MODULE-1

INTERNAL COMBUSTION ENGINES

Heat Engines

A heat engine is a device which translates chemical energy into heat energy and then into mechanical work.

Heat engines are classified as

(i) I.C engines (Internal combustion engines)

(ii) E.C engines (External combustion engines)

I.C engines

In an internal combustion engine, power is generated by the combustion of fuel, which releases heat energy from the chemical energy of the fuel. Inside the cylinder, combustion and the development of power occur.

E.C engines

External combustion engines, such as steam engines and steam turbines, are known as E.C. engines. Heat is generated in these devices when fuel is burned in a furnace. Under pressure, steam is produced using this energy. When steam is introduced into an engine, it expands and produces power.

Nomenclature of an I.C engine

Any engine will go through several cycles of operation while it is operating. In an I.C engine, a cycle consists of four operations. They occur one after other in the order as given below:

(i) Suction stroke

(ii) Compression stroke

(iii) Ignition and expansion stroke

(iv) Exhaust stroke

In order to perform the four operations, a piston reciprocates within the cylinder up and down. The piston, cylinder and other details of anengine is shown in fig.

TDC → Top dead centre → Top most position of the piston in the cylinder of vertical engines.

BDC → Bottom dead centre → Bottom most position of the piston in the cylinder of vertical engines.

IDC → Inner dead centre → Inner most position of the piston in the cylinder of horizontal engines.

ODC → Outer dead centre → Outer most position of the piston in the cylinder of horizontal engines.

Stroke → The distance (L) between two dead centres. The piston completes one stroke in ½ revolution of the crank shaft (180°).

Bore → Diameter of the cylinder (D).

Clearance volume → The space above the piston when the piston is at TDC.

Cylinder volume → The volume above the piston when the piston is at BDC.

Stroke volume → Also called swept volume. The volume displaced by the piston during a stroke is called swept volume.

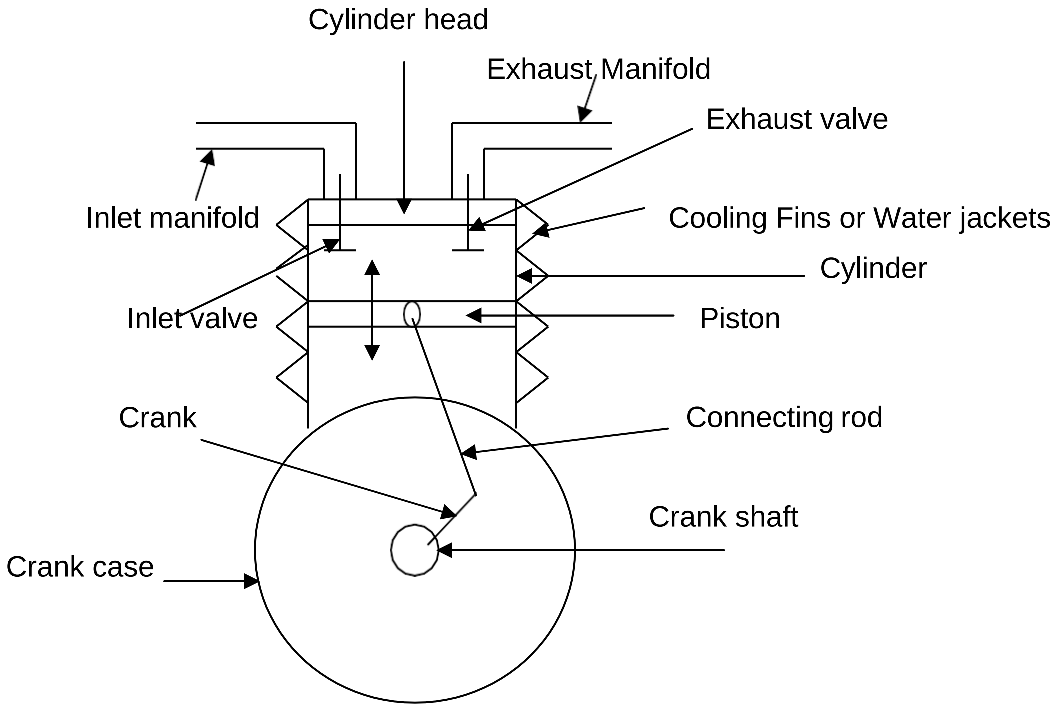
Square engine → D = L

Under square engine → D < L → Low speed engines. Large industrial engines and tractor engines are under square engines.

Over square engine → D > L → High speed engines. This is the most common engine design.

Cubic capacity → The cubic capacity of an engine is also called as engine displacement is the product of stroke volume in one cylinder and the number of cylinders in the engine.

Compression ratio → Compression ratio is the ratio of cylinder volume to the clearance volume.



Components of I.C engines

(i) Cylinder head

(ii) Cylinder block

(iii) Piston, Piston rod, Piston ring

(iv) Crank shaft

(v) Connecting rod

(vi) Camshaft

(vii) Valves

(viii) Valve operating mechanism

(ix) Flywheel

(x) Timing gears

(xi) Inlet and Exhaust manifolds

The fundamental framework for all the parts of the engine is the cylinder block. On top of the cylinder block is the cylinder head. When an engine is air-cooled, cooling fins are fitted, and when an engine is water-cooled, water jackets are provided to the cylinder head and block.

The cylinder head is held tight to the cylinder block by number of bolts and studs. The bottom portion of the cylinder block is called crank case. The piston reciprocates inside the cylinder andthe motion of the piston is transmitted to the crank shaft by connecting rod and crank assembly. Inlet and exhaust valves are provided for suction of charge and removal of exhaust gases.

Fuel is supplied to the engine from the fuel tank for combustion through fuel filter, fuel pump and fuel injector in case of C.I engines and carburetor in case of S.I engines.

Lubricating system supplies lubricating oil to the various parts of the engine where there is relative motion. This reduces friction between the parts and thereby increases engine life.

Cooling system abstracts excess heat from various engine parts which are heated dueto combustion. This prevents the failure of the components due to overheating and increasesthe engine life. The coolant may be either liquid or air.

Inlet manifold is provided on suction side which allows the charge entering the cylinder during suction process. Exhaust manifold is provided on exhaust side which allows the exhaust gases letting to atmosphere during exhaust process.

Function of components

Crank shaft: The crank shaft runs under the action of piston through the connecting rod and crank pin and transmits the work from the piston to the driven shaft.

Piston: Transmits the power developed by the combustion of fuels to the crank shaft.

Piston rings: The piston rings lubricated with engine oil produces gas-tight seal between the piston and the cylinder liners. The three main functions of piston rings in reciprocating engines are: 1. Sealing the combustion/expansion chamber, 2. Supporting heat transfer from the piston to the cylinder wall and 3. Regulating engine oil consumption.

Compression rings → Prevents leakage of high-pressure air to crank case during compression process.

Oil rings → Scraps the lubricating oil from the cylinder wall and allow it to return to the oil sump.

Connecting rod: The connecting rod changes and transmits the reciprocating motion of the piston to the continuously rotating crank pin during the working stroke and vice versa during other strokes.

Push rod and Rocker arm: The motion of the cam is transmitted to the valve through the pushrod and rocker arm. A push rod is the component of the valve system of piston engines. Its function is essentially to push the valve open. The push rod is driven by the rocker arm which is actuated by the cam.

Cam shaft: It is driven from the crank shaft by a timing gear. It operates the intake valve andthe exhaust valve through the cams, followers, push rods and rocker arms.

Crank case: The main body of the engine to which the cylinders are attached and which contains crankshaft and camshaft bearing. It protects the parts from dirt, etc.

Flywheel: A flywheel (Steel or cast-iron disc) secured on the crankshaft takes care of the fluctuations in speed and stores energy during the power stroke and releases during the other strokes. It also makes crankshaft rotation more uniform.

Governor: When the speed decreases due to increase in load the supply valve is opened by the mechanism operated by the governor and therefore speeds up again to the original speed. Ifthe speed increases due to a decrease in load the governor mechanism closes the supply valve sufficiently to slow the engine to its original speed. Thus the function of a governor is to control the fluctuations of engine sped due to changes of load.

Spark plug: The function of the spark plug is to ignite the mixture after completing the compression in the petrol engine.

Carburettor: To supply uniform air-fuel mixture in the cylinder of petrol engines through the intake manifold.

Fuel pump: It forces the fuel oil at high pressure through fuel nozzle into the cylinder at the end of compression stroke in diesel engine.

Classification of I.C engines

Based on working cycle

(i) Two stroke engines

(ii) Four stroke engines

Based on method of ignition

(i) Compression ignition engines (C.I engines)

(ii) Spark ignition engines (S.I engines)

Based on Fuel used

(i) Light fuel oil engines (Petrol engines)

(ii) Diesel engines

(iii) Gas engines

Based on applications

(i) Stationary engines

(ii) Portable engines

(iii) Automobile engines

(iv) Marine engines

(v) Aero engines

Based on arrangement of the cylinder

(i) Horizontal engines

(ii) Vertical engines

(iii) Radial engines

(iv) V-type engines

Based on speed of the engine

(i) Slow speed engines

(ii) Medium speed engines

(iii) High speed engines

Based on number of cylinders

(i) Single cylinder engines

(ii) Multi-cylinder engines

Based on method of cooling

(i) Water cooled engines

(ii) Air cooled engines

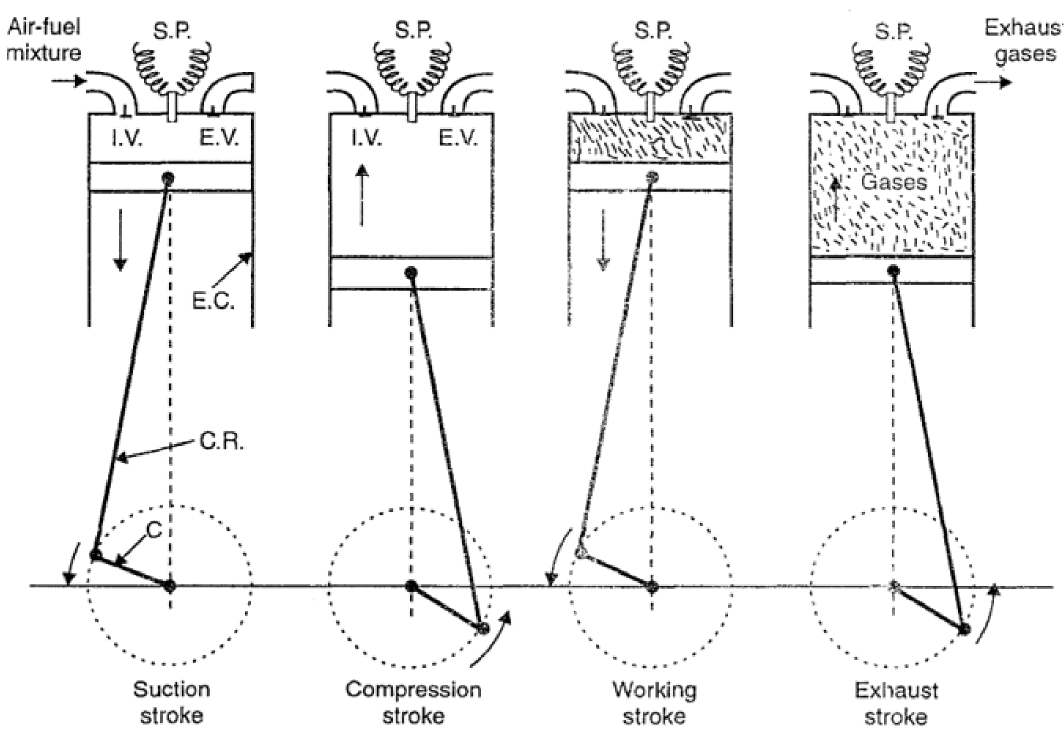
Indicator Diagram (p-V diagram) and Diagram factor

The indicator diagram is a graph between pressure and volume. This is obtained by an instrument known as "Indicator". The indicator diagrams are of two types: (1) Theoretical or Hypothetical and (2) Actual. The theoretical indicator diagram is always longer in size as compared to the actual, since in the former losses are neglected.

$$Diagram\ Factor = \frac{Area\ of\ the\ Actual\ indicator\ diagram}{Area\ of\ the\ theoretical\ indicator\ diagram}$$

Working of Four Stroke S.I Engines (Petrol engines and Gas engines)

In four stroke engine all the operations are completed in four strokes or in tworevolutions of the crank shaft.



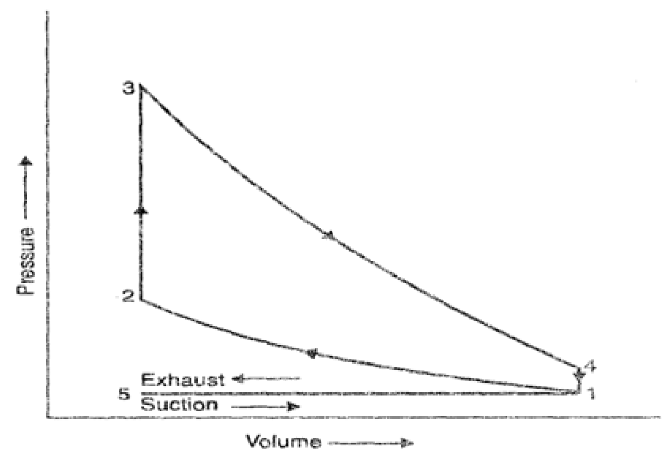
I.V = Intel valve, E.V. = Exhaust valve, E.C. = Engine cylinder, C.R. = Connecting rod
C = Crank, S.P. = Spark plug.

Suction Stroke: During this stroke (also called induction stroke) the piston moves from TDC to BDC. The inlet valve opens and proportionate fuel-air mixture is sucked in the engine cylinder. The operation is represented by the line 5 – 1. The exhaust valve remains closed throughout the stroke.

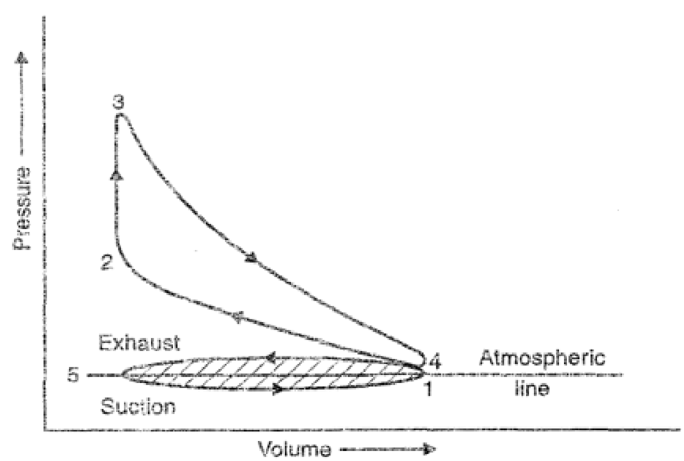
Compression Stroke: In this stroke the piston moves towards TDC and compresses the enclosed fuel air mixture drawn in the cylinder during suction stroke. The pressure of the mixture rises in the cylinder to a value of about 8 bar (1 – 2). Just before end the stroke, a high intensity spark is applied to ignite the mixture and combustion takes place at constant volume (2– 3). Both inlet and exhaust valves remain closed during this stroke.

Expansion or Power stroke: The high pressure and high temperature hot gases obtained by the combustion, throws the piston from TDC to BDC. Thus, the work is obtained in this stroke (3 –4). Both the valves remain closed during this stroke. When the piston just reaches the BDC, the exhaust valve opens and there will be sudden pressure drop and heat rejection at constant volume (4 – 1).

Exhaust Stroke: This is last stroke of the cycle. During this stroke, the used gases are allowedto escape through exhaust valve to atmosphere. The piston moves from BDC to TDC and the



Theoretical p-V diagram



Actual p-V diagram

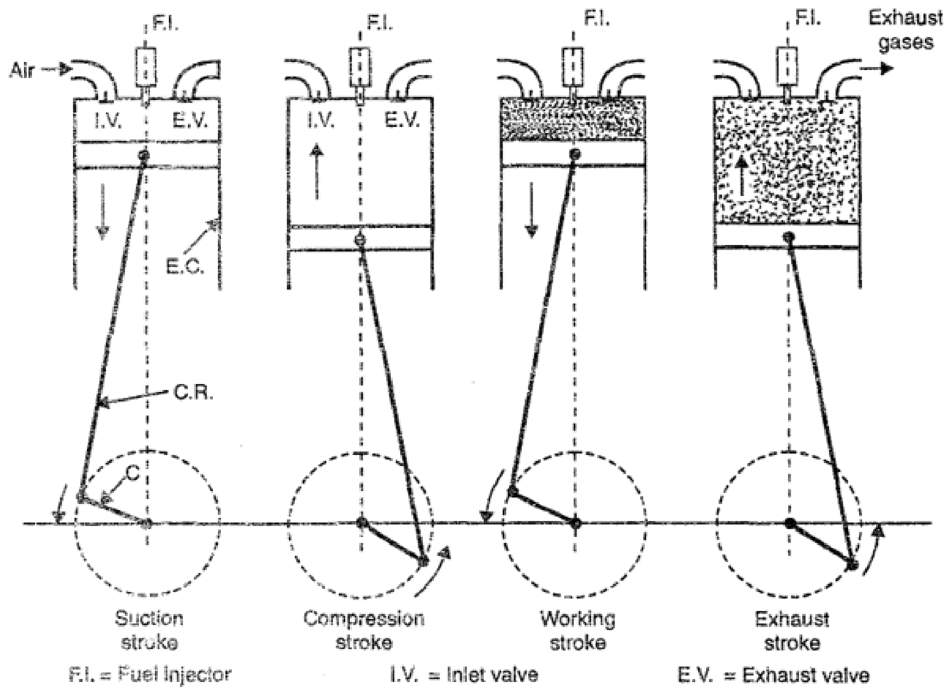
Working of Four Stroke C.I Engines (Diesel engines)

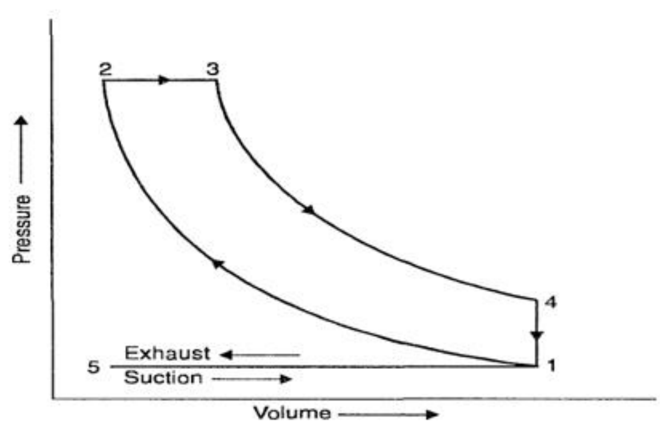
Suction Stroke: During this stroke (also called induction stroke) the piston moves from TDC to BDC. The inlet valve opens and proportionate air is sucked in the engine cylinder. The operationis represented by the line 5 – 1. The exhaust valve remains closed throughout the stroke.

Compression Stroke: In this stroke the piston moves towards TDC and compresses the enclosed air drawn in the cylinder during suction stroke. The pressure of the mixture rises in the cylinder to a value of about 35 bar (1 – 2). The temperature will be around 600ºC. Just before end the stroke, fuel is injected. Both inlet and exhaust valves remain closed during this stroke.

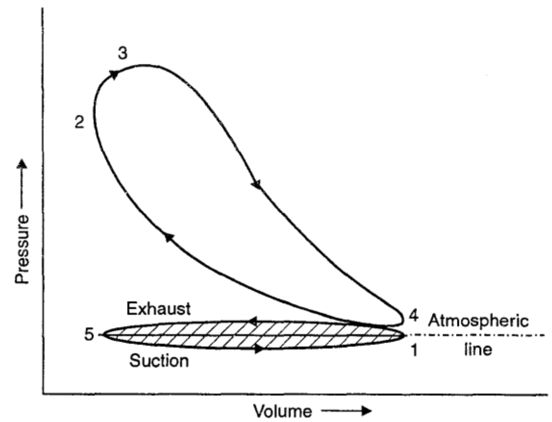
Expansion or Power stroke: As the piston starts moving from TDC, the injected fuel into the hot compressed air burn the fuel. The burning is taking place at constant pressure (2 – 3). The point2 represents the beginning of fuel injection and point 3 represents the end of fuel injection. The expansion starts at point 3 and continues up to BDC. Thus, the work is obtained in this stroke from (3 – 4). Both the valves remain closed during this stroke. When the piston just reaches the BDC, the exhaust valve opens and there will be sudden pressure drop and heat rejection at constant volume (4 – 1).

Exhaust Stroke: This is last stroke of the cycle. During this stroke, the used gases are allowedto escape through exhaust valve to atmosphere. The piston moves from BDC to TDC and the exhaust gases are driven out of the cylinder. This operation is represented by 1 – 5.





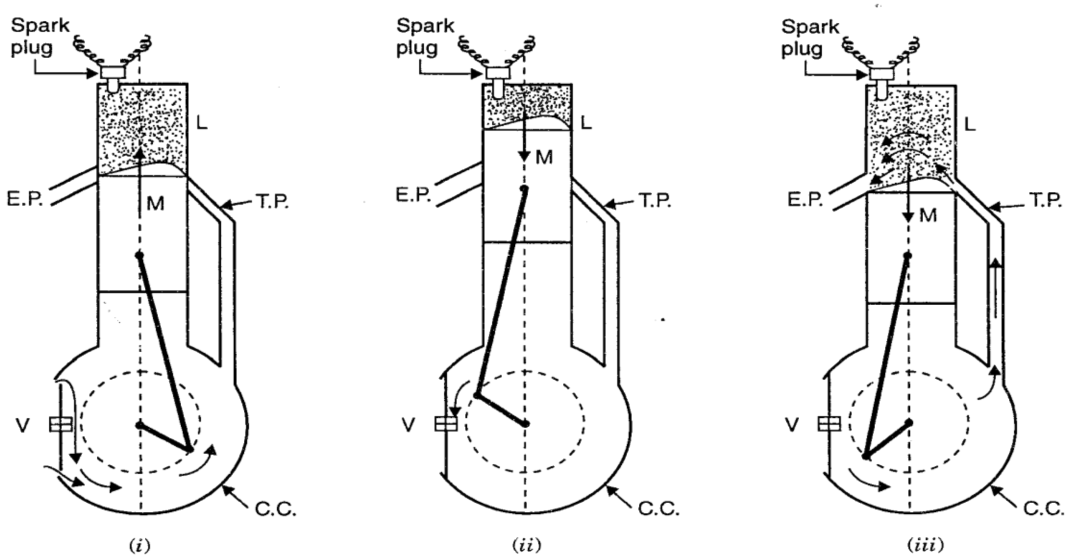
Theoretical p-V diagram



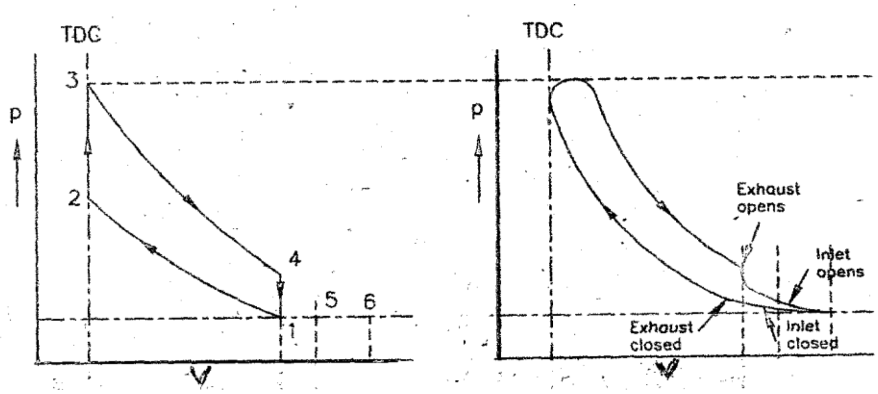
Actual p-V diagram

Working of 2-S Petrol engine

All of the operations of a two-stroke engine are completed in either two strokes or one crankshaft rotation. Ports are used in place of valves in two-stroke engines. The three ports are: (i) Inlet port (IP) (ii) Exhaust port (EP) and (iii) Transfer port (TP).



L = Cylinder E.P. = Exhaust port T.P. = Transfer port V = valve, C.C = Crank chamber



Theoretical and actual indicator diagrams of 2-S Engine

Suction stage: In this stage, while going down towards BDC, uncovers both transfer port and exhaust port. The fresh fuel-air mixture enters the cylinder through transfer port.

Compression stage: In this stage, the piston, while moving up, first covers the transfer port and then exhaust port. The air-fuel mixture is compressed. In this stage the inlet port or a valve opens and fuel air mixture enters the crank case.

Expansion stage: Shortly before the piston reaches the TDC (during compression stroke), the charge is ignited with the help of spark plug. It suddenly increases the pressure and temperature at constant volume. The piston is pushed downwards and thus the work is obtained.

Exhaust stage: In this stage, the exhaust port is opened as the piston moves downwards. The exhaust gases are sent to the atmosphere through exhaust manifold.

Working of Two Stroke C.I engine

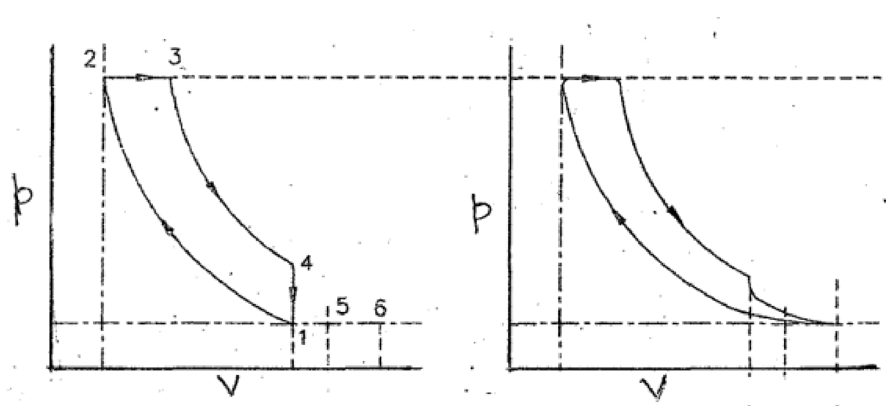
Except that fuel is admitted near the TDC, the working of two stroke cycle diesel engine is similar to that of two stroke cycle petrol engines.

Suction stage: In this stage, while going down towards BDC, uncovers both transfer port and exhaust port. The air enters the cylinder through transfer port.

Compression stage: In this stage, the piston, while moving up, first covers the transfer port and then exhaust port. The air is compressed. In this stage the inlet port or a valve opens and air enters the crank case.

Expansion stage: Shortly before the piston reaches the TDC (during compression stroke), the fuel is injected in the form of fine spray into the cylinder through the injector. At this moment the temperature of the air is sufficiently high to ignite the fuel. It suddenly increases the pressureand temperature. The fuel is continuously injected for a fraction of the crank revolution. The fuel is assumed to be burnt at constant pressure The piston is pushed downwards and thus the workis obtained.

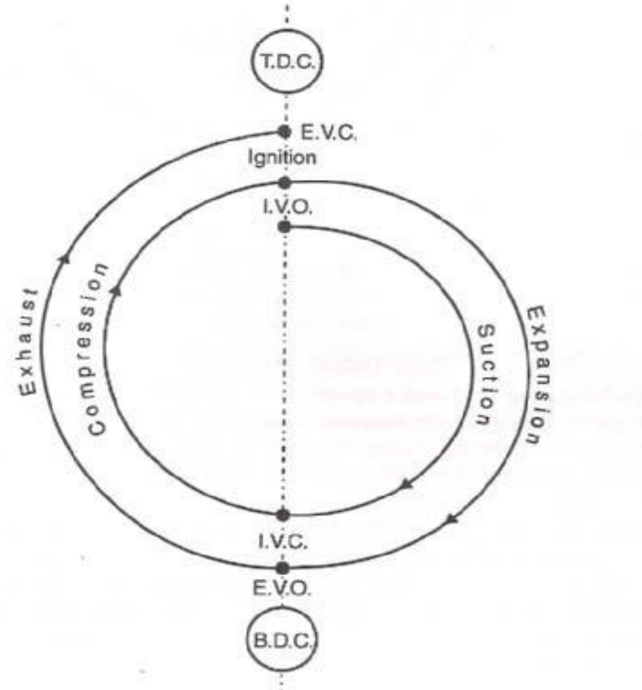
Exhaust stage: In this stage, the exhaust port is opened as the piston moves downwards. The exhaust gases are sent to the atmosphere through exhaust manifold.



Theoretical and actual p-V diagrams of Two Stroke Diesel cycle

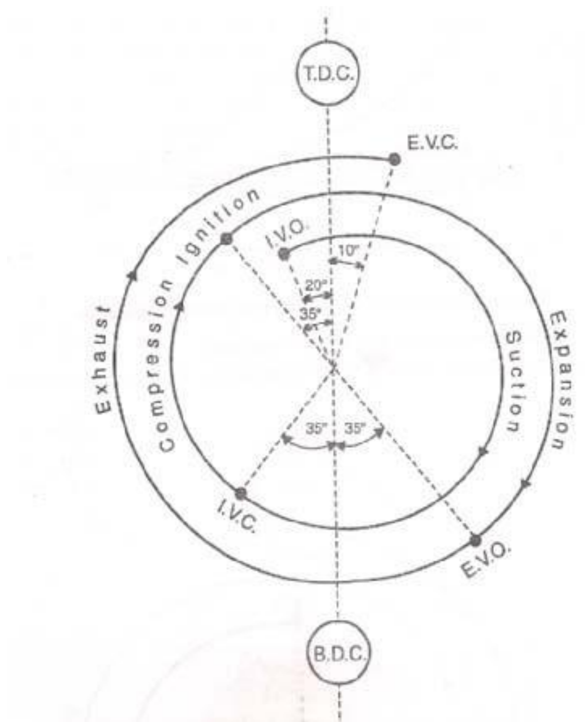
A valve timing diagram is a graphical representation of the exact moments, in the sequence of operations, at which the two valves (inlet and exhaust valves) open and close as well as firing of the fuel. It is generally expressed in terms of angular positions of the crank shaft.

Theoretical Valve Timing Diagram



The above figure shows the four-stroke cycle engine's valve timing diagram. At TDC, the inlet valve opens, and suction occurs from TDC to BDC. The intake valve closes at BDC, and compression occurs between BDC and TDC. The gasoline is ignited at TDC, and the expansion occurs from TDC to BDC. The exhaust valve opens at the end of expansion (BDC), allowing exhaust to go from BDC to TDC.

Actual Valve Timing Diagram

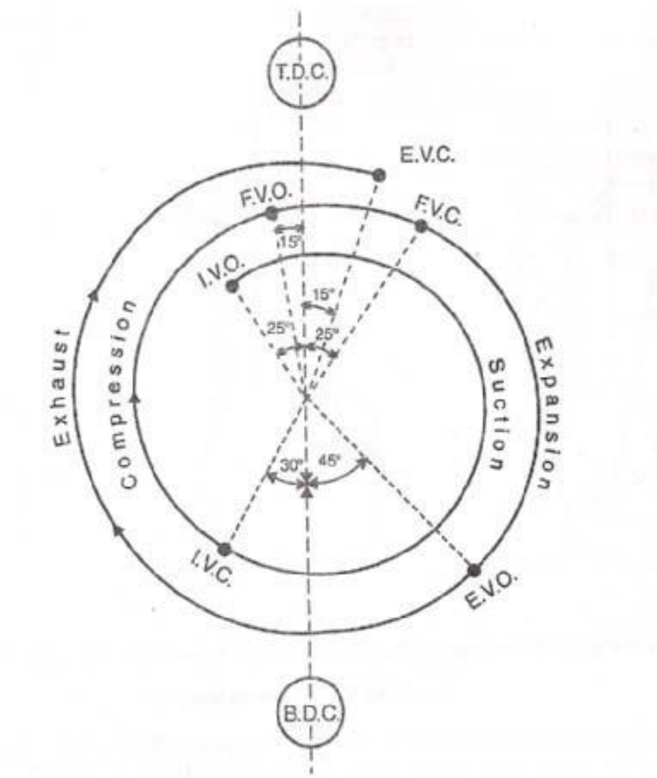


In actual practice it is difficult to open and close the valve instantaneously. The inlet valve is opened 10° to 30° in advance of the TDC position to enable the fresh charge to enterthe cylinder and to help the burnt gases at the same time, to escape to the atmosphere. The suction of the mixture continues upto 30° to 40° or even 60° after BDC position. The inlet valve closes and the compression of the entrapped mixture starts.

The spark plug produces a spark 30° to 40° before the TDC position, thus fuel gets more time to burn. The pressure becomes maximum nearly 10° past the TDC position. The exhaust valve opens 30° to 60° before BDC position and the exhaust gases are driven out of the cylinderby piston during its upward movement. The exhaust valve closes when piston is nearly 10° pastTDC position.

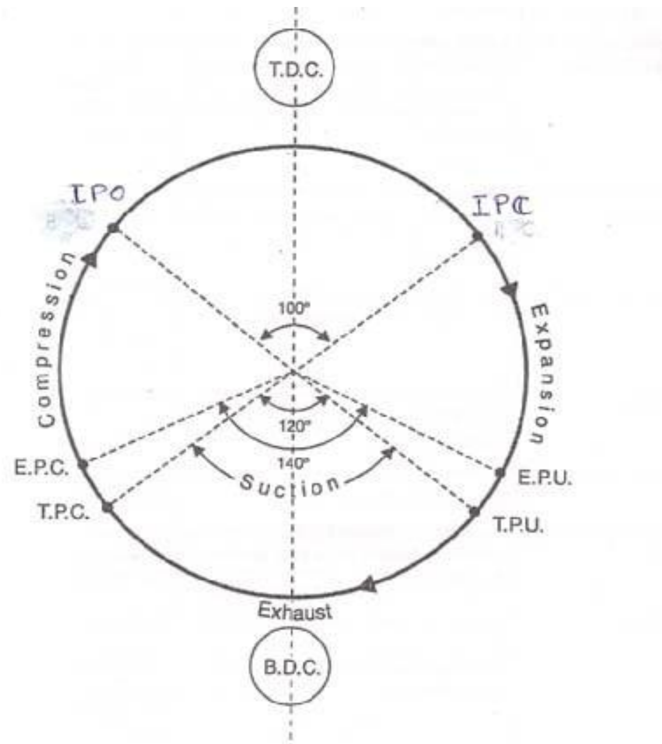
Valve Timing Diagram of Four stroke diesel engine

The inlet valve opens 10° to 25° in advance of TDC position and closes 25° to 50° after the BDC position. Exhaust valve opens 30° to 50° in advance of BDC position and closes 10° to 15° after the TDC position. The fuel injection takes place 5° to 10° before TDC position and continues up to 15° to 25° near TDC position.



Port Timing Diagram of Two stroke engine

As soon as the ignition occurs, the charge expands and the piston advances from TDC to BDC. Before the piston reaches BDC and the burned gases begin to exit the cylinder, the exhaust port first opens. The transfer port opens and the new charge enters the engine cylinder after a brief portion of the crank movement. This is carried out because the newly arriving charge aids in expelling the burned gases. At this point, the piston starts to rise as it approaches the BDC. Both the transfer port and the exhaust port close as soon as the piston advances slightly past BDC. This is done in order to simultaneously exhaust the burned gases via the exhaust port and suction new charge through the transfer port. Now that both ports are closed, the charge is compressed, and before the compression stroke is finished, it is ignited with the aid of a spark plug (for gasoline engines) or an injector (for diesel engines). This is done as the charge requires some time to ignite. By the time the piston reaches TDC, the burnt gases push the piston downwards with full force and expansion of the burnt gases takes place.



Comparison of Four stroke and Two stroke engines

Sl.No	Aspect	Four stroke	Two stroke
1	Completion of cycle	In four strokes of the piston or in two revolution of the crankshaft.	In two strokes of the piston or in one revolution of the crank shaft.
2	Flywheel required	Heavier flywheel is required.	Lighter flywheel is needed.
3	Power produced	One power stroke for two revolution.	One power stroke in one revolution. Double the power as that developed by four stroke engine (theoretically).
4	Cooling and lubrication requirements	Because of one power stroke in two revolution, lesser cooling and lubrication requirements. Lesser rate of wear and tear.	Because of one power stroke in one revolution greater cooling and lubrication requirements. Great rate of wear and tear.
5	Valve mechanism	Contains valves and maintenance required.	Contains ports. No valves. Less maintenance problems.
6	Initial cost	Because of heavy weight and complication of valve mechanism, initial cost is high.	Because of light weight and simplicity due to absence of valves, initial cost is less.

7	Volumetric efficiency	More due to more time of induction.	Less due to lesser time of induction.
8	Thermal efficiency	Higher	Lower
9	Part load efficiency	Higher	Lower
10	Applications	Used where efficiency is important. In cars, buses, trucks, industrial engines, power generators, etc.	Used where low cost, compactness and light weight is required. In scooters,ships, motor cycles, etc.

Comparison of S.I and C.I engines

Sl. No	Aspect	S.I engines	C.I engines
1	Fuel used	Petrol	Diesel
2	Air-Fuel ratio	10: 1 to 20: 1	18: 1 to 100: 1
3	Compression ratio	7 to 11	12 to 24
4	Combustion	Spark ignition	Compression ignition
5	Fuel supply	By carburetor – cheap.	By injector – expensive.
6	Cycle of operation	Otto cycle	Diesel cycle for slow speed engines. Dual cycle for high speed engines.
7	Power developed	Less	More
8	Control of power	Quantity governing	Quality governing
9	Running cost	Higher	Lower
10	Applications	Used where low cost, compactness and light weight is required. In scooters, ships, motor cycles, air crafts, etc.	Used where efficiency is important. In cars, buses, trucks, industrial engines, power generators, etc.

COMBUSTION

Introduction

- Combustion is a chemical reaction in which certain elements of the fuel like hydrogen and carbon combine with oxygen liberating heat energy and causing an increase in temperature of the gases.

- The conditions necessary for combustion are the presence of
    - combustible mixture (Fuel +oxidizer)
    - some means of initiating the process

- Depending on the type of engines, process of combustion generally takes place either in
    - a homogeneous or
    - a heterogeneous fuel vapor-air mixture

Homogeneous Mixture

- In spark-ignition engines homogeneous mixture of air and fuel is formed in the (Carburettor, PFI and DFI) then combustion is initiated at the end of compression stroke.

- Once the fuel vapor-air mixture is ignited, a flame front appears and rapidly spreads through the mixture

- The flame propagation is caused by heat transfer and diffusion of burning fuel molecules from the combustion zone to the adjacent layers of fresh mixture

- The velocity at 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,

- In a SI engine working with gasoline/petrol, the maximum flame speed is obtained when Φ is between 1.1 and 1.2, i.e., when the mixture is slightly richer than stoichiometric.

- If the equivalence ratio is outside this range the flame speed drops rapidly to a low value and ceases to propagate

- Introducing turbulence and incorporating proper mixture movement can increase flame speed in a mixture outside the above range.

- Combustion in the SI engine can be classified as Normal Combustion and Abnormal Combustion

Stages of Combustion in SI Engine

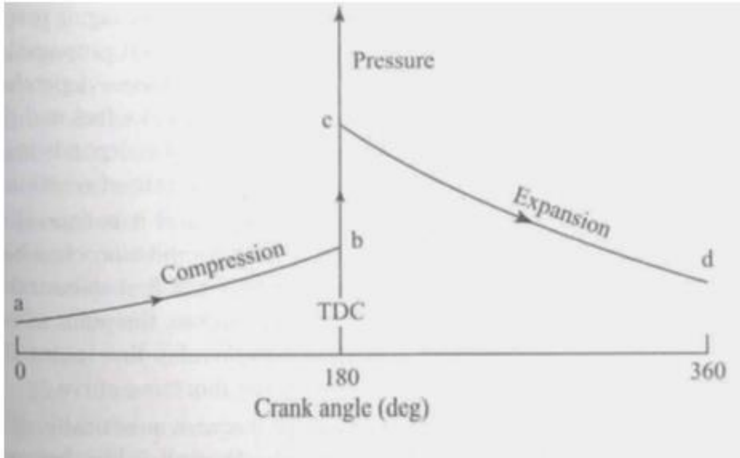


Fig. 12.1 Theoretical p-θ Diagram

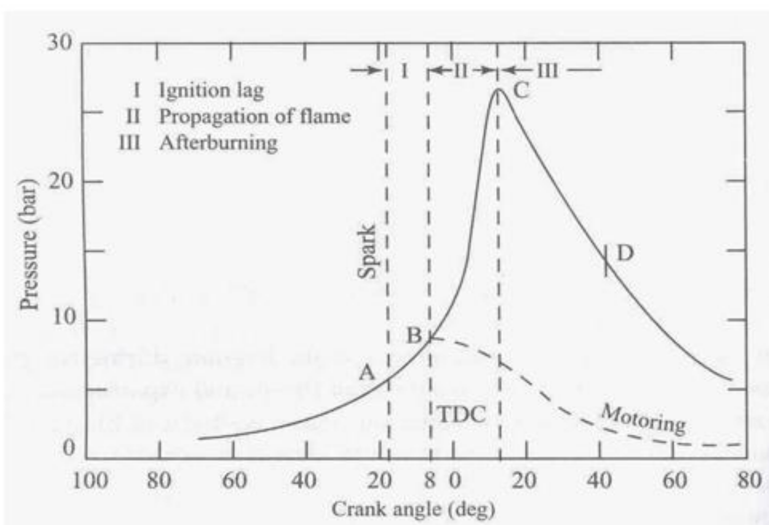
From the theoretical pressure-crank angle diagram

- a-b Compression process
- b-c Combustion process
- c-d Expansion process

The entire pressure rise during combustion takes place at constant volume,

In actual engines this does not happen. Actual SI engine combustion process consists of three stages.

The 3 stages Actual engine combustion process



- Point A is the point of spark initiation (say 20º bTDC)
- Point B is the point at which the beginning of pressure rise can be detected (say 8º bTDC)
- Point C the attainment of peak pressure.

AB-First stage (Delay Period)
BC-Second stage (flame Propagation)
CD-Third stage (after burning)

The First Stage (A-B) (Delay Period)

- The first stage is referred to as the ignition lag or preparation phase in which growth and development of a self-propagating nucleus of flame takes place

- This process is a chemical process depending upon
  - both temperature and pressure,
  - the nature of the fuel and
  - the proportion of the exhaust residual gas.
  - the relationship between the temperature and the rate of reaction.

The second stage (B-C) (flame Propagation)

- The second stage is a physical one and it is concerned with the spread of the flame throughout the combustion chamber.

- The starting point of the second stage is where the first measurable rise of pressure is seen on the indicator diagram i.e., the point where the line of combustion departs from the compression line (point B).

- During the second stage the flame propagates practically at a constant velocity.

- Heat transfer to the cylinder wall is low, because only a small part of the burning mixture comes in contact with the cylinder wall during this period.

- The rate of heat-release depends largely on
  - the turbulence intensity and
  - the reaction rate which is dependent on the mixture composition

- The rate of pressure rise is proportional to the rate of heat-release because during this stage, the combustion chamber volume remains practically constant

The Third Stage c-d (after burning)

- The third stage starts at instant at which the maximum pressure is reached on the indicator diagram (point C).

- The flame velocity decreases during this stage.

- The rate of combustion becomes low due to lower flame velocity and reduced flame front surface.

- The expansion stroke starts before this stage of combustion, with the piston moving away from the top dead centre, there can be no pressure rise during this stage.

Factors Influencing the Flame Speed

The most important factors which affect the flame speed are the turbulence, the fuel-air ratio, temperature and pressure, compression ratio, engine output and engine speed

I.Turbulence

- Flame speed is quite low in non-turbulent mixtures and increases with increasing turbulence

- Design of the combustion chamber which involves the geometry of cylinder head and piston crown increases the turbulence during the compression stroke.

- Turbulence increases the heat flow to the cylinder wall. It also accelerates the chemical reaction by increasing the rate of contact of burning and unburned particles.

- The increase of flame speed due to turbulence reduces the combustion duration and hence minimizes the tendency of abnormal combustion.

- However, excessive turbulence may extinguish the flame resulting in rough and noisy operation of the Engine.

II. Fuel-Air Ratio

- The fuel-air ratio has a very significant influence on the flame speed
- The highest flame velocities (minimum time for complete combustion) are obtained with somewhat richer mixture (point A)
    - When the mixture is made leaner or richer from point A, 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 results again in the release of less thermal energy

III. Temperature and Pressure

- Flame speed increases with an increase in intake temperature and pressure.

- A higher initial pressure and temperature may help to form a better homogeneous air-vapours mixture which helps in increasing the flame speed.

- This is possible because of an overall increase in the density of the charge.

IV. Compression Ratio

- A higher compression ratio increases the pressure and temperature of the working mixture which reduce the initial preparation phase of combustion and hence less ignition advance is needed.
- Increased compression ratio reduces the clearance volume and therefore increases the density of the cylinder gases during burning.

- Increasing the density increases the peak pressure and temperature and the total combustion duration is reduced.
- Thus, engines having higher compression ratios have higher flame speeds.

V. Engine Output

- With the increased throttle opening the cylinder gets filled to a higher density. The cycle pressure increases when the engine output is increased.
- When the output is decreased by throttling, the initial and final compression pressures decrease and the dilution of the working mixture increases.
- The smooth development of self-propagating nucleus of flame becomes unsteady and difficult.
- The main disadvantages of SI engines are the poor combustion at low loads and the necessity of mixture enrichment (Ø> between 1.2 to 1.3) which causes wastage of fuel and discharge of unburnt hydrocarbon and the products of incomplete combustion like carbon monoxide etc. in the atmosphere.

VI. Engine Speed

- The flame speed increases almost linearly with engine speed since the increase in engine speed increases the turbulence inside the cylinder.

- The time required for the flame to traverse the combustion space would be halved, if the engine speed is doubled.

ABNORMAL COMBUSTION

KNOCK AND SURFACE-IGNITION

The two major abnormal combustion processes which are important in practice, are knock and surface-ignition.

These abnormal combustion phenomena are of concern because:

1) when severe, they can cause major engine damage; and

2) Even if not severe, they are regarded as an objectionable source of noise by the engine or vehicle operator.

TYPES

- Knock is the name given to the noise which is transmitted through the engine structure when essentially spontaneous ignition of a portion of the end gas - the fuel, air, residual gas, mixture ahead of the propagating flame occurs.

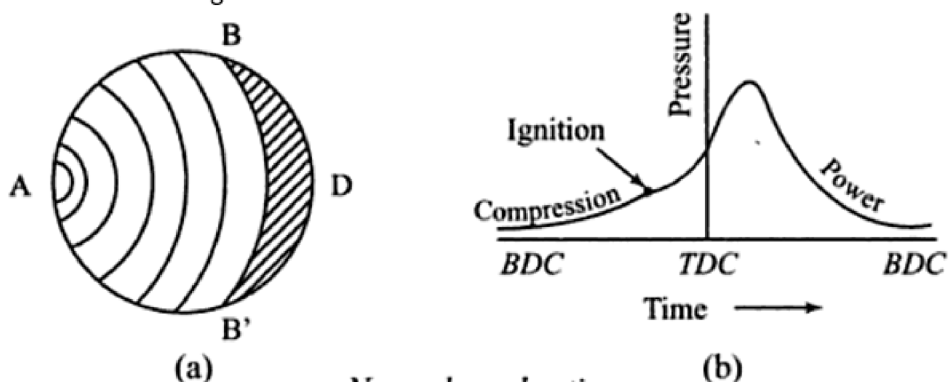
  - There is an extremely rapid release of most of the chemical energy in the end-gas, causing very high local pressures and the propagation of pressure waves of substantial amplitude across the combustion chamber.

- Surface Ignition is ignition of the fuel-air mixture by a hot spot on the combustion chamber walls such as an overheated valve or spark plug, or glowing combustion-chamber deposit: i.e., by any means other than the normal spark discharge.

- Following surface ignition, a flame develops at each surface-ignition location and starts to propagate across the chamber in an analogous manner to what occurs with normal spark-ignition.

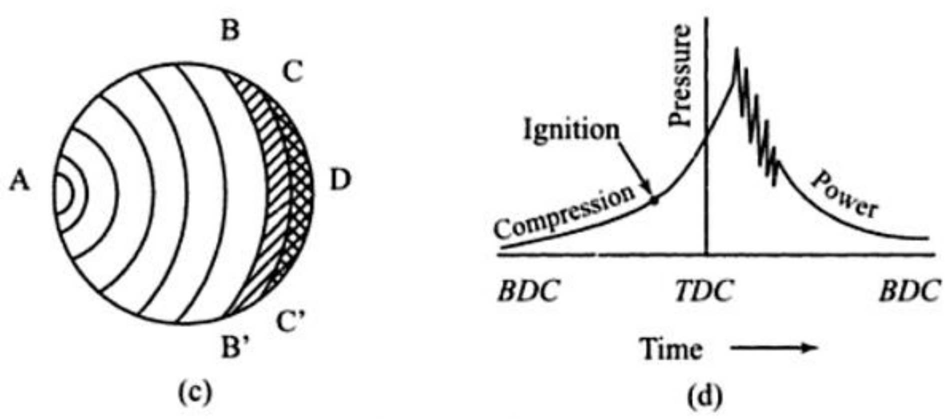
KNOCKING IN SI ENGINES

- Heat-release due to combustion in SI engines, increases the temperature and 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
- If the temperature of the unburnt mixture exceeds the self-ignition temperature of the fuel spontaneous ignition or auto-ignition occurs at various pin-point locations.
- The advancing flame front compresses the end charge BB'D farthest from the spark plug, thus raising its temperature.
- In spite of these factors if the temperature of the end charge had not reached its self-ignition temperature, the charge would not auto ignite and the flame will advance further and consume the charge BB'D.



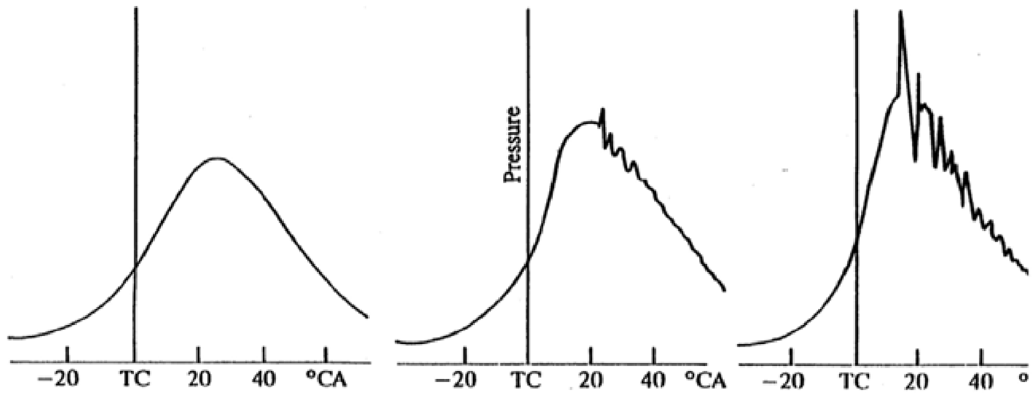
Normal combustion

- However, if the end charge BB'D reaches its auto ignition temperature the charge will auto ignite, leading to knocking combustion.
- it is assumed that when flame has reached the position BB', the charge ahead of it has reached critical auto-ignition temperature.



Combustion with detonation

- Pressure variation in the cylinder during knocking combustion for normal combustion, light knock and heavy knock, respectively



- Because of the auto ignition, another flame front starts traveling in the opposite direction to the main flame front.

- When the two flame fronts collide, a severe pressure pulse is generated.

- The presence or absence of knocking in combustion is often judged from a distinctly audible sound.

- A scientific method to detect the phenomenon of knocking is to use a pressure transducer.

Combustion In CI. Engines

- Only air is compressed through a high compression ratio (14:1 to 24:1) raising its temperature and pressure to a high value.

- Fuel is injected into the cylinders late in compression stroke through one or more injectors into highly compressed air in the combustion chamber.

- Injection time is usually about 20° of crankshaft rotation, starting at about 15° bTDC and ending about 5° aTDC.

- Combustion in a CI engine is an unsteady process occurring simultaneously at many spots in a very non-homogeneous mixture at a rate controlled by fuel injection.

- In addition to the swirl and turbulence of the air, a high injection velocity is needed to spread the fuel throughout the cylinder and cause it to mix with the air.

- After injection the fuel must go through a series of events to assure the proper combustion process:

I. Atomization. Fuel drops break into very small droplets, the smaller the original drop size emitted by the injector, the quicker and more efficient will be this atomization process.

II. Vaporization. The small droplets of liquid fuel evaporate to vapor. This occurs very quickly due to the hot air temperatures created by the high compression of CI engines.

- High air temperature needed for this vaporization process requires a minimum compression ratio in CI engines of about 12:1

- About 90% of the fuel injected into the cylinder can be vaporized within 0.001 second after injection.

III. Mixing. After vaporization, the fuel vapor must mix with air to form a mixture within the AF range which is combustible.

- This mixing is formed because of the high fuel injection velocity added to the swirl and turbulence in the cylinder air

- Self-Ignition. At about 8° bTDC, 6-8° after the start of injection, the air-fuel mixture starts to self-ignite.

- Actual combustion is preceded by secondary reactions, including breakdown of large hydrocarbon molecules into smaller species and some oxidation.

- These reactions caused by the high-temperature air, are exothermic and further raise the air temperature in the immediate local vicinity. This finally leads to an actual sustained combustion process.

- Combustion. Combustion starts from self-ignition simultaneously at many locations in the slightly rich zone of the fuel jet

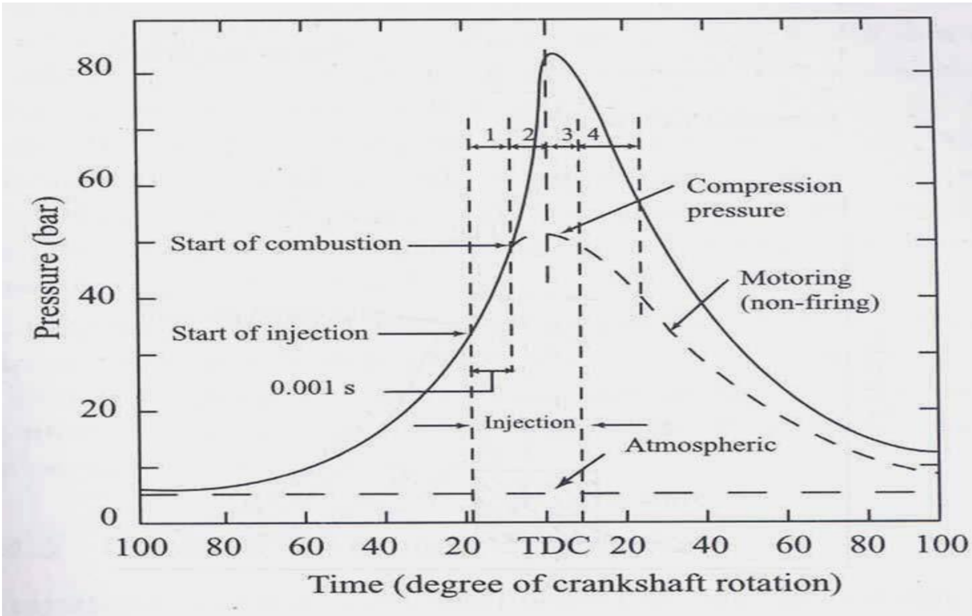
- When combustion starts, somewhere between 70% and 95% of the fuel in the combustion chamber is in the vapor state.

- When combustion starts, multiple flame fronts spreading from the many self-ignition sites quickly consume all the gas mixture which is in a correct combustible air-fuel ratio, even where self-ignition wouldn't occur.

STAGES OF COMBUSTION IN CI ENGINES

The combustion in a CI engine is considered to be taking place in four stages

- Ignition delay period
- Rapid combustion
- Controlled combustion and
- After-burning.

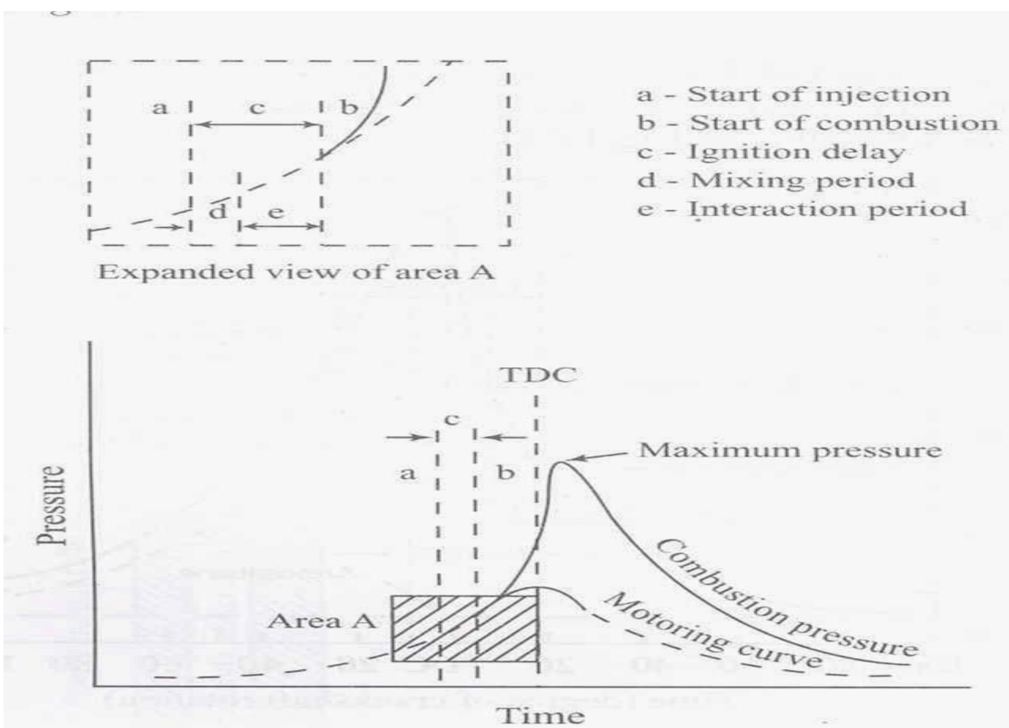


Ignition Delay Period

- Ignition delay (0.7-3ms) period is counted from the start of injection to the point where the pressure time curve separates from the compression curve indicated as start of combustion.

- The delay period in the CI engine influence both engine design and performance.

- It affects
  - combustion rate
  - knocking
  - engine starting ability
  - the presence of smoke in the exhaust.



• Point a - represents the time of injection

• Point b - represents the time at which the pressure curve (caused by combustion) first separates from the compression process

• The ignition delay period can be divided into two parts,

1. Physical delay
2. Chemical delay.

Physical 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.

The physical delay depends on

- The type of fuel,
  - for light fuel the physical delay is small
  - for heavy viscous fuels the physical delay is high.
- Injection Pressure
  - The physical delay is greatly reduced by using high injection pressures
- □ Combustion chamber temperatures and Turbulence to facilitate
  - breakup of the jet and
  - improving evaporation.

Chemical Delay:

- During the chemical delay, reactions start slowly and then accelerated ignition taking place.
- Generally, the chemical delay is larger than the physical delay.

Chemical delay depends on

- the temperature of the surroundings
- At high temperatures, the chemical reactions are faster
- In most CI engines the ignition lag is shorter than the duration of injection.

Factors Affecting the Delay Period

Many design and operating factors affect the delay period.

The important ones are:

- Cetene number
- Ignition timing
- Compression ratio
- Engine speed
- Output
- Atomization of fuel and duration of injection

- Quality of the fuel
- Intake temperature
- Intake pressure

Period of Rapid Combustion

• The period of rapid combustion also called the uncontrolled combustion, is that phase in which the pressure rise is rapid.

• The period of rapid combustion is counted from the beginning of the combustion to the point of maximum pressure on the indicator diagram.

Period of Controlled Combustion

• The temperature and pressure in the second stage are already quite 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.

Period of After-Burning

• After the injection procedure is finished, combustion continues.

• 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 process continues for a certain duration called the after-burning period.

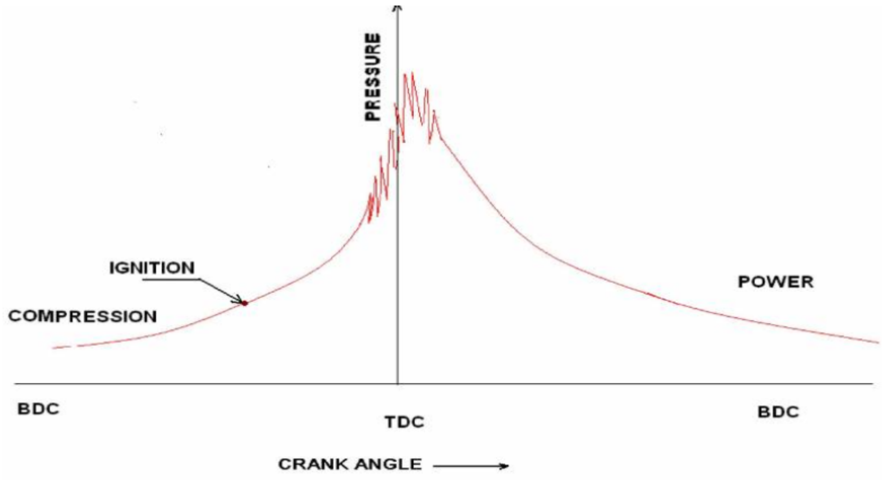
• Typically, this phase lasts for a portion of the expansion stroke and begins at the maximum cycle temperature.

• The afterburning phase duration may be correlated with crank travel angles of 70–80 degrees from TDC.

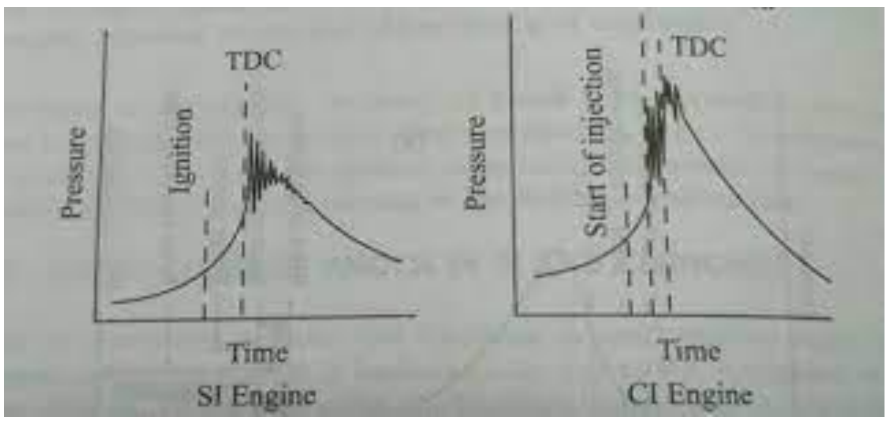
KNOCK IN CI ENGINES

If 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 a rate of pressure rise as shown resulting in a jamming of forces against the piston and rough engine operation



COMPARISON OF KNOCK IN SI AND CI ENGINES



Engine knock phenomenon in the CI engine is similar to that in the SI engine.

- In SI engine,
  - knocking occurs near the end of combustion
- In CI engine,
  - knocking occurs near the beginning of combustion.
- In order to decrease the tendency of knock
  - 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 start.