on the engine performance and its knocking tendencies. The design involves the shape of the combustion chamber, location of spark plug and location of inlet and exhaust valves. The important requirements of an SI engine combustion chamber are to provide higher power output, high thermal efficiency and smooth engine operation. Smooth engine operation is achieved by reducing the possibility of knocking by

- ⊕ Reducing the distance of flame travel by centrally locating the spark plug.
- ⊕ Satisfactory cooling of spark plug points and of exhaust valve area
- ⊕ Reducing the temperature of the last portion of charge by transferring heat to the cylinder wall

High power output and thermal efficiency is achieved by

- ⊕ High degree of turbulence in the combustion chamber
- ⊕ High volumetric efficiency (i.e) inducing more charge during intake stroke results in high output
- ⊕ Compact combustion chamber reduces the heat loss during combustion and increases the thermal efficiency.



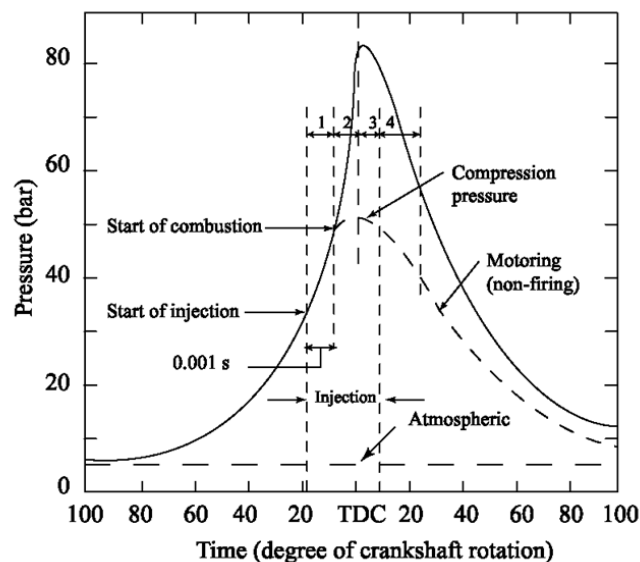
The different types of combustion chamber used in SI engine are

- ⊕ T head type
- ⊕ L head type
- ⊕ I head type
- ⊕ F head type

COMBUSTION IN CI ENGINE

The combustion in CI engine is considered to be taking place in four phases. It is divided into the ignition delay period, the period of rapid combustion, the period of controlled combustion and the period of after burning. The details are explained below.

1. Ignition delay period: The ignition period is also called the preparatory phase which is counted from the start of injection to the start of combustion. The combustion delay period is very important because it has effect on the combustion rate, knocking, engine starting ability and presence of smoke in the exhaust. The ignition delay period is divided into two parts, the physical delay and chemical delay. The physical delay is the time between the beginning of injection and the attainment of chemical reaction conditions. During this period the fuel is atomized, vaporized, mixed with air and raised to its self-ignition temperature. This physical delay depends on the type of fuel. The physical delay is greatly reduced by using high injection pressures and high turbulence to facilitate breakup of the jet and improving evaporation. The chemical delay is the period for the chemical reaction till the ignition takes place. Generally the chemical delay is larger than the physical delay.



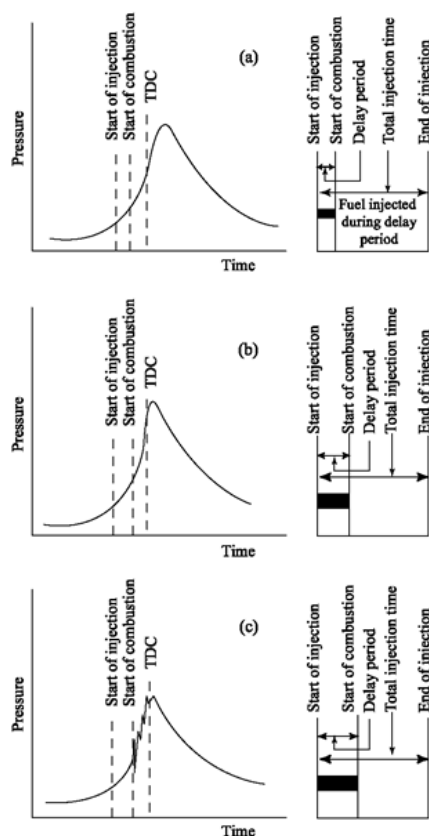
- 2. Period of rapid combustion:** The period of rapid combustion also called the uncontrolled combustion during which the pressure rise is rapid. The rate of heat release is the maximum during this period.
- 3. Period of controlled combustion:** The rapid combustion period is followed by the third stage, the controlled combustion. The temperature and pressure in the second stage is already quit high. Hence the fuel droplets injected during the second stage burn faster with reduced ignition delay as soon as they find the necessary oxygen and any further pressure rise is controlled by the injection rate. The period of controlled combustion is assumed to end at maximum cycle temperature.
- 4. Period of after burning:** The unburnt and partially burnt fuel particles left in the combustion chamber start burning as soon as they come into contact with the oxygen. This period is called as after burning period.

Factors affecting the delay period:

- (a) Compression ratio:** The compression ratio should be increased to decrease the ignition delay period

- (b) **Engine speed:** When the engine speed is increased the delay period decreases during variable speed operation
- (c) **Output:** with an increase in engine output, operating temperature increased and hence delay period decreases.
- (d) **Atomization and duration of injection:** Higher the fuel injection pressure increases the degree of atomization. The fines of atomization reduce the ignition lag.
- (e) **Injection timing:** Optimum angle of injection advance generally 20° bTDC
- (f) **Quality of fuel:** Self ignition temperature is important property which affects the delay period. A lower self-ignition temperature results in a lower delay period. Other properties which affect the delay period are volatility and viscosity.
- (g) **Intake temperature and pressure:** Increase in intake pressure and temperature will reduce the delay period.

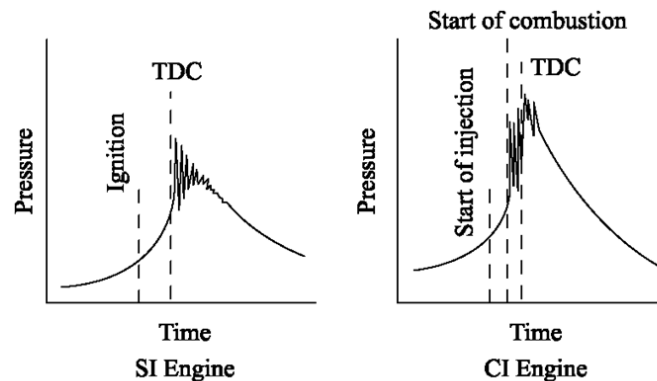
The phenomenon of knock in CI engine:



In CI engine the injection process takes place over a definite interval of time. Consequently, as the first few droplets to be injected are passing through the ignition delay period, additional droplets are being injected into the chamber. If the ignition delay of the fuel being injected is short, the first few droplets will commence the actual burning phase in a relatively short time after injection and a relatively small amount for fuel will be accumulated in the chamber when actual burning commences. As a result, the mass rate of mixture burned will be such as to produce a rate of pressure rise that will exert a smooth force on the piston. If on the other hand the ignition delay is longer the actual burning of the first few droplets is delayed and a greater quantity of fuel droplets gets accumulated in the chamber.

When the actual burning commences, the additional fuel can cause too rapid rate of pressure rise, resulting in a jamming of forces against the piston and rough engine operation.

If the ignition delay is quite long so much fuel can accumulate that the rate of pressure rise is almost instantaneous. Such a situation produces the extreme pressure differentials and violent gas vibrations known as knocking and is evidenced by audible knock.



The phenomenon is similar to that in the SI engine. However, in the SI engine knocking occurs near the end of combustion whereas in the CI engine knocking occurs near the beginning of combustion. In order to decrease the tendency of knock it is necessary to start the actual burning as early as possible after the injection begins. In other words it is necessary to decrease the ignition delay and thus decrease the amount of fuel present when the actual burning of the first few droplets starts.

Combustion chamber for CI engines

The CI engine combustion chambers are classified into two categories

- a. Direct injection type: This type of combustion chamber is also called an open combustion chamber. In this type the entire volume of the combustion chamber is located in the main cylinder and the fuel is injected into this volume
- b. Indirect injection type: In this type of combustion chamber, the combustion space is divided into two parts, one part in the main cylinder and the other part in the cylinder head. The fuel is injected usually into that part of the chamber located in the cylinder head.

These chambers are classified further into

- Swirl chambers in which compression swirl is generated
- Pre combustion chamber in which combustion swirl is induced
- Air cell chamber in which both compression and combustion swirl are induced

Direct injection chambers: These chambers mainly consist of space formed between a flat cylinder head and a cavity in the piston crown in different shapes. The fuel is injected directly into this space. The injector nozzles used for this type of chamber are generally of multi-hole type working at a high pressure (200 bar)

The main advantages of this type of chambers are

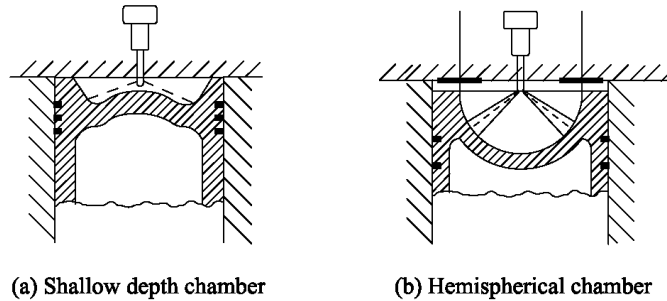
- Minimum heat loss during compression because of lower surface area to volume ration and hence, better efficiency
- No cold starting problem
- Fine atomization because of multi hole nozzle

The drawbacks of this combustion chamber are:

- High fuel injection pressure required and hence complex design of fuel injection pump
- Necessity of accurate metering of fuel by the injection system, particularly for small engine

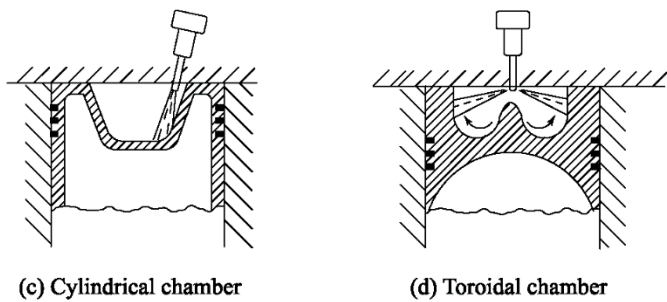
Shallow depth chamber: In shallow depth chamber the depth of the cavity provided in the piston is quite small. This chamber is usually adopted for large engines running at low speeds. Since the cavity diameter is very large, the squish is negligible

Hemispherical chamber: This chamber also gives small squish. However, the depth to diameter ratio for a cylindrical chamber can be varied to give any desired squish to give better performance



Cylindrical chamber: This design was attempted in recent diesel engines. This is a modification of the cylindrical chamber in the form of a truncated cone with base angle of 30° . The swirl was produced by masking the valve for nearly 80° of circumference. Squish can also be varied by varying the depth.

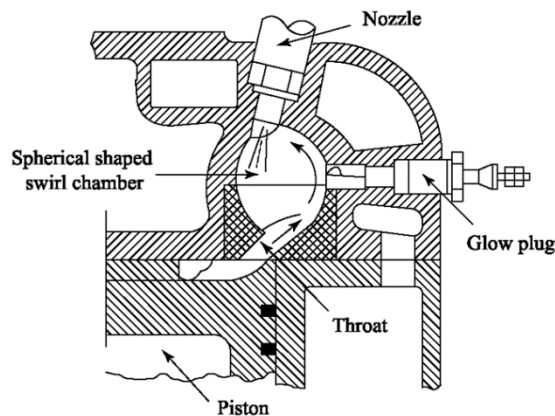
Toroidal chamber: The idea behind this shape is to provide a powerful squish along with the air movement, similar to that of the familiar smoke ring, within the toroidal chamber. Due to powerful squish the mask needed on inlet valve is small and there is better utilization of oxygen. The cone angle of spray for this type of chamber is 150° to 160°



Indirect injection chambers:

The various types of indirect injection chambers are dealt here

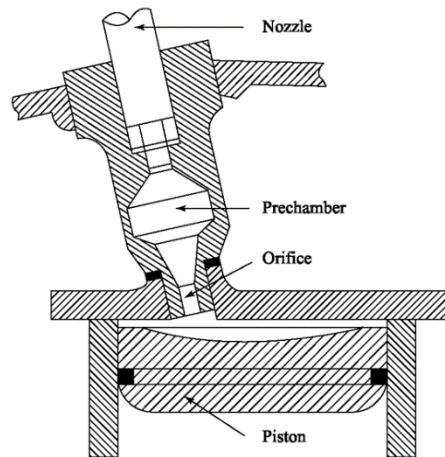
Swirl chamber:



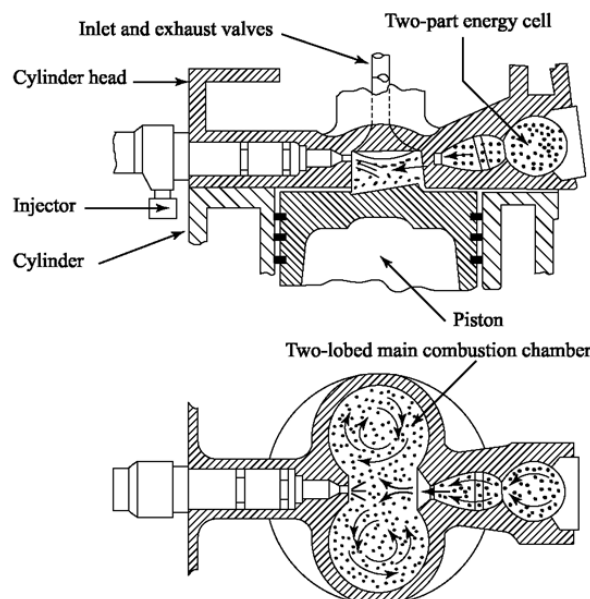
Swirl chambers consist of a spherical shaped chamber separated from the engine cylinder and located in the cylinder head. Into this chamber, about 50% of the air is transferred during the compression stroke. A throat connects the chamber to the cylinder which enters the chamber

in a tangential direction so that the air coming into this chamber is given a strong rotary movement inside the swirl chamber and after combustion, the products rush back into the cylinder through the same throat at much higher velocity. This causes considerable heat loss to the walls of the passage which can be reduced by employing a heat insulated chamber. This type of combustion chamber finds application where fuel quality is difficult to control, where reliability under adverse conditions is more important than fuel economy.

Precombustion chamber: A typical Precombustion chamber consists of an antichamber connected to the main chamber through a number of small holes. The Precombustion chamber is located in the cylinder head and its volume accounts for about 40% of the total combustion space. During the compression stroke the piston forces the air into the Precombustion chamber. The fuel is injected into the prechamber and the combustion is initiated. The resulting pressure rise forces the flaming droplets together with some air and their combustion products to rush out into the main cylinder at high velocity through the small holes. Thus it creates both strong secondary turbulence and distributes the flaming fuel droplets though out the air in the main combustion chamber where bulk of combustion takes place. About 80% of energy is released in main combustion chamber.



Air cell chamber



In this chamber the clearance volume is divided into two parts, one in the main cylinder and the other called the energy cell. The energy cell is divided into two parts, major and minor, which are separated from each other and from the main chamber by narrow orifices. During

combustion the pressure in the main chamber is higher than that inside the energy cell due to restricted passage area between the two. At the TDC, the difference in pressure will be high and air will be forced at high velocity through the opening into the energy cell and this moment the fuel injection also begins. Combustion starts initially in the main chamber where the temperature is comparatively higher but the rate of burning is very slow due to absence of any air motion. In the energy cell, the fuel is well mixed with air and high pressure is developed due to heat release and the hot burning gases blow out through the small passage into the main chamber. This high velocity jet produces swirling motion in the main chamber and thereby thoroughly mixes the fuel with air resulting in complete combustion.

The main advantages of indirect injection combustion chamber are

- Injection pressure required is low
- Direction of spraying is no very important

The drawbacks of this type of chambers are

- Poor cold starting performance requiring heater plugs
- Specific fuel consumption is high

Learning Outcome Assessment Questions

1. Four operations, namely suction, compression, expansion and exhaust, in a four stroke cycle are completed in the number of revolutions of crank shaft equal to
 - a. One
 - b. Two
 - c. Three
 - d. Four
2. The four operations, namely suction, compression, expansion and exhaust, in a four stroke cycle are completed in the number of revolutions of cam shaft equal to
 - a. One
 - b. Two
 - c. Three
 - d. Four
3. In two stroke cycle engine, the processes suction, compression, expansion and exhaust is completed in the number of revolutions of crank shaft equal to
 - a. One
 - b. Two
 - c. Three
 - d. Four
4. In spark ignition four stroke cycle engine the cam shaft runs
 - a. At twice the speed of crank shaft
 - b. At the same speed of crank shaft
 - c. At half the speed of crank shaft
 - d. At any speed irrespective of crank shaft speed
5. In a four stroke cycle diesel engine, during suction stroke
 - a. Only air is sucked in
 - b. Only fuel is sucked in
 - c. Mixture of fuel and air sucked in
 - d. None of the above
6. The following is a spark ignition reciprocating engine
 - a. Petrol engine
 - b. Diesel engine
 - c. Gas turbine
 - d. None of the above

UNIT V

INTERNAL COMBUSTION ENGINE PERFORMANCE AND AUXILIARY SYSTEMS IGNITION SYSTEM

Pollutants emission from diesel engines

Nowadays, pollution from automobiles becomes the main concern for our lovely environment. Pollutants emitted from diesel engines and petrol engines are dangerous for our environment and our precious health. Both the petrol engines and diesel engines emit pollutants in their working conditions. But the Concentration of pollutants from diesel engines and petrol engines are different. Here we are going to see the emission of different pollutants from diesel engines

Pollutants emission from diesel engines:

1. Hydrocarbons (HC)
2. Carbon Monoxide (CO)
3. Oxides of Nitrogen (NO₂)
4. Smoke and Particulate Matter
5. Aldehydes
6. Other emissions

1. Hydrocarbons:

Hydrocarbons are the significant contributors in the diesel engines emission. Black smoke from diesel engine exhaust caused by the presence of carbon particles also known as soot in the flue gases. Soot is hazardous for the health of living animals.

2. Carbon Monoxide:

Carbon Monoxide is a presence in an exhaust of both diesel engines and gasoline/petrol engines. But the concentration of Carbon Monoxide in the diesel engines is less as compared to petrol engines. If the petrol/gasoline engine produces 5% of Carbon Monoxide, then diesel engines will produce only 2% of it.

3. Oxides of Nitrogen:

When atmospheric O₂ and N₂ combine inside the combustion chamber at very high temperature, it produces Oxides of Nitrogen. Diesel engines produce very high Oxides of Nitrogen during the acceleration period because temperature reaches the highest due to complete combustion of the fuel in the chamber.

4. Smoke and Particulate Matter:

Color of exhaust smoke may be white smoke or black smoke. The presence of smoke at the exhaust contains visible products produced due to poor combustion of fuel and air. If white smoke observed in a diesel engine at cold starting and no load or low load running of the engine, it indicates piston rings of diesel engines are worn out and it needs a replacement. Black smoke in the diesel engine is caused due to incomplete combustion of fuel. The amount of black smoke is directly proportional to the load on the engine.

The ignition system is provided with SI engine, which is used to produce an electric spark at the end of the compression stroke to ignite the air fuel mixture. In the design of an ignition system, the following factors should be taken into account

- Engine design
- Engine speed
- Inlet manifold pressure
- Mixture composition

Requirement of an ignition system:

A smooth and reliable functioning of an ignition system is essential for reliable working of an engine. The requirements of such an ignition system are:

- ⊕ It should provide a good spark between the electrode of the plugs at the correct timing
- ⊕ It should function efficiently over the entire range of engine speed
- ⊕ It should be light, effective and reliable in service
- ⊕ It should be compact and easy to maintain
- ⊕ It should be cheap and convenient to handle
- ⊕ The interference of the high voltage source should not affect the functioning of radio and television receiver inside the automobile

Battery ignition system:

The essential components of the battery ignition system are

Battery: This provides the energy for ignition. The battery used may be lead acid battery or a alkaline battery. The battery is charged by the dynamo provided in the engine. The battery must be mechanically strong to withstand the strains to which it is constantly subjected to. It converts the chemical energy into electrical energy due to the electrochemical reaction taking place inside the battery

Ignition switch: Battery is connected to the primary winding of the ignition coil through an ignition switch and ballast resistor. With the help of the ignition switch the ignition system can be turned on or off.

Ballast resistor: A ballast resistor is provided in series with primary winding to regulate the primary current. The objective of this is to prevent injury to the spark coil by overheating if the engine should be operated for a long time at low speed. The coil is made of iron wire.

Ignition coil: The ignition coil consists of a magnetic core of soft iron sheet and two insulated conduction coils called primary and secondary windings. The secondary coil consists about 21000 turns of 38-40 gauge enamelled copper wire sufficiently insulated to withstand the high voltage. It is wound close to the core with one end connected to secondary terminal and other end is grounded to the metal case. The primary winding located outside the secondary coil generally formed 200-300 turns of 20 gauge copper wire. More heat is generated in primary than the secondary and with the primary coil wound over the secondary coil, it is easier to dissipate the heat. The entire unit is enclosed in a metal container and forms a neat and compact unit.

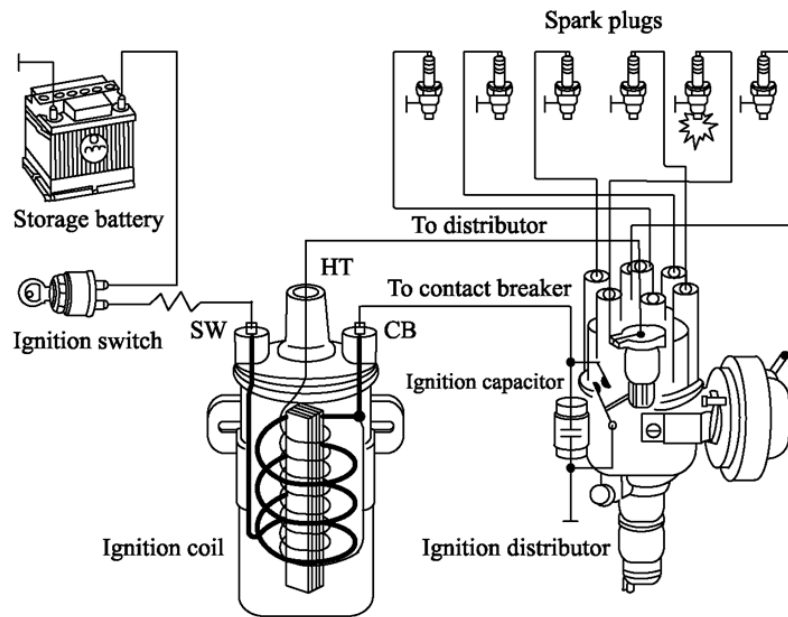


Figure: Battery Ignition system for a six cylinder engine

Contact breaker: This is a mechanical device for making and breaking the primary circuit of the ignition coil. The metal used for contact surfaces usually tungsten and diameter of contact surfaces is about 3 mm

Capacitor: The principle of construction of a ignition capacitor is the same as that of electrical capacitor. Two strips of aluminum foil and several layers of special capacitor paper, are rolled up in a solid roll. Then the roll is inserted into a metal shell for protection against moisture and damage.

Distributor: The function of the distributor is to distribute the ignition current to the individual spark plugs in correct sequence and at the correct instant of time. There two types of distributors. Brush type and gap type

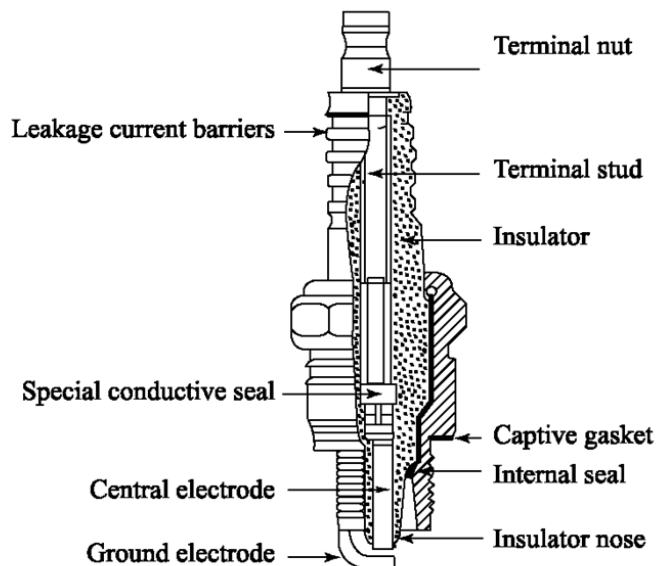


Figure: Spark Plug

Spark plug: The spark plug provides the two electrodes with a proper gap across which the high potential discharges to generate a spark and ignite the combustible mixture with in the combustion chamber. The spark plug consists of a steel shell, an insulator and two electrodes. The central electrode to which the high tension supply from the ignition coil is connected, is well insulated with porcelain or other ceramic material. The other electrode is welded to steel shell of the plug. The electrodes are usually made of high nickel alloy to withstand the severe erosion and corrosion to

which they are subjected in use. The spark plugs are usually classified as hot plugs or cold plugs depending upon the relative operating temperature range of the tip of the high tension electrode

Operation of a battery ignition system:

When the ignition switch is closed, the primary winding of the coil is connected to the positive terminal post of the storage battery. If the primary is closed through the breaker contacts, a current flows, the so called primary current. This current, flowing through the primary coil, which is wound on a soft iron core, produces a magnetic field in the core. A cam driven by the engine shaft is arranged to open the breaker points whenever an ignition discharge is required. When the breaker points open, the current which had been flowing through the points now flows into the condenser, which is connected across the points. As the condenser becomes charged, the primary current falls and the magnetic field collapses. The collapse of the field induces a voltage in the primary winding, which charges the condenser to a voltage much higher than battery voltage. The condenser then discharges into the battery, reversing the direction of both the primary current and the magnetic field. The rapid collapse and reversal of the magnetic field in the core induce a very high voltage in the secondary winding of the ignition coil. The secondary winding consists of a large number of turns of very fine wire wound on the same core with the primary. The high secondary voltage is led to the proper spark plug by means of a rotating switch called the distributor. This ignition system is used in cars and commercial vehicles.

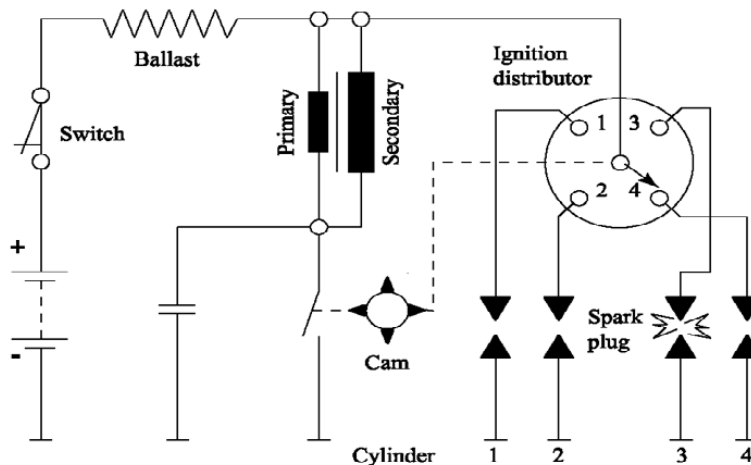


Figure: Working of Battery Ignition System

Magneto Ignition System

Magneto is a special type of ignition system with its own electric generator to provide the necessary energy for the system. It is mounted on the engine and replaces all the components of the coil ignition system except the spark plug. A magneto when rotated by the engine is capable of producing a very high voltage and does not need a battery as a source of external energy. Magneto may be rotating armature type or rotating magnet type. The working principle of the magneto ignition system is exactly the same as that of the coil ignition system. With the help of a cam, the primary circuit flux is changed and a high voltage is produced in the secondary circuit.

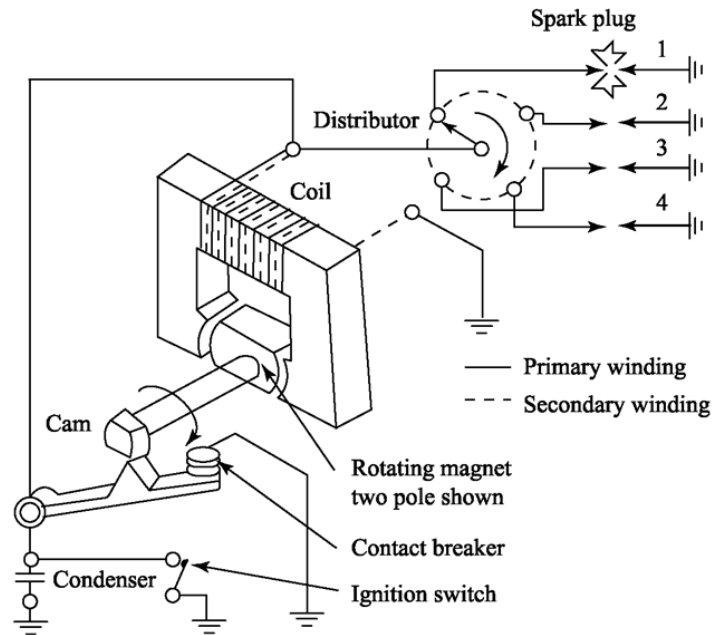


Figure: Magneto Ignition System

Comparison of battery ignition system and magneto ignition system

Battery ignition system	Magneto ignition system
Battery is necessary. Difficult to start the engine when battery is discharged	No battery is needed and therefore there is no problem of battery discharge
Maintenance problem are more due to battery	Maintenance problem are less since there is no battery
Current for the primary circuit is obtained from the battery	The required electric current is generated by the magneto
A good spark is available at the spark plug even at low speed	During starting, quality of spark is poor due to low speed
Efficiency of the system decreases with the reduction in spark intensity as engine speed rises	Efficiency of the system improves as the engine speed rises due to high intensity spark
Occupies more space	Occupies less space
Commonly employed in cars and light commercial vehicles	Mainly used in racing cars and two wheelers

FUEL SUPPLY SYSTEM FOR CI ENGINE

The fuel injection system is the most vital component in the working of CI engines. The engine performance is greatly dependent on the effectiveness of the fuel injection system. The injection system has to perform the important duty of initiating and controlling the combustion process. The schematic diagram of the fuel injection system of CI engine is shown in figure.

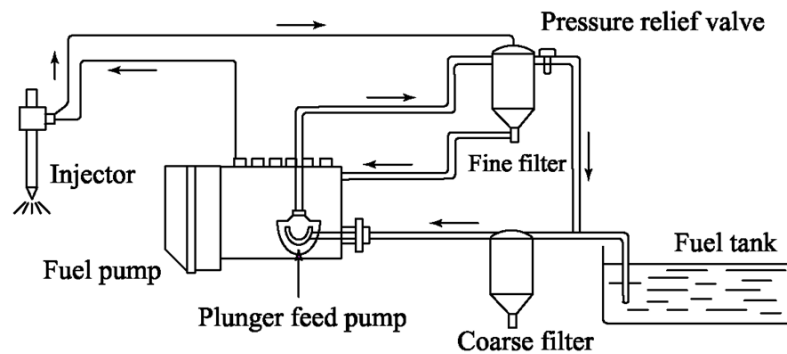


Figure: Fuel supply system for CI engine

The fuel from the tank is taken by the plunger feed pump through the coarse filter and flow to the fine filter then to the fuel pump. The coarse and fine filters remove all kinds of impurities from the fuel. The fuel pump raises the pressure of the fuel to the injection pressure approximately 200 bar and supplies the fuel to the fuel injector which injects the fuel in fine droplets. These droplets vaporize due to the heat transfer from the compressed air and form a fuel-air mixture. The temperature of the fuel reaches a value higher than its self-ignition temperature and the combustion process is initiated spontaneously. A pressure relief valve is also provided for the safety of the system. For proper running and better performance of the engine, the fuel injection system must meet the following requirements.

- ✘ Accurate metering of fuel injected per cycle
- ✘ Timing the injection of fuel correctly in the cycle
- ✘ Proper control of rate of injection so that desired heat release pattern is achieved during combustion
- ✘ Proper atomization of fuel into very fine droplets
- ✘ Proper spray pattern to ensure rapid mixing of fuel and air
- ✘ Uniform distribution of fuel throughout the combustion chamber
- ✘ To supply equal quantity of injection in the case of multi cylinder engine

The fuel injection used in the CI engine is classified into two types: (i) air injection systems and (ii) solid injection systems. They are briefly explained below.

Air Injection System

In this system, the fuel is forced into the cylinder by means of compressed air. This system is little used nowadays, because it requires a bulky multistage air compressor. This causes an increase in engine weight and reduces the brake power output further. One advantage of this type is good mixing of fuel with the air. Another advantage is the ability to utilize fuels of high viscosity.

Solid Injection System

In this system the fuel is directly injected into the combustion chamber without the aid of compressed air. This system is further classified into four types

- (a) Individual pump and nozzle system
- (b) Unit injector system
- (c) Common rail system
- (d) Distributor system

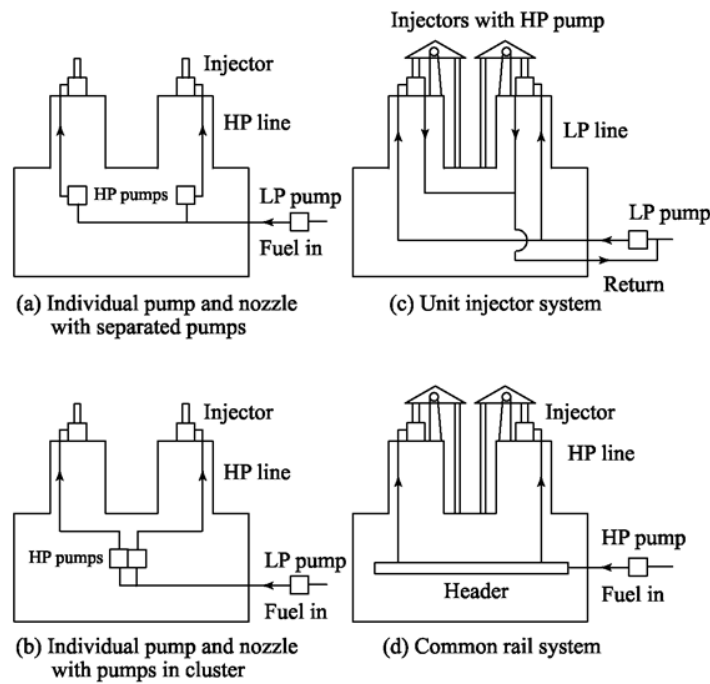


Figure: Solid injection systems

(a) Individual pump and nozzle system: (Refer figure a&b) In this system, each cylinder is provided with one pump and one injector. In this arrangement a separate metering and compression pump is provided for each cylinder. The pump may be placed close to the cylinder (figure a) or they may be arranged in a cluster (figure b). The plunger of high pressure pump is actuated by a cam and produces the fuel pressure necessary to open the injector valve at the correct time. The amount of fuel injected depends on the effective stroke of the plunger.

(b) Unit injector system: (Refer figure c) In this system the pump and injector nozzle are combined in one housing. Each cylinder is provided with one of these unit injectors. Fuel is brought up to the injector by a low pressure pump, at correct time a rocker arm actuates the plunger and thus injects the fuel into the cylinder. The amount of fuel injected is regulated by the effective stroke of the plunger.

(c) Common rail system: (Refer figure d) In the common rail system a HP pump supplies fuel under high pressure to a fuel header. From the header the fuel is supplied to the individual cylinders through pipes. The amount of fuel entering the cylinder is regulated by varying the length of the push rod stroke.

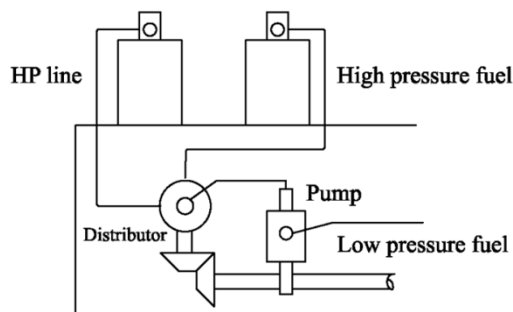


Figure: Distributor system

(d) Distributor system: (Refer figure) In this system the pump which pressurizes the fuel also meters and times it. The fuel pump after metering the required amount of fuel supplies it to a rotating distributor at the correct time for supply to each cylinder.

Fuel Injection Pump

The main objective of the fuel injection pump is to deliver accurately metered quantity of fuel under high pressure at the correct instant to the injector fitted on each cylinder. Injection pumps are generally of two types

Jerk type pump: Figure shows the Jerk type fuel injection pump.

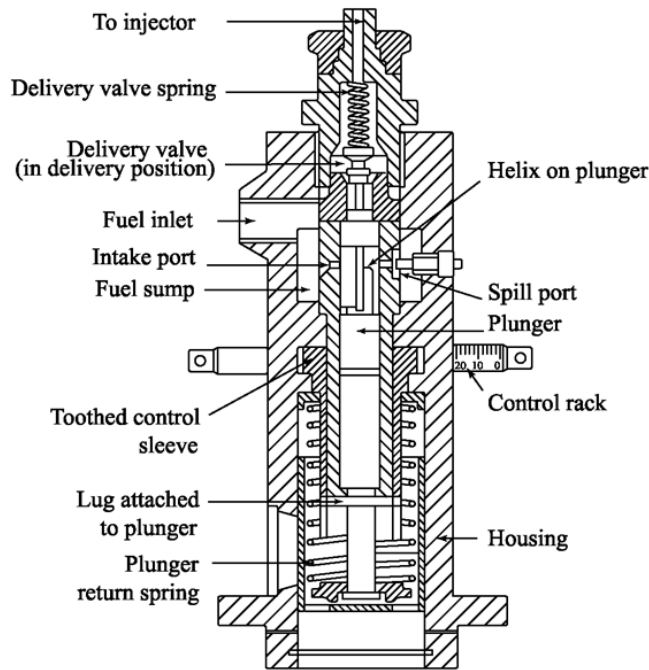


Figure: Jerk type fuel injection pump

In the Jerk type pump, the fuel is pressurized by the plunger movement. The reciprocating movement is given to the plunger by means of the cam and the rotating movement is given by the rack mechanism. When the plunger is in the bottom most position, through the intake port the fuel is admitted into the cylinder of the pump and during the upward movement of the plunger the fuel is pressurized and delivered to the injector through the opening at the top of the pump against the delivery valve spring pressure. When the control rack rotates the plunger, the high pressure fuel in the top of the cylinder is exposed to spill port through the helix on the plunger so that the pressure of the fuel decreases and injection is stopped. It is important to remember here that though the axial distance traversed by the plunger is same for every stroke, the rotation of the plunger by the rack determining the length of the effective stroke and thus the quantity of the fuel injected.

Distributor type pump: Figure shows the distributor type fuel injection pump. This pump has only a single pumping element and the fuel is distributed to each cylinder by means of a rotor. There is a central longitudinal passage in the rotor and also two sets of radial holes (each equal to the number of engine cylinders) located at different heights. One set is connected to pump inlet via central passage whereas the second set is connected to delivery lines leading to injectors of the various cylinders. The fuel is drawn into the central rotor passage from the inlet port when the pump plunger moves away from each other. Wherever, the radial delivery passage in the rotor coincides with the delivery port for any cylinder the fuel is delivered to each cylinder in turn. The main advantage of this type is small size and light in weight.

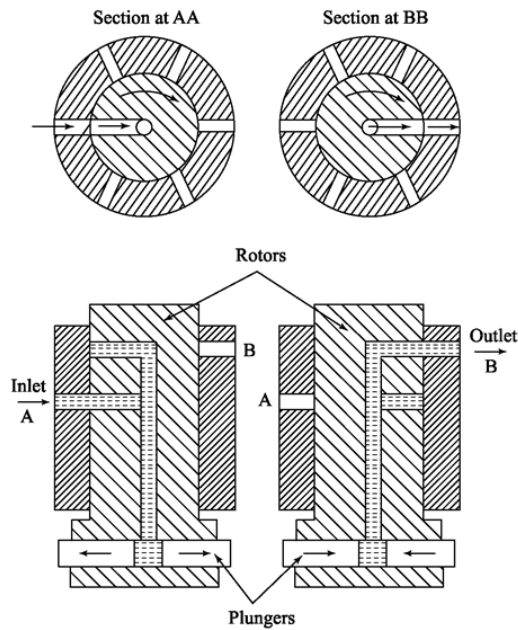
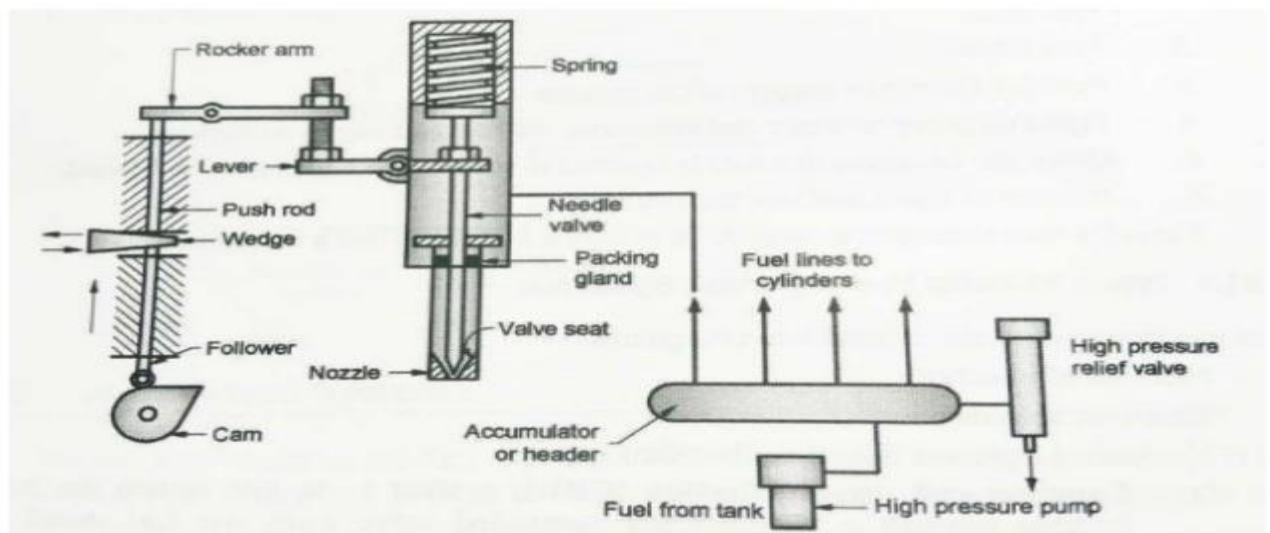


Figure: Distributor type fuel injection pump

Common Rail Direct Injection or CRDI System:

There are two different types of injection systems in the diesel engines or compression ignition (C I Engines). One is the Air Injection System and another one is Airless or Solid Injection System. In this post, we are going to learn about the Common Rail Direct Injection System CRDI System which comes under a solid injection system.



Working of CRDI System or Common Rail Direct Injection:

1. As you can see in the diagram of the CRDI system, the high-pressure pump is used to supply fuel to the accumulator or the header from the fuel tank. In case pressure in the accumulator increases beyond the limit, the high-pressure relief valve which is connected to the accumulator helps to reduce the pressure.

2. Now, this fuel from the accumulator supplied to engine cylinders using fuel lines with the help of solid injectors.
3. Another spring-loaded high-pressure relief valve used to maintain the constant pressure in the system for smooth operations. It also returns the extra fuel of the accumulator to the fuel tank.
4. In the diagram, you can see the needle valve. It is used to control the opening and closing of the nozzle while it sprays the fuel into the cylinders. The upward and downward motion of the nozzle is measured by the cam.
5. Cam is connected to the spring with the help of a rocker arm and lever. During the dwell period of the cam, spring with the help of the needle valve prevents the injection of the fuel into the cylinder.
6. The packing gland ensures the level of the fuel above the valve seat for better injection of the fuel into the cylinders.
7. The wedge plays the main role in this system. It controls the amount of fuel to be injected into the cylinder in accordance with the power required for the engine. The wedge is operated by a governor or it can be operated manually as per requirement.

Advantages of CRDI System:

- CRDI system can control the flow of fuel in accordance with the load and speed of the engine.
- This system requires only one fuel pump for multiple cylinders.
- CRDI system is beneficial for the environment as it reduces noise, smoke and particulate matter.
- It gives high power output at low rpm.
- The main advantage of the CRDI system is fuel economy.

Disadvantages of CRDI System:

- This system is complex than MPFI system and needs good engineering work.
- The CRDI system cannot suit ordinary engines.

3.10.4 Fuel Injector

Quick and complete combustion is ensured by a well-designed fuel injector. By atomizing the fuel into very fine droplets, it increases the surface area of the fuel droplets resulting in better mixing and subsequent combustion. Atomization is done by forcing the fuel through a small orifice under high pressure. The injector assembly consists of a needle valve, a compression spring, a nozzle and an injector body as shown in figure 3.24. When the fuel is supplied by the injection pump it exerts sufficient force against the spring to lift the nozzle valve and the fuel is sprayed into the combustion chamber in a finely atomized particles. After fuel from the delivery pump gets exhausted the spring pressure pushes the nozzle valve back on its seat. For proper lubrication between nozzle valve and its guide a small quantity of fuel is allowed to leak through the clearance between them and then drained back to fuel tank through leak off connection. The spring tension and hence the valve opening pressure is controlled by adjusting the screw provided at the top.

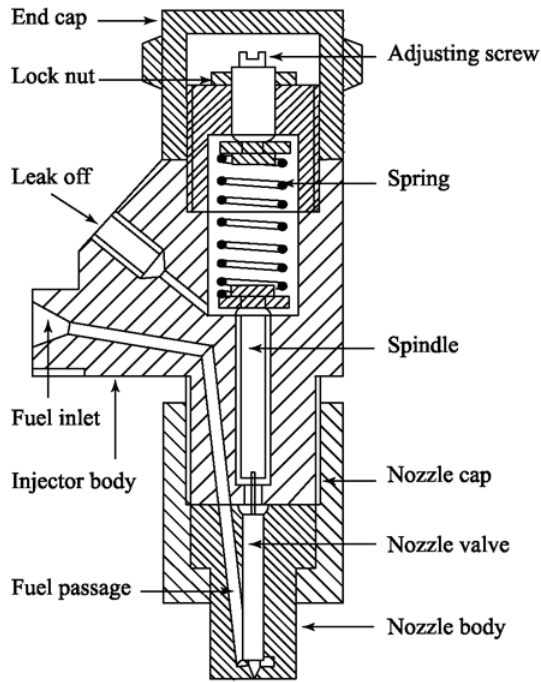


Figure: Fuel Injector

Fuel Injection Nozzle

Nozzle is that part of an injector through which the liquid fuel is sprayed into the combustion chamber. The nozzle should fulfil the following functions:

- ✎ **Atomization:** This is very important function since it is the first phase in obtaining proper mixing of the fuel and air in the combustion.
- ✎ **Distribution of fuel:** Distribution of fuel to the required areas with the combustion chamber. Factors affecting this are injection pressure, density of air and physical properties of fuel.
- ✎ **Prevention of impingement on walls:** Prevention of the fuel from impinging directly on the walls of combustion chamber or piston. This is necessary because fuel striking the walls decomposes and produces carbon deposits. This causes smoky exhaust as well as increase in fuel consumption.
- ✎ **Mixing:** Mixing the fuel and air in case of no turbulent type of combustion chamber should be taken care of by the nozzle

Various types of nozzles used in CI engine are shown in figure 3.25 and briefly explained below.

(a) The pintle nozzle: The stem of the nozzle valve is extended to form a pin or pintle which protrudes through the mouth of the nozzle. The size and shape of the pintle can be varied according to the requirement. It provides a spray operating at low injection pressures of 8 to 10 MPa. The spray cone angle is generally 60° . Advantage of this nozzle is that it avoids weak injection and dribbling. It prevents the carbon deposition on the nozzle hole.

(b) Single hole nozzle: At the centre of the nozzle body, there is a single hole which is closed by the nozzle valve. The size of the hole is usually of the order of 0.2 mm. Injection pressure is of order of 8 to 10 MPa and spray cone angle is about 15° . Major disadvantage with such nozzle is that they tend to dribble. Besides their spray angle is too narrow to facilitate good mixing unless higher velocities are used.

(c) Multi hole nozzle: It consists if a number of holes bored in the tip of the nozzle. The number of holes varies from 4 to 18 and the size from 35 to 200 μm . The hole angle may be form 20° upwards. These nozzles operate at high injection pressures of the order of 18 MPa. Their advantage lies in the

ability to distribute the fuel properly even with power air motion available in open combustion chamber.

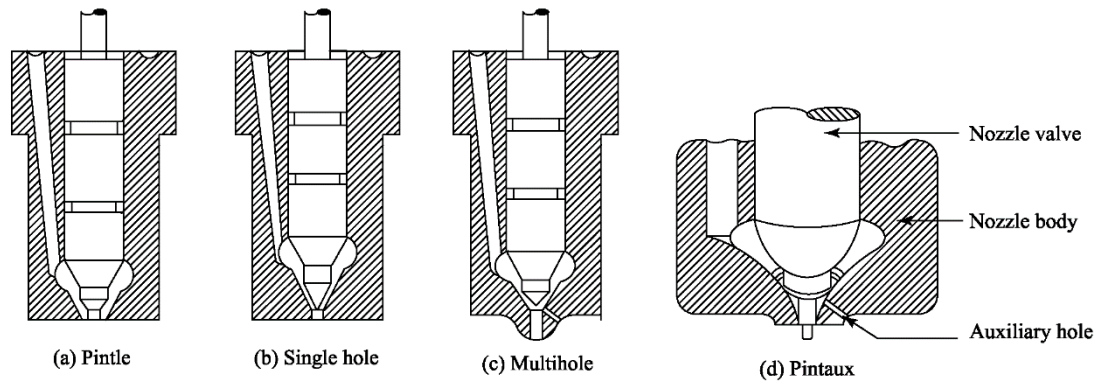


Figure: Types of nozzles

(e) **Pintaux nozzle:** It is a type of pintle nozzle which has an auxiliary hole drilled in the nozzle body. It injects a small amount of fuel through this additional hole in the upstream direction slightly before the main injection. The needle valve does not lift fully at low speeds and most of the fuel is injected through the auxiliary hole. Main advantage of this nozzle is better cold starting performance.

(f) **Indicated Power:** The power is produced inside the engine cylinder is called indicated power. The indicated power is calculated from the indicator diagram.

(g) The indicated power is calculated by: $IP = P_{im} \times A \times L \times n \times k$ kW

(h) Where P_{im} = Indicated mean effective pressure

$$P_{im} = \frac{\text{Area of the indicator diagram}}{\text{Length of indicator diagram}} \times \text{Spring constant (N/m}^2\text{/m)}$$

(i)

A = Area of the cylinder (m²),

L = Stroke length (m)

n = Number of explosions per second ($n = N$ for two stroke engine, $n = N/2$ for four stroke engine),

N = Speed of the engine in rps,

k = Number of cylinders

Brake power: The power available at engine crank shaft for external work is called brake power. The brake power is determined by Prony brake dynamometer, Rope brake dynamometer and Hydraulic dynamometer.

(j) **Prony brake dynamometer:** $BP = 2 \times \pi \times N \times T$ kW

Where T = Torque = $W \times R$,

W = Load applied (kN),

R = Radius of brake drum (m)

(k) **Rope brake dynamometer:** $BP = \pi \times D \times N \times (W - S)$ kW

Where D = Diameter of brake drum (m),

W = Weight applied at the end of the rope (kN),

S =

Spring scale reading (kN)

- (l) **Hydraulic dynamometer:** $BP = WN / 2000$ kW
Where W = brake load (kN)

- (m) **Friction power:** Friction power is the difference between indicated power and brake power of an engine.

$$FP = IP - BP$$

- (n) The friction power is the measure of internal losses in the engine. The friction power is determined by Willan's line method, Morse test, Motoring test and Retardation test.

(o)

- (p) **Brake specific fuel consumption (BSFC)** is the amount of fuel consumed per kW of brake power developed.

$$BSFC = \frac{FC}{BP} \quad \text{kg/kW s}$$

- (q) **Mechanical Efficiency** $\eta_{mech} = \frac{\text{Brake Power}}{\text{Indicated Power}}$

- (r) **Brake thermal efficiency:** $\eta_{br.the} = \frac{BP}{FC \times CV}$

- (s) **Indicated thermal efficiency** $\eta_{in.the} = \frac{IP}{FC \times CV}$

- (t) **Relative efficiency** $\eta_r = \frac{\text{Brake thermal efficiency}}{\text{Air standard efficiency}} \text{ or } \frac{\text{Indicated thermal efficiency}}{\text{Air standard efficiency}}$

- (u) **Volumetric efficiency** $\eta_v = \frac{m_{act}}{m_{th}}$

Quantity of Fuel Injected

The quantity of fuel injected per cycle is given by

$$Q = \left(\frac{\pi}{4} d^2 n \right) \times V_f \times \left(\frac{\theta}{360} \times \frac{60}{N} \right) \times \left(\frac{N_i}{60} \right)$$

Where n = number of holes in nozzle,

d = diameter of orifice,

V_f = velocity of fuel,

θ = duration of fuel injection in crank angle,

N = speed of the engine, and N_i = number of injection per min (N/2 for four stroke engine and N for two stroke engine)

A four stroke, four cylinder gasoline engine has a bore of 60 mm and a stroke of 100 mm. On test it develops a torque of 66.5 N m, when running at 3000 rpm. If the clearance volume in each cylinder is 60 cc, the relative efficiency with respect to brake thermal efficiency is 0.5 and the calorific value of the fuel is 42 MJ/kg, determine the fuel consumption in kg/h and the brake mean effective pressure.

Given: $D=60\text{cm}$,

$L=100\text{cm}$, $T=66.5\text{Nm}$, $N=3000\text{rpm}$, $CV=42000\text{ kJ/kg}$, $VC = 60\text{CC}$, $\eta_{Rbt} = 0.5$

Solution:

Brake Power: $BP = 2\pi NT$ $BP = 2 \times \pi \times 3000 \times 66.5$ $BP = 20891.59\text{ W}$

$BP = 20.89\text{kW}$

Brake Mean Effective Pressure $BP = P_{BMEP} L A n_k$

$20.89 = P_{BMEP} \times 0.1 \times \pi \times 0.0624 \times 3000 \times 2 \times 60 \times 4$ P

$BMEP = 738.83\text{ kNm}^2$

Fuel Consumption: $\eta_{BT} = \frac{BP}{\dot{m}_f \times CV}$ $\dot{m}_f = \frac{BP}{\eta_{BT} \times CV} = \frac{20.89 \times 3600}{0.25 \times 42000}$

$\dot{m}_f = 7.16\text{kg/hr}$

Brake Thermal Efficiency: $\eta_{Rbt} = \eta_{bt\text{ ideal}}$ $\eta_{bt} = \eta_{Rbt} \times \text{ideal } \eta_{bt} = 0.5 \times 0.5$ **$\eta_{bt} = 0.25$** Ideal

Efficiency: $\eta_{\text{Ideal}} = 1 - \frac{1}{r_c \gamma - 1}$ $\eta_{\text{Ideal}} = 1 - \frac{1}{5.74214 - 1}$ **$\eta_{\text{Ideal}} = 0.5$**

Where, $r_c = \frac{V_1}{V_2} = \frac{VS + VC}{VC}$ $r_c = \frac{2.83 \times 10^{-3} + 60 \times 10^{-6}}{60 \times 10^{-6}}$ $r_c = 5.742$ $VS = \pi D^2 L n_k$

$VS = \pi \times 0.0624 \times 0.1$ $VS = 2.83 \times 10^{-3}\text{m}^3$

Calculate the diameter and length of the stroke of a diesel engine working on four stroke constant pressure cycle from the following data. IP=18.75 kW rotation per minute=220 CR=14 fuel cut-off ratio=1/20th of stroke, index of expansion=1.3, index of compression=1.35, L/D=1.5. Assume the pressure and temperature of the air at inlet are 1 bar and 40°C respectively.

IP=18.75kW, N=220rpm, CR=14, L/D=1.5, $P_1 = 1\text{bar}$, $T_1 = 40^\circ\text{C}$

Cutoff Ratio: $\frac{V_3 - V_2}{V_1 - V_2} = 0.05$ $(V_1 - V_2) \rightarrow 0.05 = \rho^{-1} r_c^{-1}$ **$\rho = 1.65$**

Mean Effective Pressure:

$P_m = P_1 r_c \gamma \frac{[\gamma(\rho - 1) - r_c - 1 - \gamma(\rho - 1)]}{(\gamma - 1)(r_c - 1)}$

$P_m = 1 \times 14^{1.3} \frac{[1.3(1.65 - 1) - 14 - 1 - 1.3(1.65 - 1)]}{(1.3 - 1)(14 - 1)}$

$P_m = 3.4\text{ba}$

Indicated Power: $IP = P_{IMEP} L A n_k$

$$18.75 = 3.4 \times 10^2 \times 1.5D \times \pi \times D^2 \times 220 \times 2 \times 60 \times 1 \quad D = 0.294 \text{ m}$$

Length of Stroke: L

$$D = 1.5 L = 1.5 \times 0.294$$

$$L = 0.589$$

During an experiment on four stroke single cylinder engine the indicator diagram obtained has average height of 1 cm while indicator constant is 25 kN/m² per mm. The engine run at 300 rpm and the swept volume is 1.5 × 10⁴ cm³. The effective brake load upon dynamometer is 60 kg while the effective brake drum radius is 50 cm. The fuel consumption is 0.12 kg/min and the calorific value of fuel oil is 42 MJ/kg. The engine is cooled by circulating water around it at the rate of 6 kg/min. The cooling water enters at 35°C and leaves at 70°C. Exhaust gases leaving have energy of 30 kJ/s with them. Take specific heat of water as 4.18 kJ/kg K. Determine indicated power output, brake power output and mechanical efficiency. Also draw the overall energy balance in kJ/s.

Indicator Diagram Height = 1 cm,

Indicator Constant = 25 kN/mm per mm,

N = 300 rpm,

$$V_s = 1.5 \times 10^4 \text{ cm}^3$$

PIMEP = Ind. diagram height × Indicator Constant

$$PIMEP = 10 \text{ mm} \times 25 \text{ kN/mm} \times \text{m}^2$$

$$PIMEP = 250 \text{ kN}$$

Heat Loss due to Brake power:

$$P = 2\pi NT \times 60$$

$$BP = 4.62 \text{ kJ/s} \times 60 \quad BP = 277.2 \text{ kJ/min}$$

Unaccounted Loss:

$$Q_{ua} = Q_s - Q_w + Q_g + Q_{BP} \quad Q_{ua} = 5040 - 877.8 + 1800 + 277.2 \quad q_{ua} = 2085 \text{ kJ/min}$$

$$\% Q_w = Q_w / Q_s$$

$$\% Q_w = 877.8 / 5040$$

$$\% Q_w = 17.42$$

$$\% Q_g = Q_g / Q_s$$

$$\% Q_g = 1800 / 5040$$

$$\% Q_g = 35.71$$

$$\% Q_{BP} = Q_{BP} / Q_s$$

$$\% Q_{BP} = 277.2 / 5040$$

$$\%QBP = 5.5$$

$$\%Qun = Qun/QS$$

$$\%Qun = 2085/5040$$

$$\%Qun = 41.37$$

MECHANICAL SUPERCHARGING

Superchargers are the main category of forced induction systems. Superchargers are compressors that are driven by mechanical means. Typically, they are driven by the crankshaft of an engine with the help of belts and pulleys. They are coupled directly to the engine and this does not allow for any delay to exist between the engine and the compressor. Superchargers are classified into two categories such as positive displacement pumps (Eg. Lysholm, Roots, Eaton, Scroll, Vane) and rotodynamic pumps (Eg. Centrifugal).

Positive Displacement Type

Mechanical supercharging is probably the oldest way of boosting the IC engine [Ainsdale, 1980]. Positive displacement supercharger is simpler in construction. They are easy to install and doesn't require complicated controls in most cases. It draws power through mechanical connection to the crankshaft, and its revolution (rotational speed) is directly proportional to the speed of the engine. The engine-compressor matching is relatively easy, and the boost pressure is almost constant over the entire range of engine operating speeds. Therefore, the torque curve is flat, and the turbo-lag problem is completely overcome. In effect, a supercharged engine behaves as a naturally aspirated engine with a larger displacement volume. It is this linearity that makes designing and predicting its boosting characteristics relatively easier than turbocharging. However, a supercharged engine consumes more fuel than a turbocharged engine with comparable power since the supercharger draws power directly from the engine crankshaft.

A supercharger has two rotors, a male and a female, forming a set of chambers between themselves and the housing. The chamber's volume is changing during the rotation and thus compresses the air internally. Since the power needed to drive the

supercharger is taken directly from the crankshaft, most development work has been invested to increase the efficiency and to minimize the parasitic losses when the supercharger is not needed (i.e. part load of the engine).

The most common types of the supercharger in the market today are the Lysholm compressor and the Roots blower. Figure 2.1 & 2.2 shows the cut-away view of the Lysholm screw and roots type supercharger [Heinz, 1995]. Both are displacement pumps and from a first glance they look very similar. They differ on one big point; the Lysholm screw has internal compression while the Roots do not have internal combustion. The Lysholm Compressor works with internal compression.

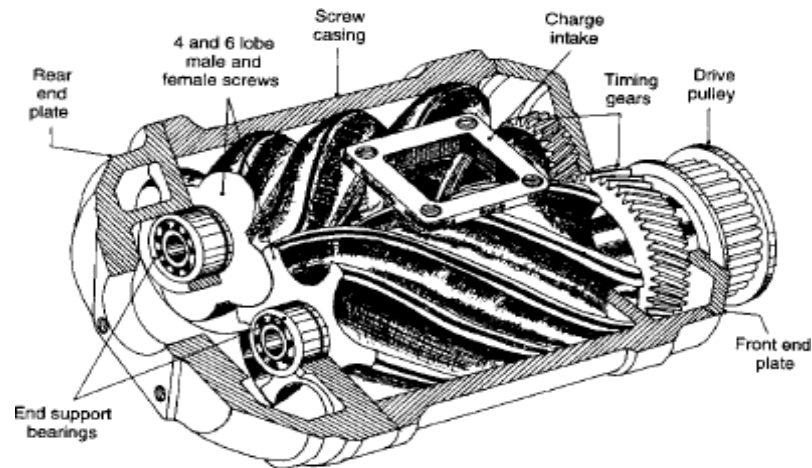


Figure 2.1 Cut-way view of the Lysholm screw supercharger [Heinz, 1995].

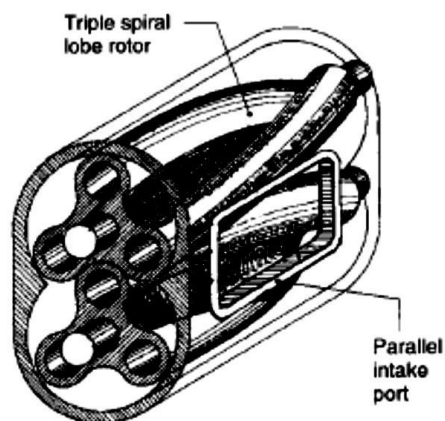


Figure 2.2 Cut- way view of the roots type supercharger [Heinz, 1995].

The Roots on the other hand works without internal compression, the compression takes place as the air is discharged from the blower outlet instead of inside the supercharger. This means that the compression takes place at isochoric conditions (i.e. constant volume). This process is known to be more power consuming and heat producing than the adiabatic process.

Centrifugal Compressor as a Supercharger

The centrifugal compressor has an isentropic efficiency that can match, and sometimes exceed, the efficiency of a Lysholm screw compressor. It is a dynamic machine where the rotor increases the internal energy of the air, both through increased density and increased velocity. The velocity is then carefully diffused to recover the kinetic energy as static pressure. Consequently, the centrifugal compressor has internal compression. Figure 2.3 shows the cut-away view of the centrifugal supercharger.

Unfortunately, the flow vs. speed characteristics of the centrifugal compressor is very non-linear. A fixed gear ratio between the compressor and the crankshaft results in a very peaky boost pressure delivery. Despite this, it has been used in cars, during the 1930s and 1950s. The speed of the centrifugal compressor is above 100000rpm and it is up to 10 times higher than roots and about 3 to 5 times the speed of a screw compressor. The need for a gearbox caused trouble for the designer. High speeds can lead to both sound problems if gears are used and the torque needed for acceleration can be rather high even if the moment of inertia is not particularly high.

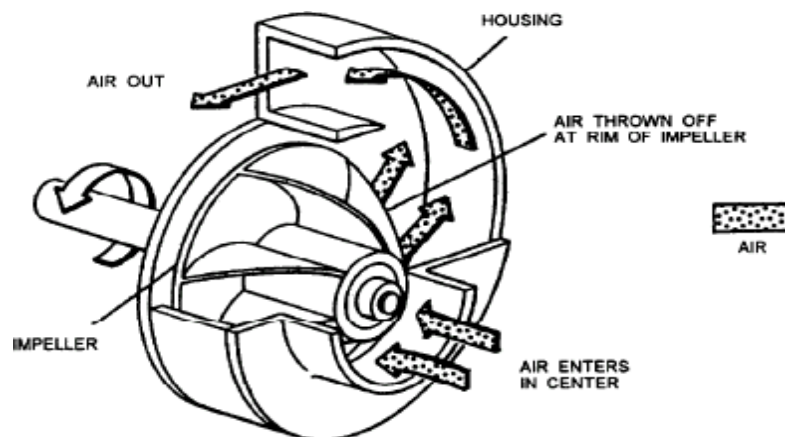


Figure 2.3 Cut view of centrifugal supercharger

Parasitic Losses

The largest problem of using a mechanical supercharger on a downsized engine is not the top-end performance, but the parasitic losses on part load. Miyagi et al., (1996) showed that for a Lysholm compressor only 20-30% of the parasitic losses come from mechanical losses and the rest from losses in the airflow, i.e. unnecessary pumping. Therefore, it is most important to try to minimize the airflow losses.

Clutch

The most obvious way of limiting the parasitic losses is to have a clutch to engage and disengage the compressor. Using a clutch has the advantage of reducing both losses in the air and the mechanical losses, assuming that the clutch is positioned on the crankshaft end of the belt. Since the compressor has a non-negligible inertia and that it rotates with high speed, it is necessary to apply large amounts of torque in order to accelerate the compressor to working speeds within reasonable time. These torque impulses will result in comfort problems if the work has to be taken from the crankshaft.

TURBOCHARGER

Turbochargers are commonly used in engines because they extract some of the energy from the exhaust gases that would have otherwise been lost [Corky Bell, 1997]. Turbochargers consist of a turbine (the component that is being spun by the passing exhaust gases) and the compressor (the component increasing the intake pressure) which is coupled to the turbine by a rotor. Figure 2.4 shows schematic layout of turbocharging system in a diesel engine.

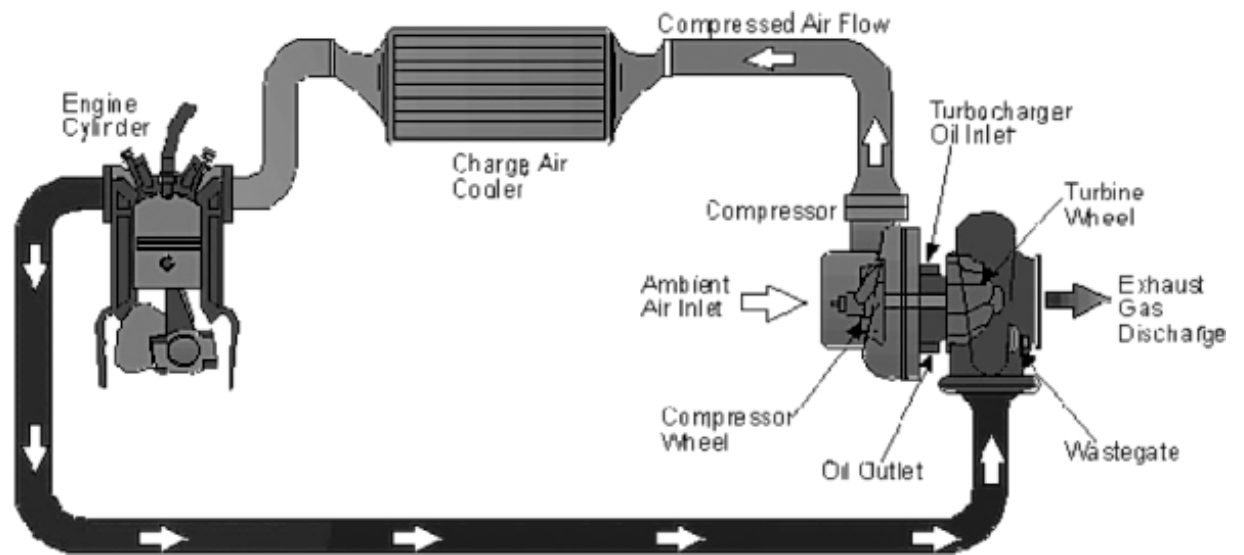


Figure 2.4 Typical schematic layout of turbocharger system of an IC engine

One of the advantages of turbochargers is that they are able to recuperate some of the energy of the exhaust gases. This makes turbochargers suitable for use in engines where efficiency is important, as well as for diesel engines that are otherwise not able to produce a high power. Another reason why turbochargers are preferred in diesel engines is because of the lower exhaust temperature [Cengel and Boles, 2006], which doesn't damage the turbine blades (unlike gas powered engines). Typically, turbines are very delicate and require special grades of oils because of their very high rotational speeds (sometimes exceeding 150000 rpm); as long with this in gas powered engine, the higher temperature of exhaust gases tends to melt the tips of the turbine blades which dramatically decreases the efficiency of the turbine which causes a significant decrease in engine power. In road going vehicles and race cars, turbochargers are well known for the turbo lag. The turbo lag is an unwanted effect and is caused because of the high turbine spool time due to the moment of inertia of the turbine and compressor. As well, it is due to the fact that the driving force of the turbine comes from the exhaust gases which are compressible. The turbo lag is in other words a delay in the turbine response

Waste Gate Operation

Some turbochargers are equipped with a waste gate [Figure 2.5]. This device allows some of the exhaust gases to bypass the turbine rotor at higher engine speeds. With

this arrangement, the turbocharger can be designed to be more effective at lower engine speeds. The waste gate consists of a valve, actuator, and connecting linkage. The actuator consists of a diaphragm and spring enclosed in canister housing. The valve is located in an exhaust bypass line. Under low boost conditions, the spring pushes against the diaphragm moving the linkage to close the waste gate valve. Turbo boost pressure is directed against the other side of the diaphragm. As boost pressure increases with increased engine speed, the diaphragm moves against spring pressure to open the valve and allow a portion of the exhaust gases to bypass the turbine wheel through a connecting line. As boost pressure drops, spring pressure moves the diaphragm and linkage to close the valve. The waste gate is preset at the factory and no adjustment can be made.

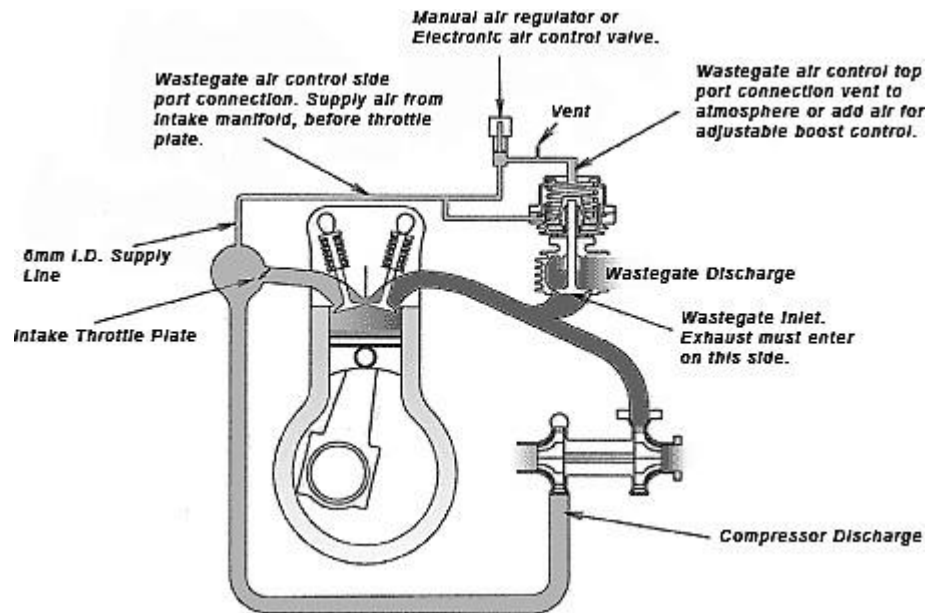


Figure 2.5 Waste gate arrangements in a turbocharged engine.

Trend of Turbo Charging Technologies

The goals that a turbocharger must satisfy are the ability to provide high-pressure turbocharging at low engine speeds, a high transient response, and high efficiency at a high pressure ratio. A fixed geometry turbine is not capable of supplying enough power to the compressor for the boost pressure required for low speed and during transient conditions. On the other hand, it offers a higher turbine inlet pressure which

leads to increased fuel consumption if the turbocharger characteristics are optimized for low engine speeds. In addition, the flow range of a centrifugal compressor is a limiting factor, and if higher boost pressures are demanded, it will be even more difficult to achieve satisfactory width of the usable range since the width of the compressor map becomes narrower as the boost pressure approaches its maximum.

Different turbocharger designs such as the variable geometry turbocharger, electrically assisted turbocharger, and two-stage turbocharger have been developed as a means of achieving the above-mentioned performance improvements. Also, the Variable-Nozzle Turbocharger (VNT), which is capable of changing the flow capacity of the turbine, is already in widespread use in diesel passenger cars. The electrically assisted turbocharger improves the transient response and, because it is excellent at achieving high-pressure turbo charging at low speeds, manufacturers are putting considerable effort into its development.

For a turbocharged engine with the Variable Nozzle Turbine (VNT), as is widely used in diesel engines, the boost pressure can be raised by controlling the variable nozzle at low engine speeds. Figure 2.6 shows an example of a VNT that was developed for use in diesel engines. In addition, improving the turbocharger efficiency in the region where the pressure ratio is high is important to reduce the turbine inlet pressure for high-pressure turbo charging.

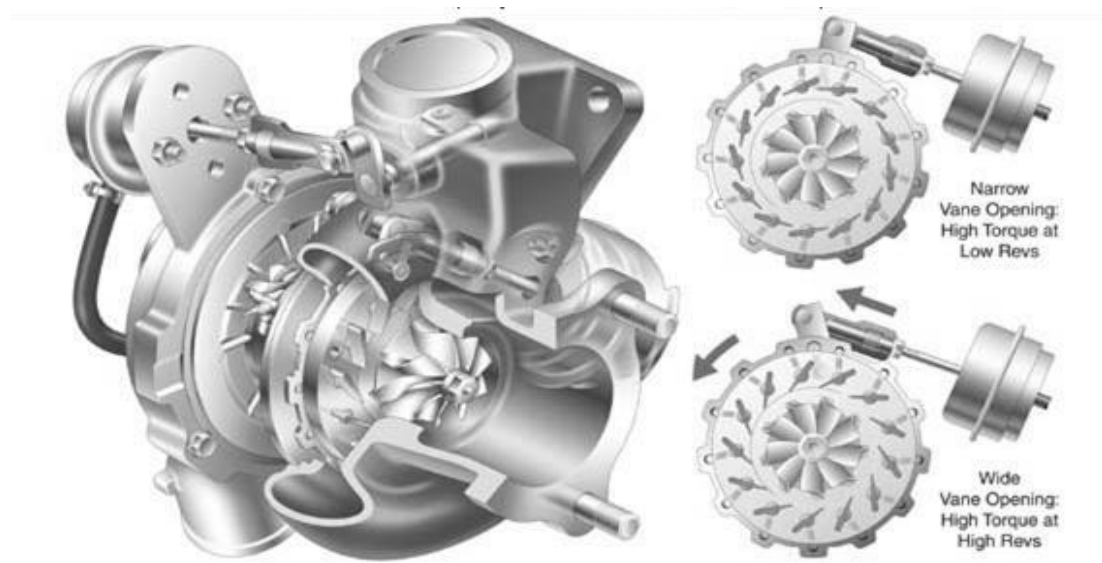


Figure 2.6 A typical example of a VNT that was developed for use in diesel engines

The VNT has rapidly gained popularity in Japan and Europe despite its higher cost because it offers the advantages of low-end torque, transient response, and lower turbine inlet pressures at high speeds, relative to conventional turbochargers. At present, the VNT is the only technology available that allows diesel engines to satisfy current emissions regulations. On the other hand, the VNT is not compatible with the high gas temperatures of gasoline engines because of its complicated structure and links. However, the amount by which the pressure can be increased at low engine speeds is limited due to the low exhaust energy, such that engine back pressure arises.

The Motor-Assist turbocharger (MAT), however, is able to raise the boost pressure at low engine speeds. So, by adding motor assistance, torque characteristics on a par with a large-displacement engine can be attained. A MAT can also recover thermal exhaust energy by acting as a dynamo at high engine speeds [Figure 2.7]. The high-speed motor has its permanent magnet installed on the shaft of the rotor while the stator is in the bearing housing. Because the motor is sensitive to heat, the cooling method is an important aspect of the development.

Moreover, the outer diameter of the permanent magnet cannot be made much bigger than already present because the combined strength of the permanent magnet and the shaft is low. To increase the power of the motor, therefore, the length of the permanent magnet has to be extended. Unfortunately, this leads to a reduction in the critical speed of the rotor shaft, vibration, and a risk of damage when operating at high speeds. Because the surge phenomenon of the compressor sometimes leads to damage to the rotor, it has been the subject of research for some time and by many different manufacturers.

Many kinds of casing treatments have been investigated to improve the surge characteristic and have been put commercialized in large-scale turbochargers. To obtain a high boost pressure over the wide operating range of a turbocharged engine, the turbocharger has to operate at a high pressure ratio and high rotational speed over a wide flow range. On the other hand, the compressor has a surge limit that is related to the flow rate and therefore cannot be operated at flow rates less than the surge limit. Otherwise, the flow becomes unstable and periodic pressure fluctuations characterized by loud noise.

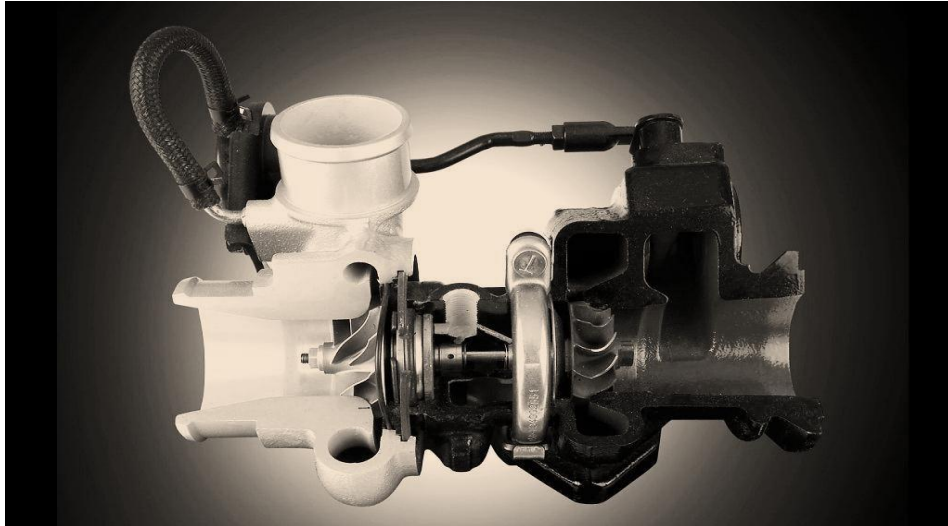


Figure Schematic layout of a MAT.

To overcome this, the rotational speed of the turbocharger has to be increased by controlling the variable nozzle vane angle or the power of the motor assistance, while shifting the surge limit of the compressor towards a lower flow rate, or eliminating it altogether, in order to increase the boost pressure at low engine speeds.

There are two ways of eliminating the surge limit. The first is the application of two-stage turbo charging whereby the small compressor of the high-pressure turbocharger is used at low engine speeds. Unfortunately, a disadvantage of two-stage turbo charging is that the system is more complex and larger than single-stage turbo charging. The second method involves bypassing the compressor discharge air to the compressor inlet so as to increase the flow rate of the compressor. This, however, causes an increase in the turbine inlet pressure due to the increase in the compressor power. As a result, the fuel consumption of the engine deteriorates. Therefore, a means of improving the surge limit of the compressor is an essential technology. There are several means of improving the surge limit of a centrifugal compressor. One effective means is to re-circulate part of the air that is compressed by the impeller to the impeller inlet by using a casing treatment on the shroud wall.

The surge flow rate can be reduced by using a compressor with a variable inlet guide vanes (VIGV) or a variable diffuser. A VIGV installed upstream from the impeller inlet can control the velocity angle of the flow at the impeller inlet, so that the flow

characteristics of the compressor can be controlled. A variable diffuser installed downstream from the impeller exit can control the flow through the diffuser where the velocity is higher than at the impeller inlet. So, the changes in the flow characteristics with the diffuser vane angle are very sensitive compared with the VIGV. And, the performance of the compressor with the variable diffuser is highly dependent on the clearances between the stationary side walls and the variable diffuser vanes.