UNIT - I

GAS AND STEAM POWER CYCLES

SYLLABUS :-

Air Standard Cycles - Otto, Diesel, Dual, Brayton - Cycle Analysis, Performance and Comparison - Rankine, reheat and regeneration cycle.

ME8493 - THERMAL ENGINEERING-I

UNIT-1

GAS & STEAM POWER CYCLES

Cycle:-

→ Cycle is defined as repeated series of operations occurring in a certain order, so that system attains its original state.

→ Cycle using air as working fluid, known as Gas power cycles.

Ideal Cycle:-

→ If cycle repeated by reapeating the process in same order.

→ All heat losses are prevented.

Working substance is assumed to be a perfect working substance.

Actual Cycle:-

→ Actual engine (or) imaginary perfect engine.

Assumptions:

→ Sources of heat supply & sink of heat rejection are external to air.

→ Cycle can be represented as p-V & T-S diagrams.

→ Working medium - Perfect gas follows $pV = mRT$.

→ Working medium has constant specific heats. $C_p = 1.005$ kJ/kg K, $C_v = 0.718$ kJ/kg K

→ Compression & expansion process are reversible adiabatic. i.e., No loss (or) gain of entropy.

→ K.E & P.E are neglected.

→ Frictionless operation.

→ Both heat supply & heat rejection are in reversible manner.

Important Parameters:-

(i) Air Standard η :-

Ratio of work done during process to heat supplied during process.

$$\eta_{air.std} = \frac{W.D}{H.S} = \frac{W}{Q_s}$$

W.D = H.S − Heat Rejected.

$$W.D = Q_s - Q_R.$$

ii) Mean Effective Pressure (P_m):-

→ Mean Pressure developed during one cycle of operation.

→ Ratio of W.D to swept volume.

$$P_m = \frac{W.D}{V_1 - V_2} = \frac{W.D}{V_s} \quad \Big/ \quad P_m = \frac{\text{Area of } p\text{-}V \text{ diagram}}{\text{Length of diagram}}$$

iii) Power (P):-

Amount of W.D by unit mass flow rate of working substance.

$$P = W.D \times m_f$$

$$P = W \times m_f.$$

CYCLES:-

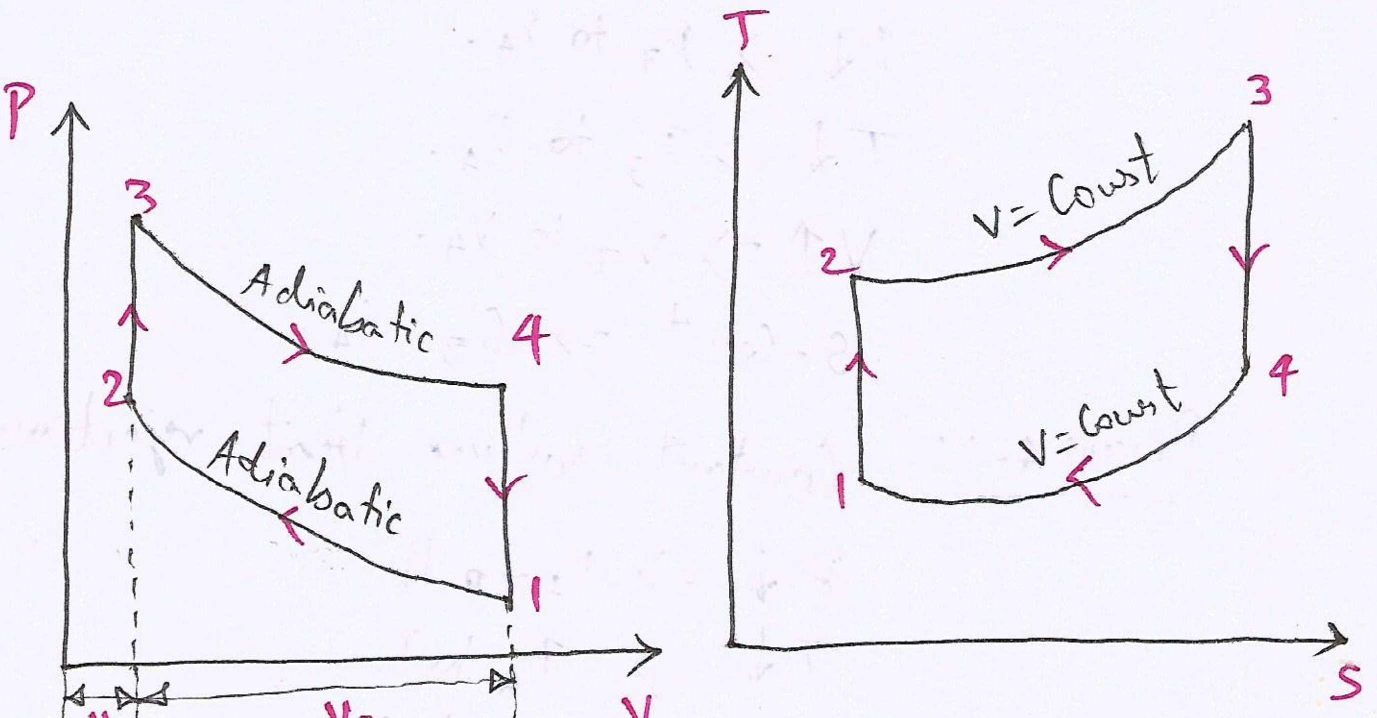
OTTO (or) CONSTANT VOLUME CYCLE:-

→ Introduced by Dr. A. N. Otto, German Scientist.

→ Petrol & gas engine

→ Four Processes.

- → Two reversible adiabatic (or) isentropic process.
- → Two constant volume process.



Process 1-2 :- Isentropic compression process :-

$P \uparrow \Rightarrow P_1$ to P_2.

$T \uparrow \Rightarrow T_1$ to T_2.

$V \downarrow \Rightarrow V_1$ to V_2.

S - Const $\Rightarrow S_1$ to S_2.

Process 2-3 :- Constant volume Heat addition :-

$P \uparrow \Rightarrow P_2$ to P_3.

$T \uparrow \Rightarrow T_2$ to T_3.

$S \uparrow \Rightarrow S_2$ to S_3.

V - Const $\Rightarrow V_2 = V_3$.

$$Q_S = m \times C_v (T_3 - T_2) \text{ kJ}$$

Process 3-4 :- Isentropic Expansion

$P \downarrow \Rightarrow P_3$ to P_4.

$T \downarrow \Rightarrow T_3$ to T_4.

$V \uparrow \Rightarrow V_3$ to V_4.

S - Const $\Rightarrow S_3 = S_4$.

Process 4-1 :- Constant volume Heat rejection

$P \downarrow \Rightarrow P_4$ to P_1

$T \downarrow \Rightarrow T_4$ to T_1

$S \downarrow \Rightarrow S_4$ to S_1

V - Const $\Rightarrow V_4 = V_1$.

$$Q_R = m \times C_v (T_4 - T_1) \text{ kJ.}$$

$$W.D = H.S - H.R = Q_S - Q_R$$

$$= [m C_v (T_3 - T_2)] - [m C_v (T_4 - T_1)]$$

Efficiency, $\eta_{Otto} = \frac{Q_S - Q_R}{Q_S}$

$$= \frac{m C_v (T_3 - T_2) - m C_v (T_4 - T_1)}{m C_v (T_3 - T_2)}$$

$$\boxed{\eta_{Otto} = 1 - \frac{T_4 - T_1}{T_3 - T_2}} \longrightarrow (1)$$

This expression in terms of temperatures. It is simplified in terms of volume ratio.

From P-V diagram,

$V_1 = V_4$, $V_C = V_2 = V_3$, V_S - Stroke (or) Swept volume

$$V_S = V_1 - V_2 = V_4 - V_3.$$

Compression Ratio, $r = \frac{\text{Total Cylinder Volume}}{\text{Clearance Volume}}$

$$r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$$

For process 1-2, Adiabatic relation,

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

$$T_2 = T_1 \times (r)^{\gamma - 1}$$

For process 3-4,

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

$$T_3 = T_4 \times (r)^{\gamma-1}$$

Sub T_2 & T_3 in (1).

$$\eta_{otto} = 1 - \frac{T_4 - T_1}{T_4 (r)^{\gamma-1} - T_1 (r)^{\gamma-1}}$$

$$= 1 - \frac{T_4 - T_1}{(T_4 - T_1)(r)^{\gamma-1}}$$

$$\boxed{\eta_{otto} = 1 - \frac{1}{(r)^{\gamma-1}}} \longrightarrow \text{Air std } \eta.$$

$$\eta_{otto} \uparrow \Rightarrow (r) \uparrow$$

<u>Mean Effective Pressure:</u>

Let assume, $V_2 = V_3 = 1 = V_c$.

$\therefore V_1 = V_4 = r$ & $\frac{P_4}{P_1} = \frac{P_3}{P_2} = r_p$ (Pressure ratio)

For process 1-2,

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r)^{\gamma} = \frac{P_3}{P_4}.$$

$$W.D,\ W = \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= \frac{1}{\gamma-1}\left[V_3\left(P_3 - P_4\left(\frac{V_4}{V_3}\right)\right) - V_2\left(P_2 - P_1\left(\frac{V_1}{V_2}\right)\right)\right]$$

$$[\because V_3 = V_2 = 1]$$

$$= \frac{1}{\gamma-1}\left[(P_3 - P_4 r) - (P_2 - P_1 r)\right]$$

$$= \frac{1}{\gamma-1}\left[P_4 r\left(\frac{P_3}{P_4 r} - 1\right) - P_1 r\left(\frac{P_2}{P_1 r} - 1\right)\right]$$

$$= \frac{1}{\gamma-1}\left[P_4 r\left(\frac{r^\gamma}{r} - 1\right) - P_1 r\left(\frac{r^\gamma}{r} - 1\right)\right]$$

$$= \frac{r}{\gamma-1}(P_4 - P_1)(r^{\gamma-1} - 1)$$

$$= \frac{P_1 r}{\gamma-1}(r^{\gamma-1} - 1)\left(\frac{P_4}{P_1} - 1\right)$$

$$W = \frac{P_1 r}{\gamma-1}(r^{\gamma-1} - 1)(r_p - 1)$$

$$V_s = V_1 - V_2 = V_2\left(\frac{V_1}{V_2} - 1\right) = r - 1$$

$$[\because V_2 = 1]$$

$$P_m = \frac{W.D}{V_s} \Rightarrow$$

$$\boxed{P_m = P_1 r\left(\frac{r_p - 1}{\gamma - 1}\right)\left(\frac{r^{\gamma-1} - 1}{r - 1}\right)}$$

Problems :- Otto Cycle :-

R.K. Rajput :-

Pg :- 969 – Ex :- 21.7

Pg :- 969 – Ex :- 21.8

Pg :- 977 – Ex :- 21.13

$$PV = mRT.$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

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

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

→ Reversible Adiabatic Process. (or) Isentropic pro.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

→ V - Constant Process

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}.$$

DIESEL CYCLE (or) CONSTANT PRESSURE CYCLE :-

$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$

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

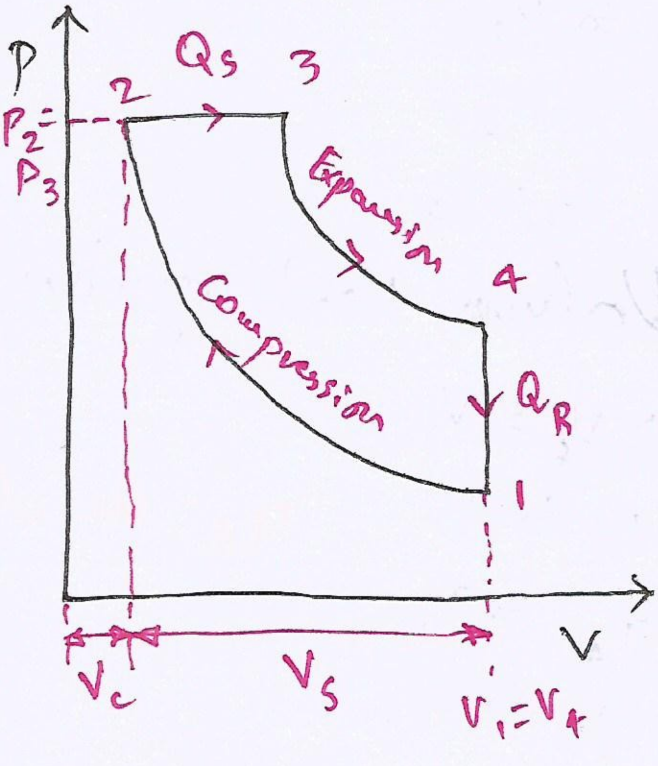
$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

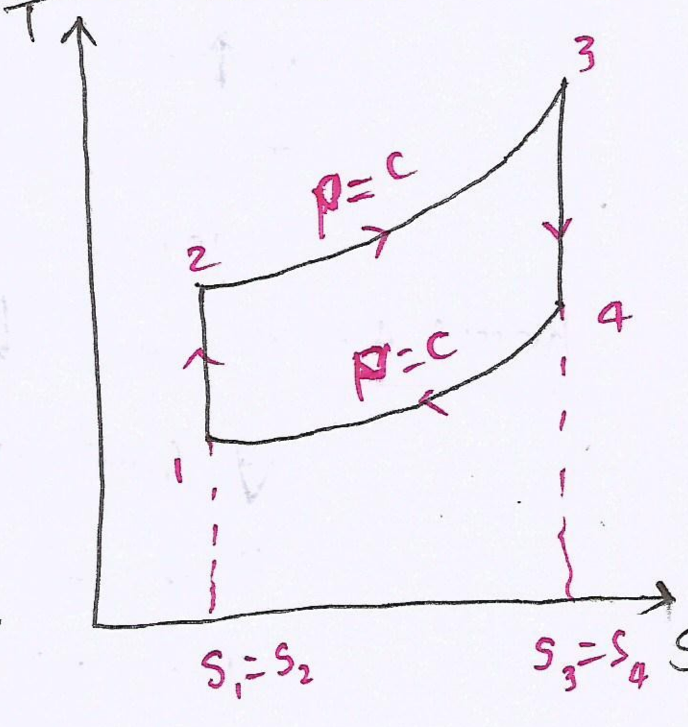
→ Rudolph Diesel.

→ Diesel engines.

→ Four Processes

- → Two reversible adiabatic (or) Isentropic
- → One constant pressure.
- → One Constant volume





Process 1 - 2 :- Isentropic Compression.

$P \uparrow \Rightarrow P_1$ to P_2.

S - Cons $\Rightarrow S_1 = S_2$.

$V \downarrow \Rightarrow V_1$ to V_2.

$T \uparrow \Rightarrow T_1$ to T_2.

Process 2-3 :- Constant Pressure Heat addition.

P - Const $\Rightarrow P_2 = P_3$.

V ↑ $\Rightarrow V_2$ to V_3. $Q_S = m \times C_p (T_3 - T_2)$

T ↑ $\Rightarrow T_2$ to T_3.

S ↑ $\Rightarrow S_2$ to S_3

Process 3-4 :- Isentropic Expansion,

P ↓ $\Rightarrow P_3$ to P_4.

V ↑ $\Rightarrow V_3$ to V_4.

T ↓ $\Rightarrow T_3$ to T_4.

S - Const $\Rightarrow S_3 = S_4$.

Process 4-1 :- Const Volume Heat rejection

V - Const $\Rightarrow V_4 = V_1$.

P ↓ $\Rightarrow P_4$ to P_1. $Q_R = m C_v (T_4 - T_1)$

T ↓ $\Rightarrow T_4$ to T_1.

S ↓ $\Rightarrow S_4$ to S_1.

$$\eta_{diesel} = \frac{Q_S - Q_R}{Q_S}$$

$$= \frac{m C_p (T_3 - T_2) - m C_v (T_4 - T_1)}{m C_p (T_3 - T_2)}$$

$$= 1 - \frac{m C_v (T_4 - T_1)}{m C_p (T_3 - T_2)}$$

$$\eta_{diesel} = 1 - \frac{(T_4 - T_1)}{\gamma \times (T_3 - T_2)}$$

$$\left[\because \frac{C_p}{C_v} = \gamma \right]$$

$$\boxed{\eta_{diesel} = 1 - \frac{(T_4 - T_1)}{\gamma \times (T_3 - T_2)}} \longrightarrow (1)$$

Simplified in terms of volume ratio,

Compression ratio, $r = \frac{V_1}{V_2} = \frac{\text{Total Vol}}{\text{clearance Vol}}$

Cutoff ratio, $\rho = \frac{\text{Cut off volume}}{\text{clearance Volume}} = \frac{V_3}{V_2}$.

Expansion ratio, $= \frac{V_4}{V_3} = \frac{V_1}{V_3} = \frac{V_1}{V_2} \times \frac{V_2}{V_3}$

$$r_e = r \times \frac{1}{\rho}$$

For process 1-2,

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

$$\boxed{T_2 = T_1 \times (r)^{\gamma - 1}}$$

For Process 2-3,

$$\frac{V_2}{T_2} = \frac{V_3}{T_3}$$

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = e.$$

$$T_3 = T_2 \times e = T_1 (r)^{\gamma-1} \times e$$

$$\boxed{T_3 = T_1 (r)^{\gamma-1} \times e}$$

For Process 3-4,

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

$$T_4 = \frac{T_3}{\left(\frac{r}{e}\right)^{\gamma-1}} = \frac{T_1 (r)^{\gamma-1} \times e}{\left(\frac{r}{e}\right)^{\gamma-1}}$$

$$T_4 = \frac{T_1 (r)^{\gamma-1} \times e \times e^{\gamma-1}}{(r)^{\gamma-1}}$$

$$\boxed{T_4 = T_1 e^{\gamma}}$$

Sub T_2, T_3 & T_4 in (1).

$$\eta_{diesel} = 1 - \frac{1}{\gamma}\left[\frac{T_1 e^{\gamma} - T_1}{T_1 (r)^{\gamma-1} e - T_1 (r)^{\gamma-1}}\right]$$

$$= 1 - \frac{1}{\gamma}\left[\frac{T_1 (e^{\gamma} - 1)}{T_1 (r)^{\gamma-1} (e-1)}\right]$$

$$\boxed{\eta_{diesel} = 1 - \frac{1}{\gamma (r)^{\gamma-1}}\left[\frac{e^{\gamma} - 1}{e - 1}\right]}$$

$r \uparrow \longrightarrow \eta \uparrow$.

Cut off ratio $\uparrow \longrightarrow \eta \downarrow$

Mean Effective Pressure (P_m):

$$W = P_2(V_3 - V_2) + \left[\frac{P_3V_3 - P_4V_4}{\gamma - 1}\right] - \left[\frac{P_2V_2 - P_1V_1}{\gamma - 1}\right]$$

$$= P_2V_2(e-1) + \left[\frac{P_3V_2e - P_4V_4r}{\gamma-1}\right] - \left[\frac{P_2V_2 - P_1rV_2}{\gamma-1}\right]$$

$$= \frac{V_2\left[P_2(e-1)(\gamma-1) + (P_3e - P_4r) - (P_2 - P_1)r\right]}{(\gamma-1)}$$

$$= \frac{V_2\left[P_2\left[(e-1)(\gamma-1)\right] + P_2\left(e - \frac{P_4}{P_2}r\right) - P_2\left(1 - \frac{P_1}{P_2}r\right)\right]}{\gamma-1}$$

$[\because P_3 = P_2]$

$$\left[\because \frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^\gamma = \frac{1}{(r)^\gamma}\right] \left[\because \frac{P_4}{P_2} = \frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^\gamma = \left(\frac{e}{r}\right)^\gamma\right]$$

$$= \frac{P_2V_2\left[(e-1)(\gamma-1) + \left[e - \left(\frac{e}{r}\right)^\gamma \times r\right] - \left[1 - \frac{r}{r^\gamma}\right]\right]}{\gamma-1}$$

$$= \frac{P_1V_1r^{\gamma-1}}{\gamma-1}\left[(e-1)(\gamma-1) + (e - e^\gamma r^{1-\gamma}) - (1 - r^{1-\gamma})\right]$$

$$\left[\because P_2 = P_1\left(\frac{V_1}{V_2}\right)^\gamma = P_1r^\gamma\right] \left[\because P_2V_2 = P_1r^\gamma V_2 \times \frac{V_1}{V_1}\right]$$

$$\left[\because P_2V_2 = P_1\frac{r^\gamma}{r}V_1\right]$$

$$\left[\because P_2V_2 = P_1V_1r^{\gamma-1}\right]$$

$$= \frac{P_1 V_1 r^{\gamma-1}\left[e\gamma - \gamma - e + 1 + e - e^{\gamma} r^{1-\gamma} - 1 + r^{1-\gamma}\right]}{\gamma - 1}$$

$$W = \frac{P_1 V_1 r^{\gamma-1}\left[\gamma(e-1) - r^{1-\gamma}(e^{\gamma}-1)\right]}{\gamma - 1}$$

$$P_m = \frac{W}{V_1 - V_2} = \frac{W}{V_1\left(1 - \frac{1}{r}\right)}$$

$$P_m = \frac{P_1 V_1 r^{\gamma-1}\left[\gamma(e-1) - r^{1-\gamma}(e^{\gamma}-1)\right]}{(\gamma-1)\, V_1\left(1-\frac{1}{r}\right)}$$

$$\boxed{P_m = \frac{P_1 r^{\gamma}\left[\gamma(e-1) - r^{1-\gamma}(e^{\gamma}-1)\right]}{(\gamma-1)(r-1)}}$$

———— x ———— x ———— x ————

<u>Problems:-</u>

<u>R.K. Rajput:-</u>

Pg:-988, Pb:-21.21.

Pg:-986, Pb:-21.17

DUAL CYCLE:-

→ Combination of Otto & Diesel Cycle.

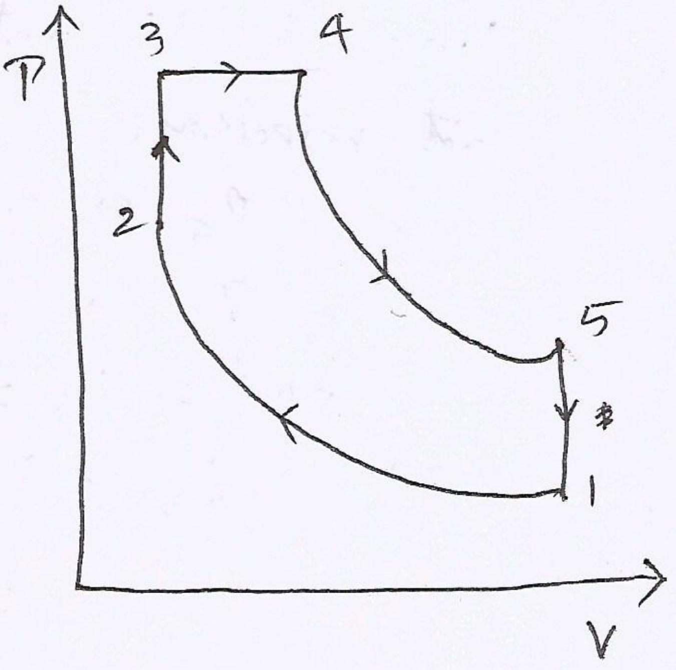
→ Mixed Cycle (or) Limited Pressure Cycle.

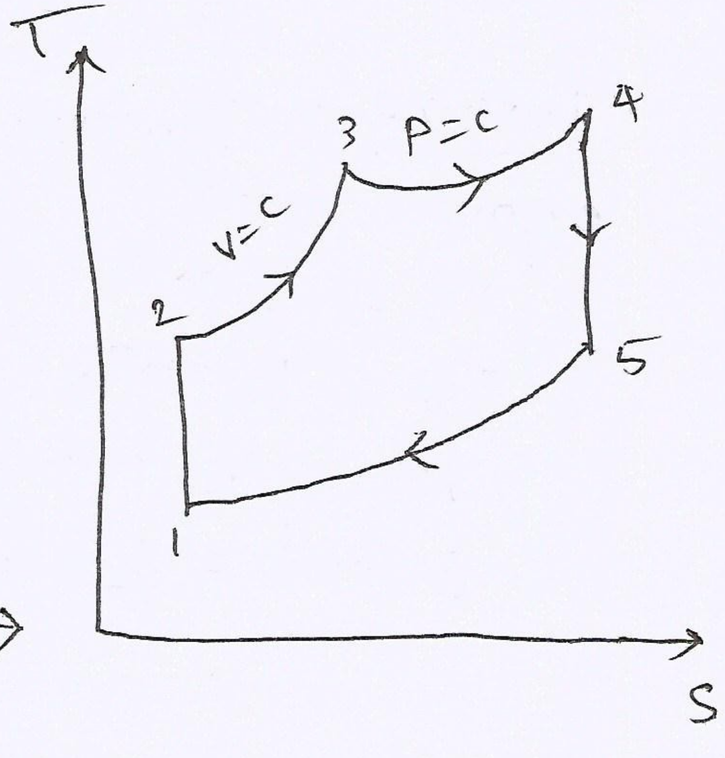
→ Q_s takes place at Const Pr & Const.V.

→ Advntg - more time available for fuel to combustion.

→ This Cycle is invariably used for diesel &, hot spot ignition engines.

→ Five Processes:-
- → Two isentropic process
- → Two Constant volume
- → One Constant Pressure.





Process 1-2 - Isentropic Compression Process:-

$P \uparrow \Rightarrow P_1$ to P_2.

$T \uparrow \Rightarrow T_1$ to T_2.

$V \downarrow \Rightarrow V_1$ to V_2.

S - Const $\Rightarrow S_1 = S_2$.

Process 2-3 - Const. Vol. Heat Addition.

$P \uparrow \Rightarrow P_2$ to P_3.

$T \uparrow \Rightarrow T_2$ to T_3. $Q_{S_1} = mC_v(T_3 - T_2)$

V - Const $\Rightarrow V_2 = V_3$.

$S \uparrow \Rightarrow S_2$ to S_3.

Process 3-4 - Const. Press. Heat Addition.

P - Const $\Rightarrow P_3 = P_4$.

$T \uparrow \Rightarrow T_3$ to T_4. $Q_{S_2} = mC_p(T_4 - T_3)$

$V \uparrow \Rightarrow V_3$ to V_4.

$S \uparrow \Rightarrow S_3$ to S_4.

Process 4-5:- Isentropic expansion process.

$P \downarrow \Rightarrow P_4$ to P_5.

$T \downarrow \Rightarrow T_4$ to T_5.

$V \uparrow \Rightarrow V_4$ to V_5.

S - Const $\Rightarrow S_4 = S_5$

Process 5-1:- Const. Vol. Heat rejection.

$P \downarrow \Rightarrow P_5$ to P_1

$T \downarrow \Rightarrow T_5$ to T_1

V - Const $\Rightarrow V_5 = V_1$

$S \downarrow \Rightarrow S_5$ to S_1.

$Q_R = mC_v(T_5 - T_1)$

Total $Q_s = Q_{s_1} + Q_{s_2}$

$$Q_s = \left[m C_v (T_3 - T_2)\right] + \left[m C_p (T_4 - T_3)\right]$$

$$\eta_{air\,std} = \frac{W}{Q_s} = \frac{Q_s - Q_R}{Q_s}$$

$$= \frac{m C_v (T_3 - T_2) + m C_p (T_4 - T_3) - m C_v (T_5 - T_1)}{m C_v (T_3 - T_2) + m C_p (T_4 - T_3)}$$

$$\boxed{\eta = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma (T_4 - T_3)}} \quad \left[\because \frac{C_p}{C_v} = \gamma\right]$$

Above equ simplified in terms of Cut off ratio & pressure ratio.

$r = \frac{V_1}{V_2}$, pressure ratio, K (or) $\beta = \frac{P_3}{P_2}$

Cut off ratio, $\rho = \frac{V_4}{V_3}$.

Expansion ratio, $r_e = \frac{V_5}{V_4} = \frac{V_1}{V_4} = \frac{V_1}{V_2} \times \frac{V_2}{V_4}$

$$= \frac{V_1}{V_2} \times \frac{V_3}{V_4} = \frac{r}{\rho}.$$

$$r_e = \frac{r}{\rho}$$

For Process 1-2 :-

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

$$T_2 = T_1 (r)^{\gamma-1}$$

For Process 2-3 :-

$$\frac{P_2}{T_2} = \frac{P_3}{T_3}.$$

$$T_3 = \frac{P_3}{P_2} T_2 \Rightarrow K.T_1 (r)^{\gamma-1} = T_3.$$

For Process :- 3-4 :-

$$\frac{V_3}{T_3} = \frac{V_4}{T_4}.$$

$$T_4 = \frac{V_4}{V_3} T_3 = e.K.T_1 (r)^{\gamma-1}$$

For Process 4-5 :-

$$\frac{T_4}{T_5} = \left(\frac{V_5}{V_4}\right)^{\gamma-1} = \left(\frac{r}{e}\right)^{\gamma-1}$$

$$T_5 = \frac{T_4}{\left(\frac{r}{e}\right)^{\gamma-1}} = \frac{T_4 \, e^{\gamma-1}}{(r)^{\gamma-1}}$$

$$= \frac{T_1 (r)^{\gamma-1} . K. e. e^{\gamma-1}}{(r)^{\gamma-1}}$$

$$\boxed{T_5 = T_1 K. e^{\gamma}}$$

Sub T_2, T_3, T_4 & T_5 in η.

$$\eta = 1 - \frac{T_1 k e^{\gamma} - T_1}{[T_1 (r)^{\gamma-1} \cdot k - T_1 (r)^{\gamma-1}] + \gamma [T_1 (r)^{\gamma-1} \cdot k \cdot e - T_1 (r)^{\gamma-1} \cdot k]}$$

$$= 1 - \frac{T_1 [k \cdot e^{\gamma} - 1]}{T_1 (r)^{\gamma-1} [(k-1) + \gamma k (e-1)]}$$

$$\boxed{\eta_{dual} = 1 - \frac{1}{(r)^{\gamma-1}} \left[\frac{k e^{\gamma} - 1}{(k-1) + \gamma k (e-1)} \right]}$$

Note:- when $k = 1 \Rightarrow \eta_{diesel} = \eta_{dual}$

$k = 1$ & $e = 1 \Rightarrow \eta_{dual} = \eta_{otto}$.

$$\boxed{\eta_{otto} > \eta_{dual} > \eta_{diesel}}$$

If $k > 1 \Rightarrow \eta_{dual}$ increases.

Mean Effective Pr (P_m) :-

$$W.D,\ W = P_3(V_4 - V_3) + \frac{P_4V_4 - P_5V_5}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= P_3V_3(e-1) + \frac{P_4 eV_3 - P_5 rV_3 - P_2V_3 - P_1 rV_3}{\gamma - 1}$$

$$\left[\because\ e = \frac{V_4}{V_3},\ V_4 = eV_3,\ V_2 = V_3\right.$$

$$V_5 = V_1 = V_1 \times \frac{V_2}{V_2} = rV_2.$$

$$\left.V_5 = rV_2 = rV_3.\right]$$

$$= \frac{P_3V_3(e-1)(\gamma-1) + P_4V_3\left[e - \frac{P_5}{P_4}r\right] - P_2V_3\left[1 - \frac{P_1}{P_2}r\right]}{\gamma - 1}$$

We know that, $\frac{P_5}{P_4} = \left(\frac{V_4}{V_5}\right)^\gamma = \left(\frac{e}{r}\right)^\gamma$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^\gamma = (r)^\gamma$$

$$P_3 = P_4.$$

$$W = \frac{V_3\left[P_3(e-1)(\gamma-1) + P_3(e - e^\gamma r^{1-\gamma}) - P_2(1 - r^{1-\gamma})\right]}{\gamma - 1}$$

$$\because K = \frac{P_3}{P_2} \Rightarrow P_3 = K \cdot P_2.$$

$$= \frac{P_2 V_2 \left[k(\rho - 1)(\gamma - 1) + k(\rho - \rho^{\gamma} r^{1-\gamma}) - (1 - r^{1-\gamma}) \right]}{\gamma - 1}$$

$$\left[\because P_2 V_2 = P_1 V_1 (r)^{\gamma - 1} \right]$$

$$= \frac{P_1 V_1 r^{\gamma - 1} \left[k\rho\gamma - k\rho - k\gamma + k + k\rho - k\rho^{\gamma} r^{1-\gamma} + r^{1-\gamma} \right]}{\gamma - 1}$$

$$W = \frac{P_1 V_1 (r)^{\gamma - 1} \left[k\gamma(\rho - 1) + (k - 1) - r^{1-\gamma}(k\rho^{\gamma} - 1) \right]}{\gamma - 1}$$

$$P_m = \frac{W}{V_1 - V_2} = \frac{W}{V_1 \left(1 - \frac{1}{r}\right)} = \frac{W}{V_1 \left(\frac{r - 1}{r}\right)}$$

$$= \frac{P_1 V_1 (r)^{\gamma - 1} \left[k\gamma(\rho - 1) + (k - 1) - r^{1-\gamma}(k\rho^{\gamma} - 1) \right]}{(\gamma - 1) V_1 \left(\frac{r - 1}{r}\right)}$$

$$\boxed{P_m = \frac{P_1 r^{\gamma} \left[k\gamma(\rho - 1) + (k - 1) - r^{1-\gamma}(k\rho^{\gamma} - 1) \right]}{(\gamma - 1)(r - 1)}}$$

——— x ——— x ———

Problems:-

R.K. Rajput - Pg:-997, Pb: 21.24.
Pg: 997, Pb: 21.25
Pg: 1000 Pb: 21.26.

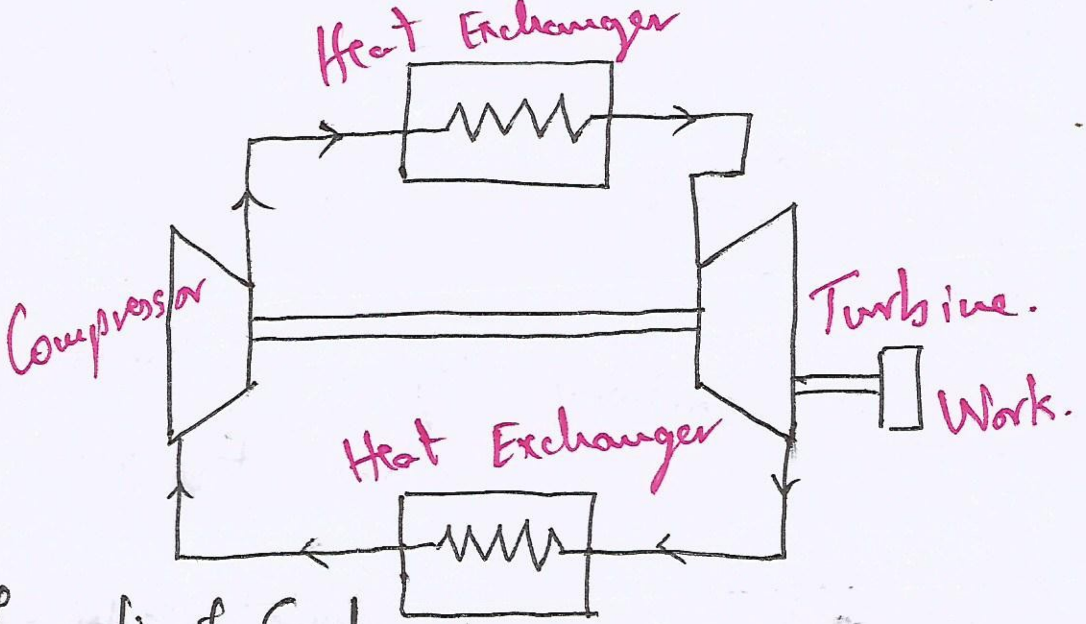
BRAYTON CYCLE:-

→ Theoretical Cycle for gas turbines.

→ Joule Cycle (or) Constant Pressure Cycle for perfect gas.

→ Four Processes

- → Two isentropic processes
- → Two Constant pressure.



Theoretical Cycle:-

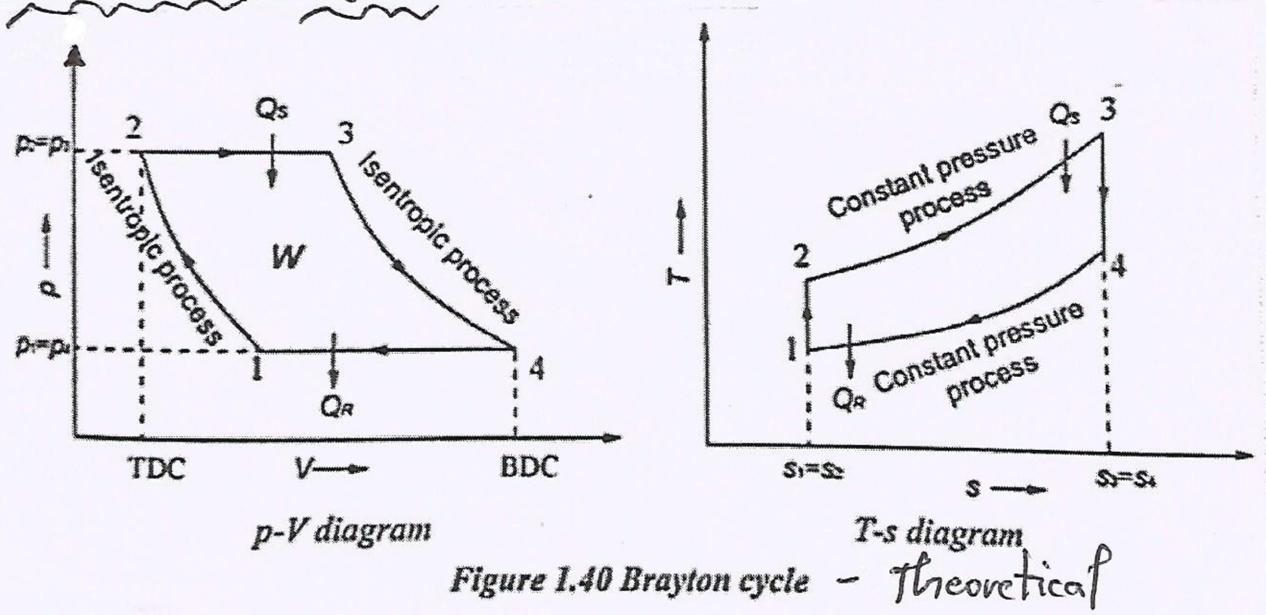


Figure 1.40 Brayton cycle – Theoretical

Process 1-2 :- Isentropic Compression.

$P\uparrow \Rightarrow P_1$ to P_2

$T\uparrow \Rightarrow T_1$ to T_2

$V\downarrow \Rightarrow V_1$ to V_2

$S-C \Rightarrow S_1 = S_2$

Compressor Work } $W_c = m\,C_p(T_2 - T_3)$

Process 2-3 :- Const Pressure Heat addition.

Compressed air into combustion chamber, fuel injected → Combustion takes place.

$P-C \Rightarrow P_2 = P_3$.

$T\uparrow \Rightarrow T_2$ to T_3.

$V\uparrow \Rightarrow V_2$ to V_3.

$S\uparrow \Rightarrow S_2$ to S_3

$Q_s = m\,C_p(T_3 - T_2)$

Process 3-4 :- Isentropic Expansion Process:-

Expansion takes place to run turbine.

$P\downarrow \Rightarrow P_3$ to P_4.

$T\downarrow \Rightarrow T_3$ to T_4.

$V\uparrow \Rightarrow V_3$ to V_4.

$S-C \Rightarrow S_3 = S_4$

Turbine Work, $W_T = m\,C_p(T_3 - T_4)$

Process 4-1 :- Constant Pressure Heat rejection

Air Cools at constant pressure.

$P-C \Rightarrow P_4 = P_1$.

$T\downarrow \Rightarrow T_4$ to T_1

$V\downarrow \Rightarrow V_4$ to V_1.

$S\downarrow \Rightarrow S_4$ to S_1

$Q_R = m\,C_p(T_4 - T_1)$

$$\eta_{Brayton} = \frac{W}{Q_S} = \frac{Q_S - Q_R}{Q_S}$$

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

$$\boxed{\eta_{Brayton} = 1 - \frac{T_4 - T_1}{T_3 - T_2}}$$

Above equ interms of compression ratio & pressure ratio,

$$r = \frac{V_1}{V_2} = \frac{V_4}{V_3}, \quad R_p \text{(or)} K = \frac{P_2}{P_1} = \frac{P_3}{P_4}.$$

For Process 1-2,

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

$$T_2 = T_1 (r)^{\gamma-1}$$

For Process 3-4,

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

$$T_3 = T_4 (r)^{\gamma-1}$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_3 = T_4 (R_p)^{\gamma-1/\gamma}$$

Sub T_2 & T_3 in equ.

In terms of Pressure ratio

$$\eta = 1 - \frac{T_4 - T_1}{T_4 (R_p)^{\frac{\gamma-1}{\gamma}} - T_1 (R_p)^{\gamma-1/\gamma}}$$

$$= 1 - \frac{(T_4 - T_1)}{(R_p)^{\frac{\gamma-1}{\gamma}} (T_4 - T_1)}$$

$$\boxed{\eta = 1 - \frac{1}{(R_p)^{\gamma-1/\gamma}}}$$

In terms of Compression ratio,

$$\eta = 1 - \frac{T_4 - T_1}{T_4 (r)^{\gamma-1} - T_1 (r)^{\gamma-1}}$$

$$\boxed{\eta = 1 - \frac{1}{(r)^{\gamma-1}}}$$

For same compression ratio,

$$\eta_{otto} = \eta_{Brayton}.$$

Work Ratio :-

Defined as ratio of,

$$\text{Work Ratio} = \frac{\text{Net Work output}}{\text{Net workdone by Turbine}} = \frac{\text{Net Work transfer}}{\text{Positive Work transfer}}$$

$$\text{Work Ratio} = \frac{W_T - W_c}{W_T}$$

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

$$= 1 - \frac{T_2 - T_1}{T_3 - T_4}$$

$$= 1 - \frac{T_1 (R_p)^{\frac{\gamma-1}{\gamma}} - T_1}{T_3 - \frac{T_3}{(R_p)^{\frac{\gamma-1}{\gamma}}}}$$

$$= 1 - \frac{T_1 \left[(R_p)^{\gamma-1/\gamma} - 1\right]}{T_3 \left[1 - \frac{1}{(R_p)^{\frac{\gamma-1}{\gamma}}}\right]}$$

$$\boxed{\text{Work Ratio} = 1 - \frac{T_1}{T_3} (R_p)^{\frac{\gamma-1}{\gamma}}}$$

For getting high work Ratio, T_3 must be much higher.

Problems:

R.K. Rajput - Pg:-1018, Pb: 21.32.

Pg:-1024, Pb:- 21.38.

Back Work Ratio:-

$$\text{Back Work ratio} = \frac{\text{Work input to Compressor}}{\text{Work output of Turbine}} = \frac{W_C}{W_T}$$

Actual Brayton Cycle:-

→ In ideal cycle, both compression and expansion are reversible.

→ But in actual Cycle, due to friction & heat loss, the processes are irreversible.

1-2-3-4 → Ideal Cycle
1-2'-3-4' → Actual Cycle

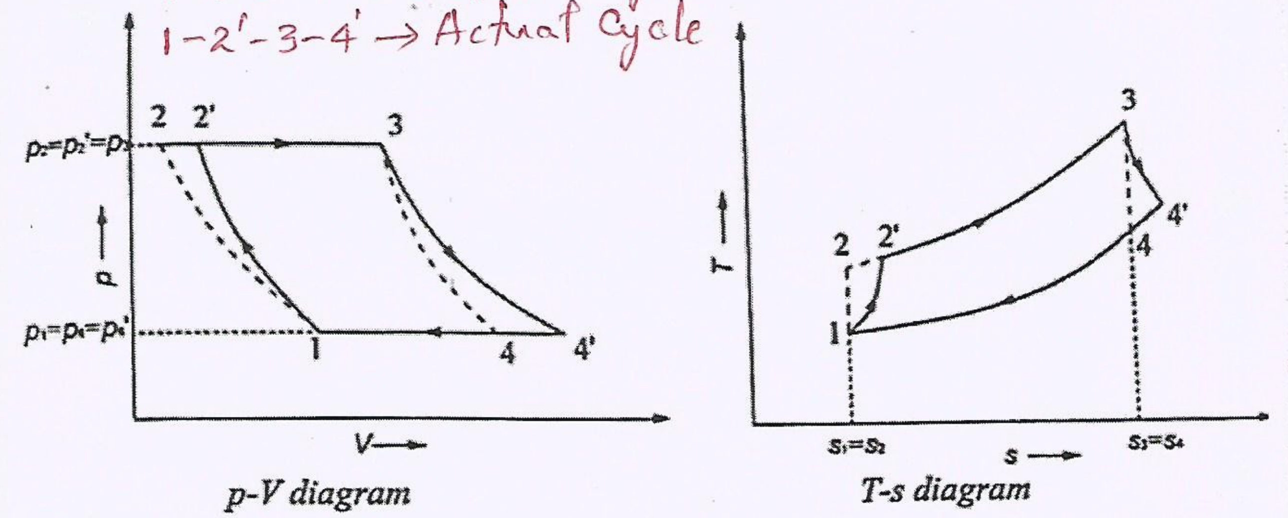


Figure 1.41 Actual Brayton cycle

Work required by Compressor,

$$W_c = m \times C_p (T_2' - T_1)$$

Work done by Turbine,

$$W_T = m \times C_p (T_3 - T_4')$$

Network available,

$$W = W_T - W_c$$

$$W = m C_p [T_3 - T_4' - T_2' + T_1]$$

Net heat supplied,

$$Q_S = m C_p (T_3 - T_2')$$

Thermal efficiency,

$$\eta_{th} = \frac{W}{Q_S} = \frac{T_3 - T_4' - T_2' + T_1}{T_3 - T_2'}$$

Isentropic η of Compressor,

$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

Isentropic η of Turbine,

$$\eta_T = \frac{T_3 - T_4'}{T_3 - T_4}$$

FORMULA

UNIT - 1 - GAS POWER CYCLES.

General :-

$C_p = 1.005$ kJ/kg.K , $C_v = 0.718$ kJ/kg.K.

$R = 0.287$ kJ/kg.K. , $\gamma = \dfrac{C_p}{C_v}$

$PV = mRT$

Reversible Adiabatic (or) Isentropic Process,

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

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

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Constant Pressure Process,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}.$$

Constant Volume Process,

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}.$$

$$\eta = \frac{\text{Work Done}}{Q_S} = \frac{Q_S - Q_R}{Q_S}.$$

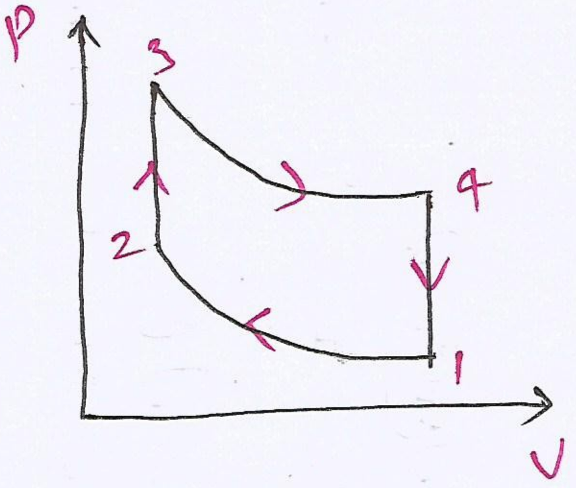
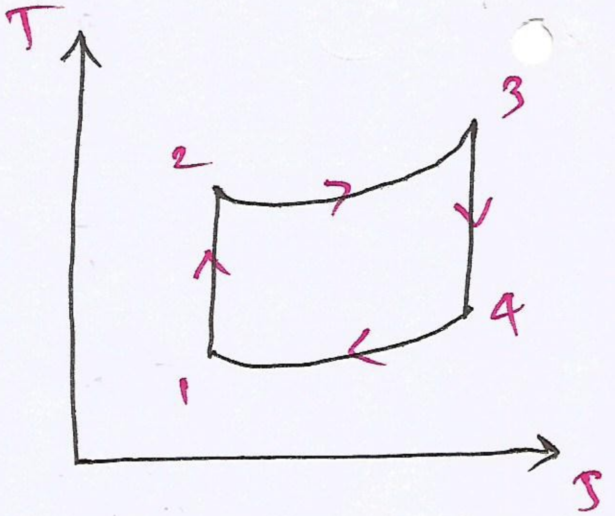
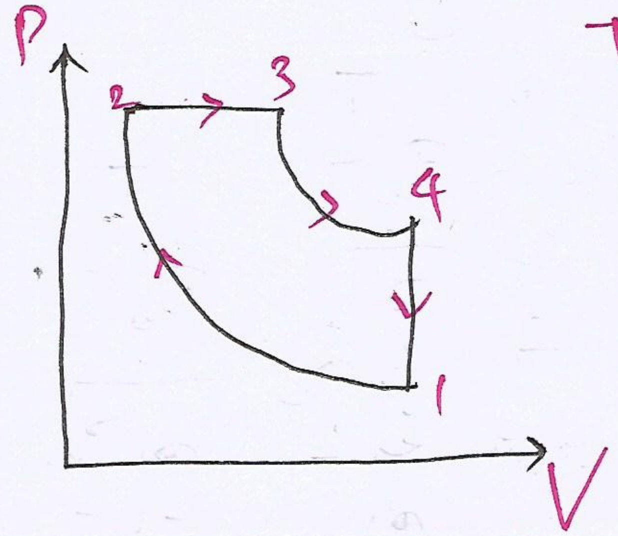
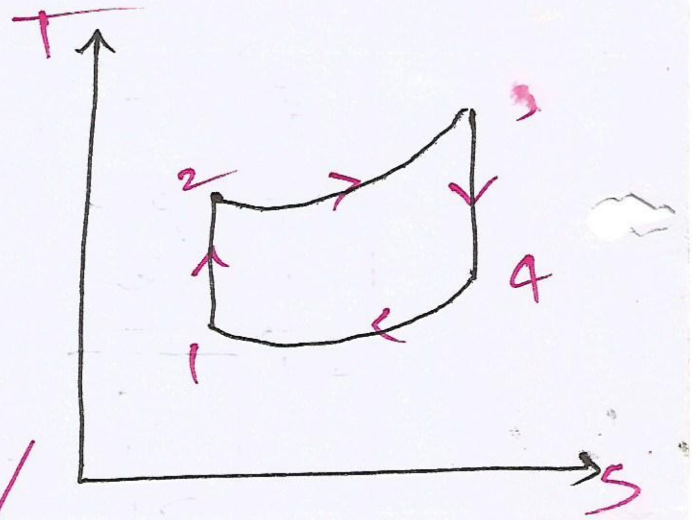
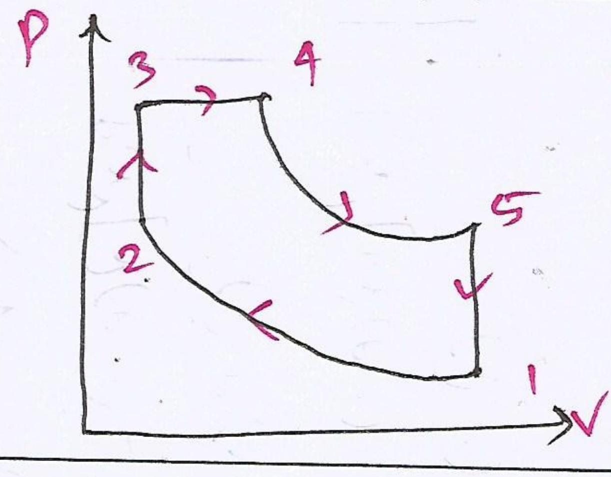
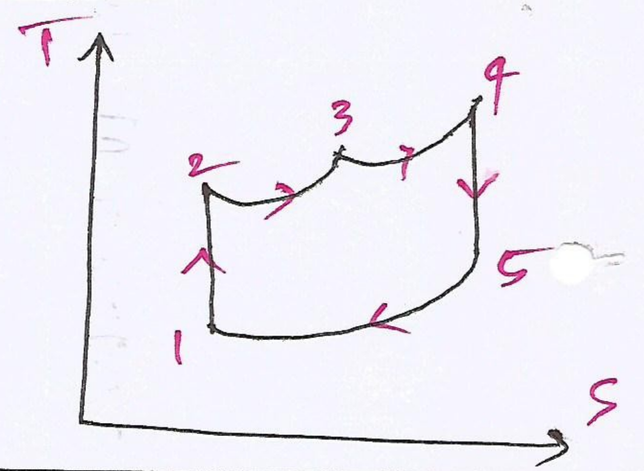
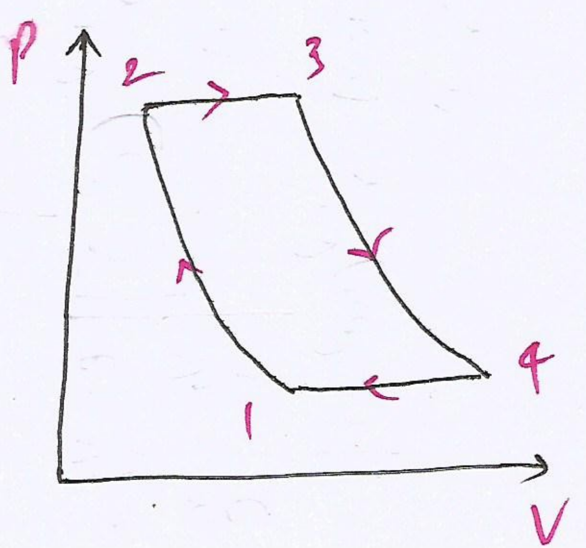
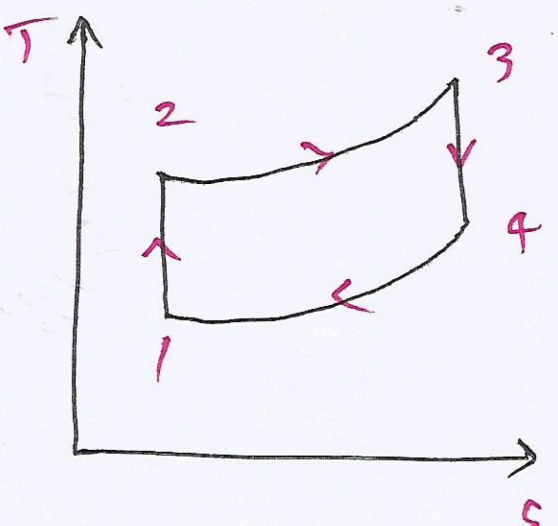
$$P_m = \frac{W}{V_s} = \frac{W}{V_1 - V_2}.$$

$$Q = m C_p \Delta T \text{ (or) } m C_v (\Delta T).$$

$$V_1 = V_s + V_c = V_s + V_2.$$

$$V_c = V_2.$$

$$r = \frac{V_1}{V_2} = \frac{V_s + V_c}{V_c}.$$

Otto (or) Const Volume Cycle	 
Diesel (or) Const Pressure Cycl.	 
Dual (or) Limiter Pressure (or) Mixed Cycle	 
Brayton (or) Joule (or) Const. Press. Cycle for perfect gas.	 

CYCLE	η (in terms of temp)	η	P_m
OTTO	$1 - \frac{T_4 - T_1}{T_3 - T_2}$	$1 - \frac{1}{(r)^{\gamma-1}}$	$P_1 r \left(\frac{r_p - 1}{\gamma - 1}\right)\left(\frac{r^{\gamma-1} - 1}{r - 1}\right)$; $r_p = \frac{P_3}{P_2} = \frac{P_4}{P_1}$
DIESEL	$1 - \frac{T_4 - T_1}{\gamma (T_3 - T_2)}$	$1 - \frac{1}{\gamma (r)^{\gamma-1}}\left[\frac{e^{\gamma} - 1}{e - 1}\right]$	$\frac{P_1 r^{\gamma}\left[\gamma(e-1) - r^{1-\gamma}\left[e^{\gamma} - 1\right]\right]}{(\gamma-1)(r-1)}$; $e = \frac{V_3}{V_2}$. $\frac{V_4}{V_3} = \frac{r}{e}$
DUAL	$1 - \frac{T_5 - T_1}{(T_3 - T_2) + \gamma(T_4 - T_3)}$	$1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{k e^{\gamma} - 1}{(k-1) + \gamma k(e-1)}\right]$; $e = \frac{V_4}{V_3}$, k (or) $\beta = \frac{P_3}{P_2}$.	$\frac{P_1 r^{\gamma}\left[k\gamma(e-1) + (k-1) - r^{1-\gamma}(k e^{\gamma} - 1)\right]}{(\gamma-1)(r-1)}$
BRAYTON	$1 - \frac{T_4 - T_1}{T_3 - T_2}$	$1 - \frac{1}{(R_p)^{\gamma-1}}$; $1 - \frac{1}{(r)^{\gamma-1}}$; $R_p = \frac{P_2}{P_1} = \frac{P_3}{P_4}$	Work Ratio $= 1 - \frac{T_1}{T_3} (R_p)^{\frac{\gamma-1}{\gamma}}$.

UNIT - II

RECIPROCATING AIR COMPRESSOR

SYLLABUS:-

Classification & Comparison, working principle, work of compression - with & without clearance, volumetric efficiency, Isothermal efficiency and Isentropic efficiency. Multistage air compressor with intercooling. Working principle and comparison of Rotary compressors with reciprocating air compressors.

AIR COMPRESSOR:-

It is a device used to increase the pressure of gas from low pressure to high pressure.

1) CLASSIFICATION OF AIR COMPRESSORS:-

a) According to working:-

* Reciprocating compressor.
* Rotary compressor.

b) According to number of stages:-

* Single stage compressor
* Multi stage compressor.

c) According to number of cylinders:-

* Single cylinder compressor.
* Multi cylinder compressor.

d) According to method of cooling:-

* Air cooled compressor.
* Water cooled compressor.

e) According to pressure limit:-

* Low (upto 1 bar) * Medium (1 to 8 bar)
* High (above 8 bar)

f) According to the capacity:-

* Low (Volume less than 0.15 m^3/s delivery)
* Medium (0.15 to 5 m^3/s) * High (above 5 m^3/s).

RECIPROCATING AIR COMPRESSOR :-

It is a machine with piston-cylinder arrangement, which takes air (or) gas during suction stroke at low pressure and then compresses it to higher pressure during delivery stroke.

Single stage Compressor - One cylinder, air sucked & compressed to higher pressure and delivered by one cycle

Multi stage Compressor - More than one cylinder. Air gets sucked in first cylinder & compressed and delivered to next cylinder, where again air is compressed and finally delivered.

2) WORKING OF SINGLE STAGE AIR COMPRESSOR :-

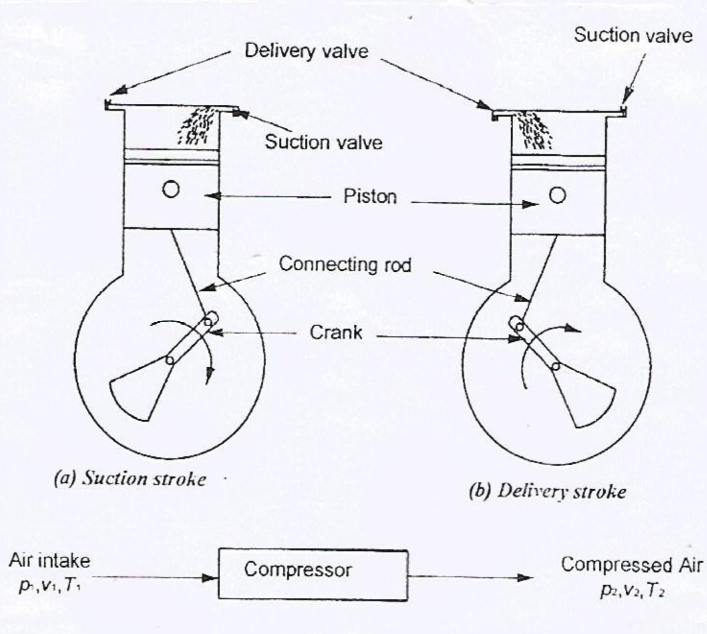


Figure 4.1 Single stage reciprocating air compressor

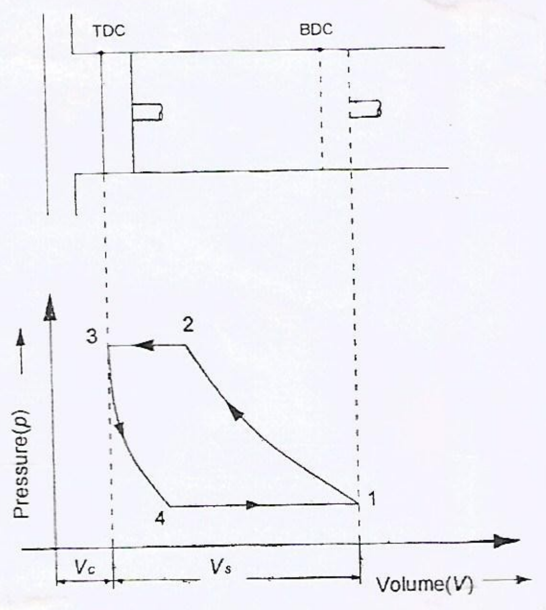


Figure 4.2 Clearance volume

* In single stage compressor, the compression of air from initial pressure to final pressure is carried out in one cylinder only.

* During suction stroke, the piston moves downward from TDC & pressure inside the cylinder falls below atmospheric pressure.

* So inlet valve opens & the air from atmosphere is sucked into cylinder until the piston reaches the BDC.

* During this stroke, delivery valve remains closed.

* When piston moves upward from BDC, both valves are closed.

* Hence the pressure inside cylinder goes on increasing till reaching required discharge pressure.

* At this stage, delivery valve opens & compressed air is delivered through this valve.

* Thus the cycle is repeated.

IMPORTANT TERMS:-

i) Suction Pressure :- (P_1)

Absolute pressure of air at inlet.

ii) Discharge Pressure :- (P_2)

Absolute pressure of air at outlet.

iii) Compression ratio :- (r)

$$r = \frac{\text{Absolute discharge pressure}}{\text{Absolute suction pressure}}$$

Always, $r > 1$. $r = \frac{\text{Total Cylinder volume}}{\text{Clearance volume}}$

iv) Suction Volume :- (V_1)

v) Stroke Volume (or) Swept Volume :- (V_s)

$$V_s = \frac{\pi}{4} D^2 L$$

D - Dia of cylinder, L - Length of piston stroke

vi) Clearance volume (V_c) :-

At TDC, piston top and cylinder head seperated by a space. This is known as clearance volume.

vii) Clearance factor (or) ratio :- (C)

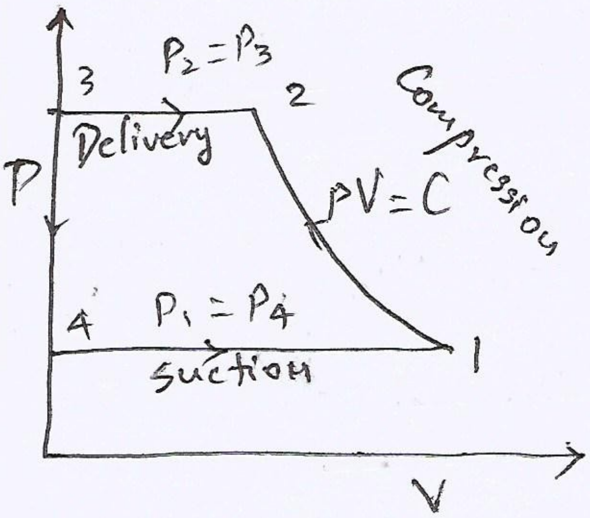
$$C = \frac{V_c}{V_s}$$

viii) Free Air Delivery :- (FAD)

FAD - Actual volume of air delivered by compressor at normal T & P.

3) Work Done by Single Stage Reciprocating Air Compressor without considering Clearance Volume:-

a) Work Done during Isothermal compression ($pV = c$)



4-1 → Suction of air at P_1

1-2 → Isothermal compression

2-3 → Discharge of air at P_2

As compression is isothermal process,

$$\text{Work Done, } W_{comp} = P_1 V_1 \ln\left[\frac{V_1}{V_2}\right]$$

Work Done by compressor = Area 1-2-3-4-1

$$W = W_{comp} + W_{Delivery} - W_{suction}$$

$$= P_1 V_1 \ln\left[\frac{V_1}{V_2}\right] + P_2 V_2 - P_1 V_1$$

For isothermal process, $P_1 V_1 = P_2 V_2$.

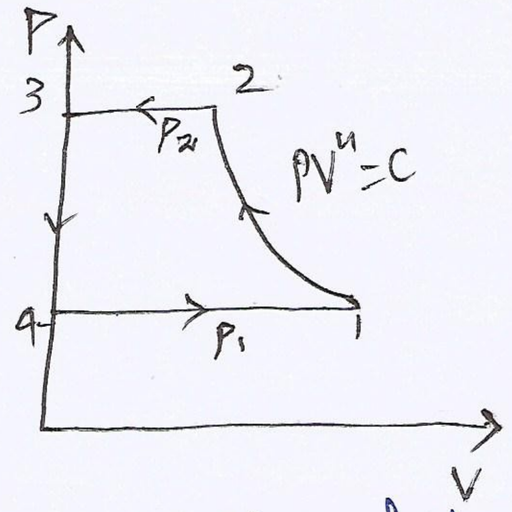
$$\therefore \boxed{W = P_1 V_1 \ln\left[\frac{V_1}{V_2}\right]}$$

W.K.T, $P_1 V_1 = P_2 V_2 \Rightarrow \frac{V_1}{V_2} = \frac{P_2}{P_1}$.

$$\therefore \boxed{W = P_1 V_1 \ln\left[\frac{P_2}{P_1}\right]}$$

$$\boxed{W = mRT_1 \ln\left[\frac{P_2}{P_1}\right]}$$

b) Work Done during Polytropic Compression ($PV^n = C$)



4 - 1 → Suction

1 - 2 → Polytropic compression

2 - 3 → Delivery.

For polytropic process, $W_{comp} = \dfrac{P_2V_2 - P_1V_1}{n-1}$

Work Done = $W_{comp} + W_{Delivery} - W_{suction}$

$$= \frac{P_2V_2 - P_1V_1}{n-1} + P_2V_2 - P_1V_1$$

$$= \frac{P_2V_2 - P_1V_1 + [(n-1)(P_2V_2)] - [(n-1)(P_1V_1)]}{n-1}$$

$$= \frac{P_2V_2 - P_1V_1 + nP_2V_2 - P_2V_2 - nP_1V_1 + P_1V_1}{n-1}$$

$$= \frac{nP_2V_2 - nP_1V_1}{n-1} = \frac{n(P_2V_2 - P_1V_1)}{n-1}$$

$$\boxed{W = \frac{n}{n-1}(P_2V_2 - P_1V_1)}$$

$$W = \frac{n}{n-1}(mRT_2 - mRT_1)$$

$$\boxed{\therefore W = \frac{n}{n-1} mRT_1 \left[\frac{T_2}{T_1} - 1\right]}$$

For polytropic process, $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$

$$\therefore W = \frac{n}{n-1} mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$\boxed{W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]}$$

c) Work Done during Isentropic (or) Reversible adiabatic compression $[PV^\gamma = C]$:-

For adiabatic process, $PV^\gamma = C$,

$$W_{comp} = \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

Work Done = $W_{comp} + W_{Delivery} - W_{suction}$

$$W = \frac{P_2V_2 - P_1V_1}{\gamma - 1} + P_2V_2 - P_1V_1$$

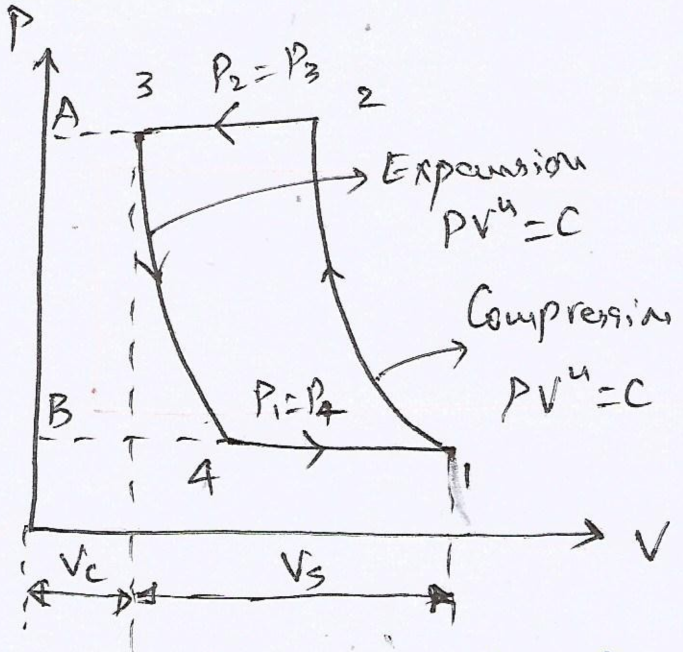
(Same as previous process)

$$W = \frac{\gamma}{\gamma - 1} mRT_1 \left[\frac{T_2}{T_1} - 1\right]$$

$$\therefore \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow W = \frac{\gamma}{\gamma-1} mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$\boxed{W = \frac{\gamma}{\gamma-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

4) **Work Done by Single stage reciprocating air compressor with clearance Volume :-**



1→2 → Compression
3−4 → Expansion
} Polytropic.

Work Done by Compressor per Cycle,

$$W = \text{Area } (1-2-3-4-1)$$

$$= \text{Area } (1-2-A-B-1) - \text{Area } (3-A-B-4-3)$$

$$W = W_{compression} - W_{Expansion}.$$

$$W = \frac{n P_1 V_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] - \frac{n}{n-1} P_4 V_4 \left[\left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}} - 1\right]$$

As, $P_1 = P_4$ & $P_3 = P_2$.

$$W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] - \frac{n}{n-1} P_1 V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} P_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] (V_1 - V_4)$$

$$\boxed{W = \frac{n}{n-1} P_1 V_a \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]}$$

V_a - Actual Vol of free air delivered per

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

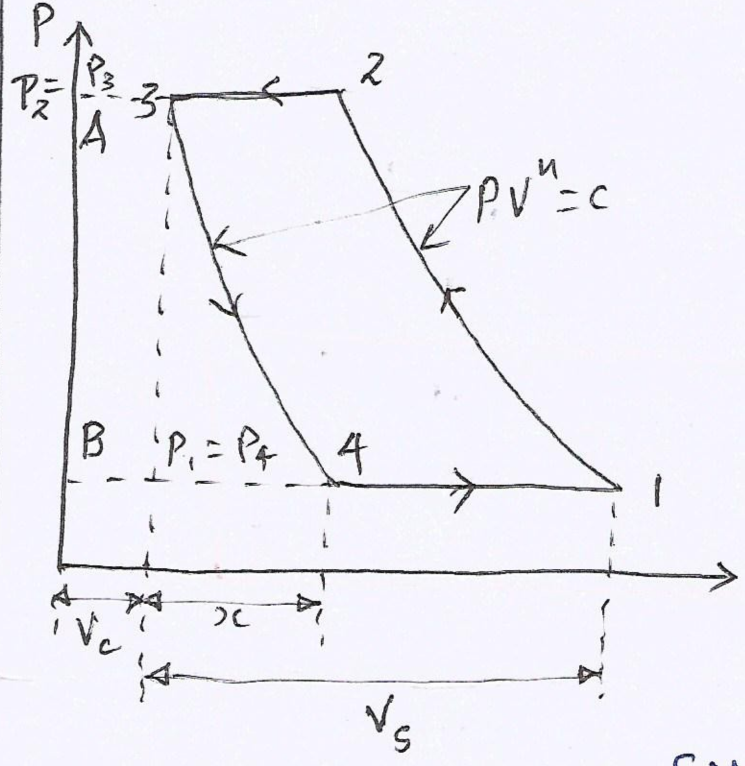
$$\left[\because P_1 V_a = mRT_1\right]$$

---

5) **Volumetric Efficiency :-**

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

$$\eta_{vol} = \frac{V_a}{V_s}$$



From fig,

$$V_a = V_s - V_x$$

$$x = V_4 - V_c$$

$$\therefore \eta_{vol} = \frac{V_s - x}{V_s}$$

$$\eta_{vol} = \frac{V_s - (V_4 - V_c)}{V_s}$$

$$\eta_{vol} = \frac{V_s - V_c\left[\frac{V_4}{V_c} - 1\right]}{V_s}$$

$$\eta_{vol} = 1 - \frac{V_c}{V_s}\left[\frac{V_4}{V_c} - 1\right] \longrightarrow (1)$$

Since both comp & expansion follows, $PV^n = C$

$$P_3 V_3^n = P_4 V_4^n \Rightarrow \frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{1/n}$$

From fig, $V_3 = V_c$, $P_4 = P_1$ & $P_3 = P_2$.

$$\frac{V_4}{V_c} = \left(\frac{P_2}{P_1}\right)^{1/n}$$

Sub $\frac{V_4}{V_c}$ in eq (1),

$$\eta_{vol} = 1 - \frac{V_c}{V_s}\left[\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} - 1\right]$$

$\because$ Clearance Ratio, $C = \frac{V_c}{V_s}$.

$$\therefore \eta_{vol} = 1 - C\left[\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} - 1\right]$$

$$\boxed{\eta_{vol} = 1 + C - C\left[\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}\right]}$$

---

1) G.K.V, Pb: 4.3, Pg: 4.13. } → without V_c
2) G.K.V, Pb: 4.4, Pg: 4.14. }
3) Univ. Sold Plans, Pg: 1, 7. } → with V_c
4) Er. K.V, Pb: 41, Pg: 4.20 → without V_c.

EFFICIENCIES IN AIR COMPRESSOR:-

i) Volumetric Efficiency:- (η_{vol})

$$\eta_{vol} = \frac{\text{Suction Volume}}{\text{stroke volume}} = \frac{V_1}{V_S}$$

$$\eta_{vol} = \frac{\text{FAD}}{\text{Displacement Volume (or) stroke Volume}}$$

ii) Isothermal Efficiency:- (η_{iso})

$$\eta_{iso} = \frac{\text{Isothermal work input}}{\text{Actual work input}}$$, during compression.

iii) Isentropic Efficiency:- (η_{isen})

$$\eta_{isen} = \frac{\text{Isentropic work input}}{\text{Actual work input}}$$, during compression.

---

6) MULTI-STAGE AIR COMPRESSOR WITH INTERCOOLING:-

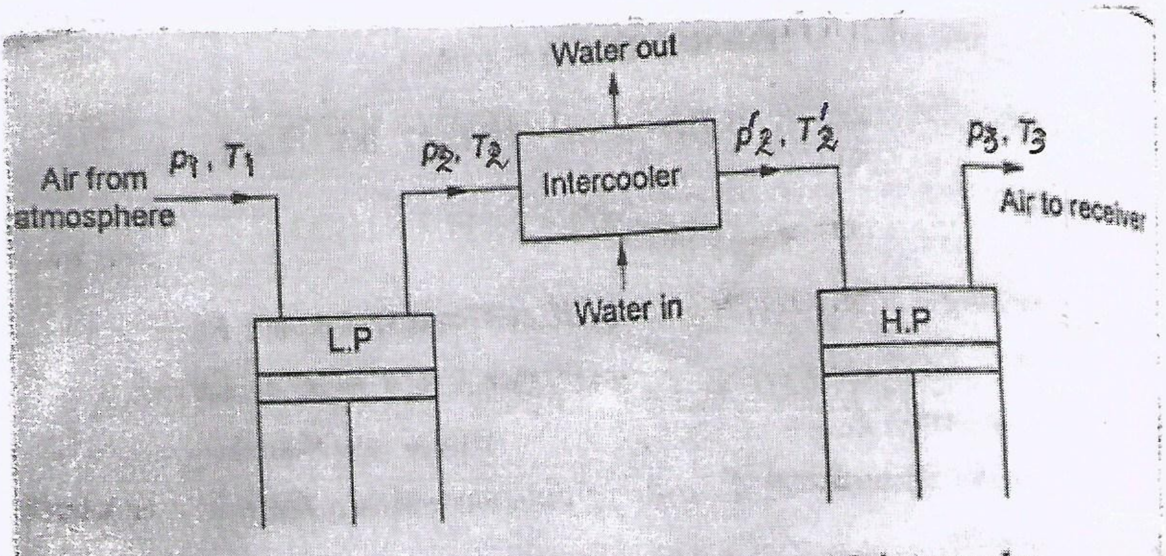


Figure 2.10 (a) Two stage compression with intercooler

* Compression of air in two (or) more cylinders in series is called Multistage compression.

* Used to get high-pressure air, specifically when compression ratio exceeds 5.

	Delivery Pressure
Single stage Compressor -	Upto 5 bar.
Two Stage Compressor -	5 to 35 bar.
Three stage Compressor -	35 to 85 bar.
Four Stage Compressor -	above 85 bar.

* It has Low-Pressure (LP) cylinder, intercooler and High-Pressure (HP) cylinder.

* Fresh air is sucked from atmosphere in LP cylinder during suction stroke at P_1 and T_1.

* After compression in LP cylinder, it is delivered to intercooler at P_2 and T_2.

* In intercooler, compressed air is cooled by lowering temperature without changing the pressure P_2 as constant.

* Then cooled air taken to HP cylinder & compressed again.

* Final high pressure air (P_3) is delivered to the receiver.

Assumptions:-

→ Both suction & delivery pressure remains constant at each stage.

→ Compression index is same at each stage.

→ Intercooling in each stage is at constant temperature.

→ Mass of air at LP & HP cylinders are same.

Advantages:-

* Higher volumetric efficiency.
* Better mechanical balance.
* Reduced leakage loss.
* Higher uniform torque.
* Sizes of two cylinders can be adjusted based on required pressure.
* Better lubrication due to lower temperature created by intercooler.
* Reduced cost of materials due to lower operating temperature.

Work done:-

Total work input = {Work input to LPC} + {Work input to HPC}

$$W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] + \frac{n}{n-1} P_2' V_2' \left[\left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 1 \right]$$

Intercooler - Perfect cooling, $P_2 = P_2'$, $P_1 V_1 = P_2' V_2'$

$$\therefore W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 + \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$\boxed{W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 2 \right]}$$

———— x ———— x ———— x ————

7) CONDITION FOR MINIMUM WORK INPUT FOR TWO STAGE COMPRESSOR (8)

Work done by two stage compressor,

$$W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2 \right] \rightarrow (1)$$

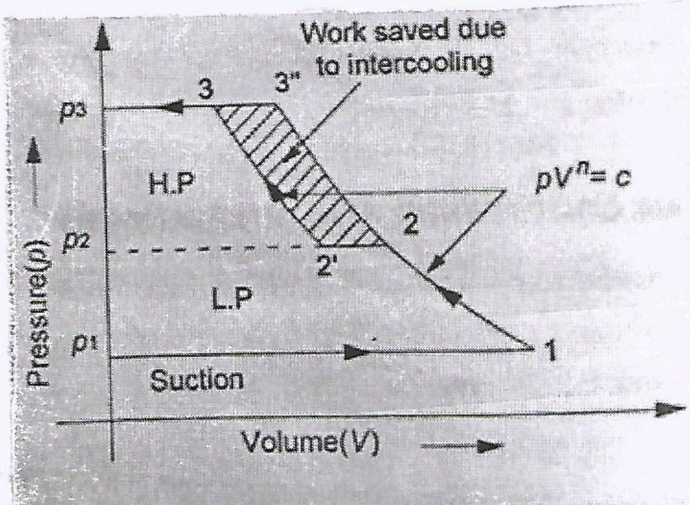


Figure 2.10 (b) p-V diagram

Inter-stage Pressure $= P_2$

Differentiating (1) with respect to P_2.

$$\frac{dw}{dP_2} = 0.$$

$$\frac{d}{dP_2}\left[\frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]\right] = 0.$$

let $\frac{n}{n-1} = K.$

$$K \frac{d}{dP_2} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{K} + \left(\frac{P_3}{P_2}\right)^{K} - 2\right] = 0.$$

$$K P_1 V_1 \left[\left(\frac{1}{P_1}\right)^{K} K (P_2)^{K-1} + (P_3)^{K}(-K)(P_2)^{-K-1}\right] = 0.$$

$$\left[K (P_1)^{-K} (P_2)^{K-1}\right] - \left[K (P_3)^{K} (P_2)^{-K-1}\right] = 0.$$

$$k(P_1)^{-k}(P_2)^{k-1} = k(P_3)^k (P_2)^{-k-1}$$

$$\frac{(P_2)^{k-1}}{(P_2)^{-k-1}} = \frac{(P_3)^k}{(P_1)^{-k}}$$

$$(P_2)^{k-1} \times (P_2)^{k+1} = (P_3)^k \times (P_1)^k.$$

$$(P_2)^{2k} = (P_3 P_1)^k$$

$$P_2^2 = P_3 P_1$$

At Inter-stage Pressure, $\boxed{P_2 = \sqrt{P_1 P_3}}$ work will be minimum

To find minimum work input,

$$P_2^2 = P_1 P_3 \longrightarrow (2)$$

$$\frac{P_2}{P_1} = \frac{P_3}{P_2} \longrightarrow (3).$$

$\div$ by P_1^2 on both sides in eq (2).

$$\frac{P_2^2}{P_1^2} = \frac{P_3}{P_1}.$$

$$\left(\frac{P_2}{P_1}\right) = \left(\frac{P_3}{P_1}\right)^{1/2} \longrightarrow (4)$$

Sub above (4) in (3),

$$\frac{P_2}{P_1} = \frac{P_3}{P_2} = \left(\frac{P_3}{P_1}\right)^{1/2} \longrightarrow (5).$$

Sub eq (5) in (1),

9

$$W_{min} = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_3}{P_1}\right)^{\frac{n-1}{2n}} + \left(\frac{P_3}{P_1}\right)^{\frac{n-1}{2n}} - 2 \right]$$

$$= \frac{n}{n-1} P_1 V_1 \left[2 \left(\frac{P_3}{P_1}\right)^{\frac{n-1}{2n}} - 2 \right]$$

$$W_{min} = \frac{2n}{n-1} P_1 V_1 \left[\left(\frac{P_3}{P_1}\right)^{\frac{n-1}{2n}} - 1 \right] \longrightarrow (6)$$

Eq (6) → Minimum Work input for two stage compressor.

Similarly,

For 3 stage compressor,

$$W_{min} = \frac{3n}{n-1} P_1 V_1 \left[\left(\frac{P_4}{P_1}\right)^{\frac{n-1}{3n}} - 1 \right]$$

For 4 stage Compressor,

$$W_{min} = \frac{4n}{n-1} P_1 V_1 \left[\left(\frac{P_5}{P_1}\right)^{\frac{n-1}{4n}} - 1 \right]$$

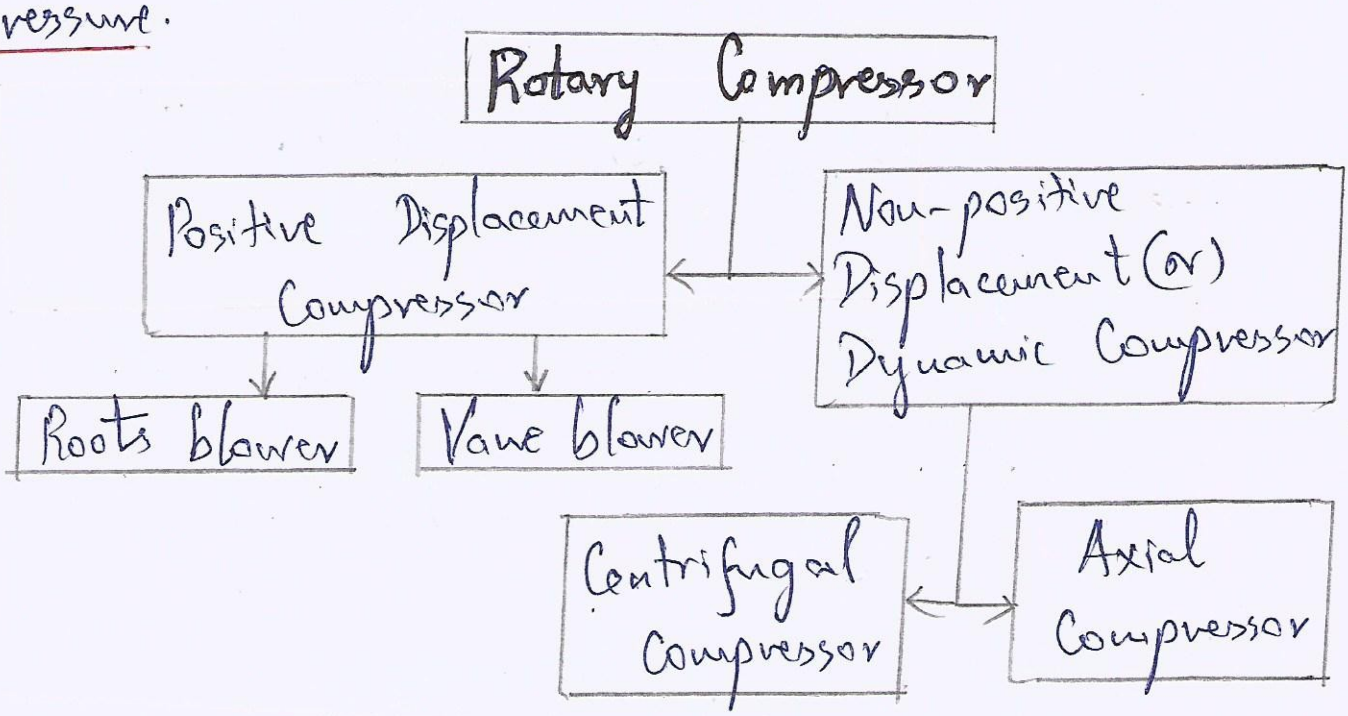
For multistages, any 'x' stage,

$$W_{min} = \frac{xn}{n-1} P_1 V_1 \left[\left(\frac{P_{x+1}}{P_1}\right)^{\frac{n-1}{xn}} - 1 \right]$$

— x — x — x —

8) ROTARY COMPRESSORS:-

Rotary compressors are used for large quantities of air at low pressure.



Positive Displacement	Non-positive Displacement
In this type of compressor, air is physically trapped between two relatively moving components & compressed to increase air pressure.	In this type, a rotating component apply its kinetic energy to air which is eventually converted into pressure energy.
	No trapping of air, only continuous motion of air.

ROOT BLOWER :-

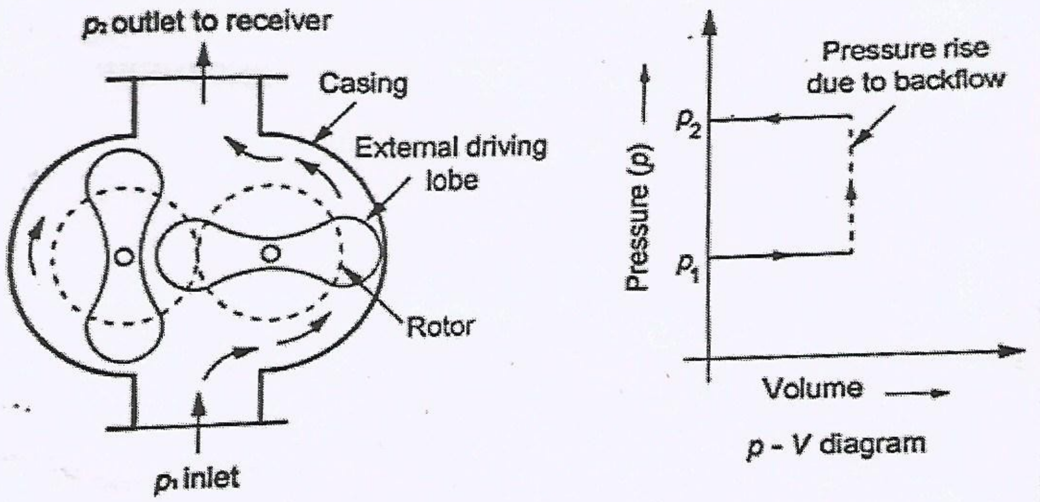


Figure 2.13 Root blower

Construction:- * Arrangement of root blower is simply a development of gear pump.

* Has two rotors called lobes, arranged at different parallel axis, rotates in opposite direction.

* To increase pressure ratio, number of lobes can be increased.

Working:- * When power is given to blower, the rotor rotates & the atmosphere air enters blower & gets trapped between lobes.

* When the exit port opens, the air rushes into inlet & mixed with trapped air & pressure increases.

* Thus the pressure of trapped air is increased by backflow of air.

Roots efficiency = $\frac{\text{Ideal Work done}}{\text{Actual Work done}}$

* Roots blower efficiency decreases with increase in pressure ratio.

VANE BLOWER:-

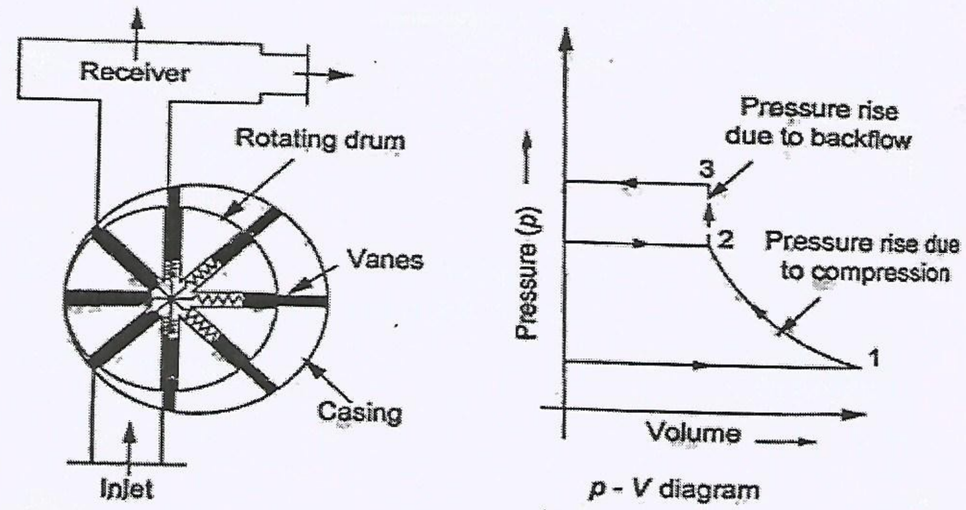


Figure 2.14 Vane blower

Construction:- * It has rotating drum, spring loaded vanes, inlet and outlet ports & casing.

* Rotor is located eccentrically inside the casing.

* Rotor carries set of spring loaded vanes, which is made of carbon fibre.

Working:- * When power is given, rotating drum rotates and the air is trapped between two vanes.

* During rotation, the trapped air compressed gradually & move towards receiver.

* When the exit port opens, the inlet air rushes as back flow of high-pressure & the air get compressed again to higher pressure.

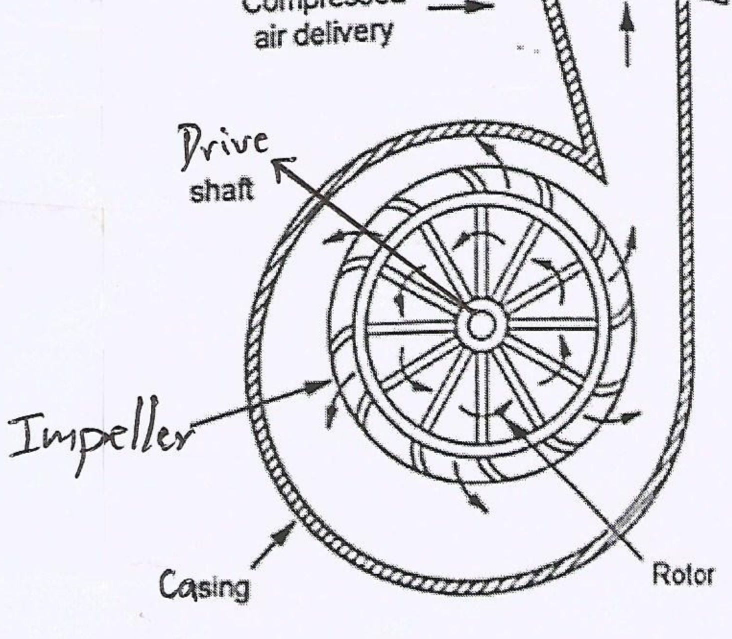
* Finally the pressurized air exits through receiver.

* In the p-V diagram, the pressure initially increased gradually (1)-(2).

* Then due to backflow, again the air gets compressed higher at (2)-(3).

CENTRIFUGAL COMPRESSOR:-

→ Air enters axially & leaves radially.



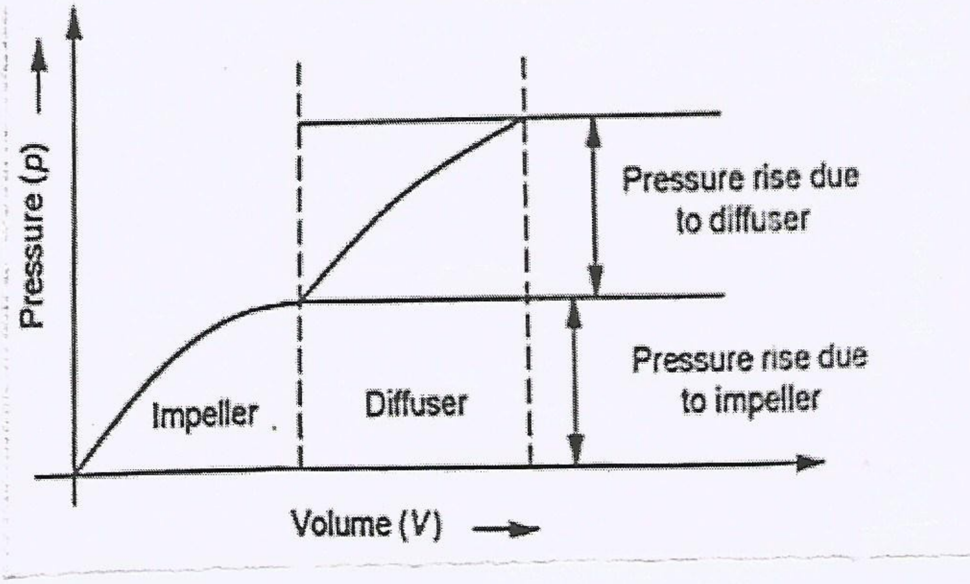
Construction:-

* It has rotating impeller, casing & diffuser.
* Impeller has a disc on which, radial blades are attached.
* Diffuser is used to convert K.E into pressure energy.
* Air coming out from the diffuser is collected in casing & takes out through outlet.
* Impeller runs at 20,000 to 30,000 rpm.

Working:-

* When power is given, the impeller rotates & sucks air.
* Air entering axially with low velocity will be partially increased while passing through impeller.
* In diffuser, the pressure of air gets increased further.
* Half of pressure rise obtained in impeller & remaining half of pressure rise will be obtained in diffuser.

* The change of pressure of air passing through impeller & diffuser is shown in the figure below.



Application :-

* Supercharging I.C engines.
* Refrigeration.
* Low-pressure units.

AXIAL FLOW COMPRESSOR :-

→ Air enters & leaves axially.

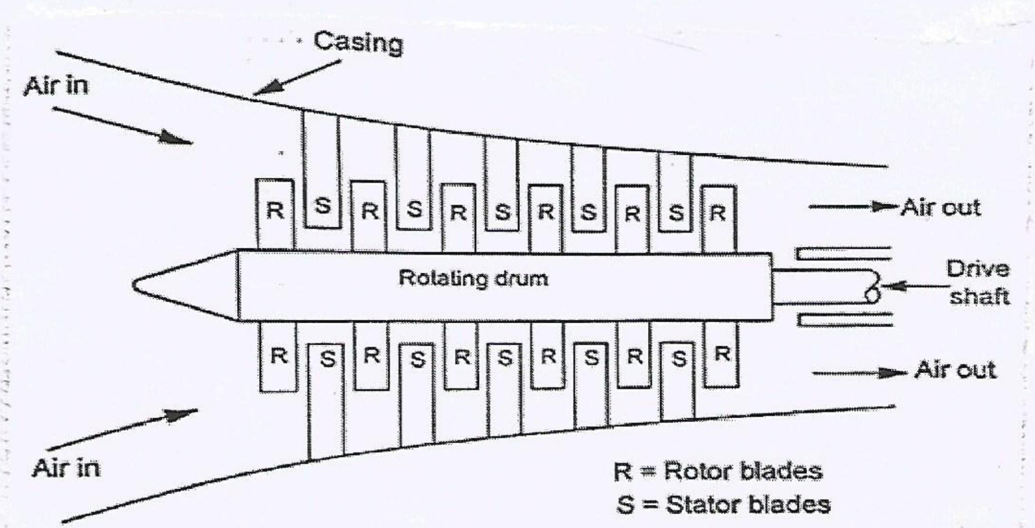


Figure 2.16 Axial compressor

Construction:-

* It has casing, rotating drum, stator & rotor blades.

* Stator blades fixed to casing, the rotor blades fixed on rotating drum.

* Casing is designed to be reducing area for the passage of air flow.

Working:-

* When power is given, the rotating drum rotates & sucks air.

* Air passes through rotor (R) and stator (S) blades.

* When air flow from one set of stator and rotor to another set, air gets compressed.

* Air is also compressed between blade & casing, due to gradual decrease in area from inlet to outlet of the compressor.

* Finally high pressure air delivered to receiver.

Application:-

* Large size gas turbines.

* High-pressure units.

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9) ROTARY SCREW COMPRESSOR:-

* It is a rotary type positive displacement mechanism.
* This compressor uses either single screw (or) two counter rotating helical screws inside casing.

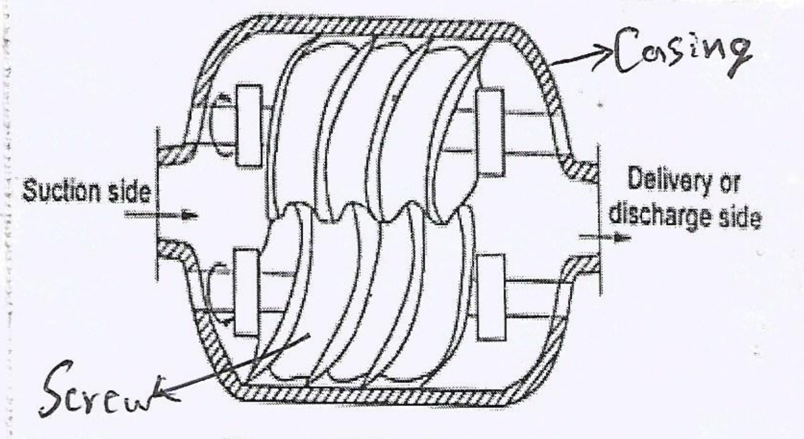


Figure 2.17 Screw compressor

* When power is given, the screws rotates & sucks air, which is trapped between screws and casing.
* Pressure increased due to compression by screws.
* Higher pressure air exits through delivery.

Application:-

* Low pressure - industrial applications.

10) COMPARISON OF COMPRESSORS :-

Rotary Vs Reciprocating

S. No.	*Rotary compressor*	*Reciprocating compressor*
1.	It is simple in construction.	Construction is complicated.
2.	Speed is high.	Speed is low.
3.	It is suitable for large rate of flow at low discharge pressure.	It is suitable for low rate of flow at very high discharge pressure.
4.	Maintenance cost is less.	Maintenance cost is high.
5.	There is no balancing problem.	Balancing is major problem.
6.	Simple lubrication system is used.	More complicated lubrication system is used.
7.	It is small in size for the same discharge as compared with reciprocating compressors.	It is large in size for the same discharge as compared with rotary compressor.
8.	Uniform delivery of air is possible.	Delivery is not uniform.
9.	Operation is smooth.	Operation is noisy.
10.	It produces less vibration when running.	It produces more vibration.

Centrifugal Vs Axial

S. No.	*Centrifugal compressor*	*Axial compressor*
1.	Starting torque is low.	Starting torque is high.
2.	Isentropic efficiency is around 70%.	Isentropic efficiency is around 85%.
3.	It is not suitable for multistage compression.	It is suitable for multistage compression.
4.	More frontal area is required.	Less frontal area is required.
5.	Manufacturing cost is low.	Manufacturing cost is high.
6.	Running cost is low.	Running cost is high.

UNIT - III

INTERNAL COMBUSTION ENGINES & COMBUSTION

SYLLABUS :-

IC Engine - classification, working, components and their functions. Ideal and actual: valve and port timing diagrams, p-v diagrams: two stroke & four stroke, and SI & CI engines comparison. Geometric, operating and performances comparison of SI & CI engines. Desirable properties and qualities of fuels. Air-fuel ratio calculation - lean & rich mixtures. Combustion in SI & CI engines - Knocking - Phenomena & control.

1) CLASSIFICATION OF IC ENGINES:-

IC - Internal Combustion engine is a heat engine which converts the chemical energy of fuel into mechanical energy.

IC engines may be classified as given below,

a) According to cycle of operation [No. of strokes]

* Two stroke cycle engine.
* Four stroke cycle engine.

b) According to thermodynamic cycle:-

* Otto Cycle engine.
* Diesel Cycle engine.
* Dual Cycle engine.

c) According to the method of Ignition:-

* Spark ignition (S.I) engine.
* Compression ignition (C.I) engine.

d) According to types of fuel used:-

* Petrol engine
* Diesel engine
* Gas engine.

e) According to method of Cooling:-

* Air-cooled Engine.
* Water-cooled engine.

f) According to the arrangement of cylinder:-

* Horizontal engine.
* Vertical engine.
* V-type engine.
* Radial type engine.

g) According to valve arrangement:-

* Overhead valve engine.
* L-head type engine
* T-head type engine
* F-head type engine.

h) According to number of cylinders:-

* Single Cylinder engine
* Multi Cylinder engine

i) According to the speed of engine:-

* Low speed engine
* Medium speed engine.
* High speed engine.

j) According to their uses:-

* Stationary engine.
* Portable engine.
* Marine engine.
* Automobile engine.

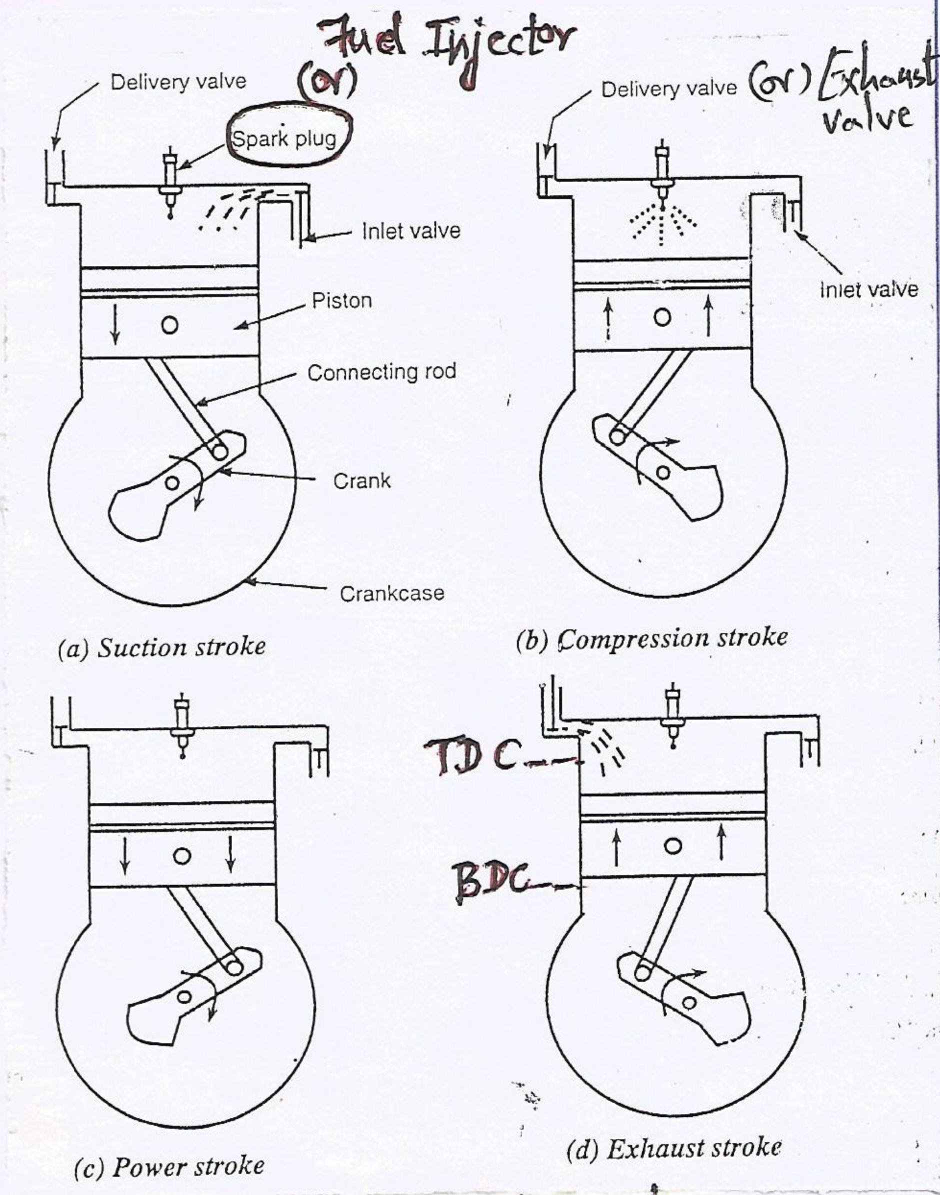
———*———x———x———

2) WORKING OF ENGINE:-

a) FOUR STROKE ENGINE:-

As the name indicates, the operation of engine consists of four strokes,

* Suction stroke
* Compression stroke
* Power (or) expansion stroke
* Exhaust stroke.



(a) Suction stroke (b) Compression stroke (c) Power stroke (d) Exhaust stroke

TDC - Top Dead Centre
BDC - Bottom Dead Centre

Petrol Engine:-

* No Fuel injector
* Only Spark plug
* Spark Ignition (S.I)
* Intake - Mixture of air & fuel during Suction stroke.

Diesel Engine:-

* Compression Ignition (C.I).
* No spark plug.
* Only Fuel injector.
* Intake - Only atmospheric air during suction stroke.

a) SUCTION STROKE:-

→ Piston moves downward from TDC to BDC, a vacuum is created inside the engine cylinder.

→ Due to this vacuum,

i) For petrol engine- mixture of air & fuel from carburettor is entered into cylinder through inlet valve.

ii) For diesel engine- only air enters into cylinder through inlet valve.

→ During this stroke, exhaust valve remains closed.

→ At the end of suction stroke, inlet valve will be closed.

b) COMPRESSION STROKE:-

→ During this stroke, both inlet & exhaust valve remains closed & piston move from BDC to TDC.

Petrol Engine	Diesel Engine.
Compression ratio: 8 to 10	15 to 20
Air/fuel mixture is compressed	Only atmospheric air gets compressed.

→ Due to compression, pressure & temperature inside cylinder increases.

c) POWER (or) EXPANSION STROKE:-

→ At the end of compression stroke, both inlet & exhaust valve closed.

i) For Petrol Engine - Spark plug ignites the air/fuel mixture.

ii) For Diesel Engine - Fuel injector injects diesel fuel over compressed air.

→ As a result of ignition, the combustion takes place, the pressure & temperature increases.

→ Due to bursting force, the piston moves from TDC to BDC, which produces mechanical work. Hence this stroke is named as expansion (or) power stroke.

d) EXHAUST STROKE:-

→ Piston move from BDC to TDC, the exhaust valve opens.

→ As the piston moves upward, the burnt gas inside the cylinder are flushed out to the atmosphere through exhaust valve.

→ This piston movement rotates the crankshaft which is connected to flywheel and gear box.

→ Inlet & exhaust valve opening are controled by Camshaft Connected to crankshaft.

———x———x———x———

3) IC ENGINE - PARTS (or) COMPONENTS & FUNCTIONS:- (or) ENGINE CONSTRUCTION:-

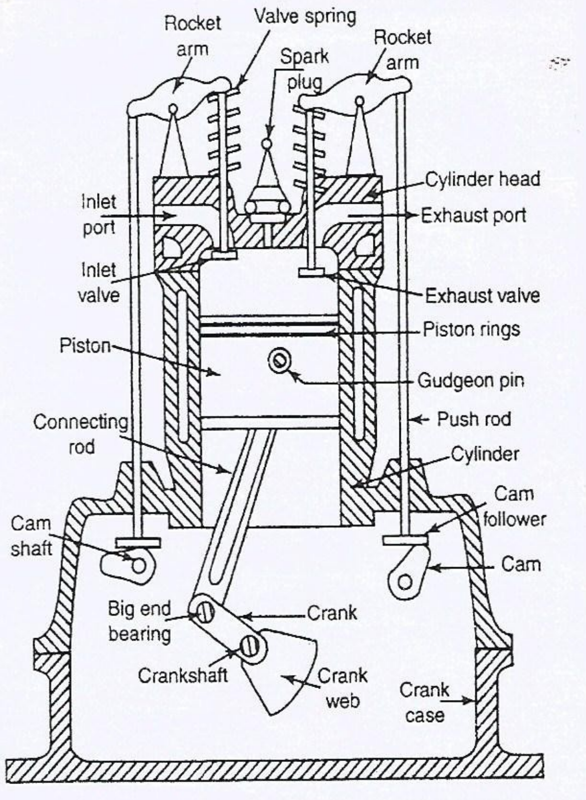


Figure 2.1 Constructional details of IC engine

a) CYLINDER:-

* In an I.C engine, cylinder is the main part, in which the piston reciprocates to develop power.

* It has to withstand very high pressure (about 70 bar) & temperature (about 2200°c) as the combustion takes place inside the cylinder.

* Therefore, it should be made of material which can withstand high temperature & pressure.

* Grey cast iron (or) aluminium with steel sleeves.

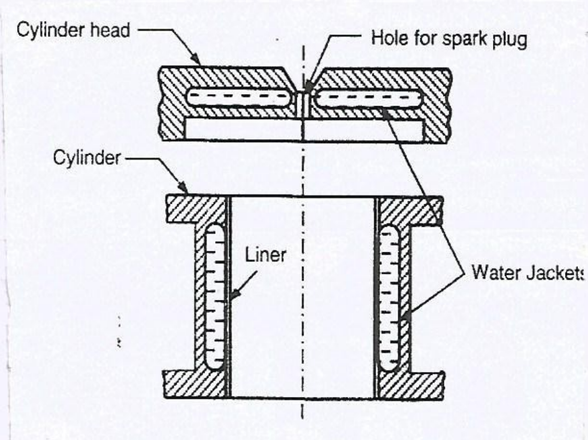
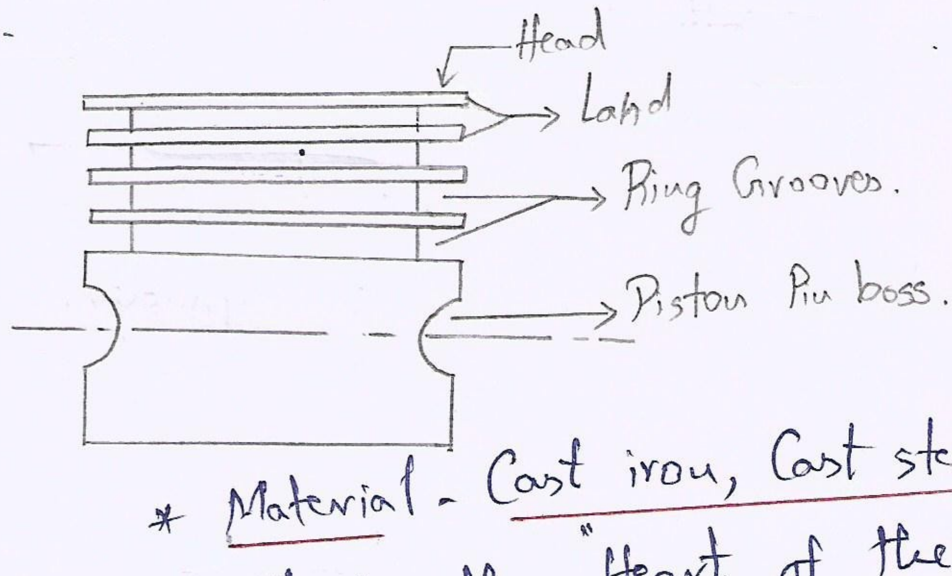


Figure 2.2 Engine cylinder

b) CYLINDER HEAD:-

* Cylinder head is bolted to the top of cylinder block.
* It houses inlet & exhaust valves.
* It also contains hole for spark plug (or) fuel injector.
* Material - Cast iron (or) aluminium alloy.

c) PISTON:-



* Material - Cast iron, Cast steel, etc.,
* It is the "Heart of the Engine". It is a cylindrical shaped mass, reciprocating inside the cylinder.
* It serves for following two purposes,

→ Act as a movable gas tight seal to keep the gases above the piston.

→ It transmits the force of explosion in the cylinder to the Crankshaft through connecting rod.

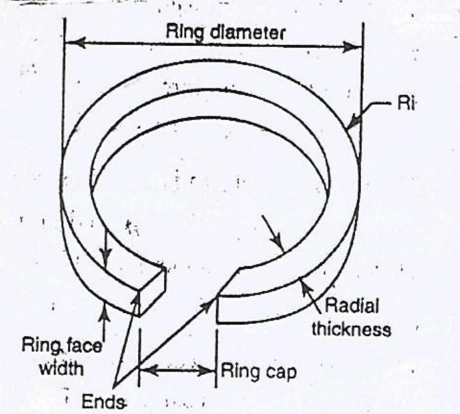
d) PISTON RINGS:-

* They are used to maintain air tight sealing between piston & cylinder to prevent gas leakages.

* They are fitted in the grooves on top portion of piston.

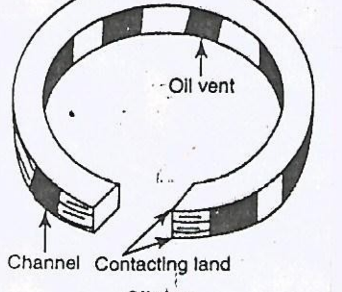
* Material - Cast iron with Silicon & manganese coated with Cadmium.

* Two types of piston rings as follows,



Compression ring

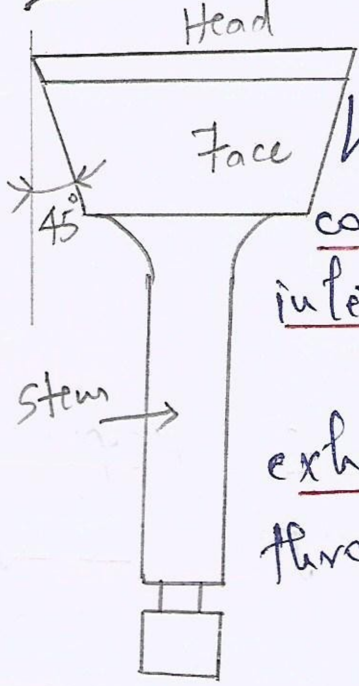
Compression ring:- Effective seal for high pressure gases inside the cylinder. Each piston has two compression rings.



Oil ring

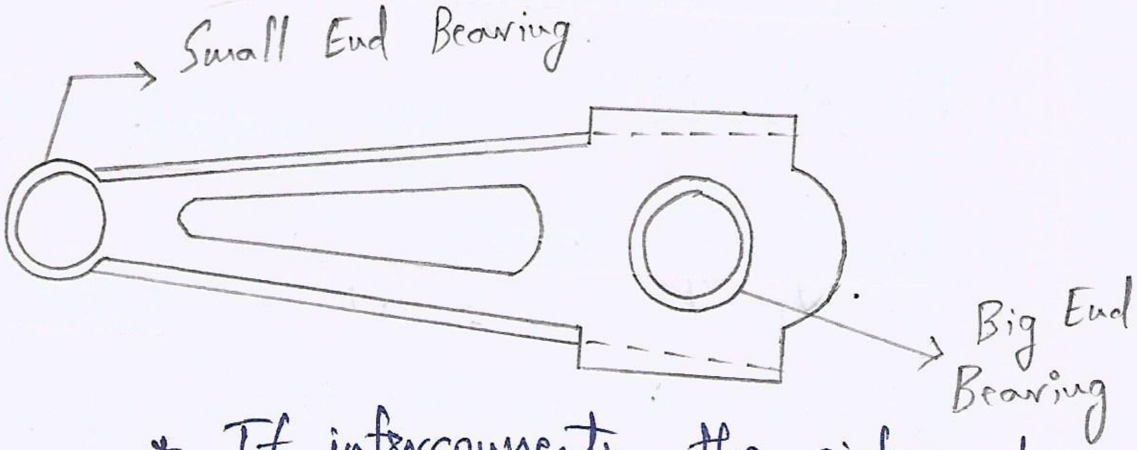
Oil ring:- Used to wipe off the excess oil from cylinder walls to the oil sump through oil vents.

e) INLET & EXHAUST VALVE :-



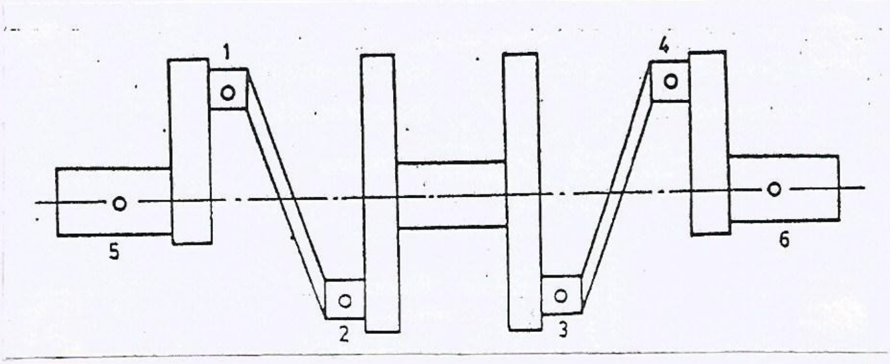
* Provided on the cylinder head for regulating the charge coming into cylinder through inlet valve.
* For discharging the exhaust products of combustion through exhaust valve.
* Material - Silicon chrome steel.

f) CONNECTING ROD :-



* It interconnects the piston & crankshaft & transmits the gas forces from piston to the crankshaft.
* Small end is connected to Gudgeon pin.
* Big end is connected to crankshaft by Crank pin.
* Material : Plain Carbon Steel.

g) CRANKSHAFT :-



* It converts reciprocating motion of piston into useful rotary motion of output shaft.

* Material - Hot billet steel, heat treated alloy steels.

h) CAMSHAFT :-

* It controls the opening & closing of two valves.

* It is driven by crankshaft through timing gears.

* Chilled cast iron, billet steel.

i) FLYWHEEL :-

* It stores energy during power stroke and releases energy during other strokes.

* It is heavy & perfectly balanced wheel usually connected to rear end of crankshaft.

* Material - Cast iron, Cast steel.

PARTS FOR PETROL ENGINE ONLY:-

* Spark plug.
* Carburettor.
* Fuel Pump

i) **Spark Plug:-** Used to initiate the combustion process at end of compression stroke by igniting compressed air/fuel mixture.

ii) **Carburettor:-** Used for atomizing & vaporizing of fuel & mixing it with air at various proportions to suit the various operating conditions of engine & this process is known as Carburetion.

iii) **Fuel Pump:-** Used to supply fuel to Carburettor.

PARTS FOR DIESEL ENGINE ONLY:-

* Fuel pump
* Fuel injector.

i) Fuel Pump:-

Used to pump the fuel from fuel tank to fuel injector at a sufficient pressure.

ii) Fuel Injector:-

Used to spray fuel in a form of very fine droplets by means of atomization.

---x---x---x---x---x---

2) WORKING OF I.C ENGINE:-

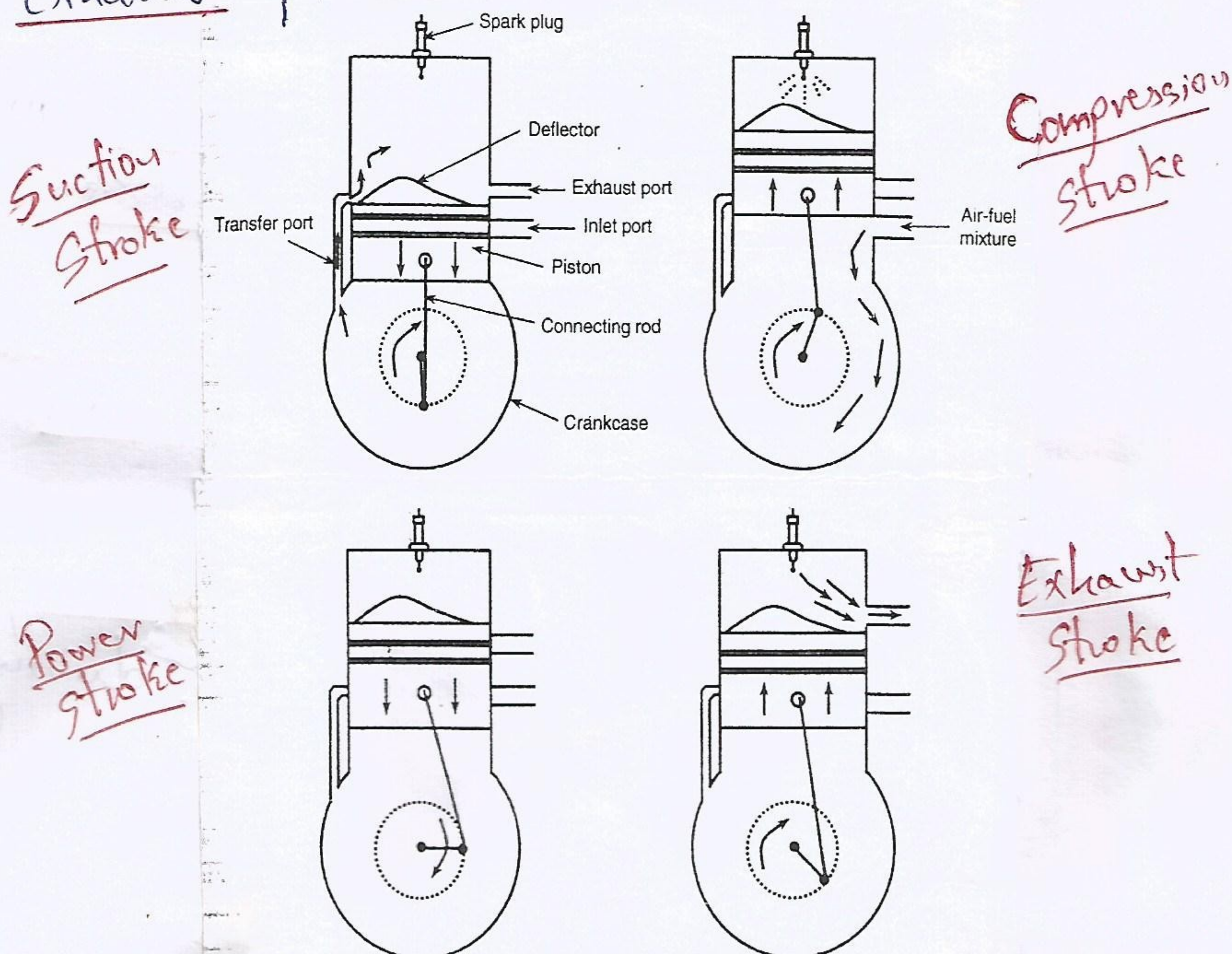
b) TWO STROKE ENGINE:-

* In 2-stroke engine, one working cycle is completed in two strokes of piston (ie, one up & down movement). or one revolution of Crankshaft.

* One working cycle comprises four processes,
  → Suction → Compression
  → Power (or) Expansion
  → Exhaust.

* First stroke - Both Suction & Compression processes.

* Second stroke - Both Power & exhaust processes.



Petrol Engine :- * Spark Ignition. (S.I)
* Only Spark plug.
* Intake - Air/fuel mixture during Suction stroke.

Diesel Engine :- * Compression Ignition
* Only Fuel injector.
* Intake - Only air during Suction stroke.

i) First Stroke:-

→ Suction & Compression Processes.

→ Piston moves upward from BDC to TDC.

→ Partially compressed air/fuel mixture enters from Crankcase into cylinder through transfer port, while piston is at BDC.

→ When piston moves upward, air in cylinder gets compressed in cylinder.

→ At end of compression stroke, ignition takes place.

→ When piston is at TDC, inlet port opens & air-fuel mixture enters into crankcase.

→ Thus suction & compression takes place simultaneously during one stroke.

ii) Second Stroke:-

→ Power (or) expansion and Exhaust processes.

→ When air-fuel mixture gets ignited, pressure & temperature of combustion products increases.

→ Gas force make piston to push downward from TDC to BDC.

→ Hence power stroke obtained.

→ When piston moves downward, the entering air-fuel mixture through transfer port pushes the exhaust gas out of exhaust valve.

→ This process is known as Scavenging.

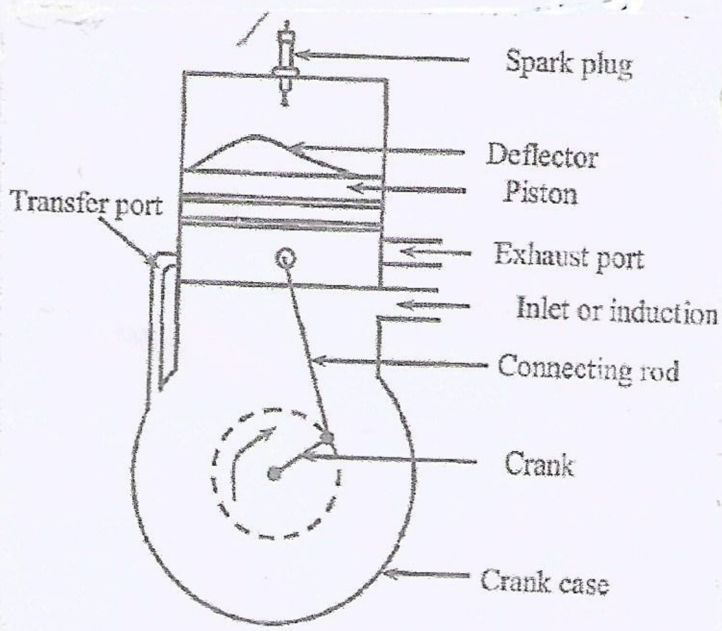


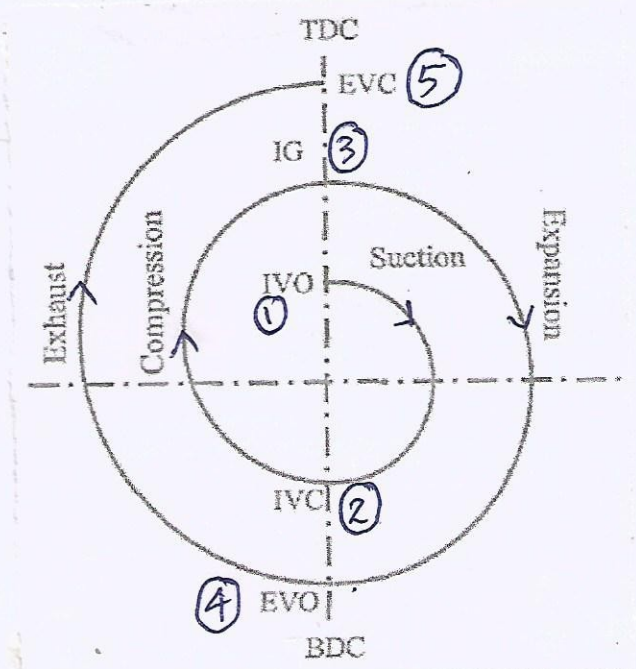
Figure 2.20 Two stroke engine

4) VALVE TIMING & PORT TIMING DIAGRAM :-

VALVE TIMING :-

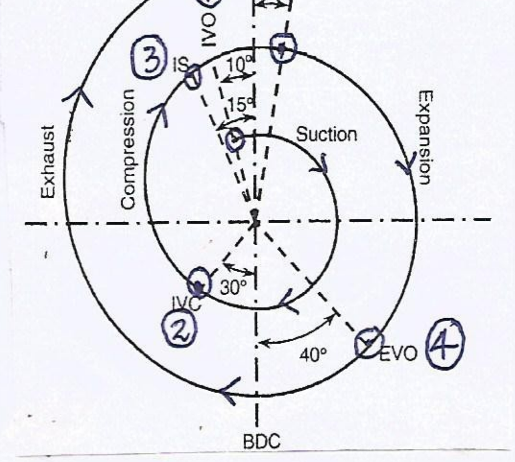
* Only 4 stroke engines (S.I & C.I)
* Exact moment at which Inlet & Exhaust valves open & close with reference to piston & crank can be shown graphically.

THEORETICAL :-



IVO - Inlet Valve Open.
IVC - Inlet Valve Close
IG - Ignition
EVO - Exhaust Valve Open
EVC - Exhaust Valve Close
TDC - Top Dead centre
BDC - Bottom Dead Centre.

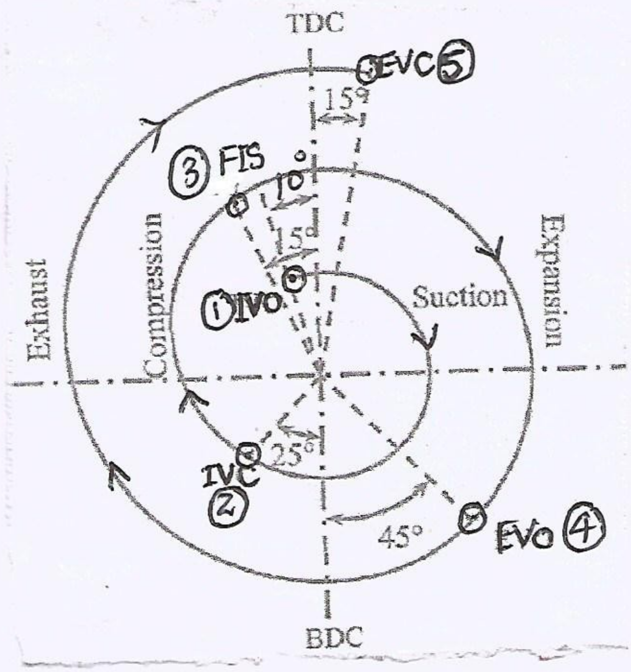
ACTUAL :- 4 stroke - Petrol S.I Engine :-



IVO - 15° before TDC.
IVC - 30° after BDC
IG - 15° before TDC.
EVO - 40° before BDC
EVC - 20° after TDC.

Valve Timing	Events during valve Timing
IVO - IVC	Air-fuel mixture sucked into cylinder
IVC - IG	Sucked air/fuel compressed.
IG	Ignition starts.
IG - EVO	Combustion takes place, power (or) expansion process occurs.
EVO - EVC	Exhaust gas flushed out.
Between 4th & 1st stroke	Both valves opens. Valve overlap period. (10°)

ACTUAL :- 4 - Stroke - Diesel - C.I Engine:-



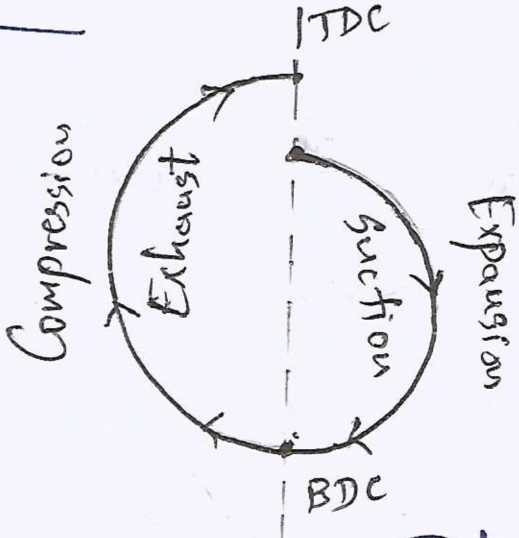
IVO - 10° before TDC.
IVC - 25° after BDC.
FIS - Fuel Injection Start
FIS - 15° before TDC.
EVO - 45° before BDC.
EVC - 15° after TDC.

* Events are same.
* Only difference is Fuel injection & Suction - only air.

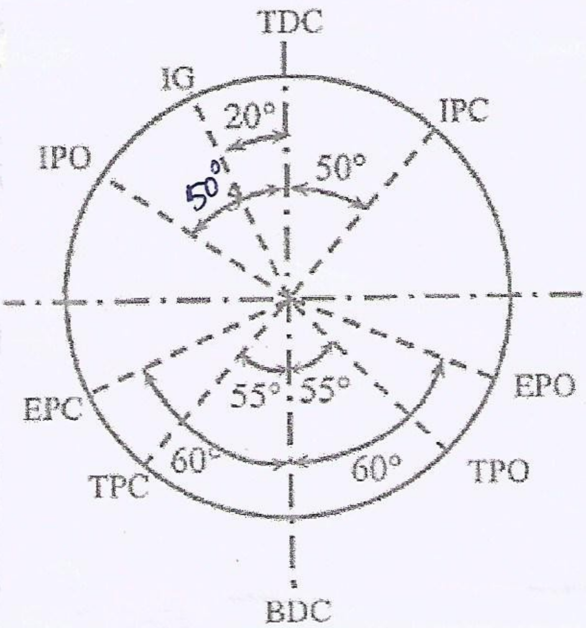
PORT TIMING :-

* Only 2 stroke engines (S.I & C.I)
* Each moment at which Inlet & Exhaust 'Ports' open & close with reference to piston & crank can be shown graphically.

THEORETICAL :-



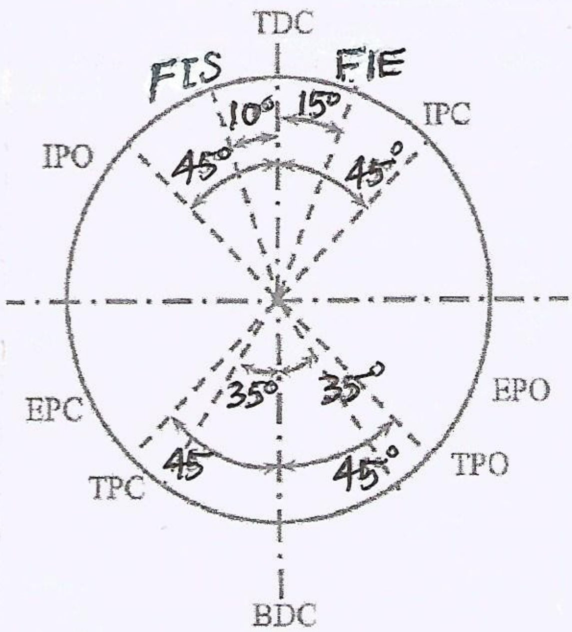
ACTUAL :- 2 Stroke - Petrol - S.I Engine :-



IPO ⇒ Inlet Port Open
IPC ⇒ Inlet Port Close
IG ⇒ Ignition Start
EPO ⇒ Exhaust Port Open
TPO ⇒ Transfer Port Open
TPC ⇒ Transfer Port Close
EPC ⇒ Exhaust Port Close
TDC ⇒ Top Dead Center
BDC ⇒ Bottom Dead Center.

S. No.	Port valve timing	Events during port timing
1.	IPO - IPC	Air-fuel mixture is sucked into the crankcase.
2.	IPC - TPO	Air-fuel mixture is partially compressed in the crankcase which is known as *crankcase compression.*
3.	TPO - TPC	Partially compressed air-fuel mixture is transferred into the engine cylinder.
4.	TPC - IS	Air-fuel mixture is compressed in the cylinder.
5.	IS	Air-fuel mixture is ignited by the spark plug and burns.
6.	IS - EPO	The burnt gases expand for doing work on the piston.
7.	EPO - EPC	Burnt gases are pushed out of the engine cylinder.

ACTUAL :- 2 Stroke - Diesel - C.I Engine :-



FIS - Fuel Injection Start
FIE - Fuel Injection End

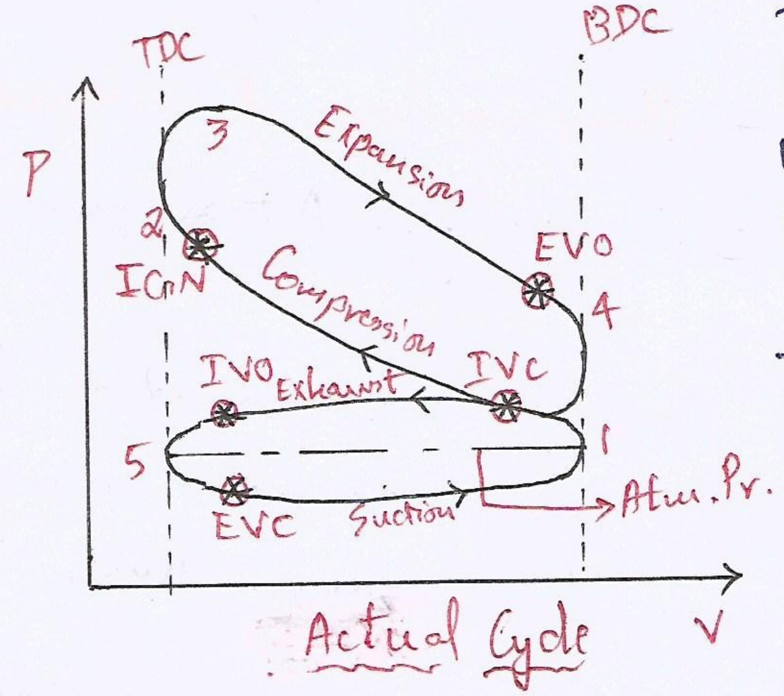
S. No.	Port timing	Events during port timing
1.	IPO - IPC	Air is sucked into the crankcase through plate valve.
2.	IPC - TPO	Air is compressed partially in the crankcase. (Crankcase compression).
3.	TPO - TPC	Partially compressed air is transferred to the engine cylinder through transfer port.
4.	TPC - FIS	Air is compressed in the cylinder. Both pressure and temperature of the air increase.
5.	FIS - FIE	Fuel is injected into the hot compressed air. Fuel mixes with hot air and burns.
6.	FIE - EPO	The burnt gases expand and move the piston to do work.
7.	EPO - EPC	Burnt gases escape to the atmosphere through the exhaust port.

5) P-V DIAGRAMS :-

P-V Diagrams - Actual vs Theoretical. (Ideal)

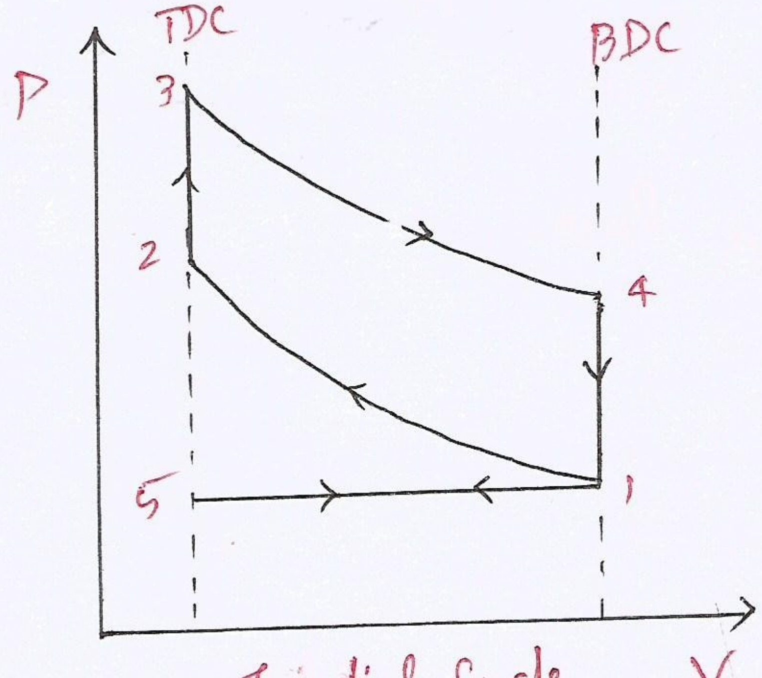
- 4 stroke — Petrol (S.I) engine / Diesel (C.I) engine.
- 2 Stroke

CYCLES FOR 4 STROKE S.I (PETROL) ENGINE :-



Actual Cycle

TDC - Top Dead Centre
BDC - Bottom Dead Centre
EVO - Exhaust Valve Open
EVC - Exhaust Valve Close
IVO - Inlet Valve Open
IVC - Inlet Valve Close
IGN - Ignition Starts



Theoretical Cycle

→ Line 5-1 represents Suction stroke.

→ Suction is possible only if pressure inside cylinder is lower than Atm. Pr.

→ Line 1-5 - Exhaust stroke.

→ Burnt gases are pushed out only if pressure inside cylinder is above Atm. Pr.

→ Area under (1-5 & 5-1) process → Small loop - Pumping loss of engine.

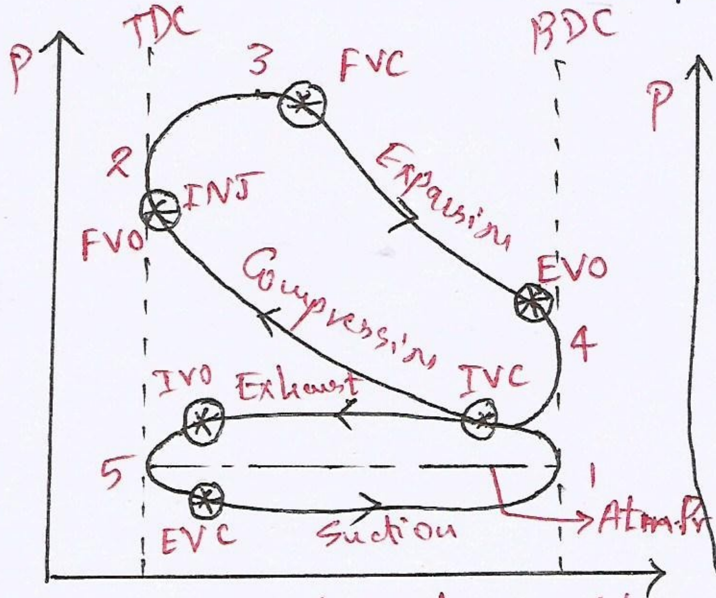
→ (*) Practically - Actual pressure rise is about half of theoretical value.

→ Corners are rounded bcoz both inlet & exhaust valve do not open (or) close suddenly, it may take some time.

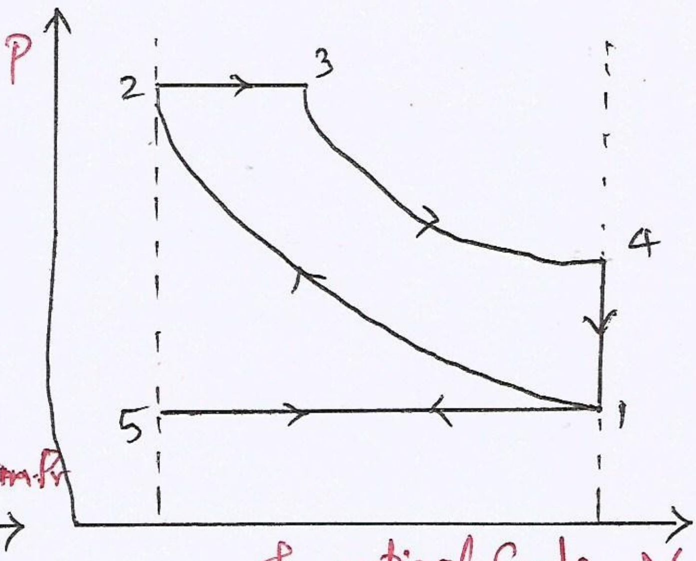
→ Theoretically, compression & expansion are followed adiabatically. But in actual cycle it is not so. Because of heat loss & pressure loss.

CYCLES FOR 4 STROKE C.I (DIESEL) ENGINE :-

INJ - Injection Starts.
FVC - Fuel Valve Close.

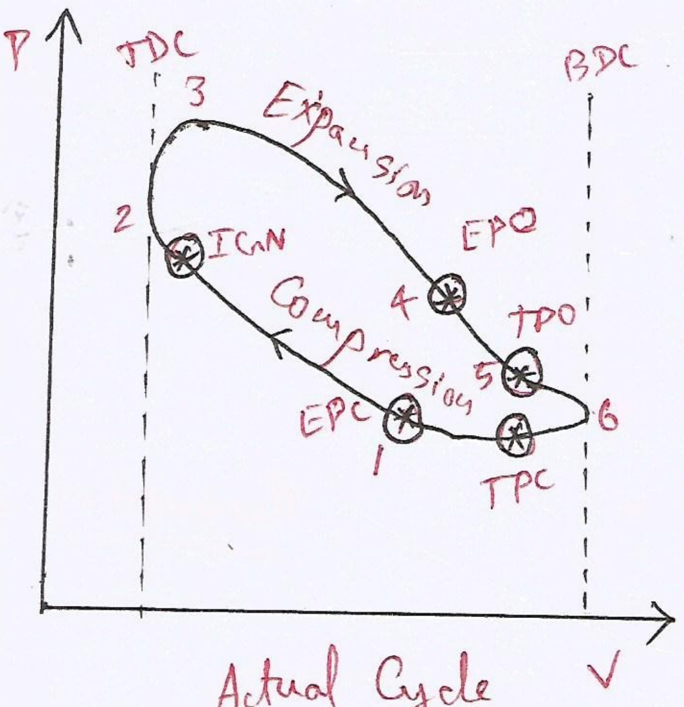


Actual Cycle

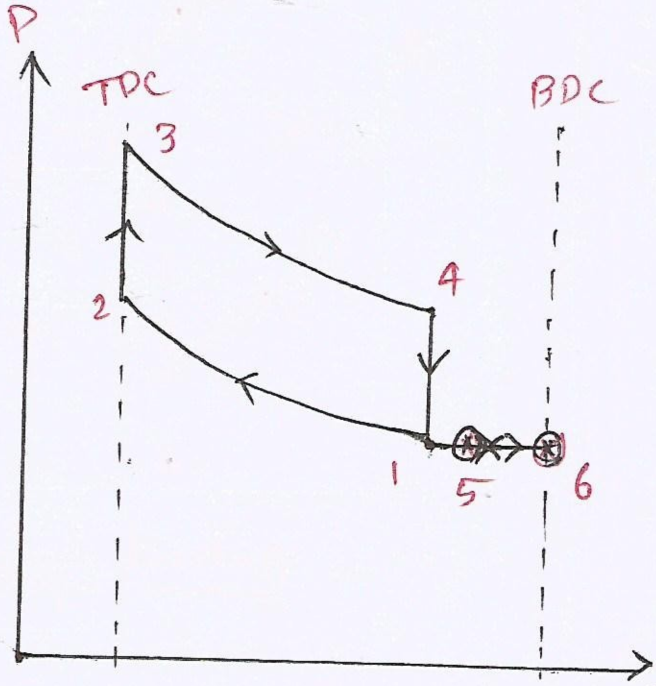


Theoretical Cycle

CYCLES FOR 2 STROKE S.I (PETROL) ENGINE :-



Actual Cycle



Theoretical Cycle

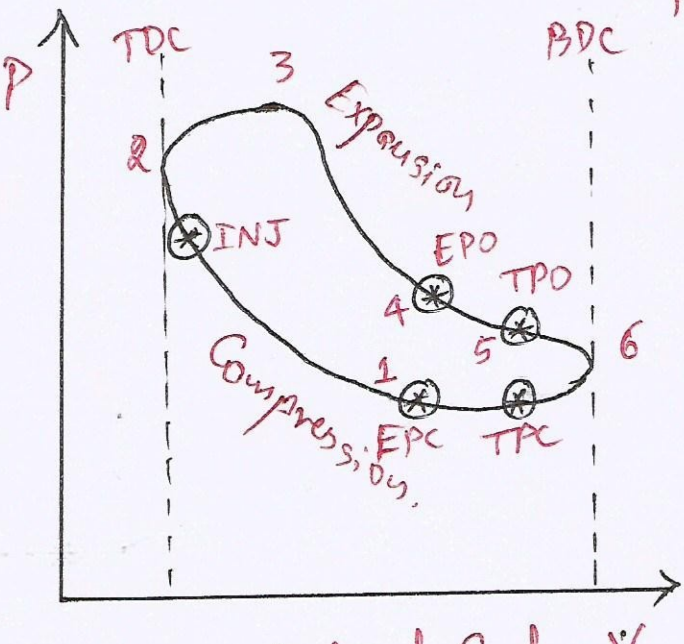
EPO - Exhaust Port Open
EPC - Exhaust Port Close
TPO - Transfer Port Open
TPC - Transfer Port Close
IGN - Ignition Starts.

→ Suction Stroke - TPO to TPC.

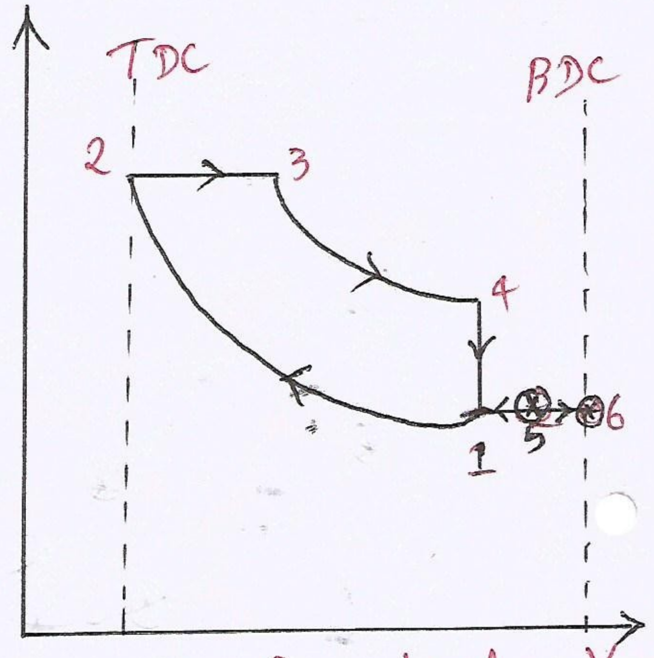
→ During half of suction stroke - Also Exhaust port opened - Now volume of air fuel mixture entered into cylinder during piston movement from TDC to BDC. (1-5-6)

→ During second half - BDC to TDC - Air fuel mixture compressed & gas (burnt gas) pushed out. (6-5-1)

CYCLES FOR 2 STROKE C.I (DIESEL) ENGINE



Actual Cycle



Theoretical Cycle

INJ - Injection Starts.

———x——— x ——— x ———

6) Comparison of Two Stroke & Four Stroke S.I & C.I Engines - Geometric, Operation & Performance

Aspects	4-Stroke	2-Stroke
Completion of Cycle	For every two revolutions, one power stroke (cycle) is produced.	For every one revolution, one power stroke (cycle) is produced.
Power production	For same size engine - power produced - small.	For same size engine - More power. (Theoretically - Twice Actually - 1.75 times)
Space	For same power - more space needed.	For same power - less space needed
Valves/Ports	Valves are required	Ports are required.
Weight of flywheel	Heavier flywheel, because of non-uniform torque of crankshaft.	Lighter flywheel, because of uniform torque of crankshaft.
Fuel Consumption	Fuel cannot escape with exhaust gas. Scavenging is better. So less fuel Consume	Fuel may escape with exhaust gas. Scavenging is poor. So high fuel consume.
Cooling & Lubrication requirement	Less	More.

Wear & Tear	Less rate	High rate
Starting of engine	Difficult	Easy.
Noise	Less, as exhaust gases are released in seperate stroke.	More noise, due to sudden release of exhaust gases.
Initial Cost	High	Low.
Volumetric Efficiency	More, due to long time available for suction	Less, due to less time of suction.
Thermal Efficiency	High	Low.
Application	Heavy vehicles, bus, lorries, truck, car, etc.,	Light vehicles like, scooters, motor cycles, etc.,

PETROL ENGINE (S.I) Vs DIESEL ENGINE (C.I)

Aspects	Petrol Engine (S.I)	Diesel Engine (C.I)
Basic Cycle	otto Cycle (or) Constant Volume heat addition Cycle	Diesel cycle (or) Constant Pressure heat addition.
Fuel	Petrol (Gasoline)	Diesel oil.
Intake	Petrol and air is admitted into cylinder during Suction stroke.	Air alone is admitted into cylinder during suction stroke.
Fuel admission	Through carburettor	Through fuel injector.
Ignition	Spark ignition	Compression ignition
Compression ratio	6 to 10	14 to 22.
Engine Speed	High due to light weight (2000 to 5000 rpm)	Due to heavy weight, low Speed - 400 rpm Medium Speed - 1200 rpm
Efficiency	Low, due to low compression ratio.	High, due to high compression ratio.
Fuel Consumption	More	Less
Fuel Cost	More	Less.

Engine Cost	Less	High.
Vibration + noise	Very less	More.
Engine life	Less than 60,000 kms	More than 1,50,000 kms.
Space	For same power, less space.	For same power, more space.
Application	Light vehicles, cars, motor cycles, etc.,	Heavy vehicles, truck, bus, etc.,

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FACTS:-

Petrol in diesel engine :-

* Petrol has higher auto ignition temperature.
* It won't burn in diesel engine.
* Engine won't run.

Diesel in Petrol engine :-

* Diesel burns with more power
* Engine run, but damage partly (or) completely.

---

7) Desirable Properties & Qualities of Fuel:-

* Fuel is a substance, which burnt while contacting & reacting with oxygen (or) air produces heat.
* Fuel comprises general combustible elements : carbon, hydrogen, sulphur, etc.,
* In combustion process, chemical energy converted into heat energy.

Classification of fuel:-

→ According to physical state exist in nature,

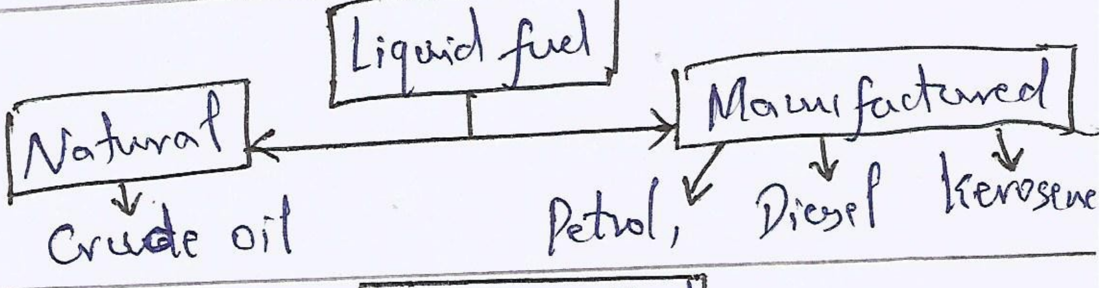
(1) Solid (2) liquid (3) Gaseous.

→ According to the mode of production,

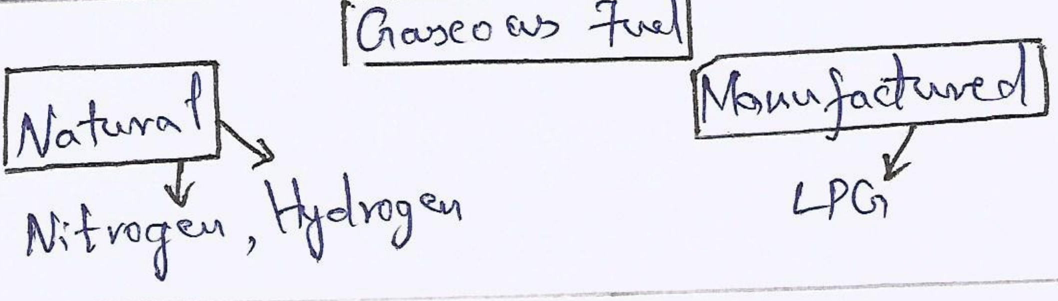
(1) Natural (2) Manufactured.

(1)

(2)



(3)



FUEL PROPERTIES :-

i) Viscosity :-

* It is the resistance offered by fuel ~~to~~ its own flow.

* Visosity should not be higher, it could cause more vibration of engine.

ii) Pour Point :-

* Pour point (or) freezing point of fuel must be less than the lowest climate temperature of atmosphere.

iii) Sulphur content :-

* During combustion of fuel, sulphur in fuel becomes sulphuric acid, which causes corrosion of engine parts.

* Sulphur content should be minimum.

iv) Volatility :-

* It is the ability to evaporate. If fuel evaporates in lower temperature, then it has high volatility.

* Fuel should have low volatity property.

vi) Calorific value :-

* It is defined as the amount of heat liberated during combustion of 1 kg (or) 1 m^3 of fuel.

* Fuel should have higher Calorific value (HCV).

CV of Petrol = 45.8 MJ/kg.

CV of Diesel = 45.5 MJ/kg.

QUALITIES OF FUEL :-

i) Petrol (or) S.I Engine Fuel :-

* Volatility should be low.

* Petrol should have good vapour lock characteristic.

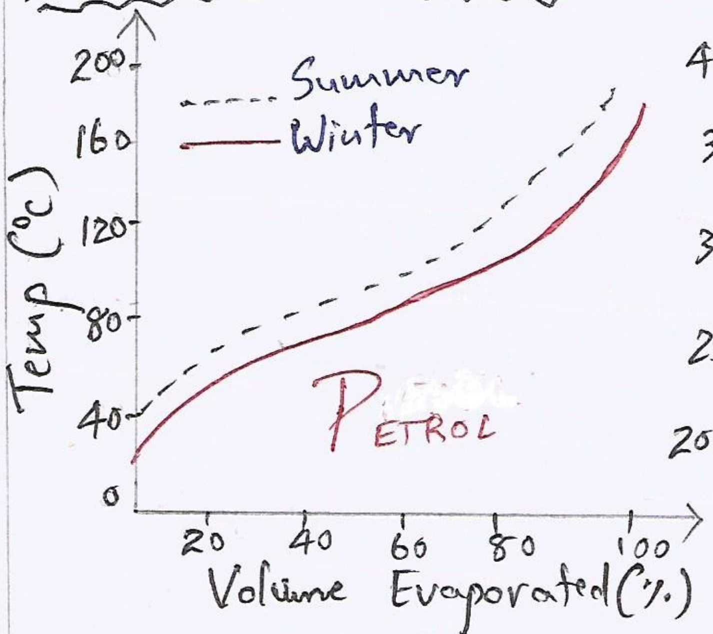
* Petrol should have higher antiknock property.

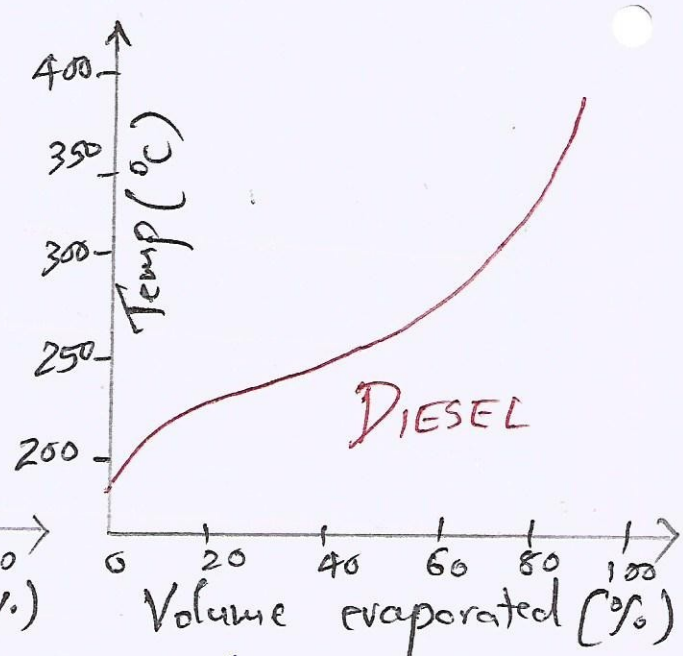
* Should have lower gum deposits and sulphur content.

* Starting & Warm up - A certain part of gasoline (or) petrol should vaporize at room temperature for easy starting.

* Low distillation temperature is preferable for engine operating condition, inorder to obtain good vaporisation of petrol.

Distillation Curves:-





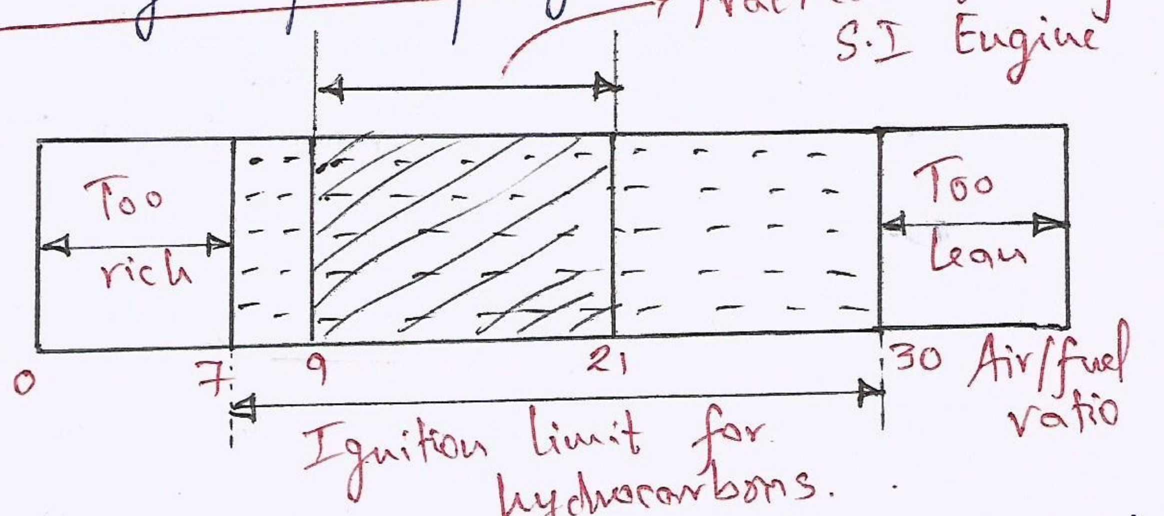
ii) Diesel (or) C.I Engine Fuel:-

* Should have sufficient volatility to produce good mixing of combustion.
* Good antiknocking character.
* Easy starting ability.
* Less smoking & odour character.
* Should have low viscosity.
* Should have less sulphur content to avoid corrosion.
* Should have high flash point and fire point.

8) COMBUSTION IN S.I ENGINE:-

→ Combustion may be defined as relatively rapid chemical combination of Carbon & hydrogen in fuel reacting with oxygen in air resulting in liberation of energy in the form of heat.

→ In S.I engine, carburettor supplies a combustible mixture of petrol & air, ignited by spark plug.



→ Ignition of charge is only possible within certain limits of air-fuel ratio.

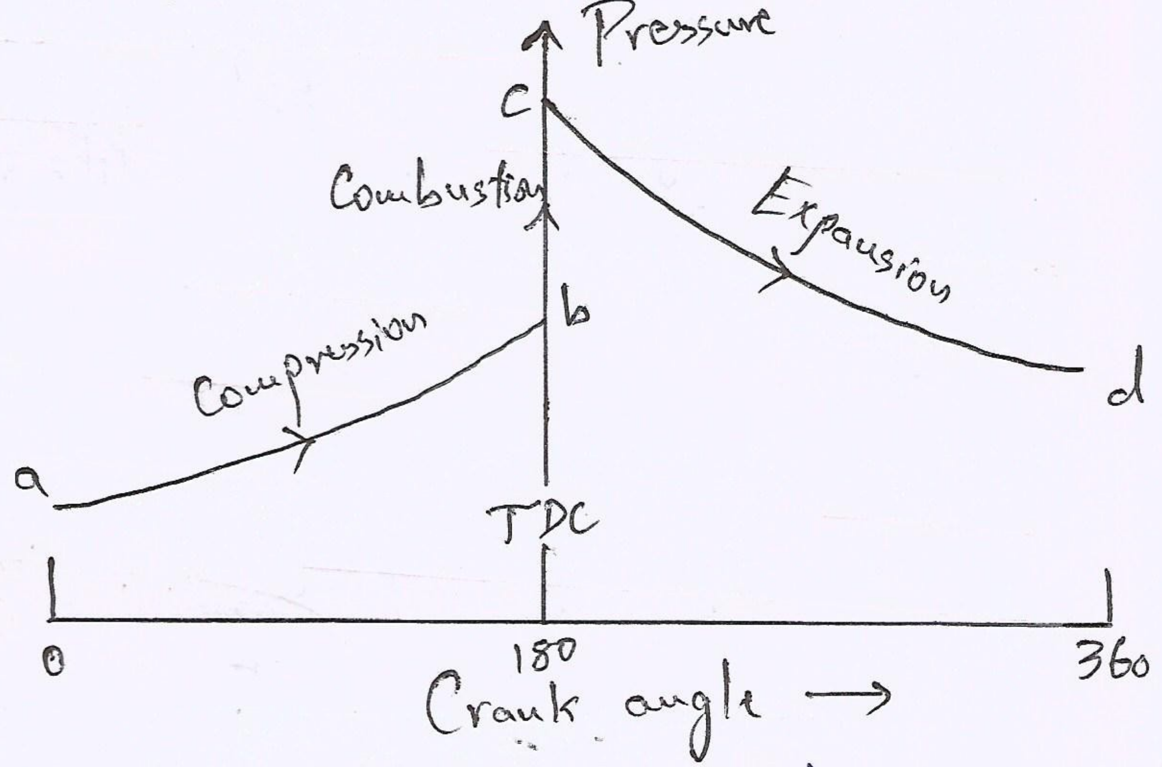
→ Upper & lower limits of ignition depends on temperature & mixture ratio.

→ Stoichiometric (relationship between reactants and products) ratio for hydrocarbon is 1:15.

→ Normal Combustion & Abnormal combustion (Knocking).

Normal Combustion:-

* Theoretical diagram of pressure - crank angle for ideal combustion cycle, (P– θ) Curve



* Actual combustion process takes place as three broad regions,

a) Ignition & flame development.

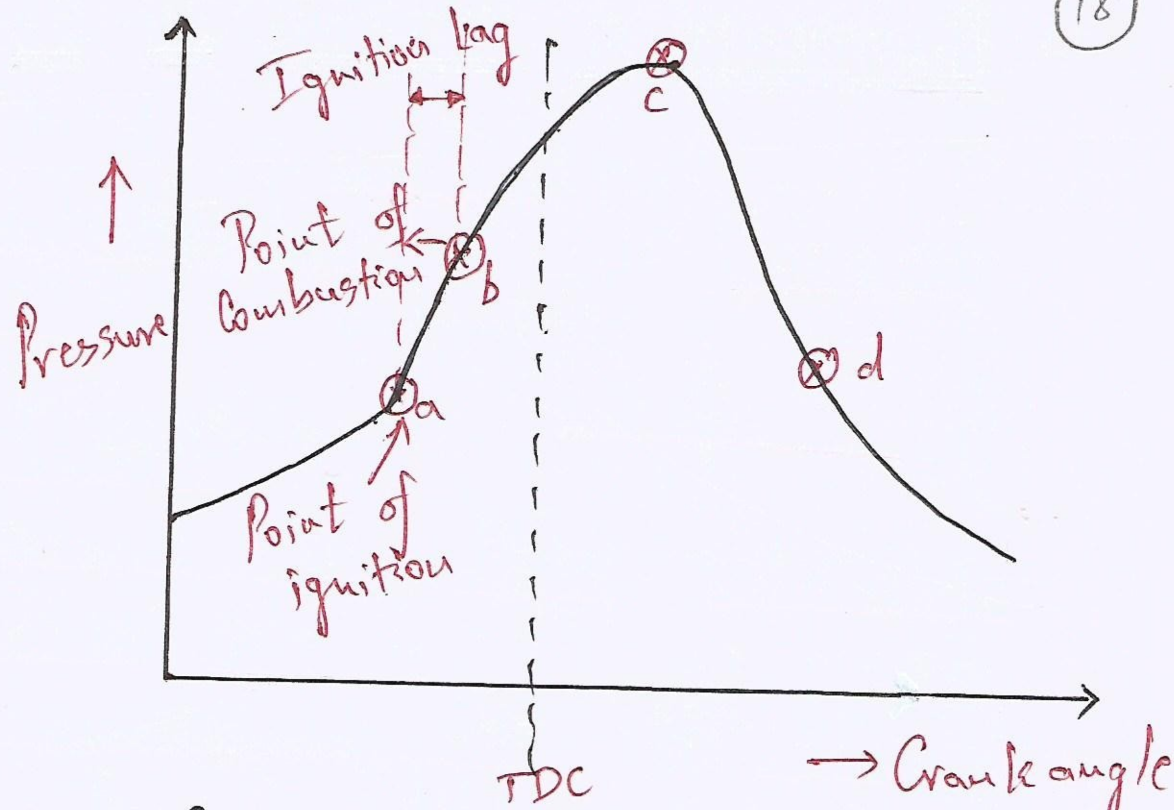
b) Flame propagation.

c) Flame termination.

a) Ignition Lag stage:-

* Time interval between spark ignition start & notable rise in pressure due to combustion is called Ignition Lag Time (a – b).

* At this time, flame starts to develop.



b) Flame Propagation Stage:-

* Once the flame is formed at 'b', it should be self sustained & able to propagate.

* After point 'b', upto 30 to 35 degree crank angle, flame propagates upto point 'c'.

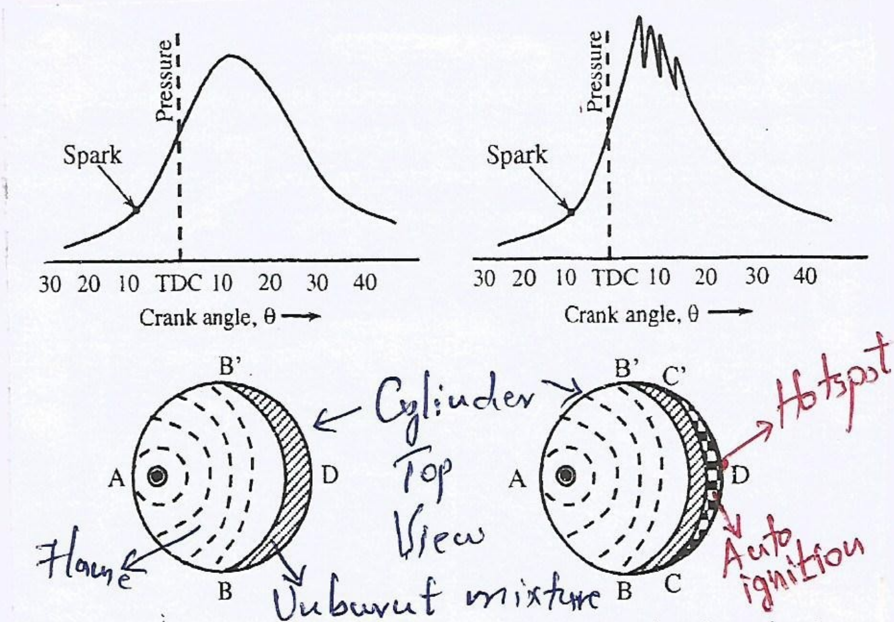
c) Flame Termination:-

* At point 'c', the flame terminates.

* When rich mixture is supplied, flame will not stop at 'c', it will continue to burn. This is known as 'After Burning'

9) PHENOMENON OF KNOCKING IN SI ENGINE:-

* Knocking is also known as detonation. (or) abnormal combustion.
* Knocking is due to pre-ignition (or) auto ignition.
* If the temperature of fuel/air mixture raised due to hotspot regions in engine, the mixture will self-ignite without the aid of spark plug.
* This is called Self-ignition (or) Auto-ignition.



(a) Normal combustion (b) Detonation or knock combustion

Normal Combustion:-

* Fuel/air mixture ignites at point 'A', flame develops & propagates towards BB'.

* Propagated flame BB', compresses the unburnt mixture in the area BB'D.

* Then it gets burned as complete combustion.

Detonation (or) Knocking:-

* During abnormal combustion, the cylinder wall temperature is higher which acts as 'hotspot', at 'D'.

* Ignition starts at 'A', then flame propagates & travel towards BB'.

* Unburnt mixture behind BB' compressed, which get autoignited at 'D' due to higher temperature.

* This pre-ignition is called as detonation, which creates high pressure wave & causes vibration of engine parts.

Factors influencing knocking:-

→ Temperature factor

* Higher Compression ratio.
* Supercharging.
* Temp of cylinder & its wall is higher.

→ **Density Factor**

* Mass of charge – high
* Inlet temp of mixture – high
* Retarding spark timing.

→ **Time Factor**

* Turbulence. – low
* Engine size & speed – low
* Spark plug location.

→ **Composition Factor.**

* Air-fuel ratio – Low
* Octane value. – Low
* Molecular structure.

Reduction (or) Control of knocking :-

* Decrease compression ratio.
* Decrease mass of charge.
* Decrease inlet temp. of charge.
* Provide coolant to cylinder.
* Increase turbulence.
* Increase engine speed.
* Decrease distance of flame travel.
* Using rich air-fuel mixture.

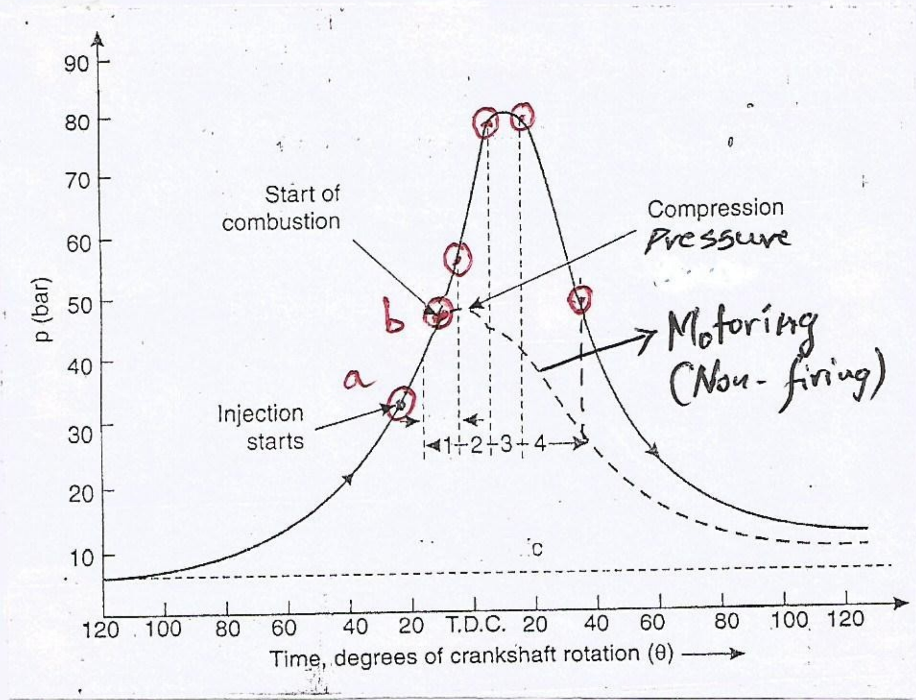
——x——x——x——

10) # COMBUSTION IN C.I ENGINES (or) DIESEL :-

* In C.I engine, Air-fuel mixture is not homogenous & fuel remains in liquid phase.

* Hence quantity of air supplied is 50 to 70% higher than stoichiometric mixture.

Four Stages of Combustion :-



① Ignition Delay Period / Pre-flame combustion

② Uncontrolled combustion.

③ Controlled combustion.

④ After burning.

a) Ignition Delay Period / Pre-flame combustion:-

* Fuel does not ignite immediately upon injection.

* There is a finite period of lag between injection & burning time. This is known as ignition delay period.

* In figure, gap between a-b is ignition delay period.

* Delay period can be divided into physical delay and chemical delay.

b) Uncontrolled combustion / Rapid combustion:-

* In this phase, rapid rise in pressure occurs.

* During delay period, a small amount of fuel accumulated in the cylinder, which burns rapidly causing a steep rise in pressure.

* Period of rapid combustion is measured from the 'start of combustion' to the maximum pressure on the diagram.

* Rate of heat-release is maximum during this phase.

c) Controlled Combustion:-

* Rapid combustion period is followed by the third stage, the controlled combustion.

* Temp & pressure in second stage are higher, that fuel droplets injected burn almost as soon as entering cylinder.

* Further pressure rise could be controlled by injection rate.

* Period of controlled combustion assumed to end at maximum cycle temperature.

d) After-Burning:-

* Combustion does not stop after completion of injection process.

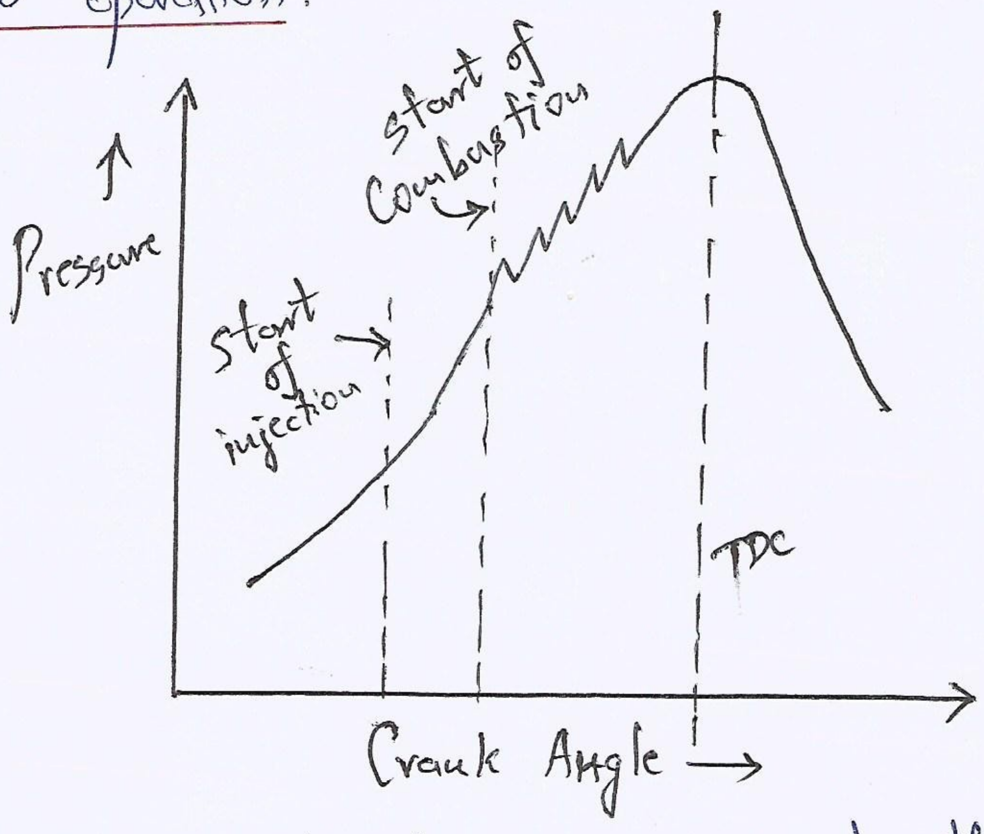
* Unburnt and partially burnt fuel particles left in combustion chamber start burning as soon as they contact with oxygen.

* This process continues for certain duration called after-burning period.

* This burning may continue in expansion stroke up to 70 to 80% crank travel from TDC.

PHENOMENA OF KNOCKING IN C.I ENGINES

* In C.I engine, knocking is related to delay period.
* When delay period is longer, accumulation of fuel droplets causes rapid pressure rise due to ignition.
* It results in jamming of forces against piston that leads to rough engine operation.



* Knocking occurs at the begining of combustion.
* At longer ignition delay period, accumulated fuel causes pressure rise & leads to violent gas vibration, which is evidenced by audible knock.

* The phenomenon of knocking is similar to S.I engine. Only difference is,

In S.I engine - knocking occurs near END of combustion.

In C.I engine - knocking occurs near START of combustion.

Factors Influencing knocking:-

→ Compression ratio → Engine Speed
→ Injection Timing → Fuel quality.
→ Intake temperature & pressure.

Methods of Controlling knocking:-

* Using better fuel having higher Cetane Number (CN), which has lower delay period.
* Controlling rate of fuel supply.
* By adding chemicals called dopes, which increase CN.
* Dopes - Ethyl nitrate.
  Amyle nitrate.
* Increasing swirl

———x———x———x———

COMPARISON OF KNOCK IN S.I & C.I ENGINES:-

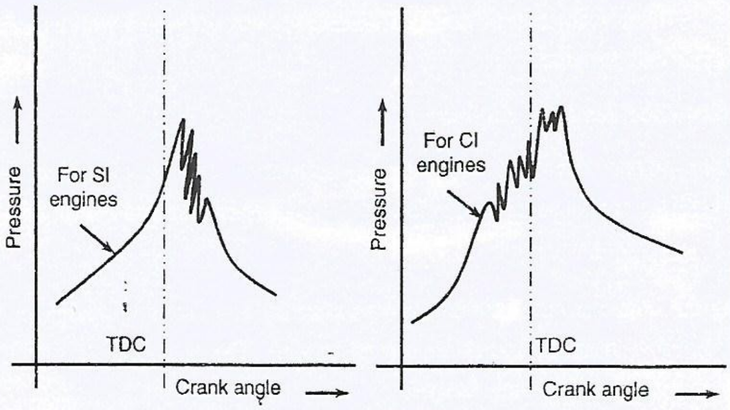


Figure 2.52 Knocking in SI and CI engines

S.I Engine	C.I Engine.
* Knocking occurs at end of combustion.	At start of combustion.
* Knocking takes place in homogenous mixture, therefore rate of pressure rise is higher.	Mixture - non homogenous. So rate of pressure rise is lower.
* Pre ignition occurs.	Only air is compressed, hence no pre-ignition.
* Fuel should have longer delay period to avoid knocking.	* Fuel should have shorter delay period to avoid knocking.
* Difficult to distinguish between knocking & non-knocking condition.	Easy to distinguish.

12) **AIR - FUEL RATIO :-**

a) Stochiometric Ratio (or) theoretical ratio (or) Minimum Quantity of Air :-

$$\text{Stochiometric ratio} = \frac{\text{Amount of air required for complete Combustion}}{\text{1 kg of fuel.}}$$

b) Actual Air-fuel ratio : of Excess Air :-

$$\text{Percentage Excess Air} = \frac{(\text{Actual Air-Fuel ratio}) - (\text{Stochiometric Air-Fuel ratio})}{\text{Stochiometric Air-Fuel ratio}}$$

c) Equivalence Ratio :-

$$\text{Equivalence Ratio} = \frac{\text{Actual Air-Fuel ratio}}{\text{Stochiometric Air-Fuel ratio}}$$

d) Time Loss Factor :-

It is defined as loss due to time required for mixing of air & fuel for combustion.

e) Determination of air supplied per kg of fuel :-

Mass of air supplied, $m_a = \frac{1}{33}\left[\frac{C \times N}{C_1 + C_2}\right]$

C - % of Carbon in fuel, N - % of Nitrogen

C_1 - % of Carbon Monoxide, C_2 - % of CO_2.

f) Flue Gas Analysis:-

* Exhaust gas from combustion process is known as Flue gas (or) Stack gas.

* Flue gas analysis used for calculating both efficiency of combustion & emission levels.

* Measures CO, CO_2, Nox, Oxygen Nitrogen, Hydrocarbon, Sulphur dioxide.

g) Combustion Equation for Hydrocarbon Fuel:-

* Hydrocarbon fuel represented by C_nH_{2n+2} (or) C_aH_b.

* Combustion Equation is,

$$C_aH_b + \left(\frac{3a+1}{2}\right) O_2 = aCO_2 + \frac{b}{2} H_2O$$

PROBLEMS ON AIR-FUEL RATIO:-

1) Write down combustion reaction equation for following fuels, a) Ethane, b) Methane, c) Propane, d) Butane, e) Heptane, f) Octane.

Soln:-

Generalised Combustion Equation,

$$C_aH_b + \left(\frac{3a+1}{2}\right)O_2 = aCO_2 + \frac{b}{2}H_2O.$$

a) Ethane - C_2H_6.

$$C_2H_6 + \left(\frac{(3\times2)+1}{2}\right)O_2 = 2CO_2 + \frac{6}{2}H_2O.$$

$$C_2H_6 + \frac{7}{2}O_2 = 2CO_2 + 3H_2O.$$

b) Methane - C_1H_4

$$C_1H_4 + \left(\frac{(3\times1)+1}{2}\right)O_2 = 1CO_2 + \frac{4}{2}H_2O.$$

$$CH_4 + 2O_2 = CO_2 + 2H_2O.$$

c) Propane - C_3H_8.

$$C_3H_8 + \left(\frac{(3\times3)+1}{2}\right)O_2 = 3CO_2 + \frac{8}{2}H_2O.$$

$$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O.$$

d) Butane - C_4H_{10}

$$C_4H_{10} + \left(\frac{(3\times4)+1}{2}\right)O_2 = 4CO_2 + \frac{10}{2}H_2O$$

$$C_4H_{10} + \frac{13}{2}O_2 = 4CO_2 + 5H_2O.$$

e) Heptane - C_7H_{16}

$$C_7H_{16} + \left(\frac{(3\times7)+1}{2}\right)O_2 = 7CO_2 + \frac{16}{2}H_2O$$

$$C_7H_{16} + \frac{22}{2}O_2 = 7CO_2 + 8H_2O.$$

f) Octane - C_8H_{18}

$$C_8H_{18} + \left(\frac{(3\times8)+1}{2}\right)O_2 = 8CO_2 + \frac{18}{2}H_2O$$

$$C_8H_{18} + \frac{25}{2}O_2 = 8CO_2 + 9H_2O.$$

---

2) Volumetric Analysis of flue gas determined by Orsat Apparatus given below,
$CO_2 = 10\%$, $CO = 2\%$, $O_2 = 10\%$, $N_2 =$ rest.
Convert same analysis into mass analysis.

Soln:-

$$\%\text{ of } N_2 = 100 - (\%\ CO_2 + CO + O_2)$$

$$= 100 - (10 + 2 + 10)$$

$$N_2 = 78\%$$

Constituent	% by Volume (a)	Molecular Weight (b)	Proportional Mass $c = a \times b$	% by mass $d = \frac{c}{\Sigma c} \times 100$
CO_2	10	44	440	14.67
CO	2	28	56	1.87
O_2	10	32	320	10.67
N_2	78	28	2184	72.8
			$\Sigma C = 3000$	

3) Calculate stochiometric (or) theoretical Air-Fuel (A/F) ratio for complete combustion of Ethane.

Soln:-

Combustion Equation for ethane - C_2H_6

$$C_2H_6 + \left(\frac{(3\times 2)+1}{2}\right) O_2 = 2CO_2 + \frac{6}{2} H_2O.$$

$$C_2H_6 + \frac{7}{2} O_2 = 2CO_2 + 3H_2O.$$

By applying molecular weight,

For $2C_2H_6 + 7O_2 = 4CO_2 + 6H_2O$.

$2C_2H_6 = 2[(2\times 12) + (6\times 1)] = 60$ kg

$7O_2 = 7(2\times 16) = 224$ kg.

It means,

60 kg of C_2H_6 requires 224 kg of O_2 for complete combustion.

Stochiometric A/F ratio $= \frac{224}{60}$

Stochiometric A/F ratio $= 3.73:1$ by volume basis.

For mass basis,

% of O_2 in air = 23% by mass.

$\therefore$ A/F ratio $= 3.73 \times \frac{100}{23}$

Mass Basis, A/F ratio $= 16.22:1$

---

4) Petrol used in engine is approximated to both methane and ethane. Calculate theoretical A/F ratio. If 30% excess air is supplied, find actual A/F ratio.

Solu:-

Methane - CH_4, Ethane - C_2H_6.

$$(CH_4 + C_2H_6) + \left[\frac{[(3\times1)+1] + [(3\times2)+1]}{2}\right] O_2 = (1+2)CO_2 + (4+6)H_2O$$

$$2(CH_4 + C_2H_6) + 11\, O_2 = 6\, CO_2 + 20\, H_2O.$$

By applying molecular weight,

$$2(CH_4 + C_2H_6) = 2([12 + (4 \times 1)] + [(2 \times 12) + (6 \times 1)])$$

$$= \quad kg$$

$$11\ O_2 = 11(2 \times 16) = 352\ kg.$$

92 kg of $(CH_4 + C_2H_6)$ requires 352 kg of O_2 for complete combustion.

$$\text{Stochiometric A/F ratio} = \frac{352}{92} = 3.826 : 1$$

$$\text{By mass basis, A/F ratio} = 3.826 \times \frac{100}{23}$$

$$= 16.635 : 1.$$

$$\%\ \text{Excess air} = \frac{\text{Actual A/F} - \text{Stochiometric A/F}}{\text{Stochiometric A/F}}$$

$$0.3 = \frac{\text{Actual A/F} - 16.635}{16.635}$$

$$\text{Actual A/F ratio} = 21.63 : 1$$

---x---x---x---

13) LEAN & RICH MIXTURES:-

a) Rich Mixture:-

→ Air-Fuel mixture with high concentration of fuel than standard mixture is known as Rich mixture.

→ Stochiometric A/F ratio = 15 : 1

→ Rich mixture, A/F ratio = 13 : 1

→ Rich mixture preferred for,

* When engine is under load.
* To use all oxygen in cylinder.
* For too much gasoline.
* Cold weather, for easy starting.

→ Rich burn engine may generate more power but efficiency is less.

b) Lean Mixture:-

→ Air-Fuel mixture with high concentration of air is known as lean mixture.

→ A/F ratio may be as lean as 65 : 1 [by mass).

→ Excess air in lean burn engine - emit less pollutants (hydrocarbons)

→ It reduce throttling losses.

→ Used for higher compression ratio engines.

→ Lean burn engine result in jerking & damaging.

→ Main drawback is higher NO_x emission due to higher oxygen.

→ Need for catalytic converter to reduce NO_x.

UNIT- IV.

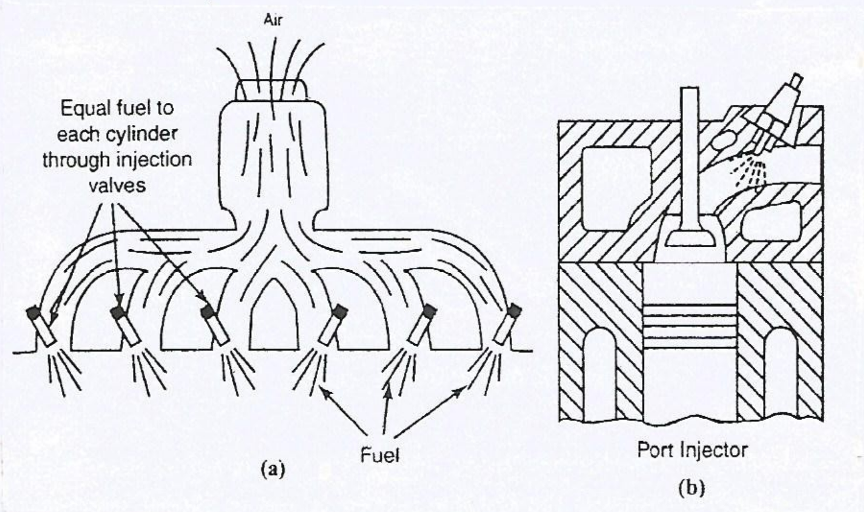
INTERNAL COMBUSTION ENGINE PERFORMANCE AND SYSTEMS

SYLLABUS:-

Performance parameters and calculations. Morse and Heat Balance tests. Multipoint Fuel injection system and Common rail direct injection systems. Ignition systems - Magneto, Battery & Electronic. Lubrication & Cooling systems. Concepts of Supercharging & Turbo-charging - Emission Norms.

1) # MULTIPOINT FUEL INJECTION SYSTEM (MPFI) ①

* Used for S.I Engine.
* Also called as Port Injection System.
* In this MPFI, there is an injection valve for each cylinders to spray fuel in intake manifold.
* Main advantage is, there is more time for mixing air & petrol.



* MPFI system has three major components as follows,
  → Air intake system.
  → Fuel delivery system.
  → Electronic control system.

Air intake system:-

* Air is filtered by air cleaner and passes through throttle body.

* Opening and closing of throttle valve is controlled by Electronic Control Unit (ECU) based on demand.

→ Throttle body - It is interlocked with accelerator pedal for controlling the amount of intake air.

→ Idle air control valve - Controls opening of bypass air passage, which is finally drawn air into intake manifold.

Fuel Delivery System:-

* Fuel pumped by fuel pump & cleaned by fuel filter.

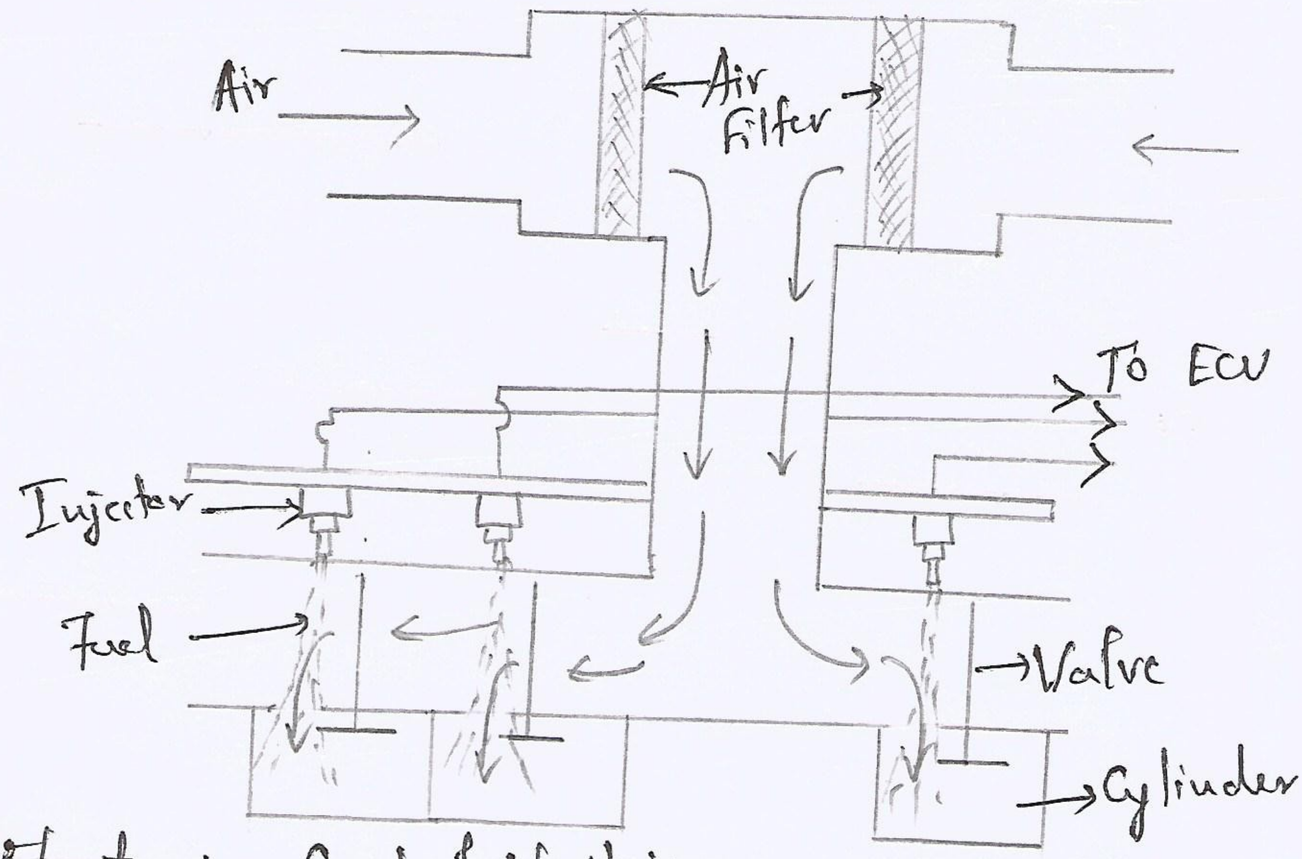
* It is then feed into each injector under pressure according to ECU.

* Important components of fuel delivery system are,

→ Fuel Pump - Feed fuel into injector.

→ Pressure regulator - Controls injector pressure.

→ Injector - At each cylinder in between intake manifold and delivery



Electronic Control Unit :-

* ECU has various sensors, controlling fuel injection, speed, fuel pump, ignition system, etc.,

* ECU controls timing of fuel injection.

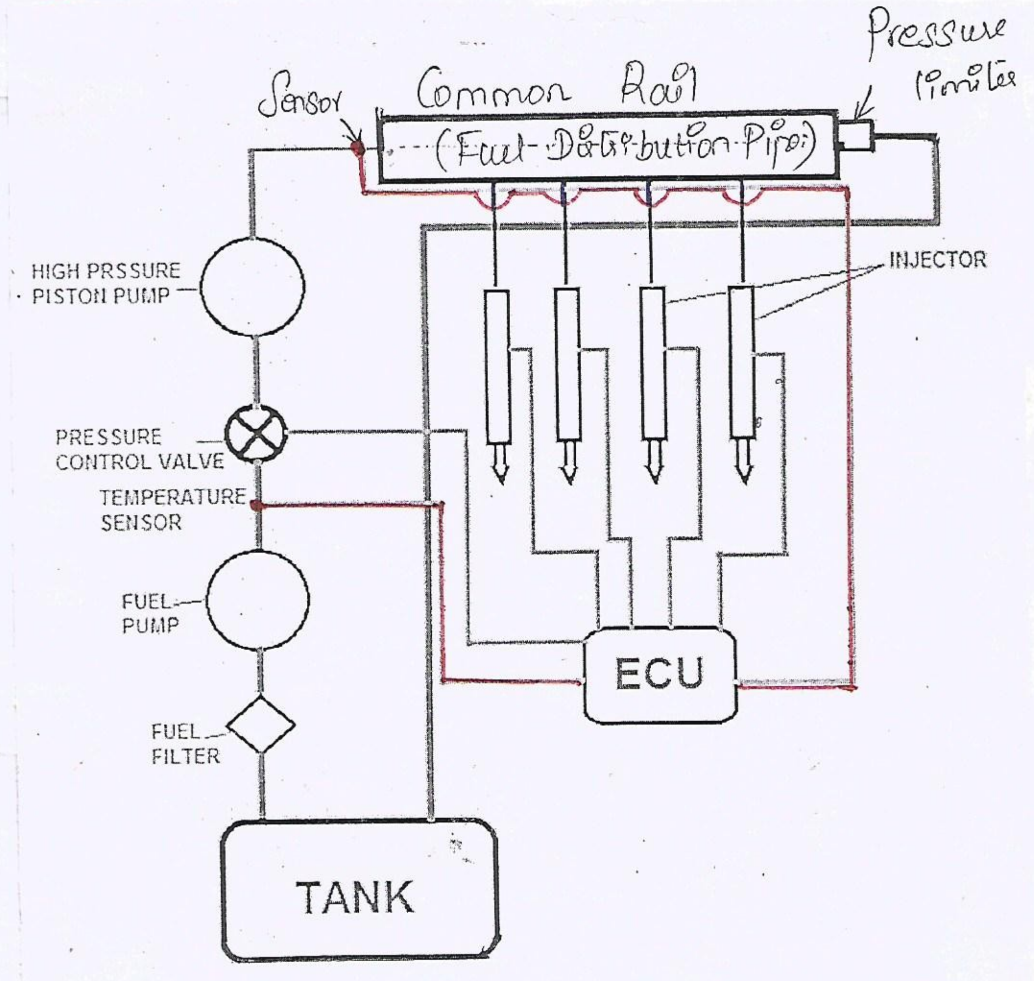
* It controls bypass airflow and idle air control valves for following purpose,

→ To keep engine at idle speed.
→ To improve starting performance.
→ To regulate air-fuel ratio.
→ To improve drivability, while engine is warmed up.

7) **COMMON RAIL DIESEL INJECTION SYSTEM**

CRDI :-

* Used for C.I engines.
* CRDI works in coordination with engine ECU.
* ECU calculate the timing of injection and quantity of injection through sensors.
* CRDI has solenoid injectors (electrically operated).
* Based on ECU signal, the CRDI injects fuel directly into the combustion chamber.
* CRDI injects Diesel five times more accurate than normal systems.



* Due to accurate injection, greater reduction of emission, thereby improving fuel efficiency.

* Various components of CRDI,

→ High pressure fuel pump

→ Common fuel rail.

→ Injectors.

→ Engine Control Unit (ECU).

Working:-

* ECU senses the engine speed and load and temperature of cylinder.

* ECU sends the data to pressure control valve, which regulates the amount of fuel from fuel tank.

* Fuel pumped by fuel pump and reaches fuel distributor pipe.

* From distributor pipe, the fuel gets injected inside the each of cylinders.

* ECU agains collects the pressure data from injector as feedback and control the fuel quantity for next cycle.

* This cycle repeats.

Advantages:-

* Initial cost is low.
* Delivers 25% higher power & torque than normal injection systems.
* Pick up is efficient.
* Higher mileage.
* Lower emission.
* Lower noise
* Lower fuel consumption.
* Lower vibration.
* Improved performance.

Disadvantages:-

* Complicated design.
* Maintenance cost is high.
* Some other parts of engine has to be modified according to CRDI.

IGNITION SYSTEMS :-

→ This system supplies high-voltage of current (about 20,000 Volts) to spark plug for producing spark inside cylinder.

→ Spark is provided in various cylinders according to firing order.

→ Types of ignition systems,

* Battery Ignition System.
* Magneto Ignition System.
* Electronic Ignition System.

3) BATTERY IGNITION SYSTEM :- (COIL)

* Used in petrol (or) S.I engines.

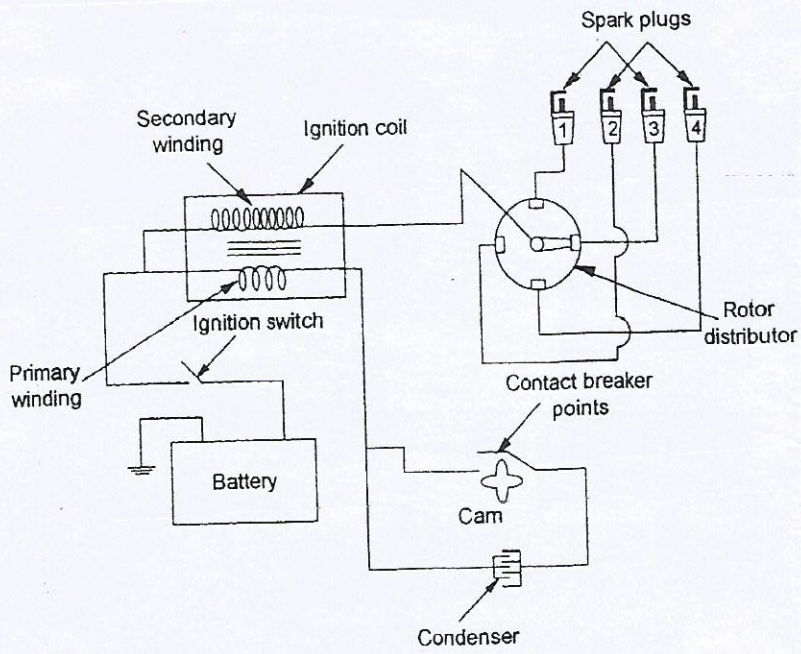


Figure 2.48 Battery ignition system

Construction:-

i) Battery:-

* Electrical power source.
* Provides voltage 6 or 12 Volts

ii) Ignition Coil:-

* Used to step up battery voltage from [6 (or) 12 Volts to 20,000 (or) 30,000 volts] required for spark.

iii) Distributor:-

* Distributes high voltage to respective spark plug.

iv) Condenser:-

* Used to avoid excess sparking. It is connected across contact breaker.

v) Spark plug:-

* Fitted on engine cylinder head.

Working:-

* System has two circuits,

→ Primary circuit - Battery, primary coil, Condenser & Contact breaker

→ Secondary circuit - Secondary coil, Spark plug & Distributor.

* When primary circuit is closed by contact breaker, current begins to flow through primary coil.

* EMF induced in secondary coil is proportional to rate at which the magnetic flux increases due to primary current flow.

* When primary circuit is opened by contact breaker, the magnetic field collapses.

* A very high voltage of the 10,000 to 20,000 volts is induced in the secondary coil due to sudden collapse.

* This collapse of magnetic field achieved by condenser.

* This voltage is supplied to the corresponding spark plug.

Advantages:-

* Provides better spark at low speeds.

* Spark efficiency remains unaffected by various positions.

Disadvantage:-

* Weight is higher than Magneto ignition system.

* Wiring mechanism is more complicated.

4) MAGNETO IGNITION SYSTEM:-

* In this system, the battery is replaced with a magneto.

* Used in two wheelers such as motor cycles, scooters, etc.,

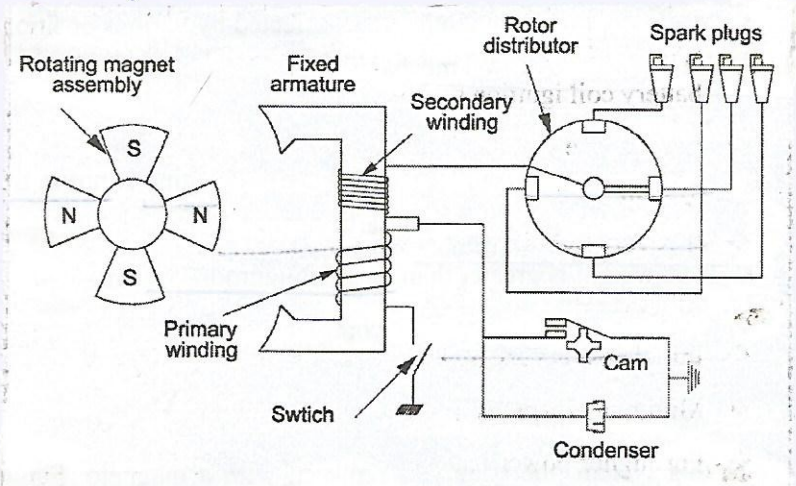


Figure 2.66 Magneto ignition system

Construction:-

* Has rotating magnet assembly driven by an engine and a fixed armature.

→ Primary Circuit - Primary winding, condenser, Contact Breaker.

→ Secondary Circuit - Secondary winding, Distributor & spark plugs.

Working:-

i) When contact breaker - CLOSED:-

* Current flows in primary circuit.

* Magnetic field produced in primary winding.

* When primary current is at the highest peak, the contact breaker points will be opened by cam.

ii) When contact breaker - OPENED :-

* There is a break in primary circuit.

* Magnetic field in primary winding is callapsed.

* High voltage of 15,000 Volts is generated in secondary winding.

* This voltage is distributed to respective spark plugs.

Advantages :-

* Less maintenance & more reliable.

* Less space compared to battery ignition system.

* Less weight & compact size.

Disadvantage :-

* High initial cost.

* Minimum 75 rpm required to start engine.

* For high power engines, additional device necessary to start ignition.

5) ELECTRONIC IGNITION SYSTEM:-

* Main drawbacks of battery & magneto ignition systems are as follows,

→ Contact breaker points will wear out.

→ As contact breaker is a mechanical device, it cannot operate precisely.

→ Only 400 sparks per second is possible, which limits engine speed.

→ Inefficient at low speed.

* To overcome these above drawbacks, electronic ignition system are assisted to the engine.

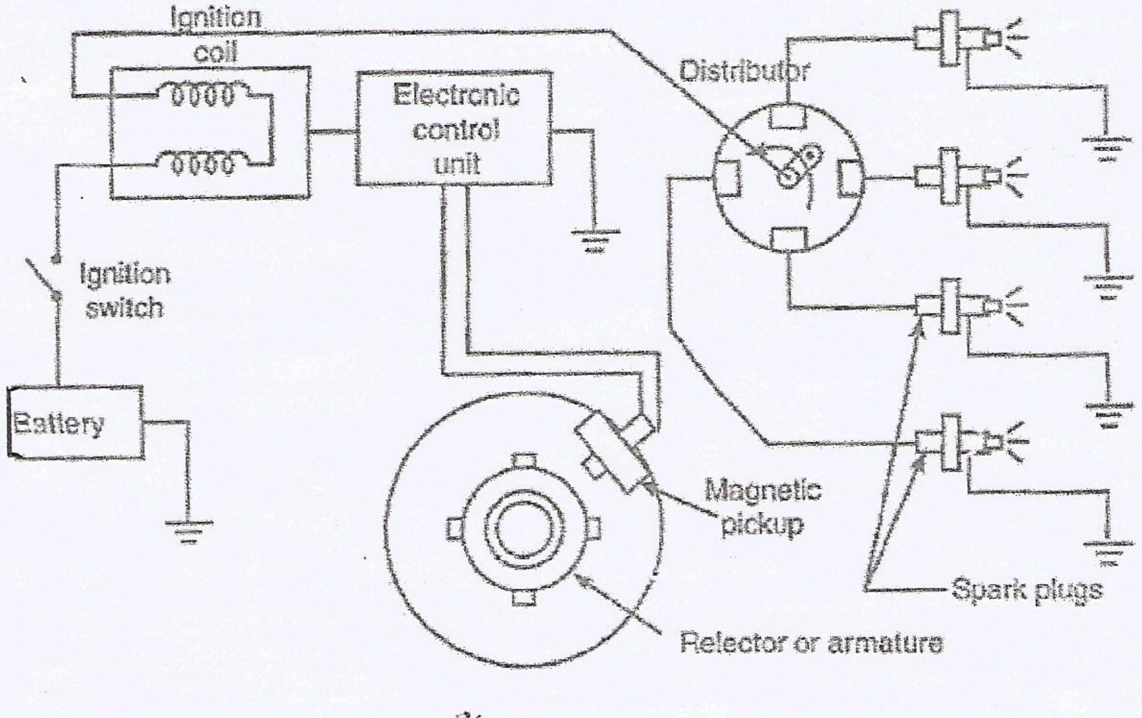


Figure 2.69 Electronic ignition system

Construction:-

* It has battery, ignition switch, electronic control unit, magnetic pick-up, armature, ignition coil, distributor and spark plug.

* In this system, a magnetic-pick-up is used instead of contact breaker in battery & magneto ignition systems.

* Magnetic pick-up is a sensor coil, which passes magnetic flux produced by permanent magnet.

* Armature mounted on distributor used to modulate magnetic flux and send to magnetic pick-up.

Working:-

* When ignition coil is closed & switch is 'ON', armature rotates & provide the path for magnetic flux from permanent magnet.

* Magnetic flux is passed to Pick up each time when armature teeth meets pick-up coil, then electric pulse is generated.

* This pulse triggers ECU, which stops current flow in primary coil & leads to collapse in primary circuit.

* This leads to generation of high voltage in secondary coil, which produces spark in spark plug.

* Thus again armature rotates & makes spark plug in next cylinder to produce spark.

* This cycle continues for each cylinder ignition.

Advantages:-

* As armature, pickup, ECU are non-contact parts, they won't wear like contact breaker.

* Adjustment of engine timing is not necessary.

* Accurate control of timing.

—x—x—x—

6) LUBRICATION IN I.C ENGINES :-

→ In both S.I and C.I engines, the moving parts rub against each other causing frictional force bcoz of which heat generated & engine parts wear easily.

→ To reduce friction, wear & tear, lubricant is used in between the rubbing surfaces.

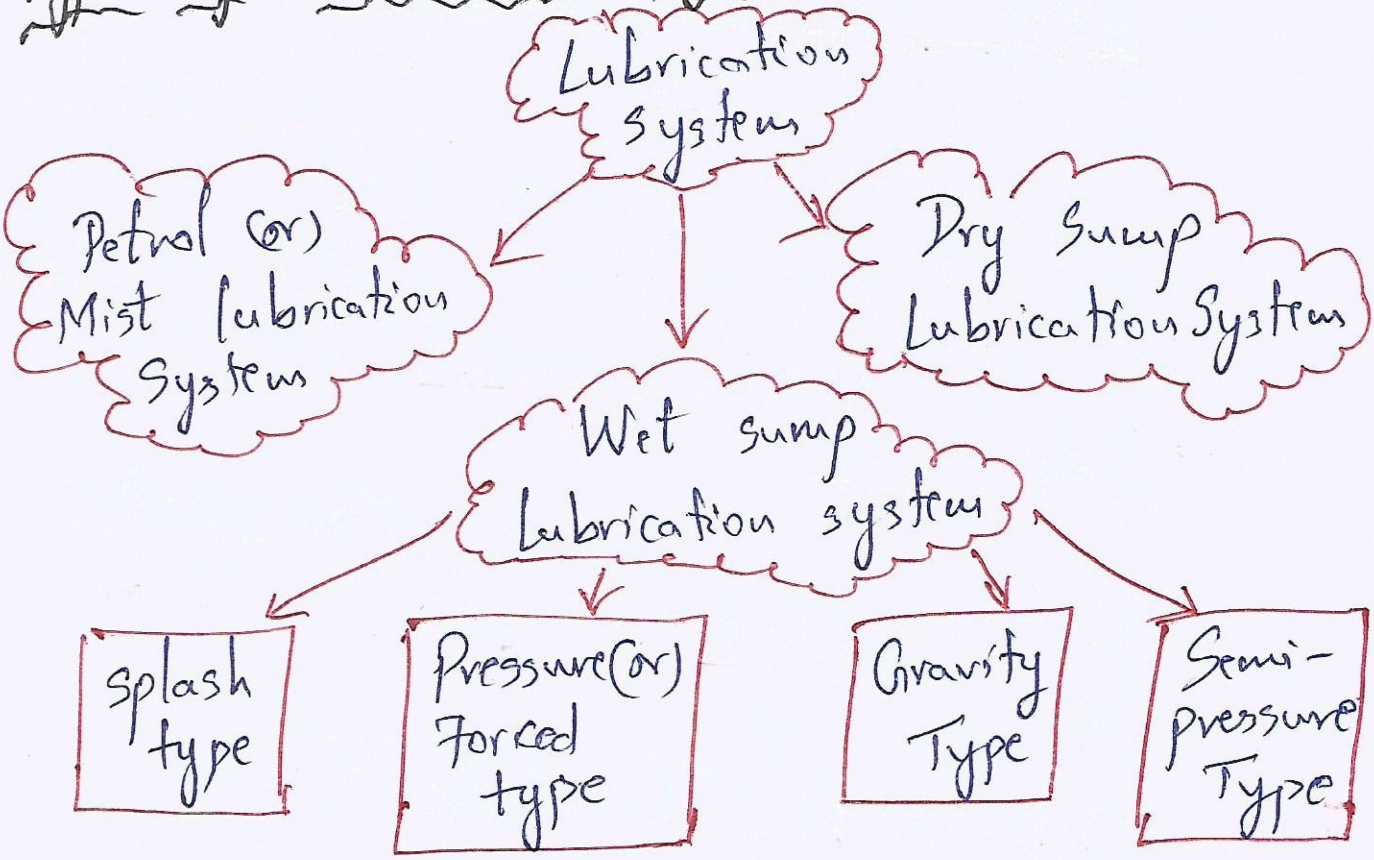
Parts to be lubricated:-

* Crankshaft bearings
* Camshaft bearings.
* Valve mechanisms
* Gudgeon pin bearings.
* Piston rings and walls of cylinder.
* Timing gears.

Functions of Lubrication System:-

* Reduce friction between rubbing surfaces.
* Reduce wear & tear.
* Reduce temperature of working parts.
* Reduce noise.
* Reduce power loss due to friction

Types of Lubrication System:-



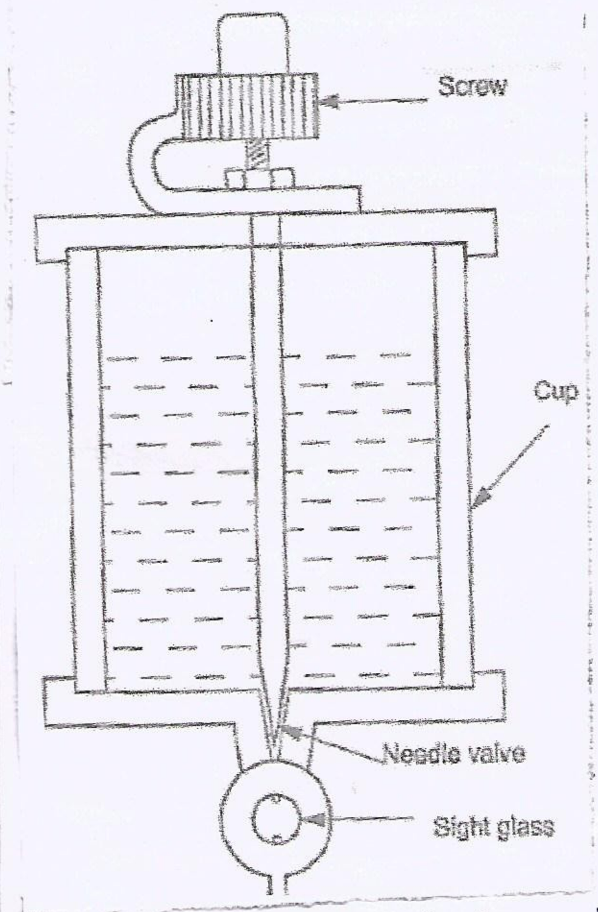
a) Petrol (or) Mist Lubrication System:-

* Used for 2-Stroke engines, light vehicles (Scooters & Motorcycles).
* 3 to 6% lubricating oil is added with petrol to petrol tank.
* Oil & petrol is injected through carburetor.
* Petrol gets vaporized & oil in the form of mist goes into cylinder.
* This oil mist lubricates the moving parts like piston, cylinder walls, connecting rod, etc.,
* Eg:- Oil mixing with petrol in TVS 50 bike.

Wet Sump Type	Dry Sump Type
Lubrication oil stored in the oil sump.	Lubrication oil not stored in oil sump. It is kept seperately in a tank.

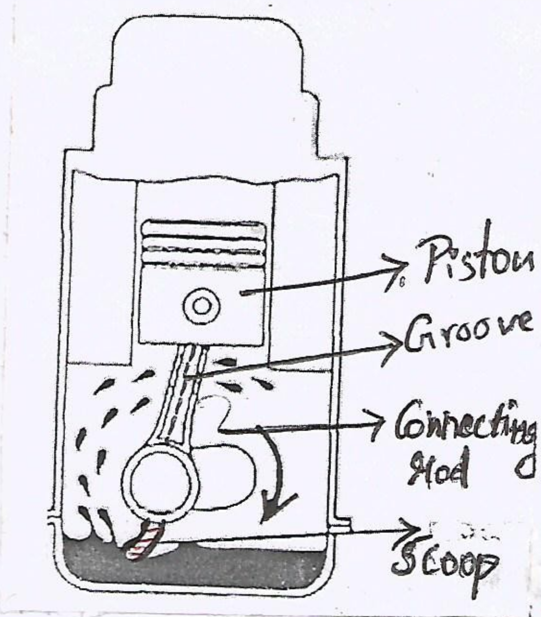
b) Wet Sump Lubrication System:-

i) Gravity Lubrication System:-



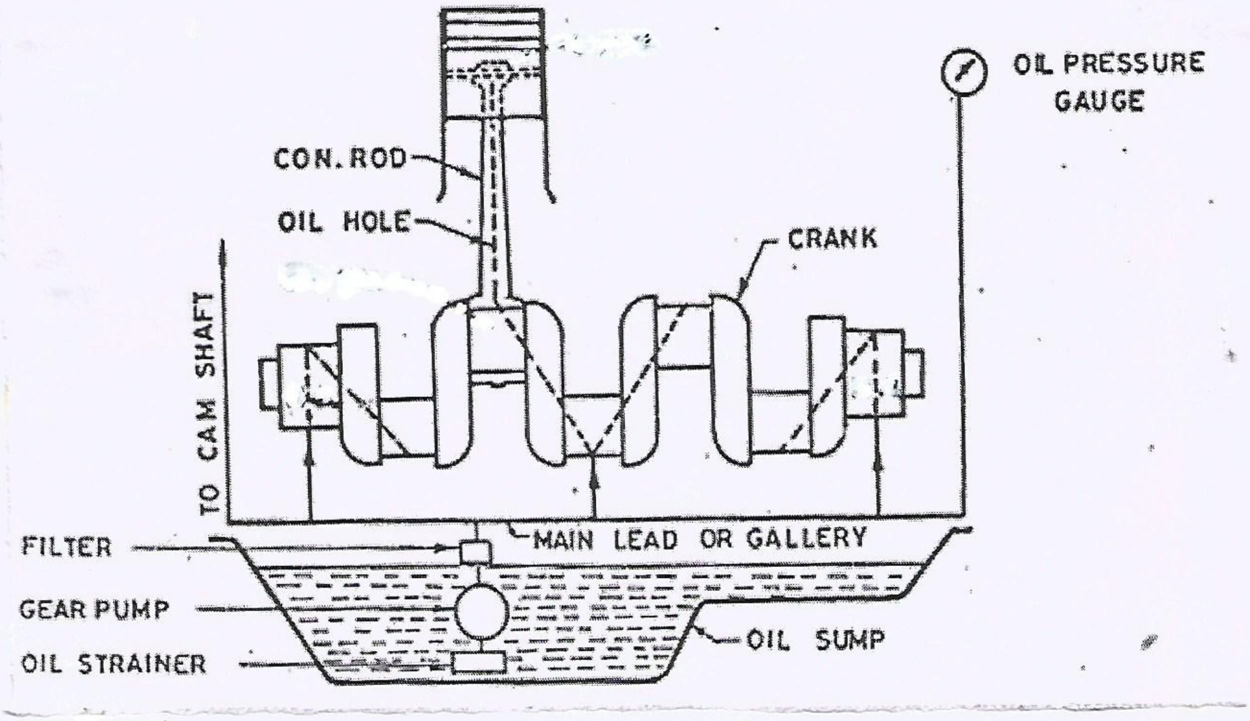
* Oil is supplied to parts by means of gravity.
* It has cup and needle arrangement.
* Needle valve is adjusted by screw.
* Valve raise - increase the oil flow.
* Valve lower - decrease the oil flow.
* Used for external moving parts lubrication like bearings, cross head, crank pins.

ii) Splash Lubrication System:-



* Oil sump is fixed to the bottom of the crank case.
* When piston reaches BDC for each cycle, a scoop fixed to connecting rod will dip in sump.
* When piston moves up, the oil in scoop will be splashed to piston, cylinder wall, connecting rod.
* Groove in connecting rod supply oil to the other parts.
* Groove will also facilitate the flow of oil back to sump for reuse.

iii) Pressure (or) Forced Type:-



* Oil is pumped by gear pump from sump through oil stainer.

* Oil is filtered in filter & flown to main lead.

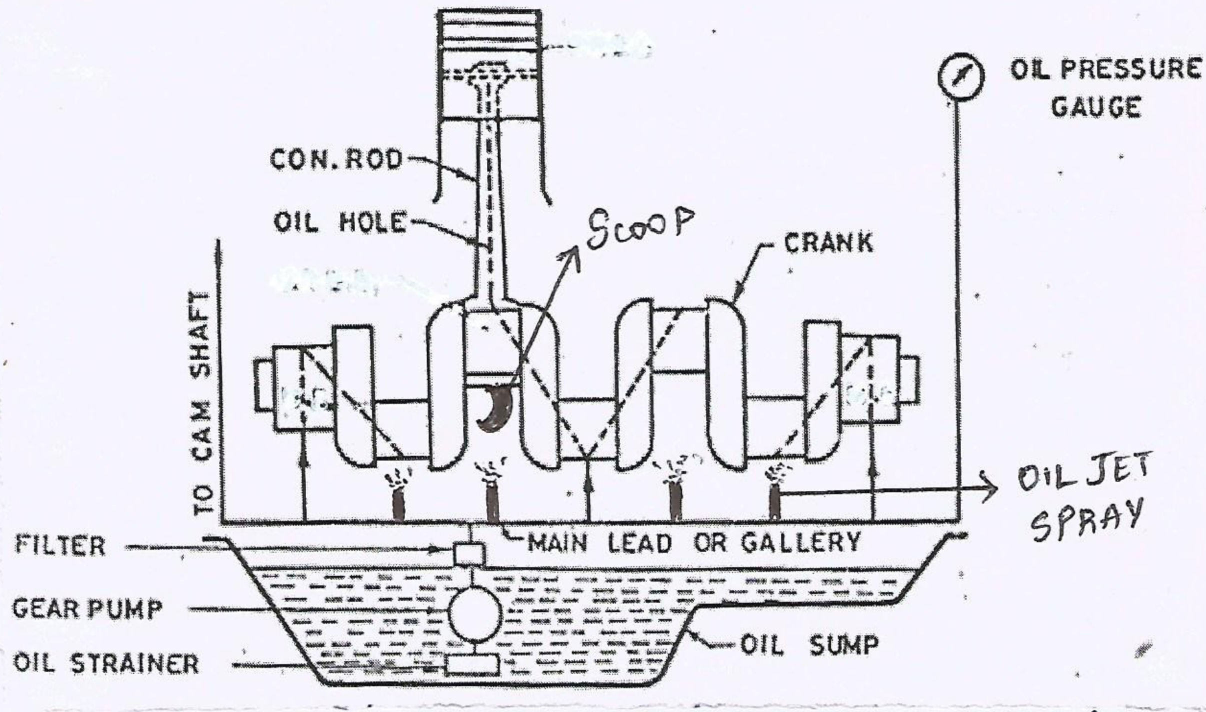
* From main lead, oil is supplied to many smaller leads.

* through main and smaller leads, all the parts will be lubricated.

* After lubrication, oil falls into sump.

* Used for high engine loads.

iii) Semi - Pressure Lubrication System:-



* Also known as partial pressure system.

* Modification of splash lubrication system.

* It is the combination of Splash and pressure lubrication system.

* Scoop are used for splashing the oil.

* Oil jets are used to direct the oil from sump to scoop.

c) Dry Sump Lubrication System:-

* Similar to pressure lubrication systems.

* But oil is kept in a seperate tank, not in oil sump.

* Oil is fed to engine by pressure pump.

* Oil falling into sump, will be flown back to tank by a seperate scavenge pump.

* Used in aircraft engines

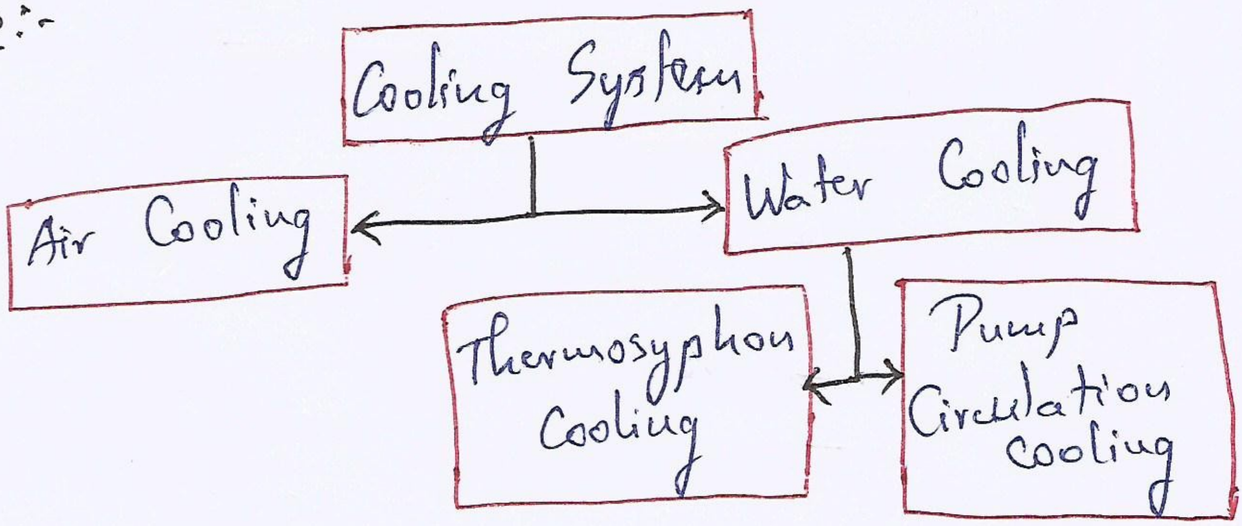
x ——— x ——— x ———

7) COOLING SYSTEMS:-

Purpose of cooling system:-

* In I.C engines, the combustion takes place at about 2500°C.
* Temperature of cylinder, walls, head, piston and valve continues to raise.
* If these parts are not cooled, then it will damage (or) even melted.
* Meanwhile, too much of cooling will reduce thermal efficiency of engine.
* Hence, the cooling system has to maintain temperature of 200 to 250°C.

Types:-



* Generally for automobiles, air cooling and water cooling system will be used.

a) Air Cooling System:-

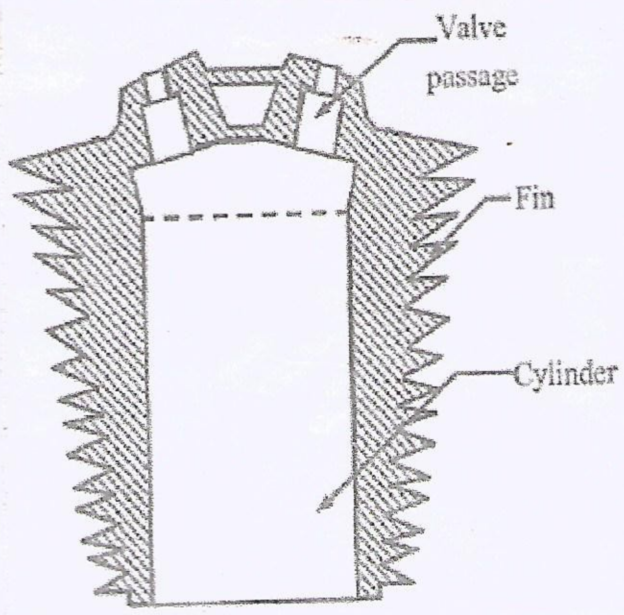


Figure 2.88 Cylinder with Fins

* Method of cooling an engine by using atmospheric air is called air cooling system.

* Used in motor-cycles with FINS over engine. and also in cars.

* By fins, the area of contact of hot engine surface and atmospheric air has been increased for easy heat transfer.

* Motorcycles - air flow achieved by forward motion of vehicle.

* Cars - air flow achieved by a fan (or) blower.

Advantage:-

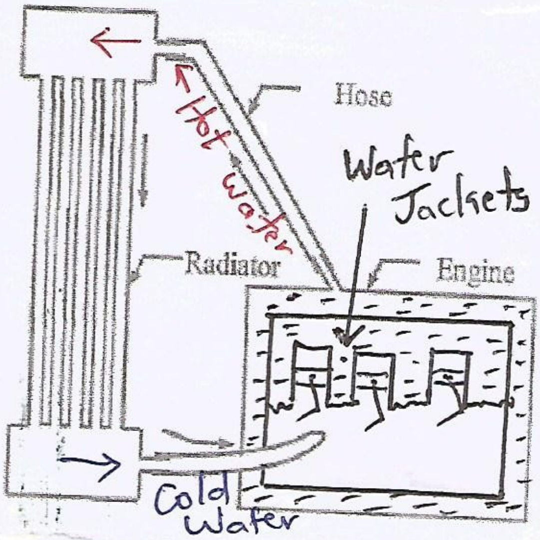
→ Light weight, since no radiator.
→ No coolant needed.
→ Faster warming up.
→ Easy maintenance

Disadvantage:-

→ Less efficient than water cooling.
→ Produce noise
→ Only suitable for small engines.

b) Water Cooling System (or) Radiator :-

i) Thermosyphon System :-



* Thermosyphon – The principle of hot water going up and cold water coming down due to density difference.

* Hot water – low density.
Cold water – high density.

* No need of pump to circulate the water.

* Hot water from engine circulating around the cylinder walls and other engine surfaces, goes to the top of radiator.

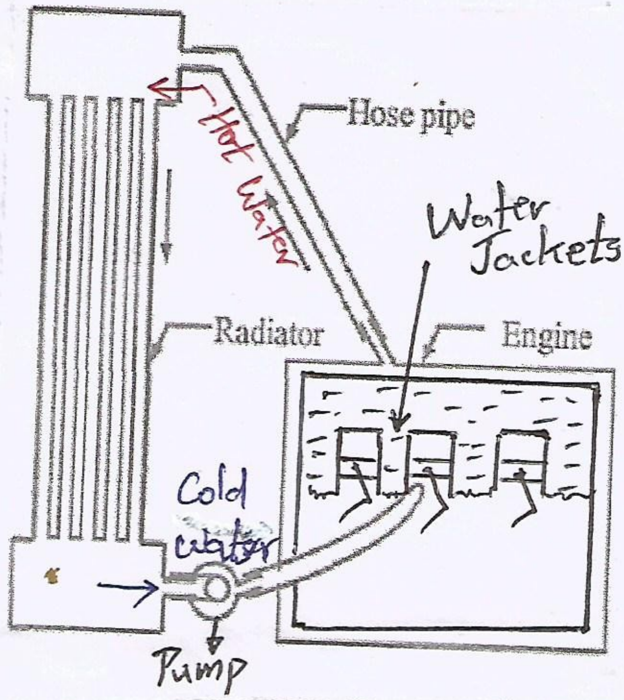
* In radiator, hot water flows down due to gravity.

* Atmospheric air crossing the radiator tubes, absorbs heat from hot water and becomes cold and moves downward.

* Again this water goes to cylinder to absorb heat.

* It is simple and cheap, but cooling is slow.

ii) Pump Circulation System:-



* To make thermosyphon system more effective, a water pump is implemented.

* Pump is driven by a V-belt from a pulley on engine crankshaft.

* Water jackets around the cylinders make use of water to absorb heat and this hot water is circulated by water pump to radiator for cooling.

* Water pump increases the flow rate by regulating the water flow with automatic thermostat valve.

* It improves engine efficiency.

AIR COOLING SYSTEM Vs WATER COOLING SYSTEM

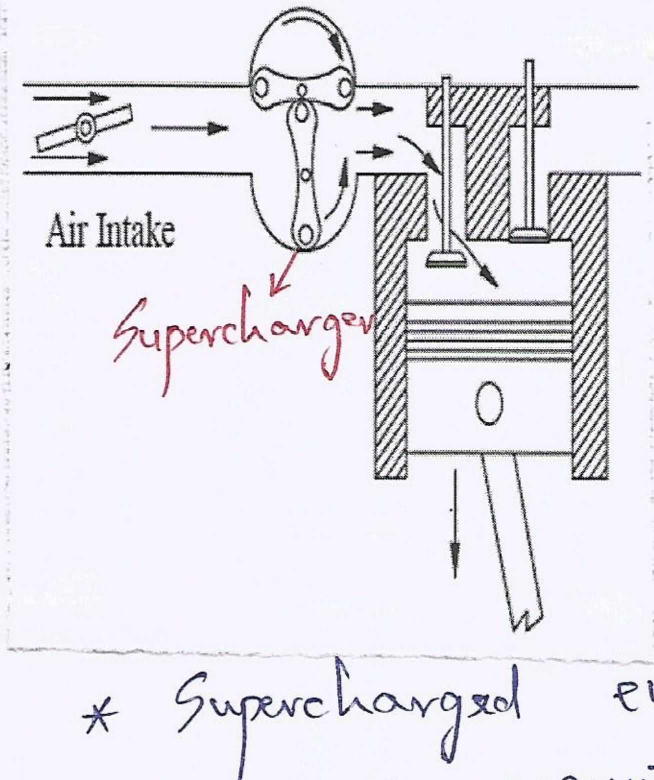
AIR COOLING SYSTEM	WATER COOLING SYSTEM
Weight of the engine is less	Weight is more due to water in the radiator
No problem of leakage or freezing of water	Both the problem is exist
More noise	Less noise as water dampens the vibration
Maintenance of the cooling system is easier	Maintenance is difficult
Control of temperature is different	It can be easily controlled by fitting a thermostat
The heat transfer rate in the system is less	The heat transfer rate in the system is more
Air cooling system is mostly used in small vehicles like scooters, mopeds, motor cycles etc…	Water cooling system is used in medium and high capacity engines like car, bus, trucks etc…

8) SUPERCHARGING AND TURBOCHARGING :-

Power output of engine depends upon the amount of air induced per unit time and degree of utilization of air and thermal efficiency of engine.

Supercharging :-

* It is the method of increasing air capacity of engine.
* Device used to increase the air density is called supercharger.
* Supercharger is a blower (or) compressor.



* Supercharged engine gives better power for same amount of fuel

* A turbine which acts as a compressor is connected to the crankshaft through a belt.

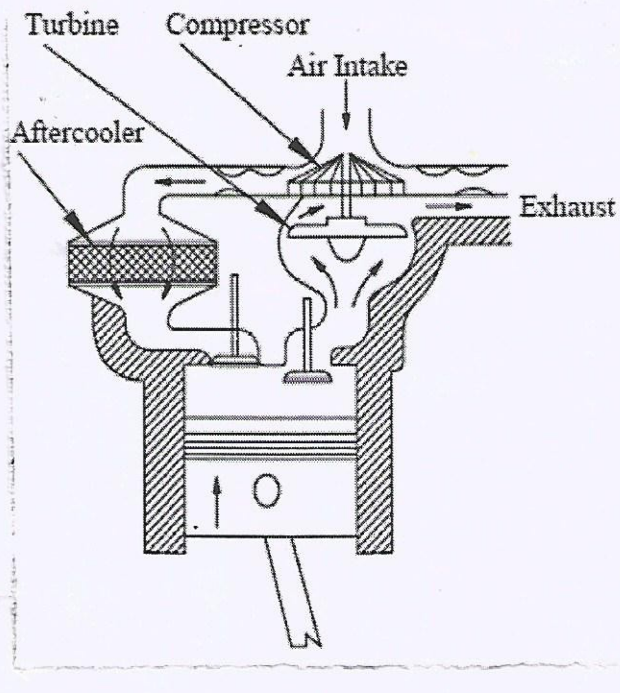
* When combustion begins, the crankshaft rotates the belt connecting the compressor rotates.

* It sucks more air and improve air fuel mixture.

* Thus complete combustion occurs and the power output increases for same amount of fuel.

Turbocharging :-

* Turbocharging is also the process of supercharging, in which the turbine is run by exhaust gas.



* Exhaust gas from the engine flows through the blades of gas turbine, where the mechanical work is done by the gas turbine.

* The wheel of turbine runs the compressor which compresses the fuel (diesel) or air (for petrol engine).

* It improves air capacity in the engine.

* By using turbocharger, the fuel economy is also improved by using kinetic energy of exhaust gas.

Purpose of Supercharging & Turbocharging:-

→ To reduce weight per horse power in aero engines.

→ To reduce space occupied by engine in marine engines.

→ To have better turbulence.

→ To improve volumetric η at high altitudes in aero engines and at high speed in race cars.

→ To maintain power at high altitude, where less oxygen available for burning

SUPERCHARGER	TURBOCHARGER
They are basically compressors.	They have both turbine & compressor on same shaft.
Extra power needed	No need of extra power
Draw power from engine	Power from exhaust gas
Connected to intake manifold.	Turbine connected to exhaust pipe & compressor connected to intake.
Suitable for small engine	Heavy engines.
Supercharger starts working when engine start.	Turbocharger waits for exhaust gas to start it.
Cost is less	Cost is less.
Maintenance is easy.	Difficult maintenance, since it need lubrication
Immediate power delivery.	Lag in power delivery as it takes time to spin up to speed.
Greater acceleration.	Higher speed.
Less efficient.	More efficient.

9) EMISSION NORMS:-

Emissions From Automobiles:-

→ Automobile emissions play a major role in environmental pollution.

→ Day-by-day the number of vehicles increases resulting in higher emission.

→ Incomplete combustion of fuel in automobile emit polluted engine exhaust.

→ Main engine emissions are,

* Carbondioxide (CO_2) - Hydrocarbon in fuel converted into CO_2 about 13.7% of exhaust gas.
* Water (H_2O) - 13.1% of exhaust
* Nitrogen (N_2) - 71.5% of exhaust
* Soot (or) Particulate Matters - 1% of exhaust.
* Carbon monoxide (CO).
* Oxides of nitrogen [NO_x).

Emission Norms:-

→ Emission norms for automobiles are standards set by the authority of different countries.

→ Main aim is to control the environmental pollution.

→ Two important norms followed in India are,

* European Standard - Euro
* Bharath Stage Norm - BS.

Indian Emission Standard:-

For 2 wheeler & 3 wheeler.

Standard	Reference	Date
Bharat Stage II	Euro 2	1 April 2005
Bharat Stage III	Euro 3	1 April 2010
Bharat Stage IV	Euro 4	1 April 2017
Bharat Stage VI	Euro 6	April 2020 with mandate (proposed)

'Euro' Standard	'BS' Standard
'Euro' standards tested at Sub-zero temperature in European Country	'BS' test done at 24 to 28°C.
'Euro' tested at maximum speed of 120 km/hr.	'BS' test done at maximum vehicle speed of 90 km/hr.

Indian Emission Norms:-

For 4 wheeler vehicles.

Standard	Reference	YEAR	Region
India 2000	Euro 1	2000	Nationwide
Bharat Stage II	Euro 2	2001	NCR*, Mumbai, Kolkata, Chennai
		2003	NCR*, 13 Cities
		2005	Nationwide
Bharat Stage III	Euro 3	2005	NCR*, 13 Cities
		2010	Nationwide
Bharat Stage IV	Euro 4	2010	NCR*, 13 Cities
		2017	Nationwide
Bharat Stage V	Euro 5	(to be skipped)	
Bharat Stage VI	Euro 6	2018	Delhi NCR
		2020	Nationwide

* National Capital Region (Delhi)

Comparison between BS III & BS IV:-

Petrol Emission Norms (All figures in g/km)

Standard	Reference	Norm	Co	HC	NOx	HC+NOx
BS III	Euro 3	2.30	0.20	0.15	--	--
BS IV	Euro 4	1.00	0.10	0.08	--	--

Diesel Emission Norms (All figures in g/km)

Standard	Reference	Norm	Co	HC	NOx	HC+NOx
BS III	Euro 3	0.64	—	0.50	0.56	0.05
BS IV	Euro 4	0.50	—	0.25	0.30	0.025

PERFORMANCE CALCULATION :-

1) Indicated Power, $IP = \frac{P_m L A N K}{60000}$ (kW)

P_m - I. Mean Effective Pressure

L - Stroke Length, A - Area, N - Speed,

k - No of Cylinder.

$N = \frac{N}{2}$ - For 4 stroke Engine.

$N = N$ - For 2 stroke Engine.

2) Brake Power, $BP = \frac{P_m L A N K}{60000}$ (kW).

$$BP = \frac{2\pi N T}{60000}$$

T - Torque (N.m)

3) Fuel Power, [scribbled] $= m_f \times C.V.$

m_f - mass of fuel rate (kg/hr) (or) (kg/s)

m_f = Oil Consumption x Density (ρ)

C.V - Calorific Value.

4) Friction Power, $FP = IP - BP$.

5) Mechanical η, $\eta_{mech} = \frac{BP}{IP}$.

6) Indicated thermal η, $\eta_{IT} = \frac{IP}{\left(\frac{m_f \times CV}{3600}\right)}$.

7) Brake thermal η, $\eta_{BT} = \frac{BP}{\left(\frac{m_f \times CV}{3600}\right)}$.

8) Relative η, $\eta_R = \dfrac{\eta_{IT}}{\eta_{air\cdot std}}$

9) Volumetric η, $\eta_{vol} = \dfrac{\text{Vol of charge during Suction}}{\text{Swept Volume}}$

10) Brake Specific fuel Consumption,

$$BSFC = \frac{m_f}{BP} \quad (kg/kW\text{-}hr)$$

$$BSFC = \frac{3600}{\eta_{BT} \times C.V}$$

$$ISFC = \frac{3600}{\eta_{IT} \times C.V}$$

Internal Combustion Engines - Unit 2.

13 (a) A four-cylinder, four-stroke oil engine 10 cm in diameter and 15 cm in stroke develops a torque of 185 Nm at 2000 rpm. The oil consumption is 14.5 lit/hr. Specific gravity of oil is 0.82 & Calorific Value is 42000 kJ/kg. If IMEP taken from indicator diagram is 6.7 bar, find (i) Mechanical η, (ii) Brake thermal η, (iii) Brake Mean Effective Pressure, (iv) Specific fuel consumption in litres on brake power basis. (Nov / Dec - 2015)

Given:

Bore dia, $D = 10\,cm = 0.1\,m$.

Stroke length, $L = 15\,cm = 0.15\,m$.

Torque, $T = 185\,Nm$.

Speed, $N = 2000\,rpm$.

Oil consumption $= 14.5\,lit/hr$.

$C.V = 42000\,kJ/kg$, $\rho = 0.82$

IMEP, $P_m = 6.7\,bar$.

Soln:

$$\text{Indicated Power, } IP = \frac{P_m L A N K}{60{,}000}$$

$N = \frac{N}{2}$ → For 4 stroke engine.

$K = 4$ → For 4 Cylinder.

$$IP = \frac{6.7 \times 10^5 \times 0.15 \times \frac{\pi}{4} \times 0.1^2 \times \frac{2000}{2} \times 4}{60{,}000} = 52.62\,kW$$

Brake Power, $BP = \frac{2\pi NT}{60,000}$

$$= \frac{2\times\pi\times 2000\times 185}{60000} = 38.74$$

$BP = 38.74$ kW.

Mech $\eta = \frac{BP}{IP}$ $= \frac{38.74}{52.62} = 0.7363$

$\eta_{mech} = 73.63\%$

Fuel Power, $FP = m_f \times C.V$ $= \frac{14.5}{3600} \times 0.82 \times CV$

$FP = 138.72$ kW.

Brake Thermal $\eta = \frac{BP}{FP}$ $= \frac{38.74}{138.72} = 0.279$

$\eta_{BT} = 27.9\%$

Specific Fuel Consumption, $SFC = \frac{14.5}{38.74}$

$SFC = 0.374$ lit/kW hr.

Brake Mean Effective Pressure, BMEP

$$BMEP = \frac{BP \times 60000}{ALNK}$$

$$= \frac{38.746 \times 60000}{\frac{\pi}{4}\times 0.1^2 \times 0.15 \times \frac{2000}{2} \times 4}$$

$$= 493329 \text{ N/m}^2$$

$BMEP = 4.93$ bar

Following data relate to 4-cylinder four-stroke petrol engine. Air-fuel ratio by weight = 16:1, Calorific value = 45200 kJ/kg, $\eta_{mech} = 82\%$, $\eta_{airstd} = 52\%$, $\eta_{relative} = 70\%$, $\eta_{vol} = 78\%$, stroke/bore ratio = 1.25, Suction conditions = 1 bar, 25°C. r.p.m = 2400 & power at brakes = 72 kW. Calculate (i) Compression ratio. (ii) Indicated thermal η (iii) Brake specific fuel consumption (April/May 2017)

Given:-

A/F ratio = 16 : 1, No of Cylinder, n = 4.

C.V = 45200 kJ/kg, $\eta_{mech} = 82\%$, $\eta_{airstd} = 52\%$.

$\eta_{rel} = 70\%$, $\eta_{vol} = 78\%$, stroke/bore = 1.25.

N = 2400 rpm, $P_1 = 1$ bar, $T_1 = 298$ K.

Brake Power, B.P = 72 kW.

Soln:-

(i) Compression Ratio, r:-

$$\eta_{airstd} = 1 - \frac{1}{(r)^{\gamma-1}}$$

$$0.52 = 1 - \frac{1}{(r)^{1.4-1}}$$

$$(r)^{0.4} = 2.08$$

$$\boxed{r = 6.2}$$

(ii) $\eta_{ind.\ thermal}$:-

$$\eta_{rel} = \frac{\eta_{thermal}}{\eta_{airstd}}$$

$0.7 = \frac{\eta_{I.T}}{0.52} \Rightarrow \eta_{I.T} = 0.7 \times 0.52$

$$\eta_{IT} = 36.4\%$$

(iii) Brake specific fuel consumption :-

$$I.P = \frac{B.P}{\eta_{mech}} = \frac{72}{0.82} = 87.8 \text{ kW}$$

$$\eta_{I.T} = \frac{I.P}{\dot{m}_f \times C.V}$$

$$0.364 = \frac{87.8}{\dot{m}_f \times 45200}$$

$$\dot{m}_f = 0.00533 \text{ kg/s}$$

$$B.S.F.C = \frac{\dot{m}_f}{B.P}$$

$$= \frac{0.00533}{72} \text{ kg/kWs}$$

$$= \frac{0.00533 \times 3600}{72}$$

$$B.S.F.C = 0.2665 \text{ kg/kWh}$$

Air consumption for a four-stroke petrol engine is measured by means of a circular orifice of diameter 3.2 cm. The co-efficient of discharge for the orifice is 0.62 and the pressure across the orifice is 150 mm of water. The barometer reads 760 mm of Hg. Temperature of air in the room is 20°c. The piston displacement volume is 0.00178 m^3. The compression ratio is 6.5. The fuel consumption is 0.135 kg/min of calorific value 43400 kJ/kg. The brake power developed at 2500 r.p.m is 28 kW. Determine:

(i) The volumetric efficiency on the basis of air alone

(ii) The air-fuel ratio

(iii) The brake mean effective pressure

(iv) The relative efficiency on the brake thermal efficiency basis. (NOV / Dec — 2016).

Solution:

Diameter of circular orifice, $d = 3.2\,cm = 0.032\,m$

Co-efficient of discharge, $C_d = 0.62$

Pressure across orifice, $h_w = 150\,mm$ of water

Temperature of air in the room = 20°c

Piston displacement = 0.00178 m^3

Compression ratio, $r = 6.5$

Fuel consumption = 0.135 kg/min

Calorific value of fuel $C = 43900\,kJ/kg$

Brake power $B.P = 28\,kW$

Speed = 2500 r.p.m

$K = \frac{1}{2}$ --- For 4 stroke cycle, Engines.

(i) Volumetric efficiency on the basis of air alone.

$$PV = mRT$$

$$\frac{m}{V} = \frac{P}{RT} = \frac{1.0132 \times 10^5}{287 \times (20+273)} = 1.2\ kg/m^3$$

150 mm of H_2O $= \frac{150}{1000} \times 1000 = 150\ kg/m^2$

Thus head of air column causing flow

$$H = \frac{150}{1.2} = 125\ m$$

The air flow through the orifice

$$= \text{Air consumption} = C_d \times A \times \sqrt{2gH}$$

$$= 0.62 \times \frac{\pi}{4} \times (0.032)^2 \times \sqrt{2 \times 9.81 \times 125}$$

$$= 0.0247\ m^3/s$$

Therefore, air consumption per stroke

$$= \frac{0.0247 \times 60}{\left[\frac{2500}{2}\right]} = 0.001185\ m^3$$

Volumetric efficiency,

$$\eta_{vol} = \frac{\text{Air consumption of stroke}}{\text{piston displacement}}$$

$$= \frac{0.001185}{0.00178} = 0.665 \text{ or } 66.5\%.$$

(ii) Air-Fuel ratio

Mass of air drawn into the cylinder per min

$= 0.0247 \times 60 \times 1.2 = 1.778$ kg/min

$$= \frac{1.778}{0.135} = 13.67 : 1$$

(iii) Brake mean effective pressure, P_{mb}:

$$B.P = \frac{\eta \times P_{mb} LANK \times 10}{6}$$

$$28 = \frac{1 \times P_{mb} \times 0.00178 \times 2500 \times \frac{1}{2} \times 10}{6}$$

$$P_{mb} = \frac{28 \times 6 \times 2}{0.00178 \times 2500 \times 10} = 7.55 \text{ bar}$$

iv Relative efficiency :

$$\eta_{air-standard} = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(6.5)^{1.4-1}}$$

$= 0.527$ or 52.7 %.

Brake thermal efficiency

$$\eta_{th.(B)} = \frac{B.P}{m_f \times C} = \frac{28}{\frac{0.135}{60} \times 43900}$$

$= 0.2835$ or 28.35 %.

$$\eta_{relative} = \frac{\eta_{thermal (B)}}{\eta_{air-standard}} = \frac{0.2835}{0.527} = 0.5379 \text{ or}$$

53.79 %.

$\eta_{relative} = 53.79$ %.

HEAT BALANCE TEST (or) SHEET

* Performance of an engine is studied using heat balance test.
* Complete record of heat supplied and heat rejected by I.C engine during a certain time is entered as a tabular column form, which is known as Heat balance sheet.
* All heat energy supplied to an engine cannot be converted into useful work completely.
* Sources of heat losses are given below,
  - → Heat rejected to cooling water.
  - → Heat carried by exhaust gas.
  - → Unaccounted heat loss (radiation, incomplete combustion, observation error etc.,

Credit	KJ	%	Debit	KJ	%
Heat supplied by fuel (Q_s)	---	100	1) Heat equivalent to I.P or B.P	-	-
			2) Heat carried away by Cooling water (Q_w)	-	-
			3) Heat carried away by exhaust gas (Q_g)	-	-
			4) Unaccounted Heat loss (Q_{ua})	-	-
	-	100	Total	-	100

Heat Balance Sheet Problem:-

16.b) The following observations were made during a trial of a single-cylinder four-stroke cylinder gas engine having cylinder diameter of 180 mm and stroke of 240 mm.
Duration of trial = 30 min, Total no. of revolution = 9000, Total no. of explosion = 4450, Gross imep = 5.35 bar, Pumping imep = 0.35 bar, Net load on brake wheel = 40 kg, Diameter of brake wheel drum = 0.96 m, Total gas used at NTP = 2.4 m^3, Calorific Value of gas at NTP = 19 MJ/m^3, Total air used = 36 m^3, Pressure of air = 720 mm of Hg, Temperature of air = 17°C, Density of air at NTP = 1.29 kg/m^3, Temperature of exhaust gas = 350°C, Room temperature = 17°C, Specific heat of exhaust gas = 1 kJ/kg K. Cooling water circulated = 80 kg, Rise in temperature of cooling water = 30°C.

Draw up heat balance sheet & estimate mechanical and indicated thermal efficiencies of engine. Take R = 287 J/kg K.

(April / May 2019).

Soln:-

$$IP = \frac{P_m LAn}{60000}$$

$$= \frac{5 \times 10^5 \times 0.24 \times \left(\frac{\pi}{4} \times 0.18^2\right) \times 4450}{60000 \times 30}$$

$IP = 7.55$ kW.

$$BP = \frac{\pi d N W}{60000}$$

$$= \frac{\pi \times \underset{(m)}{0.96} \times \underset{(kg)}{9000} \times 40 \times \underset{(m/s^2)}{9.81}}{60000 \times \underset{(s)}{30}}$$

$BP = 6.16$ kW.

$$\left[\begin{array}{l} kg \cdot m/s^2 = N \\ W = Nm/s = J/s \end{array}\right]$$

Heat Supplied, $Q_s = \text{volume} \times C.V$

$$Q_s = \frac{2.4 \times 19000}{30} = 1520 \text{ kJ/min}$$

Heat Equivalent of B.P = 6.16×60 $(kJ/s \times 60)$

$= 369.6$ kJ/min

Heat lost to cooling medium $\}$ $Q_w = m_w \times C_p \times \Delta T$

Specific heat $\}$ C_p of water $= 4.18$ kJ/kg.K

$\Delta T = 30°C$ (or) 30 K.

$$\therefore Q_w = \frac{80}{30} \times 4.18 \times 30$$

$Q_w = 334.4$ kJ/min

Total air used = $36\ m^3$ at 720 mm of Hg

Volume of air used at NTP $= 36 \times \frac{273}{290} \times \frac{720}{760}$

$V = 32.1\ m^3$.

Mass of air used = Volume (m^3) $\times$ Density (kg/m^3)

$= \frac{32.1 \times 1.29}{30}$

$m_a = 1.38$ kg/min

Mass of gas at NTP, $m_g = \frac{PV}{RT}$

$= \frac{1 \times 10^5 \times 2.4}{287 \times 273} = 3.06$ kg

$m_g = \frac{3.06}{30} = 0.102$ kg/min

Total mass of exhaust gas $= m_a + m_g$

$= 1.38 + 0.102$

$m_G = 1.482$ kg/min

Heat lost to exhaust gas, $Q_g = m_G \times C_p \times \Delta T$

$Q_g = 1.482 \times 1 \times (350 - 17)$

$Q_g = 493.5$ kJ/min

Unaccounted loss, heat lost by radiation, $Q_{ua} = 1520 - (369.6 + 334.4 + 493.5)$

$Q_{ua} = 322.5$ kJ/min

Mechanical Efficiency, $\boxed{\eta_m = \frac{BP}{IP} \times 100}$

$= \frac{6.16}{7.55} \times 100$

$\eta_m = 81.6\%$

Indicated thermal efficiency $\boxed{\eta_{IT} = \frac{IP \times 60}{Q_s} \times 100}$

$= \frac{7.55 \times 60}{1520} \times 100$

$\eta_{IT} = 29.8\%$

Heat Balance Sheet :- (On minute basis)

Credit	kJ	%	Debit	kJ	%
Heat Supplied by fuel (Q_s)	1520	100	i) Heat equivalent to BP	369.6	24.3
			ii) Heat lost to cooling water (Q_w)	334.4	21.9
			iii) Heat lost to exhaust gas (Q_g)	493.5	32.5
			iv) Unaccounted heat loss (Q_{ua})	322.5	21.22
Total	1520	100	Total	1520	100

MORSE TEST (OR) MEASUREMENT OF IP OF MULTI-CYLINDER ENGINE :-

Morse test is used to find the indicated power of each cylinder of a high-speed multicylinder IC engine without using indicator diagram.

Procedure :-

① Find all B.P of cylinders and made it equal to B.P, during operation of all cylinders.

② Cut-off one cylinder. Speed of engine decreases.

③ Now, B.P of remaining cylinders determined.

④ Similarly, each cylinder is cut-off one by one and find out remaining cylinders B.P.

For four Cylinder Engine :-

Indicated power = IP_1, IP_2, IP_3, IP_4

Brake power = BP_1, BP_2, BP_3, BP_4.

Friction power = FP_1, FP_2, FP_3, FP_4.

$$IP = BP + FP \Rightarrow BP = IP - FP.$$

$$BP = (IP_1 + IP_2 + IP_3 + IP_4) - (FP_1 + FP_2 + FP_3 + FP_4). \rightarrow (1)$$

Cut-off 1st Cylinder,

$IP_1 = 0$, Friction power same.

$$\therefore BP_{1co} = (IP_2 + IP_3 + IP_4) - (FP_1 + FP_2 + FP_3 + FP_4) \rightarrow (2).$$

Subract ⇒ (2) from (1),

$$BP - BP_{1co} = IP_1.$$

Similarly,

$$IP_2 = BP - BP_{2co}$$

$$IP_3 = BP - BP_{3co}$$

$$IP_4 = BP - BP_{4co}$$

$\therefore$ Total IP of engine $= IP_1 + IP_2 + IP_3 + IP_4$.

---x---x---x---x---

Morse Test Problems:-

16a) In a test of a 4-Cylinder, 4-stroke engine 75 mm bore and 100 mm stroke, the following results were obtained at full throttle at particular constant speed and with fixed setting of fuel supply of 6.0 kg/h.

B.P with all cylinder working = 15.6 kW
B.P with Cylinder (1) Cutoff = 11.1 kW
B.P with Cylinder (2) Cutoff = 11.03 kW
B.P with Cylinder (3) Cutoff = 10.88 kW
B.P with Cylinder (4) Cutoff = 10.66 kW

If C.V of fuel = 83,600 kJ/kg & clearance volume = 0.0001 m³, Calculate (i) η_{mech}, (ii) η_{IT} iii) $\eta_{air\ standard}$.

(Nov/Dec 2019)

Soln:-

$$IP = BP + FP \Rightarrow \boxed{B.P = IP - FP}$$

By Morse test,

$$\boxed{IP_1 = BP - BP_{1co}} = 15.6 - 11.1 = 4.5\ kW$$

$$IP_2 = BP - BP_{2co} = 15.6 - 11.03 = 4.57\ kW$$

$$IP_3 = BP - BP_{3co} = 15.6 - 10.88 = 4.72\ kW$$

$$IP_4 = BP - BP_{4co} = 15.6 - 10.66 = 4.94\ kW$$

$$\boxed{IP = IP_1 + IP_2 + IP_3 + IP_4}$$

$$= 4.5 + 4.57 + 4.72 + 4.94$$

$$IP = 18.73\ kW.$$

i) η_{mech} :-

$$\eta_{mech} = \frac{B.P}{I.P} \times 100$$

$$= \frac{15.6}{18.73} \times 100$$

$$\eta_{mech} = 83.3\ \%$$

ii) η_{IT} :-

$$\eta_{IT} = \frac{IP}{m_f \times CV}$$

$$= \frac{18.73}{\frac{6}{3600} \times 83600}$$

$$\eta_{IT} = 13.44\ \%$$

iii) Air standard η :-

$$\eta_{airstd} = 1 - \frac{1}{(r)^{\gamma-1}}$$

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

Stroke Volume, $V_s = \frac{\pi}{4} \times D^2 \times L = \frac{\pi}{4} \times 0.075^2 \times 0.1$

$$V_s = 0.0004417\ m^3.$$

Clearance Volume, $V_c = 0.0001\ m^3.$

$$r = \frac{V_s + V_c}{V_c} = \frac{0.0004417 + 0.0001}{0.0001}$$

$$r = 5.4.$$

$$\eta_{air.std} = 1 - \frac{1}{(5.4)^{1.4-1}} = 49\ \%$$

2) A 4-Cylinder petrol engine has a bore of 60 mm & a stroke of 90 mm. Its rated speed is 2800 rpm and it is tested at this speed against brake which has a torque arm of 0.37 m. The net brake load is 160 N and the fuel consumption is 8.986 litres/h. The specific gravity of petrol used is 0.74 and it has a lower C.V of 44100 kJ/kg. A Morse test is carried out and cylinders are cut out in the order 1, 2, 3, 4 with corresponding brake loads of 110, 107, 104 and 110N respectively. Calculate for this speed: (i) Engine torque, (ii) Brake mean effective pressure, (iii) Brake thermal η (iv) Specific fuel Consumption (SFC), (v) Mechanical η_{mech}, (vi) Indicated mean effective pressure.

Given:-

No. of Cylinders, $n = 4$.

Bore, $D = 60\ mm = 0.06\ m$,

Stroke, $L = 90\ mm = 0.09\ m$, Speed, $N = 2800\ rpm$

Torque arm $= 0.37\ m$, Net brake load $= 160\ N$.

Specific gravity of petrol $= 0.74$.

Fuel consumption, $\dot{m}_f = 8.986$ litres/h

$= 8.986 \times 0.74$

$\dot{m}_f = 6.65\ kg/hr$

$C.V = 44100\ kJ/kg$

Soln:-

i) Engine Torque:-

$$T = \text{Net break load} \times \text{Torque arm}$$

$= 160 \times 0.37$

$T = 59.2$ Nm.

Brake Power, $BP = \frac{2\pi NT}{60000}$

$= \frac{2\pi \times 2800 \times 59.2}{60000}$

$BP = 17.36$ kW.

ii) Brake Mean Effective Pressure (P_m):-

$$B.P = \frac{n P_m LANk \times 10}{6}$$ $\left[k = \frac{1}{2} \text{ for } 4\text{-cylinder}\right]$

$$17.36 = \frac{10 \times 4 \times P_m \times 0.09 \times \left(\frac{\pi}{4} \times 0.06^2\right) \times 2800 \times \frac{1}{2}}{6}$$

$P_m = 7.31$ bar.

iii) Brake Thermal η:-

$$\eta_{BT} = \frac{BP}{\dot{m}_f \times CV} = \frac{17.36}{\frac{6.65}{3600} \times 44100}$$

$\eta_{BT} = 21.3\%$

iv) Specific Fuel Consumption (SFC):-

$$SFC = \frac{\dot{m}_f}{BP} = \frac{6.65}{17.36}$$

$$SFC = 0.383 \, kg/kWh.$$

v) η_{mech} :-

$$\eta_{mech} = \frac{BP}{IP} \times 100$$

$IP_1 = BP - BP_{100} = 160 - 110 = 50 \, N.$

$IP_2 = BP - BP_{200} = 160 - 107 = 53 \, N.$

$IP_3 = BP - BP_{300} = 160 - 104 = 56 \, N.$

$IP_4 = BP - BP_{400} = 160 - 110 = 50 \, N.$

$IP = 50 + 53 + 56 + 50 = 209 \, N.$

$$\eta_{mech} = \frac{160}{209} \times 100 = 76.5\%.$$

vi) Indicated mean effective pressure (P_i) :-

$$\eta_{mech} = \frac{P_m}{P_i}$$

$$P_i = \frac{P_m}{\eta_{mech}} = \frac{7.31}{0.765}$$

$$P_i = 9.55 \, bar.$$

UNIT - V

GAS TURBINES

SYLLABUS:-

Gas turbine cycle analysis - Open and closed cycle. Performance and its improvement - Regenerative, Intercooled, Reheat cycles and their combinations. Materials for turbines.

GAS TURBINES:-

→ It is an internal combustion engine that converts chemical energy of fuel into mechanical energy.

→ Used in aircraft engines, marine engines, etc.,

TYPES OF GAS TURBINES:-

→ According to cycle of operation, (3)
* Open Cycle * Closed cycle * Semiclosed cycle

→ According to process, (2)
* Constant pressure * Constant volume

→ According to number of shafts, (2)
* Single shaft * Multi-shaft.

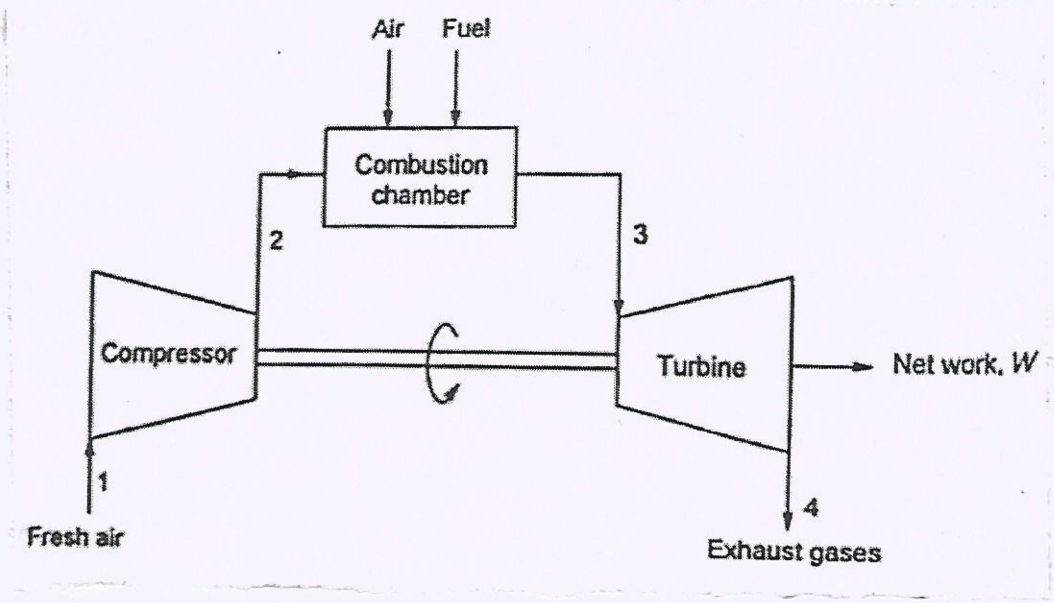
→ According to type of load, (3)
* Peak load * Stand-by * Base load.

→ According to application, (3)
* Aircraft * Marine * Locomotive

→ According to type of fuel, (3)
* Liquid * Gas * Solid

→ According to use (2)
* Industrial * Aircraft.

1) COMPONENTS OF GAS TURBINE (or) WORKING



a) Compressor:-

* Used to draw atmospheric air & compress it to required pressure
* Compressed air transferred to combustion chamber.

b) Combustion chamber:-

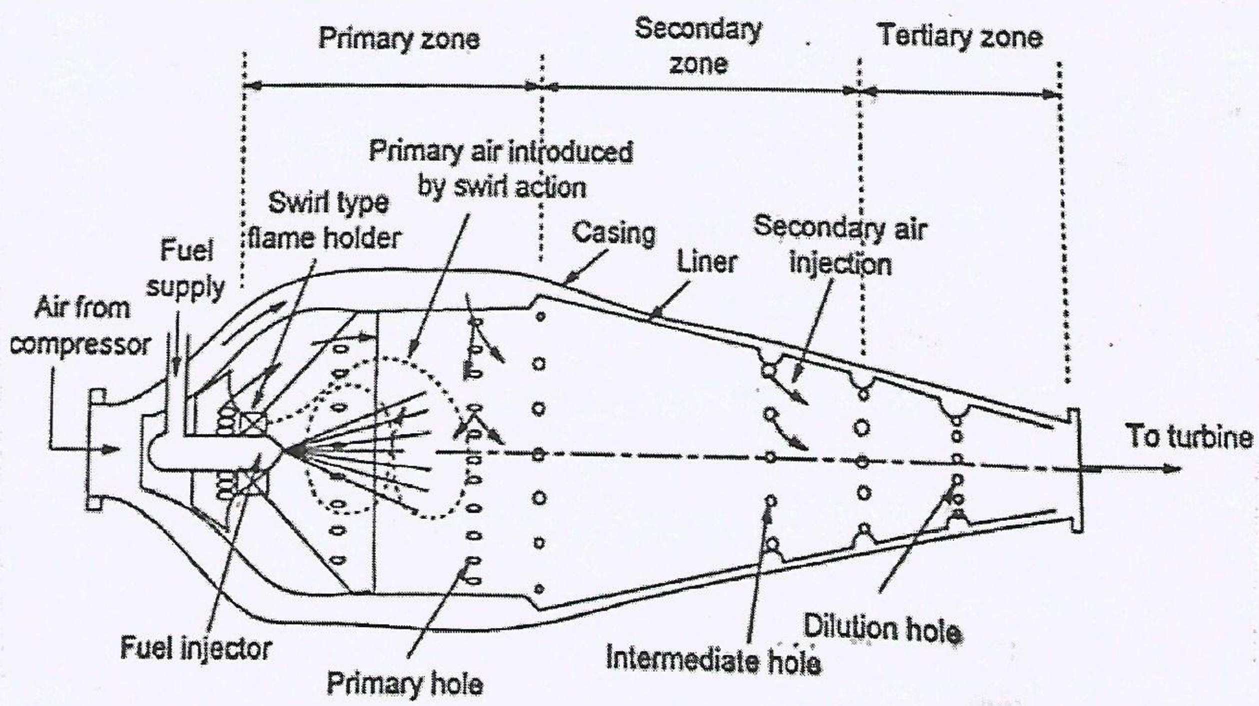


Figure 5.1 Combustion chamber

(a) Fuel injector - Used to inject fuel in combustion chamber.

c) Turbine:-

* Combusted products with high pressure & temperature expanded in turbine.

* Here heat energy gets converted into mechanical energy by rotating turbine blades.

d) Generator:-

* Mechanical energy of turbine could be converted into electrical energy by using generator.

Combustion Zones:-

Primary Zone - 15 to 20% air mixes with fuel.

Secondary Zone - 30% air supplied to flame for complete combustion.

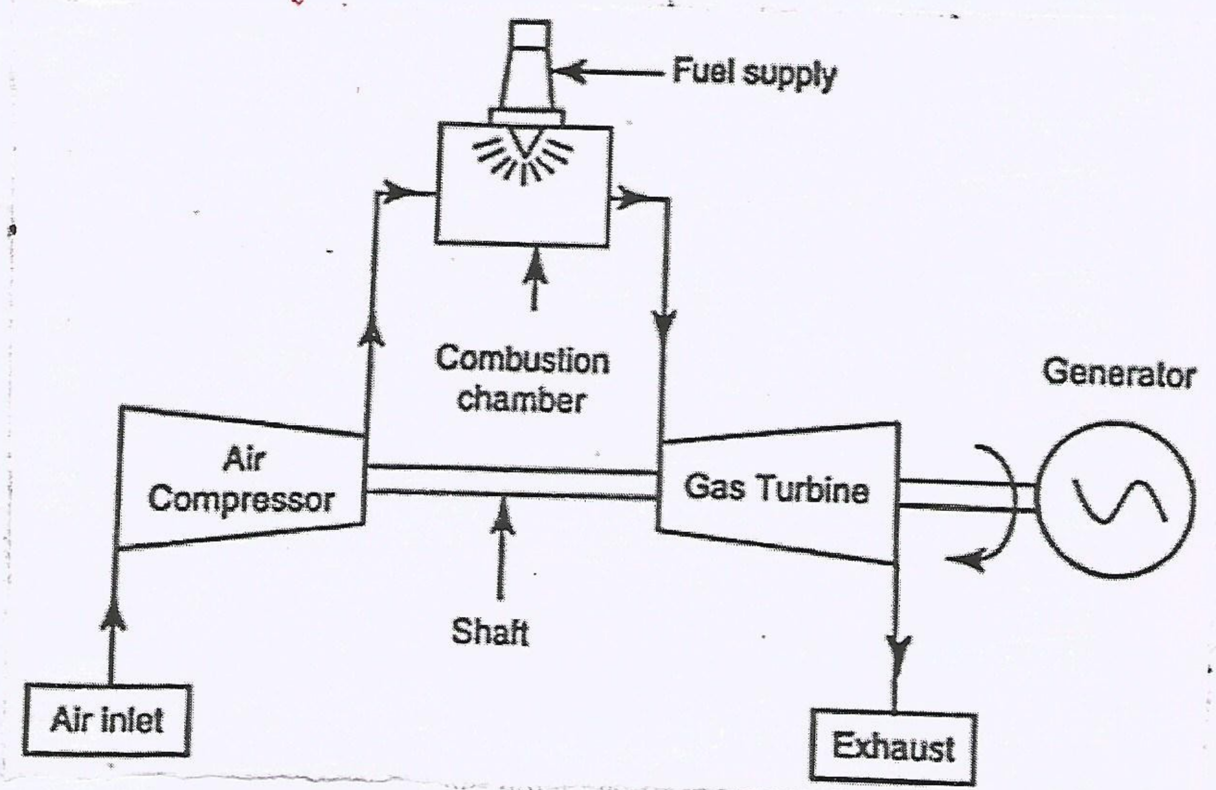
Tertiary Zone - 50% air mixed with burnt gases to cool down the temperature.

---x---x---x---

2) OPEN CYCLE GAS TURBINE:-

→ In this turbine, both inlet and outlet ends are open to atmosphere, hence termed as open cycle gas turbine.

→ Also known as continuous combustion gas turbine.



→ Initially atmospheric air is drawn by rotary compressor, in which pressure & temperature increases isentropically.

→ This compressed air is passed through combustion chamber, in which fuel is injected for combustion.

→ During combustion of fuel, heat is added under constant pressure, which increases temperature of air.

→ Now high pressure & temperature gas expanded in turbine to run the turbine blades.

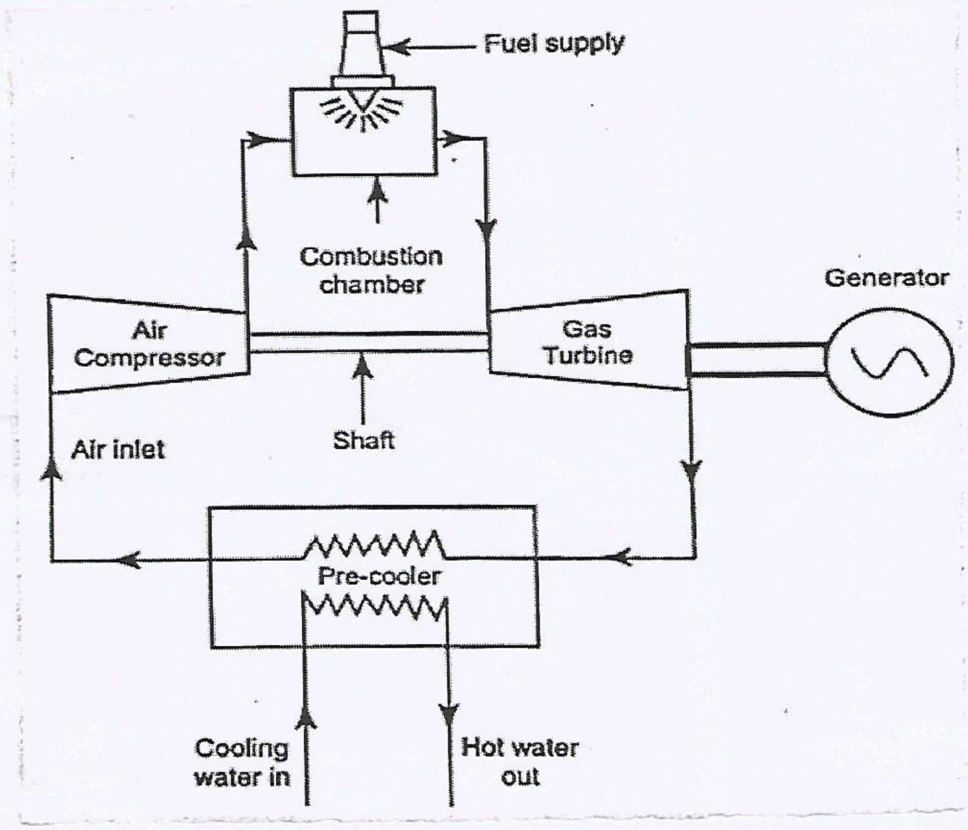
→ Generator coupled with turbine generates electricity.

→ Finally the gas exhausted into atmosphere.

→ Hence in this turbine, working fluid (air) is used only once.

CLOSED CYCLE GAS TURBINE:-

→ In this turbine, both the inlet and outlet are closed, that is not open to atmosphere.



→ Here, an additional component named Precooler is used, which is a type of heat exchanger.

→ Initially air is compressed isentropically in compressor to increase pressure and temperature.

→ Then transferred to Combustion chamber for combustion with fuel for further increase in temperature as Constant pressure process.

→ Then the gas expanded isentropically in turbine to produce mechanical work & electricity in generator.

→ the combusted gas is exhausted to atmosphere in Open Cycle type. But in this closed cycle type, the gas is cooled for using again with the help of Precooler.

→ In precooler, the cooling water absorbs heat from gas ~~at~~ constant pressure condition and the same air is passed through compressor for next cycle of power generation.

Open Cycle Gas Turbine	Closed Cycle Gas Turbine
Advantages	Disadvantages
No precooler required.	A seperate precooler arrangement is needed
For same power developed, size of weight of turbine is less.	Size and weight is high.
Initial cost of mainten--ance cost are less.	High.
Combustion efficiency is more.	Less.
Coolant not required	Coolant required for pre-cooler.
Response to load variation is high	Less.
Disadvantages	Advantages
Part load efficiency is low with respect to power developed.	Efficiency is same throughout the cycle.
Blades are worn by combustion products.	They do not wear.
Thermal stress - High	Low.
High quality fuel needed	Low quality is enough.
Starting of plant - difficult.	Easy.

Gas Turbines	IC Engines (Diesel & Petrol Engine)
It is an external combustion engine, in which fuel burnt outside the engine.	It is an internal combustion engine, in which fuel is burnt inside the cylinder.
Expansion of flue gas takes place in turbine	Expansion of flue gas takes place inside cylinder
Net work output - high	Less.
Efficiency = 20% to 25%	Efficiency = 35% to 40%
Running of power plant is continuous.	Intermittent.
Cost of installation, operating & maintenance are high.	Less.
Plant Capacity - high.	Less.
Lubrication Cost - Less	High.
Need ash handling process.	No need.
Life of plant - High	Less.
Operating temperature & pressure are high. So special metals required.	No need of special metals.

3) GAS TURBINE CYCLE ANALYSIS :-

* BRAYTON Cycle is the theoretical cycle for gas turbines.
* Both Ideal (Theoretical) & Actual cycles have been discussed in UNIT - 1 (pg No :-).

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4) OPTIMUM PRESSURE RATIO FOR MAXIMUM SPECIFIC WORK OUTPUT :-

Pressure ratio, $R_p = \frac{P_2}{P_1} = \frac{P_3}{P_4}$

* 'Optimum pressure ratio' $(R_p)_{opt}$ → Pressure ratio at which work capacity is maximum.
* Pressure ratio is optimum when $T_2 = \sqrt{T_1 \times T_3}$.

Without considering machine efficiencies :-

$$R_p = \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\gamma/\gamma-1} \longrightarrow (1)$$

Sub T_2 in (1).

$$(R_p)_{opt} = \left[\frac{(T_1 \times T_3)^{1/2}}{T_1}\right]^{\frac{\gamma}{\gamma-1}}$$

$$\boxed{(R_p)_{opt} = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{\gamma-1} \times \frac{1}{2}}} \rightarrow (A)$$

Net work output/cycle,

$$W = m C_p (T_3 - T_4) - m C_p (T_2 - T_1) \rightarrow (2)$$

From Brayton Cycle analysis,

$$T_4 = \frac{T_3}{(R_p)^{\frac{\gamma-1}{\gamma}}}, \quad T_2 = T_1 (R_p)^{\frac{\gamma-1}{\gamma}}$$

Sub T_4 & T_3 in (2).

$$W = m C_p \left[\left[T_3 - \frac{T_3}{(R_p)^{\frac{\gamma-1}{\gamma}}} \right] - \left[T_1 (R_p)^{\frac{\gamma-1}{\gamma}} - T_1 \right] \right]$$

$$W = m C_p \left[T_3 \left(1 - \frac{1}{(R_p)^{\frac{\gamma-1}{\gamma}}} \right) - T_1 \left((R_p)^{\frac{\gamma-1}{\gamma}} - 1 \right) \right] \rightarrow (3)$$

Differentiating (3) w.r.t 'R_p'.

$$\frac{dW}{dR_p} = m C_p \left[\left[T_3 \times \frac{\frac{\gamma-1}{\gamma}}{(R_p)^{\frac{\gamma-1}{\gamma}+1}} \right] - \left[T_1 \times \frac{\gamma-1}{\gamma} \times (R_p)^{\frac{\gamma-1}{\gamma}-1} \right] \right] = 0$$

$$T_3 \times \frac{\frac{\gamma-1}{\gamma}}{(R_p)^{\frac{\gamma-1}{\gamma}+1}} = T_1 \times \frac{\gamma-1}{\gamma} \times (R_p)^{\frac{\gamma-1}{\gamma}-1}$$

$$T_3 \times \frac{1}{(R_p)^{\frac{\gamma-1}{\gamma}+1}} = T_1 \times (R_p)^{\frac{\gamma-1}{\gamma}-1}$$

$$\frac{T_3}{T_1} = (R_p)^{\frac{\gamma-1}{\gamma}+1} \times (R_p)^{\frac{\gamma-1}{\gamma}-1}$$

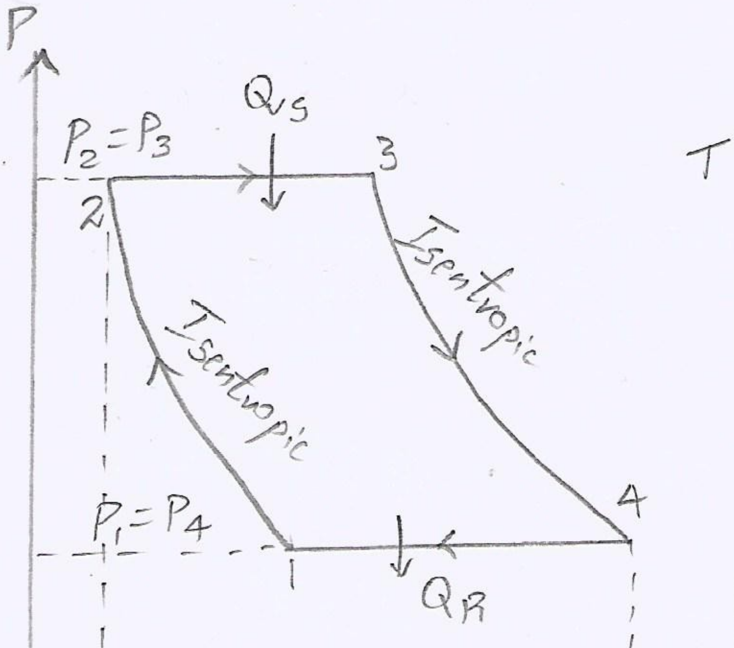
$$\frac{T_3}{T_1} = (R_p)^{2\times\frac{\gamma-1}{\gamma}}$$

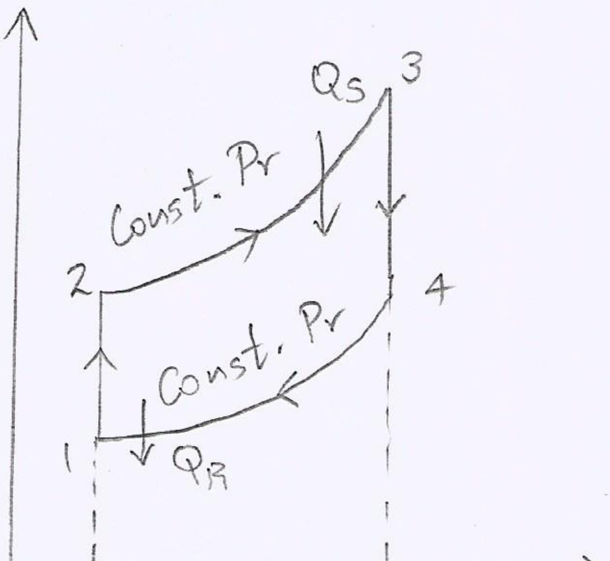
$$R_p = \left(\frac{T_3}{T_1}\right)^{\frac{1}{2}\times\frac{\gamma}{\gamma-1}} \longrightarrow (A)$$

Hence derived.

With considering machine efficiencies:-

$$R_p = \left[\eta_c \times \eta_T \times \frac{T_3}{T_1}\right]^{\frac{1}{2}\times\frac{\gamma}{\gamma-1}}$$





IMPROVEMENTS OF GAS TURBINE CYCLES:-

Efficiency of gas turbine cycle can be improved by four ways,

→ Brayton Cycle with regeneration.
→ Brayton Cycle with intercooling.
→ Brayton Cycle with reheating.
→ Brayton Cycle with combined regeneration, intercooling and reheating.

—x— —x— —x—

5) GAS TURBINE CYCLE WITH REGENERATION:-

* Exhaust gas temperature from turbine is higher than inlet air temperature.
* This temperature of exhaust gas could be used for heating the inlet air by using a heat exchanger named as 'regenerator'.
* It will reduce the energy requirement of fuel, hence increasing the efficiency of cycle.

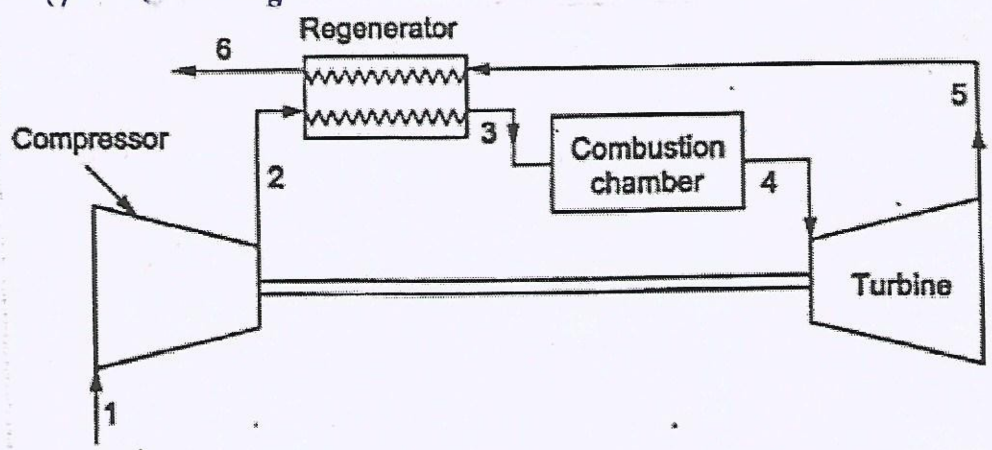


Figure 5.5(a) Brayton cycle with regenerator

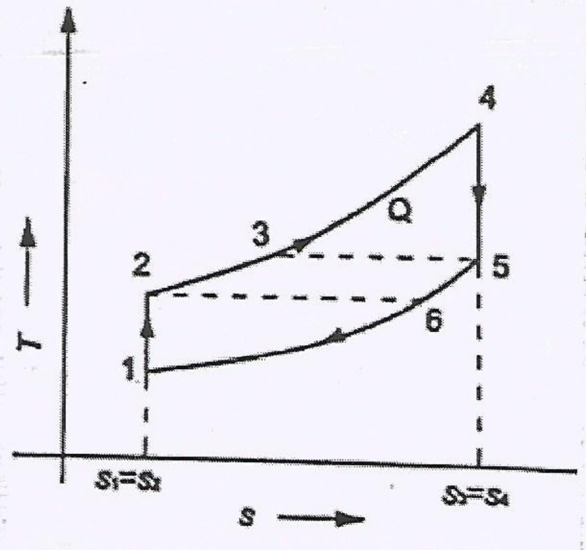


Figure 5.5 (b) T-s diagram

①-② → Air drawn by compressor & compressed isentropically.

②-③ → Air heated in regenerator by exhaust gas at constant pressure.

③-④ → Combustion takes place in combustion chamber. Hence temperature of air increased further.

④-⑤ → Expansion takes place in turbine.

⑤-⑥ → Exhaust gas reaches the regenerator, where it gives some heat to inlet air.

* In ideal cycle, $T_3 = T_5$. But in actual cycle, $T_3 < T_5$.

Effectiveness, $\epsilon = \frac{T_3 - T_2}{T_5 - T_6} = \frac{T_3 - T_2}{T_5 - T_2}$ [$\because T_2 = T_6$]

Heat Supplied, $Q_S = C_p(T_4 - T_3)$

Heat rejected, $Q_R = C_p(T_6 - T_1)$

Turbine Work, $W_T = C_p(T_4 - T_5)$

Compressor Work, $W_C = C_p(T_2 - T_1)$.

Efficiency, $\eta = 1 - \left(\frac{Q_R}{Q_S}\right) = 1 - \left[\frac{T_6 - T_1}{T_4 - T_3}\right]$

For ideal cycle, $T_3 = T_5$, $T_2 = T_6$.

$$\eta = 1 - \left[\frac{T_2 - T_1}{T_4 - T_5}\right] = 1 - \left[\frac{T_1\left(\frac{T_2}{T_1} - 1\right)}{T_4\left(1 - \frac{T_5}{T_4}\right)}\right]$$

W.K.T, $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

$$\frac{T_5}{T_4} = \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

$\left[\because P_5 = P_1 = P_6 ;\ P_2 = P_3 = P_4\right]$

$$\therefore \eta = 1 - \left[\frac{T_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{T_4\left[1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}\right]}\right]$$

$$= 1 - \left[\frac{T_1\left(\frac{\left[P_2^{\frac{\gamma-1}{\gamma}} - P_1^{\frac{\gamma-1}{\gamma}}\right]}{(P_1)^{\frac{\gamma-1}{\gamma}}}\right)}{T_4\left(\frac{\left[P_2^{\frac{\gamma-1}{\gamma}} - P_1^{\frac{\gamma-1}{\gamma}}\right]}{(P_2)^{\frac{\gamma-1}{\gamma}}}\right)}\right] = 1 - \frac{T_1}{T_4}\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\boxed{\eta = 1 - \frac{T_1}{T_4}(R_p)^{\frac{\gamma-1}{\gamma}}}$$

$\therefore$ Efficiency of cycle depends on Pressure ratio (R_p).

---

6) GAS TURBINE WITH INTERCOOLING:-

* By providing intercooler between compressors for multistage compression, the efficiency (thermal) of Brayton cycle can be increased.

* By using intercooler in multistage compression, the work required for the cycle could be minimized.

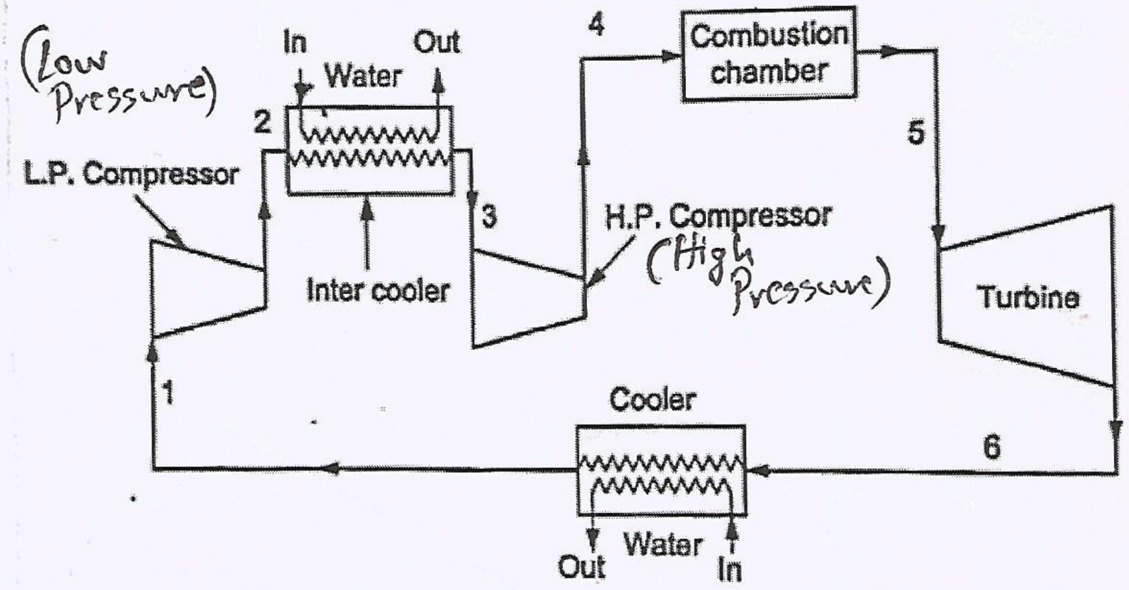


Figure 5.6(a) Brayton cycle with intercooler

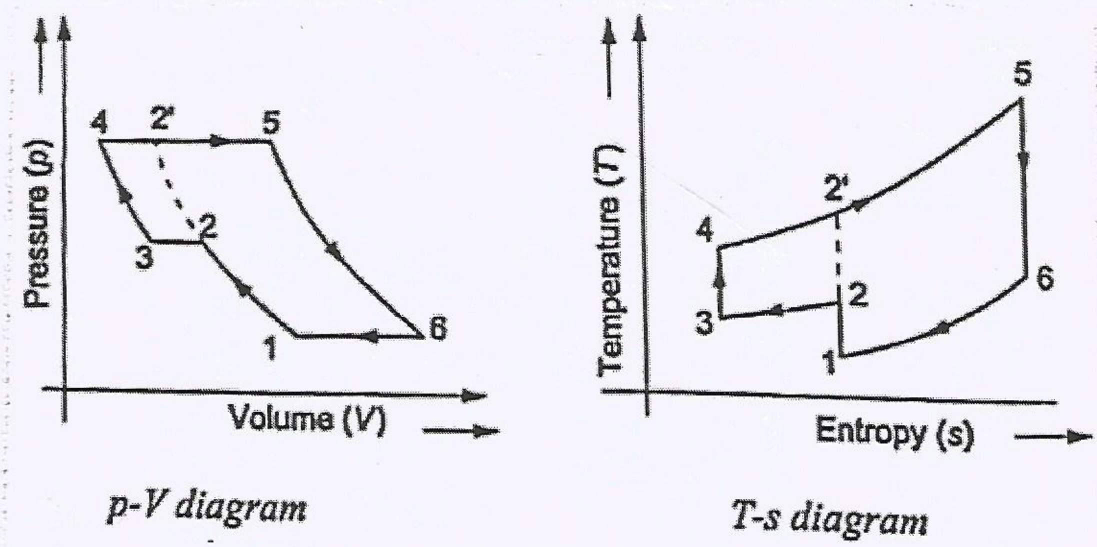


Figure 5.6(b) p-V and T-s diagram

① - ② → Air is drawn in L.P compressor and compressed. Temp & Pressure increased.

② - ③ → Temperature of air reduced by intercooler using cooling water.

③ - ④ → Temperature reduced air is again compressed in H.P compressor.

④ - ⑤ → Compressed air involves in combustion in combustion chamber.

⑤ - ⑥ → Exhaust gas expanded in turbine to produce work

⑥ - ① → Exhaust gas is cooled in Cooler for using air again for next cycle.

[1 - 2′ - 5 - 6 - 1] → Ideal cycle without intercooler.

[1 - 2 - 3 - 4 - 5 - 6 - 1] → Ideal cycle with intercooler.

* Area under 2 - 3 - 4 - 2′ in p-v diagram represents increased net work output. [∵ $w = pdv$]

Turbine Work, $W_T = C_p(T_5 - T_6)$

L.P & H.P Compressors work, $W_C = [C_p(T_2 - T_1) + C_p(T_4 - T_3)]$

Network output, $W = W_T - W_C$.

For perfect intercooling, $\boxed{T_1 = T_3 \ \& \ T_2 = T_4}$

$$\boxed{P_3 = P_2 = \sqrt{P_1 \times P_4} = \sqrt{P_5 \times P_6}} \quad [\because P_1 = P_6, \ P_4 = P_5]$$

7) GAS TURBINE CYCLE WITH REHEATER:-

* Like 'intercooler' in multistage compression, 'reheater' is used for multistage expansion for increasing net work output.
* Like 'intercooler' inbetween two compressors, 'reheater' is used between two turbines.
* Exhaust gas after expansion in first turbine is reheated & again send to another turbine for producing more work.

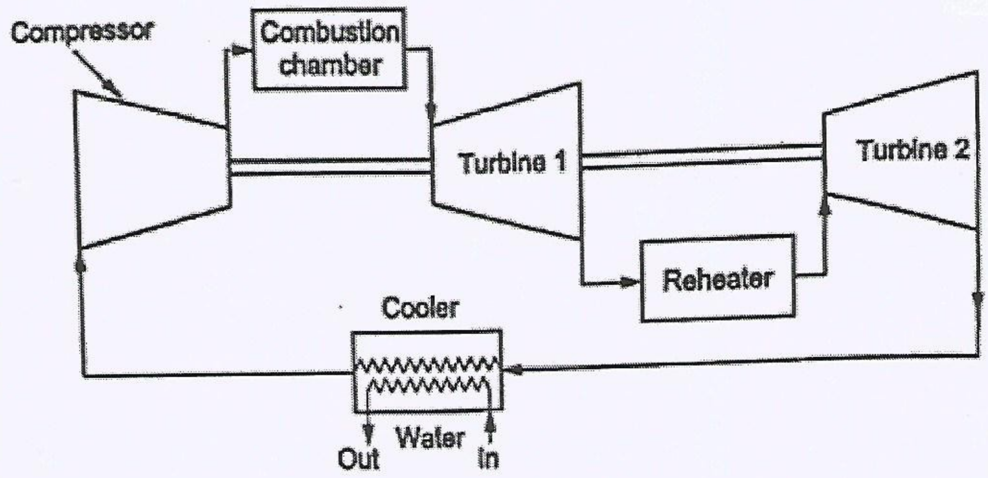
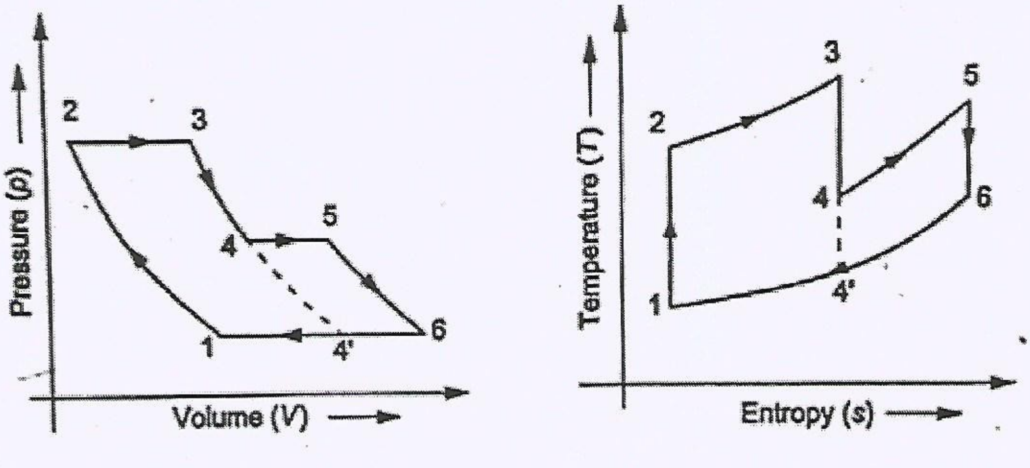


Figure 5.7(a) Brayton cycle with reheater



p-V diagram *T-s diagram*

Figure 5.7(b) p-V and T-s diagram

① - ② → Air is drawn & compre- (10)
-ssed in compressor isentropically.

② - ③ → Compressed air involved in combustion process in combustion chamber.

③ - ④ → High pressure & high temp gas expanded in Turbine 1 as isentropically.

④ - ⑤ → Exhaust gas from Turbine 1 heated in 'reheater'.

⑤ - ⑥ → Reheated gas expanded in Turbine 2.

⑥ - ① → Exhaust gas from 'Turbine-2' is cooled & used again.

* Area under 4-5-6-4'-4 in p-v diagram represents increased net workoutput.

* Process 1-2-2'-5-6 → Without reheater.
Process 1-2-3-4-5-6 → With reheater

Compressor work, $W_c = C_p(T_2 - T_1)$

Turbine 1 & 2 Work, $W_T = C_p(T_3 - T_4) + C_p(T_5 - T_6)$

Network done, $W = W_T - W_c$

For obtaining maximum work,

$$\frac{P_3}{P_4} = \frac{P_5}{P_6}$$

$$P_4 = P_5 = \sqrt{P_3 \times P_6} = \sqrt{P_1 \times P_2} \quad \left[\because P_1 = P_6,\ P_2 = P_3\right]$$

———x——— ———x——— ———x——— ———

8) GAS TURBINE CYCLE WITH INTERCOOLING, REHEATING & REGENERATION:-

* All three methods are combined for improving thermal efficiency of Brayton Cycle.

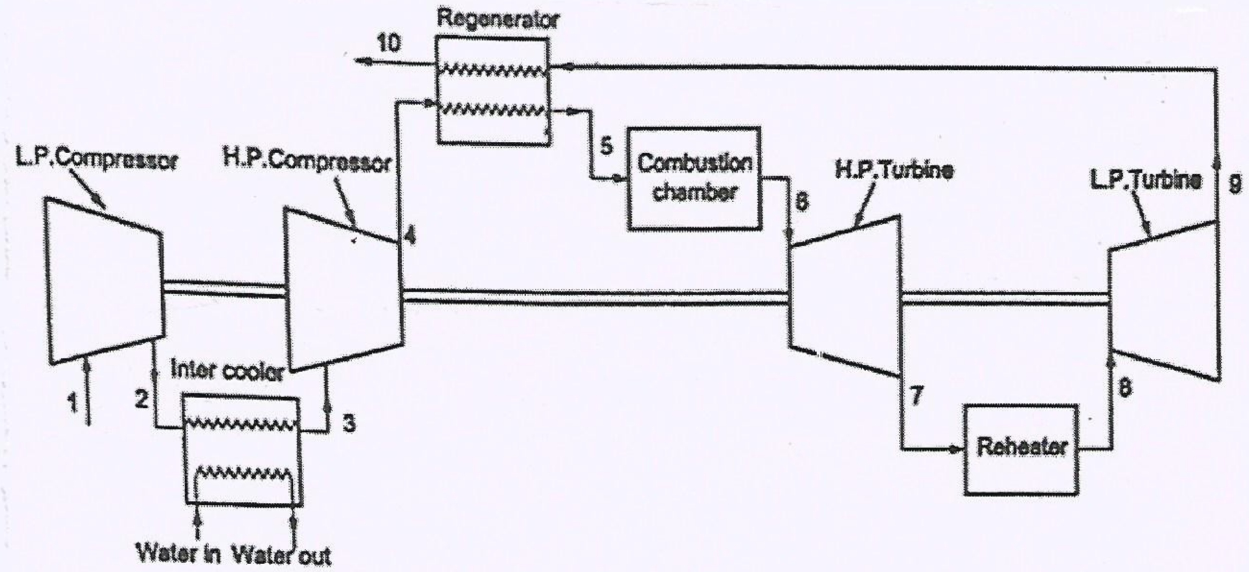


Figure 5.8 (a) Brayton cycle with intercooler, reheater and regenerator

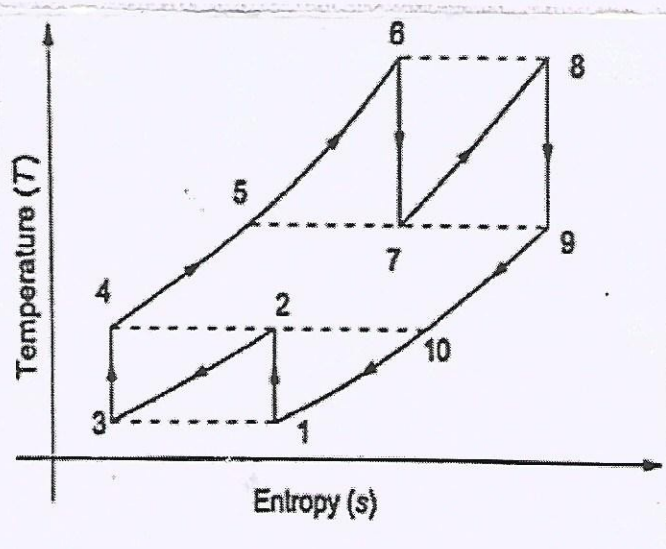


Figure 5.8 (b) T-s diagram

Compressor Work,

$$W_c = C_p(T_2 - T_1) + C_p(T_4 - T_3)$$

Turbine Work,

$$W_T = C_p(T_6 - T_7) + C_p(T_8 - T_9)$$

Network output,

$$W = W_T - W_c.$$

Heat Supplied,

$$Q_S = C_p(T_6 - T_5) + C_p(T_8 - T_7)$$

Heat rejected, $Q_R = C_p(T_{10} - T_1) + C_p(T_2 - T_3)$.

Thermal efficiency, $\eta_{the} = 1 - \frac{Q_R}{Q_S}$

$$\eta_{the} = 1 - \frac{(T_6 - T_5) + (T_8 - T_7)}{(T_{10} - T_1) + (T_2 - T_3)}$$

9) CONDITION FOR BEST PERFORMANCE (or) FOR MINIMUM COMPRESSOR WORK (or) FOR MAXIMUM TURBINE WORK.

* Intercooling and reheating always reduce thermal efficiency unless accompanied by regeneration.

* Gas turbine cycle with all three methods produce best performance.

[NOTE :- 'Explain previous question']

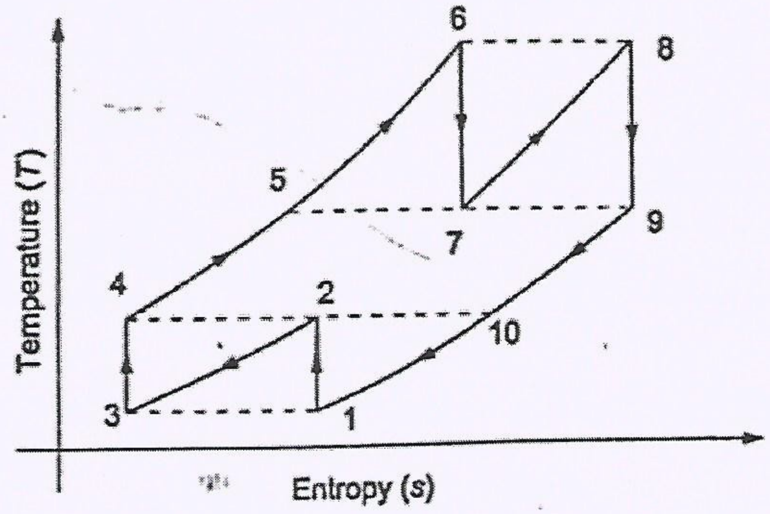


Figure 5.9 Two stage compression and expansion with regenerator

* Conditions for best performance as follows,

* $P_2 = \sqrt{P_1 P_3}$ → Minimum Compressor Work

* $\left[P_4 = \sqrt{P_3 P_5} \quad P_7 = \sqrt{P_6 P_9} \right]$ → Maximum Turbine Work.

10) MATERIALS FOR GAS TURBINES:-

Approach for Material Selection:-

→ Initial Approach

* Ability to withstand at elevated temperature.

* Strength to weight ratio play important role in weight reduction.

→ Challanges in approach based on operating temperature

* Stress and creep properties.

* Low Cycle - Fatigue life.

* Oxidation of hot corrosion resistant.

Main Parts & its materials:-

a) Compressor:-

* Challenges:- High strength, Centrifugal stress, Fatigue, Temperature range upto 1200°F.

* Material:- Titanium Alloy, due to its high strength to weight ratio.

b) Compressor Blades:-

* Challenges:- stress corrosion resistance, increased tensile strength, high cycle fatigue strength, resistance to acidic salt environment.

* Material:- 12% chromium containing Martensitic stainless steel.

c) Combustion Chamber:-

* Challenges:- High temperature, creep strength, Oxidation & Corrosion resistance.

* Material:- Nickel based alloys.

* Combustor liners provided with Thermal Barrier Coating (TBC).

d) Turbine Blade & Vanes:-

* Challenges:- High temperature, Creep and oxidation resistance.

* Material:- Nickle based alloys and aluminium based alloys.

e) Nozzle:-

* Challenge:- High strength at high temperature.

* Material:- Cobalt based alloys and Nickle based superalloy.

f) Vanes:-

* Challenge:- Strength upto a relatively high fraction of melting point.

* Material:- Oxide Dispersion Strengthened (ODS) Superalloys.

Coating on Turbine Blade:-

* Used to form protective and adherent oxide layer.

* Protect base material from oxidation & corrosion attack.

* Following are types of coatings,

→ Aluminide Coating.

→ Thermal Barrier Coating.

Advanced Materials under R&D:-

* Ceramics.
* Intermetallics.
* Polymer matrix composites.
* Titanium based composites.
* Ceramic matrix composites.

Above materials are under Research & Development aiming for weight reduction & strength enhancement.