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 (Carburetor, 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 mixtures outside the above range.
- *Combustion in the SI engine can be classified as Normal Combustion and Abnormal Combustion*

Stages of Combustion in SI Engine

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.

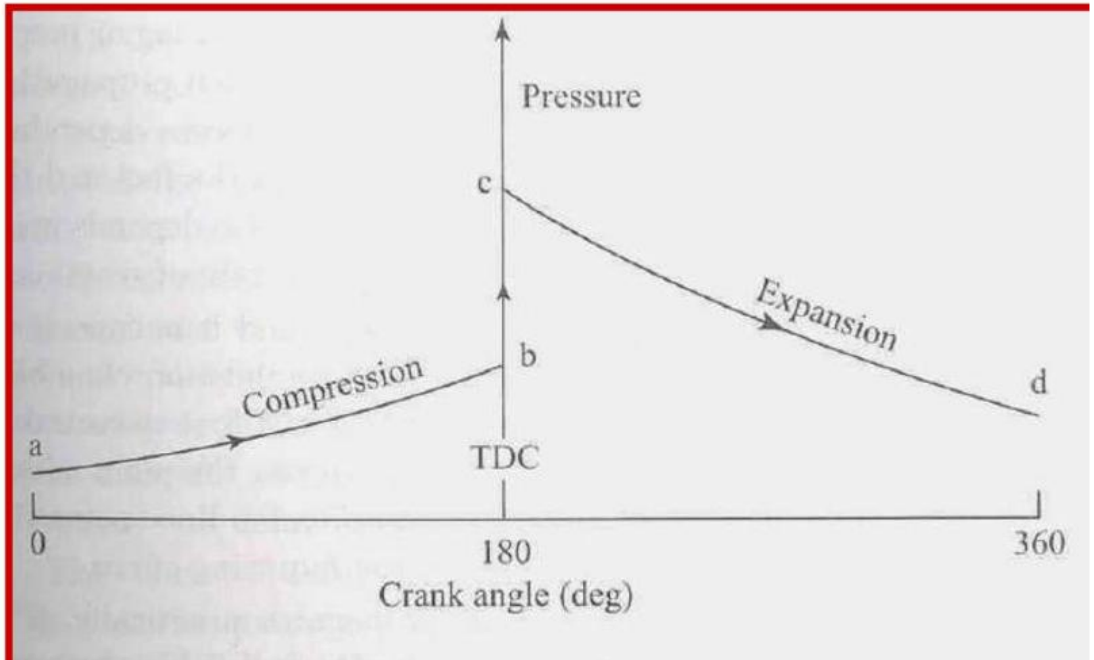


Fig. 12.1 Theoretical p-θ Diagram

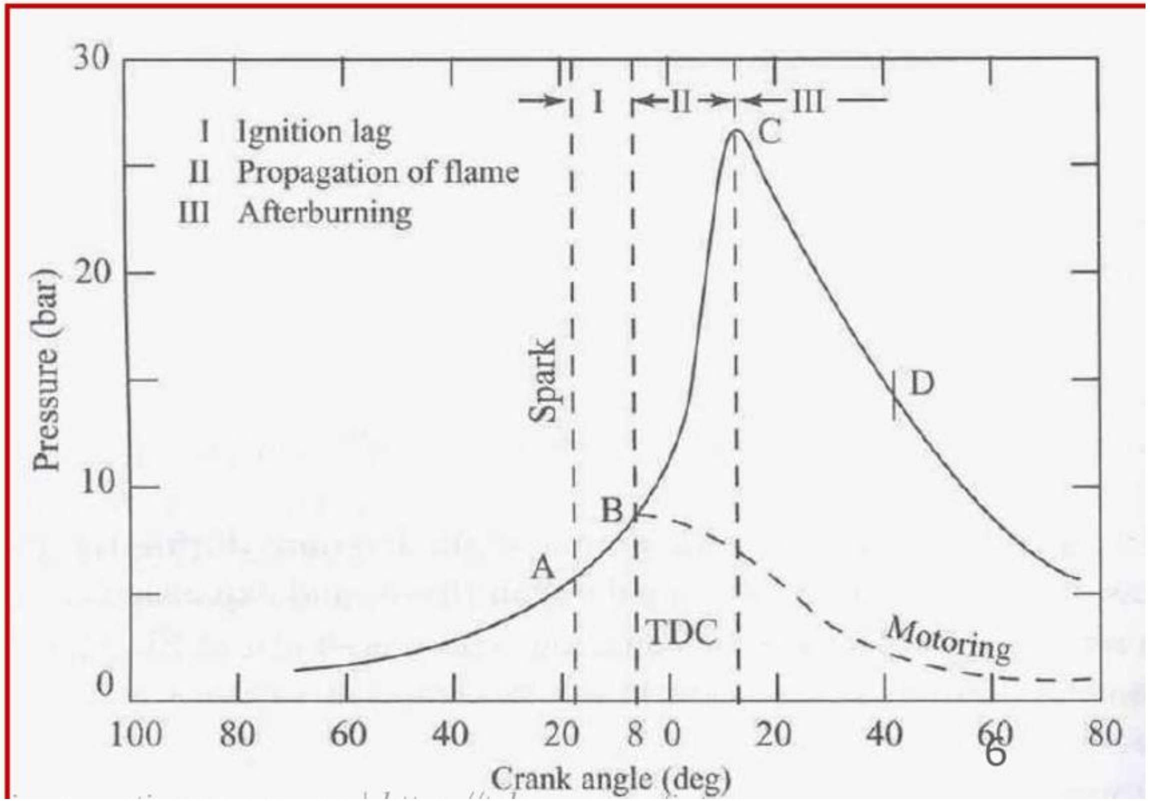
The 3 stages Actual engine combustion process

- *Point A is the point of spark initiation* (*say* 20^0*bTDC*)
- *Point B is the point at which the beginning of pressure rise can be detected* (*say* 8^0 *bTDC*)
- *Point C the attainment of peak pressure.*

AB-First stage (Delay Period)

BC-Second stage (flame Propagation)

CD -Third stage (wall Quenching)



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 second stage (B-C) (flame Propagation)

- 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 (Wall Quenching)

- 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.*

Flame Front Propagation

The two important factors which determine *the rate of movement of the flame front* across *the combustion chamber* are:

- **Reaction rate:** is the result of a *purely chemical combustion process in which the flame eats its way into the unburned charge*

- **Transposition rate:** is due to *the physical movement of the flame front relative to the cylinder wall* and is also *the result of pressure differential between the burning gases and the unburnt gases* in the combustion chamber.

Flame Front Propagation

A-B

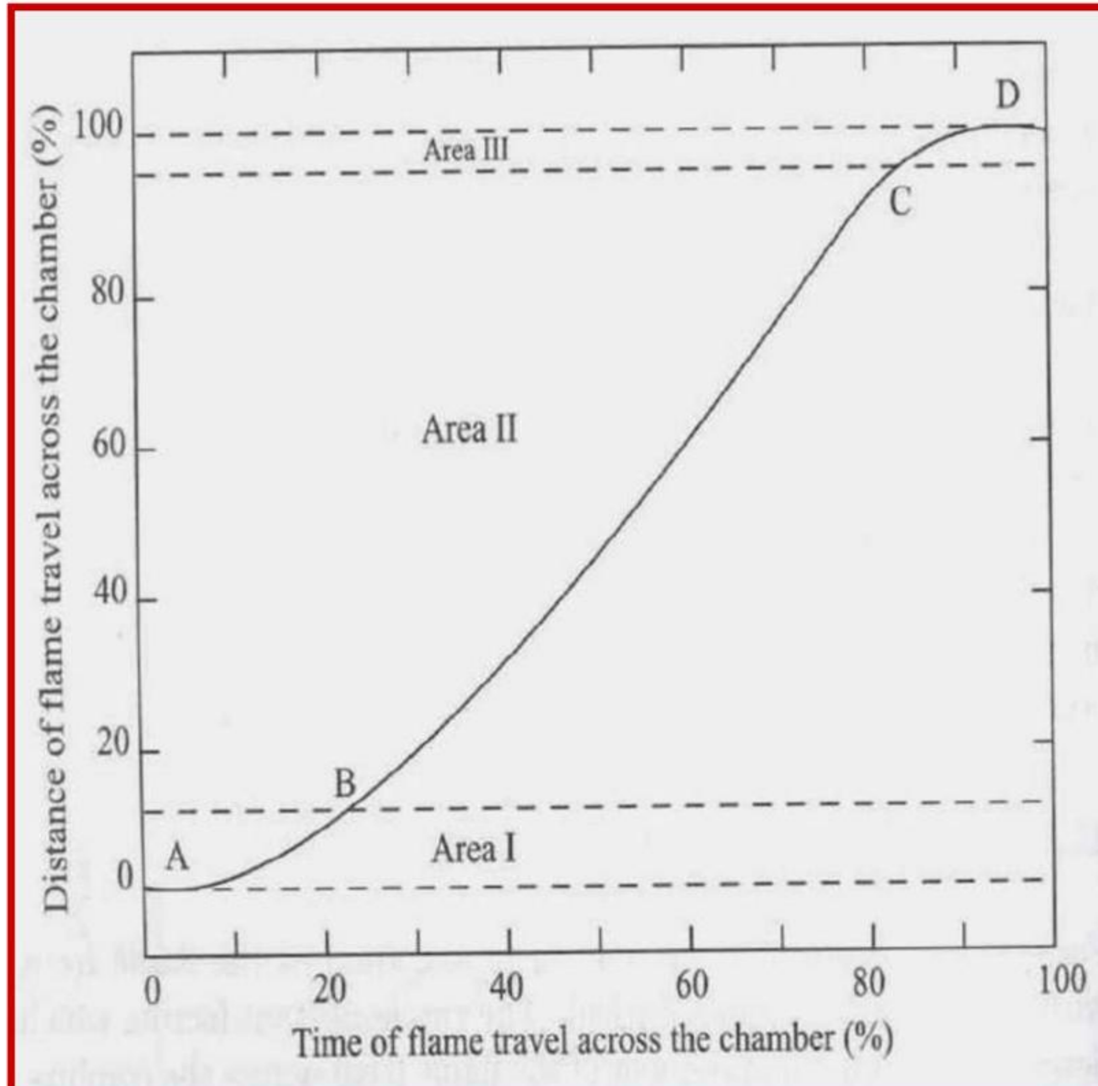
- low transposition rate
- low reaction rate

B-C

- Increased Flame propagation
- high transposition rate
- High reaction rate

C-D

- low transposition rate
- low reaction rate



Area I-(A-B)

- The flame front progresses relatively slowly due to a low transposition rate. Comparatively small mass of charge burned at the start.

- The low reaction rate plays a dominant role resulting in a slow advance of the flame.

- The lack of turbulence reduces the reaction rate and hence the flame speed.

Area II (B-C)

- As the *flame front leaves the quiescent zone and proceeds into more turbulent areas* (area II) where it consumes a greater mass of mixture, it *progresses more rapidly and at a constant rate (B-C)*

Area III (C-D)

- The *volume of unburned charge is very less towards the end of flame travel* and so *the transposition rate again becomes negligible thereby reducing the flame speed.*

- The *reaction rate is also reduced again* since *the flame is entering a zone of relatively low turbulence (C-D)*

Other 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.*

I. Turbulence

- *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

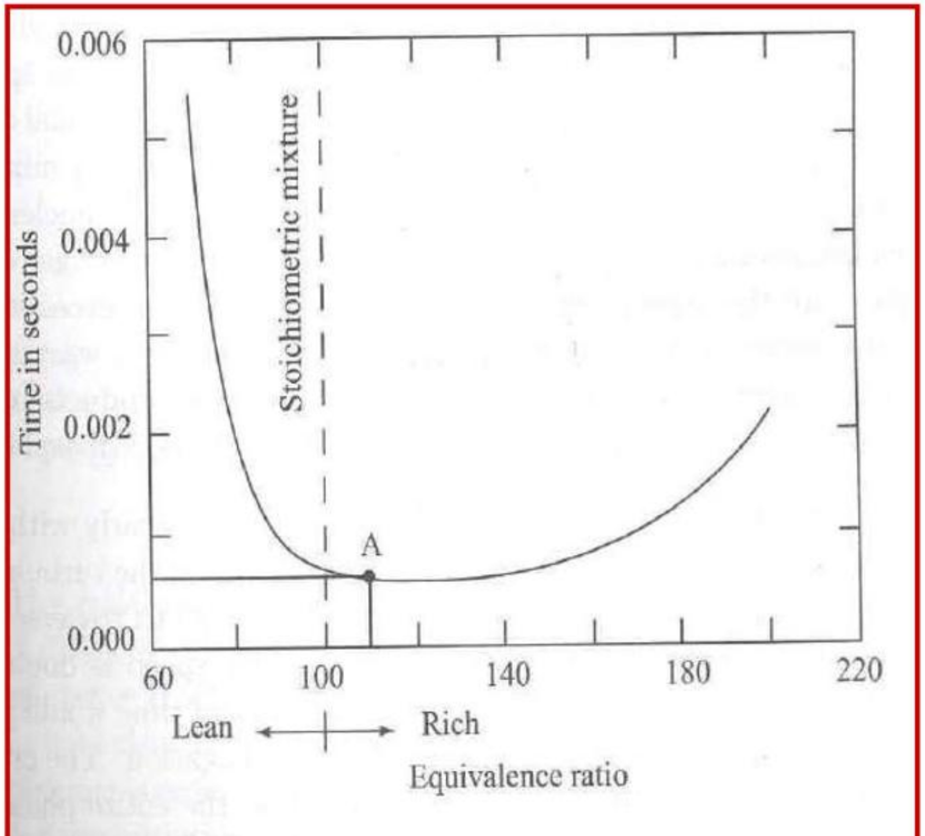


Fig. 12.4 Effect of Mixture Strength on the Rate of Burning

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-vapors 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.

RATE OF PRESSURE RISE

- The ***rate of pressure rise in an engine combustion chamber*** exerts a considerable influence on
  - ***The peak pressure developed,***
  - ***The power produced and***
  - ***The smoothness with which the forces are transmitted to the piston.***
- The ***rate of pressure rise*** is mainly dependent upon the ***rate of combustion of mixture*** in the cylinder.

RATE OF PRESSURE RISE

Curve I is for a high, **curve II** for the normal and **curve III** for a low rate of combustion.

- With *lower rate of combustion longer time is required to complete the combustion* which necessitates *the initiation of burning at an early point on the compression stroke.*

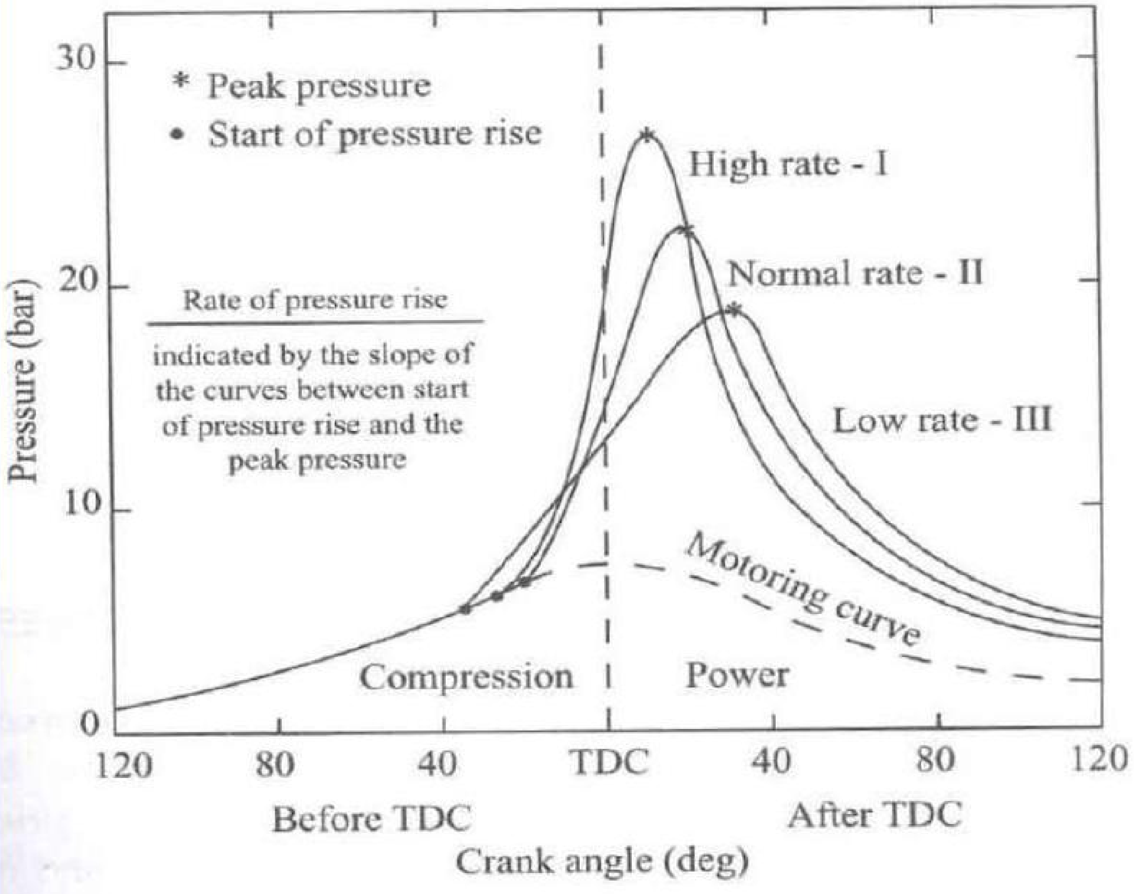


Fig. 12.5 Illustrations of Various Combustion Rates

RATE OF PRESSURE RISE

- *Higher rate of combustion* results in *higher rate of pressure rise* producing *higher peak pressures at a point closer to TDC.*

- *Higher peak pressures closer to TDC produce a greater force acting through a large part of the power stroke* and hence, *increase the power output of the engine*.

- The *higher rate of pressure rise causes rough running of the engine* because of *vibrations produced in the crankshaft rotation.*

RATE OF PRESSURE RISE

- It also tends to *promote an undesirable occurrence known as knocking.*

- A *compromise between these opposing factors* is accomplished by designing and operating the engine in such a manner that *approximately one-half of the maximum pressure is reached by the time the piston reaches TDC.*

- This results in *the peak pressure being reasonably close to the beginning of the power stroke*, yet *maintaining smooth engine operation.*

ABNORMAL COMBUSTION

- KNOCK AND SURFACE-IGNITION

- Abnormal combustion reveals itself in many ways. 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.

Description: Abnormal combustion

- 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.

causes for end gas combustion

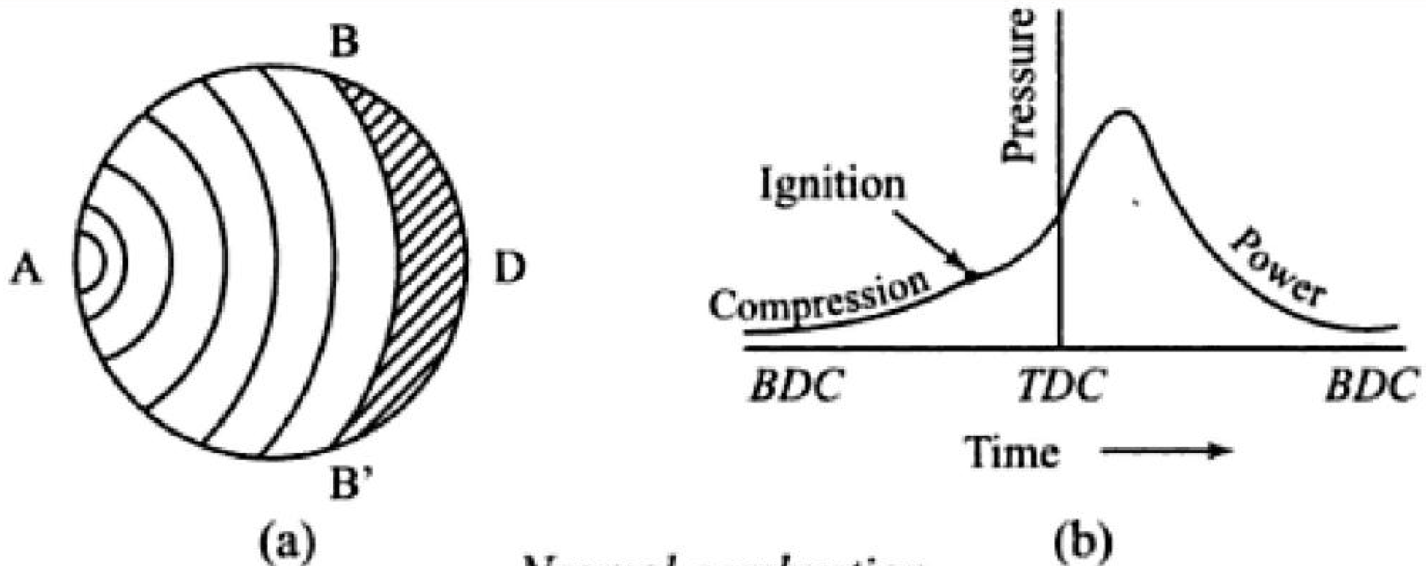
- *Heat-release due to combustion in SI engines, increases the temperature and the pressure,* **of** *the burned part of the mixture above those of the unburned mixture*

- 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*.

causes for end gas combustion

- The advancing flame *front* compresses *the end charge BB'D* farthest from the spark plug, thus raising its temperature.

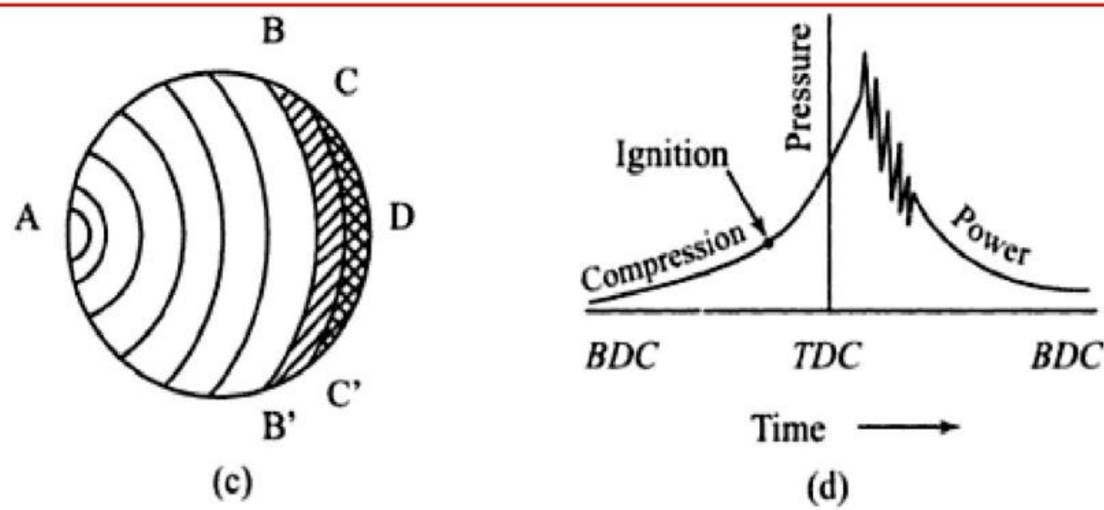


Normal combustion

- 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.

Knock In SI Engines

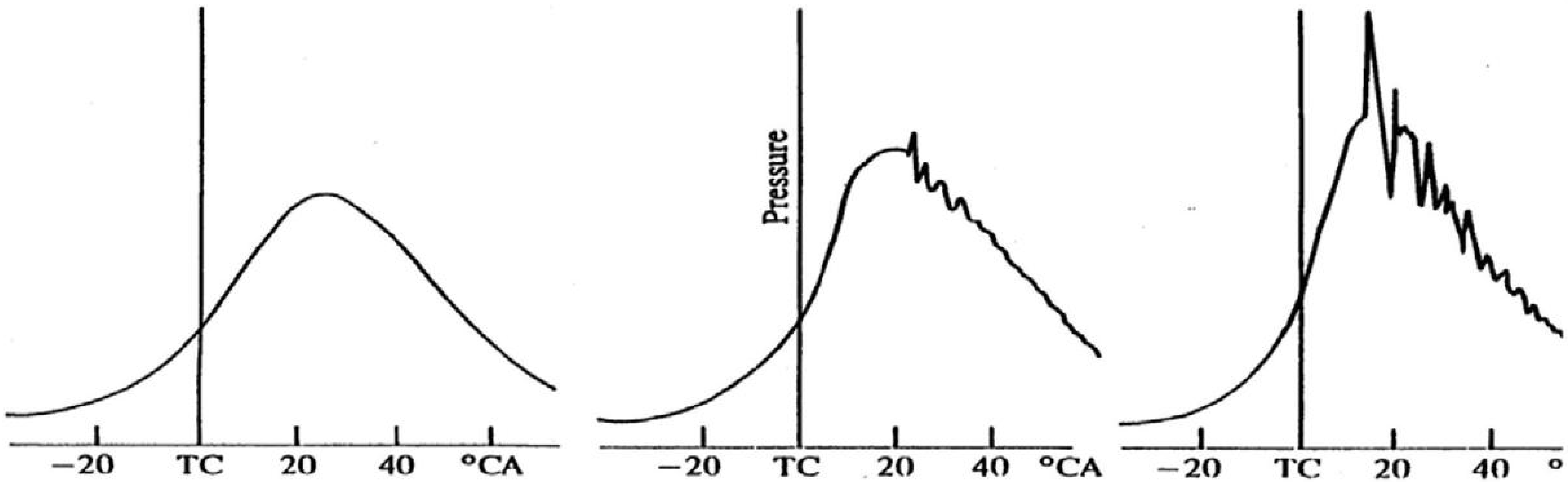
- However, *if the end charge BB'D reaches its auto ignition temperature the charge will auto ignite, leading to knocking combustion.*
- it is assumed that when flame has reached the position BB', *the charge ahead of it has reached critical auto-ignition temperature.*

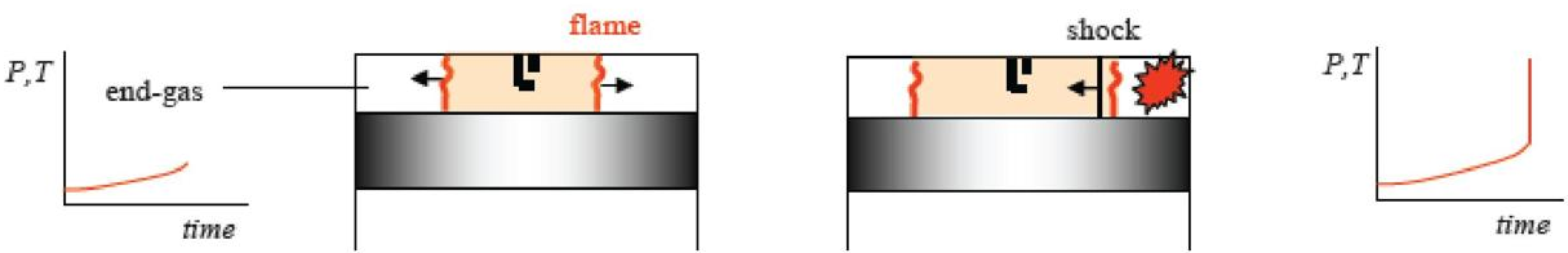


Combustion with detonation

Knock in SI Engines

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





Knock In SI Engines

- *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.*

Knock In SI Engines

- knocking is very much dependent on the properties of fuel.
- If the unburned charge does not reach its auto ignition temperature there will be no knocking.
- If the ignition delay period is longer the time required for the flame front to burn through the unburned charge will be short, then there will be no knocking.
- Hence, in order to avoid or inhibit detonation, and a high auto ignition temperature, a long ignition delay are the desirable qualities for SI engine fuels.

Effect of Engine Variables on Knock

- **Effect of temperature**
  - Reduced temperature of the unburned charge reduce the possibility of knocking by reducing the temperature of the end charge for auto ignition.

- **Effect of Compression Ratio**
  - Increase in compression ratio increases the pressure and temperature of the gases at the end of the compression stroke, increases the tendency for knocking.

Effect of Engine Variables on Knock

- ***Effect of density***
  - *Reduction in density of the charge tends to reduce knocking by providing lower energy release.*
  - *The overall increase in the density of the charge due to higher compression ratio* increases *the pre-flame reactions in the end charge* thereby *increasing the knocking tendency of the engine.*

Inlet Temperature of the Mixture:

- *Increase in the inlet temperature of the mixture* makes *the compression temperature higher thereby, increasing the tendency of knocking.*
- *Further, volumetric efficiency will be lowered.* Hence, *a lower inlet temperature is always preferable to reduce knocking.*

Effect of Engine Variables on Knock

- **Mass of inducted charge**
  - A *reduction in the mass* of the inducted charge into the cylinder by throttling or reducing the amount of supercharging *reduces both temperature and density of the charge* at the time of ignition .*This decreases the tendency of knocking .*
- ***Temperature of the Combustion Chamber Walls***
  - *To prevent knocking the hot spots in the combustion chamber should be avoided.*
  - Since, *the spark plug and exhaust valve are two hottest parts in the combustion chamber, the end gas should not be compressed against them*

Effect of Engine Variables on Knock

Retarding the Spark Timing:

- Retarding the spark timing from the optimized timing, i.e., having the spark closer to TDC, the peak pressures are reached farther down on the power stroke and are thus of lower magnitude.
- This might reduce the knocking. However, the spark timing will be different from the MBT timing affecting the brake torque and power output of the engine.

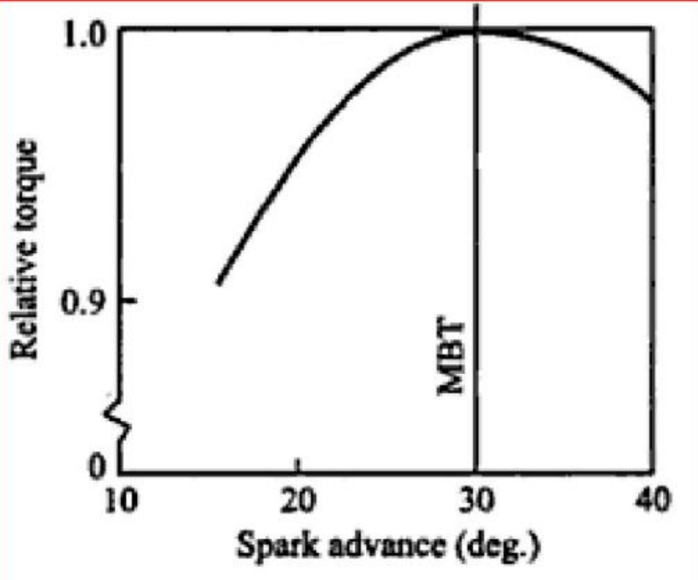


Figure 6.7 Effect of spark advance on brake torque.

Effect of Engine Variables on Knock

Power Output of the Engine

- A *decrease in the output of the engine* decreases the temperature of the cylinder and the combustion chamber walls and *also the pressure of the charge* thereby *lowering mixture and end gas temperatures. This reduces the tendency to knock.*

Turbulence

- *Turbulence depends* on *the design of the combustion chamber* and on *engine speed.*
- *Increasing turbulence increases the flame speed and reduces the time available for the end charge to attain auto ignition* conditions thereby *decreasing the tendency to knock.*

Effect of Engine Variables on Knock

Engine Speed

- An *increase in engine speed increases the turbulence* of the mixture considerably *resulting in increased flame speed, and reduces the time available for pre-flame reactions.* Hence *knocking tendency is reduced at higher speeds.*

Flame travel Distance

- The *knocking tendency is reduced by shortening the time required for the flame front to traverse the combustion chamber.*
- *Engine size, combustion chamber shape, and spark plug position* are the three important factors governing the flame travel distance

Effect of Engine Variables on Knock

Engine size

- The flame requires a longer time to travel across the combustion chamber of a larger engine.
- Therefore, a *larger engine has a greater tendency for knocking* than a smaller engine since there is more time for the end gas to auto ignite.
- *Hence, an SI engine is generally limited to size of about 150 mm bore.*

Combustion Chamber Shape

- Generally, *the more compact the combustion chamber is, the shorter is the flame travel and the combustion time and hence better antiknock characteristics.*

Effect of Engine Variables on Knock

- The combustion chambers are made as *spherical as possible to minimize the length of the flame travel for a given volume*.
- If *the turbulence in the combustion chamber is high*, *the combustion rate is high and consequently combustion time and knocking tendency are reduced.*
- Hence, *the combustion chamber is shaped in such a way as to promote turbulence.*

Location of Spark Plug

- *In order to have a minimum flame travel*, *the spark plug is centrally located* in the combustion chamber, *resulting in minimum knocking tendency.*
- The *flame travel can also be reduced by using two or more spark plugs* in case of large engines.

Composition Factors

Fuel-Air Ratio:

- The flame speeds are affected by fuel-air ratio. Also the flame temperature and reaction time are different for different fuel-air ratios.
- Maximum flame speed and temperature is obtained when *$\Phi \approx 1.1$-1.2.*

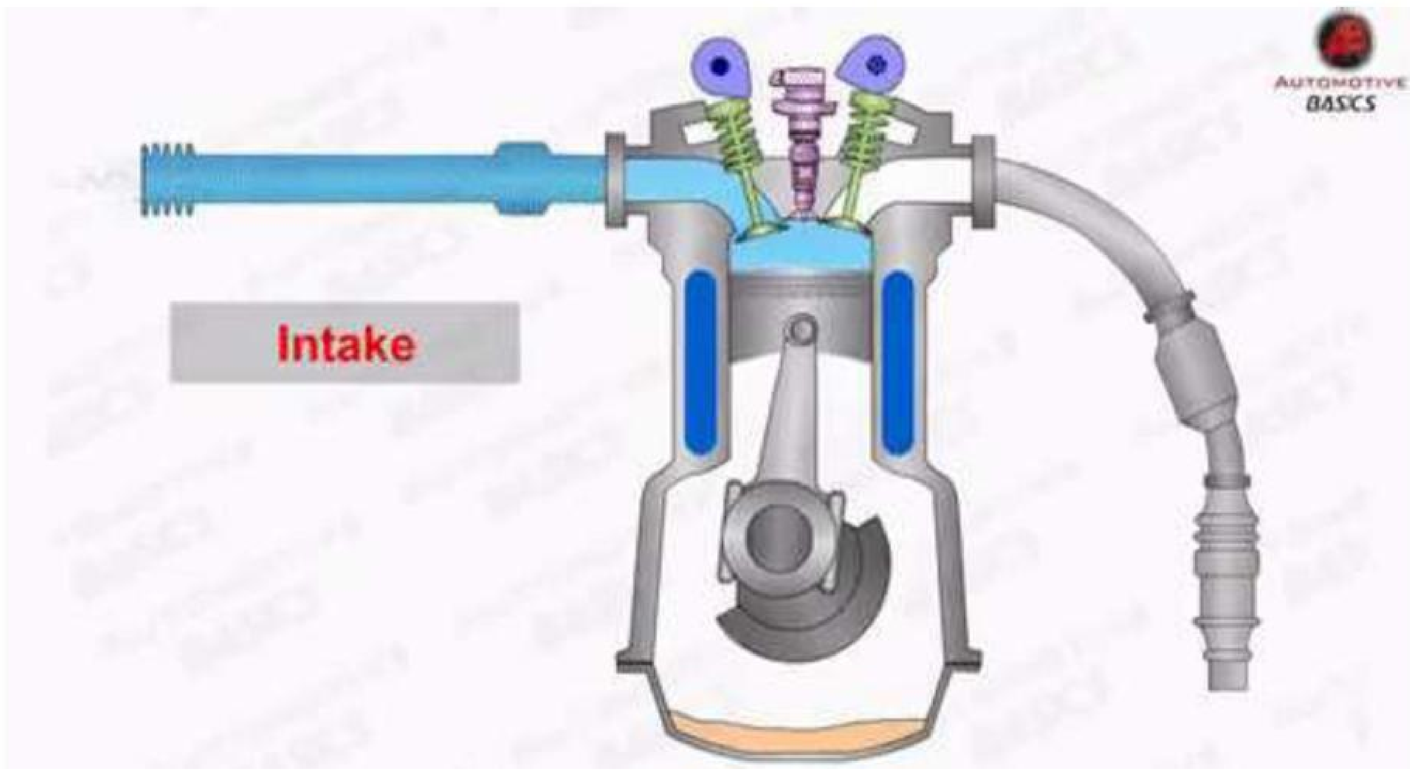
Octane Value of the Fuel

- *A higher self-ignition temperature of the fuel and a low pre-flame reactivity would reduce the tendency of knocking.*
- In general, *Paraffin series of hydrocarbon have the maximum and aromatic series the minimum tendency to knock*. The naphthene series comes in between the two

Table 12.1 Summary of Variables Affecting Knock in an SI Engine

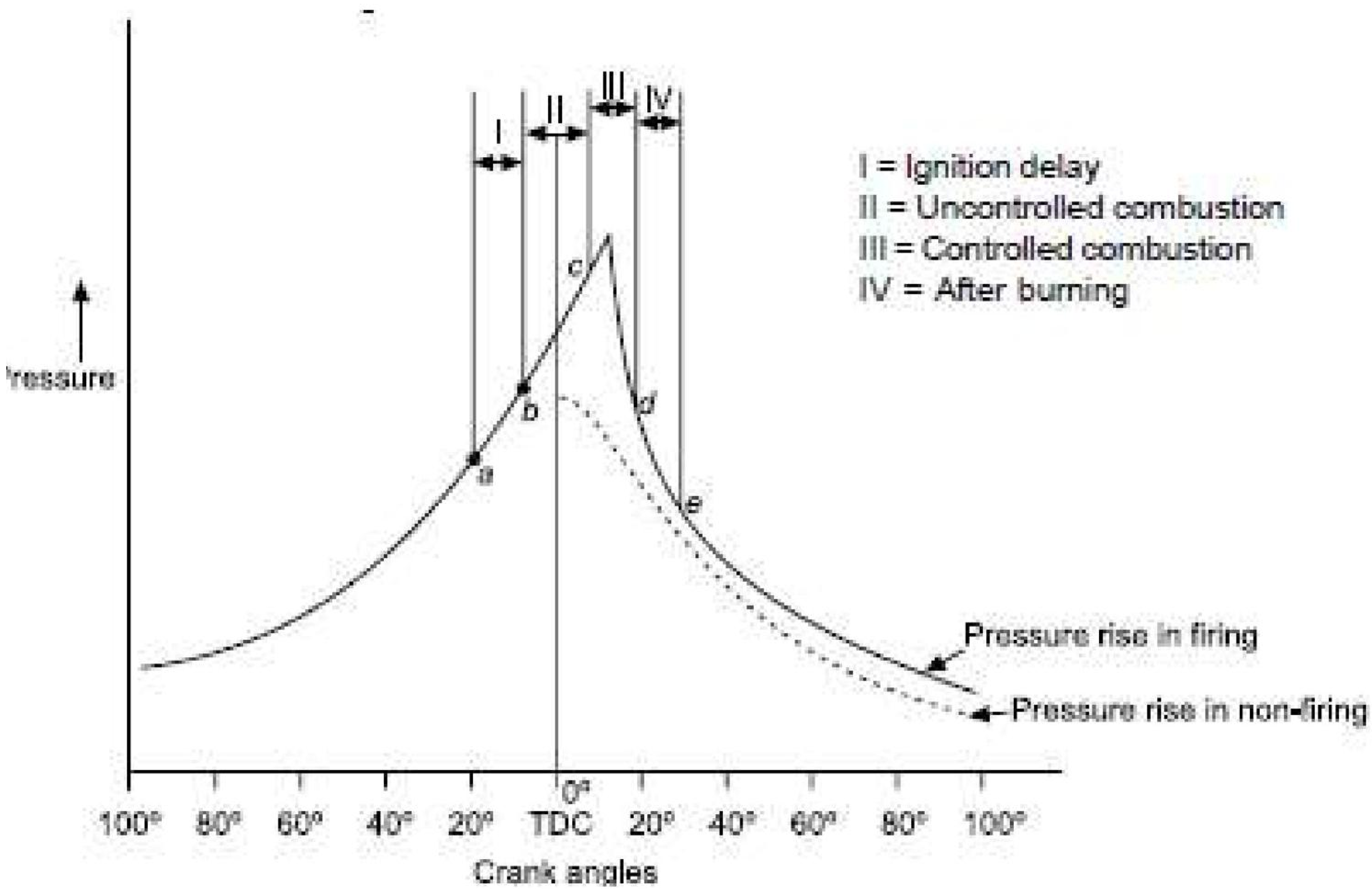
Increase in variable	Major effect on unburned reduce charge	Action to be taken to knocking	Can operator usually control?
Compression ratio	Increases temperature & pressure	Reduce	No
Mass of charge inducted	Increases pressure	Reduce	Yes
Inlet temperature	Increases temperature	Reduce	In some cases
Chamber wall temperature	Increases temperature	Reduce	Not ordinarily
Spark advance	Increases temperature & pressure	Retard	In some cases
A/F ratio	Increases temperature & pressure	Make very rich	In some cases
Turbulence	Decreases time factor	Increase	Somewhat (through engine speed)
Engine speed	Decreases time factor	Increase	Yes
Distance of flame travel	Increases time factor	Reduce	No

COMBUSTION PHENOMENON IN *COMPRESSION IGNITION* ENGINES



PARTICULARS	SI ENGINE (petrol)	CI ENGINE (diesel)
COMP. RATIO	8 TO 10	15 TO 20
A/F RATIO	8:1 to 10:1 (14.7 : 1)	15:1to 18:1 (70:1)
C.V	45.8 MJ/kg	45.5 MJ/kg
FLASH POINT	–43 °C	>52 °C
S.I.T	260°C	210°C
Comp. Temp	350°C	600°C to 700°C
Comp. Pr	20 bar	Depends on C.R.(C.R x 1 bar)
Comb. Temp	1000°C	2500°C
Comb. Pr	50 bar	100bar

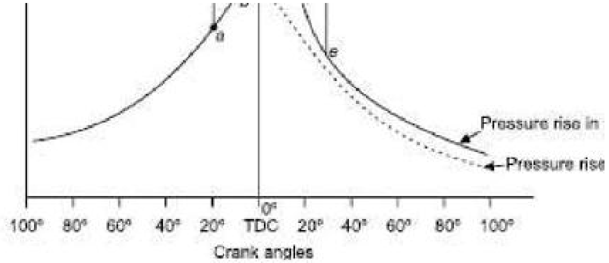
STAGES OF COMBUSTION IN CI ENGINES



Combustion in CI Engines

- Combustion in CI engines differ from SI engine due to the basic fact that CI engine combustion is unassisted combustion occurring on its' own.
- In CI engine the fuel is injected into combustion space after the compression of air is completed.
- Due to excessively high temperature and pressure of air the fuel when injected in atomised form gets burnt on its' own and burning of fuel is continued till the fuel is injected.
- Theoretically this injection of fuel and its' burning should occur simultaneously up to the cut-off point, but this does not occur in actual CI engine. Different significant phases of combustion are explained as under.

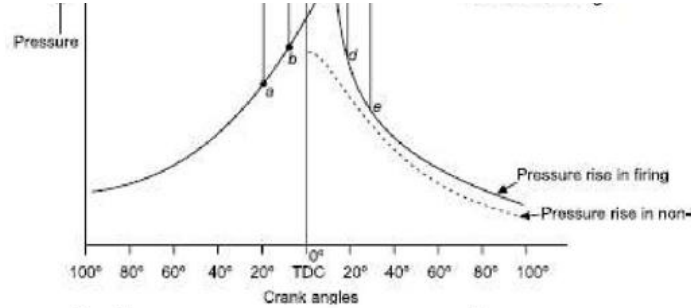
STAGES OF COMBUSTION IN CI ENGINES



(i) Ignition Delay Period

- Injection of fuel (atomized form) is initiated into the combustion space containing compressed air.
- Fuel upon injection does not get burnt immediately instead some time is required for preparation before start of combustion.
- Fuel droplet injected into high temperature air first gets transformed into vapour (gaseous form) and then gets enveloped around by suitable amount of oxygen present so as to form combustible mixture.
- Subsequently, if temperature inside is greater than self ignition temperature at respective pressure then ignition starts.

STAGES OF COMBUSTION IN CI ENGINES



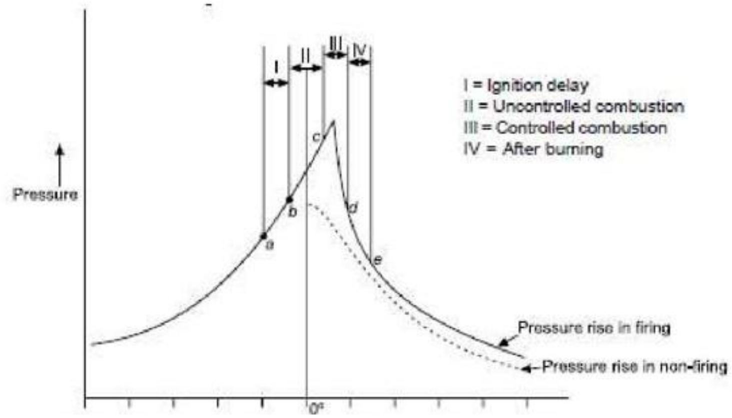
(i) Ignition Delay Period contd…

- Thus, the delay in start of ignition may be said to occur due to 'physical delay' i.e. time consumed in transformation from liquid droplet into gaseous form, and 'chemical delay' i.e. time consumed in preparation for setting up of chemical reaction (combustion).
- Ignition delay is inevitable stage and in order to accommodate it, the fuel injection is advanced by about 20° before TDC. Ignition delay is shown by *a – b in Fig., showing* pressure rise during combustion.
- Fuel injection begins at '*a*' *and ignition begins at 'b'*. *Theoretically, this* ignition delay should be as small as possible.

STAGES OF COMBUSTION IN CI ENGINES

(ii) Uncontrolled Combustion

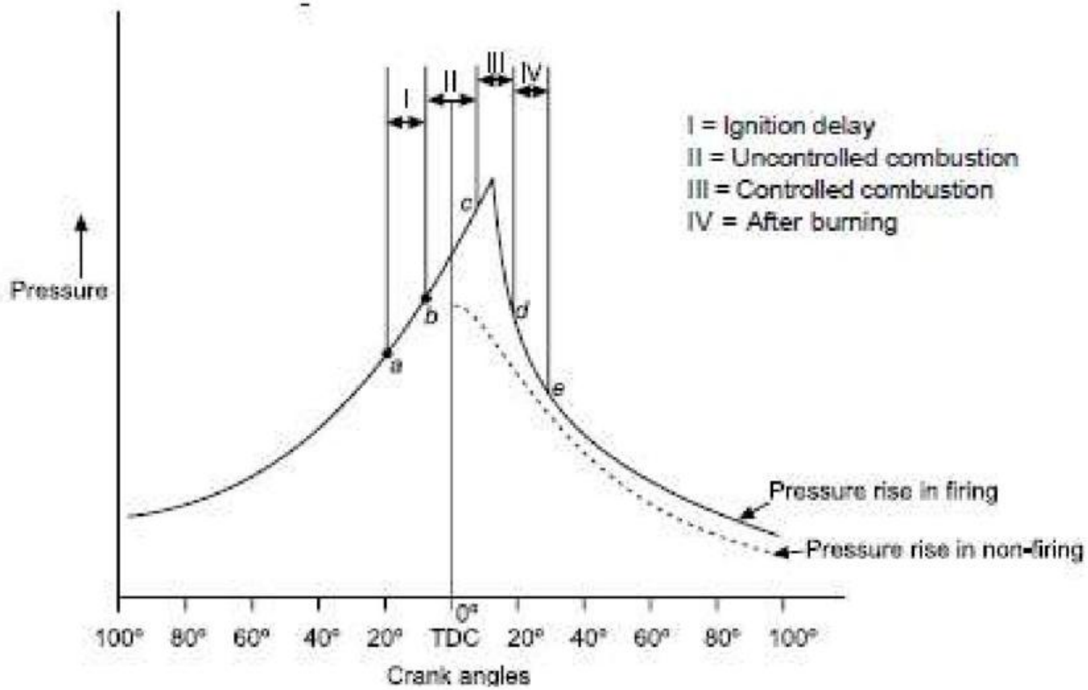
- During the ignition delay period the injection of fuel is continued as it has begun at point '*a*' and shall continue upto the point of cut-off.
- During this period, the continuous fuel injection results in accumulation of fuel in combustion space.
- The moment when ignition just begins means,if the sustainable flame front is established then this accumulated fuel also gets burnt rapidly.
- This burning of accumulated fuel occurs in such a manner that combustion process becomes uncontrolled resulting into steep pressure rise as shown from '*b*' to '*c*'.



STAGES OF COMBUSTION IN CI ENGINES

(ii) Uncontrolled Combustion contd..

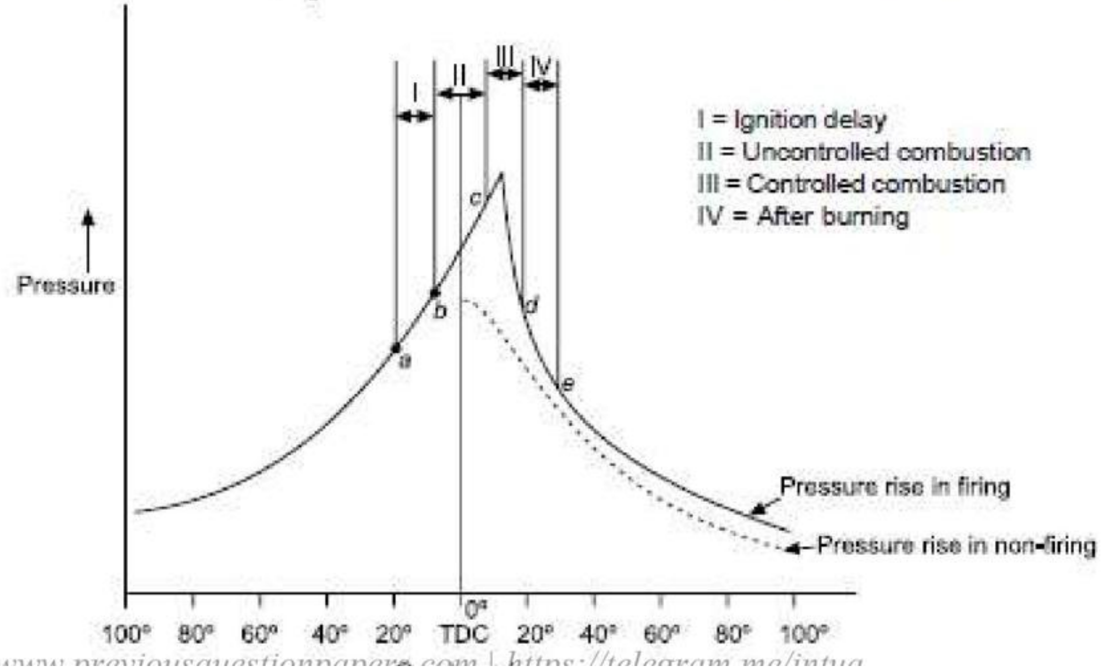
- *The uncontrolled burning* continues till the collected fuel gets burnt.
- During this 'uncontrolled combustion' phase if the pressure rise is very abrupt then combustion is termed as 'abnormal combustion' and may even lead to damage of engine parts in extreme conditions.



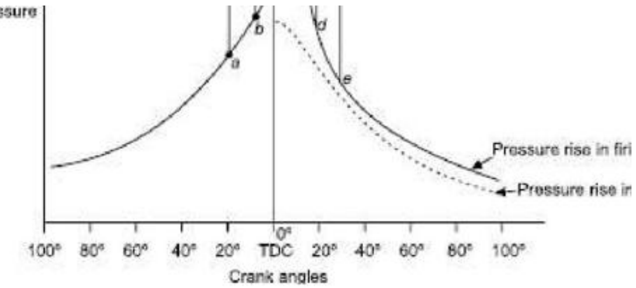
STAGES OF COMBUSTION IN CI ENGINES

(ii) Uncontrolled Combustion contd..

- 'Uncontrolled combustion' depends upon the 'ignition delay' period as during ignition delay itself the accumulation of un-burnt fuel occurs and its' burning results in steep pressure rise.
- Hence in order to have minimum uncontrolled combustion the ignition delay should be as small as possible.
- During this uncontrolled combustion phase about one-third of total fuel heat is released.



STAGES OF COMBUSTION IN CI ENGINES



(iii) Controlled Combustion

- After 'uncontrolled combustion' is over then the rate of burning matches with rate of fuel injection and the combustion is termed as '**controlled combustion**'.
- Controlled combustion is shown between 'c' *to 'd' and during this phase maximum of heat gets evolved in controlled manner.*
- *In controlled* combustion phase rate of combustion can be directly regulated by the rate of fuel injection i.e. through fuel injector.
- Controlled combustion phase has smooth pressure variation and maximum temperature is attained during this period.
- It is seen that about two-third of total fuel heat is released during this phase.

STAGES OF COMBUSTION IN CI ENGINES

(iv) After Burning

- After controlled combustion, the residual if any gets burnt and the combustion is termed as ‘after burning’.
- This after burning may be there due to fuel particles residing in remote position in combustion space where flame front could not reach.
- ‘After burning’ is spread over 60 – 70° of crank angle rotation and occurs even during expansion stroke.

FACTORS AFFECTING DELAY PERIOD IN CI ENGINES*

- Compression Ratio

  Increase in CR increases the temperature of air. Autoignition temperature decreases with increased density. Both these reduce the delay period(DP).

- Engine Power Output

  With an Increase in engine power, the operating temperature increases. A/F ratio decreases and DP decreases

- Engine Speed

  DP decreases with increasing engine speed, as the temperature and pressure of compressed air rises at high engine speeds.

- Injection Timing

  The temperature and pressure of air at the beginning of injection are lower for higher injection advance. The DP increases with increase in injection advance or longer injection timing. The optimum angle of injection is 20° BTDC

FACTORS AFFECTING DELAY PERIOD IN CI ENGINES*

- Atomization of fuel

  Higher fuel injection pressures increase the degree of atomization. The fineness of atomization reduces the DP due to higher A/V ratio of the spray droplets.

- Injection Pressure

  Increase injection pressure reduces the auto ignition temperature and hence decreases DP.

- Fuel Properties

  Low SIT reduces DP. Other fuel properties which affect DP are volatility, surface tension, latent heat and viscosity.

- Intake Temperature

  High intake temperature increase the air temperature after compression , which reduces DP.

FACTORS AFFECTING DELAY PERIOD IN CI ENGINES*

- Engine Size

  Large engines operate at lower speeds, thus increasing the DP in terms of crank angle.
- Cetane No.

  Fuels with high cetane no. Have lower DP.
- F/A ratio

  With increasing F/A ratio, operating temperature increases and thus DP decreases.
- Combustion Chamber Shape

  Engines with pre-combustion chambers will have low DP.
- Injection Duration

  Increase in injection duration, results in higher quantity of fuel injected which reduces DP.

23.33. DELAY PERIOD (OR IGNITION LAG) IN C.I. ENGINES

— In C.I. (compression ignition) engine, the fuel which is in atomised form is considerably colder than the hot compressed air in the cylinder. Although the actual ignition is almost instantaneous, an appreciable time elapses before the combustion is in full progress. This time occupied is called the *delay period* or *ignition lag. It is the time immediately following injection of the fuel during which the ignition process is being initiated and the pressure does not rise beyond the value it would have due to compression of air* :

— The delay period extends for about 13°, movement of the crank. The time for which it occurs decreases with increase in engine speed.

The *delay period depends upon the following :*

(*i*) Temperature and pressure in the cylinder at the time of injection.

(*ii*) Nature of the fuel mixture strength.

(*iii*) Relative velocity between the fuel injection and air turbulence.

(*iv*) Presence of residual gases.

(*v*) Rate of fuel injection.

(*vi*) To small extent the finess of the fuel spray.

The delay period increases with load but is not much affected by injection pressure.

— *The delay period should be as short as possible since a long delay period gives a more rapid rise in pressure and thus causes knocking.*

23.34. DIESEL KNOCK

If the delay period in C.I. engines is long a large amount of fuel will be injected and accumulated in the chamber. The auto-ignition of this large amount of fuel may cause high rate of pressure rise and high maximum pressure which may cause *knocking* in diesel engines. A long delay period not only increases the amount of fuel injected by the moment of ignition but also improves the homogeneity of the fuel-air mixture and its chemical preparedness for explosion type self-ignition similar to detonation is S.I. engines.

The following are the ***differences*** in *the knocking phenomena of the S.I. and C.I. engines* :

1. In the S.I. engine, the detonation occurs near the end of combustion whereas in the C.I. engine detonation occurs near the beginning of combustion.
2. The detonation in the S.I. engine is of a homogeneous charge causing very high rate of pressure rise and very high maximum pressure. In the C.I. engine, the fuel and air are imperfectly mixed and hence the rate of pressure rise is normally lower than that in the detonating part of the charge in the S.I. engine.
3. In the C.I. engine the fuel is injected into the cylinder only at the end of the compression stroke, there is no question of pre-ignition as in S.I. engine.
4. In the S.I. engine, it is relatively easy to distinguish between knocking and non-knocking operation as the human ear easily finds the distinction.

Air Compressor

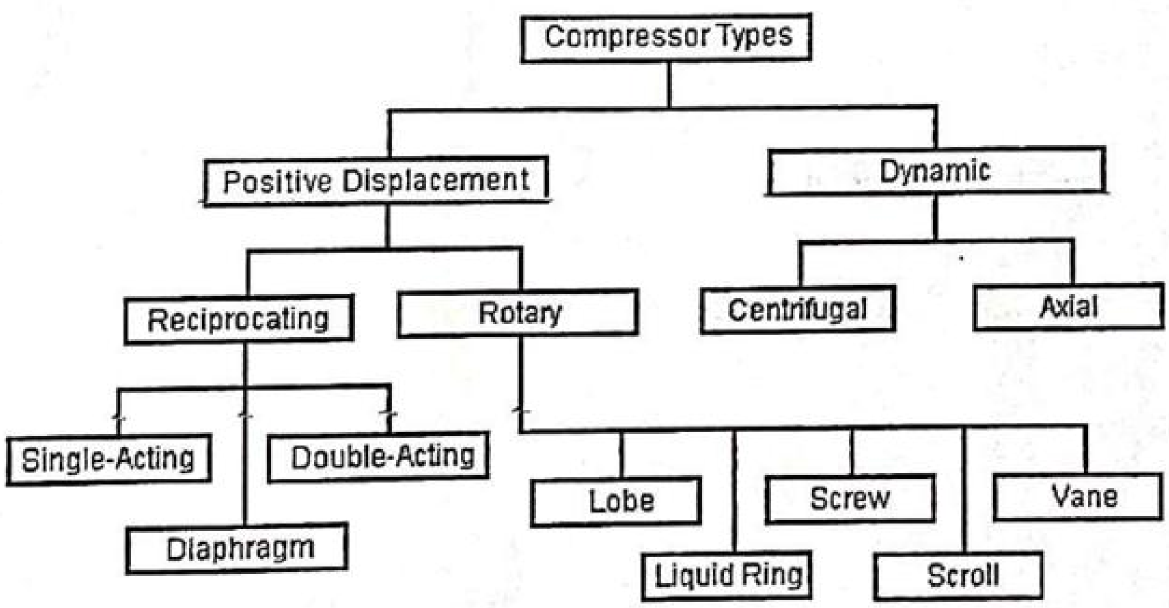
Introduction of Air Compressor

- Air compressor is a machine, sucks air at low pressure low temperature form atmosphere and compresses it to high pressure and high temperature.
- It is driven by external source like as prime mover.
- The compression of air required some amount of work to be done on it.
- The compressor used for supplying large amount of air to machine.

Compressed Air is used in

- Operating pneumatic drills, riveters, road drills
- Paint spraying
- In starting & supercharging of I.C. engines
- In gas turbine plants, Jet engines, Air motors etc.
- In the operation of lifts, rams, pumps
- For producing blast of air in blast furnaces & bessemer converters.
- For filling the air in tube of tyre
- To operate blast furnaces

Classification of air compressors



- **Positive displacement compressors** causes movement by trapping a fixed amount of air, then forcing (displacing) that trapped volume into the discharge pipe.
  Positive displacement compressors work on the principle of increasing the pressure of air by reducing the volume of air in an enclosed chamber

- **The dynamic compressor** is continuous flow compressor is characterized by rotating impeller to add velocity and thus pressure to fluid.
  Dynamic compressors works on the principle of imparting the energy by rotating vanes of impeller on air flowing through casing that increases pressure in air
  It is widely used in chemical and petroleum refinery industry for specific services.

Classification:

According to working

- Reciprocating Compressors
- Rotary Compressors

According to action

- Single acting Compressors
- Double acting Compressors

According to No. of stages

- Single Stage Compressors
- Multi Stage Compressors

Technical Terms

Inlet pressure: It is absolute pressure of air at the inlet of a compressor

Discharge Pressure: It is the absolute pressure of air at the outlet of the compressor

Pressure ratio:

$$\text{Pressure Ratio} = \frac{\text{Discharge Pressure}}{\text{Inlet pressure}} > 1$$

Since the discharge pressure is always greater than the inlet pressure, pressure ratio is always greater than unity.

Compression ratio: It is the ratio of volume when piston at BDC position to volume when piston at TDC position

It is denoted by R_c.

V_s = Clearance volume.

V_c = Swept volume.

Capacity of compressor:

It is the volume of free air actually delivered by compressor in m^3 per minute.

Free Air Delivery (FAD):

- The free air delivered is the actual volume of air delivered when reduced to normal intake pressure and temperature, and expressed in cubic meter per minute.
- Capacity of compressor is generally given in terms of free air delivery.
- $3m^3$/min compressor means that ir ompresses$3m^3$/min of free air.

Swept volume:

The volume swept by the piston when it moves between TDC to BDC.

It is also called stroke volume.

$$\text{Swept volume} = \frac{\pi}{4} D^2 L$$

Mean effective pressure

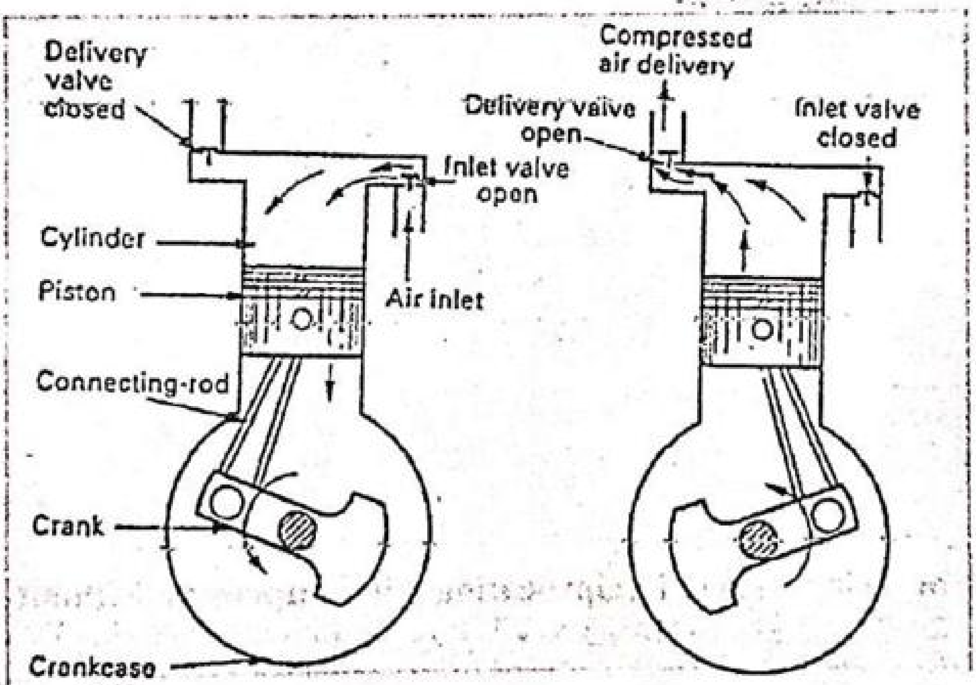
$$\text{Mean effective presure} = \frac{\text{Workdone per cycle}}{\text{Stroke volume}}$$

Reciprocating air compressor

Single stage reciprocating compressor

Working:

1. The single stage reciprocating compressor is shown in figure. The single stage reciprocating compressor working is same as engine.
2. **Suction stroke**: During the downward motion of the piston, the pressure inside the cylinder falls below the atmospheric pressure and the inlet valve is opened due to the low pressure.
3. The air is taken into the cylinder until the piston reaches bottom dead positions.
4. **Compression Stroke**: As the piston starts moving upward, the inlet valve is closed and the pressure is increasing continuously until the pressure inside the cylinder is above the pressure of delivery side to the receiver.
5. **Delivery**: Then delivery valve open and air transfer to receiver.
6. The cycle is repeated.



Note:

1. In a single acting reciprocating air compressor, the suction, compression & delivery of air takes place in two strokes of piston or one revolution of the crank shaft.
2. In a double acting reciprocating compressor, suction, compression & delivery of air takes place <u>on both sides of piston.</u>

∴ This compressor will supply double the volume of air than single acting. (neglecting volume of piston rod).

Work done by a Single Stage Reciprocating Air compressor (SS RAC)

Additional reading:

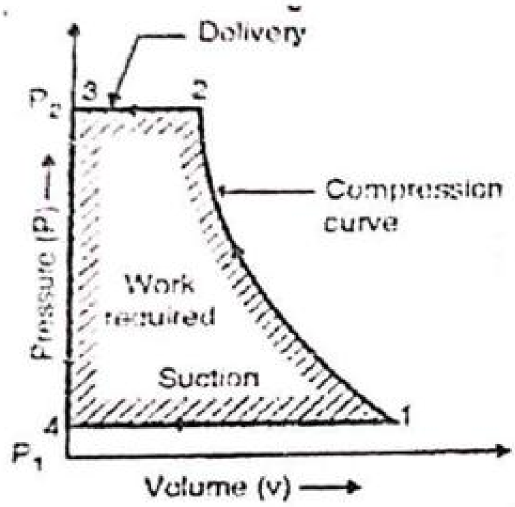
In a reciprocating air compressor, the air is first sucked, compressed and then delivered. So there are three different operations of the compressor.

- ➢ Work is done on the piston during the suction of the air.
- ➢ Similarly, work is done by the piston during compression as well as delivery of the air.

A little consideration will show that the work done by a reciprocating air compressor is mathematically equal to the work done by the compressor during suction.

Here we shall discuss the following two important cases of work done:

1. When there is no clearance volume in the cylinder, and
2. When there is some clearance volume



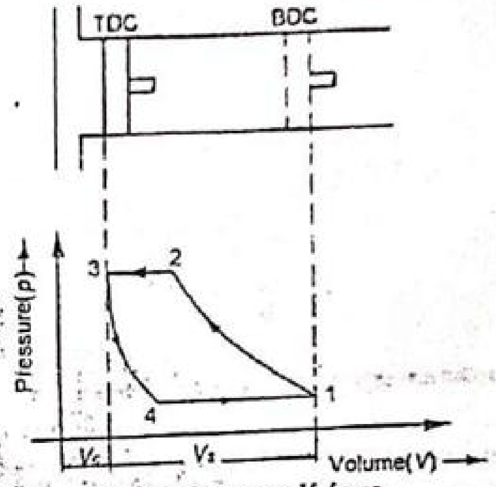
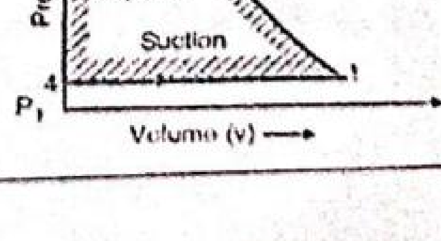


Fig. 4.2 Clearance Volume

Work done by a single stage Reciprocating Air compressor without clearance volume

Additional reading:

The p-v diagram of a single acting single stage reciprocating air compressor without clearance volume is shown in Fig. We know that during return stroke, the air is compressed by its major part (i.e., compression Stroke 1-2) at constant temperature. The compression continues till the pressure (p_2) in the cylinder is sufficient to force open the delivery valve at 2. After that no more compression takes place with the inward movement of the piston. Now during the remaining part of compression Stroke, the compressed air is delivered till the piston head reached the cylinder end. After that, the air is sucked from the atmosphere during the suction stroke 4-1 at pressure p_1.



Consider a single stage reciprocating air compressor without clearance volume delivering air from one side of the piston only.

Let p_1 = *Initial pressure of air (before compression),*

v_1 = *Initial volume of air (before compression),*

T_1 = *Initial temperature of air (before compression),*

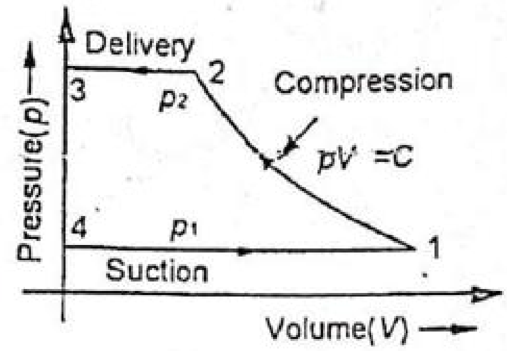
p_2, v_2, T_2 = *Corresponding values for the final conditions (i.e., at the delivery points),*

and r = *pressure ratio (i.e.,* p_2/p_1*)*

As a matter fact, the compression of air may be isothermal, polytropic or isentropic (reversible adiabatic). Now, we shall find out the amount of work done in compressing the air in all the above mentioned three cases.

Case 1: Work done during isothermal compression (PV=C)

The p-v diagram for a single stage single acting compressor is shown in figure.



~~Process 4-1: Suction of air at pressure p_1~~

Process 1-2: Air is compressed isothermally from pressure p_1 to p_2

Process 2-3: Delivery or discharge of air at pressure p_2

Work done by the compressor per cycle,

$$W = Area\ 1-2-3-4-1$$

$$= W_{Compression} + W_{Delivercy} - W_{Suction}$$

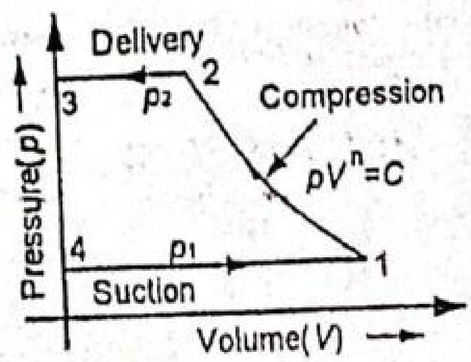
$$= 2.3 p_2 \upsilon_2 \log\left[\frac{V_1}{V_2}\right] + p_2\upsilon_2 - p_1\upsilon_1$$

$$= 2.3\ p_1\upsilon_1 \log\left[\frac{V_1}{V_2}\right] = 2.3 p_1\upsilon_1 \log\frac{p_2}{p_1} \text{.....}(\because p_1\upsilon_1 = p_2\upsilon_2 \text{, for isothermal process})$$

$$= 2.3\ p_1\upsilon_1 \log r = 2.3\ mRT_1 \log r \text{.....}(\because p_1\upsilon_1 = mRT_1)$$

Case 2: Work done during polytropic compression (pv^n = Con)

The polytropic compression is shown by the line 1-2 in Fig.



Process 4-1: Suction of air at pressure p_1

Process 1-2: Air is compressed polytropically from pressure p_1 to p_2

Process 2-3: Delivery or discharge of air at pressure p_2

Work done by the compressor per cycle,

$$W = Area\ 1-2-3-4-1$$

$$= W_{Compression} + W_{Delivery} - W_{Suction}$$

$$= \frac{p_2 v_2 - p_1 v_1}{n-1} + p_2 v_2 - p_1 v_1$$

$$= \frac{p_2 v_2 - p_1 v_1 + (n-1)\, p_2 v_2 - (n-1)\, p_1 v_1}{n-1}$$

$$= \frac{p_2 v_2 - p_1 v_1 + n p_2 v_2 - p_2 v_2 - n p_1 v_1 + p_1 v_1}{n-1}$$

$$= \frac{n}{n-1}(p_2 v_2 - p_1 v_1) \qquad ...(i)$$

$$= \frac{n}{n-1} * (p_1 v_1)\left(\frac{P_2 v_2}{P_1 v_1} - 1\right) \qquad ...(ii)$$

We also know that for polytropic compression,

$$p_1 v_1^{\,n} = p_2 v_2^{\,n}$$

$$\therefore \left(\frac{v_2}{v_1}\right)^n = \frac{P_1}{P_2} \Rightarrow \frac{v_2}{v_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$$

Substituting the value of v_2/v_1 in equation (ii),

$$W = \frac{n}{n-1} * p_1 v_1 \left[\frac{P_2}{P_1}\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} - 1\right]$$

$$= \frac{n}{n-1} * p_1 v_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} * mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \qquad ...(iii)$$

The equation (i) may also be written as:

$$W = \frac{n}{n-1}(p_2 v_2 - p_1 v_1)$$

$$\frac{n}{n-1}(mRT_2 - mRT_1) \qquad (\because p_1 v_1 = mRT_1\ \&\ p_2 v_2 = mRT_2)$$

$$= \frac{n}{n-1} mR(T_2 - T_1) \qquad ...(iv)$$

$$= \frac{n}{n-1} mRT_1 \left(\frac{T_2}{T_1} - 1\right)$$

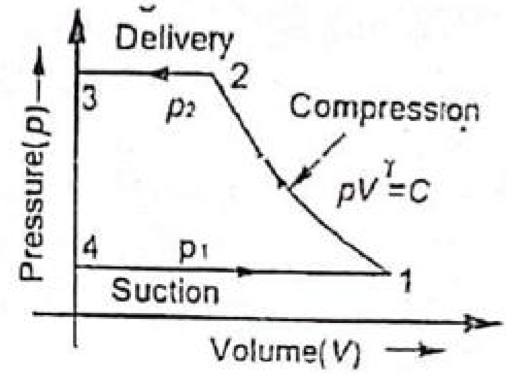
Case 3: Work done during isentropic compression

The p-v diagram for a single stage single acting compressor is shown in figure.

Process 4-1: Suction of air at pressure p_1

Process 1-2: Air is compressed isentropically from pressure p_1 to p_2

Process 2-3: Delivery or discharge of air at pressure p_2



$\therefore$ Work done on the air per cycle,

$$W = Area\ 1-2-3-4-1$$

$$= W_{Compression} + W_{Delivery} - W_{Suction}$$

$$= \frac{p_2 v_2 - p_1 v_1}{\gamma - 1} + p_2 v_2 - p_1 v_1$$

$$= \frac{p_2 v_2 - p_1 v_1 + (n-1)\, p_2 v_2 - (n-1)\, p_1 v_1}{\gamma - 1}$$

$$= \frac{p_2 v_2 - p_1 v_1 + n p_2 v_2 - p_2 v_2 - n p_1 v_1 + p_1 v_1}{\gamma - 1}$$

$$= \frac{\gamma}{\gamma - 1}(p_2 v_2 - p_1 v_1) \quad ...(i)$$

$$= \frac{\gamma}{\gamma - 1} * (p_1 v_1)\left(\frac{P_2 v_2}{P_1 v_1} - 1\right) \quad ...(ii)$$

$$W = \frac{\gamma}{\gamma - 1} * p_1 v_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$= \frac{\gamma}{\gamma - 1} * mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$= \frac{\gamma}{\gamma - 1} * mR(T_2 - T_1)$$

We know that the ratio of specific heats.

$$\frac{c_p}{c_v} = \gamma; \quad c_p - c_v = R$$

or $$R = c_p\left[1 - \frac{1}{\gamma}\right] = c_p\left[\frac{\gamma - 1}{\gamma}\right]$$

Now work done, $W = \frac{\gamma}{\gamma - 1} * mR(T_2 - T_1)$

$$= \frac{\gamma}{\gamma - 1} * mc_p\left[\frac{\gamma - 1}{\gamma}\right](T_2 - T_1) = c_p(T_2 - T_1)$$

We see that the work done on the air during isentropic compression is equal to the heat required to raise the temperature of air from T_1 to T_2 at a constant pressure.

Note: The work done on the air is minimum when the compression is isothermal (i.e., when n=1) and it is maximum when the compression is isentropic (i.e., when $n=\gamma$) because isothermal line has less slope than isentropic line. It may be noted that in order to perform isothermal process, the compression should be very slow so that the temperature is maintained constant, which is not possible in actual practice. However, the isothermal compression may be approached, if

1. the air or water cooling is done during the compression.
2. The cold water is sprayed (injected) in the cylinder during the compression, and
3. In multi-stage compressors, inter cooling is done.

Power Required to Drive a Single-stage Reciprocating Air Compressor

We have already obtained in the last article the expressions for the work done (W) per cycle during isothermal, polytropic and isentropic compression.

The power required to drive the compressor may be obtained from the usual relation.

$$P = \frac{WN_w}{60} \text{ watts}$$

If N is the speed of the compressor in r.p.m., then number of working strokes per minute.

$$N_w = N \quad \text{..... (For single acting compressor)}$$

$$= 2N \quad \text{..... (For double acting compressor)}$$

Note: Since the compression takes in three different ways, therefore power obtained from different works done will be different. In general, following are the three values of power obtained:

$$\text{1. Isothermal power} = \frac{W_{\text{(in isothermal compression)}} N_W}{60} \text{ watts}$$

$$\text{2. Isentropic power} = \frac{W_{\text{(in isentropic compression)}} N_W}{60} \text{ watts}$$

$$\text{3. Indicated power} = \frac{W_{\text{(in polytropic compression)}} N_W}{60} \text{ watts}$$

The indicated power is also known as air power of the compressor.

Work done by reciprocating Air compressor with clearance volume

In the previous articles, we have assumed that there is no clearance volume in the compressor cylinder. But in actual practice, it is not possible to reduce the clearance volume to zero, for mechanical reasons.

.Moreover, it is not desirable to allow the piston head to come in contact with the cylinder head. In addition to this, the passage leading to the inlet and outlet valves always contribute to clearance volume. In general, the clearance volume is expressed as some percentage of the piston displacement.

The p-v diagram of a single stage acting reciprocating air compressor with clearance volume (v_c) is shown in Fig.

Let

p_1 = *initial pressure of air (before compression),*

v_1 = *initial volume of air (before compression),*

T_1 = *initial temperature of air (before compression),*

p_2, v_2, T_2 = *Corresponding values for the final conditions (i.e., at the delivery points),*

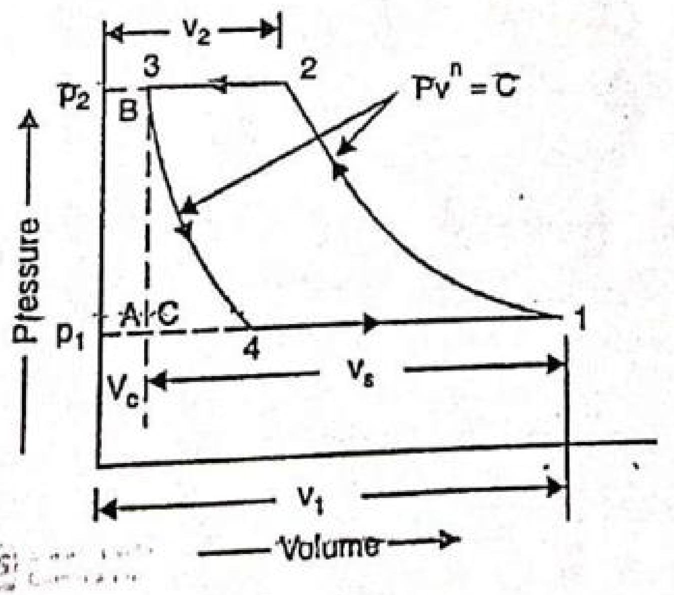
r = *pressure ratio (i.e., p_2/p_1)*

v_c = *clearance volume(i.e., volume at point 3),*

v_s = *Stroke volume* = $v_1 - v_c$, *and*

n = *Polytropic index for compression and expansion.*

We know that during return stroke, the air is compressed by its major part i.e., compression stroke 1-2. This compression continues, till the pressure p_2 in the cylinder is sufficient to force open the delivery valve at 2. After that, no more compression takes place with the inward movement of the piston. Now during the remaining part of compression stroke, compressed air is delivered till the piston reaches at 3. At this stage, there will be some air (equal to clearance volume) left in the clearance space of the cylinder at pressure p_2.



After that, air in the clearance space will expand during some part of outward stroke of the piston i.e., expansion stroke 3-4. This expansion continues till the pressure p_4 in the cylinder is sufficient to force open the inlet valve at 4. After that the air is sucked from the atmosphere during the suction stroke 4-1 at pressure p_1.

Though the compression and expansion of air may be isothermal, isentropic or polytropic, yet for all calculation purpose, it is assumed to be polytropic.

We know that work done by the compressor per cycle,

W = Area 1-2-3-4 = Area A-1-2-B -Area A-4-3-B

$$= \frac{n}{n-1} * p_1 v_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] - \frac{n}{n-1} * p_1 v_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

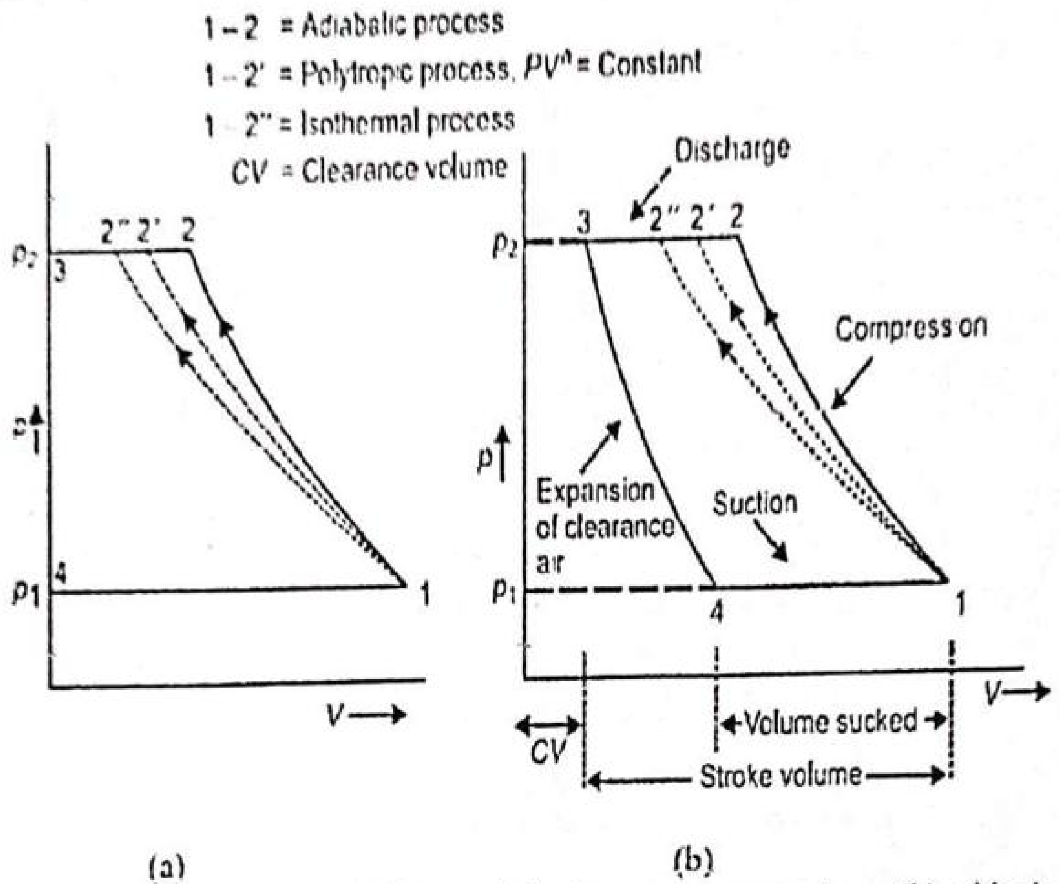
$$= \frac{n}{n-1} * p_1 (v_1 - v_4) \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} * p_1 v_a \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \qquad (\because v_1 - v_4 = v_a = \text{actual volume of air sucked in})$$

$$= \frac{n}{n-1} * mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \qquad (\because p_1 v_a = mRT_1)$$

We, see that the ***clearance volume does not effect the work done on the air and the power required for compressing the air.*** This is due to the reason that the work required to compress the clearance volume air is theoretically regained during its expansion from 3 to 4.

Note: The terms v_4 and $(v_1 - v_4)$ are known as expanded clearance volume and effective swept volume respectively.



(2) Compression cycle on p-V diagram (a) without clearance volume (b) with clearance volume

Note:

During isentropic compression,

~~Work done on the air~~ = heat required to raise the temp. of air from T_1 to T_2 at cost. Pr.

Note:

1. Work done on the air is minimum, when compression is isothermal. Work done on the air is maximum, when compression is isothermal. Explanation from the graph
2. In order to perform isothermal process, the compression should be very slow. So that the temperature is maintained constant, which is not possible in actual practice.

   However, the isothermal compression may be approached, if

   - The air or water cooling is done during the compression.
   - The cold water is sprayed (or injected) in the cylinder during compression.
   - In milts stage compressions, inter cooling is done

Multistage Compression

In the previous article, we have considered the compression of air in single stage. In other words, air is sucked, compressed in the cylinder and then delivered at a higher pressure. But sometimes, the air is required at a high pressure. In such case, either we employ a large pressure ratio (in single cylinder) or compress the air in two or more cylinders in series.

If we employ single stage compression for production of high pressure air (say 8 to 10 bar), it suffers the following drawbacks:

1. The size of the cylinder will be too large.
2. Due to compression, temperature of air increases. It is difficult to reject heat from the air in the small time available during compression.
3. Sometimes, the temperature of air, at the end of compression, is too high. It may heat up the cylinder head or burn the lubricating oil.

In order to overcome the above mentioned difficulties, two or more cylinders are provided in series with inter-cooling arrangement between them. Such an arrangement is known as multistage compression.

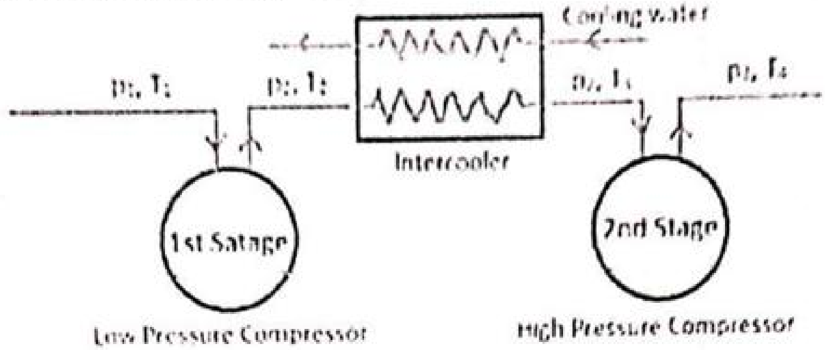
Advantages of Multistage Compression

Following are the main advantages of multistage compression over single stage compression:

1. The work done per kg of air is reduced in multistage compression with intercooler as compared to single stage compression for the same delivery pressure.
2. It improves the volumetric efficiency for the given pressure ratio.
3. The sizes of the two cylinders (i.e. high pressure and low pressure) may be adjusted to suit the volume and pressure of the air.
4. It produces the leakage loss considerably.
5. It gives more uniform torque, and hence a smaller size flywheel is required.
6. It provides effective lubrication because of lower temperature range.
7. It reduces the cost of compressor.
8. Better mechanical balance can be achieved with multi-stage compressor.
9. The pressure and hence temperature range in each stage is reduced.

Two-stage Reciprocating Air Compressor with Intercooler.

A schematic arrangement for a two-stage reciprocating air compressor with water cooled intercooler is shown in Figure.



Two-stage compressor with Intercooler

- First of all, the fresh air is sucked from the atmosphere in the low pressure (L.P) cylinder during its suction stroke at intake pressure p_1 and temperature T_1.
- The air, after compression in the L.P. cylinder (i.e. first stage) from 1 to 2, is delivered to the intercooler at pressure p_2 and temperature T_2.
- Now the air is cooled in the intercooler from 2 to 3 at constant pressure p_2 and ~~from temperature T_2 to T_3. After that, the air is sucked in the high pressure (H.P.)~~ cylinder during its suction stroke.
- Finally, the air, after further compression in the H.P. cylinder (i.e. second stage) from 3 to 4. It delivered by the compressor at pressure p_3 and temperature T_4.

Assumption in Two-stage Compression with Intercooler.

The following simplifying assumptions are made in case of two stage compression with intercooler:

1. The effect of clearance is neglected.
2. There is no pressure drop in the intercooler.
3. The compression in both the cylinders(i.e. L.P. and H.P.) is polytrophic (i.e. $pv^n=C$)
4. The suction and delivery of air takes place at constant pressure.

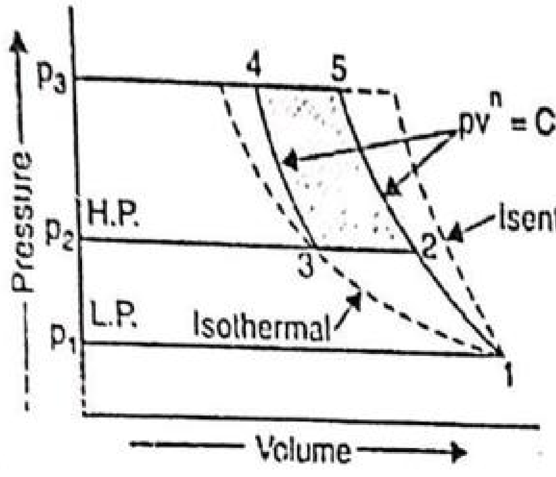
Intercooling of Air in a Two-stage Reciprocating Air Compressor

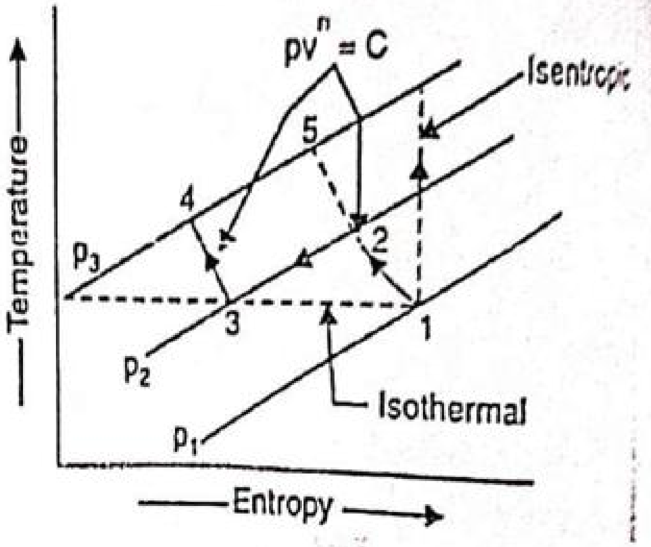
In the previous article, we have discussed the working of a two-stage reciprocating air compressor with an intercooler in between in between the two stages. As a matter of fact, efficiency of the intercooler plays an important role in the working of a two-stage reciprocating air compressor .

Following two type of intercooling are important from the subject point of view:

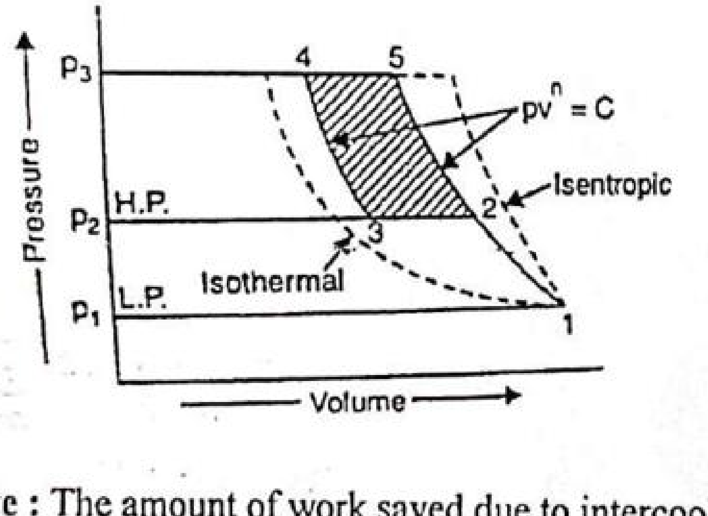
1. **Complete or perfect intercooling:** When the temperature of the air leaving the intercooler (i.e. T_3) is equal to the original atmospheric air temperature (i.e. T_1),

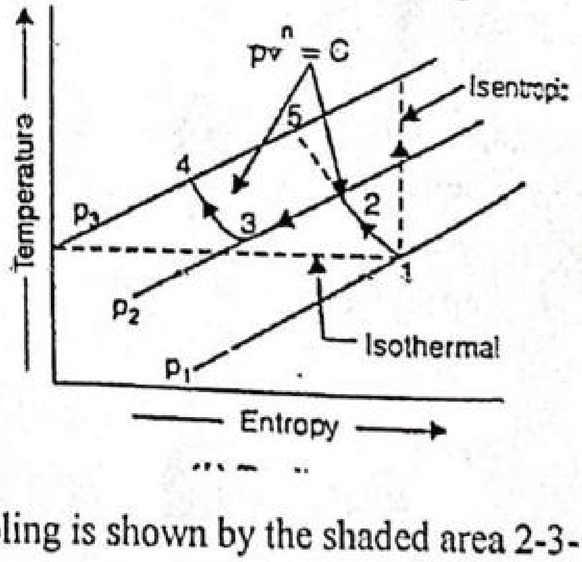
then the intercooling is known as complete or perfect intercooling. In this case, the point 3 lies on the isothermal curve as shown in fig





2. **Incomplete or imperfect intercooling:** When the temperature of the air leaving the intercooler (i.e. T_3) is more than the original atmospheric air temperature (i.e. T_1), then the intercooling is known as incomplete or imperfect intercooling. In this case, the point 3 lies on the right side of the isothermal curve as shown in fig.





Note : The amount of work saved due to intercooling is shown by the shaded area 2-3-4-5. In both the cases, to some scale. The amount of work saved with incomplete the intercooling is less than that in case of complete intercooling.

Work done by a Two-stage Reciprocating Air Compressor with Intercooler

Consider a two-stage reciprocating air compressor with intercooler compressing air in it L.P and H.P. cylinders.

Let p_1 = Pressure of air entering the L.P. cylinder.

v_1 = Volume of the L.P. Cylinder.

p_2 = Pressure of air leaving the L.P. cylinder or entering the H.P. cylinder.

v_2 = Volume of H.P. Cylinder.

p_3 = Pressure of air leaving the H.P. cylinder, and

n = Polytropic index for both cylinders.

Now, We shall consider both the cases of incomplete intercooling

Case 1. When the intercooling is incomplete

We know that work done per cycle in L.P. cylinder.

$$W_1 = \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] \text{.....................} \quad \text{(i)}$$

Similarly, work done per cycle in compressing air in H.P. cylinder,

$$W_2 = \frac{n}{n-1} \times p_2 v_2 \left[\left(\frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 1 \right] \text{.....................} \text{(ii)}$$

$\therefore$ Total work done per cycle.

$$W = W_1 + W_2$$

$$= \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] + \frac{n}{n-1} \times p_2 v_2 \left[\left(\frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$= \frac{n}{n-1} \left[p_1 v_1 \left\{ \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right\} + p_2 v_2 \left\{ \left(\frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 1 \right\} \right] \text{...(iii)}$$

Case 2. When the intercooling is complete

In case of complete intercooling. $p_1 v_1 = p_2 v_2$. Therefore substituting this value in equation (iii)

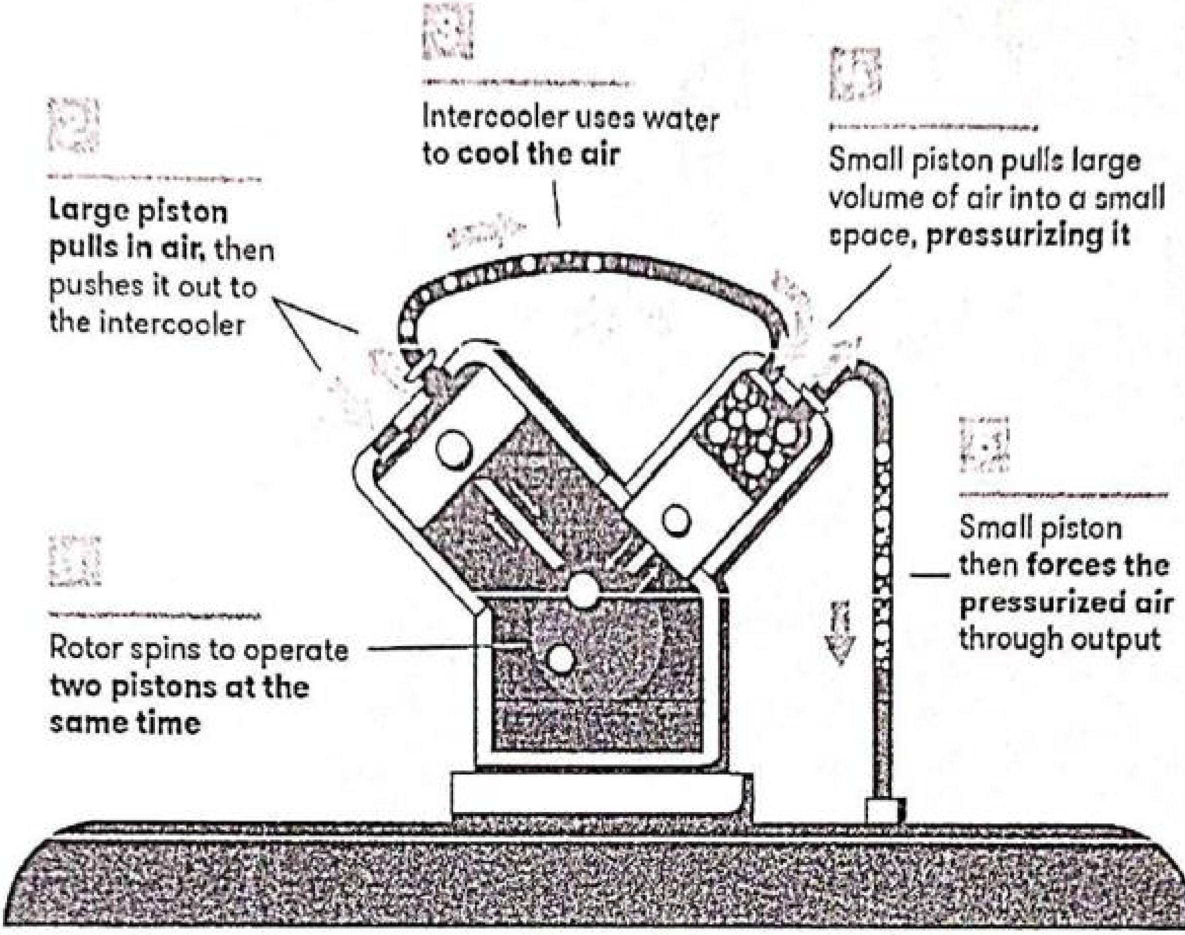
$$W = \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} + \left(\frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 2 \right]$$

$$= \frac{n}{n-1} \times mRT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} + \left(\frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 2 \right]$$

☞ The intercooler pressure "P_2" for minimum work required is given by $P_2 = \sqrt{P_1 P_3}$

P_1= Intake pr. of air

P_3= delivery pr. of air



Example: Estimate the work done by two stage reciprocating single acting up compressor to compress $2.8m^3$ of air per min at 1.05 bar and 10^0C to a final pressure of 35 bar. The intermediate receiver cools the air at 30^0C and 5.6 bar pressure. For air, take n=1.4.

Solution. Given: v_1=2.8 m^3/min; p_1=1.05 bar=1.05x10^5N/m^2; T_1=10^0C = 10+273=283; p_3= 35 bar; T_3= 30^0C = 30 +273 = 303 K; p_2=5.6 bar =5.6X10^5 N/m^2; n=1.4

Let v_2 = Volume of the high pressure cylinder.

We know that $\dfrac{p_1v_1}{T_1} = \dfrac{p_2v_2}{T_3}$

or $$v_2 = \frac{p_1v_1T_3}{P_2T_1} = \frac{1.05\times10^5\times2.8\times303}{5.6\times10^5\times283} = 0.562\ m^3/\min$$

$\therefore$ Work done by the compressor,

$$W = \frac{n}{n-1}\left[p_1v_1\left\{\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}-1\right\}+p_2v_2\left\{\left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}}-1\right\}\right]$$

$$=\frac{1.4}{1.4-1}\left[1.05\times10^5\times2.8\left\{\left(\frac{5.6}{1.05}\right)^{\frac{1.4-1}{1.4}}-1\right\}+5.6\times10^5\times0.562\times\left\{\left(\frac{35}{5.6}\right)^{\frac{1.4-1}{1.4}}-1\right\}\right]$$

$$=3.5\left[1.803\times10^5+2.166\times10^5\right]=13.9\times10^5\,N-m/\min$$

Power Required to Drive a Two-stage Reciprocating Air Compressor

We have already obtained in the last article the expressions for the work done (W) per of a two-stage reciprocating air compressor may be obtained from the usual relation.

$$p = \frac{W \times N_w}{60} \text{ Watts}$$

N_w = Number of working strokes per minute.

Ratio of cylinder diameters :

D_1, D_2 are diameters of L.P. & H.P. cylinders reciprocating.

P_1= Pressure of air entering the LP Cylinder.

P_2= Pressure of air leaving the LP Cylinder (or intercooler pressure).

P_3= Pressure of air leaving the HP Cylinder.

For complete intercooling,

$$p_1 v_1 = p_2 v_2$$

$$\Rightarrow \frac{p_2}{p_1} = \frac{v_1}{v_2} = \frac{\frac{\pi}{4} D_1^2 L}{\frac{\pi}{4} D_2^2 L} = \left(\frac{D_1}{D_2}\right)^2$$

$$\Rightarrow \frac{D_1}{D_2} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{2}}$$

$$\Rightarrow \frac{D_1}{D_2} = \left(\frac{p_3}{p_1}\right)^{\frac{1}{4}} \qquad \because \frac{p_2}{p_1} = \frac{p_3}{p_1}$$

$$\therefore \frac{D_1}{D_2} = \left(\frac{p_2}{p_1}\right)^{1/2} = \left(\frac{p_3}{p_1}\right)^{1/4}$$

☞ Inter cooling in multi-stage compressors is done to minimize the work of compression.

Efficiencies of Reciprocating air compressor

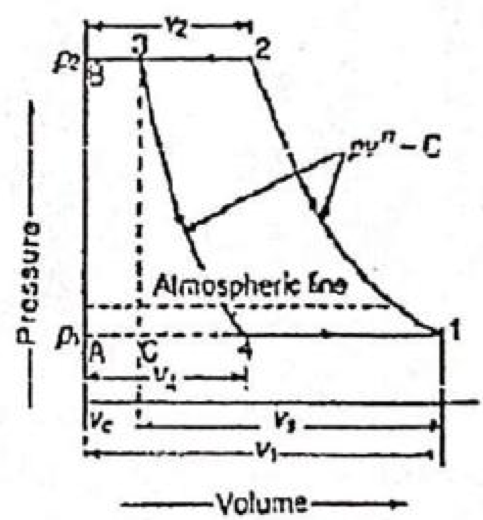
Volumetric Efficiency

- It is the ratio of actual free air delivered to the displacement of the compressor.
- It is also defined as the ratio of volume of free arc sucked into the compressor per cycle to the stroke volume of the cylinder.
-

P_1 = Initial pressure of air (before compression),
V_1 = Initial volume of air (before compression).
T_1 = Initial temperature of air (before compression),
P_2, V_2, T_2 = Corresponding values for the final conditions (i.e. at delivery point),
P_a, V_a, T_a = Corresponding values for the ambient (i.e. N.T.P.) condition
V_c = Clearance volume,
Vs = Swept volume of the piston, and
n = Polytropic index.

- In actual practice, the temperature at the end of suction i.e. at point 1 is not atmospheric because the fresh air passes over hot valves and mixes with the residual air.
- Also, the pressure at point 1 is not atmospheric as there are obstructions in Suction of fresh air. Applying general gas equation to the atmospheric condition of air and the condition of air before compression, we have

$$\frac{p_a V_a}{T_a} = \frac{P_1(V_1 - V_4)}{T_1}$$



∴ Volume of air sucked referred to ambinet conditions,

$$V_a = \frac{P_1 T_a}{P_a T_1}(V_1 - V_4)$$

$$\eta = \frac{V_a}{V_s} = \frac{\text{Actual Volume of free air taken per cycle}}{\text{Theoretical volume of air taken inside}}$$

$$= \frac{\text{Volume of free air taken per cycle}}{\text{Stroke volume of the cylinder}}$$

$$\eta = \frac{V_a}{V_s} = \frac{P_1 T_a}{P_a T_1}\left(\frac{V_1 - V_4}{V_s}\right) = \frac{P_1 T_a}{P_a T_1}\frac{(V_s + V_c) - V_4}{V_s} \qquad (\because V_1 = V_c + V_s)$$

$$= \frac{P_1 T_a}{P_a T_1}\left(1 + \frac{V_c}{V_s} - \frac{V_4}{V_s}\right) = \frac{P_1 T_a}{P_a T_1}\left(1 + \frac{V_c}{V_s} - \frac{V_4}{V_c} x \frac{V_c}{V_s}\right)$$

$$= \frac{P_1 T_a}{P_a T_1}\left(1 + C - C.\frac{V_4}{V_s}\right) \qquad \because \frac{V_c}{V_s} = C = \text{Clearance ratio}$$

$$= \frac{P_1 T_a}{P_a T_1}\left(1 + C - C\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}\right)$$

$$\left(\begin{array}{l} \because p_3 v_3^n = p_4 v_4^n \Rightarrow \frac{v_4}{v_3} = \left(\frac{p_3}{p_4}\right)^{\frac{1}{n}} \\ \Rightarrow \frac{v_4}{v_c} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} \qquad \because v_3 = v_c \end{array}\right)$$

When the ambient and suction conditions are same, then $P_a = P_1$ and $T_a = T_1$.

$$\eta_{vol} = 1 + C - C\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}$$

- $\eta_{vol.}$ of reciprocating comp. is different when it is with or without clearance vol.
- *$\eta_{vol.}$ of reciprocating air compressor is about 70 to 90%.*
- *$\eta_{vol.}$ of a compressor decreases with increase in compression ratio.*

The criterion for the thermodynamic efficiency

of the reciprocating air compressor is ISOTHERMAL. - due to slow speed of the piston & cooling of the cylinder, the compression of air is approx. isothermal.	of the centrifugal air compressor is ISENTROPIC. - due to high speed of the rotor & without any cooling arrangement, the compression of air is approx. isentropic.

Isothermal efficiency

It is the ratio of work (or power) required to compress the air isothermally to the actual work (or power) required to compress the air for the same pressure ratio.

$$\eta = \frac{\text{Isothermal power}}{\text{Indicated power}} = \frac{\text{Isothermal workdone}}{\text{Indicated work done}} = \frac{2.3 p_1 v_1 \log\left(\frac{p_2}{p_1}\right)}{\frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]} = \frac{2.3 \log\left(\frac{p_2}{p_1}\right)}{\frac{n}{n-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]}$$

Overall Isothermal efficiency

It is the ratio of the isothermal power to the shaft power or brake power of the motor or engine required to drive the compressor

$$\eta_o = \frac{\text{Isothermal power}}{\text{Shaft power power or BP of motor}}$$

Mechanical efficiency

It is the ratio of the indicated power to the shaft power or brake power of the motor or engine required to drive the compressor.

$$\eta_m = \frac{\text{Indicated power}}{\text{Shafld power power or BP of motor}}$$

Isentropic Efficiency

It is the ratio of the isentropic power to the shaft power or brake power required to drive the compressor.

$$\eta_i = \frac{\text{Isentropic power}}{\text{BP required to drive the compressor}}$$

Rotary compressor

Whenever large quantities of air of gas at relatively low pressure, rotary compressors are used.

They are classified as

1. Positive displacement compressors
2. Non- positive displacement compressors (or) Dynamic compressors.

Positive displacement compressors

The rotary positive displacement compressors are smaller than the reciprocating compressor at a given flow rate. The air is compressed adiabatically but uncooled. In positive displacement rotary type compressor, the air is entrapped in between two sets of engaging surfaces. The pressure rise is either by back flow of air (as in roots blower) or both by variation in the volume and back flow (as in vane blower).

Examples: 1.Vane blower 2.Roots blower

Non positive displacement compressors

In dynamic compress, the air is not trapped in specific boundaries but it flows continuously and steadily through the machine. The energy from the impeller is transferred to the air as the air flows through the machine and the pressure rise is primarily due to dynamic effects.

Examples: 1. Centrifugal compressor 2. Axial flow compressor

Rolling piston type compressor (fixed vane type)

Construction

1. Figure 1 shows a schematic view of a rolling piston compressor. It consists of a rolling piston which is the roller in Figure 1,
2. A rolling piston (impeller) is fixed on an eccentric shaft in a stationary cylinder.
3. The cylinder which holds the roller and a vane-spring mechanism.

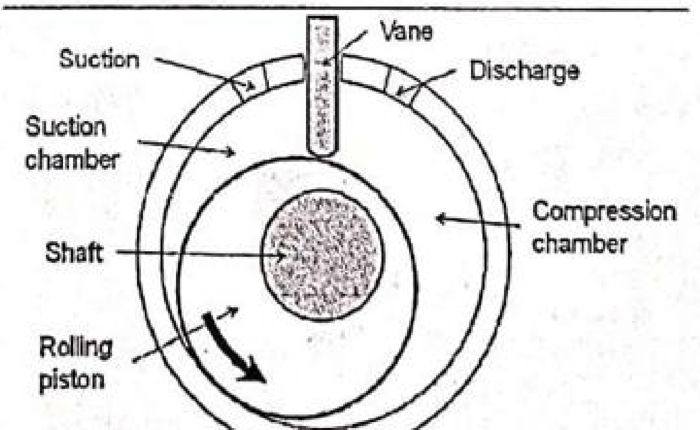


Figure 1: Schematic of a rolling piston compressor

4. A spring-loaded vane (blade) is set into the slot of the cylinder. Blade moves up and down in a slot in such a way that it will be always in positive contact with the rolling piston while it rotates.
5. This vane separates the suction and discharge port of the compressor, so the blade is also known as sealing blade.

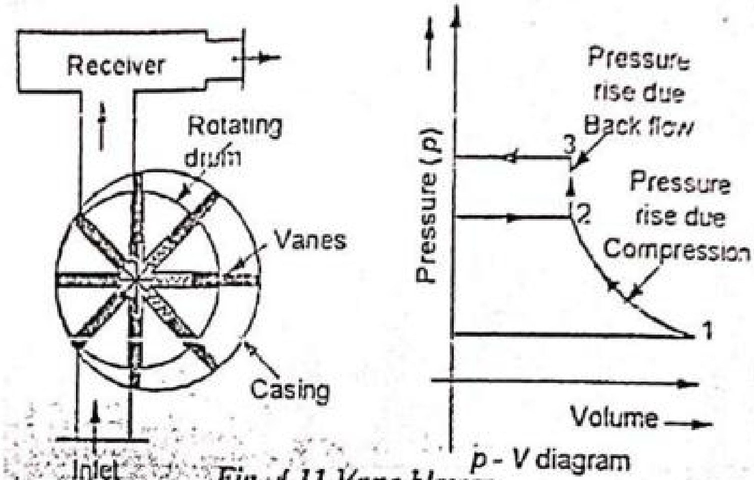
Working

1. When the shaft operates, the rolling piston that is mounted on the shaft eccentrically rotates in the cylinder, rolling against the inner wall of the cylinder.
2. During the rotation of the rolling piston, there will be space formed between the vane, the cylinder and the rolling piston.
3. The changes in the size of the space results in suction, compression and discharge of the working fluid.

Vane compressor (Multi Vane type):

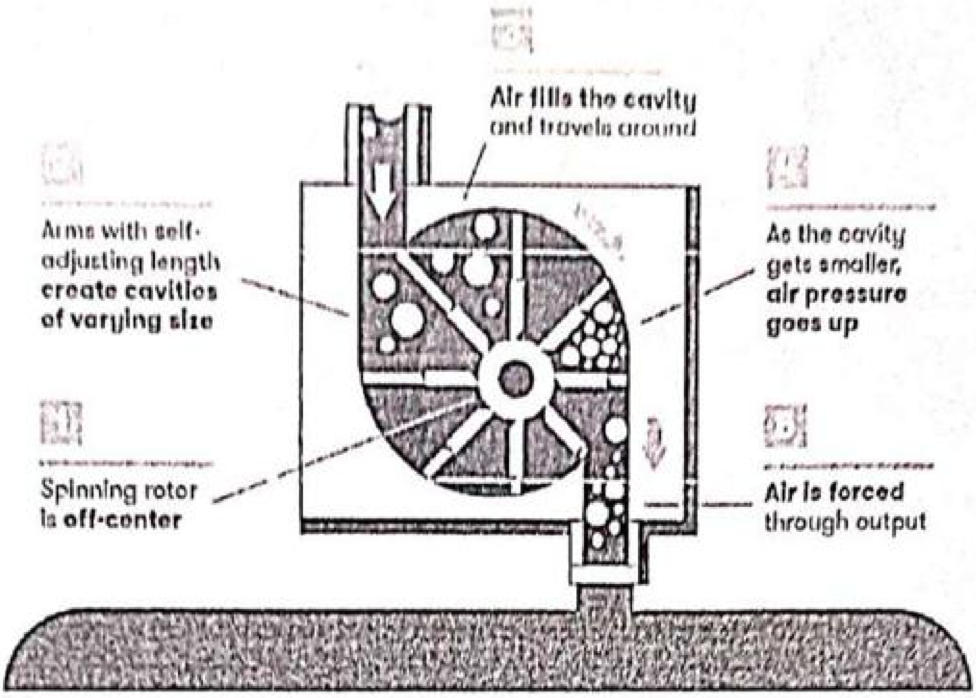
Construction:

1. It consists of casing, rotating drum, spring loaded vanes, rotor, inlet and outlet ports.
2. The rotor is located eccentrically in a cylindrical casing.
3. The rotor carries a set of spring located vanes.
4. **As the rotor rotates, the vanes slides radially in and out of the rotor**

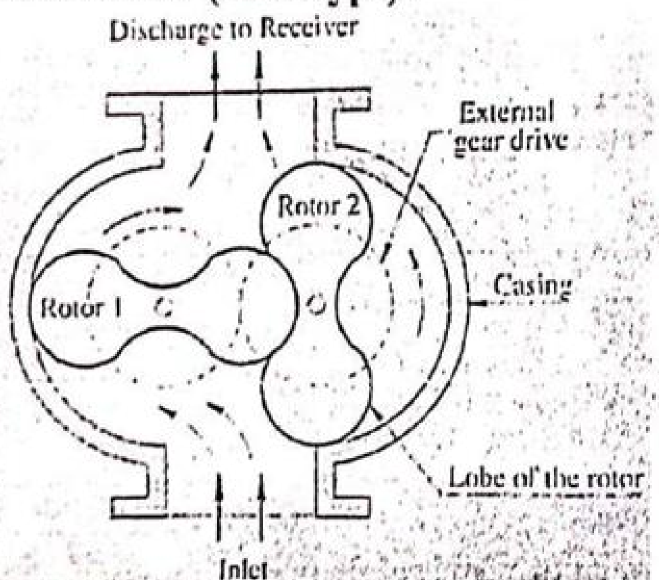


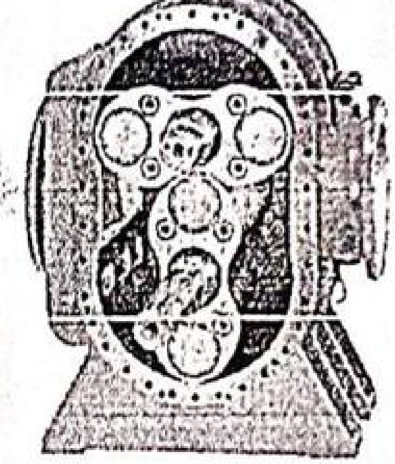
Working:

1) The vane compressor is shown in figure.
2) When the power is given to the vane blower, the air (say volume V_1) at atmospheric pressure P_1, is trapped between two consecutive vanes in root blower.
3) As the rotor turns, compression is achieved as the volume goes from a maximum at intake port to minimum at the exhaust port.
4) As the rotation continues, the trapped air is first compressed reversibly from condition 1 to 2 as the compression take place due to decreasing volume between the rotor and casing, provide for trapped air.
5) This partially compressed air is delivered to the receiver.
6) When the outlet is opened, there is a backflow of high pressure air from the receiver. This back flow air mixes up with the entrapped air. So partially compressed air pressure is further increased.
7) The high pressure air is delivered to receiver after the equalization of the pressure in receiver.
8) **In vane blower, the pressure of air is increased first by decreasing volume and then by back flow of air as shown in the figure.**



Root blower (Lobe type):



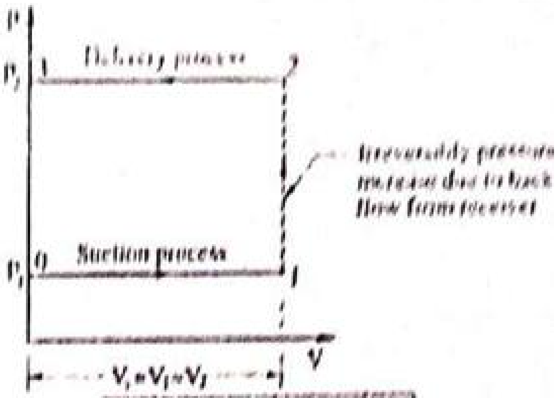


Construction

2) It consists of two rotors (called *lobes*) driven by externally, one of the rotor is connected to drive and another is driven by first rotor.
3) The two rotors rotate in opposite direction.
4) The lobes of the rotor are of epicycloids, hypocycloid or involute profile to ensure correct matching
5) A very small clearance is provided between the casing and rotor to prevent wear. Then increase the pressure ratio.
6) The lobes are so designed that they provide an air tight joint at the point of their contact.

Working

1. When the power is given to the roots blower, rotors rotate and the air (say of volume, V_s) at atmospheric pressure is trapped between the left hand rotor and casing.
2. The trapped air moves along the casing to get delivered to receiver.
3. At the same time, when the exit port opens, some high pressure air rushes back (back flow) from the receiver and mix irreversibly with entrapped air (V_s) until pressure is equalized. Thus the pressure of the entrapped air is increased by the back flow of air.
4. Then air is delivered to receiver.



P-V diagram for roots blower

Note:

1. The delivery of air into receiver is not continuously even the rotor revolves with uniform speed.

If two rotor has two lobes then air delivered is 4V and if three lobes then 6V per revaluation.

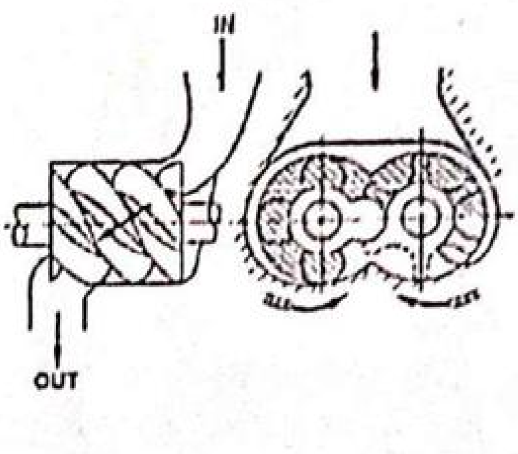
Note: Roots blower compressor Vs. Vane Blower compressor

- In both the above cases, the air is delivered to the receiver by the rotating lobes or vanes.
- When the rotating lobe or vane uncovers the exit port, some air (under high pressure) from the receiver flows back into the pockets formed between lobes & casing or vanes & casing.
- This back flow of air mixes up with the entrapped air, and continues until the pressure in the pockets & receiver are equalized.
- The process of back flow of air is an irreversible compression process.

Screw compressor

Construction

1. In screw compressor, the suction and delivery valve replaced by port and a piston replaced by helical screw.
2. It consists of two helical screws which are mesh with each other.
3. An electrical motor drives a male rotor and female are driven by male rotor.



Working

1. The screw compressor is shown in figure.

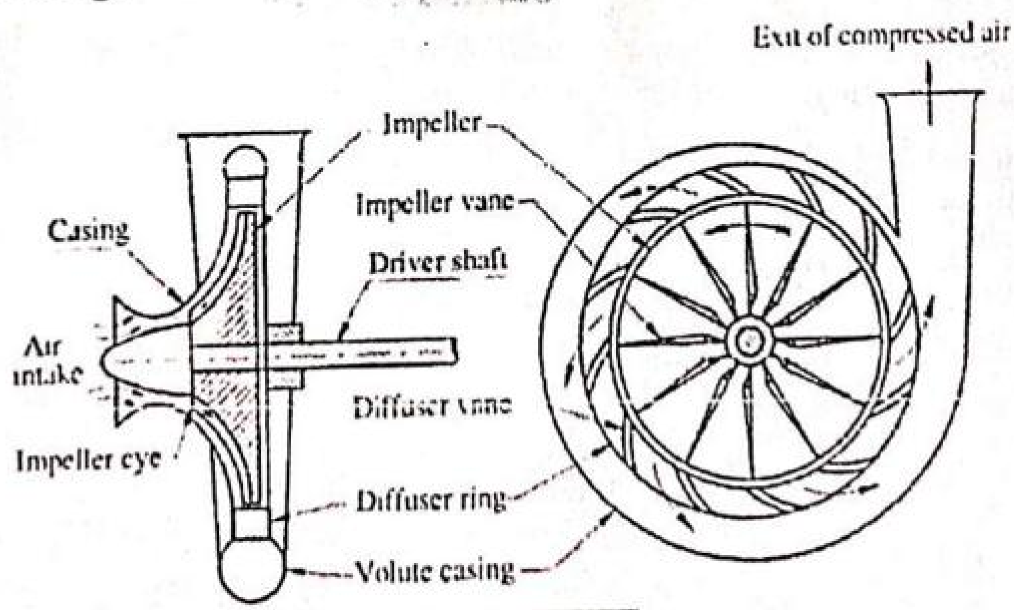
2. The screw compressor is driven by external source like electric motor.
3. When the male rotor shaft is rotate then female is mesh with male gear.
4. The air, gas is drawn into the inlet port, the rotor is continuous to turn inter lobe space increase in size, and gas, air flow continuously into compressor.
5. Male lobe with female interlobe space on the suction end and progressively compresses the air in axial direction of discharge proof.
6. At the point determine by the designed built in volume ratio, the discharge port is uncovered and the compressed air is discharge.
7. The cycle is repeated.

Centrifugal compressor

In Centrifugal compressor, air enters axially and leaves radially.

Construction

1) It consists of rotating impeller, diffuser, casing, driven shaft, impeller eye etc.
2) The impeller consists of a disc on which radial blades (or vanes) are attached. The impeller is surrounded by casing.
3) The impeller can run at speed 20,000 to 30,000 rpm.
4) The diffuser is important part of compressor which surrounding the impeller and provides diverging passage for air flow thus increasing the pressure air.
5) The casing is so designed that the K.E. of air is converted into pr. energy before it leaves the casing.

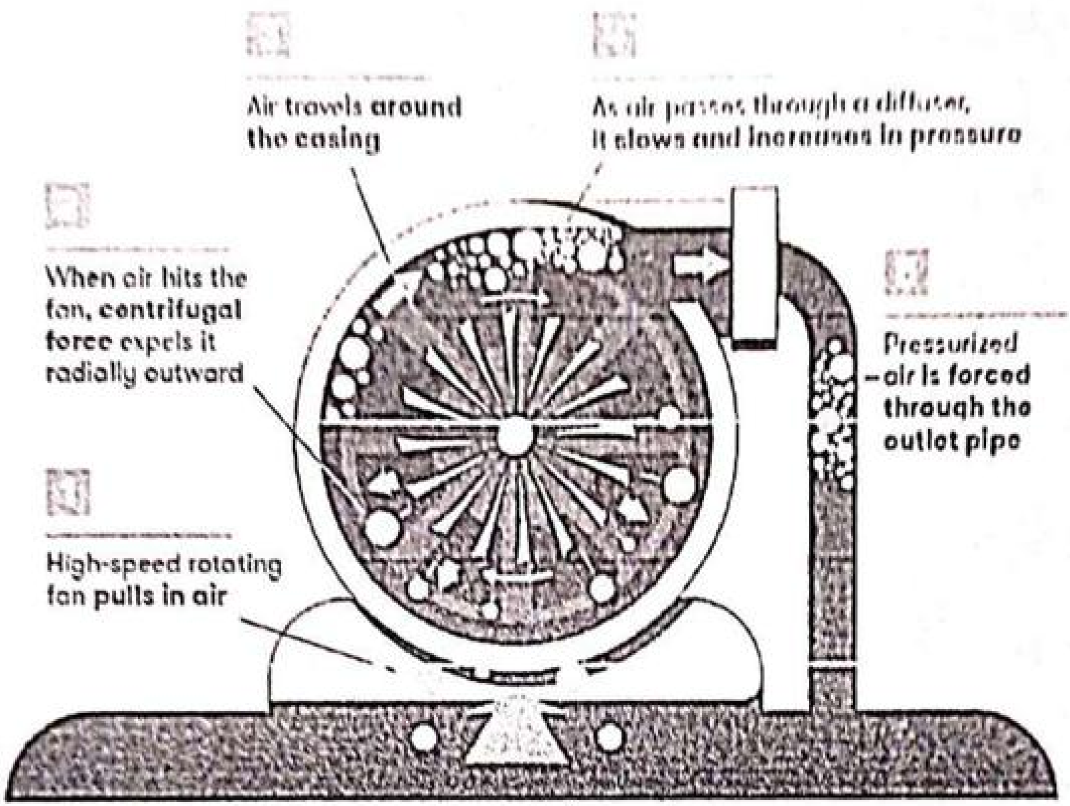


Centrifugal compressor

Working:

1) The centrifugal compressor is shown in figure.
2) When the power is given to the compressor, the impeller rotates and air is drawn into the impeller eye in an axial direction.
3) Due to centrifugal force, the air flows radially outward through the impeller.
4) The air leaves the impeller tip with high velocity and enters the diffuser.

5) The diffuser reduces the high velocity of air. As a result, in the diffuser, kinetic energy is converted in to pressure energy.
6) The flow from the diffuser is collected in a spiral passage from which it is discharged to receiver.
7) The procedure is repeated.



Applications

Centrifugal compressors are suitable for super charging of IC engines, refrigeration and low pressure units.

Work done by the centrifugal compressor:

(Similar to that of single acting reciprocating air compressor).

$$W = 2.3\, p_1 \upsilon_1 \log \frac{\upsilon_1}{\upsilon_2} (\upsilon_1 - \upsilon_4) = 2.3\, mRT_1 \log r \quad (\textit{for isothermal compression})$$

$$= \frac{n}{n-1} p_1 \upsilon_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n}{n-1}} - 1 \right] \quad (\textit{for Polytropic compression})$$

$$= \frac{\gamma}{\gamma-1} p_1 \upsilon_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n}{n-1}} - 1 \right] = mcP(T_2 - T_1) \quad (\textit{for isentropic compression})$$

Axial Flow Compressor

In axial flow compressor, air enters axially and leaves axially.

Construction

- It consists of casing, rotating drum, moving blades (rotor blades), and fixed blades (stator blades).
- The fixed blades (stator blades) are fixed to the casing.
- The moving blades are fixed on the rotating drum.
- The air flow passage is gradually reduced from the inlet to the outlet of the compressor.

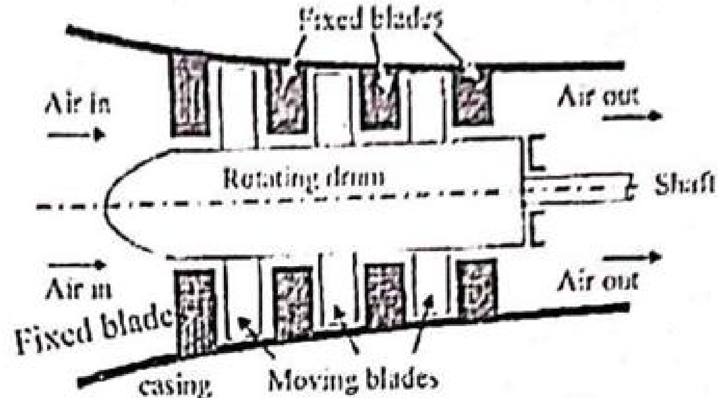


Fig. Principal components of the axial flow compressor.

Working

- When the power is given to the compressor, the rotating drum rotates and it creates suction of air into the compressor.
- Due to suction, air enters through the compressor inlet and passes through the fixed and moving blades.
- As the air flows from one set of fixed and moving blades to another set, air gets compressed. The air is also compressed between the casing and the blades.
- Pressure of the air is further increased due to gradual decrease in passage area from the inlet to the outlet of the compressor.
- Finally the air at high pressure is delivered to the receiver.

Applications: The axial flow compressors are most suitable for large size gas turbine plants and high pressure units.

Centrifugal Compressor	Axial flow compressor
➢ Flow of air is perpendicular to the axis of compressor. ➢ Low manufacturing & running cost. ➢ Requires low starting torque. ➢ Not suitable for multi staging. ➢ Requires large frontal area for a given rate of flow.	➢ Flow of air is parallel to the axis of compressor. ➢ High manufacturing & running cost. ➢ Requires high starting torque. ➢ Suitable for multi staging. ➢ Requires less frontal area for a given rate of flow. *It makes the compressor suitable for air crafts.*

Comparison between reciprocating compressor and rotary compressor:

	Reciprocating Compressor		Rotary Compressor
1	Compression is take place between piston and cylinder reciprocating motion of cylinder and piston.	1	Compression is take place due to rotary motion of blades.
2	Delivery pressure is high.	2	Delivery pressure is low.
3	Delivery of air is not continuous	3	Delivery of air is continuous.
4	It has more moving part, more wear and tear, more lubrication and maintenance required.	4	It has less moving part, less wear and tear, less lubrication and less maintenance.
5	Used when high pressure and small quantity is required.	5	Used when low pressure and large quantity is required.
6	In reciprocating the inlet and delivery valve are required.	6	In rotary the valve is replaced by port and housing.
7	Speed of compressor is low because unbalanced forced.	7	Speed of compressor is high because balanced forced.

Application of reciprocating compressor:

1) To spray painting shop.
2) In workshop, for cleaning the machine.
3) In automobile service station for cleaning the vehicle.
4) For operation of pneumatic tools.
5) Blast in blast furnace.
6) Boosting of I.C. engine.

Application of rotary compressor:

1) Petrol chemical factory.
2) Refrigeration factory.
3) Supercharging of petrol and diesel engine.
4) Oil refinery plant.

Turbine blades	Centrifugal compressor blades
▪ Passage between the blades is converging. ▪ Due to converging passage, the flow gets accelerated. But the pressure decreases. ▪ The flow is more stable.	▪ Is diverging. ▪ Due to diverging passage, the flow gets diffused or decelerated. But the pressure increases. ▪ The flow is less stable.

Purification of air to remove oil, moisture and dust:

1. Air contains varying quantity of moisture depending on temperature and relative humidity of the air.
2. This moisture when retain in the system may causes corrosion, wear and tear of equipment, machine and tool due to compression, the temperature of air increases.

After cooler:

1. After cooler is the most commonly used device to remover moisture but is reduce compressed air temperature.
2. After cooler is a heat exchanger which uses water or air to cool down the compressed air. As dry bulb temperature reduces its dew point also reduce.

Drier-stainer:

1. The function of the drier stainer is to remove the moisture and impurities.
2. A drier stainer is tubular metal container or housing arranged in connection in circuit.
3. A separate air filter is also used in system which removes dust and soot and the impurities to achieved fresh air form atmosphere.

Method of energy saving in air compressor:

1) The isothermal compression requires least amount of energy. For achieving the isothermal compression the speed of the compressor should be low which required more time for completion of compression process.

Inter-stage cooling:

1. The compression process is divided into two or more stage. The compressed air in fresh is passed through intercooler before passing through second stage.
2. In intercooler air is cooled due to original temperature.

Water jacketing:

1) The water is kept circulating around the compressor and air is cooled. This method is partially effective due to reduction in heat transfer rate to the wall.

Another method for energy saving in air compressor is:

1. Install equipment interlocked solenoid cut-off valve in the system so that air is supply to a machine can be switched off when not in use.
2. Use multistage compression as it consumes less power for the some output then a single stage compressor.
3. Reduce compressor delivery pressure whenever possible to save energy.
4. By using regenerative air drier, this uses the heat of compressed air to remove moisture.
5. Install manometer across the filter and monitor the pressure drop as a fluid to replace the filter element.

How to select a particular type of compressor ?

(Graph showing operating regions of various compressors)

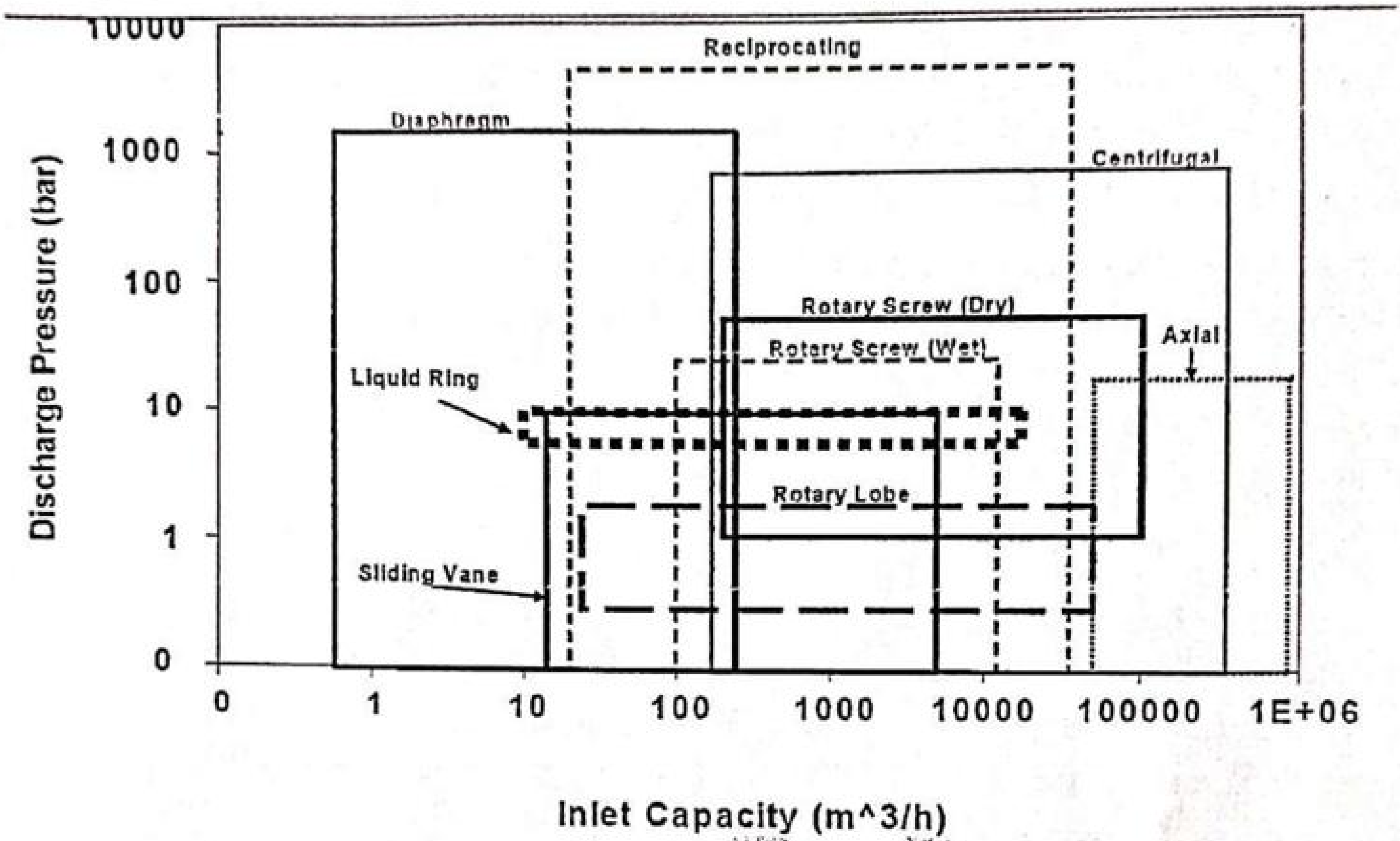


Table 1b. Summary of Typical Operating Characteristics of Compressors (US Units)

	Inlet Capacity (acfm)	Maximum Discharge Pressure (psig)	Efficiency (%)	Operating Speed (rpm)	Maximum Power (HP)	Application
Dynamic Compressors						
Centrifugal	100 - 200,000	10,000	70 – 87	1,800 - 50,000	50,000+	Process gas & air
Axial	30,000 - 500,000	250	87 - 90+	1,500 - 10,000	100,000	Mainly air
Positive Displacement Compressors						
Reciprocating (Piston)	10 - 20,000	60,000	80 – 95	200 - 900	20,000	Air & process gas
Diaphragm	0.5 – 150	20,000	60 – 70	300 - 500	2,000	Corrosive & hazardous process gas
Rotary Screw (Wet)	50 - 7,000	350	65 – 70	1,500 - 3,600	2000	Air, refrigeration & process gas
Rotary Screw (Dry)	120 – 58,000	15 – 700	55 – 70	1,000 - 20,000	8,000	Air & dirty process gas
Rotary Lobe	15 - 30,000	5 - 25	55 - 65	300 - 4,000	500	Pneumatic conveying, process gas & vacuum
Sliding Vane	10 - 3,000	150	40 – 70	400 - 1,800	450	Vacuum service & process gas
Liquid Ring	5 - 10,000	80 - 150	25 – 50	200 - 3,600	400	Vacuum service & corrosive process gas