Combustion & Combustion Chamber in SI Engines

VEERAPANDIAN.K
AP/MECH

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.

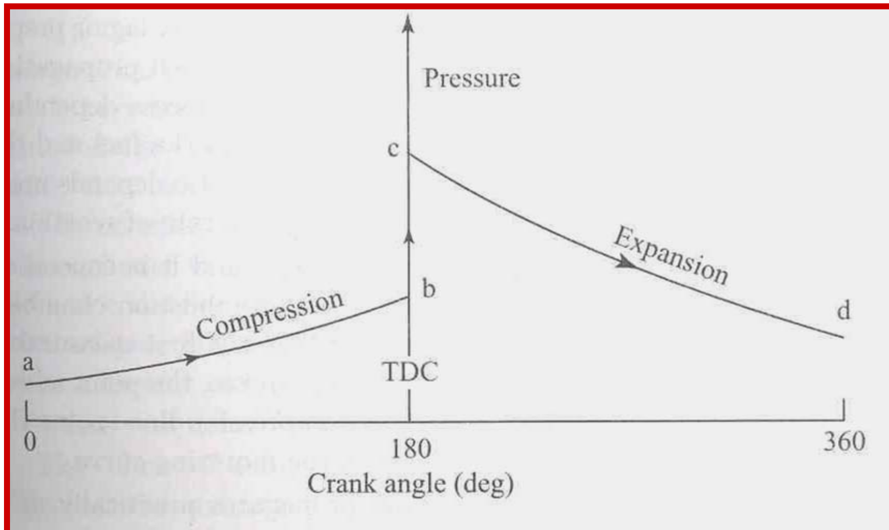


Fig. 12.1 Theoretical p-θ Diagram

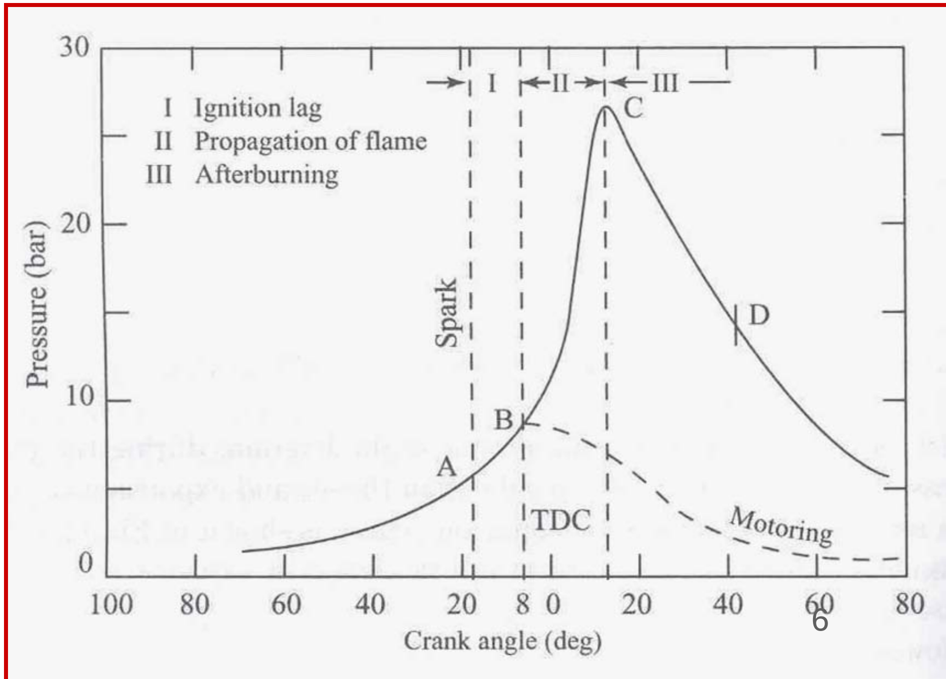
The 3 stages Actual engine combustion process

- Point A is the point of spark initiation (say 20^0bTDC)
- 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

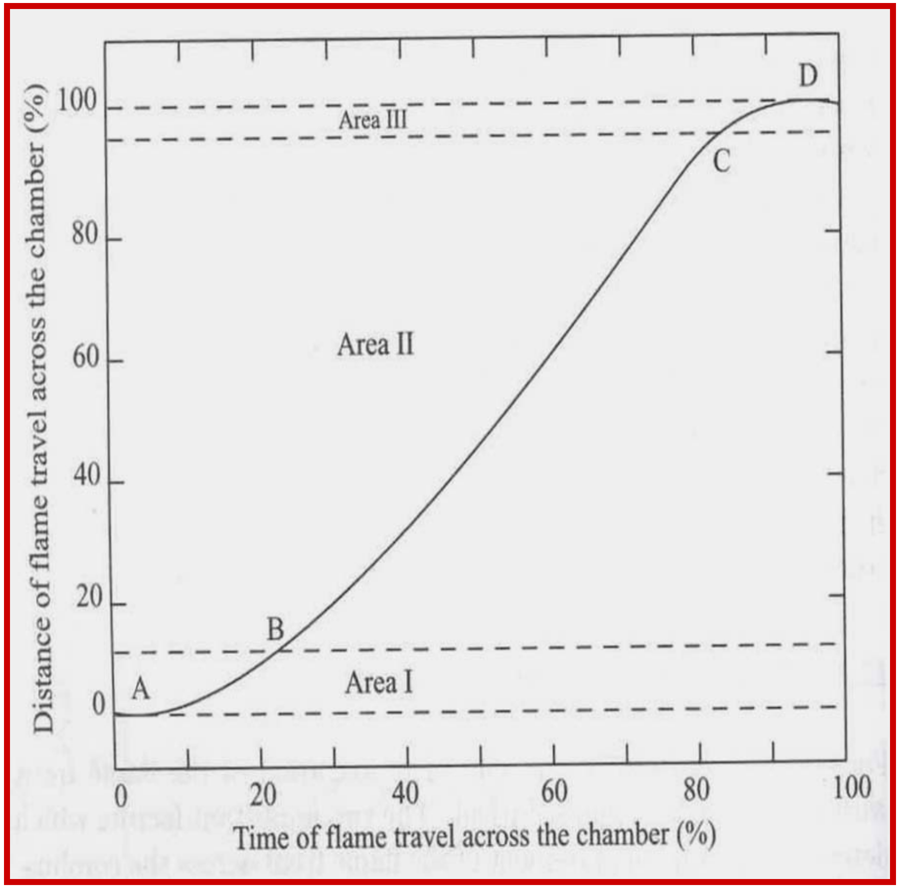
- low transposition rate
- low reaction rate

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

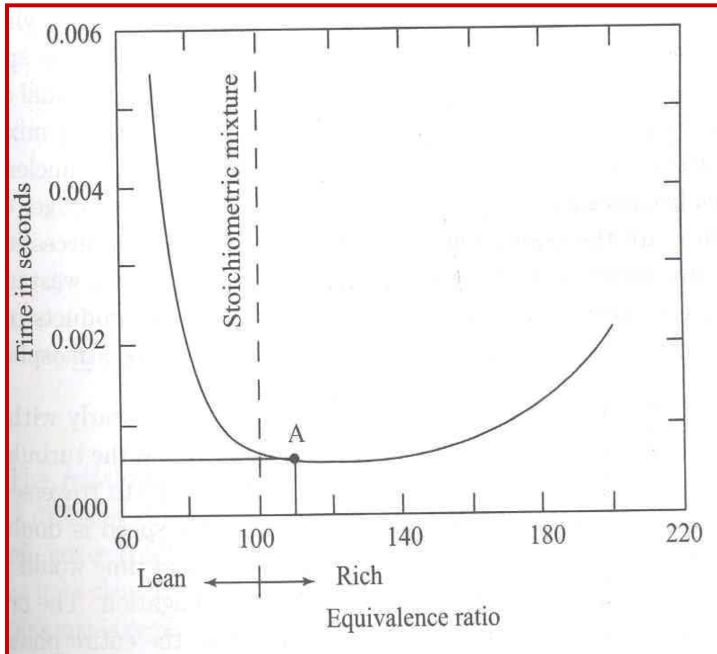


Fig. 12.4 Effect of Mixture Strength on the Rate of Burning

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.*

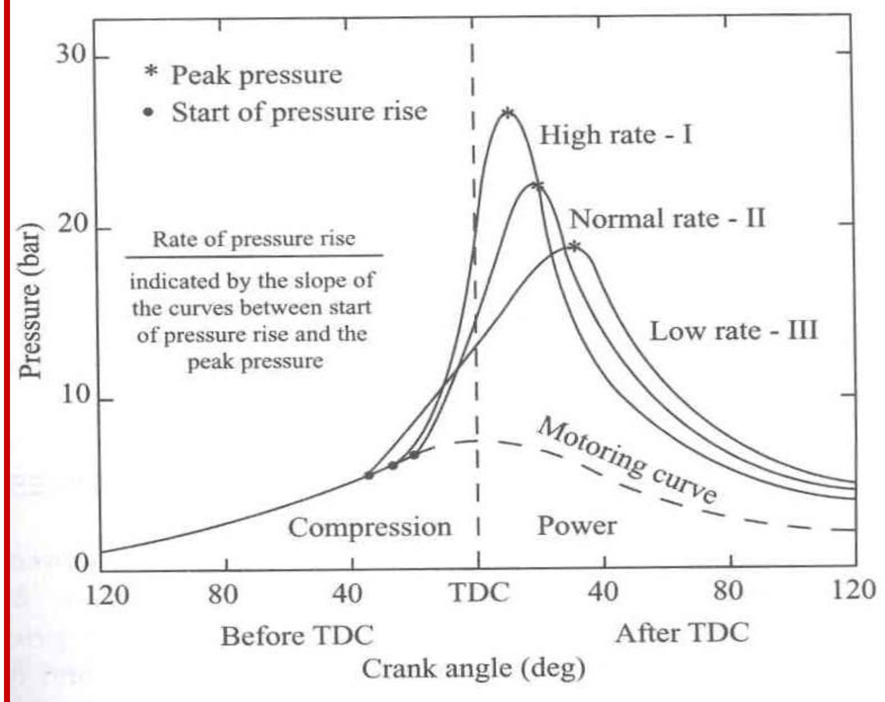


Fig. 12.5 Illustrations of Various Combustion Rates

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.

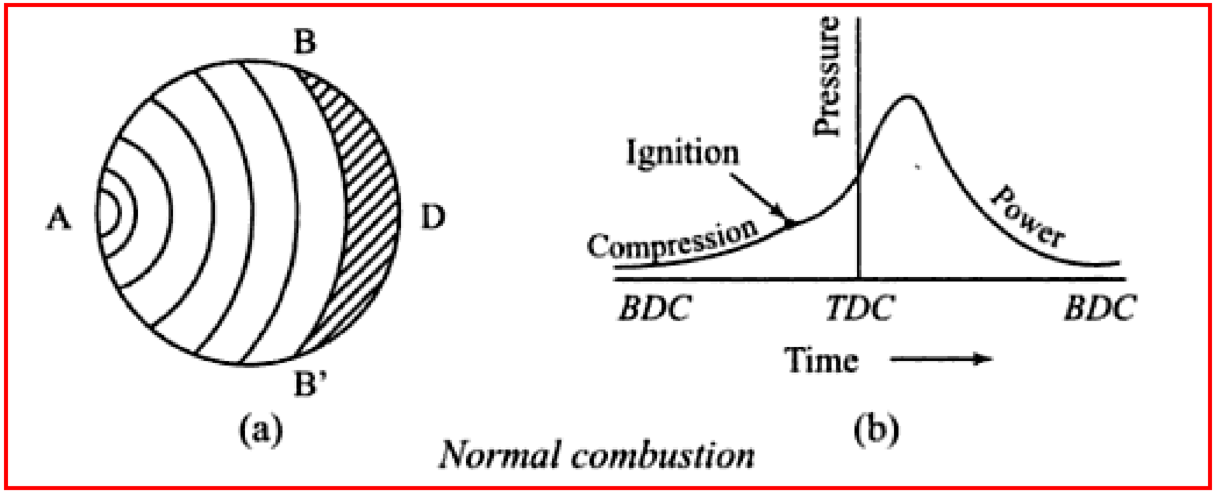
- Surface Ignition is ignition of the fuel-air mixture by a hot spot on the combustion chamber walls such as an overheated valve or spark plug, or glowing combustion-chamber deposit: i.e., by any means other than the normal spark discharge.
  - Following surface ignition, a flame develops at each surface-ignition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

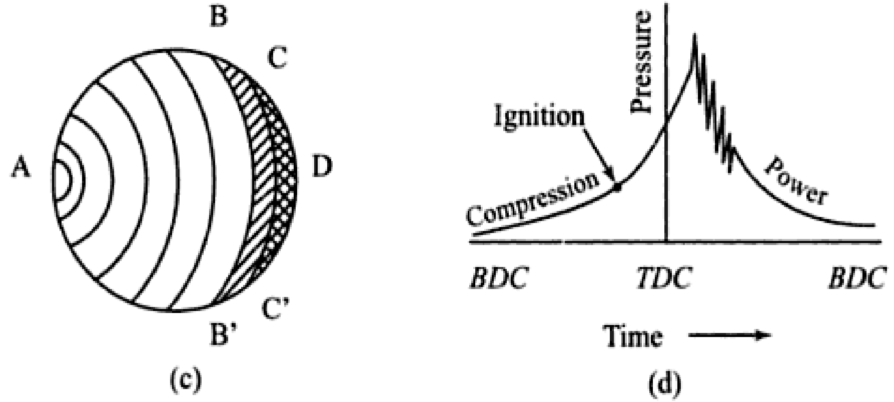
- The advancing flame *front* compresses *the end charge BB'D* farthest from the spark plug, thus raising its temperature.



- 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

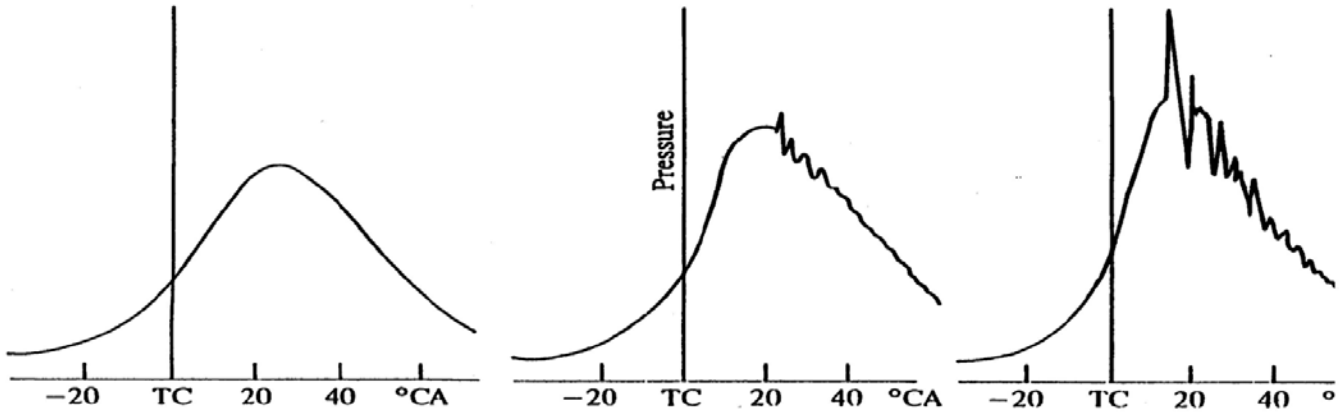
- However, *if the end charge BB'D reaches its auto ignition temperature the charge will auto ignite, leading to knocking combustion.*
- it is assumed that when flame has reached the position BB', *the charge ahead of it has reached critical auto-ignition temperature.*

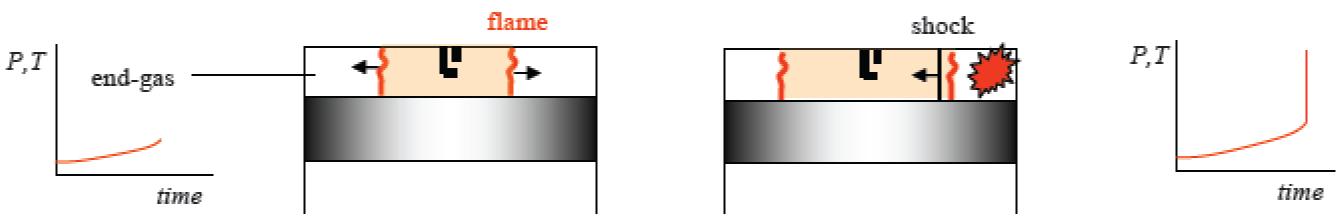


Combustion with detonation

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.*

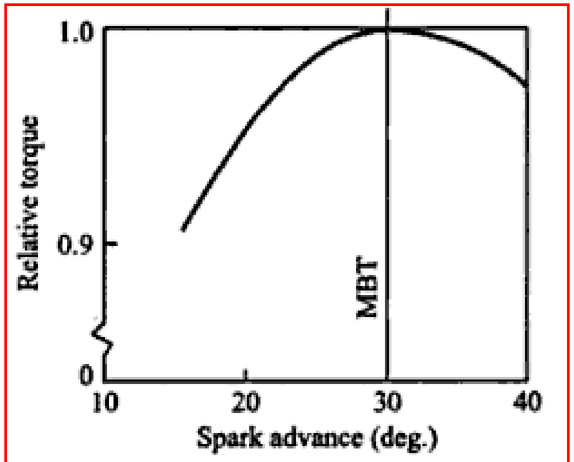


Figure 6.7 Effect of spark advance on brake torque.

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 Chambers For SI Engines

- The design of the combustion chamber for an SI engine has an important influence on the *engine performance and its knocking tendencies*.
- The design involves
  - *the shape of the combustion chamber,*
  - *the location of spark plug and*
  - *the location of inlet and exhaust valves.*
- The *important requirements of an SI engine* combustion chamber are
  - *to provide high power output with minimum octane requirement,*
  - *high thermal efficiency and*
  - *smooth engine operation.*

Combustion Chambers For SI Engines

I. Smooth engine operation

- The aim of any engine design is to have *a smooth operation and a good economy.*
- These can be achieved by the following:

a. *Moderate Rate of Pressure Rise*

- Limiting the rate of pressure rise as well as the position of the peak pressure with respect to TDC affect smooth engine operation.

Combustion Chambers For SI Engines

b. *Reducing the Possibility of Knocking*

- Reduction in the possibility of knocking in an engine can be achieved by,
  - ***Reducing the distance of the flame travel*** by centrally locating the spark plug and also by avoiding pockets of stagnant charge.
  - ***Satisfactory cooling of the spark plug and of exhaust valve area*** which are the source of hot spots in the majority of the combustion chambers.
  - ***Reducing the temperature of the last portion of the charge***, through application of a high surface to volume ratio in that part where the last portion of the charge burns.

Combustion Chambers For SI Engines

II. High Power Output and Thermal Efficiency

This can be achieved by considering the following factors:

a. A high degree of turbulence is needed to achieve a high flame front velocity.

- Turbulence is induced by *inlet flow configuration or squish*
- *Squish is the rapid radial movement of the gas trapped in between the piston and the cylinder head into the bowl or the dome.*
- *Squish can be induced in spark-ignition engines by having a bowl in piston or with a dome shaped cylinder head.*

Combustion Chambers For SI Engines

b. High Volumetric Efficiency

- More charge during the suction stroke, results in an increased power output.
- This can be achieved by providing ample clearance around the valve heads,
- large diameter valves and straight passages with minimum pressure drop.

c. Improved anti-knock characteristics

- Improved anti-knock characteristics permits the use of a higher compression ratio resulting in increased output and efficiency.

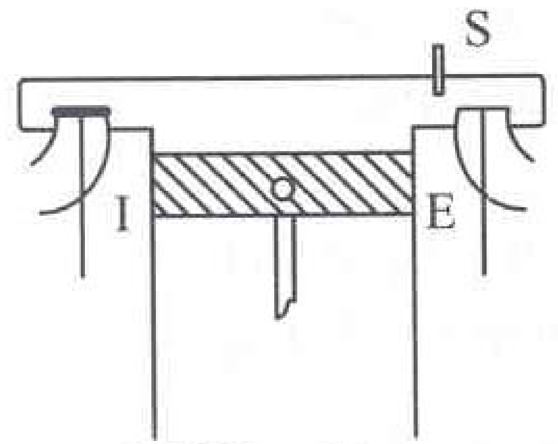
Combustion Chambers For SI Engines

d. *A Compact Combustion Chamber*

- Reduces heat loss during combustion and increases the thermal efficiency.
- Different types combustion chambers have been developed over a period of time Some of them are shown in Fig.
  - T-Head Type
  - L-Head Type
  - I-Head Type or Overhead Valve
  - F-Head Type

T-Head Type:

- The T-head combustion chambers were used in the early stage of engine development.
- Since the distance across the combustion chamber is very long, *knocking tendency is high in this type of engines.*
- *This configuration provides two valves on either side of the cylinder, requiring two camshafts.* From the manufacturing point of view, providing two camshafts is a disadvantage.

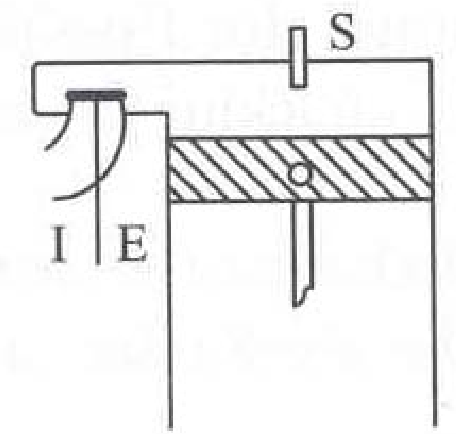


(a) T-head type

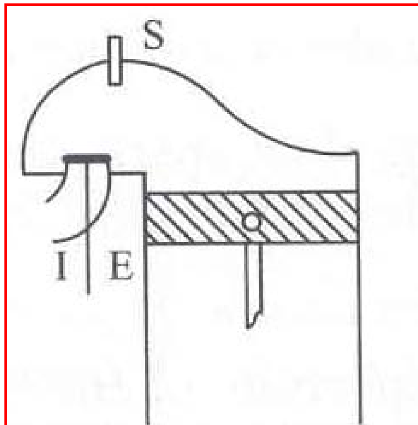
L-Head Type

- A modification of the T-head type of combustion chamber is the L-head type which *provides the two valves on the same side of the cylinder and the valves are operated by a single camshaft.*

- *The main objectives of the Ricardo's turbulent head design, Fig (c), axle to obtain fast flame speed and reduced knock*



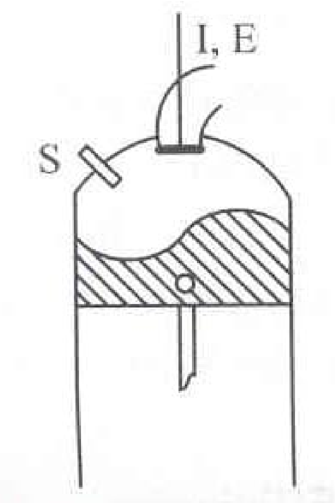
(b) L-head type



(c) L-head type

I Head Type or Overhead Valve:

- *In which both the valves are located on the cylinder head.*
- The overhead valve engine is superior to a side valve or an L-head engine at high compression ratios.
- Some of the important characteristics of this type of valve arrangement are:
  - *less surface to volume ratio and therefore less heat loss*
  - *less flame travel length and hence greater freedom from knock*
  - *higher volumetric efficiency from larger valves or valve lifts*



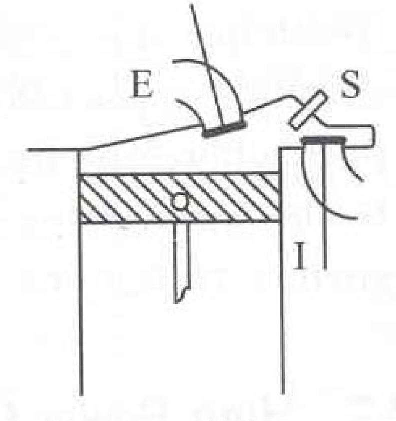
(d) I-head type

F-Head Type:

The F-head type of valve arrangement is a compromise between L-head and I-head types.

Combustion chambers in which one valve is in the cylinder head and the other in the cylinder block are known as F-head combustion chambers

Modern F-head engines have exhaust valve in the head and inlet valve in the cylinder block.



(e) F-head type

The main disadvantage of this type is that the inlet valve and the exhaust valve are separately actuated by two cams mounted on to camshafts driven by the crankshaft through gears.