

INTERNAL COMBUSTION ENGINES AND GAS TURBINES

MODULE - I

1. INTRODUCTION:

The **internal combustion engine** is a heat engine that converts chemical energy in a fuel into mechanical energy, usually made available on a rotating output shaft. Chemical energy of the fuel is first converted to thermal energy by means of combustion. This thermal energy raises the temperature and pressure of the gases within the engine, and the high-pressure gas then expands against the mechanical mechanisms of the engine. This expansion is converted by the mechanical linkages of the engine to a rotating crankshaft, which is the output of the engine. The crankshaft, in turn, is connected to a transmission and/or power train to transmit the rotating mechanical energy to the desired final use.

I. ENGINE CLASSIFICATIONS

- **Types of Ignition**

(a) **Spark Ignition (SI)**. An SI engine starts the combustion process in each cycle by use of a spark plug. The spark plug gives a high-voltage electrical discharge between two electrodes which ignites the air-fuel mixture in the combustion chamber surrounding the plug. In early engine development, before the invention of the electric spark plug, many forms of torch holes were used to initiate combustion from an external flame.

(b) **Compression Ignition (CI)**. The combustion process in a CI engine starts when the air-fuel mixture self-ignites due to high temperature in the combustion chamber caused by high compression.

- **Engine Cycle**

(a) **Four-Stroke Cycle**. A four-stroke cycle experiences four piston movements over two engine revolutions for each cycle.

(b) **Two-Stroke Cycle**. A two-stroke cycle has two piston movements over one revolution for each cycle.

- **Valve Location (see Fig. 1-4)**

(a) Valves in head (overhead valve), also called **I Head** engine.

(b) Valves in block (flat head), also called **L Head** engine.

(c) One valve in head (usually intake) and one in block, also called **F Head** engine

- **Basic Design**

(a) **Reciprocating**. Engine has one or more cylinders in which pistons reciprocate back and forth.

(b) **Rotary**. Engine is made of a block (stator) built around a large non-concentric rotor and crankshaft.

- **Air Intake Process**

(a) **Naturally Aspirated**. No intake air pressure boost system.

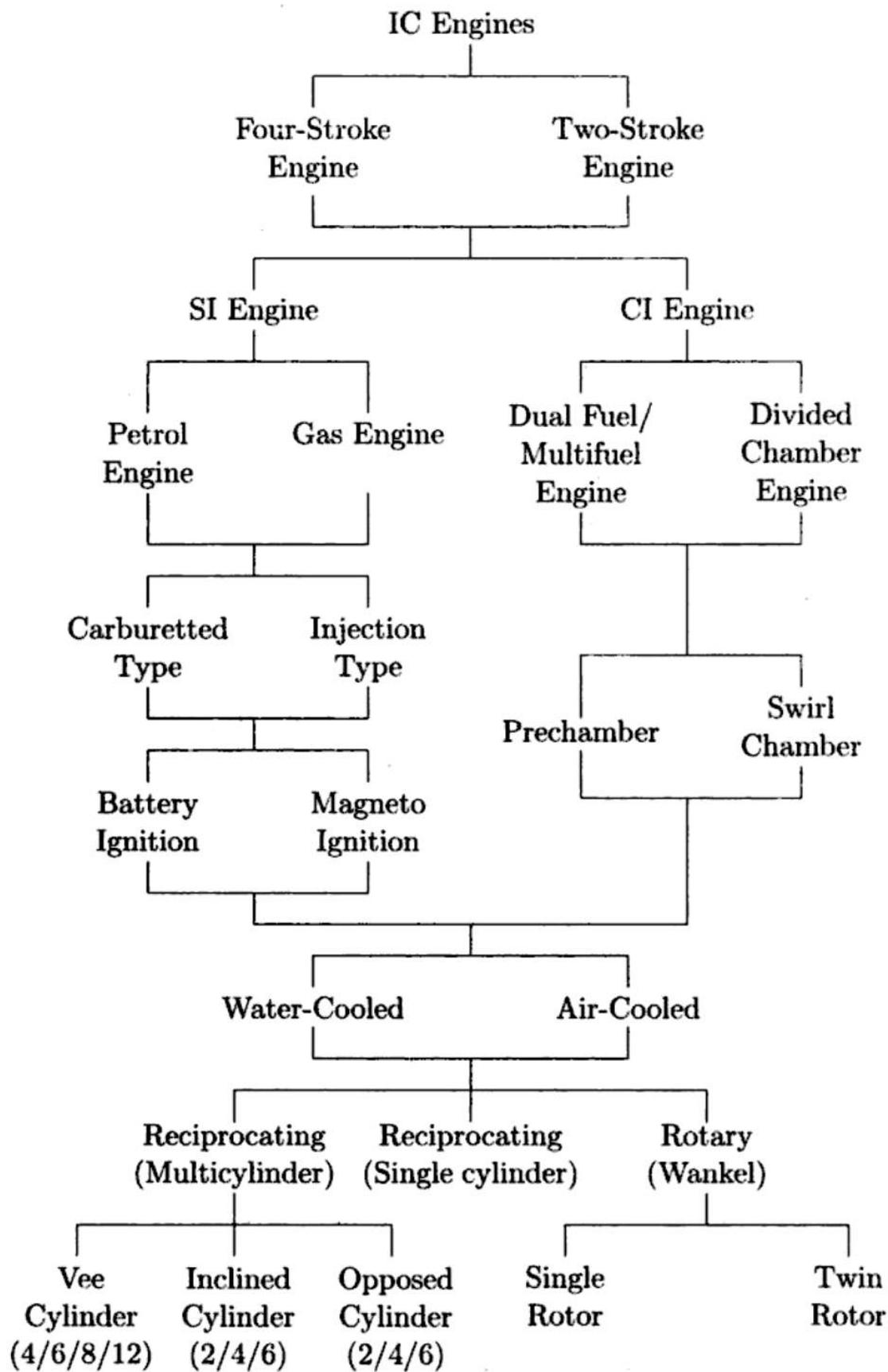
(b) **Supercharged**. Intake air pressure increased with the compressor driven off of the engine crankshaft (Fig. 1-8)

(c) **Turbocharged**. Intake air pressure increased with the turbine-compressor driven by the engine exhaust gases (Fig. 1-9).

(d) **Crankcase Compressed**. Two-stroke cycle engine which uses the crankcase as the intake air compressor. Limited development work has also been done on design and construction of four-stroke cycle engines with crankcase compression.

- **Method of Fuel Input for SI Engines**

- (a) **Carbureted.** fuel supplied through the carburettor
- (b) **Multipoint Port Fuel Injection.** fuel injected into inlet ports or inlet manifold, fuel injected into the cylinder just before ignition one or more injectors at each cylinder intake.
- (c) **Throttle Body Fuel Injection.** Injectors upstream in intake manifold.
- **Fuel Used**
 - (a) Gasoline.
 - (b) Diesel Oil or Fuel Oil.
 - (c) Gas, Natural Gas, Methane.
 - (d) LPG.
 - (e) Alcohol-Ethyl, Methyl.
 - (f) Dual Fuel. There are a number of engines that use a combination of two or more fuels. Some, usually large, CI engines use a combination of methane and diesel fuel.
- **According to the working cycle-**
 - (a) **Otto Cycle** (constant volume heat addition cycle/SI) engine
 - (b) **Diesel Cycle** (constant pressure heat addition cycle/CI) engine
 - (c) **Dual Combustion Cycle**
- **Type of Cooling**
 - (a) **Air Cooled.**
 - (b) **Liquid Cooled, Water Cooled**
- **Cylinder arrangement**
 - a) Vertical, horizontal,
 - b) inline,
 - c) V-type,
 - d) radial,
 - e) opposed cylinder or piston engines.
- **Application**
 - (a) Automobile, Truck, Bus.
 - (b) Locomotive.
 - (c) Stationary.
 - (d) Marine.
 - (e) Aircraft.
 - (f) Small Portable, Chain Saw, Model Airplane.



ii. Engine nomenclature

- **Piston Area (A)** : The area of circle of diameter equal to the cylinder bore (cm^2).
- **Cylinder Bore (D)** : Nominal inner diameter of the working cylinder (mm)
- **Stroke (L)**: The nominal distance through which a working piston moves between two successive reversals of its direction of motion.(m)
- **Dead Centre**: The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).
 - (a) *Bottom dead centre (BDC)*: Dead centre when the piston is nearest to the crankshaft.
 - (b) *Top dead centre (TDC)*: Dead centre when the position is farthest from the crankshaft.
- **Displacement Volume or Swept Volume (V_s)**: The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as,

$$\begin{array}{|c|} \hline V_s = A \times L \\ \hline V_s = \frac{\pi}{4} d^2 \times L \\ \hline \end{array}$$

- **Clearance Volume (V_c)**: The nominal volume of the space on the combustion side of the piston at the top dead centre.
- **Cylinder Volume (V_T)**: Total volume of the cylinder.

$$V_T = V_s + V_c$$

$$\frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c}$$

- **Stroke to Bore ratio(L/D)**:
 - $d < L$ – Under square engine
 - $d = L$ – Square engine
 - $d > L$ – Over square engine
- **Compression Ratio (r)**: ratio of total cylinder volume when piston is at BDC

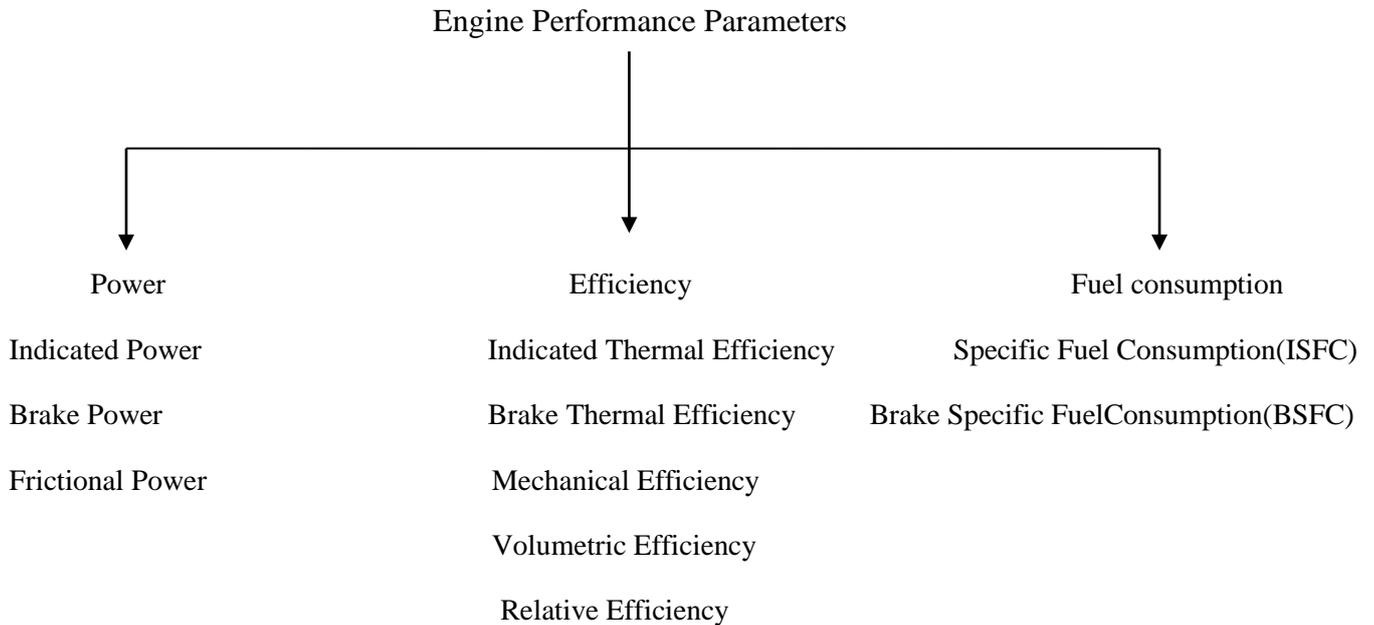
$$r = \frac{V_T}{V_c}$$

- **Cubic Capacity** : displacement volume of a cylinder multiplied by number of cylinders in an engine. No of cylinders = k

$$\text{Cubic capacity} = V_s \times k$$

- **Piston speed** : average piston speed = $2LN$ [N = Engine speed]

iii. Engine Operating and Performance Parameters



Indicated Power (ip) : power utilised to drive the piston available at piston head (kW)

$$ip = \frac{p_{im} V_s n K}{1000 \times 60}$$

p_{im} = indicated mean effective pressure (N/m^2),

n = number of strokes per minute [(N/2) 4stroke, (N) 2 stroke]

$$ip = \frac{p_{im} L A n K}{60000}$$

Brake Power (bp) : actual power available at crankshaft after friction and pumping loss while transmission from connecting rod to crankshaft .(kW)

$$bp = \frac{p_{bm} L A n K}{60000}$$

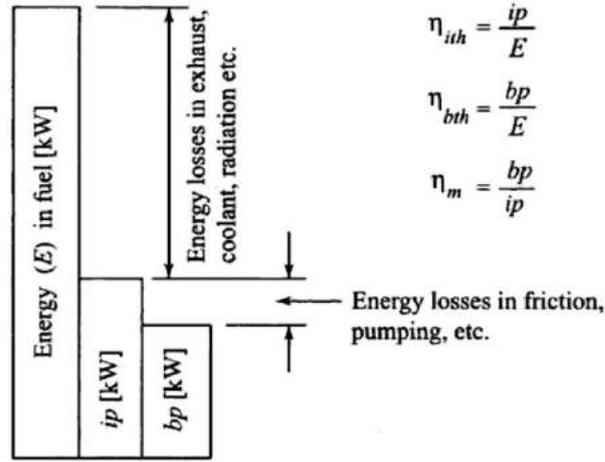
$$bp = \frac{2\pi NT}{60000}$$

Frictional Power (fp) : energy loss which is used for driving auxiliary devices (feed pump, valve & ignition system)

$$fp = ip - bp$$

$$fp = ip - bp$$

$$ip = bp + fp$$



$$\eta_{ith} = \frac{ip}{E}$$

$$\eta_{bth} = \frac{bp}{E}$$

$$\eta_m = \frac{bp}{ip}$$

Indicated Thermal Efficiency (η_{ith}): ratio of energy in indicated power to input fuel energy

$$\eta_{ith} = \frac{ip}{m_f \times CV} \quad m_f = \text{mass of fuel/s}$$

Brake Thermal Efficiency (η_{bth}): ratio of energy in brake power to input fuel energy

$$\eta_{bth} = \frac{bp}{m_f \times CV}$$

Mechanical Efficiency (η_m): ratio of brake power (delivered power) to indicated power (power to piston)

$$\eta_m = \frac{bp}{ip} = \frac{bp}{bp + fp}$$

$$\eta_m = \frac{\eta_{bth}}{\eta_{ith}}$$

Volumetric Efficiency (η_v) it is defined as ratio of actual mass of air drawn into engine during a given of time to the theoretical mass which should have been drawn in during that same period of time, based upon total piston displacement of engine, surrounding atmospheric pressure and temperature (**breathing ability of engine**)

$$\eta_m = \frac{m_{act}}{m_{th}}$$

Relative Efficiency (η_{rel}) : ratio of thermal efficiency of actual cycle to that of ideal cycle (**Efficiency ratio**).

$$\eta_{rel} = \frac{\text{Actual thermal efficiency}}{\text{Air-standard efficiency}}$$

Specific Fuel Consumption : (sfc) = $\frac{\text{Fuel consumption per unit time}}{\text{power}}$

It is inversely proportional to thermal efficiency of engine

$$\begin{aligned} \text{Indicated Specific Fuel Consumption (ISFC)} &= \frac{\text{Fuel consumption (kg/h)}}{ip(\text{kW})} \\ &= \frac{m_f}{ip} \text{ (kg/kWh)} \end{aligned}$$

$$\begin{aligned} \text{Brake Specific Fuel Consumption (BSFC)} &= \frac{\text{Fuel consumption (kg/h)}}{bp(\text{kW})} \\ &= \frac{m_f}{bp} \text{ (kg/kWh)} \end{aligned}$$

(F/A) Fuel-Air or Air- Fuel ratio (A/F)

$$\begin{aligned} \frac{F}{A} &= \frac{m_f}{m_a} \\ \frac{A}{F} &= \frac{m_a}{m_f} \end{aligned}$$

Equivalence Ratio (Φ) Ratio of actual fuel-air ratio to stoichiometric fuel-air ratio .

$$\begin{aligned} \Phi &= \frac{\text{actual fuel-air ratio}}{\text{stoichiometric fuel-air ratio}} & \Phi < 1 \text{ (lean mix)} \\ & & \Phi = 1 \text{ (stoichiometric mix)} \\ & & \Phi > 1 \text{ (rich mix)} \end{aligned}$$

Calorific Value (CV) : Calorific value of fuel is thermal energy released per unit quantity of fuel when burned completely and product of combustion are cooled back to the initial temperature of combustible mixture.

Mean effective pressure (p_m) : average pressure inside the cylinder based upon power output.

Indicated mean effective pressure (p_{im}) (imep): $\frac{\text{Area of the indicator diagram}}{\text{length of the indicator diagram}}$

$$p_{im} : \frac{\text{Net work of cycle}}{V_1 - V_2}$$

Brake Mean Effective Pressure (p_{bm}) (bmep): portion of imep which goes into development of useful power.

$$\text{imep} = \text{bmep} + \text{fmep}$$

$$\frac{\text{bmep}}{\text{imep}} = \frac{\text{bp}}{\text{ip}} = \eta_m$$

Four Stroke Spark Ignition Engine (SI) or Petrol Engine

The four-stroke cycle petrol engines operate on Otto (constant volume) cycle shown in Since ignition in these engines is due to a spark, they are also called spark ignition engines. The four different strokes are:

I) Suction Stroke

ii) Compression Stroke

iii) Working Or Power Or Expansion Stroke

iv) Exhaust Stroke.

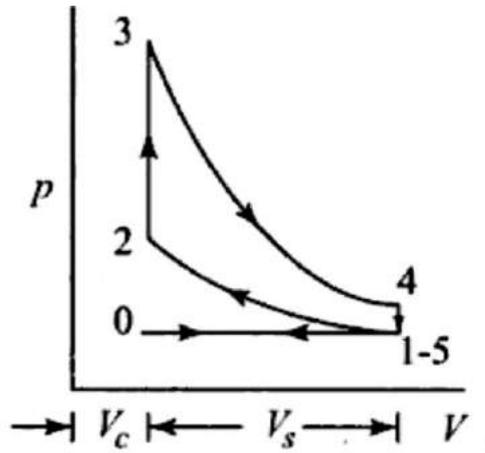
The construction and working of a four-stroke petrol engine is shown

Suction Stroke : During suction stroke, the piston is moved from the top dead centre to the bottom dead centre by the crank shaft. The crank shaft is revolved either by the momentum of the flywheel or by the electric starting motor. The inlet valve remains open and the exhaust valve is closed during this stroke. The proportionate air-petrol mixture is sucked into the cylinder due to the downward movement of the piston. This operation is represented by the line AB on the P-V diagram.

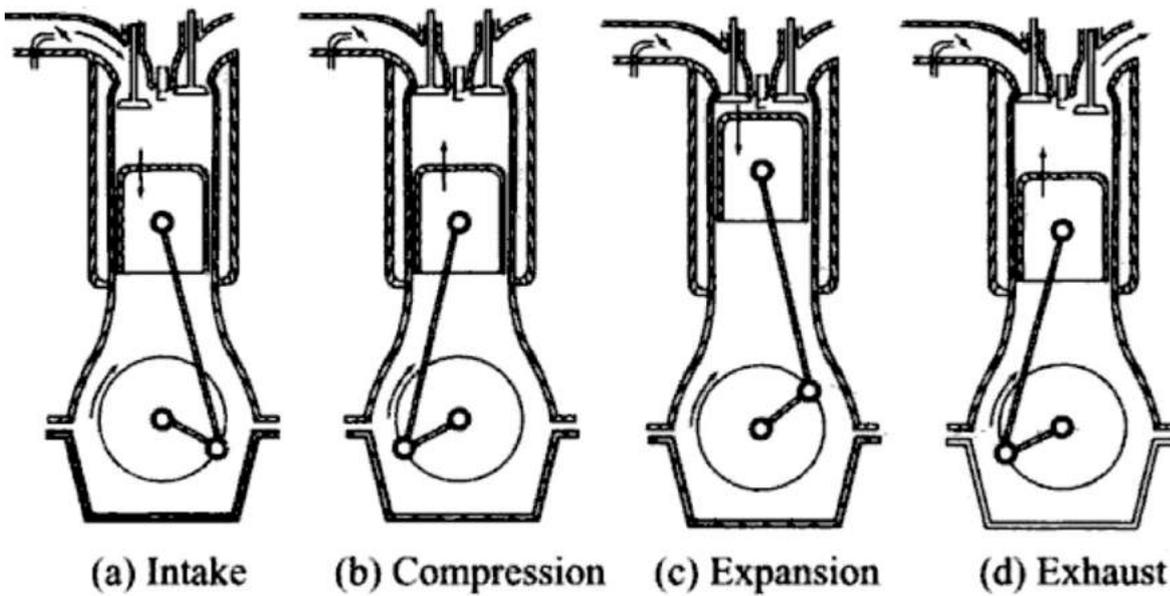
Compression Stroke: During compression stroke, the piston moves from bottom dead centre to the top dead centre, thus compressing air petrol mixture. Due to compression, the pressure and temperature are increased and is shown by the line BC on the P- V diagram. Just before the end of this stroke the spark - plug initiates a spark, which ignites the mixture and combustion takes place at constant volume as shown by the line CD. Both the inlet and exhaust valves remain closed during this stroke.

Working Stroke: The expansion of hot gases exerts a pressure on the piston. Due to this pressure, the piston moves from top dead centre to bottom dead centre and thus the work is obtained in this stroke. Both the inlet and exhaust valves remain closed during this stroke. The expansion of the gas is shown by the curve DE.

Exhaust Stroke: During this stroke, the inlet valve remains closed and the exhaust valve opens. The greater part of the burnt gases escapes because of their own expansion. The drop in pressure at constant volume is represented by the line EB. The piston moves from bottom dead centre to top dead centre and pushes the remaining gases to the atmosphere. When the piston reaches the top dead centre the exhaust valve closes and cycle is completed. This stroke is represented by the line BA on the P- V diagram. The operations are repeated over and over again in running the engine. Thus a four stroke engine completes one working cycle, during this the crank rotate by two revolution.



Ideal PV dia of 4 stroke SI engine



Working principle of four stroke SI Engine

Four Stroke Compression Ignition Engine (CI) or Diesel Engine.

The four stroke cycle diesel engine operates on diesel cycle or constant pressure cycle. Since ignition in these engines is due to the temperature of the compressed air, they are also called compression ignition engines.

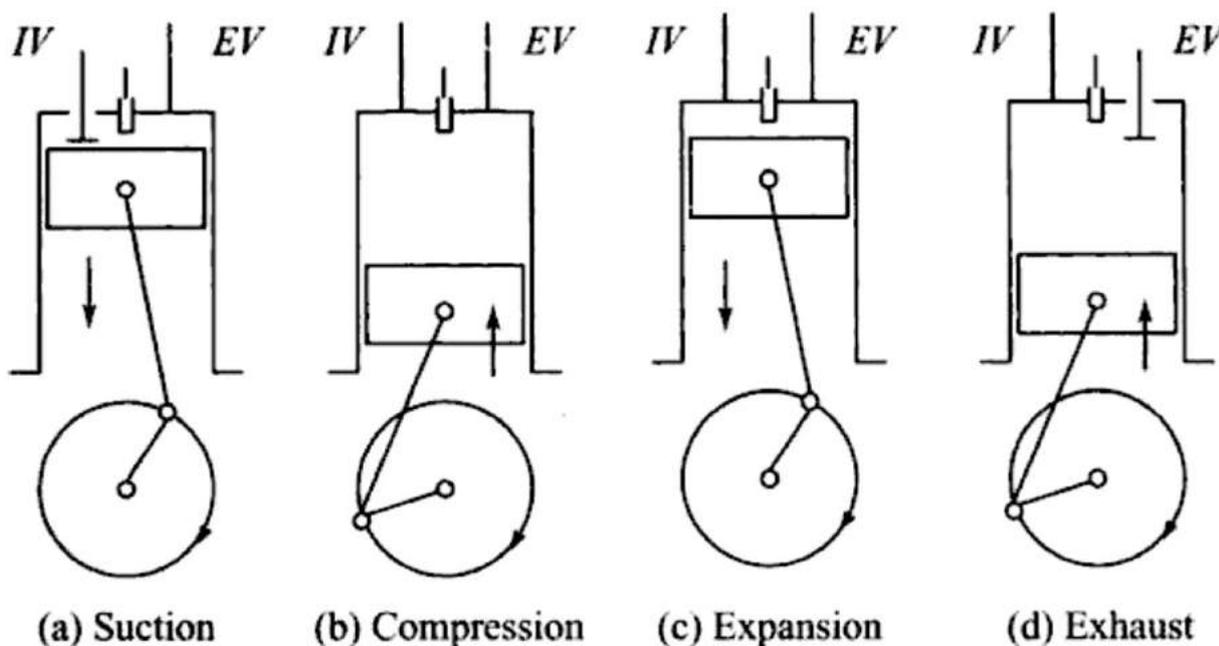
Suction Stroke: During suction stroke, the piston is moved from the top dead centre to the bottom dead centre by the crankshaft. The crankshaft is revolved either by the momentum of the flywheel or by the power generated by the electric starting motor. The inlet valve remains open and the exhaust valve is closed during this stroke. The air is sucked into the cylinder due to the downward movement of the piston.

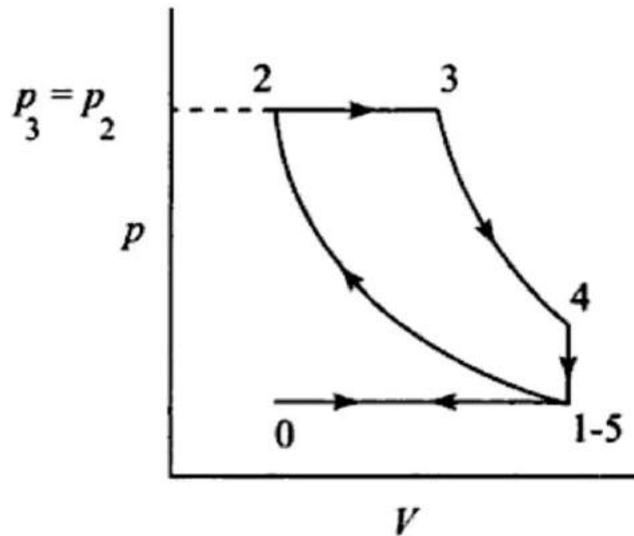
Compression Stroke: The air drawn at the atmospheric pressure during suction stroke is compressed to high pressure and temperature as piston moves from the bottom dead centre to top dead centre. This operation is represented by the curve BC on the P- V diagram. Just before the end of this stroke, a metered quantity of fuel is injected into the hot compressed air in the form of fine sprays by means of fuel injector. The fuel starts burning at constant pressure shown by the line CD. At point D, fuel supply is cut off, Both the inlet and exhaust valves remain closed during this stroke.

Working Stroke: The expansion of gases due to the heat of combustion exerts a pressure on the piston. Under this impulse, the piston moves from top dead centre to the bottom dead centre and thus work is obtained in this stroke. Both the inlet and exhaust valves remain closed during this stroke. The expansion of the gas is shown by the curve DE.

Exhaust Stroke: During this stroke, the inlet valve remains closed and the exhaust valve opens. The greater part of the burnt gases escapes because of their own expansion. The vertical line EB represents the drop in pressure at constant volume. The piston moves from bottom dead centre to top dead centre and pushes the remaining gases to the atmosphere. When the piston reaches the top dead centre the exhaust valve closes and the cycle is completed.

Working principle of four stroke CI Engine



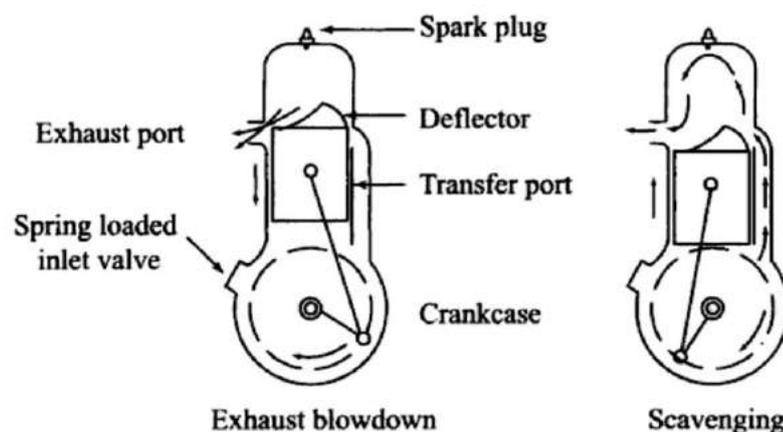


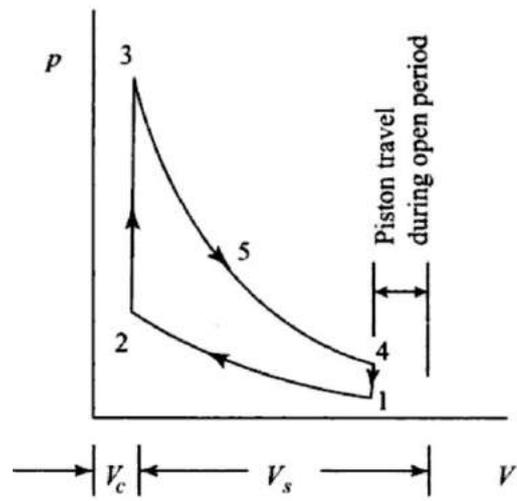
Ideal PV dia of 4 stroke CI engine

2 Stroke SI Engine

Upward Stroke : During the upward stroke, the piston moves from bottom dead centre to top dead centre, compressing the air-petrol mixture in the cylinder. The cylinder is connected to a closed crank chamber. Due to upward movement of the piston, a partial vacuum is created in the crankcase, and a new charge is drawn into the crank case through the uncovered inlet port. The exhaust port and transfer port are covered when the piston is at the top dead centre position. The compressed charge is ignited in the combustion chamber by a spark provided by the spark plug.

Downward Stroke: As soon as the charge is ignited, the hot gases force the piston to move downwards, rotating the crankshaft, thus doing the useful work. During this stroke the inlet port is covered by the piston and the new charge is compressed in the crank case .Further downward movement of the piston uncovers first the exhaust port and then the transfer port . The burnt gases escape through the exhaust port. As soon as the transfer port opens, the compressed charge from the crankcase flows into the cylinder. The charge is deflected upwards by the hump provided on the head of the piston and pushes out most of the exhaust gases. It may be noted that the incoming air-petrol mixture helps the removal of burnt gases from the engine cylinder. If in case these exhaust gases do not leave the cylinder, the fresh charge gets diluted and efficiency of the engine will decrease. The cycle of events is then repeated.





Ideal Indicator Diagram of a Two-Stroke SI Engine

Four-Stroke Engine

The thermodynamic cycle is completed in four strokes of the piston or in two revolutions of the crankshaft. Thus, one power stroke is obtained in every two revolutions of the crankshaft.

Because of the above, turning moment is not so uniform and hence a heavier flywheel is needed.

Again, because of one power stroke for two revolutions, power produced for same size of engine is less, or for the same power the engine is heavier and bulkier.

Because of one power stroke in two revolutions lesser cooling and lubrication requirements. Lower rate of wear and tear.

Four-stroke engines have valves and valve actuating mechanisms for opening and closing of the intake and exhaust valves.

Because of comparatively higher weight and complicated valve mechanism, the initial cost of the engine is more.

Volumetric efficiency is more due to more time for induction.

Thermal efficiency is higher; part load efficiency is better.

Used where efficiency is important, viz., in cars, buses, trucks, tractors, industrial engines, aeroplanes, power generation etc.

Two-Stroke Engine

The thermodynamic cycle is completed in two strokes of the piston or in one revolution of the crankshaft. Thus one power stroke is obtained in each revolution of the crankshaft.

Because of the above, turning moment is more uniform and hence a lighter flywheel can be used.

Because of one power stroke for every revolution, power produced for same size of engine is twice, or for the same power the engine is lighter and more compact.

Because of one power stroke in one revolution greater cooling and lubrication requirements. Higher rate of wear and tear.

Two-stroke engines have no valves but only ports (some two-stroke engines are fitted with conventional exhaust valve or reed valve).

Because of light weight and simplicity due to the absence of valve actuating mechanism, initial cost of the engine is less.

Volumetric efficiency is low due to lesser time for induction.

Thermal efficiency is lower; part load efficiency is poor.

Used where low cost, compactness and light weight are important, viz., in mopeds, scooters, motorcycles, hand sprayers etc.

Solved examples

1.1 The cubic capacity of a four-stroke over-square spark-ignition engine is 245 cc. The over-square ratio is 1.1. The clearance volume is 27.2 cc. Calculate the bore, stroke and compression ratio of the engine.

Solution

$$\begin{aligned}\text{Cubic capacity, } V_s &= \frac{\pi}{4} d^2 L = \frac{\pi}{4} \frac{d^3}{1.1} = 245 \\ d^3 &= 343 \\ \text{Bore, } d &= \mathbf{7 \text{ cm}} \quad \underline{\underline{\text{Ans}}} \\ \text{Stroke, } L &= \frac{7}{1.1} = \mathbf{6.36 \text{ cm}} \quad \underline{\underline{\text{Ans}}} \\ \text{Compression ratio, } r &= \frac{V_s + V_c}{V_c} \\ &= \frac{245 + 27.2}{27.2} = \mathbf{10} \quad \underline{\underline{\text{Ans}}}\end{aligned}$$

1.2 The mechanical efficiency of a single-cylinder four-stroke engine is 80%. The frictional power is estimated to be 25 kW. Calculate the indicated power (*ip*) and brake power (*bp*) developed by the engine.

Solution

$$\begin{aligned}\frac{bp}{ip} &= 0.8 \\ ip - bp &= 25 \\ ip - 0.8 \times ip &= 25 \\ ip &= \frac{25}{0.2} = \mathbf{125 \text{ kW}} \quad \underline{\underline{\text{Ans}}} \\ bp &= ip - fp = 125 - 25 = \mathbf{100 \text{ kW}} \quad \underline{\underline{\text{Ans}}}\end{aligned}$$

1.3 A 42.5 kW engine has a mechanical efficiency of 85%. Find the indicated power and frictional power. If the frictional power is assumed to be constant with load, what will be the mechanical efficiency at 60% of the load?

Solution

$$\begin{aligned} \text{Indicated power, } ip &= \frac{bp}{\eta_m} = \frac{42.5}{0.85} = \mathbf{50 \text{ kW}} \quad \underline{\underline{\text{Ans}}} \\ \text{Frictional power, } fp &= ip - bp = 50 - 42.5 \\ &= \mathbf{7.5 \text{ kW}} \quad \underline{\underline{\text{Ans}}} \\ \text{Brake power at 60\% load} &= 42.5 \times 0.6 = 25.5 \text{ kW} \\ \text{Mechanical efficiency } \eta_m &= \frac{bp}{bp + fp} = \frac{25.5}{25.5 + 7.5} \\ &= 0.773 = \mathbf{77.3\%} \quad \underline{\underline{\text{Ans}}} \end{aligned}$$

AIR STANDARD CYCLES

3.5 THE OTTO CYCLE

The main drawback of the Carnot cycle is its impracticability due to high pressure and high volume ratios employed with comparatively low mean effective pressure. Nicolaus Otto (1876), proposed a constant-volume heat addition cycle which forms the basis for the working of today's spark-ignition engines. The cycle is shown on p - V and T - s diagrams in Fig.3.5(a) and 3.5(b) respectively.

When the engine is working on full throttle, the processes 0→1 and 1→0 on the p - V diagram represents suction and exhaust processes and their effect is nullified. The process 1→2 represents isentropic compression of the air when the piston moves from

bottom dead centre to top dead centre. During the process 2→3 heat is supplied reversibly at constant volume. This process corresponds to spark-ignition and combustion in the actual engine. The processes 3→4 and 4→1 represent isentropic expansion and constant volume heat rejection respectively.

At point 1, the piston is at the bottom dead centre (BDC) position and air is trapped inside the engine cylinder. As the piston moves upwards with valves closed, air is compressed isentropically, represented by process 1—2. At point 2, the piston reaches the top dead centre (TDC) position. Heat is supplied to the air from an outer source the constant volume process 2—3. In an actual engine, it is equivalent to burning of fuel instant by an electric spark. At point 3, air is at its highest pressure and

. It is now able to push the piston from TDC to BDC and hence produces the work output. This process of expansion is an isentropic process represented by process 3-4. At the end of this expansion process, the heat is rejected at constant volume represented by process 4—1. The cycle is thus completed.

Let us summarize:

Process 1—2 is reversible adiabatic or isentropic compression. There is no heat transfer.

Process 2—3 is reversible constant volume heating.

Process 3—4 is reversible adiabatic or isentropic expansion. There is no heat transfer.

Process 4—1 is reversible constant volume heat rejection.

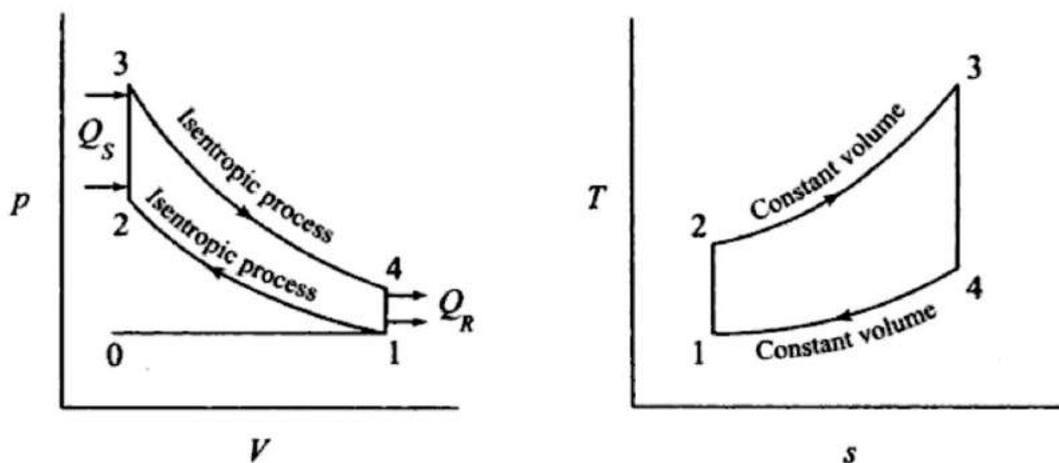


Fig. 3.5 Otto Cycle

3.5.1 Thermal Efficiency

The thermal efficiency of Otto cycle can be written as

$$\eta_{Otto} = \frac{Q_S - Q_R}{Q_S} \quad (3.14)$$

Considering constant volume processes 2→3 and 4→1, the heat supplied and rejected of air can be written as

$$Q_S = mC_v(T_3 - T_2) \quad (3.15)$$

$$Q_R = mC_v(T_4 - T_1) \quad (3.16)$$

$$\begin{aligned} \eta_{Otto} &= \frac{m(T_3 - T_2) - m(T_4 - T_1)}{m(T_3 - T_2)} \\ &= 1 - \frac{T_4 - T_1}{T_3 - T_2} \end{aligned} \quad (3.17)$$

Considering isentropic processes 1→2 and 3→4, we have

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{(\gamma-1)} \quad (3.18)$$

and

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{(\gamma-1)} \quad (3.19)$$

But the volume ratios V_1/V_2 and V_4/V_3 are equal to the compression ratio, r . Therefore,

$$\frac{V_1}{V_2} = \frac{V_4}{V_3} = r \quad (3.20)$$

therefore,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad (3.21)$$

From Eq.3.21, it can be easily shown that

$$\frac{T_4}{T_3} = \frac{T_1}{T_2} = \frac{T_4 - T_1}{T_3 - T_2} \quad (3.22)$$

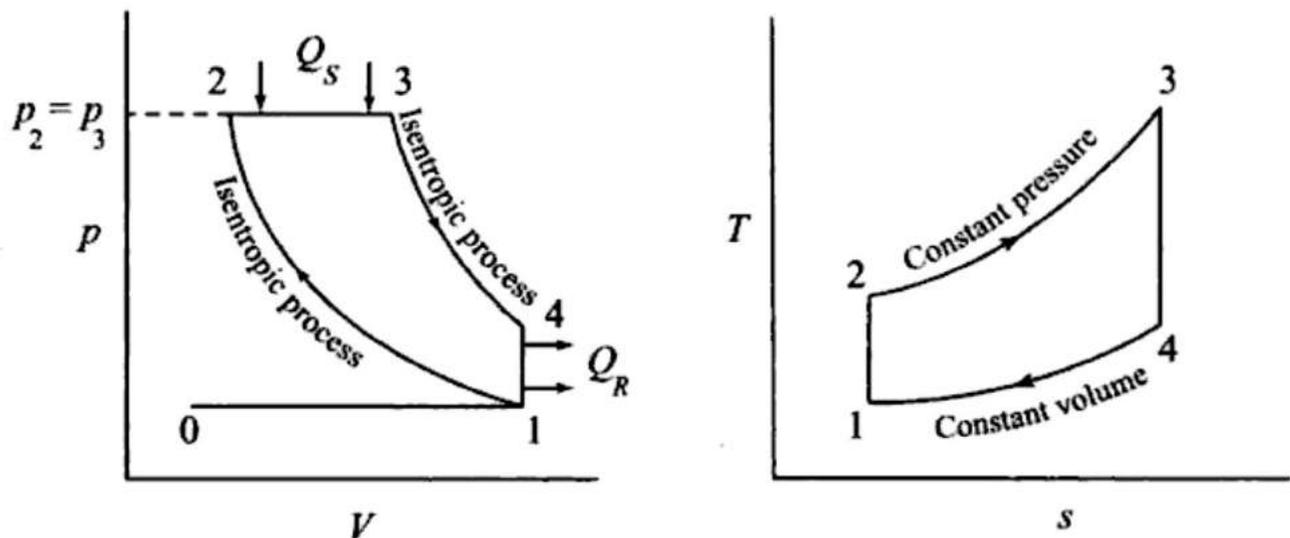
$$\eta_{Otto} = 1 - \frac{T_1}{T_2} \quad (3.23)$$

$$= 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{(\gamma-1)}} \quad (3.24)$$

$$= 1 - \frac{1}{r^{(\gamma-1)}} \quad (3.25)$$

DIESEL CYCLE

In this cycle, heat is added at constant pressure and rejected at constant volume. The compression and expansion processes are isentropic. The p-V and T-s diagrams are shown



Process 1—2 is isentropic compression. There is no heat transfer.

Process 2—3 is reversible constant pressure process. Heat is supplied during this process.

Process 3—4 is isentropic expansion. There is no heat transfer.

Process 4—1 is reversible constant volume process. Heat is rejected during this process

3.6.1 Thermal Efficiency

The thermal efficiency of the Diesel cycle is given by

$$\begin{aligned}
 \eta_{Diesel} &= \frac{Q_S - Q_R}{Q_S} \\
 &= \frac{mC_p(T_3 - T_2) - mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} \\
 &= 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)} \\
 &= 1 - \frac{1}{\gamma} \left(\frac{T_4 - T_1}{T_3 - T_2} \right)
 \end{aligned}$$

Considering the process 1→2

$$T_2 = T_1 \left(\frac{V_1}{V_2} \right)^{(\gamma-1)} = T_1 r^{(\gamma-1)}$$

Considering the constant pressure process 2→3, we have

$$\begin{aligned}
 \frac{V_2}{T_2} &= \frac{V_3}{T_3} \\
 \frac{T_3}{T_2} &= \frac{V_3}{V_2} = r_c \quad (\text{say})
 \end{aligned}$$

$$T_3 = T_2 r_c$$

From Eqs.3.34 and 3.35, we have

$$T_3 = T_1 r^{(\gamma-1)} r_c$$

Considering process 3→4, we have

$$\begin{aligned}
 T_4 &= T_3 \left(\frac{V_3}{V_4} \right)^{(\gamma-1)} \\
 &= T_3 \left(\frac{V_3}{V_2} \times \frac{V_2}{V_4} \right)^{(\gamma-1)}
 \end{aligned}$$

$$= T_3 \left(\frac{r_c}{r} \right)^{(\gamma-1)}$$

From Eqs.3.36 and 3.37, we have

$$\begin{aligned} T_4 &= T_1 r^{(\gamma-1)} r_c \left(\frac{r_c}{r} \right)^{(\gamma-1)} = T_1 r_c^\gamma \\ \eta_{Diesel} &= 1 - \frac{1}{\gamma} \left[\frac{T_1 (r_c^\gamma - 1)}{T_1 (r^{(\gamma-1)} r_c - r^{(\gamma-1)})} \right] \\ &= 1 - \frac{1}{\gamma} \left[\frac{(r_c^\gamma - 1)}{r^{(\gamma-1)} r_c - r^{(\gamma-1)}} \right] \\ &= 1 - \frac{1}{r^{(\gamma-1)}} \left[\frac{r_c^\gamma - 1}{\gamma (r_c - 1)} \right] \end{aligned}$$

DUAL CYCLE

In the Otto cycle, combustion is assumed at constant volume while in Diesel cycle combustion is at constant pressure. In practice they are far from real. Since, some time interval is required for the chemical reactions during combustion process, the combustion cannot take place at constant volume. Similarly, due to rapid uncontrolled combustion in diesel engines, combustion does not occur at constant pressure. The Dual cycle, also called a mixed cycle or limited pressure cycle, is a compromise between Otto and Diesel cycles. Figures 3.8(a) and 3.8(b) show the Dual cycle on p - V and T - s diagrams respectively.

In a Dual cycle a part of the heat is first supplied to the system at constant volume and then the remaining part at constant pressure.

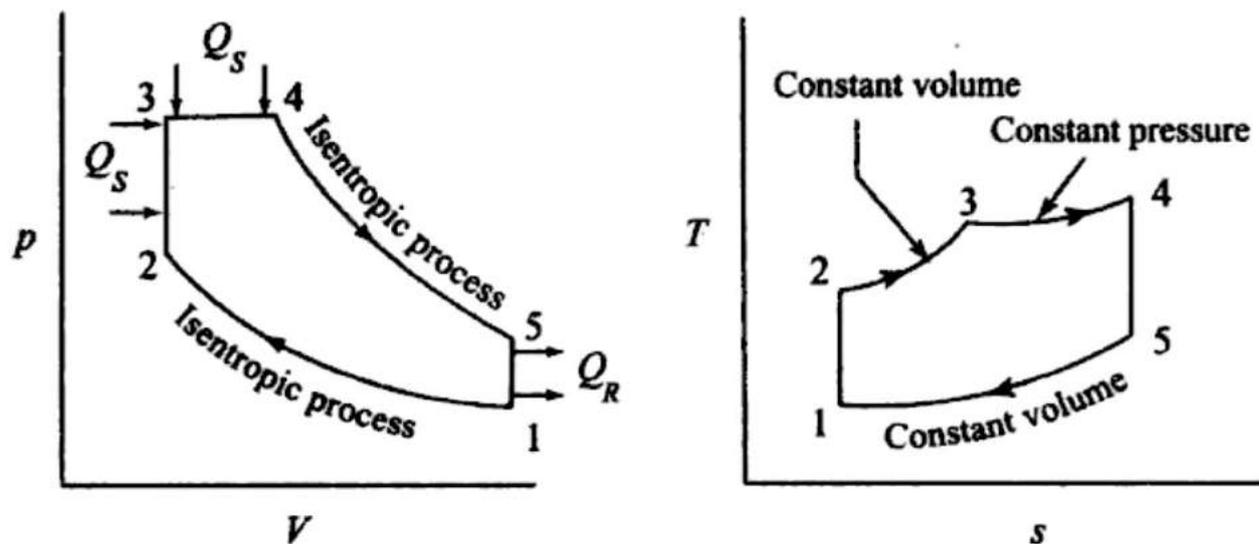


Fig. 3.8 Dual Cycle

COMPARISON OF THE OTTO, DIESEL AND DUAL CYCLES

3.8.1 Same Compression Ratio and Heat Addition

The Otto cycle $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1$, the Diesel cycle $1 \rightarrow 2 \rightarrow 3' \rightarrow 4' \rightarrow 1$ and the Dual cycle $1 \rightarrow 2 \rightarrow 2'' \rightarrow 3'' \rightarrow 4'' \rightarrow 1$ are shown in p - V and T - s diagrams in Fig.3.9(a) and 3.9(b) respectively for the same compression ratio and heat input.

From the T - s diagram, it can be seen that Area $5236 = \text{Area } 523'6' = \text{Area } 522''3''6''$ as this area represents the heat input which is the same for all cycles.

All the cycles start from the same initial state point 1 and the air is compressed from state 1 to 2 as the compression ratio is same. It is seen from the T - s diagram for the same heat input, the heat rejection in Otto cycle (area 5146) is minimum and heat rejection

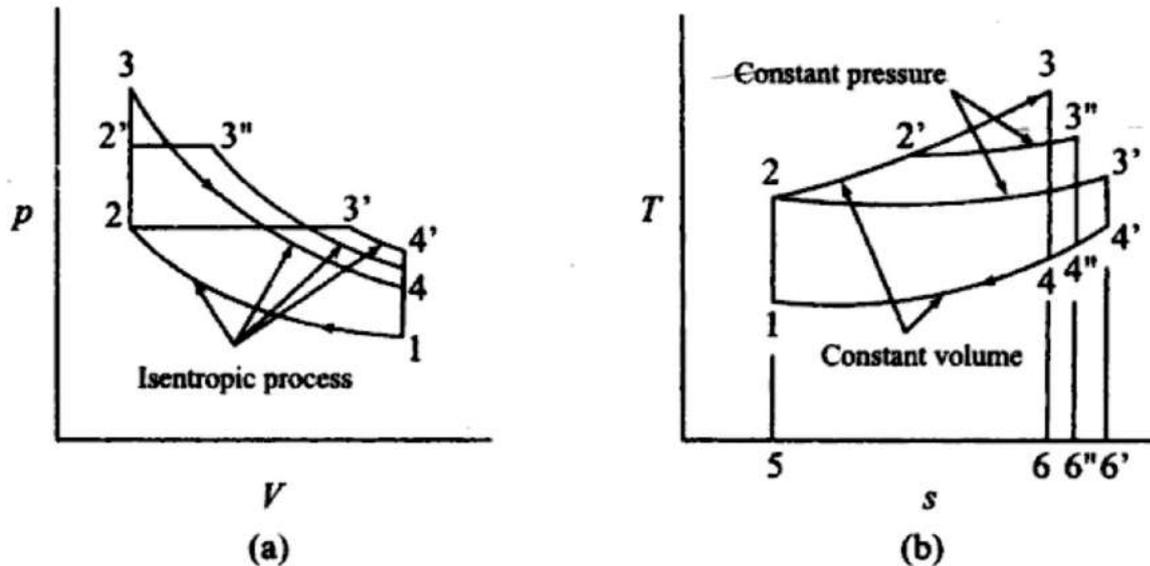


Fig. 3.9 Same Compression Ratio and Heat Addition

in Diesel cycle (514'6') is maximum. Consequently Otto cycle has the highest work output and efficiency. Diesel cycle has the least efficiency and Dual cycle having the efficiency between the two.

FUEL AIR CYCLES

The theoretical cycle based on actual properties of the cylinder gas is called FUEL AIR Approximation. It provides a rough idea for comparison with actual performance. The Air standard cycle gives an estimate of engine performance which is much greater than actual performance. For example : Actual indicated thermal efficiency of a petrol engine of say 7:1 Compression ratio is in order of 15 % where as Air standard efficiency is in order of 54%. Main reason of divergence is over simplification in using the values of properties of working fluid for the cycle analysis, non – instantaneous burning and valve operations and incomplete combustion.

In air cycle approximation we have assumed that air is a perfect gas having constant specific heats. In actual engine , working fluid is not air but mixture of air ,fuel and exhaust gases. Further more, specific heats of working fluid are not constant but increase with rise in temperature and at high temperature the combustion products are subjected to dissociation.

Assumption made for Fuel air cycle

The following assumptions are made for the analysis of Fuel air cycle

- Prior to combustion there is no chemical change in either fuel or air
- Subsequent to combustion, the change is always in chemical equilibrium
- There is no heat exchange between the gases and the cylinder wall in any process. That is processes are adiabatic. In addition, expansion and compression process are frictionless.
- In case of reciprocating engines, it is assumed that fluid motion can be ignored inside the cylinder
- The burning takes place instantaneously at TDC (in the case of petrol engines)
- The fuel is completely vaporized and perfectly mixed with the air (for petrol engines).

Factors considered for Fuel air cycles

i). **The actual composition of the cylinder gases:** The cylinder gases contain fuel, air, water vapour in air and residual gas. During the operation of engine Fuel/Air ratio changes which changes relative amount of CO₂, water vapour also etc.

ii). **Variation of specific heats of gases with the temperature rise.** Specific heat increase with temperature except for mono-atomic gases.

iii). **The effect of dissociation :** The fuel air mixture does not completely combine chemically at high temperature (above 1600K), therefore, at equilibrium conditions of gases like CO₂, H₂, O₂ may be present.

iv) **Variation in the number of molecules :** The number of molecules present after combustion depend upon fuel air ration and upon the pressure and temperature after combustion.

I. THE ACTUAL COMPOSITION OF THE CYLINDER GASES

The air fuel ratio changes during the engine operation. This change in air fuel ratio affects the composition of the gases before combustion as well as after combustion particularly the percentage of carbon dioxide, carbon monoxide, water vapour etc. in the exhaust gases. In four stroke engines, fresh charges as it enters the engine cylinder comes in contact with the burnt gases left in the clearance space of the previous cycle. The amount of exhaust gases varies with speed and load on the engine. Fuel air cycle analysis takes into account the fact and the results are computed using COMBUSTION Charts. Today this types of analysis is done using computer.

II. VARIATION OF SPECIFIC HEATS OF GASES

The specific heat of any substance is the ratio of the heat required to raise the temperature of a unit mass of substance through one degree centigrade. In case of gases temperature can be raised in two ways : either at constant pressure or at constant volume. Accordingly we have two specific heats C_p and C_v . In general specific heats are not constant. The specific heats varies largely with temperature but not so significantly with pressure except at high pressure

REASONS FOR VARIATION OF SPECIFIC HEATS OF GASES.

The internal energy of gas is largely due to translational, rotational and vibrational energy of

molecules. The energy of vibration increases rapidly with temperature and since only translational energy is measured by temperature, specific heat must increase to account for absorption of energy which increases the vibration. Thus the energy of vibration of poly atomic gas will undergo considerable change with temperature and also specific heat. The change of specific heat of monatomic gases is not considerable as molecules of monatomic gases has only translational energy.

Figure shows the effects variation of specific heats of representative gases with temperature

Note : $K = C_P / C_V$

Change of Internal Energy during a process with variable specific heat (July 2007)

Small change in internal energy of unit mass of a gas for small change in temperature is given by

$$du = C_v dt$$

= Now we put $C_v = b + K T$ and integrate between 1 & 2

III. LOSS DUE TO DISSOCIATION EFFECT

Dissociation is a process of disintegration of combustion products at high temperature. This can also be considered as reverse process to combustion. During dissociation, heat is absorbed whereas during combustion heat is released. In I C engines, mainly dissociation of CO₂ into CO and O₂ occurs, whereas there is a little dissociation of H₂O

Dissociation of CO₂ (at 1000 deg C)



Dissociation of O₂ (at 1200 deg C)



The arrows in both directions in the above equations indicate that, limiting temperature is attained when the reaction has same rate for either direction.

Dissociation, in general, lowers the temperature and consequently pressures at the beginning of the stroke and causes a loss of power and efficiency. If the mixture is weaker, it gives temperature lower than those required for dissociation to take place. If the mixture is richer, during combustion it gives out CO and O₂ both of which suppresses the dissociation of CO₂.

EFFECT OF DISSOCIATION ON MAX TEMPERATURE OF THE CYCLE

Figure shows the effect of dissociation on the maximum temperature for different

F/A ratio. In the absence of the dissociation, max temperature occurs at chemically correct F/A ratio, with dissociation, the maximum temperature occurs when mixture is slightly 10% rich.

The dissociation reduces the maximum temperature by about 300 deg C even at chemically correct air fuel ratio.

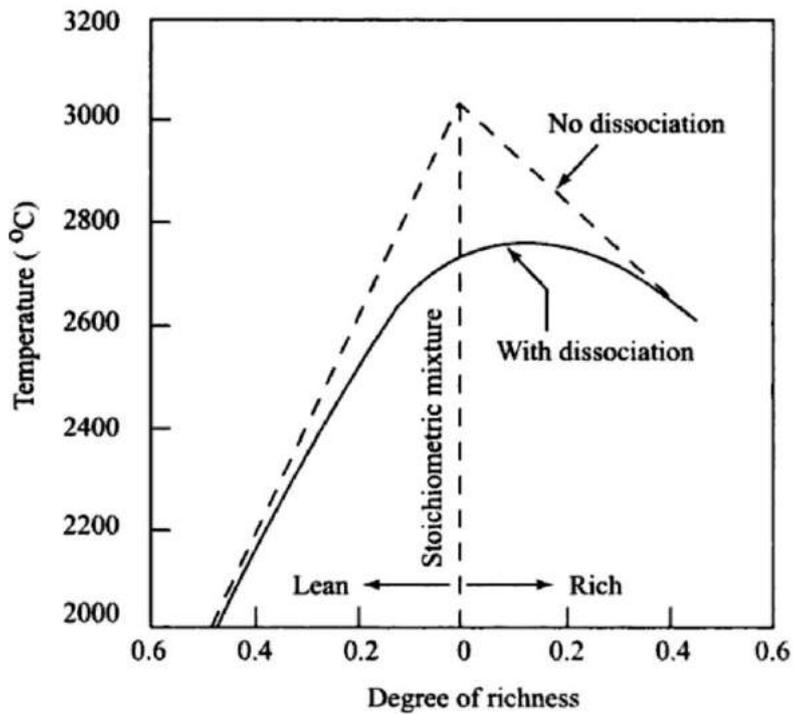


Fig. 4.2 Effect of Dissociation on Temperature

EFFECT OF DISSOCIATION ON POWER

The effect of dissociation on Brake power for four stroke SI engine at constant RPM is shown in the Figure. BP of engine is maximum when the air fuel ratio is stoichiometric and there is no dissociation. The depth of shaded area between 2 BP curves shows the loss of power due to dissociation at Fuel air mixture . When the mixture is lean there is no dissociation. As the mixture becomes rich maximum temperature rises and dissociation starts. The maximum dissociation occurs at stoichiometric air fuel ratio. The dissociation starts declining at rich mixture because of increased quantity of CO in burned gases.

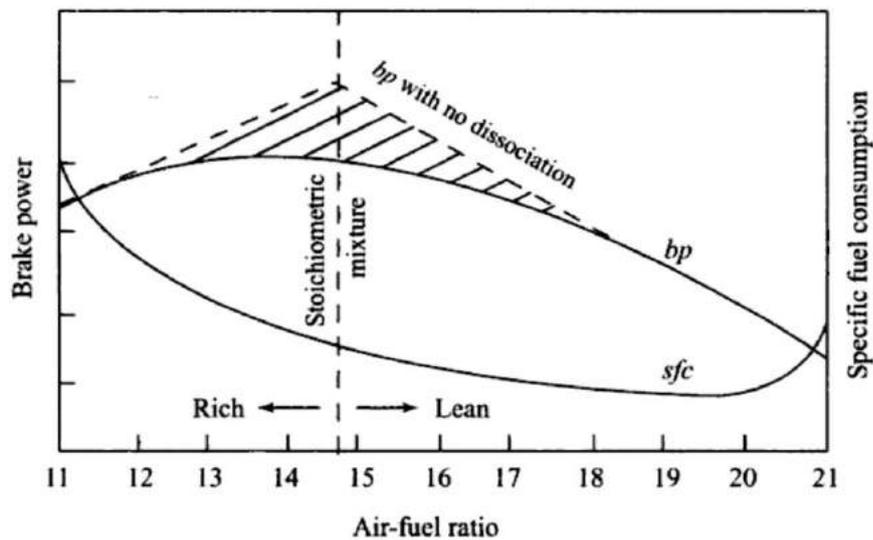


Fig. 4.3 Effect of Dissociation on Power

EFFECT OF DISSOCIATION ON OTTO CYCLE

The effect of dissociation on Otto cycle is shown in adjacent figure. Because of lower maximum temperature due to dissociation, the maximum pressure of cycle also falls and state of gas after combustion is shown by point 31 instead of 3. If there is no re-association during expansion, the expansion follows the process 31-411 but if there is some re-association, due to fall of temperature, then the expansion follows the process 31-41. It is obvious from the figure, the phenomenon causes loss of power and efficiency of the engine.

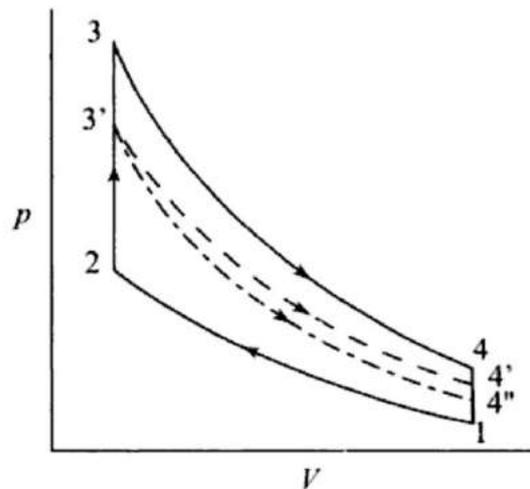


Fig. 4.4 Effect of Dissociation shown on a p - V Diagram

IV. VARIATION IN THE NUMBER OF MOLECULES :

The number of moles or molecules present in cylinder after combustion depends upon the A/F ratio and extent of reaction in cylinder. According to gas law, $pV = M\hat{A}T$, where V molal volume, M is the number of kg moles. \hat{A} is the universal gas constant. It is obvious from the equation that pressure depends on the moles present. This has direct effect on the amount of work developed by the gases in the cylinder

ACTUAL CYCLES

Actual cycle efficiency is much lower than Air standard efficiency due to various losses occurring in actual engine operations. They are :

1. Losses due to variation of specific heats
2. Chemical equilibrium losses or dissociation losses
3. Time losses

4. Losses due to incomplete combustion
5. Direct heat losses
6. Exhaust blow down gases
7. Pumping losses.

If we subtract losses due to variable specific heat and dissociation from the air standard cycle we get fuel air cycle analysis and if we further subtract other above losses from fuel air cycle we can very closely approximate the actual cycle.

Factors that affect the deviation of actual cycles from Theoretical cycle.

Actual cycle for IC engine differ from Air standard cycles in many respects as listed below

1. Working substance is not air. But mixture of air, fuel during the suction and compression and many gases during the expansion and exhaust.
2. Combustion of fuel not only adds heat but changes the chemical composition
3. Specific heat of gases changes with respect to temperature
4. The residual gases change the composition , temperature and amount of fuel charge.
5. The constant volume combustion is not possible in reality
6. Compression and expansions are not isentropic
7. There is always some heat loss due to heat transfer from hot gases.
8. There is exhaust blow down due to early opening of exhaust valve
9. There are losses due to leakages and friction

COMPARISION OF AIR STANDARD CYCLE, FUEL AIR CYCLE AND ACTUAL CYCLE IN SI ENGINE ON THE BASIS OF OPERATION AND WORKING

AIR CYCLE

- The working medium is air throughout the cycle. It is assumed to be an ideal gas with constant properties.
- The working medium does not leave the system, and performs cyclic processes.
- There are not inlet and exhaust strokes.
- The compression and expansion processes are isentropic.
- The heat addition and rejection are instantaneous at T.D.C. and B.D.C. respectively, at constant volume.

FUEL-AIR CYCLE

- The cylinder gases contain fuel, air, water vapour and residual gases.
- The fuel-air ratio changes during the operation of the engine which changes the relative amounts of CO water vapour etc.

- The variations in the values of specific heat and g with temperature, the effects of dissociation, and the variations in the number of molecules before and after combustion

Besides taking the above factors into consideration, the following assumptions are commonly made for the operation in

- No chemical change prior to combustion.
- Ch is always in equilibrium after combustion.
- Compression and expansion processes are frictionless, adiabatic.
- Fuel completely vaporized and mixed with air.
- Burning takes place instantaneously, at constant volume, at T.D.C.

The fuel air cycle gives a very good estimate of the actual engine with regards to efficiency, power output, peak pressure, exhaust temperature etc.

ACTUAL CYCLE

- The working substance is a mixture of air and fuel vapour, with the products of combustion left from the previous cycle.
- The working substance undergoes change in the chemical composition.
- Variation in specific heats takes place. Also the temperature and composition changes due to residual gases occur.
- The combustion is progressive rather than instantaneous.
- Heat transfer to and from the working medium to the cylinder walls take place.
- Exhaust blow down losses i.e. loss of work due to early opening of the exhaust valves take place.
- Gas leakage and fluid friction are present.

COMBUSTION CHARTS

Combustion charts or Equilibrium charts are thermodynamic charts embodying characteristics of cylinder gases that are employed for computing fuel air cycles, avoiding laborious calculations. J.B. Heywood developed a new set of charts in SI units, following the approach of Newhall and Starkman. Nowadays, these charts are not much used and have been replaced by computer models. However, these charts are useful to analyze the fuel-air cycles where a limited number of calculations are required.

Two types of charts are developed for each fuel:

1. Unburned mixture charts for the properties of gases before combustion.
2. Burned mixture charts for the properties of burned gases after combustion under chemical equilibrium.

Unburned Mixture Charts

The properties of the gases depend upon the air/fuel ratio and the residual gases in the mixture.

For different operating conditions of the engine the air/fuel ratio and the amount of residual gases change, therefore an infinite number of charts would theoretically be required. However, a limited number of charts are used to cover the range of mixtures normally used in SI engines. The thermodynamic charts developed for unburned mixtures are designed specifically for application to internal combustion engine cycle processes. The thermodynamic properties of each of the fuel- air mixtures considered are represented completely by a set of two charts. The first is indeed for use in the determination of mixture temperature, pressure and volume at the beginning and end of the compression process, and the other is for the determination of the corresponding internal energy and enthalpy values.

Burned Mixture Charts.

These charts are prepared on the basis of combustion of 1 kg of air with specific weight of fuel. The combustion product composition was considered to include H, H₂, H₂O, OH, CO, CO₂, N, N₂, O, O₂ and NO. Energy, enthalpy and Entropy values for each of chemical species over full range of temperatures can be obtained from these charts. In addition, the determination of equilibrium products composition requires equilibrium constants for each of dissociation reactions. Professor J B Heywood used data from JANAF thermodynamic data tables published by the Joint army Navy air force panel on Chemical thermodynamics. Each chart is a plot of internal energy versus entropy for a particular fuel and equivalence ratio. Lines of constant temperature, pressure and specific volumes are drawn on each chart.

FUELS & FUEL INJECTION

In IC engines, the chemical energy contained in the fuel is converted into mechanical power by burning (oxidizing) the fuel inside the combustion chamber of the engine.

Fuels suitable for fast chemical reaction have to be used in IC engines, they are following types-

(a) Hydrocarbons fuels derived from the crude petroleum by proper refining process such as thermal and catalytic cracking method, polymerisation, alkylation, isomerisation, reforming and blending.

(b) Alternative fuels such as-Alcohols (methanol, ethanol)

Natural gas (methane)

LPG (propane, butane)

Hydrogen

***Classification of petroleum fuels used for IC engine:**

Liquid hydrocarbons- Engine fuels are mainly mixtures of hydrocarbons, with bonds between hydrogen and carbon atoms. During combustion these bonds are broken and new bonds are formed with oxygen atoms, accompanied by the release of chemical energy. Principal products are carbon dioxide and water vapour. Fuels also contain small amounts of S, O₂, N₂, H₂O. The different constituents of

crude petroleum which are available in liquid hydrocarbons are- paraffins, naphthenes, naphthenes, olefins, aromatics.

(i) Paraffin-

-Paraffins or alkanes can in general be represented by C_nH_{2n+2}

-All the carbon bonds are single bonds – they are “saturated” high number of H atoms, high heat content and low density (620 – 770 kg/m³)

-The carbon atoms can be arranged as a straight chain or as branched chain compounds.

-Straight chain group (normal paraffins)

shorter the chain, stronger the bond

not suitable for SI engines – high tendency for autoignition according to the value of “n” in the formula, they are in gaseous (1 to 4), liquid (5 to 15) or solid (>16) state.

(ii) Naphthenes-

-Also called as cycloparaffins and represented as C_nH_{2n}

-Saturated hydrocarbons which are arranged in a circle have stable structure and low tendency to autoignite compared to alkanes (normal paraffins)

-Can be used both in SI-engines and CI-engines

-Low heat content and high density (740 – 790 kg / m³)

(iii) Olefins-

-Olefins or alkenes are represented as Mono olefins C_nH_{2n} or Dio-olefins C_nH_{2n-2}

-Olefins have the same C-to-H ratio and the same general formula as naphthenes, their behavior and characteristics are entirely different

-They are straight or branch chain compounds with one or more double bond. The position of the double bond is indicated by the number of first C atom to which it is attached, i.e.,

$CH_2=CH.CH_2.CH_2.CH_3$ called pentene-1

$CH_3.CH=CH_2$ called butene-2

-Olefinic compounds are easily oxidized, have poor oxidation stability

-Can be used in SI-engines, obtained by cracking of large molecules low heat content and density in the range 620 – 820 kg / m³.

(ii) Cracking process

-There are two types of cracking process for engine fuel production: thermal cracking and catalytic cracking

(a) Thermal cracking: It takes place through the creation of HC free radicals by C to- C bond scission

-The feed is heated to around 500 - 600 OC and 70 - 100 bars and passed into a soaking chamber where cracking takes place. The cracked products are fractionated. The product is relatively unstable and

requires the use of antioxidants and other treatments to prevent gum formation in use. It has relatively poor MON (motor octane number).

(b)Catalytic cracking: It is the most important and widely used process for converting heavy refinery streams to lighter products – to increase the ratio of light to heavy products from crude oil.

-Compared to thermal cracking, it has higher yield, improved quality product for gasoline (not for diesel fuel) and superior economics.

-A fluidized bed of catalyst is used – feed is introduced into it. Catalyst flows from one vessel to another through a pipe (between reactor and regenerator). Cracked oil vapour pass to fractionating towers where smaller molecules are separated from heavier products (gas, catalytic naphtha, cycle oils and residue).

-Aluminium silicate known as zeolite is used as a catalyst – has high activity and suppress the formation of light olefins.

(iii)Alkylation: It is a process for producing a high-octane gasoline component (alkylate) by combining light olefins with isobutane in the presence of a strongly acidic catalyst (sulfuric or hydrofluoric acid).

(iv)Isomerization: It is a process for converting straight chain paraffins to branch chain – used to provide isobutane feed for the alkylation process or to convert relatively low-octane quality of straight paraffins to more valuable branch chain molecules.

eg. n-pentane with RON (research octane number) 62 can be converted to isopentane with RON 92

-Process involves contacting HCs with a catalyst (platinum on a zeolite base) and separating any unchanged straight paraffins for recycle through the unit. The product is clean burning and has better RON quality.

(v)Polymerization: It is a process where light olefins such as propene and butenes are reacted together to give heavier olefins which have good octane quality and low vapour pressure in gasoline.

-Most commonly used catalyst is phosphoric acid

-The product is almost 100 % olefinic and has relatively poor MON compared with RON.

eg. $\text{CH}_3\text{CH}_2\text{CH}=\text{CH}_2 + \text{CH}_3\text{CH}=\text{CH}_2 \rightarrow \text{CH}_3(\text{CH}_2)_4\text{CH}=\text{CH}_2$

butene propene heptene

***Alternative fuels:**

(a) Alcohols: These include methanol (methyl alcohol), ethanol (ethyl alcohol), propanol (propyl alcohol), butanol (butyl alcohol) as compounds

-The OH group which replaces one of the H atoms in an alkane, gives these compounds their characteristic properties

-Specific heating value is lower than gasoline (42 – 43 MJ/kg)

methanol (19.7 MJ/kg) and ethanol (26.8 MJ/kg)

-For air-fuel mixture SHV is comparable with gasoline (MJ/kg-mixture at stoichiometric mixtures)

-Other alcohol groups such as dihydric and trihydric alcohols are not used as a fuel in IC engines

(i) Methanol

- Can be obtained from natural gas – has near and long-term potential
- Has high octane quality (130 RON, 95 MON)
- Can be used in low-concentration (5-15 %) in gasoline to increase octane number of the mixture

Problems;

- Poor solubility in gasoline, toxicity, low energy content (about half of gasoline), high latent heat of vaporization and oxygen content
- Contribute to poor driveability, incompatibility with some metals

(ii) Ethanol

- Produced from biomass
 - It is made from the sugars found in grains, such as: Corn, Sorghum, and Barley
- Other sources of sugars to produce ethanol include: Potato skins, Rice, Sugar cane, Sugar beets, Yard clippings, Bark, Switch grass etc.

- Has high octane number – can be used in low–concentrations in gasoline
- Most of the ethanol used in the United States today is distilled from corn
- Scientists are working on cheaper ways to make ethanol by using all parts of plants and trees rather than just the grain.
- About 99% of the ethanol produced in the United States is used to make "E10" or "gasohol," a mixture of 10% ethanol and 90% gasoline.
- Any gasoline powered engine can use E10, but only specially made vehicles can run

(b) Biodiesel:

- It is methyl or ethyl ester of a fatty acid produced from vegetable oil of edible or non edible types or animal fat or algae, by transesterification process using catalysts.
- Has better lubricating properties and much higher cetane ratings than today's low sulfur diesel fuels.
- Its addition reduces the fuel system wear.
- Can be used in the pure form (B100), or may be blended with petroleum diesel in any concentration in most diesel engines for transportation purpose.
- But, the engine may face problems, such as low temperature operation, less durability and drop in power. New diesel fuel injection systems, such as common rail systems are equipped with materials that are compatible with biodiesel (B100).
- Biodiesel offers a substantial reduction in particulate matter (25%-50%) and a marginal increase of NO_x (1%-6% when it is used as an alternative fuel in a CI engine).
- The major problems associated with biodiesel are (i) poor oxidation stability, (ii) higher viscosity and density, (iii) lower calorific value, and (iv) cold flow property.
- Blends of 20% and lower biodiesel can be used in diesel engines with no, or only minor modifications.

(c) Biogas:

-Produced by the anaerobic decomposition of organic materials such as cow dung and other waste such as cornhusks, leaves, straw, garbage, flesh of car cusses, poultry droppings, pig dung, human excreta, sewage and the plants specially grown for this purpose like water hyacinth, algae, certain types of grasses. Also any cellulosic organic material of animal or plant origin which is easily bio-degradable is a potential raw material for biogas production. -Also produced by pyrolysis and hydrogasification methods

-Contains a mixture of methane (50-60% vol), CO₂ (30-45%), hydrogen (5-10%), nitrogen (0.5-7%) and small traces of other gases such as hydrogen sulphide and oxygen

-It is a clean, but slow burning gas and having value between 5000 to 5500 kcal/kg or 38131 kJ/m³

-The octane rating of biogas is 130 and ignition temperature is 650 °C

-Can be used to operate both compression ignition (diesel) and spark ignition (petrol) engines. CI engines can operate on dual-fuel (biogas+diesel) operation and pilot injection operation in which small quantity of diesel is required for igniting the mixture of air and biogas

-80% saving of diesel oil can be achieved

-Drawback of biogas is present of CO₂. The engine performance can be improved by reducing the CO₂ content in biogas.

(d) Hydrogen:

-Clean burning fuel and has the highest energy content per unit mass of any chemical fuels which can reduce the dependency on hydrocarbon based fuels

Production:

Most common method of producing hydrogen involves splitting water (H₂O) into its component parts of hydrogen (H₂) and oxygen (O). There are different methods to produce hydrogen-

i. Steam reformation or partial oxidation of hydrocarbons such as natural gas, naphtha or crude oil. It converts methane into hydrogen and carbon monoxide by reaction with steam over a nickel catalyst.

ii. Coal gasification- Hydrogen made from coal can probably be justified as a fuel for special applications where the unique characteristics of hydrogen can be put to advantage such as its weight or its non-polluting characteristics.

iii. Electrolysis- it uses electrical current to split water into hydrogen at the cathode (+) and oxygen at anode (-) [3].

iv. Thermo chemical method- it utilizes heat to achieve the chemical splitting of water to its elements without the need for intermediate electricity generation and without the need to use the extremity high temperature of 2500 °C or more.

v. Photo-electrolysis- it uses sunlight and catalysts to split water. In this method, a current is generated by exposing on or both electrodes to sunlight. Hydrogen and oxygen gases are liberated at the 2 electrodes by the decomposition of water. A catalyst may be included to facilitate the electrode process.

vi. Biological and photo-biological water splitting use sunlight and biological organisms to split water.

vii. Thermal water splitting uses a very high temperature (approximately 1000 °C) to split water.

viii. Biomass gasification uses selected microbes to break down a variety of biomass feed stocks into hydrogen.

Utilization of hydrogen gas:

Hydrogen can be utilized for the following purpose:

i. Residential use- hydrogen can be used in domestic cooking (stoves), radiant space heaters, electricity for lighting and for operating domestic appliances (e.g. refrigerator) which could be generated by means of fuel cells, with hydrogen gas at one electrode and air at other.

ii. Industrial use- hydrogen can be used as a fuel or a chemical reducing (i.e. oxygen removal) agent. It can also be used instead of coal or coal derived gases, to reduce oxide ores (iron ore) to the material (iron).

iii. Air craft application- The earliest application of liquid hydrogen fuel is expected to be in a jet air craft. Cold liquid hydrogen can be used directly or indirectly to cool the engine and the air frame surfaces of a high speed air craft.

iv. Electric power generation- It comprises the production of electricity by using hydrogen in fuel cell system. Hydrogen could also be used as a means for storing and distributing electrical energy. The objective of developing fuel cell power stations is to centralized and local generation of electricity.

iv. As an alternative transport fuel- Hydrogen is tried as an alternative fuel in internal combustion engine. The stoichiometric hydrogen air mixture burns seven times as fast as the corresponding gasoline air mixture which is a great advantage in internal

Methods of using Hydrogen as a fuel in CI engines

i. A mixture of fuel gas and air, with an approximately constant fuel to air ratio is introduced into the cylinder intake manifold. The engine power is controlled by varying the quantity of mixture entering the cylinder by means of throttle valve. It is not safe because the mixture is formed in the manifold.

ii. The hydrogen is injected directly into the engine cylinder through a valve under pressure and air is inducted through another intake valve. This method is safer one, since hydrogen and air are supplied

separately; an explosive mixture is occurred inside the cylinder only. The engine power output is controlled by varying the pressure of hydrogen gas from about 14 atm at low power to 70 atm at high power.

iii. During the intake stroke, the hydrogen gas at normal or moderate pressure is drawn through the throttle valve into the engine cylinder whereas unthrottled air is drawn in through the intake port. The variation of engine power can be achieved with adjustment of hydrogen inlet throttle. The changes in fuel proportion as well as power is developed due to supply of un throttle air and power variation is possible because of the wide composition range over which hydrogen-air mixture can be ignited [1].

Advantages of using Hydrogen fuelled engine

- i. It provides high efficiency because it utilizes a higher proportion of the energy in the fuel.
- ii. The amount of carbon monoxide and hydrocarbons in the exhaust is very small since they are originating only from the cylinder lubricating oil.
- iii. It can be easily available because it is produced by electrolysis of water.
- iv. Fuel leakage to environment is not pollutant.

Disadvantages of using Hydrogen fuelled engine

- i. Due to high heat release the combustion temperature may be high and also a level of nitrogen oxide is high. It can be reduced by reducing the combustion temperature by injecting water vapor into the cylinder from the exhaust.
- ii. It requires heavy, bulky fuel storage both in vehicle and at the service station.
- iii. Difficulty in refueling and possibility of detonation.
- iv. Poor engine volumetric efficiency- gaseous fuel will displace some of inlet air and poor volumetric efficiency will result.
- v. Fuel cost would be high at present day technology [2].

(e) Natural Gas:

-Natural gas is present in the earth and is often produced in association with the production of crude oil. Processing is required to separate the gas from petroleum liquids and to remove contaminants. First, the gas is separated from free liquids such as crude oil, hydrocarbon condensate, water and entrained solids. The separated gas is further processed to meet certain pipelines quality specifications with respect to

water content, hydrocarbon dew point, heating value and hydrogen sulphide content. Generally, a gas sweetening plant removes hydrogen sulphide and other sulfur compounds

- Over 70% of the natural gas is formed by methane.

-It is Colorless, odorless and mostly constitutes methane which is a relatively unreactive hydrocarbon.

Utilization:

-Natural gas is widely used for different purposes such as space heating, electricity generation, industrial processes, agricultural, raw material for petrochemical industry, residential, commercial and utility markets

-On a gallon equivalent basis, natural gas costs less than gasoline, diesel fuel or any other alternative fuel. Natural gas currently supplies over 25% of the energy demand because of its quality.

-can either be stored on board a vehicle in tanks as compressed natural gas (CNG) at pressure of 16 to 25 bar or cryogenically cooled to a liquid state (-127 °C) as liquefied natural gas (LNG) at pressure of 70 to 120 bar. As a fuel and with a single throttle body injector it works best in an engine system. LNG is used in heavy duty vehicles where use of CNG would still entail space and load carrying capacity penalties. The fuel storage system of natural gas as LNG instead of CNG is less than half the weight and volume of CNG system. So, it can be easily transportable than CNG.

(i) CNG (Compressed Natural Gas)

-Natural gas consists of elements of compressor, some sort of compressed gas storage and dispensing unit of CNG into vehicles

-Two types of CNG refueling system- slow fill and fast fill. In slow fill system, several vehicles are connected to the output of the compressor at one time. These vehicles are then refilled over several hours of compressor operation. In fast fill systems, enough CNG is stored so that several vehicles can be refueled one after the other, just like refueling from a single gasoline dispenser

-The storage system of CNG is arranged as several tanks in cascade form. The CNG pressure in cascade is higher than the maximum storage pressure of the cylinder on the vehicle. The cascade attempts to deliver as much of its CNG to vehicles as possible before the pressure difference decreases to where the flow rate slows dramatically. A dryer should include in most CNG refueling systems to remove water vapor, impurities and hydrogen sulphide from natural gas before it is compressed. If water vapor is present then it can condense in the vehicle fuel system, causing corrosion especially if hydrogen sulphide is present. CNG driven vehicles with catalytic converter have less CO and HC emission but NOx emission is high.

(ii) LPG (Liquefied Petroleum Gas)

-LPG is available in the market in two forms- one is propane and the other is butane. Propane is popular alternative fuel because of its infrastructure of pipe lines, processing facilities and storage for its

efficient distribution and also it produces fewer emissions. Propane is produced as a byproduct of natural gas processing and crude oil refining

-Natural gas contains LPG, water vapor and other impurities and about 55% of the LPG is compressed from natural gas purification. LPG is a simple mixture of hydrocarbon mainly propane/propylene (C₃S) and butane/ butylenes (C₄S)

-Propane is an odorless, nonpoisonous gas which has lowest flammability range.

Utilization of LPG

LPG is used as a fuel in heating appliances and vehicles. It is increasingly used as an aerosol propellant and a refrigerant, replacing chlorofluorocarbons in an effort to reduce damage to the ozone layer

-In Europe, LPG is used as an alternative to electricity and heating oil (kerosene).It can also be used as power source for combined heat and power technologies (CHP). CHP is the process of generating both electrical power and useful heat from a single fuel source. This technology has allowed LPG to be used not just as fuel for heating and cooking, but also for de-centralized generation of electricity

-LPG has higher potential as an alternate fuel for IC engine.

Advantages of LPG

-Emission is much reduced by the use of LPG.

-LPG mixes with air at all temperatures.

-Uniform mixture can be supplied to all cylinders of multi-cylinder engine.

-Engine with high compression ratio (10:1) can use propane.

-There is cost saving of about 50% and longer life with LPG running engine.

Disadvantages of LPG

(i) A good cooling system is necessary because LPG vaporizer uses engine coolant to provide the heat to convert the liquid LPG to gas [2].

(ii) The weight of vehicle is increased due to the use of heavy pressure cylinder for storing LPG.

(iii) A special fuel feed system is required for LPG.

(iv) Requirement of safety device to prevent accident due to explosion of gas cylinders or leakage in the gas pipes.

(f) Producer Gas:

-Producer gas is a product of oxidation-reduction reactions of air with biomass. Biomass is chemically composed of elements C, H, O and some N and hence the oxidation results in products of combustion like CO₂ and H₂O. The molecules of O₂ in the air oxidises C and H to produce these products. The gases which are at high temperature due to partial oxidation pass through a bed of charcoal (which is produced because of oxidation reaction itself) and the reduction reaction of these gases with carbon leads to carbon monoxide and hydrogen

-Volumetric composition of producer gas is CO (16-20%), H₂ (16-18%), CO₂ (8-10%) and some traces of higher hydrocarbons. Producer gas has a high percentage of N₂, since air is used. So it has a low heat value. Density of producer gas is 0.9 to 1.2 kg/m³

-Producer gas is used in reciprocating engines and furnace. It needs little air to burn stoichiometrically and raise the temperature to a value of 1500 K at normal temperature and pressure. It is also used to power gas turbines (which are well-suited to fuels of low calorific value), spark ignited engines (where 100% petrol fuel replacement is possible) or diesel internal combustion engines (where 40% - 15% of the original diesel fuel) is still used to ignite the gas.

(g) Blast Furnace Gas:

It is a byproduct of melting iron ore in steel plants. It principally consists of CO and contains low heat value similar to producer gas. It consists of about 60% nitrogen, 18-20% CO₂ and some amount of oxygen which are not flammable. It may be combined with natural gas or coke oven gas before combustion or a flame support with richer gas or oil is provided to sustain combustion. The auto ignition temperature of blast furnace gas is approximate 630 °C and it has Lower Explosive Limit (LEL) of 27% & Upper Explosive Limit (UEL) of 75% in an air-gas mixture at normal temperature and pressure. The gas is hazardous due to higher concentration of carbon monoxide [50]. It should be cleaned properly because it contains lot of dust particles. Blast furnace gas depends upon types of fuel used and method of operating the blast furnace.

(h) Coke Oven Gas:

It is produced during the making of coke. It is also resulting from oxidation-reduction reactions of coal or coke with air and sometimes steams. It depends upon the type of coal used and operation method of oven. The composition of coke oven gas is H₂ (54% vol), CH₄ (24%), CO (8%), CO₂ (6%) and some traces of higher hydrocarbon and nitrogen. With the application of heat the heavier hydrocarbons are cracked and volatile portion of coal is driven off and results in high composition of H₂ and CH₄. Its heat value per cubic meter is only about one half that of natural gas and density is 0.40 kg/m³.

***General Fuel Specifications:**

Different properties of fuels have,

Relative density (specific gravity)

Fuel composition

Specific heating value

Flash point

Viscosity

Surface tension

Freezing point

(a) Relative density (specific gravity):

It is related to the measurement of the ratio of the weight of a given volume of fuel to the weight of the same volume of water, both at 20 OC and 101.325 kPa

For gasoline, the relative density is around 0.72 to 0.78 - which is equivalent to an API (American petroleum institute) range of 65 to 50,

$\rho = 700 - 800$ [kg/m³], for unleaded gasoline this value is higher due to the aromatics

For diesel fuel, $\rho = 830 - 950$ [kg/m³]

(b) Fuel composition:

C and H: carbon content of aromatics is around 89 %, and of paraffins and naphthenes is around 86 %

Benzene: max allowable concentration is specified because it is highly toxic material, the level is 5 %

Sulphur content: HC fuels contain free sulphur, hydrogen sulphide and other sulphur compounds which are objectionable it is a corrosive element that can corrode fuel lines, carburettor and injection pump. It will unite with oxygen to form sulphur dioxide, which in presence of water at low T, forms sulphurous acid.

-It has low ignition T, promote knock in SI engines. limited to approx 250 ppm (50 ppm is aimed for low pollutant emitting vehicles)

Gum deposits: gasoline with unsaturated HCs forms gum in the engine, paraffin, naphthene and aromatic HCs also form some gum – it causes operating difficulties, sticking valves and piston rings, deposits in the manifold etc.

Water: both dissolved and free water can be present in gasoline, free water is undesirable because it can freeze and cause problems. Dissolved water is usually unavoidable during manufacture.

Lead: for leaded and unleaded gasoline max lead content is specified, lead causes pollution and destroys catalytic converters in the exhaust system.

Manganese: used for antiknock in gasoline (MMT), max amount is specified, 0.00025 to 0.03 gMn/L

Oxygenates: oxygenated compounds such as alcohols are used in gasoline to improve octane rating. In USA gasohol (10% ethanol contains 3.5% oxygen), TBA and methanol up to 3.5% oxygen methanol up to 5% volume, MTBE up to 15% are used. In EC monoalcohols and ethers with atm boiling points lower than the final atm boiling point of gasoline in the standards can be used. Higher concentrations require modifications on the vehicles

- carburetor or fuel injection system must be modified to compensate for the oxygen content of the fuel. Blends with 15% methanol can be used.

(C) Specific heating value:

-Specific heating value, H_u is a measure of the energy content of the fuel per unit mass (kJ/kg or kcal/kg)

-Gaseous fuels sp heating value is given in terms of energy content per unit volume (kJ/liter or kJ/m³, kcal/m³)

-In IC engines lower heating value is given as the combustion products contain water in vapour form.

For gasoline and diesel fuel

$H_u=42000-44000$ kJ/kg or $H_u=10200-10500$ kcal/kg

-Heating value of the combustible air-fuel mixture is a decisive factor for engine performance.

(d) Flash point:

-Flash point is the lowest temperature of a sample at which the fuel vapour starts to ignite when in contact with a flame (ignition source).

-Marcusson method – fuel container is slowly heated, while the fuel vapour is in contact with an open flame – T is measured

-For gasoline it is 25 oC, diesel fuel 35 oC and heavy diesel 65 oC

(e) Viscosity:

-Viscosity is an important parameter for CI engines, also influences fuel metering orifices since Re is an inverse function of fuel viscosity lower the viscosity, smaller the diameter of the droplets in the spray.

-Below certain limits, low viscosity increases the leaks in the fuel system. It is a strong function of T – must be given at certain T values

at 50 oC, 1.5 – 5.0 Engler or 0.5 to 0.6 centistokes

(f) Surface tension:

-Surface tension is a parameter which effects the formation of fuel droplets in sprays

-increasing the surface tension will reduce mass flow and air-fuel ratio in gasoline engines

-lower the value, smaller the droplet diameter

diesel fuel value is in the range of 0.023 – 0.032 N/m

and for gasoline it is 0.019 – 0.023 N/m

(g) Freezing point:

-the precipitation of paraffin crystals in winter can lead to clogged filters. It can be prevented by either removing paraffins from the fuel or adding flow improvers (additives).

-Antifreezing properties are determined by its filterability.

-For gasoline freezing point is –65 oC and for diesel fuel –10 oC

***Important fuel specifications for gasoline**

(a) Gasoline volatility:

Benzene for example has vapor pressure of 0.022 MPa at 38 OC in a closed container of 38 OC,

benzene evaporates until the partial p

has a value of 0.022 MPa, If T is raised to 80.5 OC, then saturation p

will be 0.1 MPa and will be constant during the boiling

For gasoline it is not possible to indicate a single value of evaporation T or vapor pressure.

Gasoline contains large number of compounds - up to about 400

It has a smooth distillation curve - with good fractionation efficiency

Low fractionation efficiency effects engine performance at different operating conditions:

If distillation curve is displaced downward, gasoline becomes more volatile - poor hot start, vapor lock, high evaporative losses

Gasoline distillation curve:

Gasoline having boiling point up to 70 OC controls ease of starting and hot weather problems such as vapor lock

Mid-range controls the driving in cold weathers, particularly at warm up period of engine. It also influences the ice forming in carburetor.

Back end of the curve contains all the heavier, high boiling point compounds and these have high heat content - they are important in improving fuel economy for fully warmed up engine.

Some of the heavier compounds may pass into the crankcase and dilute the crankcase oil. They are not readily combusted as the lighter compounds - cause combustion chamber deposits.

Fig. 12. Distillation curve

%10 evaporation point should be at low T for start up at cold temperatures - at hot weathers this may cause problems - vapor lock.

50% evaporation should be slightly above 100 OC at summer and slightly below 100 OC at winter. For warmed up engine conditions this point is not important.

90% evaporation must not be high - produces fuel film on intake manifold walls and dilutes lubricating oil. Back end of the curve must not exceed 215 OC.

Gasoline volatility should be arranged according to weather conditions -particularly ambient T. Altitude has some minor effect due to pressure changes.

It is also effected by the characteristics of the vehicle itself (drivability, fuel system design etc).

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Cold starting:

For SI engines to start, A/F ratio must be within the ignitable range, ie in general must be between 7:1 to 20:1 by weight.

When the engine is cold, it is difficult to ignite lean mixtures, because fuel may not vaporize sufficiently - under these conditions the mixture is rich to bring it to ignitable range. This is done by the injection time or by the use of a choke with carburetted engines.

Measurement of gasoline volatility:

Tests usually define Reid Vapour Pressure - ASTM Distillation test and Vapour/Liquid ratio.

Reid vapour pressure - obtained at air-to-liquid ratio of 4:1 and temperature 37.8 oC.

Fuel is filled into a metal chamber which is connected to an air chamber and that is connected to a pressure gauge. The apparatus is immersed in water bath at 37.8 oC and is shaken until constant p is obtained - Reid VP

For gasoline allowable RVP is 0.7 bar in summer and 0.9 bar in winter (at 37.8 oC)

ASTM Distillation procedure - distillation rate is controlled by the heat input - distillation curve is plotted (temperature vs % evaporated).

(b)Antiknock quality of gasoline:

-Knock occurs when the unburnt gases ahead of flame front (the end gases) spontaneously ignite causing a sudden rise in pressure accompanied by a characteristic pinging sound – this result in a loss of power and can lead to damage the engine.

-Combustion chamber shape, spark plug location, ignition timing, end gas temperatures, in cylinder gas motion, air-fuel ratio of the mixture, fuel specifications etc. effects the occurrence of knock.

-Compression ratio of the engine also strongly effects knock. The higher the CR, the better the thermal efficiency - but the greater the tendency for knock to occur.

-Critical compression ratio - when knock starts. So higher fuel octane quality is required.

-Autoignition of the end gases causes a rapid increase of p, producing p waves which resonate in the combustion chamber at a frequency of between 5000 - 8000 Hz, depending on the geometry of the chamber

Knock results in an increase of T in the cylinder and causes a severe damage to engine components like cylinder head gasket, piston, spark plugs etc.

Octane number:

-In 1929 Octane scale was proposed by Graham Edgar. In this scale two paraffinic HCs have been selected as standards (PRF, primary reference fuels)- iso-octane (2-2-4 trimethyl pentane) with very high resistance to knock (arbitrary assigned a value of 100) and n-heptane with extremely low knock resistance (assigned a value of 0).

-Octane number of the fuel is the volume percentage of iso-octane in a blend with n-heptane (PRF), that shows the same antiknock performance as test fuel tested in standard engine and standard conditions.

-Test engine for determining Octane values, was developed by Cooperative Fuel Research Committee (CFR). It is a single cylinder, variable CR engine.

-Two different test conditions specifies the Research Octane Number (RON) and the Motor Octane Number (MON)

-Antiknock Index = $(RON + MON) / 2$

-TEL is added to the PRF to increase the ON above 100 or n-heptane is added to the sample to reduce ON below 100, then nonlinear extrapolation is applied

ON can be increased by antiknock agents - at less expense than modifying HC composition by refinery process.

Most effective agents are lead alkyls -

TEL - tetraethyl lead, $(C_2H_5)_4 Pb$

TML - tetramethyl lead,

MMT

addition of about 0.8 g lead per litre, provides a gain of about 10 ON in gasoline

***Important fuel specifications for diesel**

(a) Viscosity:

-Viscosity of a fluid indicates its resistance to flow - higher the viscosity, the greater the resistance to flow.

-It may be expressed as absolute viscosity (Poise, P) or kinematic viscosity (stoke, St).

-It varies inversely with temperature, usually given at 20 - 40 OC

-Fuel atomization depends on viscosity

2 - 8 mm²/s (cSt) at 20 OC

-Lower the viscosity, smaller the diameter of the droplets in the spray

(b) Surface tension:

-Surface tension is a parameter which effects the formation of fuel droplets in sprays

-Lower the value, smaller the droplet diameter

-Diesel fuel 0.023 – 0.032 N/m

(c) Cetane number:

-Cetane number is used to specify the ignition quality of diesel fuel.

-Running on low Cetane number will produce cold start problems. Peak cylinder pressure, combustion noise and HC emissions will increase -more fuel will be injected before ignition, less time for combustion.

-Higher CN results in a sooner ignition - extremely high CN may ignite before adequate Fuel-Air mixing can take place - higher emissions. Power output can be reduced if burning starts too early.

Measurement of cetane number:

-Cetane number is measured by comparing the “ignition delay time” of the sample fuel with a mixture of cetane ($C_{16}H_{34}$) and alphas-methyl naphthalene ($C_{10}H_7CH_3$). The Cetane percentage in the mixture gives the CN of the sample fuel.

-CN of the reference fuel cetane is arbitrarily set at 100, and of alphas-methyl naphthalene at 0.

-CFR engine is used to measure the compression ratio at which ignition starts. CR is gradually increased while the engine is driven by an electric motor - a curve of CN vs critical CR is obtained.

-Inlet air temp is $30\text{ }^{\circ}\text{C}$ and cooling water temp is at $100\text{ }^{\circ}\text{C}$

An easier and practical method to obtain Cetane Number is by calculating the Diesel Index.

CARBURETION

The process of preparing a combustible fuel-air mixture outside engine cylinder in SI engine is known as carburetion.

Important factors which affect the process of carburetion are given below;

-time available for the mixture preparation i.e. atomisation, mixing and the vaporisation

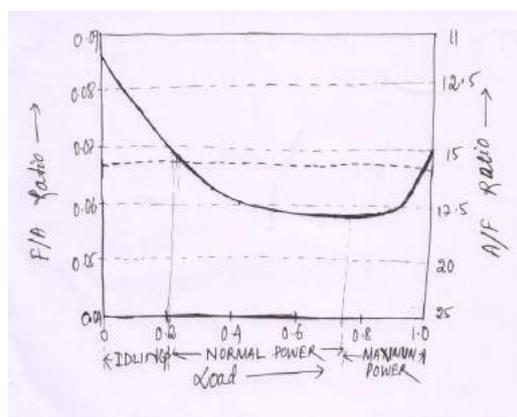
-Temperature of the incoming air

-quality of the fuel supply

-design of combustion chamber and induction system

***Mixture requirements for steady state operation:**

Three main areas of steady state operation of automotive engine which require different air



(a) Idling and low load:

-from no load to about 20% of rated power

-No load running mode is called idling condition

-very low suction pressure give rise to back flow of exhaust gases and air leakage

- increases the amount of residual gases and hence increase the dilution effects
- Rich mixture i.e. F/A ratio 0.08 or A/F ratio 12.5:1 provide smooth operation of the engine

(b) Normal power range or cruising range:

- from about 20% to 75% of rated power
- dilution by residual gases as well as leakage decreases, hence fuel economy is important consideration in this case
- maximum fuel economy occurs at A/F ratio of 17:1 to 16.7:1
- mixture ratios for best economy are very near to the mixture ratios for minimum emissions

(c) Maximum power range:

- from about 75% to 100% of rated power
- mixture requirements for the maximum power is a rich mixture, of A/F about 14:1 or F/A 0.07
- Rich mixture also prevents the overheating of exhaust valve at high load and inhibits detonation
- in multi-cylinder engine the A/F ratio are slightly lower

***Mixture requirements for transient operation:**

- Carburettor has to provide mixture for transient conditions under which speed, load, temperature, or pressure change rapidly
- evaporation of fuel may be incomplete in the transient condition, quantity of fuel may be increasing and decreasing

(a) Starting and warm up requirements:

- engine speed and temperature are low during the starting of the engine from cold
- during starting very rich mixture about 5 to 10 times the normal amount of petrol is supplied i.e. F/A ratio 0.3 to 0.7 or A/F ratio 3:1 to 1.5:1
- mixture ratio is progressively made leaner to avoid too rich evaporated fuel-air ratio during warm up condition
- too high volatility may form vapour bubbles in the carburettor and fuel lines particularly when engine temperatures are high
- too low volatility may cause the petrol to condense on the cylinder walls, diluting and removing the lubricating oil film

(b) Acceleration requirements:

- Acceleration refer to an increase in engine speed resulting from the opening of the throttle
- acceleration pump is used to provide additional fuel

***Simple Carburettor:**

- provide air-fuel mixture for all operating conditions
- Carburettor depression is pressure differential in the float chamber and venture throat which causes discharge of fuel into the air stream

- flow is controlled by small hole of fuel passage
- pressure at the throat at the fully open throttle condition lies between 4 and 5 cm of Hg and seldom exceeds 8 cm Hg
- petrol engine is quantity governed
- Drawback of simple carburettor is that it provides too rich and too lean mixture due to vacuum created at the throat is too high and too small which is undesirable

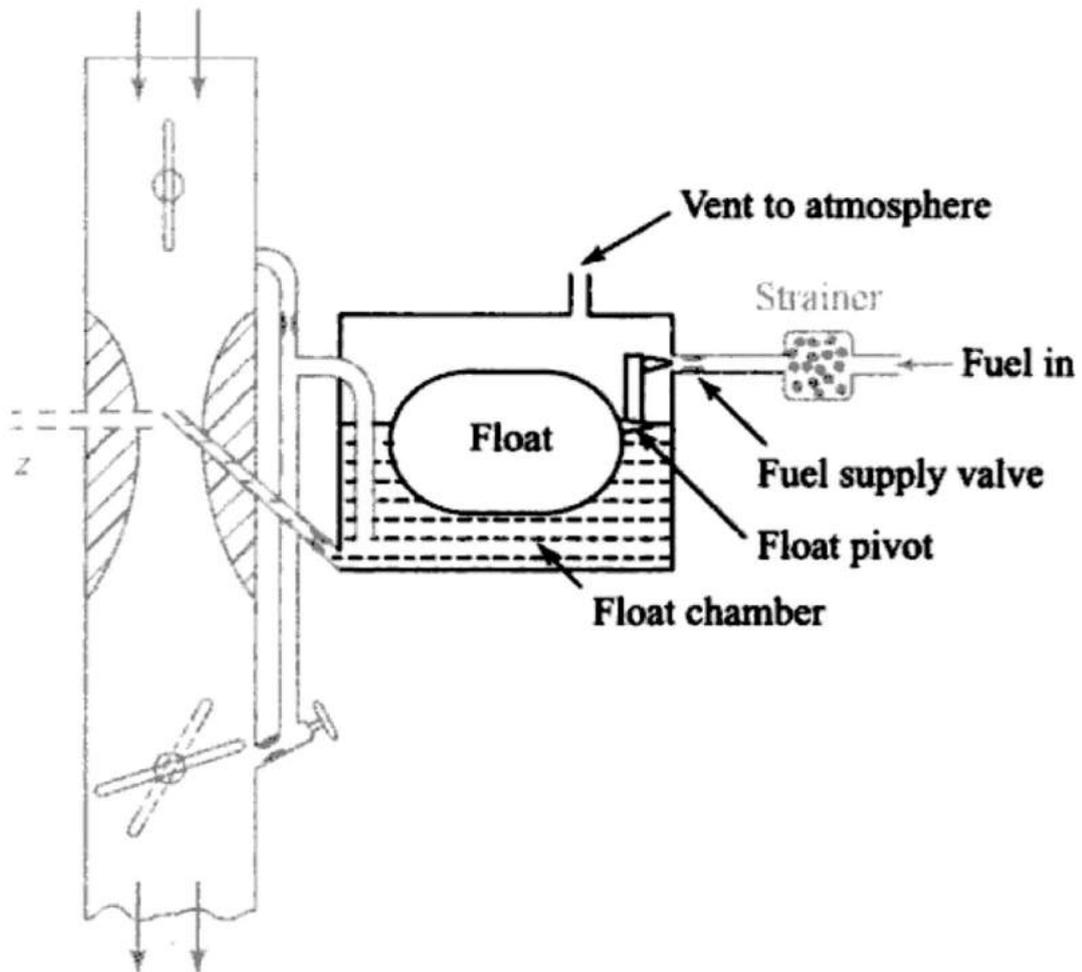


Fig. 8.9 Float Chamber

Complete Carburettor:

Additional systems used with simple carburettor can help the engine to operate at all conditions, which are given below,

(i) Main metering system:

- provide constant fuel-air ratio at wide range of speeds and loads.

-mainly based upon the best economy at full throttle (A/F ratio about 15.6:1)

The different metering systems are,

Compensating jet device:-Addition to the main jet, a compensating jet is provided to provide the leanness effect

Emulsion tube or air bleeding device:

-mixture correction is done by air bleeding alone

-in this arrangement main metering jet is fitted about 25 mm below the petrol level which is called as submerged jet

Back suction control or pressure reduction method:

-in this arrangement large vent line connects the carburettor entrance with the top of the float chamber and another small orifice line is connected with the top of the float chambers with venture throat

-it creates pressure differences according to engine operating conditions

Auxiliary valve carburettor:

-Valve spring of auxiliary valve lift the valve during increase of engine load which increases the vacuum at venture

-Allows more admittance more additional air and the mixture is not over rich

Auxiliary port carburettor:

-opening of butterfly allows more air inductance which decreases quantity of fuel drawn

-used in aircraft carburettors

(ii) Idling system:

-Idling jet is added for the idling and low load operation which requires rich mixture of about A/F ratio 12:1

-consists of small fuel line from the float chamber to a point of throttle side

-gradual opening of throttle may stop the idling jet

(iii) Power enrichment or economiser system:

-this system provides the richer mixture for maximum power range of operation

-It has meter rod economiser of large orifice opening to the main jet as the throttle is opened beyond a certain point

-rod is tapered or stepped

(iv) Acceleration pump system:

-Engine acceleration condition or rapid increase in engine speed may open the throttle rapidly which will not be able to provide rich mixture

-acceleration pump of spring loaded plunger is used for fuel supply

(v) Choke:

-Rich mixture is required during cold starting period, at low cranking speed and before the engine warmed up condition

-butterfly type valve or choke is used between the entrance to the carburettor and venture throat to meet the requirement

-spring loaded by-pass choke is used in higher speeds

***Carburettor types:**

(i) Open choke:Zenith, solex and carter

Constant vacuum type: S.U. carburettor

(ii) updraught type

Horizontal or downdraught: mixture is assisted by gravity in its passage to the engine induction

(a) Solex carburettor:

-provide ease of starting, good performance, and reliability

-used in Fiat and standard cars and Willey jeep

-Bi-starter is used for cold starting

-well of emulsion system is used for idling and slow running condition

-diaphragm type acceleration pump is used for increasing speed case

(b) Carter carburettor:

-downdraft type carburettor used in jeep

-has triple venture diffusing type choke in which smallest lies above the level float chamber, other two below the petrol level, one below other

-multiple venturies result in better formation of the mixture at very low speeds causing steady and smooth operation at very low and high engine speed

-mechanical metering method is used

-choke valve is provided in the air circuit for cold starting

-plunger type acceleration pump is used

(c) S.U. carburettor:

-constant air-fuel ratio is maintained due to vacuum depression

-has only one jet

-no separate idling jet or acceleration pump

-constant high velocity air across the jet may avoid the use of idling jet

-jet lever arrangement provides the rich mixture in cold starting

-used in many British cars and Hindustan ambassador car

Drawbacks of modern carburettor:

-improper mixture proportion in multi-cylinder engine

-loss of volumetric efficiency due to obstruction of flow of mixture from choke tubes, jets, throttle valve etc.

-wear of carburettor parts

-Freezing at low temperature

-surging when carburettor is tilted or during acrobatics in aircraft

-backfiring in fuel pipe line

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Petrol injection:

- to avoid above problem of modern carburettor, petrol injection is used like in diesel engine
- petrol injected during the suction stroke in the intake manifold at low pressure
- injection timing is not much critical as like in diesel engine
- continuous injection and timed injection methods are used

Continuous injection:

- fuel is sprayed at low pressure continuously into the air supply
- amount of fuel is governed by air throttle opening
- in supercharged engine, fuel injected in the form of multiple spray into the suction side of the centrifugal compressor
- provide efficient atomisation of fuel and uniform mixture strength to all cylinder
- higher volumetric efficiency
- one fuel injection pump and one injector

Timed injection system:

- similar to high speed diesel engine
- components are fuel feed or lift pump, fuel pump and distributor unit, fuel injection nozzles and mixture controls
- mixture controls are automatic for all engine operating conditions

(i) Multiple plunger jerk pump system:

- pump with separate plunger and high injection nozzle pressure for each cylinder
- 100 to 300 bar pressure
- measured quantity of fuel for definite time and over definite period is delivered

(ii) Low pressure single pump and distributor system:

- single plunger or gear pump supply fuel at low pressure to a rotating distributor
- pressure about 3.5 to 7 bar

(a) Lucas petrol injection system:

- firstly used in racing car
- single distributor system with novel metering device
- line pressure is maintained at 7 bar
- metering distributor and control unit distributes the required amount of fuel at correct time and interval
- has shuttle arrangements for metering unit
- in aircraft engine two injectors and spark plug provided for direct injection of fuel in CC

(b) Electronic fuel injection

Fuel delivery system:

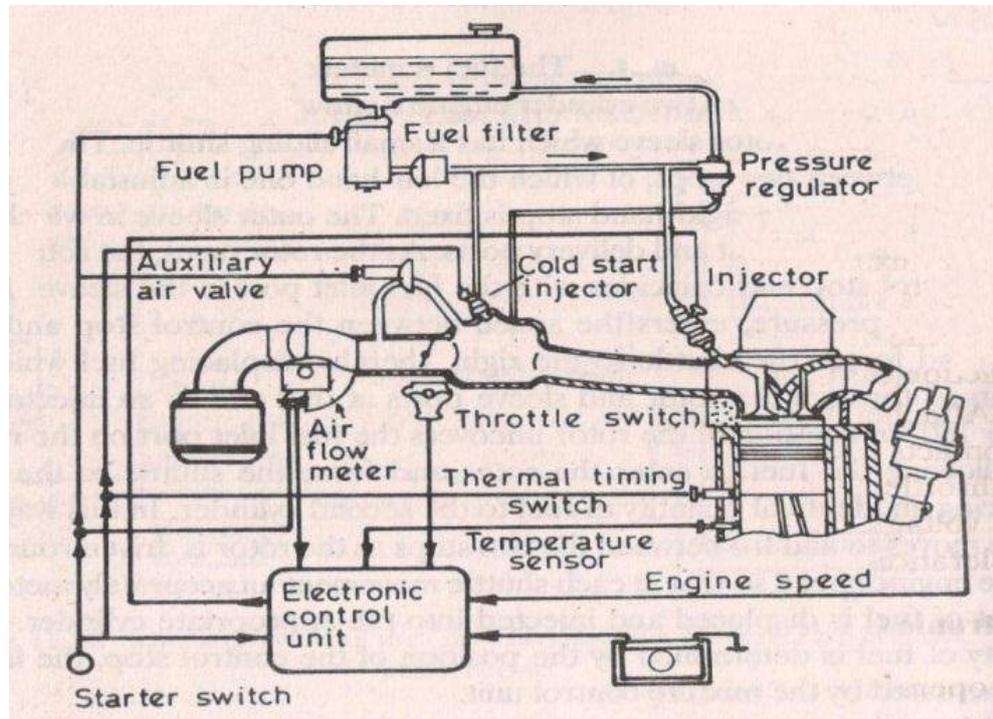
- electrically driven fuel pump draws fuel from tanks to distribute

-fuel and manifold pressure kept constant by pressure regulator

Air induction system:

-air flow meter generate voltage signal according to air flow

-cold start magnetic injection valve give good fuel atomisation and also provide extra



Electronic fuel injection system- L-Jetronic with air flow meter

Electronic control unit (ECU):

-sensors for manifold pressure, engine speed and temperature at intake manifold

-sensor measures operating data from locations and transmitted electrically to ECU

Injection timing:

-injected twice for every revolution of crank shaft

-triggering of injectors

***Diesel injection system:**

Requirements of diesel injection system:

-fuel must introduce precisely defined period of cycle

-amounts metered very accurately

-rate of injection meet desired heat release pattern

-quantities of fuel meet changing speed and load condition

-good atomisation of fuel

-good spray pattern for rapid mixing of fuel and air

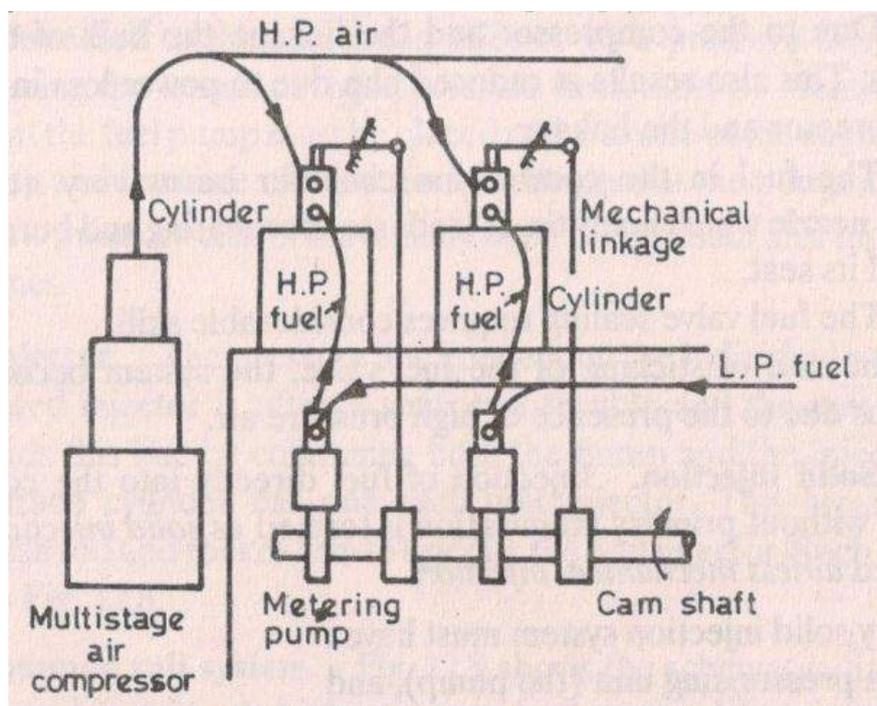
-no dribbling and after injection of fuel i.e. sharp injection

- injection timing suits the speed and load requirements
- distribution of fuel in multi-cylinder should uniform
- weight, size and cost of fuel injection system should be less

Types of diesel injection system:

(a) Air injection system:

- fuel supplied through camshaft driven fuel pump
- fuel valve is also connected with high pressure airline to inject into cylinder
- multi-stage compressor which supply air at a pressure of about 60 to 70 bar



. Air injection system

IGNITION

Ignition timing:

It is very important, since the charge is to be ignited just before (few degrees before TDC) the end of compression, since when the charge is ignited, it will take some time to come to the required rate of burning.

Ignition Advance:

The purpose of spark advance mechanism is to assure that under every condition of engine operation, ignition takes place at the most favourable instant in time i.e. most favourable from a standpoint of engine power, fuel economy and minimum exhaust dilution. By means of these mechanisms the advance angle is accurately set so that ignition occurs before TDC point of the piston. The engine speed and the engine load are the control quantities required for the automatic adjustment of the ignition timing. Most of the engines are fitted with mechanisms which are integral with the distributor and automatically regulate the optimum spark advance to account for change of speed and load. The two mechanisms used are:

- (a) Centrifugal advance mechanism, and
- (b) Vacuum advance mechanism

Factors affecting energy requirement of ignition system

(a) Effect of series resistance:

- Energy dissipated during discharge and hence circuit energy stored in capacitance is more
- longer discharge time

(b) Effect of electrode material:

- ignition energy for electrode gaps larger than the quenching distance varies with materials for the electrode and increases with any change to material having higher boiling point

(c) Effect of stray inductance:

- presence of small stray inductance cause oscillatory discharge
- larger resistance, minimum inductance longer the discharge time

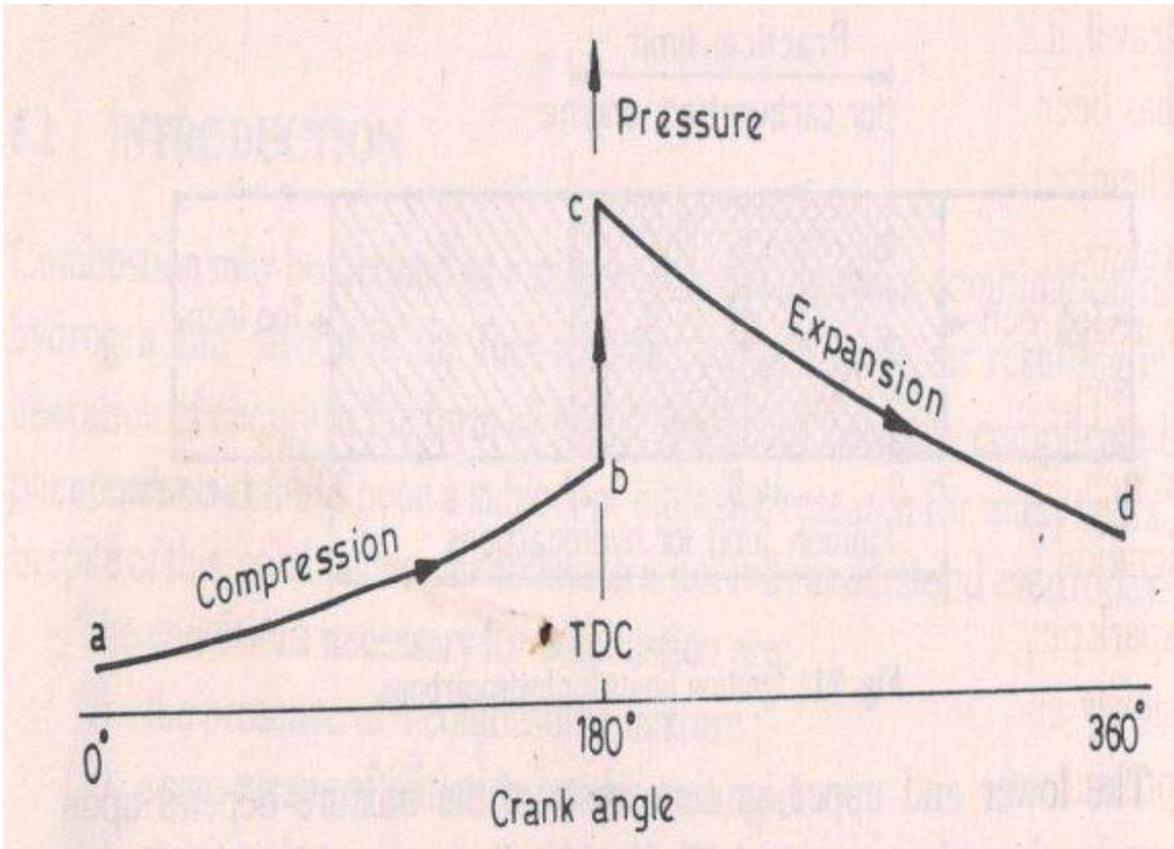
(d) Effect of electrode configuration:

- reduction in the capacitance reduces the discharge time and increase in the gas resistance which reduces the diameter of the spark channel
- increase the electrode gap means supply of ignition energy over interval of time decreases and spark channel also reduces

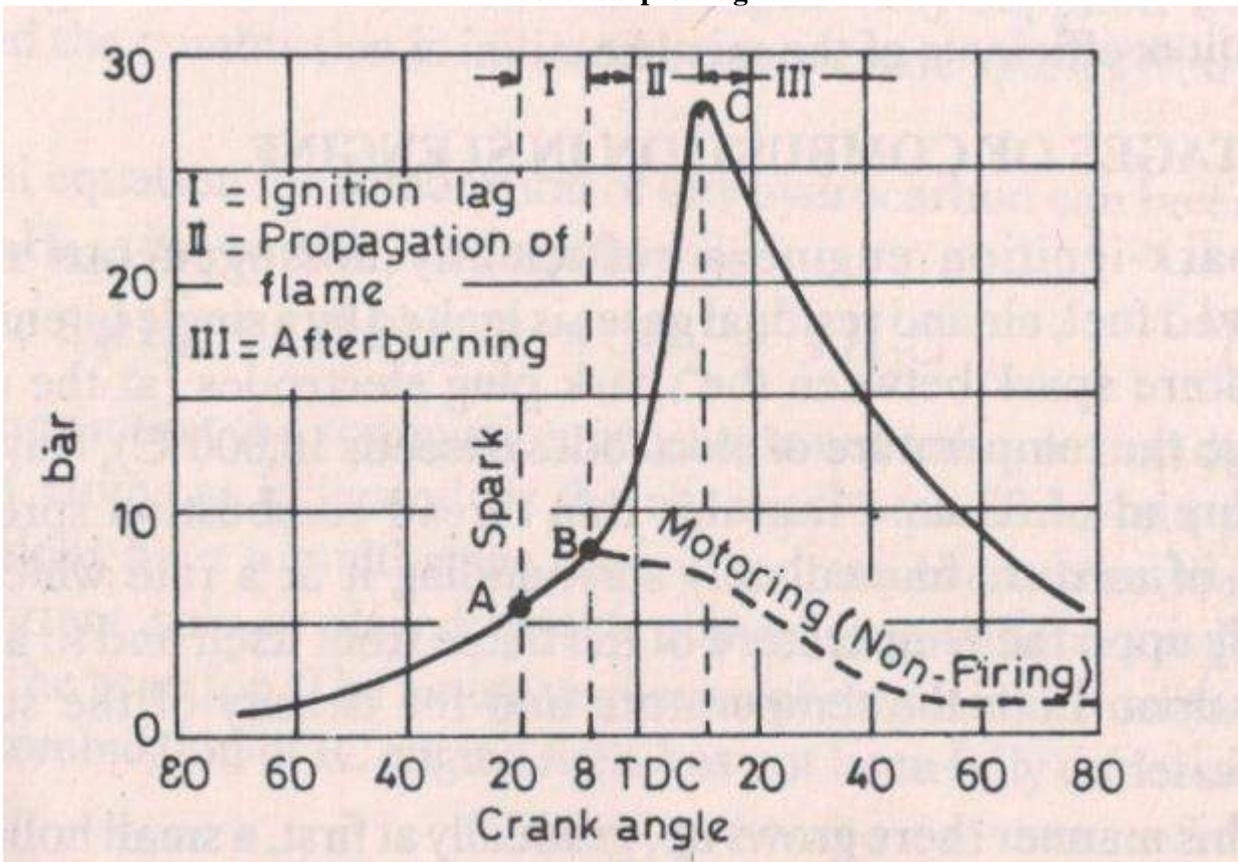
***Stages of SI engine combustion**

In SI engine homogeneous mixture of vaporised fuel, air and residual gases is ignited by a single intense and high temperature spark between the spark plug electrode (electrodes exceeds 10,000 °C) and generate pre-flame which spreads to envelope of mixture for Combustion.

Three stages of combustion in SI engine are



Theoretical p-θ diagram



Stages of combustion in SI engine

I-Ignition lag or preparation phase (AB):

- growth and development of a semi propagating nucleus of flame
- chemical process depending upon the nature of the fuel, upon both temperature and pressure, the proportion of the exhaust gas, and also upon the temperature coefficient of the fuel, that is, the relationship of oxidation or burning
- point A shows the passage of spark and point B is the first rise of pressure
- ignition lag is generally expressed in terms of crank angle
- Ignition lag is very small and lies between 0.00015 to 0.0002 seconds
- ignition lag of 0.002 seconds corresponds to 35 deg crank rotation when the engine is running at 3000 RPM
- Angle of advance increase with the speed

II-propagation of flame (BC):

- Period from the point B where the line of combustion departs from the compression line to point C, the maximum rise of pressure in P- θ diagram
- flame propagates at the constant velocity
- Heat transfer to the cylinder wall is low
- rate of heat release depends upon the turbulence intensity and reaction rate

III-After burning (CD):

- After point C, the heat release is due to the fuel injection in reduced flame front after the starts of expansion stroke
- no pressure rise during this period

***Effect of engine variables on Ignition lag**

Fuel: High self-ignition temperature of fuel longer the ignition lag.

Mixture ratio: mixture richer than the stoichiometric ratio provide shorter ignition lag

Initial temperature and pressure: increasing the intake temperature and pressure, increasing the compression ratio, chemical reaction rate and retarding the spark all reduce the ignition lag

Electrode gap: lower the compression ratio and higher the electrode gap is desirable

-voltage required at the spark plug electrode to produce spark is found to increase with decrease in fuel-air ratio and with increase in compression ratio and engine load

Turbulence: directly proportional to engine speed

-engine speed does not affect much ignition lag measured in milliseconds

-but ignition lag increases linearly with engine speed when measured in degree crank angle

-spark advance is desirable in higher engine speed

***Effect of engine variables on flame propagation**

Rate of flame propagation affects the combustion process in SI engines. Higher combustion efficiency and fuel economy can be achieved by higher flame propagation velocities. Unfortunately flame velocities for most of fuel range between 10 to 30 m/second.

The factors which affect the flame propagations are

1. Air fuel ratio

2. Compression ratio

3. Load on engine

4. Turbulence and engine speed

5. Other factors

1. A:F ratio: The mixture strength influences the rate of combustion and amount of heat generated. The maximum flame speed for all hydrocarbon fuels occurs at nearly 10% rich mixture. Flame speed is reduced both for lean and as well as for very rich mixture. Lean mixture releases less heat resulting lower flame temperature and lower flame speed. Very rich mixture results incomplete combustion and also results in production of less heat and flame speed remains low.

2. Compression ratio: The higher compression ratio increases the pressure and temperature of the mixture and also decreases the concentration of residual gases. All these factors reduce the ignition lag and help to speed up the second phase of combustion. The maximum pressure of the cycle as well as mean effective pressure of the cycle with increase in compression ratio. Figure above shows the effect of compression ratio on pressure (indirectly on the speed of combustion) with respect to crank angle for same A: F ratio and same angle of advance. Higher compression ratio increases the surface to volume ratio and thereby increases the part of the mixture which after-burns in the third phase.

3. Load on Engine: With increase in load, the cycle pressures increase and the flame speed also increases. In S.I. engine, the power developed by an engine is controlled by throttling. At lower load and higher throttle, the initial and final pressure of the mixture after compression decrease and mixture is also diluted by the more residual gases. This reduces the flame propagation and prolongs the ignition lag. This is the reason, the advance mechanism is also provided with change in load on the engine. This difficulty can be partly overcome by providing rich mixture at part loads but this definitely increases the chances of afterburning. The after burning is prolonged with richer mixture. In fact, poor combustion at part loads and necessity of providing richer mixture are the main disadvantages of SI engines which causes wastage of fuel and discharge of large amount of CO with exhaust gases.

4. Turbulence: Turbulence plays very important role in combustion of fuel as the flame speed is directly proportional to the turbulence of the mixture. This is because, the turbulence increases the mixing and heat transfer coefficient or heat transfer rate between the burned and unburned mixture. The turbulence of the mixture can be increased at the end of compression by suitable design of the combustion chamber (geometry of cylinder head and piston crown). Insufficient turbulence provides low flame velocity and

incomplete combustion and reduces the power output. But excessive turbulence is also not desirable as it increases the combustion rapidly and leads to detonation. Excessive turbulence causes to cool the flame generated and flame propagation is reduced. Moderate turbulence is always desirable as it accelerates the chemical reaction, reduces ignition lag, increases flame propagation and even allows weak mixture to burn efficiently.

Engine Speed

The turbulence of the mixture increases with an increase in engine speed. For this reason the flame speed almost increases linearly with engine speed. If the engine speed is doubled, flame to traverse the combustion chamber is halved. Double the original speed and half the original time give the same number of crank degrees for flame propagation. The crank angle required for the flame propagation, which is main phase of combustion will remain almost constant at all speeds. This is an important characteristic of all petrol engines.

Engine Size

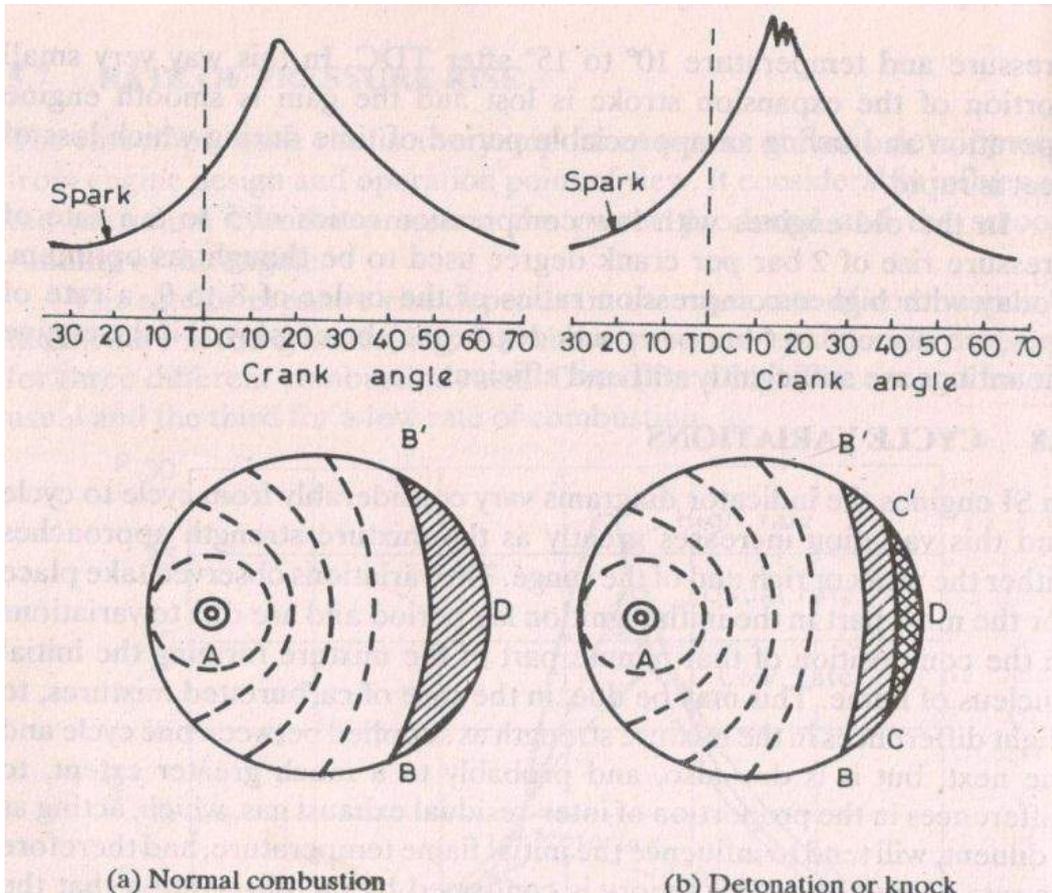
Engines of similar design generally run at the same piston speed. This is achieved by using small engines having larger RPM and larger engines having smaller RPM. Due to same piston speed, the inlet velocity, degree of turbulence and flame speed are nearly same in similar engines regardless of the size. However, in small engines the flame travel is small and in large engines large. Therefore, if the engine size is doubled the time required for propagation of flame through combustion space is also doubled. But with lower RPM of large engines the time for flame propagation in terms of crank would be nearly same as in small engines. In other words, the number of crank degrees required for flame travel will be about the same irrespective of engine size provided the engines are similar.

5. Other Factors: Among the other factors, the factors which increase the flame speed are supercharging of the engine, spark timing and residual gases left in the engine at the end of exhaust stroke. The air humidity also affects the flame velocity but its exact effect is not known. Anyhow, its effect is not large compared with A:F ratio and turbulence.

***Detonation or knocking**

Knocking is due to auto ignition of end portion of unburned charge in combustion chamber. As the normal flame proceeds across the chamber, pressure and temperature of unburned charge increase due to compression by burned portion of charge. This unburned compressed charge may auto ignite under certain temperature condition and release the energy at a very rapid rate compared to normal combustion process in cylinder. This rapid release of energy during auto ignition causes a high pressure differential in combustion chamber and a high pressure wave is released from auto ignition region. The motion of high pressure compression waves inside the cylinder causes vibration of engine parts and pinging noise and it is known as knocking or detonation. This pressure frequency or vibration frequency in SI engine can be up to 5000 Cycles per second. Denotation is undesirable as it affects the engine performance and

life, as it abruptly increases sudden large amount of heat energy. It also put a limit on compression ratio at which engine can be operated which directly affects the engine efficiency and output



***Auto ignition**

A mixture of fuel and air can react spontaneously and produce heat by chemical reaction in the absence of flame to initiate the combustion or self-ignition. This type of self-ignition in the absence of flame is known as Auto-Ignition. The temperature at which the self-ignition takes place is known as self-igniting temperature. The pressure and temperature abruptly increase due to auto-ignition because of sudden release of chemical energy. This auto-ignition leads to abnormal combustion known as detonation which is undesirable because its bad effect on the engine performance and life as it abruptly increases sudden large amount of heat energy. In addition to this knocking puts a limit on the compression ratio at which an engine can be operated which directly affects the engine efficiency and output.

***Pre-ignition**

Pre-ignition is the ignition of the homogeneous mixture of charge as it comes in contact with hot surfaces, in the absence of spark. Auto ignition may overheat the spark plug and exhaust valve and it remains so hot that its temperature is sufficient to ignite the charge in next cycle during the compression

stroke before spark occurs and this causes the pre-ignition of the charge. Pre-ignition is initiated by some overheated projecting part such as the sparking plug electrodes, exhaust valve head, metal corners in the combustion chamber, carbon deposits or protruding cylinder head gasket rim etc. pre-ignition is also caused by persistent detonating pressure shockwaves scoring away the stagnant gases which normally protect the combustion chamber walls. The resulting increased heat flow through the walls, raises the surface temperature of any protruding poorly cooled part of the chamber, and this therefore provides a focal point for pre-ignition.

Effects of Pre-ignition

- It increase the tendency of denotation in the engine
- It increases heat transfer to cylinder walls because high temperature gas remains in contact with for a longer time
- Pre-ignition in a single cylinder will reduce the speed and power output
- Pre-ignition may cause seizer in the multi-cylinder engines, only if only cylinders have pre-ignition

***Effect of detonation**

The harmful effects of detonation are as follows:

1. *Noise and roughness:* knocking produces a loud pulsating noise and pressure waves. These waves vibrate back and forth across the cylinder. The presence of vibratory motion causes crankshaft vibrations and the engine runs rough.

2. *Mechanical damage:*

(a) High pressure waves generated during knocking can increase rate of wear of parts of combustion chamber. Sever erosion of piston crown (in a manner similar to that of marine propeller blades by cavitation), cylinder head and pitting of inlet and outlet valves may result in complete wreckage of the engine.

(b) Detonation is very dangerous in engines having high noise level. In small engines the knocking noise is easily detected and the corrective measures can be taken but in aero-engines it is difficult to detect knocking noise and hence corrective measures cannot be taken. Hence severe detonation may persist for a long time which may ultimately result in complete wreckage of the piston.

3. *Carbon deposits:* Detonation results in increased carbon deposits.

4. *Increase in heat transfer:* Knocking is accompanied by an increase in the rate of heat transfer to the combustion chamber walls.

The increase in heat transfer is due to two reasons.

-The minor reason is that the maximum temperature in a detonating engine is about 150°C higher than in a non-detonating engine, due to rapid completion of combustion

-The major reason for increased heat transfer is the scouring away of protective layer of inactive stagnant gas on the cylinder walls due to pressure waves. The inactive layer of gas

normally reduces the heat transfer by protecting the combustion and piston crown from direct contact with flame.

5. *Decrease in power output and efficiency:* Due to increase in the rate of heat transfer the power output as well as efficiency of a detonating engine decreases.

6 *Pre-ignition:* increase in the rate of heat transfer to the walls has yet another effect. It may cause local overheating, especially of the sparking plug, which may reach a temperature high enough to ignite the charge before the passage of spark, thus causing pre-ignition. An engine detonating for a long period would most probably lead to pre-ignition and this is the real danger of detonation.

***Effect of engine operating variables on the engine knocking Detonation**

The various engine variables affecting knocking can be classified as:

- Temperature factors
- Density factors
- Time factors
- Composition factors

(a) Temperature factors:

Increasing the temperature of the unburned mixture increase the possibility of knock in SI engine, the effect of following engine parameters on the temperature of the unburned mixture:

- Raising the compression ratio: Increasing the compression ratio increases both the temperature and pressure (density of the unburned mixture). Increase in temperature reduces the delay period of the end gas which in turn increases the tendency to knock.
- Supercharging: It also increases both temperature and density, which increase the knocking tendency of engine
- Coolant temperature: Delay period decreases with increase of coolant temperature, decreased delay period increase the tendency to knock
- Temperature of the cylinder and combustion chamber walls: The temperature of the end gas depends on the design of combustion chamber. Sparking plug and exhaust valve are two hottest parts in the combustion chamber and uneven temperature leads to pre-ignition and hence the knocking.

(b) Density factors:

Increasing the density of unburnt mixture will increase the possibility of knock in the engine. The engine parameters which affect the density are as follows:

- Increased compression ratio increase the density
- Increasing the load opens the throttle valve more and thus the density
- Supercharging increase the density of the mixture
- Increasing the inlet pressure increases the overall pressure during the cycle. The high pressure end gas decreases the delay period which increase the tendency of knocking.

-Advanced spark timing: quantity of fuel burnt per cycle before and after TDC position depends on spark timing. The temperature of charge increases by increasing the spark advance and it increases with rate of burning and does not allow sufficient time to the end mixture to dissipate the heat and increase the knocking tendency

(c) Time factors:

Increasing the time of exposure of the unburned mixture to auto-ignition conditions increase the possibility of knock in SI engines.

Flame travel distance: If the distance of flame travel is more, then possibility of knocking is also more. This problem can be solved by combustion chamber design, spark plug location and engine size.

Compact combustion chamber will have better anti-knock characteristics, since the flame travel and combustion time will be shorter. Further, if the combustion chamber is highly turbulent, the combustion rate is high and consequently combustion time is further reduced; this further reduces the tendency to knock.

Location of sparkplug: A spark plug which is centrally located in the combustion chamber has minimum tendency to knock as the flame travel is minimum. The flame travel can be reduced by using two or more spark plugs.

Location of exhaust valve: The exhaust valve should be located close to the spark plug so that it is not in the end gas region; otherwise there will be a tendency to knock.

Engine size: Large engines have a greater knocking tendency because flame requires a longer time to travel across the combustion chamber. In SI engine therefore, generally limited to 100mm

Turbulence of mixture: decreasing the turbulence of the mixture decreases the flame speed and hence increases the tendency to knock. Turbulence depends on the design of combustion chamber and one engine speed.

(d) Composition:

The properties of fuel and A/F ratio are primary means to control knock :

(i) Molecular Structure: The knocking tendency is markedly affected by the type of the fuel used.

Petroleum fuels usually consist of many hydro-carbons of different molecular structure. The structure of the fuel molecule has enormous effect on knocking tendency. Increasing the carbon-chain increases the knocking tendency and centralizing the carbon atoms decreases the knocking tendency. Unsaturated hydrocarbons have less knocking tendency than saturated hydrocarbons.

Paraffins

-Increasing the length of carbon chain increases the knocking tendency.

-Centralising the carbon atoms decreases the knocking tendency.

-Adding methyl group (CH₃) to the side of the carbon chain in the centre position decreases the knocking tendency.

Olefins

-Introduction of one double bond has little effect on anti-knock quality but two or three double bond results less knocking tendency except C and C

Napthenes and Aromatics

-Napthenes have greater knocking tendency than corresponding aromatics.

-With increasing double-bonds, the knocking tendency is reduced.

-Lengthening the side chains increases the knocking tendency whereas branching of the side chain decreases the knocking tendency.

(ii) Fuel-air ratio: The most important effect of fuel-air ratio is on the reaction time or ignition delay.

When the mixture is nearly 10% richer than stoichiometric (fuel-air ratio =0.08) ignition lag of the end gas is minimum and the velocity of flame propagation is maximum. By making the mixture leaner or richer (than F/A 0.08) the tendency to knock is decreased. A too rich mixture is especially effective in decreasing or eliminating the knock due to longer delay and lower temperature of compression.

(iii) Humidity of air: Increasing atmospheric humidity decreases the tendency to knock by decreasing the reaction time of the fuel

STAGES OF COMBUSTION IN CI ENGINE

1. Ignition delay period:

The period between the start of fuel injection into the combustion chamber and the start of combustion is termed as ignition delay period. The start of combustion is determined from the change in slope on p- θ diagram or from heat release analysis of the p- θ data, or from luminosity detector in experimental conditions. Start of injection can be determined by a needle-lift indicator to record the time when injector needle lifts off its seat. Start of combustion is more difficult to determine precisely. It is best identified from the change in slope of heat release rate, determined from cylinder pressure data. In DI engines ignition is well defined, in IDI engines ignition point is harder to identify

Physical processes are fuel spray atomization, evaporation and mixing of fuel vapour with cylinder air.

Good atomization requires high fuel-injection pressure, small injector hole, optimum fuel viscosity, high cylinder pressure (large divergence angle).

Rate of vaporization of the fuel droplets depends on droplet diameter, velocity, fuel volatility, pressure and temperature of the air.

Chemical processes similar to that described for auto ignition phenomenon in premixed fuel-air, only more complex since **heterogeneous reactions** (reactions occurring on the liquid fuel drop surface) also occur.

Chemical delay is more effective for the duration of the ignition delay period.

Ignition delay period is in the range of

0.6 to 3 ms for low-compression ratio DI diesel engines,

0.4 to 1 ms for high-compression ratio, turbocharged DI diesel engines,

0.6 to 1.5 ms for IDI diesel engines

2. Rapid or uncontrolled or pre-mixed combustion phase:

Combustion of the fuel which has mixed with air within flammability limits during ignition delay period occurs rapidly in a few crank angle degrees - high heat release characteristics in this phase. If the amount of fuel collected in the combustion chamber during the ignition delay is much - high heat release rate results in a rapid pressure rise which causes the diesel knock.

For fuels with low cetane number, with long ignition delay, ignition occurs late in the expansion stroke - incomplete combustion, reduced power output, poor fuel conversion efficiency. If the pressure gradient is in the range 0.4 - 0.5 MPa/oCA, engine operation is not smooth and diesels knock starts. This value should be in the range 0.2 to 0.3 MPa/oCA for smooth operation (max allowable value is 1.0 MPa/oCA) of the engine.

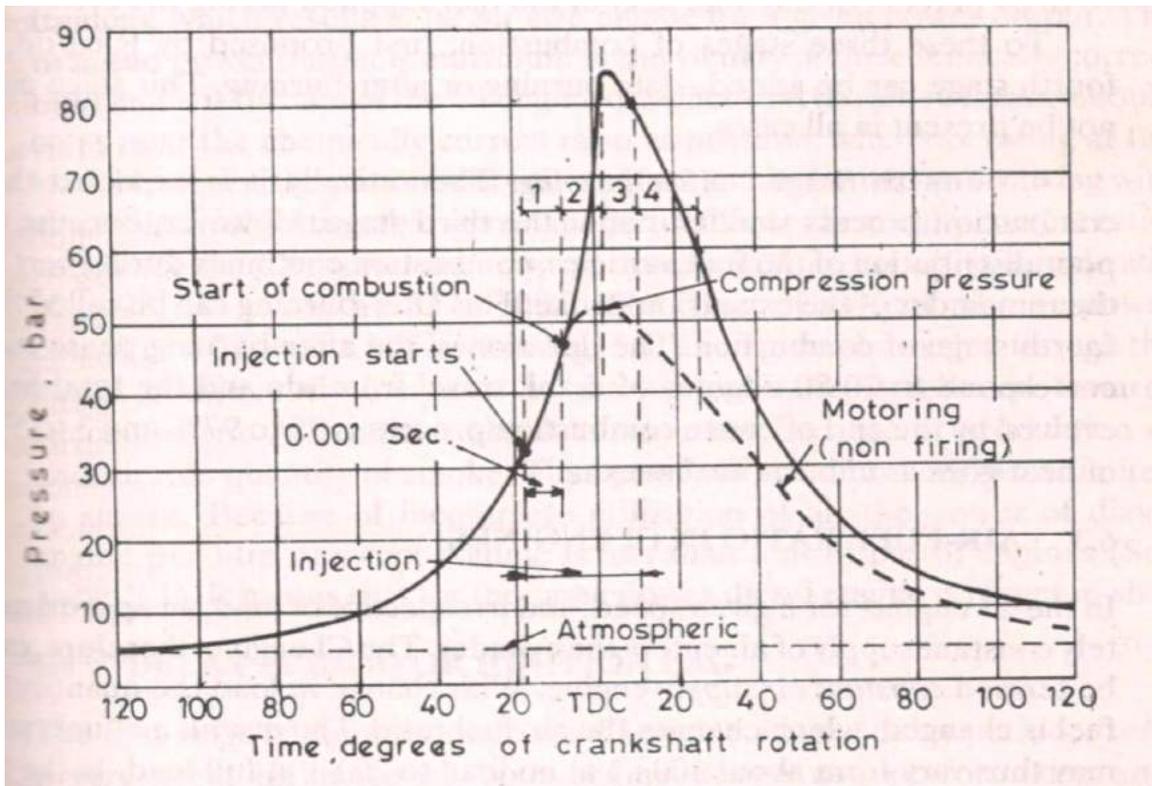
3. Controlled or diffusion combustion phase:

Once the fuel and air which is pre-mixed during the ignition delay is consumed, the burning rate (heat release rate) is controlled by the rate at which mixture becomes available for burning. The rate of burning in this phase is mainly controlled by the mixing process of fuel vapour and air. Liquid fuel atomization, vaporization, pre flame chemical reactions also affect the rate of heat release.

Heat release rate sometimes reaches a second peak (which is lower in magnitude) and then decreases as the phase progresses. Generally it is desirable to have the combustion process near the TDC for low particulate (soot) emissions and high performance (and efficiency).

4. After burning or late combustion phase:

Heat release rate continues at a lower rate into the expansion stroke -there are several reasons for this: a small fraction of the fuel may not yet burn, a fraction of the energy is present in soot and fuel-rich combustion products and can be released. The cylinder charge is non-uniform and mixing during this phase promotes more complete combustion and less



* Variables affecting delay period

(i) Cetane number

Both physical and chemical properties of the fuel are important. Ignition quality of the fuel is defined by its cetane number. Straight chain paraffinic compounds (normal alkanes) have

highest ignition quality, which improves as the chain length increases. Aromatic compounds, alcohols have poor ignition quality.

-Cetane number can be increased by ignition-accelerating additives like organic peroxides, nitrates, nitrites and various sulphur compounds. Most important (commercially) is alkyl nitrates – about 0.5% by vol in a distillate fuel increase CN by 10.

-Normal diesel fuel has CN of 40 to 55 (high speed 50 – 60, low speed 25 – 45)

(ii) Injection timing

-At normal operating conditions min ignition delay (ID) occurs with start of injection at 10 to 15 OCA BTDC

-Cylinder temperature and pressure drops if injection is earlier or later (high at first but decrease as delay proceeds)

(iii) Injection quantity (load)

-Reducing engine load changes AFR, cools down the engine, reduces wall temperatures, reduces residual gas temperatures and increase ID

-Droplet size, injection velocity and rate Ignition quality within practical limits do not have significant effect on ID

-Increase in injection pressure produces only modest decrease in ID Injector nozzle diameter -effects of droplet size but has no significant effect on ID

(iv) Intake air temperature and pressure

-Reducing intake air T and p increase ID

-Strong dependence of ID on charge temperature below 1000 K – above this value effect of intake air conditions is not significant.

(v) Engine speed

Increase in engine speed increases the air motion and turbulence, reduces ID time slightly (in ms), in terms of CA degrees ID increases almost linearly.

-A change in engine speed, changes “temp~time” and “pressure~time” relationships

(vi) Combustion chamber design

-Spray impingement on the walls effect fuel evaporation and ID increase in compression ratio, increase p and T and reduces ID

-Reducing stroke volume, increase surface area to volume ratio, increase engine cooling and increase ID

(vii) Swirl rate

-Change of evaporation rate and air-fuel mixing - under normal operating conditions the effect is small.

-At start-up (low engine speed and temperature) more important, high rate of evaporation and mixing is obtained by swirl

(viii) Oxygen concentration

Residual gases reduce O₂ concentration and reducing oxygen concentration increases ID

DIESEL KNOCK

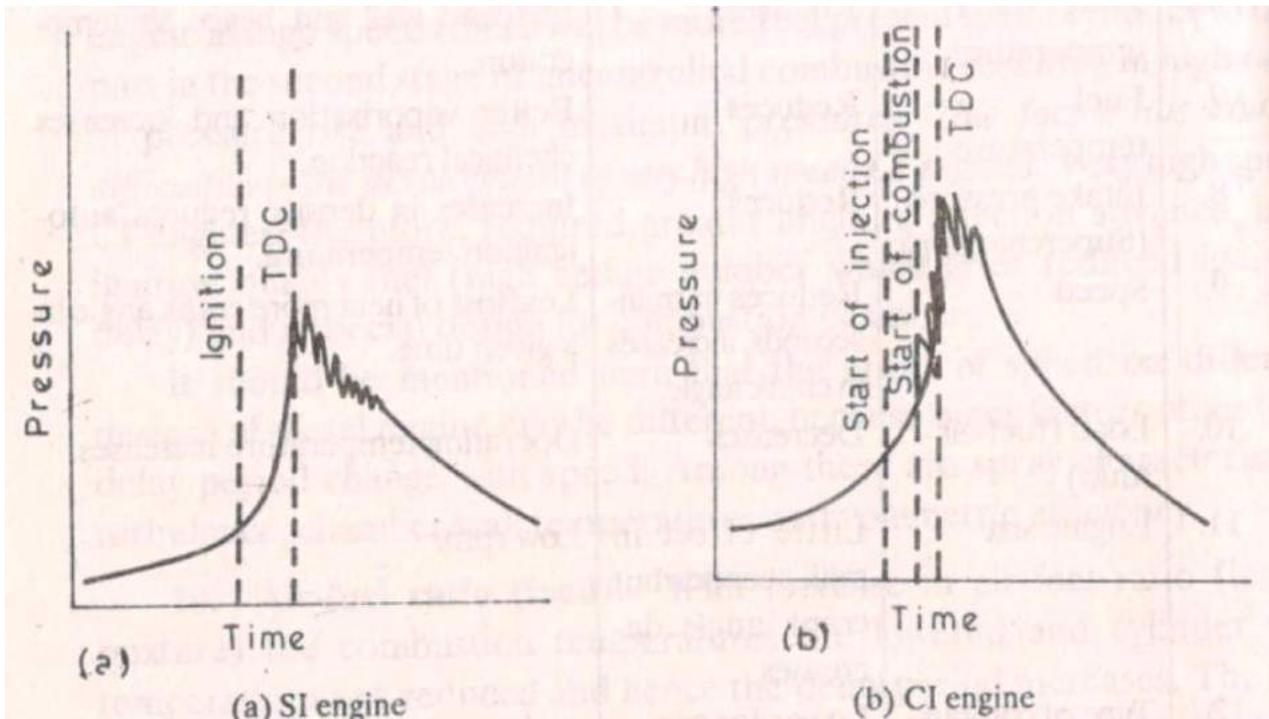
-CI engine detonation occurs in the beginning of combustion

-In CI engine the fuel and air are imperfectly mixed and hence the rate of pressure rise is normally cause audible knock. Rate of pressure rise may reach as high as 10 bar/°CA

-High engine vibration is the symptoms of knocking

-no pre-ignition or premature ignition as like SI engine.

Detonation in SI and CI engine



COMBUSTION CHAMBER

(i) According to the swirl of air

- (a) Induction swirl or open chamber or non-turbulent chamber
- (b) Compression swirl
- (c) Combustion induced swirl

(ii) According to speed of the engine

(a) Low speed engine ($n < 1500$ rpm):

- Shallow, swirl-less combustion chambers
- Direct, multi-jet fuel injection

(b) Medium speed engine ($n = 1500-3000$ rpm):

- Deep combustion chambers with intensive swirl of charge
- Direct injection of atomised fuel

(c) high speed engine ($n = 3000-5000$ rpm):

- Pre-chambers (sectional combustion chambers)
 - Indirect injection of fuel into the pre-chamber

GAS TURBINES

Two types of gas turbine,

- (a) Open cycle gas turbine
- (b) Closed cycle gas turbine

(a) Open cycle gas turbine:

-Working on Joule cycle or Brayton cycle

-Air is compressed in a rotary compressor and passed into a combustion chamber where fuel is burnt, the products of combustion are made to impinge over rings of turbine blades with high velocity and work is produced. After the work done by the combustion products, rest are given to the atmosphere.

-60% of work produced is used to drive the compressor and rest is available as useful power

-For starting purpose, it is first motored to minimum speed, called coming in speed, before the fuel is turned on

-About 5% power output by the motor is used to start the turbine

To improve the turbine performance intercooler, heat exchanger and reheat cycles are used with simple gas turbine cycle.

(b) Closed cycle gas turbine:

-Working fluid air or other gas is circulated continuously inside the machine

- Working fluid does not come in contact with the atmospheric air or fuel

-Heat to working fluid is given externally by the burning of the fuel that is why it is external combustion engine

-Turbine exhaust rejects heat in a cooler

Advantage of closed cycle gas turbine:

-Due to externally fired, cheaper fuel such as coal can be used

-Products of combustion is not in directly contact with turbine blades, hence fouling and heat transfer from the surface of the blade can be avoided

-Part load efficiency is improved by changing the pressure ratio and varying the quantity of working fluid keeping as cycle temperature constant and at constant speed

-High operating pressure causes low specific volume for the working fluid reducing the size of machines, heat exchangers and piping

-Heat transfer coefficients are higher which reduces the heat exchanger size

Disadvantage of closed cycle gas turbine:

-more complicated and costly system

- Air heaters alone represent over 30% of total mass and cost
- system is not sufficiently strong to resist high pressure

Simple Gas Turbine:

Following assumptions are made in analysis of ideal gas turbine,

- Compression and expansion process are reversible adiabatic
- Kinetic energy does not change at the inlet and exit
- No pressure loss
- Same chemical composition of working fluid
- Heat exchanger is counter flow type with 100% efficiency

The various operations are as follows :

Operation 1-2. The air is compressed isentropically from the lower pressure p_1 to the upper pressure p_2 , the temperature rising from T_1 to T_2 . No heat flow occurs.

Operation 2-3. Heat flows into the system increasing the volume from V_2 to V_3 and temperature from T_2 to T_3 whilst the pressure remains constant at p_2 . Heat received = $mcp (T_3 - T_2)$.

Operation 3-4. The air is expanded isentropically from p_2 to p_1 , the temperature falling from T_3 to T_4 . No heat flow occurs.

Operation 4-1. Heat is rejected from the system as the volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at p_1 . Heat rejected = mcp

