

## Unit – I

### Syllabus:

Gas power cycles: Otto, diesel, dual combustion cycles, description and representation on P-v and T-s diagram, thermal efficiency, mean effective pressure on air standard basis- comparison of cycles, Brayton cycle

- Evaluate thermal efficiency of Otto, diesel, dual cycle and Brayton cycle and they can represent on P-v and T-s diagrams
- Compare various gas power cycles
- Understand vapour power cycles
- Understand refrigeration cycles
- Evaluate performance of refrigeration cycles

### ➤ Air-Standard Assumptions

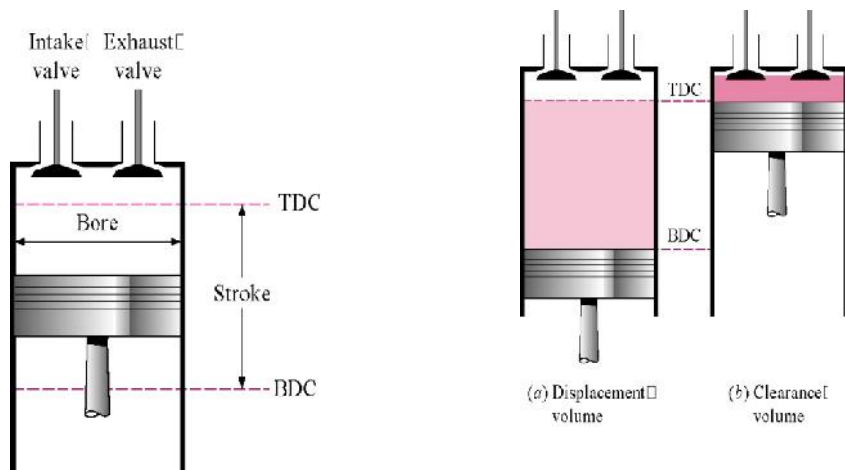
In our study of gas power cycles, we assume the working fluid is air, and the air undergoes a thermodynamic cycle even though the working fluid in the actual power system does not undergo a cycle.

To simplify the analysis, we approximate the cycles with the following assumptions:

- The air continuously circulates in a closed loop and always behaves as an ideal gas.
- All the processes that make up the cycle are internally reversible.
- The combustion process is replaced by a heat-addition process from an external source.
- A heat rejection process that restores the working fluid to its initial state replaces the exhaust process.
- The cold-air-standard assumptions apply when the working fluid is air and has constant specific heat evaluated at room temperature (25°C or 77°F).

### ➤ Terminology for Reciprocating Devices

The following is some terminology we need to understand for reciprocating engines—typically piston-cylinder devices. Let's look at the following figures for the definitions of top dead center (TDC), bottom dead center (BDC), stroke, bore, intake valve, exhaust valve, clearance volume, displacement volume, compression ratio, and mean effective pressure.

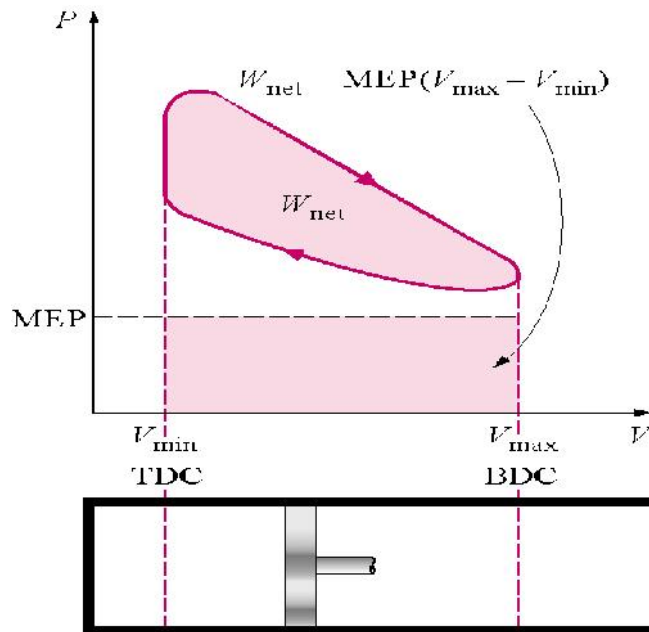


- The compression ratio  $r$  of an engine is the ratio of the maximum volume to the minimum volume formed in the cylinder.

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_{BDC}}{V_{TDC}}$$

- The mean effective pressure (**MEP**) is a fictitious pressure that, if it operated on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

$$MEP = \frac{W_{net}}{V_{max} - V_{min}} = \frac{W_{net}}{v_{max} - v_{min}}$$

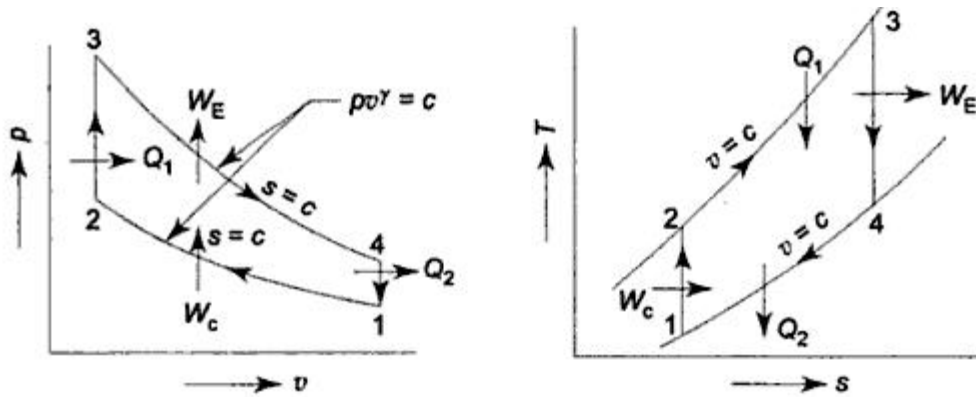


- **Otto Cycle (Constant Volume Cycle):**

This ideal heat engine cycle was proposed in 1862 by Beau de Rochas. In 1876 Dr. Otto designed an engine to operate on this cycle. The Otto engine immediately became so successful from a commercial stand point, that its name was affixed to the cycle used by it.

The ideal p - v and T-s diagrams of this cycle are shown in fig. In working out the air-standard efficiency of the cycle, the following assumptions are made:

- The working fluid (working substance) in the engine cylinder is air, and it behaves as a perfect gas, i.e., it obeys the gas laws and has constant specific heats.
- The air is compressed adiabatically (without friction) according to law  $pv = C$
- The heat is supplied to the air at constant volume by bringing a hot body in contact with the end of the engine cylinder.
- The air expands in the engine cylinder adiabatically (without friction) during the expansion stroke.
- The heat is rejected from the air at constant volume by bringing a cold body in contact with the end of the engine cylinder.



- Process 1 → 2 Isentropic compression
- Process 2 → 3 Constant volume heat addition
- Process 3 → 4 Isentropic expansion
- Process 4 → 1 Constant volume heat rejection

Consider one kilogram of air in the engine cylinder at point (1). This air is compressed adiabatically to point (2), at which condition the hot body is placed in contact with the end of the cylinder. Heat is now supplied at constant volume, and temperature and pressure rise; this operation is represented by (2-3). The hot body is then removed and the air expands adiabatically to point (4). During this process, work is done on the piston. At point (4), the cold body is placed at the end of the cylinder. Heat is now rejected at constant volume, resulting in drop of temperature and pressure. This operation is represented by (4-1). The cold body is then removed after the air is brought to its original state (condition). The cycle is thus completed. The cycle consists of two constant volume processes and two reversible adiabatic processes. The heat is supplied during constant volume process (2-3) and rejected during constant volume process (4-1). There is no exchange of heat during the two reversible adiabatic processes (1-2) and (3-4).

The performance is often measured in terms of the cycle efficiency.

$$y_{th} = \frac{W_{net}}{Q_{in}}$$

Thermal Efficiency of the Otto cycle

$$y_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Now to find  $Q_{in}$  and  $Q_{out}$ .

Apply first law closed system,  $V = \text{constant}$ .

Heat supplied during constant volume operation (2-3), Heat rejected during constant volume operation (4-1) is

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$Q_{net, 23} = \Delta U_{23}$$

$$Q_{net, 23} = Q_{in} = m C_v (T_3 - T_2)$$

$$Q_{net, 41} = \Delta U_{41}$$

$$Q_{net, 41} = -Q_{out} = m C_v (T_1 - T_4)$$

$$Q_{out} = -m C_v (T_1 - T_4) = m C_v (T_4 - T_1)$$

The thermal efficiency becomes

$$\begin{aligned} \eta_{th, Otto} &= 1 - \frac{Q_{out}}{Q_{in}} \\ &= 1 - \frac{m C_v (T_4 - T_1)}{m C_v (T_3 - T_2)} \end{aligned}$$

$$\begin{aligned} \eta_{th, Otto} &= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \\ &= 1 - \frac{T_1(T_4 / T_1 - 1)}{T_2(T_3 / T_2 - 1)} \end{aligned}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \frac{T_4}{T_3}$$

Since  $V_3 = V_2$  and  $V_4 = V_1$

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

or

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

The Otto cycle efficiency becomes

$$\eta_{th, Otto} = 1 - \frac{T_1}{T_2}$$

Since process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1}$$

Where the compression ratio is

$$r = \frac{v_{\max}}{v_{\min}} = \frac{v_1}{v_2}$$

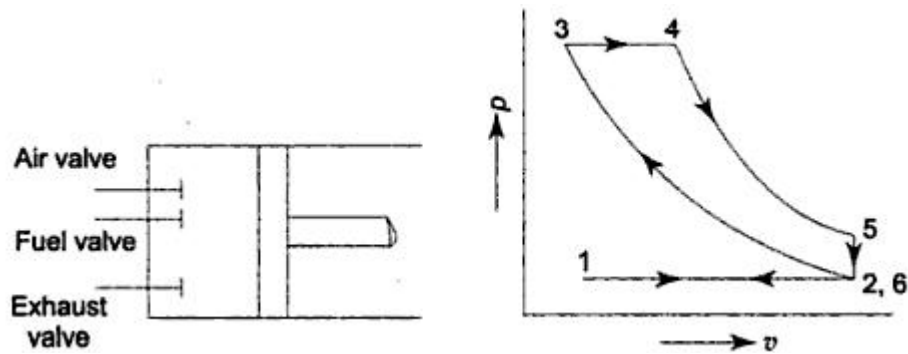
$$\eta_{th, Otto} = 1 - \frac{1}{r^{k-1}}$$

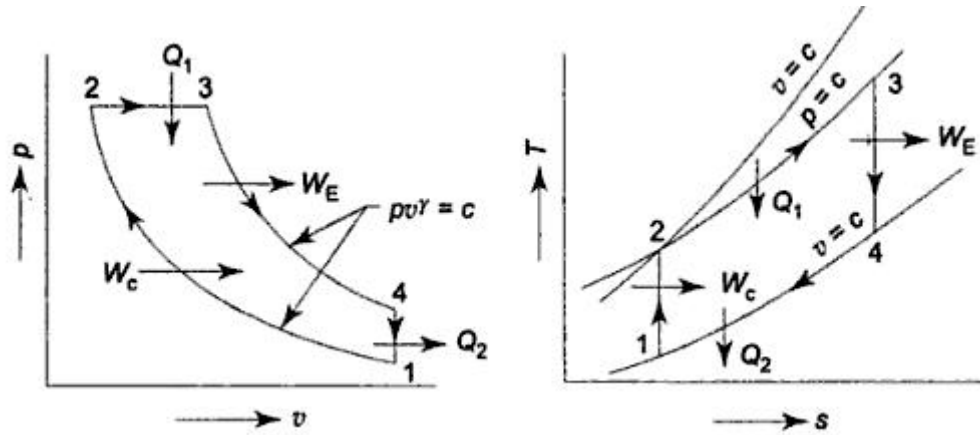
➤ **Air-Standard Diesel Cycle (or constant pressure cycle):**

The air-standard Diesel cycle is the ideal cycle that approximates the Diesel combustion engine

Process	Description
1-2	isentropic compression
2-3	Constant pressure heat addition
3-4	isentropic expansion
4-1	Constant volume heat rejection

The  $P$ - $v$  and  $T$ - $s$  diagrams are





$$\text{Heat supplied} = Q_1 = Q_{2-3} = mc_p (T_3 - T_2)$$

$$\text{Heat Rejected} = Q_2 = Q_{4-1} = mc_v (T_4 - T_1)$$

$$\text{Efficiency} = \eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v (T_4 - T_1)}{mc_p (T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{\gamma (T_3 - T_2)}$$

The efficiency may be expressed terms of any two of the following.

$$\text{Compression Ratio} = r_k = \frac{v_1}{v_2}$$

$$\text{Expansion Ratio} = r_e = \frac{v_4}{v_3}$$

$$\text{Cut-off ratio} = r_c = \frac{v_3}{v_2}$$

$$r_k = r_e \cdot r_c$$

Process 3-4

$$\frac{T_4}{T_3} = \left( \frac{v_3}{v_4} \right)^{\gamma-1} = \frac{1}{r_e^{\gamma-1}}$$

$$T_4 = T_3 \left( \frac{v_3}{v_4} \right)^{\gamma-1} = T_3 \frac{r_e^{\gamma-1}}{r_k^{\gamma-1}}$$

Process 2-3

$$\frac{T_2}{T_3} = \frac{p_2 v_2}{p_3 v_3} = \frac{v_2}{v_3} = \frac{1}{r_e}$$

$$T_2 = T_3 \frac{1}{r_e}$$

Process 1-2

$$\frac{T_1}{T_2} = \left( \frac{v_2}{v_1} \right)^{\gamma-1} = \frac{1}{r_k^{\gamma-1}}$$

$$T_1 = T_2 \frac{1}{r_k^{\gamma-1}} = \frac{T_3}{r_c} \frac{1}{r_k^{\gamma-1}}$$

By substituting T1, T2 and T4 in the expression of efficiency

$$\eta = 1 - \frac{T_3 \frac{r_c^{\gamma-1}}{r_k^{\gamma-1}} - T_3 \frac{1}{r_c r_k^{\gamma-1}}}{T_3 - T_3 \frac{1}{r_c}}$$

$$\eta_{diesel} = 1 - \frac{1}{r_c^{\gamma-1}} \cdot \frac{r_c^{\gamma-1}}{r_c - 1}$$

➤ **Dual Cycle (mixed cycle/ limited pressure cycle):**

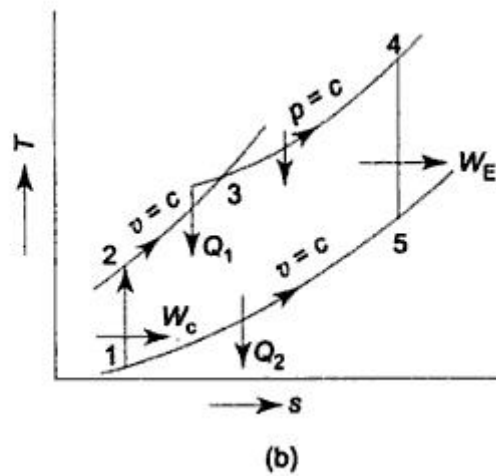
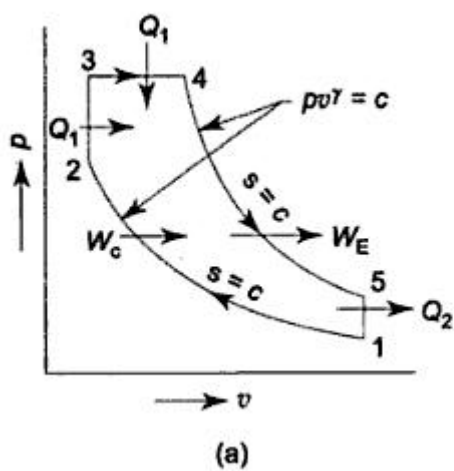
Process 1 → 2 Isentropic compression

Process 2 → 3 Constant volume heat addition

Process 3 → 4 Constant pressure heat addition

Process 4 → 5 Isentropic expansion

Process 5 → 1 Constant volume heat rejection





Thermal Efficiency:

$$\text{where } r_c = \frac{v_3}{v_{2.5}} \text{ and } r = \frac{P_3}{P_2}$$

Note, the Otto cycle ( $r_c=1$ ) and the Diesel cycle ( $a=1$ ) are special cases:

$$y_{Otto} = 1 - \frac{1}{r^{k-1}} \quad y_{Diesel}^{const\ c_v} = 1 - \frac{1}{r^{k-1}} \left[ \frac{1}{k} \cdot \frac{(r_c^k - 1)}{(r_c - 1)} \right]$$

The use of the Dual cycle requires information about either:

- i) The fractions of constant volume and constant pressure heat addition (common assumption is to equally split the heat addition), or
- ii) Maximum pressure  $P_3$ .

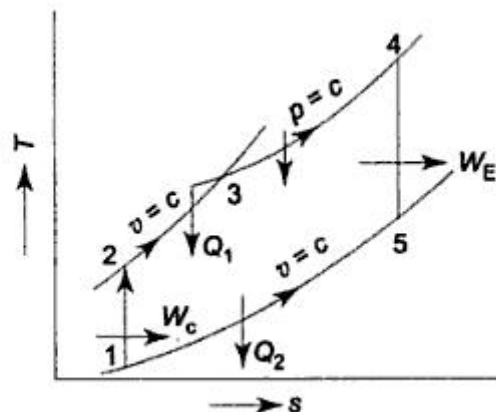
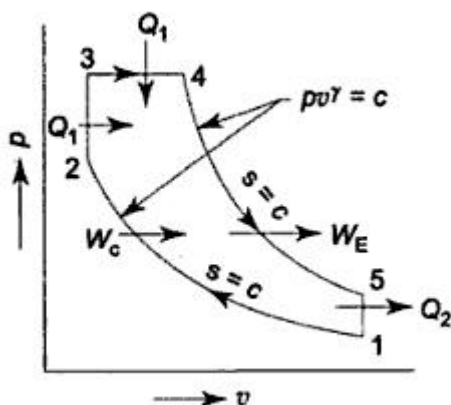
$$Q_1 = mc_v(T_3 - T_2) + mc_p(T_4 - T_3)$$

$$Q_2 = mc_v(T_5 - T_1)$$

Here  $Q_1$  = heat input

$Q_2$  = Out put

$$y = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_5 - T_1)}{mc_v(T_3 - T_2) + mc_p(T_4 - T_3)} = 1 - \frac{T_5 - T_1}{(T_3 - T_2) + x(T_4 - T_3)}$$



$$\text{Compression Ratio} = r_k = \frac{v_1}{v_2}$$

$$\text{Expansion Ratio} = r_e = \frac{v_4}{v_3}$$

$$\text{constant-volume-pressure-ratio} = r_p = \frac{P_3}{P_2}$$

$$r_k = r_c \cdot r_e$$

$$r_e = \frac{r_k}{r_c}$$

process 3-4

$$r_c = \frac{v_4}{v_3} = \frac{T_4 P_3}{P_4 T_3} = \frac{T_4}{T_3}$$

$$T_3 = \frac{T_4}{r_c}$$

Process 2-3

$$\frac{P_2 v_2}{T_2} = \frac{P_3 v_3}{T_3}$$

$$T_2 = T_3 \frac{P_2}{P_3} = \frac{T_4}{r_p r_c}$$

process-1-2

$$\frac{T_1}{T_2} = \left( \frac{v_2}{v_1} \right)^{\gamma-1} = \frac{1}{r_k^{\gamma-1}}$$

$$T_1 = \frac{T_4}{r_p \cdot r_c \cdot r_k^{\gamma-1}}$$

Process 4-5

$$T_1 = \frac{T_4}{r_p \cdot r_c \cdot r_k^{\gamma-1}}$$

$$\frac{T_5}{T_4} = \left( \frac{v_4}{v_5} \right)^{\gamma-1} = \frac{1}{r_e^{\gamma-1}}$$

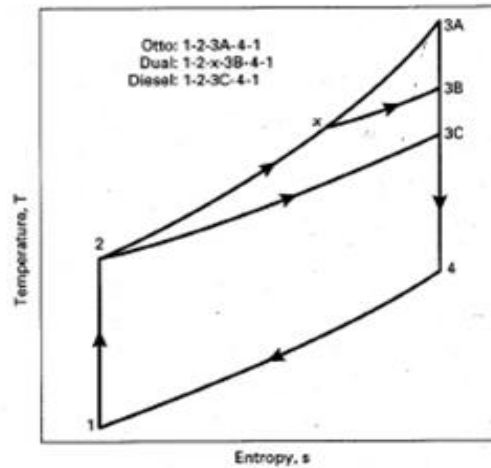
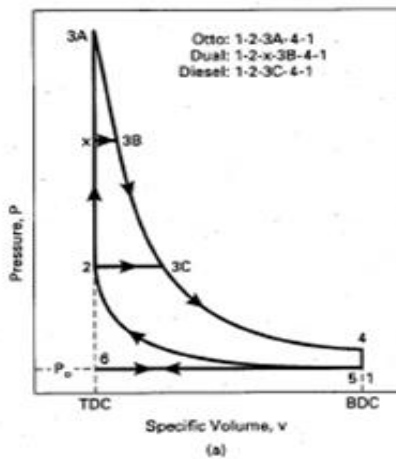
$$T_5 = T_4 \frac{r_c^{\gamma-1}}{r_k^{\gamma-1}}$$

Substituting T1, T2, T3 and T4 values

$$\eta_{dual} = 1 - \frac{T_4 \frac{r_c^{x-1}}{r_k^{x-1}} - \frac{T_4}{r_p \cdot r_c \cdot r_k^{x-1}}}{\left(\frac{T_4}{r_c} - \frac{T_4}{r_p r_c}\right) + x \left(\frac{T_4}{r_c} - \frac{T_4}{r_c}\right)} = 1 - \frac{1}{r_k^{x-1}} \frac{r_p r_c^{x-1}}{r_p - 1 + x r_p (r_c - 1)}$$

➤ **Comparison of cycles:**

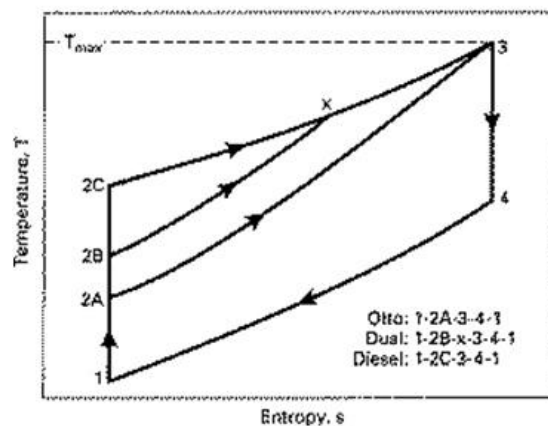
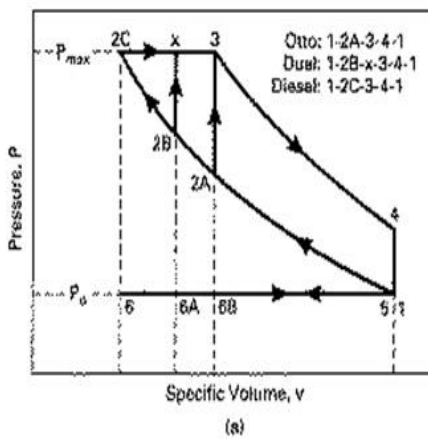
- ❖ For the same inlet conditions  $P_1, V_1$  and the same compression ratio  $P_2/P_1$ :



For the same initial conditions  $P_1, V_1$  and the same compression ratio:

$$\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$$

- ❖ For the same inlet conditions  $P_1, V_1$  and the same peak pressure  $P_3$ :



For the same initial conditions  $P_1, V_1$  and the same peak pressure  $P_3$

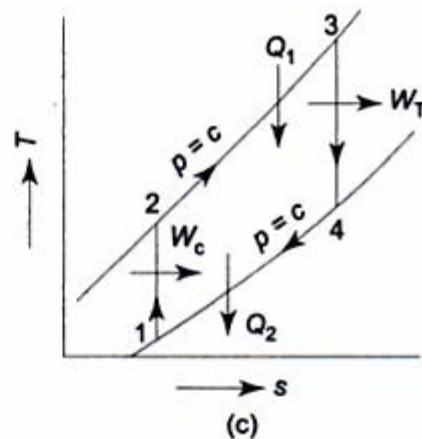
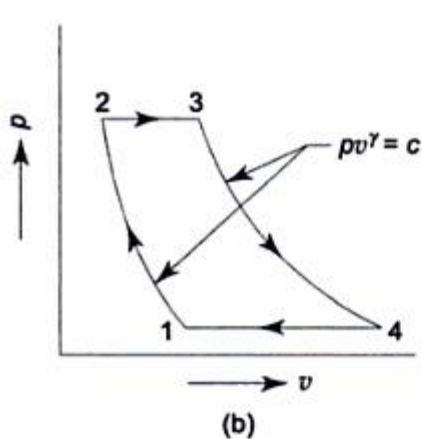
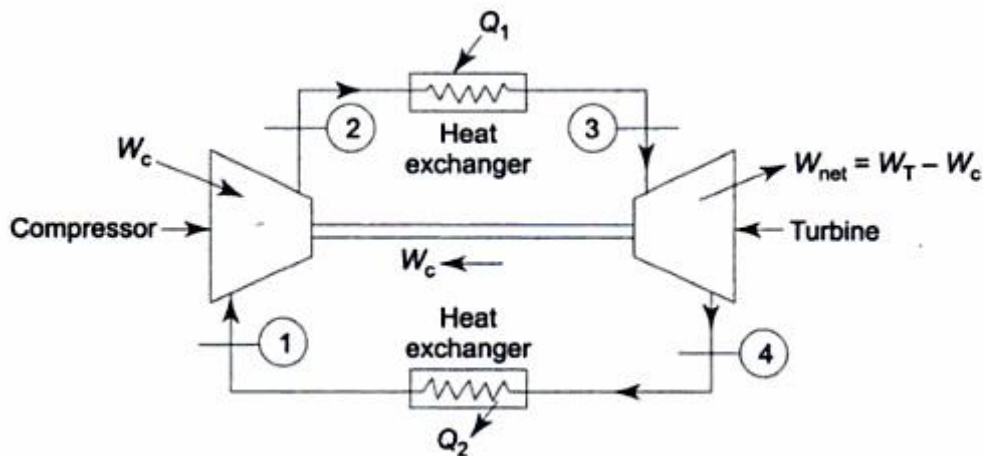
(Actual design limitation in engines):

$$\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$$

➤ **Brayton Cycle (or Joule cycle)**

The Brayton cycle is the air-standard ideal cycle approximation for the gas-turbine engine. This cycle differs from the Otto and Diesel cycles in that the processes making the cycle occur in open systems or control volumes. Therefore, an open system, steady-flow analysis is used to determine the heat transfer and work for the cycle.

We assume the working fluid is air and the specific heats are constant and will consider the cold-air-standard cycle.



The closed cycle gas-turbine engine

The  $T$ - $s$  and  $P$ - $v$  diagrams for the

## Closed Brayton Cycle

Process	Description
1-2	Isentropic compression (in a compressor)
2-3	Constant pressure heat addition
3-4	Isentropic expansion (in a turbine)
4-1	Constant pressure heat rejection

Thermal efficiency of the Brayton cycle

$$\eta_{th, Brayton} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Now to find  $Q_{in}$  and  $Q_{out}$ .

Apply the conservation of energy to process 2-3 for  $P = \text{constant}$  (no work), steady-flow, and neglect changes in kinetic and potential energies.

$$\begin{aligned}\dot{E}_{in} &= \dot{E}_{out} \\ \dot{m}_2 h_2 + \dot{Q}_{in} &= \dot{m}_3 h_3\end{aligned}$$

The conservation of mass gives

$$\begin{aligned}\dot{m}_{in} &= \dot{m}_{out} \\ \dot{m}_2 &= \dot{m}_3 = \dot{m}\end{aligned}$$

For constant specific heats, the heat added per unit mass flow is

$$\begin{aligned}\dot{Q}_{in} &= \dot{m}(h_3 - h_2) \\ \dot{Q}_{in} &= \dot{m}C_p(T_3 - T_2) \\ q_{in} &= \frac{\dot{Q}_{in}}{\dot{m}} = C_p(T_3 - T_2)\end{aligned}$$

The conservation of energy for process 4-1 yields for constant specific heats

$$\begin{aligned}\dot{Q}_{out} &= \dot{m}(h_4 - h_1) \\ \dot{Q}_{out} &= \dot{m}C_p(T_4 - T_1) \\ q_{out} &= \frac{\dot{Q}_{out}}{\dot{m}} = C_p(T_4 - T_1)\end{aligned}$$

The thermal efficiency becomes

$$\begin{aligned}
 y_{th, Brayton} &= 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{q_{out}}{q_{in}} \\
 &= 1 - \frac{C_p (T_4 - T_1)}{C_p (T_3 - T_2)}
 \end{aligned}$$

$$\begin{aligned}
 y_{th, Brayton} &= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \\
 &= 1 - \frac{T_1 (T_4 / T_1 - 1)}{T_2 (T_3 / T_2 - 1)}
 \end{aligned}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{x-1}{x}}$$

$$\frac{T_3}{T_4} = \left( \frac{p_3}{p_4} \right)^{\frac{x-1}{x}}$$

Since  $P_3 = P_2$  and  $P_4 = P_1$ ,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

or

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

The Brayton cycle efficiency becomes

$$y_{th, Brayton} = 1 - \frac{T_1}{T_2}$$

Since process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{x-1}{x}} = r_p^{\frac{x-1}{x}}$$

$$\frac{T_1}{T_2} = \frac{1}{r_p^{\frac{x-1}{x}}}$$

Where the pressure ratio is  $r_p = P_2/P_1$  and

$$y_{th, Brayton} = 1 - \frac{1}{r_p^{(x-1)/x}}$$

## **Module - I**

### **INTRODUCTION**

#### **Heat engine:**

A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work. It is classified into two types-

- (a) External combustion engine
- (b) Internal combustion engine

#### ***External combustion engine:***

In this engine, the products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle.

Examples:

\*In the steam engine or a steam turbine plant, the heat of combustion is employed to generate steam which is used in a piston engine (reciprocating type engine) or a turbine (rotary type engine) for useful work.

\*In a closed cycle gas turbine, the heat of combustion in an external furnace is transferred to gas, usually air which the working fluid of the cycle.

#### ***Internal combustion engine:***

In this engine, the combustion of air and fuels take place inside the cylinder and are used as the direct motive force. It can be classified into the following types:

1. According to the basic engine design- (a) Reciprocating engine (Use of cylinder piston arrangement), (b) Rotary engine (Use of turbine)
2. According to the type of fuel used- (a) Petrol engine, (b) diesel engine, (c) gas engine (CNG, LPG), (d) Alcohol engine (ethanol, methanol etc)
3. According to the number of strokes per cycle- (a) Four stroke and (b) Two stroke engine
4. According to the method of igniting the fuel- (a) Spark ignition engine, (b) compression ignition engine and (c) hot spot ignition engine
5. According to the working cycle- (a) Otto cycle (constant volume cycle) engine, (b) diesel cycle (constant pressure cycle) engine, (c) dual combustion cycle (semi diesel cycle) engine.

6. According to the fuel supply and mixture preparation- (a) Carburetted type (fuel supplied through the carburettor), (b) Injection type (fuel injected into inlet ports or inlet manifold, fuel injected into the cylinder just before ignition).
7. According to the number of cylinder- (a) Single cylinder and (b) multi-cylinder engine
8. Method of cooling- water cooled or air cooled
9. Speed of the engine- Slow speed, medium speed and high speed engine
10. Cylinder arrangement-Vertical, horizontal, inline, V-type, radial, opposed cylinder or piston engines.
11. Valve or port design and location- Overhead (I head), side valve (L head); in two stroke engines: cross scavenging, loop scavenging, uniflow scavenging.
12. Method governing- Hit and miss governed engines, quantitatively governed engines and qualitatively governed engine
14. Application- Automotive engines for land transport, marine engines for propulsion of ships, aircraft engines for aircraft propulsion, industrial engines, prime movers for electrical generators.

**Comparison between external combustion engine and internal combustion engine:**

External combustion engine	Internal combustion engine
*Combustion of air-fuel is outside the engine cylinder (in a boiler)	* Combustion of air-fuel is inside the engine cylinder (in a boiler)
*The engines are running smoothly and silently due to outside combustion	* Very noisy operated engine
*Higher ratio of weight and bulk to output due to presence of auxiliary apparatus like boiler and condenser. Hence it is heavy and cumbersome.	* It is light and compact due to lower ratio of weight and bulk to output.
*Working pressure and temperature inside the engine cylinder is low; hence ordinary alloys are used for the manufacture of engine cylinder and its parts.	* Working pressure and temperature inside the engine cylinder is very much high; hence special alloys are used
*It can use cheaper fuels including solid fuels	*High grade fuels are used with proper filtration
*Lower efficiency about 15-20%	*Higher efficiency about 35-40%
* Higher requirement of water for dissipation of energy through cooling system	*Lesser requirement of water
*High starting torque	*IC engines are not self-starting

**Main components of reciprocating IC engines:**

**Cylinder:** It is the main part of the engine inside which piston reciprocates to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above

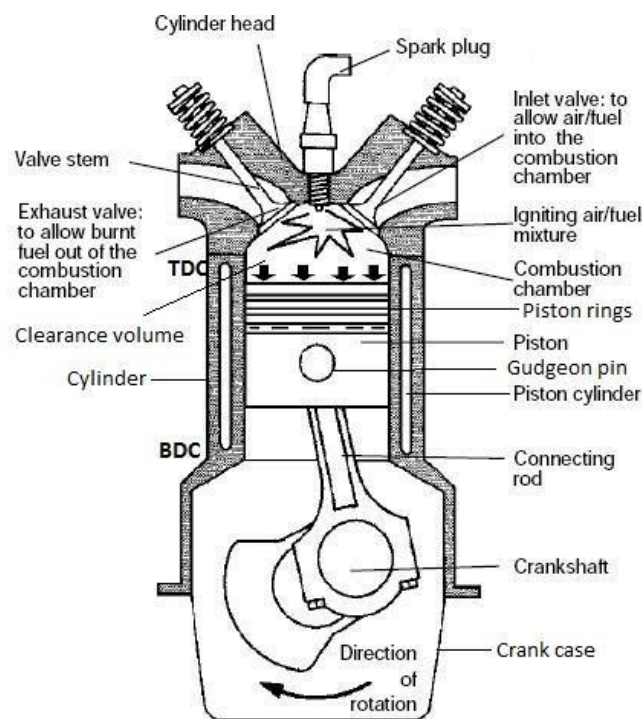


2000 °C. The ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminum alloys. In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.

**Cylinder head:** The top end of the cylinder is covered by cylinder head over which inlet and exhaust valve, spark plug or injectors are mounted. A copper or asbestos gasket is provided between the engine cylinder and cylinder head to make an air tight joint.

**Piston:** Transmit the force exerted by the burning of charge to the connecting rod. Usually made of aluminium alloy which has good heat conducting property and greater strength at higher temperature.

Figure 1 shows the different components of IC engine.



**Fig. 1. Different parts of IC engine**

**Piston rings:** These are housed in the circumferential grooves provided on the outer surface of the piston and made of steel alloys which retain elastic properties even at high temperature. 2 types of rings- compression and oil rings. Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

**Connecting rod:** It converts reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke. The smaller end of the connecting rod is connected with the piston by gudgeon pin and bigger end of the connecting rod is connected with the crank

with crank pin. The special steel alloys or aluminium alloys are used for the manufacture of connecting rod.

**Crankshaft:** It converts the reciprocating motion of the piston into the rotary motion with the help of connecting rod. The special steel alloys are used for the manufacturing of the crankshaft. It consists of eccentric portion called crank.

**Crank case:** It houses cylinder and crankshaft of the IC engine and also serves as sump for the lubricating oil.

**Flywheel:** It is big wheel mounted on the crankshaft, whose function is to maintain its speed constant. It is done by storing excess energy during the power stroke, which is returned during other stroke.

### **Terminology used in IC engine:**

1. Cylinder bore (D): The nominal inner diameter of the working cylinder.
2. Piston area (A): The area of circle of diameter equal to the cylinder bore.
3. Stroke (L): The nominal distance through which a working piston moves between two successive reversals of its direction of motion.
4. 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.
5. 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,

$$V_s = A \times L$$

6. Clearance volume ( $V_c$ ): the nominal volume of the space on the combustion side of the piston at the top dead centre.

7. Cylinder volume (V): Total volume of the cylinder.

$$V = V_s + V_c$$

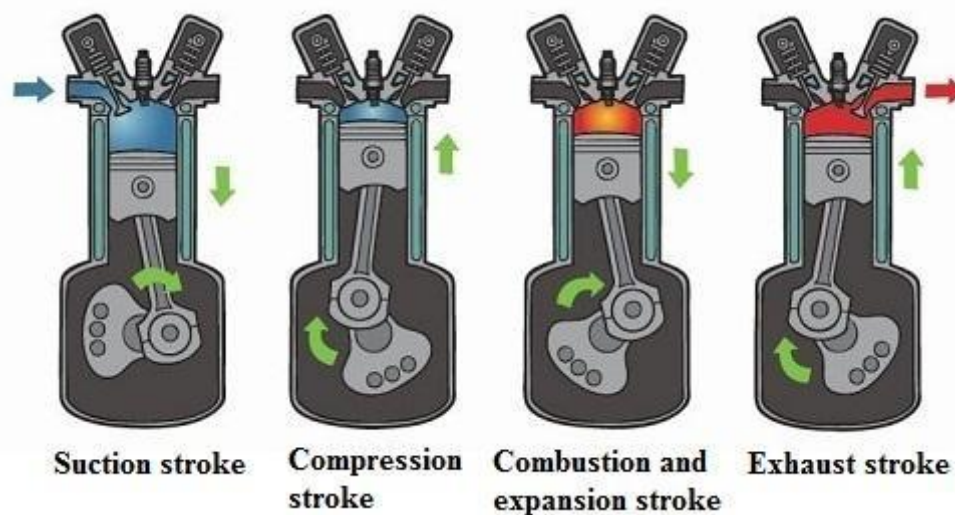
8. Compression ratio (r): —

### **Four stroke engine:**

- Cycle of operation completed in four strokes of the piston or two revolution of the piston.

- (i) Suction stroke (suction valve open, exhaust valve closed)-charge consisting of fresh air mixed with the fuel is drawn into the cylinder due to the vacuum pressure created by the movement of the piston from TDC to BDC.
- (ii) Compression stroke (both valves closed)-fresh charge is compressed into clearance volume by the return stroke of the piston and ignited by the spark for combustion. Hence pressure and temperature is increased due to the combustion of fuel
- (iii) Expansion stroke (both valves closed)-high pressure of the burnt gases force the piston towards BDC and hence power is obtained at the crankshaft.
- (iv) Exhaust stroke (exhaust valve open, suction valve closed)- burned gases expel out due to the movement of piston from BDC to TDC.

Figure 2 show the cycle of operation of four stroke engine.

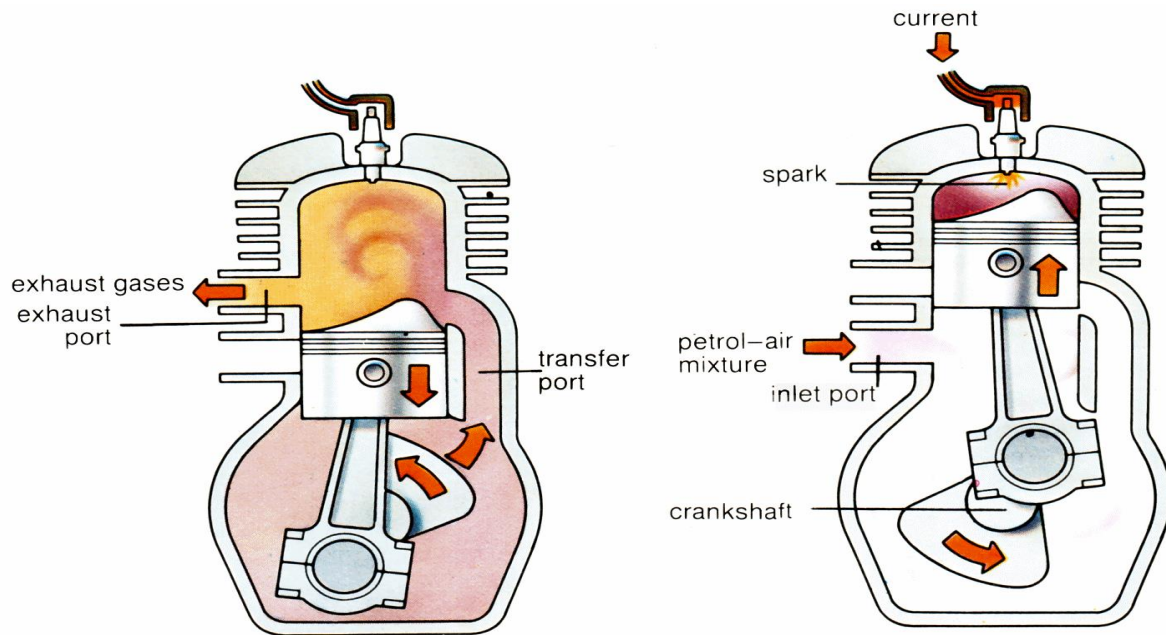


**Fig. 2.** Cycle of operation in four stroke engine

### **Two stroke engine:**

- No piston stroke for suction and exhaust operations
- Suction is accomplished by air compressed in crankcase or by a blower
- Induction of compressed air removes the products of combustion through exhaust ports
- Transfer port is there to supply the fresh charge into combustion chamber

Figure 3 represents operation of two stroke engine



**Fig. 3.** Cycle of operation in two stroke engine

**Comparison of Four-stroke and two-stroke engine:**

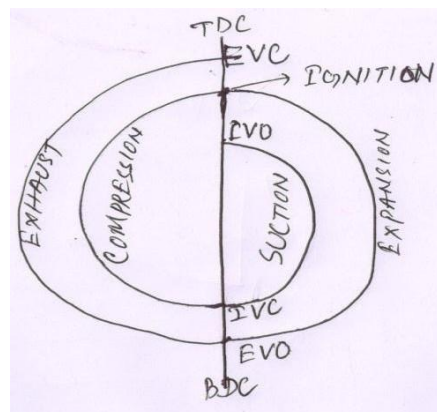
<b>Four-stroke engine</b>	<b>Two-stroke engine</b>
1. Four stroke of the piston and two revolution of crankshaft	Two stroke of the piston and one revolution of crankshaft
2. One power stroke in every two revolution of crankshaft	One power stroke in each revolution of crankshaft
3. Heavier flywheel due to non-uniform turning movement	Lighter flywheel due to more uniform turning movement
4. Power produce is less	Theoretically power produce is twice than the four stroke engine for same size
5. Heavy and bulky	Light and compact
6. Lesser cooling and lubrication requirements	Greater cooling and lubrication requirements
7. Lesser rate of wear and tear	Higher rate of wear and tear
8. Contains valve and valve mechanism	Contains ports arrangement
9. Higher initial cost	Cheaper initial cost
10. Volumetric efficiency is more due to greater time of induction	Volumetric efficiency less due to lesser time of induction
11. Thermal efficiency is high and also part load efficiency better	Thermal efficiency is low, part load efficiency lesser
12. It is used where efficiency is important.	It is used where low cost, compactness and light weight are important.
<u>Ex-cars, buses, trucks, tractors, industrial engines, aero planes, power generation etc.</u>	<u>Ex-lawn mowers, scooters, motor cycles, mopeds, propulsion ship etc.</u>

### Comparison of SI and CI engine:

SI engine	CI engine
Working cycle is Otto cycle.	Working cycle is diesel cycle.
Petrol or gasoline or high octane fuel is used.	Diesel or high cetane fuel is used.
High self-ignition temperature.	Low self-ignition temperature.
Fuel and air introduced as a gaseous mixture in the suction stroke.	Fuel is injected directly into the combustion chamber at high pressure at the end of compression stroke.
Carburettor used to provide the mixture. Throttle controls the quantity of mixture introduced.	Injector and high pressure pump used to supply of fuel. Quantity of fuel regulated in pump.
Use of spark plug for ignition system	Self-ignition by the compression of air which increased the temperature required for combustion
Compression ratio is 6 to 10.5	Compression ratio is 14 to 22
Higher maximum RPM due to lower weight	Lower maximum RPM
Maximum efficiency lower due to lower compression ratio	Higher maximum efficiency due to higher compression ratio
Lighter	Heavier due to higher pressures

### Valve timing diagram:

The exact moment at which the inlet and outlet valve opens and closes with reference to the position of the piston and crank shown diagrammatically is known as valve timing diagram. It is expressed in terms of degree crank angle. The theoretical valve timing diagram is shown in Fig. 4.



**Fig. 4. Theoretical valve timing diagram**

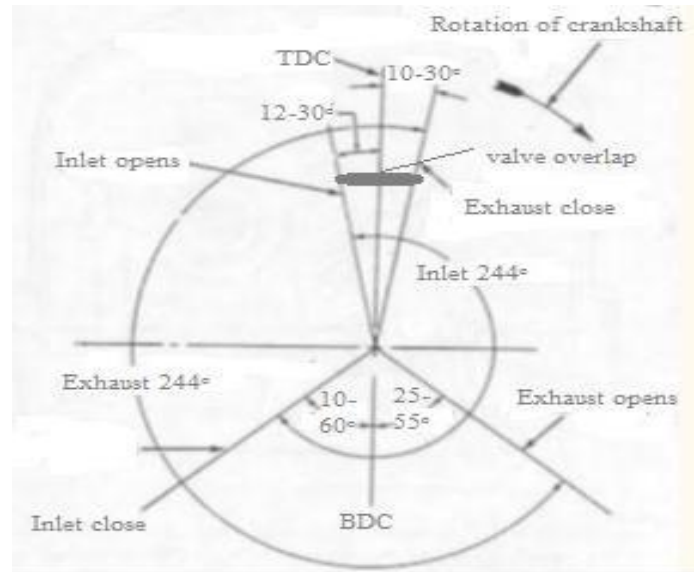
But actual valve timing diagram is different from theoretical due to two factors-mechanical and dynamic factors. Figure 4 shows the actual valve timing diagram for four stroke low speed or high speed engine.

### ***Opening and closing of inlet valve***

-Inlet valve opens 12 to 30° CA before TDC to facilitate silent operation of the engine under high speed. It increases the volumetric efficiency.

-Inlet valve closes 10-60° CA after TDC due to inertia movement of fresh charge into cylinder i.e. ram effect.

Figure 5 represents the actual valve timing diagram for low and high speed engine.



**Fig. 5. Actual valve timing diagram for low and high speed engine**

### ***Opening and closing of exhaust valve***

Exhaust valve opens 25 to 55° CA before BDC to reduce the work required to expel out the burnt gases from the cylinder. At the end of expansion stroke, the pressure inside the chamber is high, hence work to expel out the gases increases.

Exhaust valve closes 10 to 30° CA after TDC to avoid the compression of burnt gases in next cycle. Kinetic energy of the burnt gas can assist maximum exhausting of the gas. It also increases the volumetric efficiency.

Note: For low and high speed engine, the lower and upper values are used respectively

### ***Valve overlap***

During this time both the intake and exhaust valves are open. The intake valve is opened before the exhaust gases have completely left the cylinder, and their considerable velocity assists in drawing in the fresh charge. Engine designers aim to close the exhaust valve just as the fresh charge from the intake valve reaches it, to prevent either loss of fresh charge or unscavenged exhaust gas.

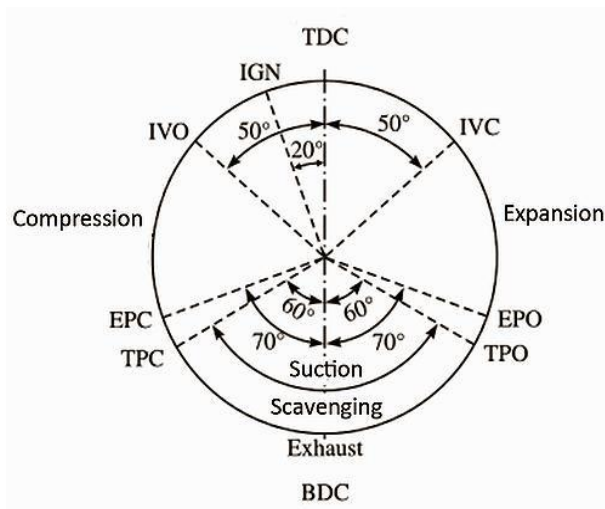
### **Port timing diagram:**

-Drawn for 2-stroke engine

-No valve arrangement

-3 ports- inlet, transfer and exhaust

Figure 6 shows port timing diagram for 2-stroke engine



**Fig. 6. Port timing diagram for 2-stroke engine**

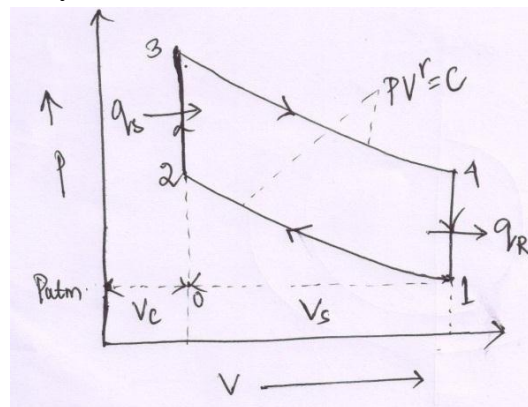
**Working cycle:**

(a) **Otto cycle-** thermodynamic cycle for SI/petrol engine

-Reversible adiabatic compression and expansion process

-Constant volume heat addition (combustion) and heat rejection process (exhaust)

Figure 7 depicts the Otto cycle



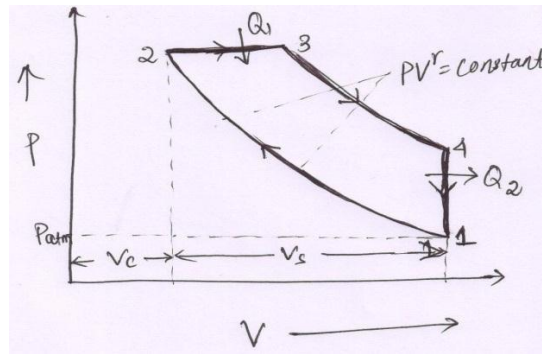
**Fig. 7. Otto cycle**

(b) **Diesel cycle-** thermodynamic cycle for low speed CI/diesel engine

-Reversible adiabatic compression and expansion process

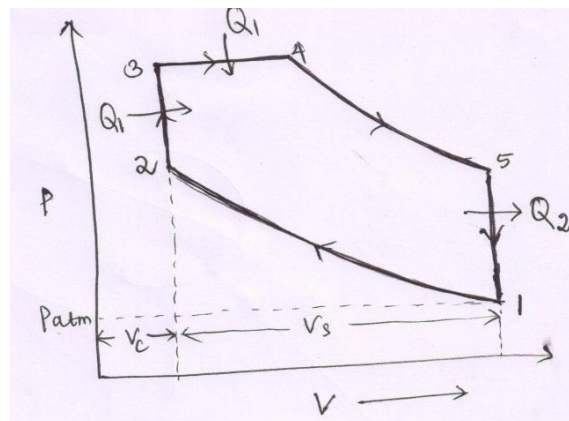
-Constant pressure heat addition (combustion) and heat rejection process (exhaust)

Figure 8 depicts the diesel cycle.



- (c) **Dual cycle or limited pressure cycle**-thermodynamic cycle for high speed diesel and hot spot ignition engine
- Reversible adiabatic compression and expansion process
  - Constant pressure and constant volume heat addition (combustion) and heat rejection process

Figure 9 shows the P-V diagram of Dual cycle.



**Fig. 9. Dual cycle**

## **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

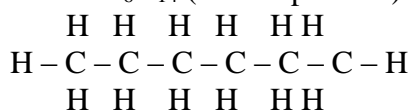
### **\*Classification of petroleum fuels used for IC engine:**

**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, O<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>O. 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/m<sup>3</sup>)
- 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.

Hexan C<sub>6</sub>H<sub>14</sub> (normal paraffin)



- Branched chain compounds (isoparaffins)  
When four or more C atoms are in a chain molecule it is possible to form isomers, they have the same chemical formula but different structures, which often leads to very different chemical properties.

Example: Iso-octane- C<sub>8</sub>H<sub>18</sub>

#### **(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 / m<sup>3</sup>)

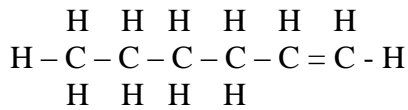
#### **(iii) Olefins-**

- 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<sub>2</sub>=CH.CH<sub>2</sub>.CH<sub>2</sub>.CH<sub>3</sub> called pentene-1  
CH<sub>3</sub>.CH=CH<sub>3</sub> 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

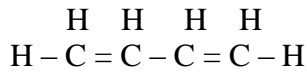
density in the range 620 – 820 kg / m<sup>3</sup>

Alkenes are such as,

Hexen (mono-olefin)



Butadien (dio-olefin)

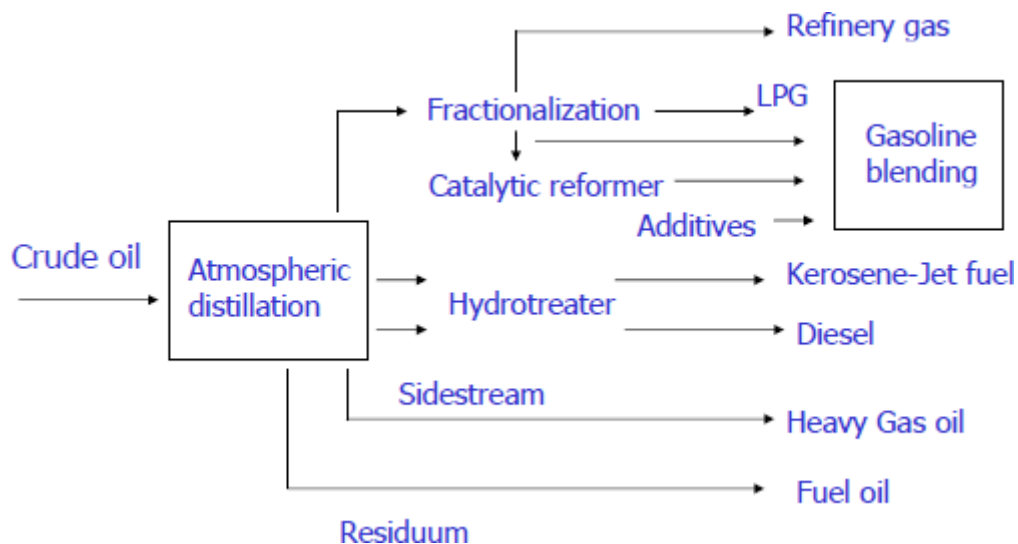


#### (iv) Aromatics-

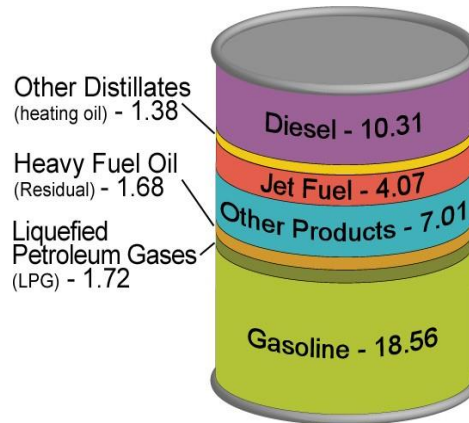
- These are so called due to aromatics odour and represented as C<sub>n</sub>H<sub>2n-6</sub>
- They are based on a six-membered ring having three conjugated double bonds
- Aromatic rings can be fused together to give polynuclear aromatics, PAN, also called polycyclic aromatic hydrocarbons, PAH simplest member is benzene (C<sub>6</sub>H<sub>6</sub>)
- Can be used in SI-engines, to increase the resistance to knock not suitable for CI-engines due to low cetene number
- Low heat content and high density in the range 800 – 850 kg / m<sup>3</sup>

#### \*Refinery processes:

Crude oil is the liquid part of the naturally occurring organic material composed mostly of HCs that is trapped geologically in underground reservoirs – it is not uniform and varies in density, chemical composition, boiling range etc. for different fields. The refinery processes involved in production of different range of fuel is shown in Fig. 10 and Fig. 11.



**Fig. 10. Refinery processes**



**Fig. 11. Products made from crude oil**

**(i) Distillation process**

-This is the initial process used in all refineries – aims to separate the crude oil into different boiling range fractions, each of which may be a product in its own right, a blend component or feed for further processing step

-Crude oil contains many thousands of different HCs, each has its own boiling point – lightest are gases at ambient temperature but can remain dissolved in heavier liquid HCs unless temperature is raised, heaviest are solids at ambient temperature but stay in solution unless temperature is lowered.

Gasoline distillation temperature is 35 – 200 °C

Jet fuel 35 - 150

Diesel fuel 175 – 370

Heavy fuels, oil 370 – 550

-Generally distillation of crude oil produces 30% gasoline, 20-40 % diesel fuel, 20 % heavy fuels, 10-20 % heavy oils.

**(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 °C 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 on E85, a fuel that is 85% ethanol and 15% gasoline

### **(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<sub>x</sub> (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), CO<sub>2</sub> (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/m<sup>3</sup>
- 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 CO<sub>2</sub>. The engine performance can be improved by reducing the CO<sub>2</sub> 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 ( $H_2O$ ) into its component parts of hydrogen ( $H_2$ ) 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 extremely 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 one 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.
- v. 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

combustion engines, leading to higher engine speeds and greater thermal efficiency [2]. Hydrogen fuel used in IC engines is in automobiles, buses, trucks and farm machinery.

### ***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 NO<sub>x</sub> 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 (C<sub>3</sub>S) and butane/ butylenes (C<sub>4</sub>S)

-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 CO<sub>2</sub> and H<sub>2</sub>O. The molecules of O<sub>2</sub> 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%), H<sub>2</sub> (16-18%), CO<sub>2</sub> (8-10%) and some traces of higher hydrocarbons. Producer gas has a high percentage of N<sub>2</sub>, since air is used. So it has a low heat value. Density of producer gas is 0.9 to 1.2 kg/m<sup>3</sup>

-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% CO<sub>2</sub> 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 H<sub>2</sub> (54% vol), CH<sub>4</sub> (24%), CO (8%), CO<sub>2</sub> (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 H<sub>2</sub>and CH<sub>4</sub>. Its heat value per cubic meter is only about one half that of natural gas and density is 0.40 kg/m<sup>3</sup>.

### **\*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 °C 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,

$\rho = 700 - 800 \text{ [kg/m}^3\text{]}$ , for unleaded gasoline this value is higher due to the aromatics

For diesel fuel,  $\rho = 830 - 950 \text{ [kg/m}^3\text{]}$

**(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  $\text{kJ/m}^3$ ,  $\text{kcal/m}^3$ )

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

For gasoline and diesel fuel

$H_u=42000-44000 \text{ kJ/kg}$  or  $H_u=10200-10500 \text{ kcal/kg}$

-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  $25 \text{ }^\circ\text{C}$ , diesel fuel  $35 \text{ }^\circ\text{C}$  and heavy diesel  $65 \text{ }^\circ\text{C}$

**(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  $50 \text{ }^\circ\text{C}$ , 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  $0.023 - 0.032 \text{ N/m}$

and for gasoline it is  $0.019 - 0.023 \text{ N/m}$

**(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  $-65 \text{ }^\circ\text{C}$  and for diesel fuel  $-10 \text{ }^\circ\text{C}$

**\*Important fuel specifications for gasoline**

**(a) Gasoline volatility:**

Benzene for example has vapor pressure of  $0.022 \text{ MPa}$  at  $38 \text{ }^\circ\text{C}$  in a closed container of  $38 \text{ }^\circ\text{C}$ , benzene evaporates until the partial p

has a value of  $0.022 \text{ MPa}$ , If T is raised to  $80.5 \text{ }^\circ\text{C}$ , then saturation p will be  $0.1 \text{ MPa}$  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

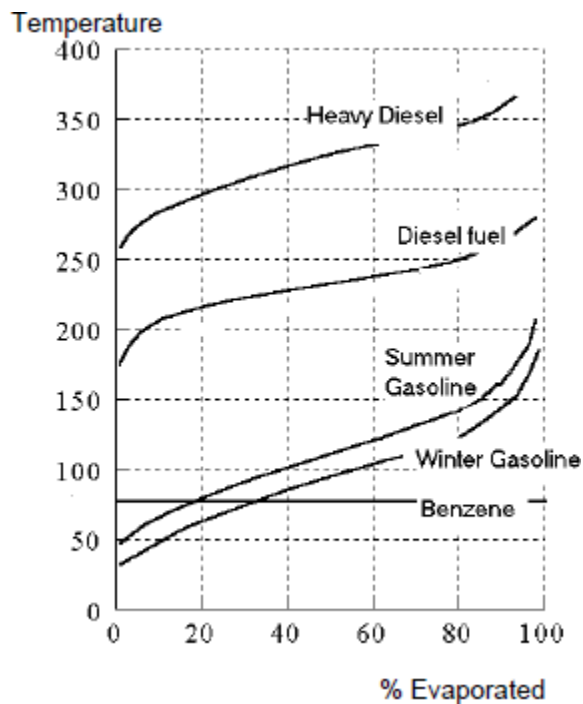
**Gasoline distillation curve:**

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).

**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 °C.

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 °C 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 °C)

**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 °C

-Fuel atomization depends on viscosity

2 - 8 mm<sup>2</sup>/s (cSt) at 20 °C

-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<sub>16</sub>H<sub>34</sub>) and alphas-methyl naphthalene (C<sub>10</sub>H<sub>7</sub>CH<sub>3</sub>). 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 °C and cooling water temp is at 100 °C

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

Increasing the DI, increases the tendency to ignite.

-AP is obtained by heating equal amounts of aniline and diesel fuel. While cooling down, the temp at which the aniline separates from the mixture is the AP

-Cetane number is in the range of,

50 - 60 for high speed Diesel engines

25 - 45 for low speed Diesel engines

Normal Diesel fuel CN is 40 - 55

DI of 50 gives a CN of around 50

### **\*Carburetion:**

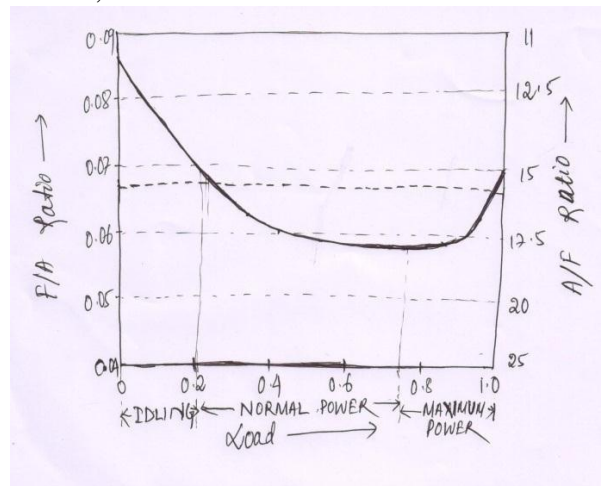
The process of preparing a combustible fuel-air mixture outside engine cylinder in SI engine is known as carburetion.

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 fuel ratio are discussed below,



**Fig. 13. Main areas of automotive engine operation**

#### ***(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:***

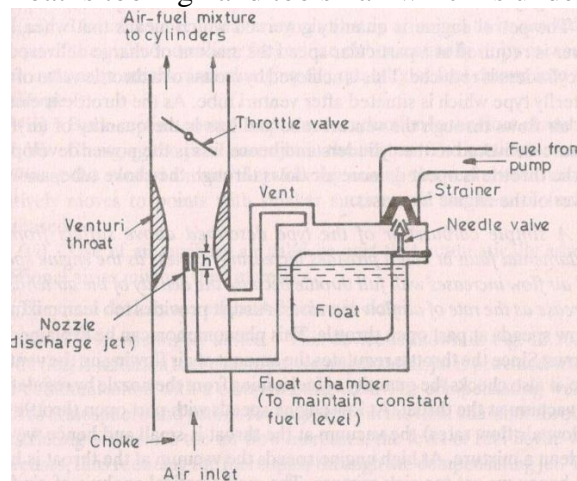
- engine speed and temperature are low during the starting of the engine from cold
- during starting very rich mixture about 5 to 10 times the normal amount of petrol is supplied i.e. F/A ratio 0.3 to 0.7 or A/F ratio 3:1 to 1.5:1
- mixture ratio is progressively made leaner to avoid too rich evaporated 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 venturi 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. 14. A simple carburettor**

### **\*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 sof 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 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 venturi 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 Willy 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 venturi 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

### **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:***

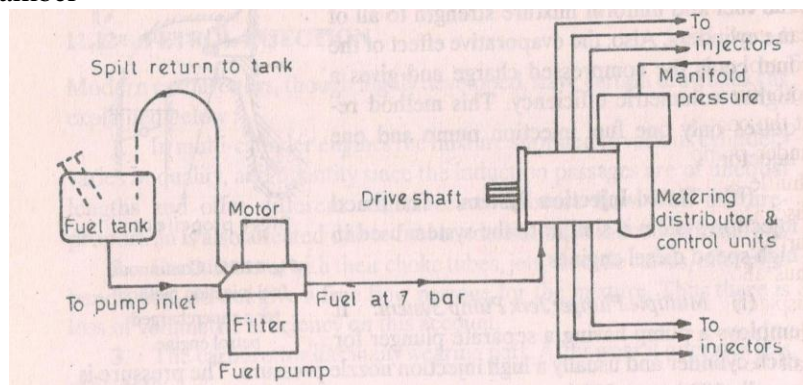
- pump with separate plunger and high injection nozzle pressure for each cylinder
- 100 to 300 bar pressure
- measured quantity of fuel for definite time and over definite period is delivered

#### ***(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 combustion chamber



**Fig. 15. Lucas petrol injection system for 6-cylinder petrol engine**

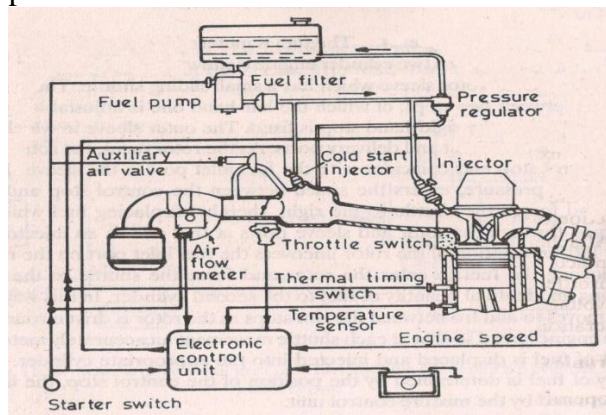
### ***(b) Electronic fuel injection***

#### 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 fuel during warm up condition



**Fig. 16. 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:**

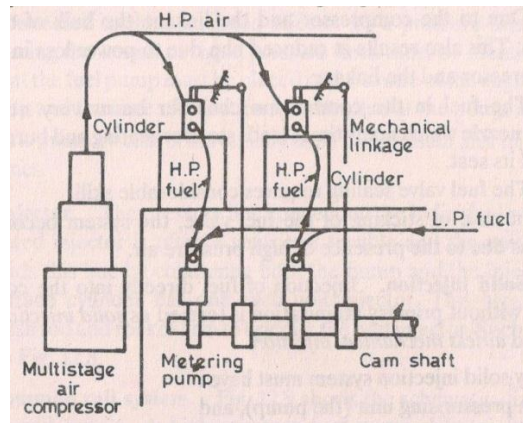
#### ***Requirements of diesel injection system:***

- 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



**Fig. 17. Air injection system**

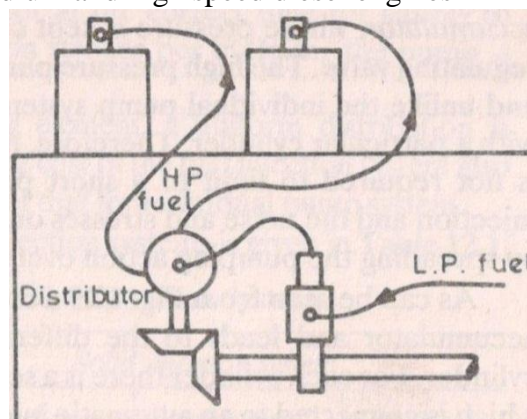
- blast air sweeps the fuel along with it
- good atomisation results in good mixture formation and hence high mean effective pressure
- heavy and viscous fuels are used
- fuel pump require small pressure
- but it is complicated due to compressor arrangement and expensive
- bulky engine and low bhp
- overheating and burning of valve seat

**(b) Solid injection system:**

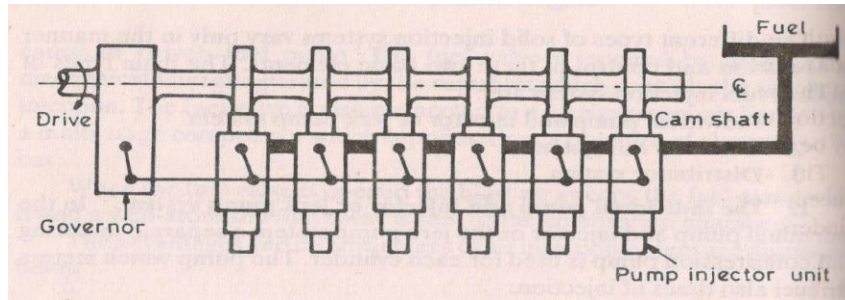
- Fuel directly injected to combustion chamber without primary atomisation termed as solid injection.
- Also known as airless mechanical injection
- 2 units-pressurise and atomising unit
- 3 different types which are described below,

**(i) Individual pump and injector or jerk pump system:**

- separate metering and compression pump is used for each cylinder
- reciprocating fuel pump is used to meter and set the injection pressure of the fuel
- heavy gear arrangements which gives jerking noise, hence name is given is jerk pump
- jerk pump is used for medium and high speed diesel engines



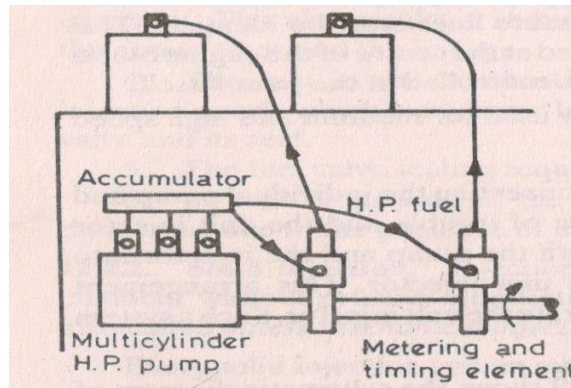
**Fig. 18. Individual pump and injector or jerk pump system**



**Fig. 19. Unit injector**

(ii) *Common rail system:*

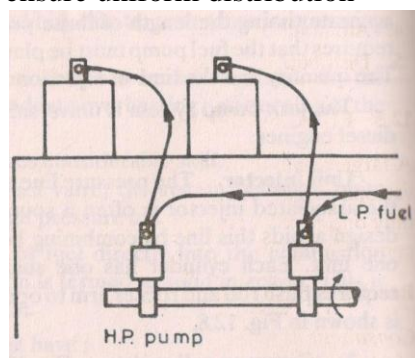
- high pressure fuel pump delivers fuel to an accumulator whose pressure is constant
- plunger type of pump is used
- driving mechanism is not stressed with high pressure hence noise is reduced
- common rail or pipe is connected in between accumulator and distributing elements
- separate metering and timing elements connected to automatic injector
- self-governing type



**Fig. 20. Common rail system**

(iii) *Distributor system:*

- fuel pump pressurises, meters and times the fuel supply to rotating distributor
- number of injection strokes per cycle for the pump equals to the number of cylinder
- One metering element which ensure uniform distribution



**Fig. 21. Distributor system**

**\* Fuel Injectors**

3 main types of fuel injectors,

**Blast injector:**

- these are superseded by mechanically operated injectors used in air injection system

**Mechanically operated injector:**

-consist of a set of camshaft, cams and rocker gear and other cams for controlling the timing of the fuel injection

**Automatic injector:**

-consists of spring loaded needle valve and operated hydraulically by the pressure of fuel  
-quantity of fuel is metered by the fuel pump

**Types of nozzles:**

(a) Depends on the type of combustion chamber,

**Open combustion chamber:**

-fuel seeks air  
-air swirl is created due to inclined induction port  
-multi-hole nozzle injects fuel at a pressure of about 200 to 300 bar to slow moving air  
-provide good cold starting performance and improved thermal efficiency

**Pre-combustion chamber:**

-air velocity is very much high  
-single hole nozzle with 65 to 100 bar injection pressure is used  
-used in high speed engine due to rapid combustion  
-external heating device for easy starting of the engine

(b) Open and closed type of nozzle,

Open type:

-consists of fuel orifices and open to burner  
-cheap and less efficient  
ex- opposed piston two-stroke Junkers diesel engine

Closed type: pressure drop is minimised compared to open type

(c) Different types of nozzle for different combustion chamber

(i) Single hole nozzle:

-used in open combustion chamber  
-size of hole larger than 0.2 mm  
-very high injection pressure required

(ii) Multi-hole nozzle:

-no. of hole varies from 4 to 18 and the size from 1.5 to 0.35 mm  
-injection rate is not uniform

(iii) Pintle nozzle:

-a projection or pintle is provided in the nozzle to avoid weak injection and dribbling  
-pintle may be cylindrical or conical shape  
-cone angle varied from 0 to 60°  
-provide good atomisation and reduced penetration  
-fuel pressures are lower than single and multi-hole nozzle

(iv) Pintaux nozzle:

-injected fuel in upstream of air  
-development of pintle nozzle with auxiliary hole drilled in the nozzle body  
-reduced delay period and increased thermal efficiency