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, Striling 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 ahead 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.
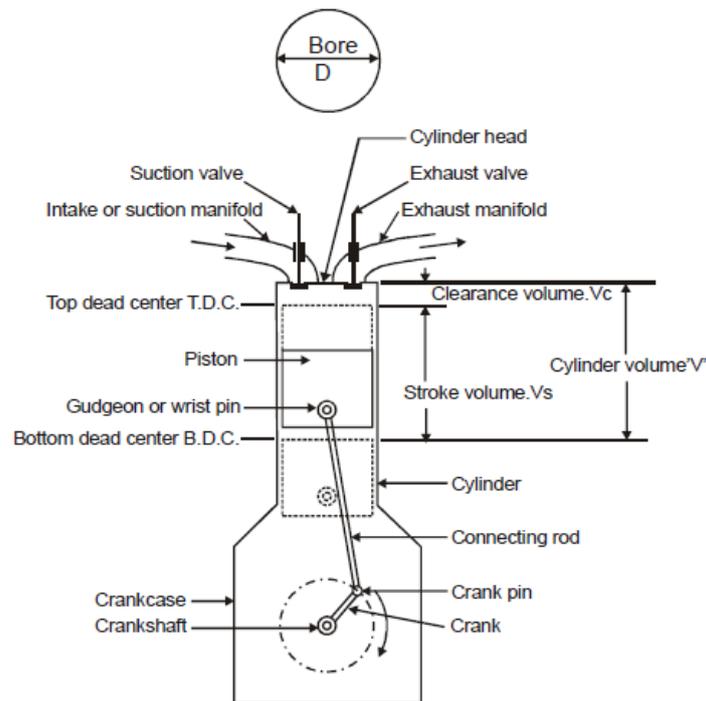
Figure 3.1 Cross section of an Internal Combustion Engine

(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 a wheel is attached to the output shaft and this wheel is called the flywheel. The variation of the net torque decreases with

2

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, alluminium alloy
Piston	Cast iron, alluminium alloy
Piston rings	Silicon cast iron
Wrist pin	Steel
Valves	Alloy steel
Connecting rod	Steel
Crankshaft	Alloy steel, SG iron
Crankcase	Alluminium 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

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

(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 COMBUSTON ENGINES

Internal Combustions 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, powered 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

(xi) 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.
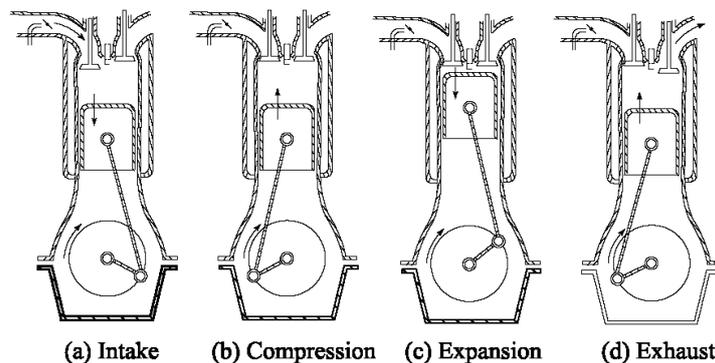

(a) Intake   (b) Compression   (c) Expansion   (d) Exhaust

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 ºC. 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.
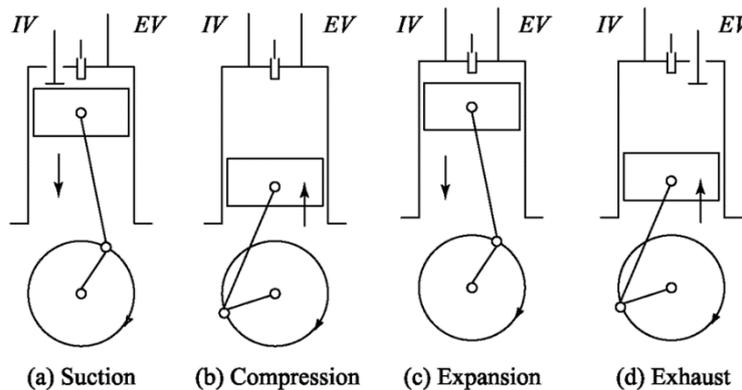

(a) Suction   (b) Compression   (c) Expansion   (d) Exhaust

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 stars 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.
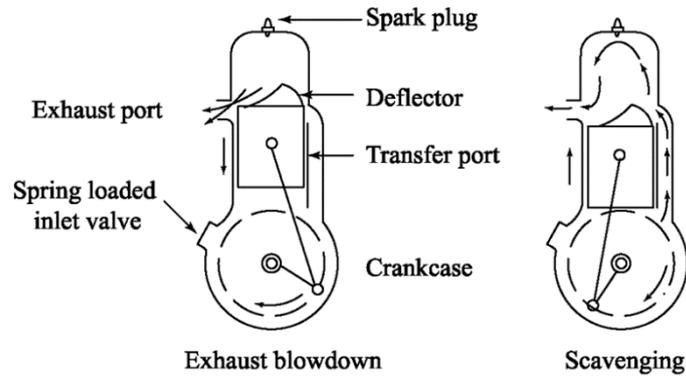
Figure Two stroke cycle engine

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 stokes 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.

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 12-3-4 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

0-1 Suction
1-2 Compression
2-3 Heat addition
3-4 Expansion
4-0 Exhaust

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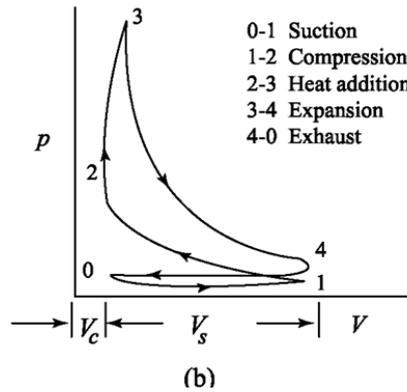
Figure Actual P-V diagram of four stroke Otto cycle engine

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
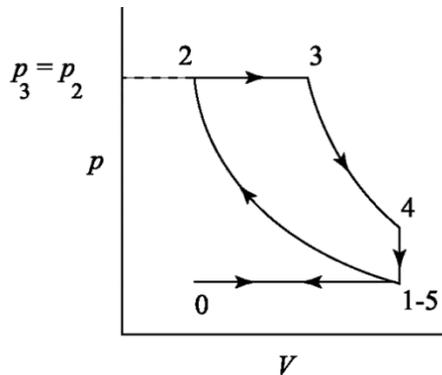

Figure Theoretical P-V diagram of four stroke Diesel cycle engine

<table>
<tr><th colspan="5">Table</th></tr>
<tr><th></th><th>Inlet valve</th><th>Exhaust valve</th><th>Piston movement</th><th>Process</th></tr>
<tr><td>Suction stroke (5–1)</td><td>Opened</td><td>Closed</td><td>TDC to BDC</td><td>The air is drawn into the cylinder at constant pressure.</td></tr>
<tr><td>Compression stroke (1–2)</td><td>Closed</td><td>Closed</td><td>BDC to TDC</td><td>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)</td></tr>
</table>

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 12-3-4 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.
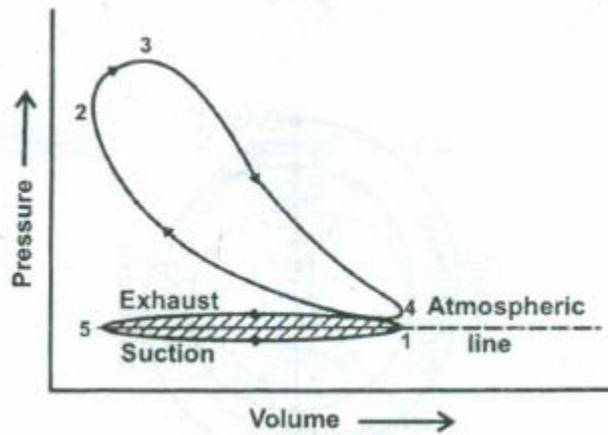

Figure Actual P-V diagram of four stroke Diesel cycle engine

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.
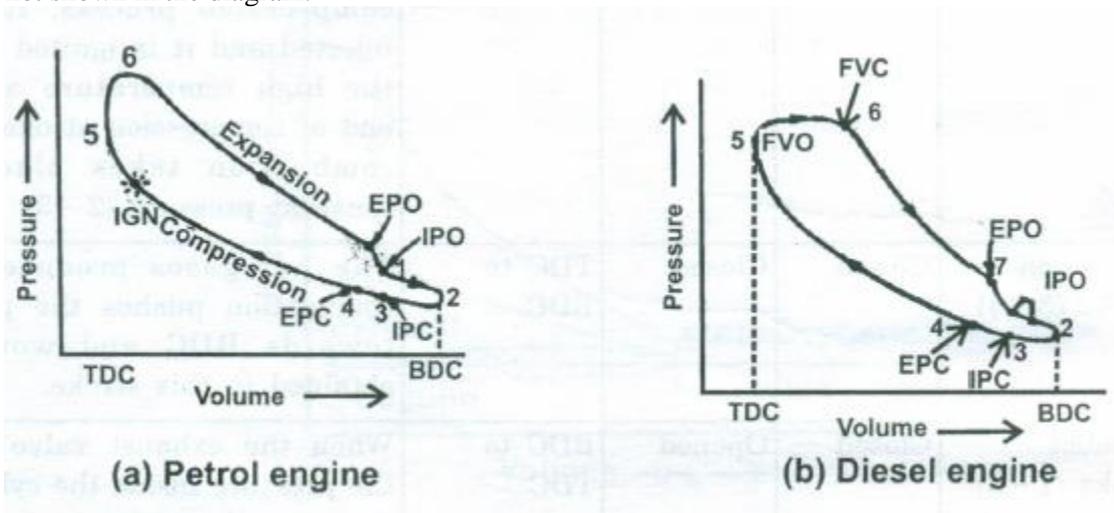

Figure P-V diagram of two stroke cycle engine

11

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.

| Theoretical | Actual |
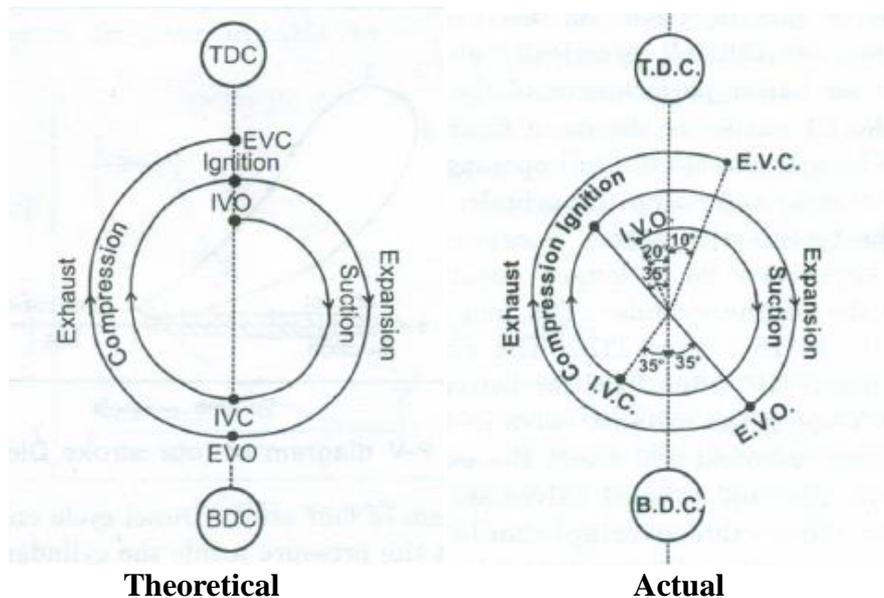
Instant opening and closing of valves are practically difficult and the valve opening and closing timings are modified for better performance of the engine. The actual valve timing diagram of four stroke SI engine is shown in figure (actual). The inlet valve is opened $10^o$to 30° before TDC which enable 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
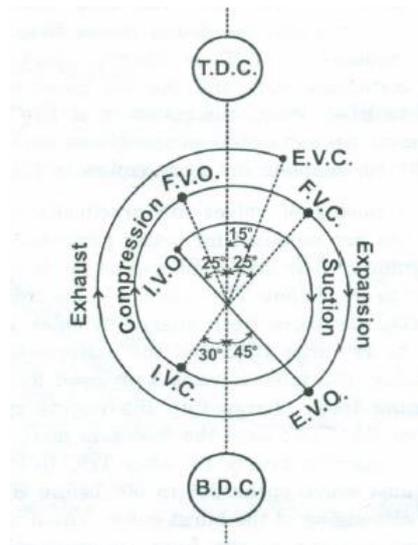
Actual valve timing diagram of CI engine

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.
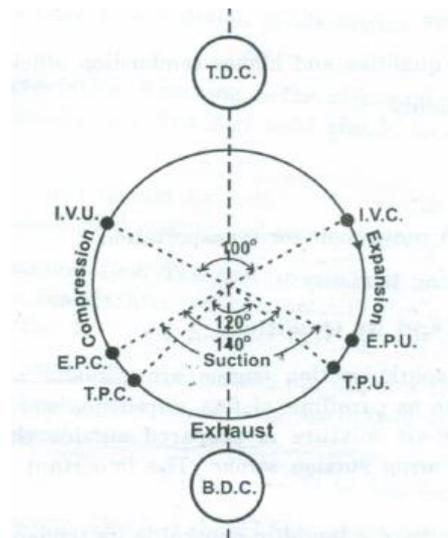
Port timing diagram of two stroke cycle engine

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 stoke 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.
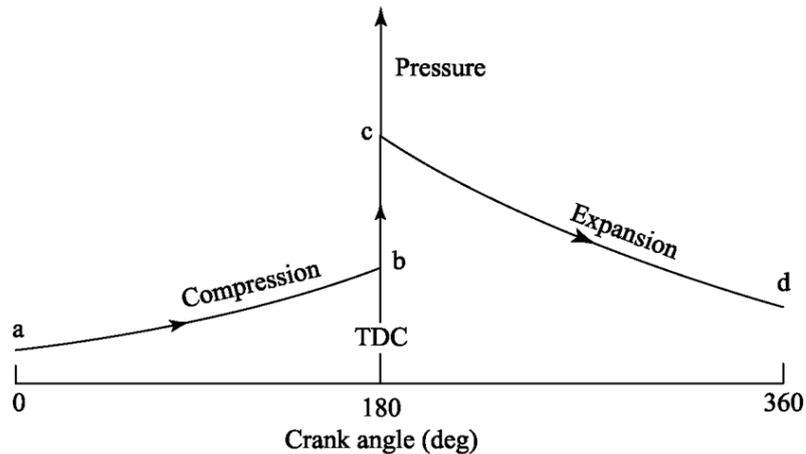
Stages of combustion in SI engine

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.
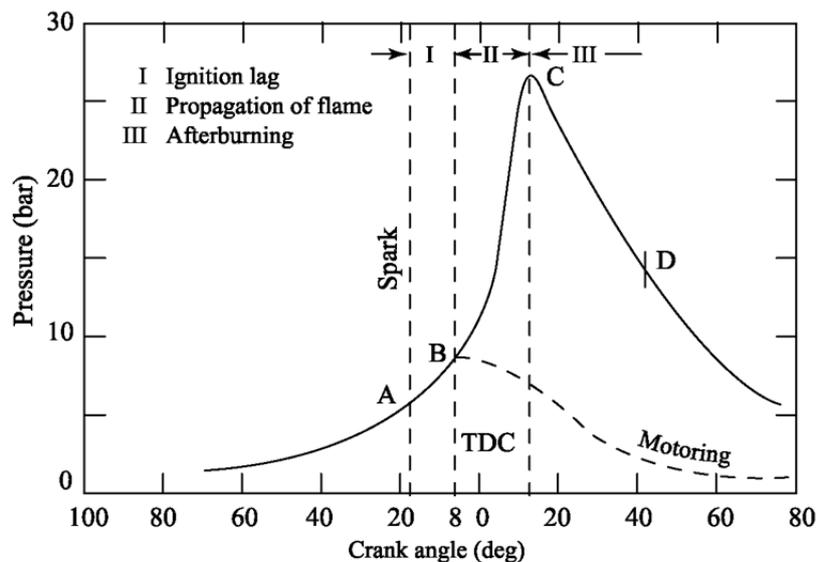
Flame front propagation:

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.

Normal combustion

16
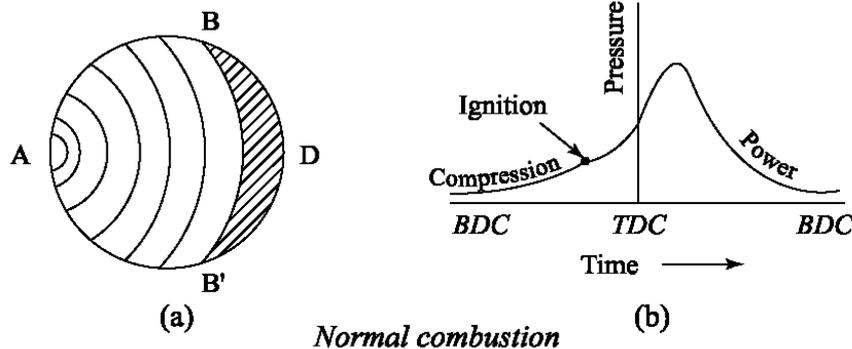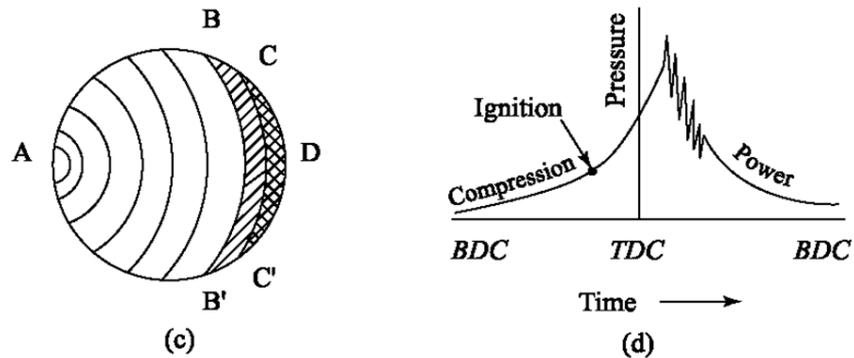
Combustion with detonation

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 conditionwill 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.
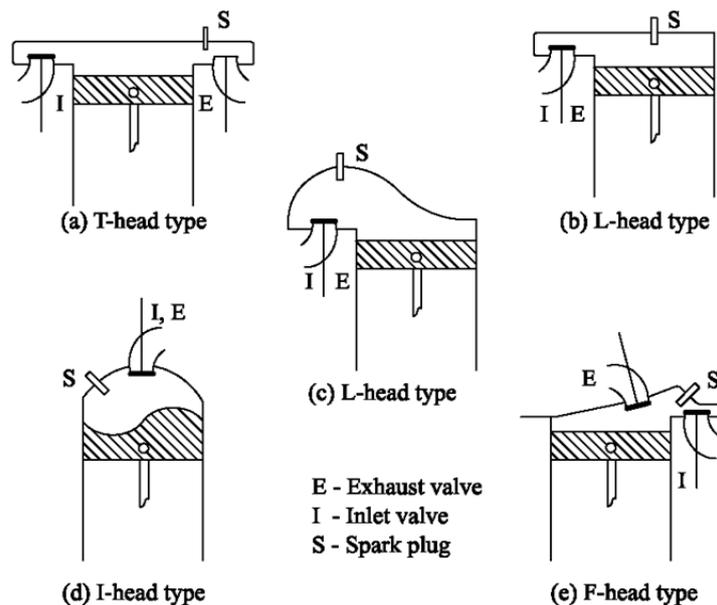
Combustion chamber for SI engine:

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.


(a) T-head type

(b) L-head type

(c) L-head type

(d) I-head type

(e) F-head type

E - Exhaust valve
I - Inlet valve
S - Spark plug

The different types of combustion chamber used in SI engine are

⊕ T head type

⊕ L head type

⊕ I head type

⊕ F head type

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.
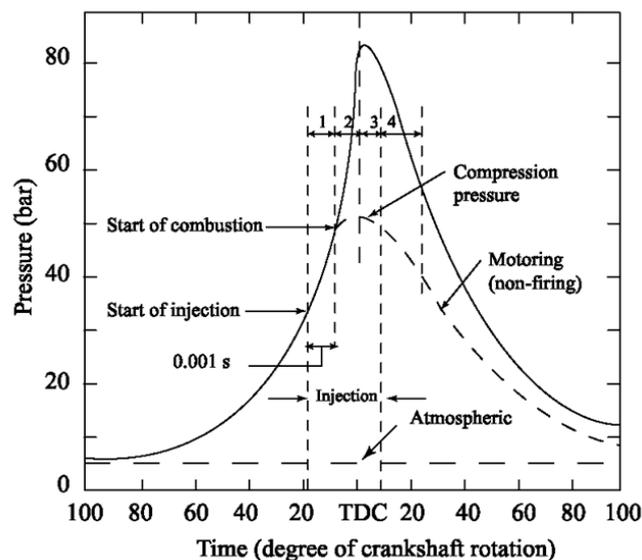

2. **Period of rapid combustion:** The period of rapid combustion also called the uncontrolled combustion during which the pressure raise is rapid. The rate of heat release is the maximum during this period.

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 20^0bTDC

(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.
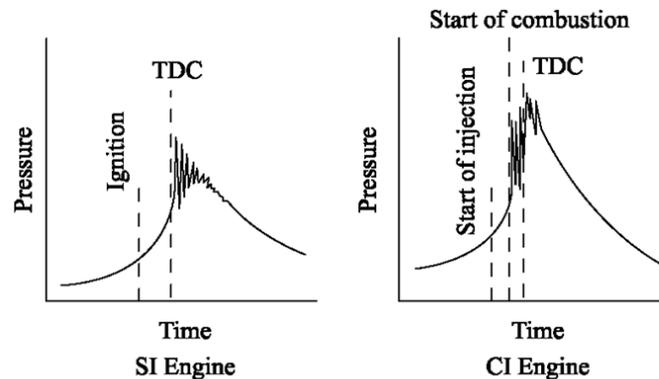
The phenomenon of knock in CI engine:
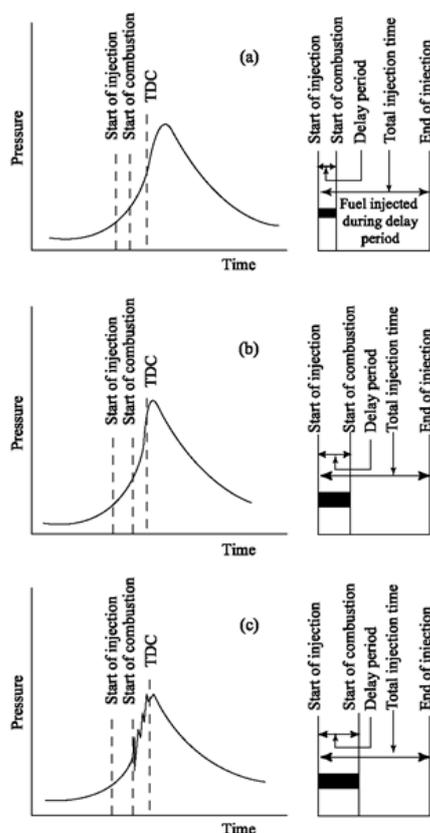
In CI engine the injection process takes place over a definite interval of time. Consequently, as the first few droplets to be injected are passing through the ignition delay period, additional droplets are being injected into the chamber. If the ignition delay of the fuel being injected is short, the 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 a 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 engineoperation.

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 provded 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

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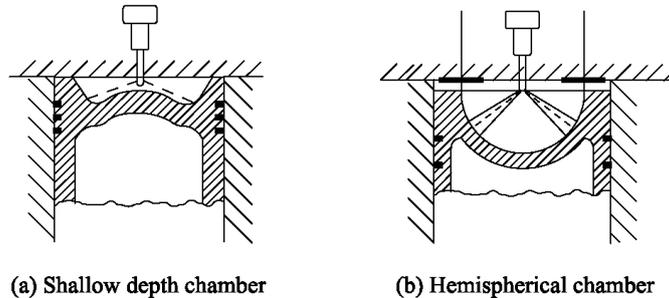
Cylindrical chamber: This design was attempted in recent diesel engines. This is a modification of the cylindrical chamber in the form of a truncated cone with base angle of 30° The swirl was produced by masking the valve for nearly 80° of circumference. Squish can also be varied by varying the depth.

Torodial 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°

(c) Cylindrical chamber   (d) Toroidal chamber
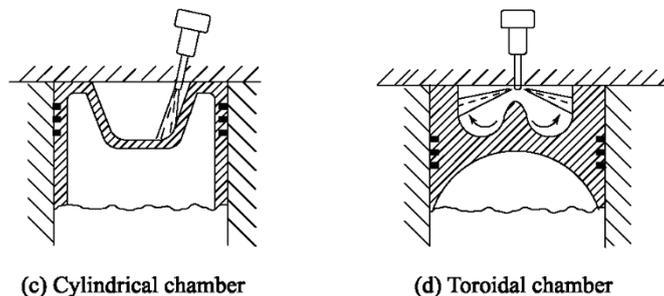
Indirect injection chambers:

The various types of indirect injection chambers are dealt here

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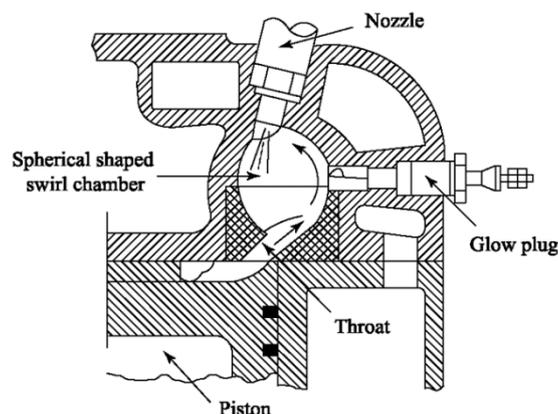
Swirl chambers consist of a spherical shaped chamber separated from the engine cylinder and located in the cylinder head. Into this chamber, about 50% of the air is transferred during the compression stroke. A throat connects the chamber to the cylinder which enters the chamber

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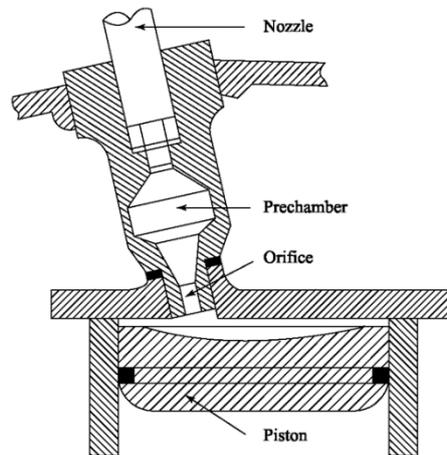
Air cell chamber
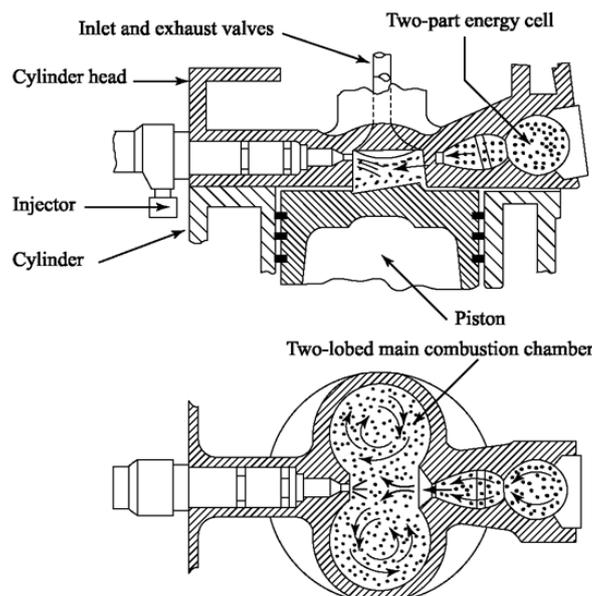
In this chamber the clearance volume is divided into two parts, one in the main cylinder and the other called the energy cell. The energy cell is divided into two parts, major and minor, which are separated from each other and from the main chamber by narrow orifices.During

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