AALIM MUHAMMED SALEGH COLLEGE OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

ME 8493 – THERMAL ENGINEERING – 1

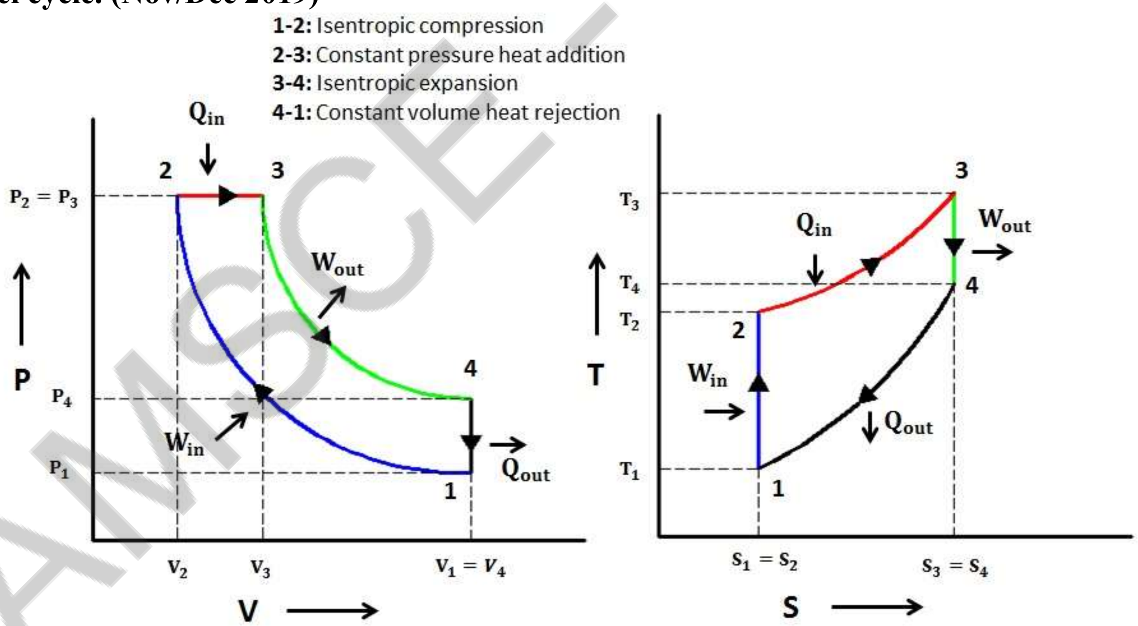
QUESTION BANK

UNIT – 1

GAS AND STEAM POWER CYCLES

PART – A

1. **What are the assumptions made in air standard cycle? (May 2019)**
    - The working fluid is a perfect gas. It follows the law of pv=mRT
    - The compression and expansion process are reversible adiabatic
    - The working fluid should not undergo any chemical change throughout the cycle
    - Kinetic and potential energies of the working fluid are neglected
    - No heat loss between the system and surroundings
2. **Plot the Diesel engine cycle on P-V and T-S diagram. Name the various process of the diesel cycle. (Nov/Dec 2019)**



P-V and T-S Diagram of Diesel Cycle

3. **Define mean effective pressure and comment its application in internal combustion engines? (Apr/May 2019)**
   Mean effective pressure is defined as the constant pressure acting n the piston during working stroke. It is also defined as the ratio of work done to the stroke volume or piston displacement volume.
   Mean effective pressure (MEP)
   p_m= work done/ stroke volume or piston displacement volume
4. **What are the factors influencing the ideal Brayton cycle efficiency? (April/May 2019)**
   The following factors influencing the ideal Brayton cycle efficiency
   - ✓ The net work output of the cycle
   - ✓ Heat supplied
5. **Define air standard cycle efficiency? (Nov/Dec 2018)**
   Air standard efficiency is the ratio of work done during the process to the heat supplied during the process.
   Air standard efficiency = work done / heat supplied
   Air standard efficiency I taken as the ideal efficiency of an internal combustion engine. In this case we imagine air is used instead of petrol or fuel oil mixed with air to form a gas.
6. **Define cut-off ratio. (Nov/Dec 2018)**
   It is defined as the ratio of volume after the expansion to the volume before the expansion.

7. **Write any four differences between Otto and Diesel cycle?**

Otto cycle	Diesel cycle
It consists of two isentropic and two constant volume processes	It consists of two adiabatic, one constant volume and one constant pressure processes
Heat addition takes place in constant volume process	Heat addition takes place in constant pressure process
Efficiency is high	Efficiency is less
Compression ratio is equal to expansion ratio	Compression ratio is greater than expansion ratio

8. **Define mean effective pressure as applied to gas power cycles.**
   Mean effective pressure is defined as the constant pressure acting on the piston during the working stroke. It is also defined as the ratio of work done to the stroke volume of the piston displacement volume.
9. **What is thermodynamic cycle?**
   Thermodynamic cycle is defined as the series of processes performed on the system, such that the system attains its original state.
10. **What is an air standard cycle/ why such cycles are used?**
    Air standard cycle is an thermodynamic cycle, which used air, as the working fluid is known as air standard cycle. To carry out the analysis of heat engines, the concept of air standard cycles are used.

11. Define air standard efficiency.

Air standard efficiency is an ideal efficiency. It is defined as the ratio of work done by the heat supplied. Actual efficiency of an engine will always less than the ideal or air standard efficiency.

12. What are the various types of gas power cycles?

- Otto cycle
- Diesel cycle
- Brayton cycle
- Carnot cycle
- Dual combustion cycle

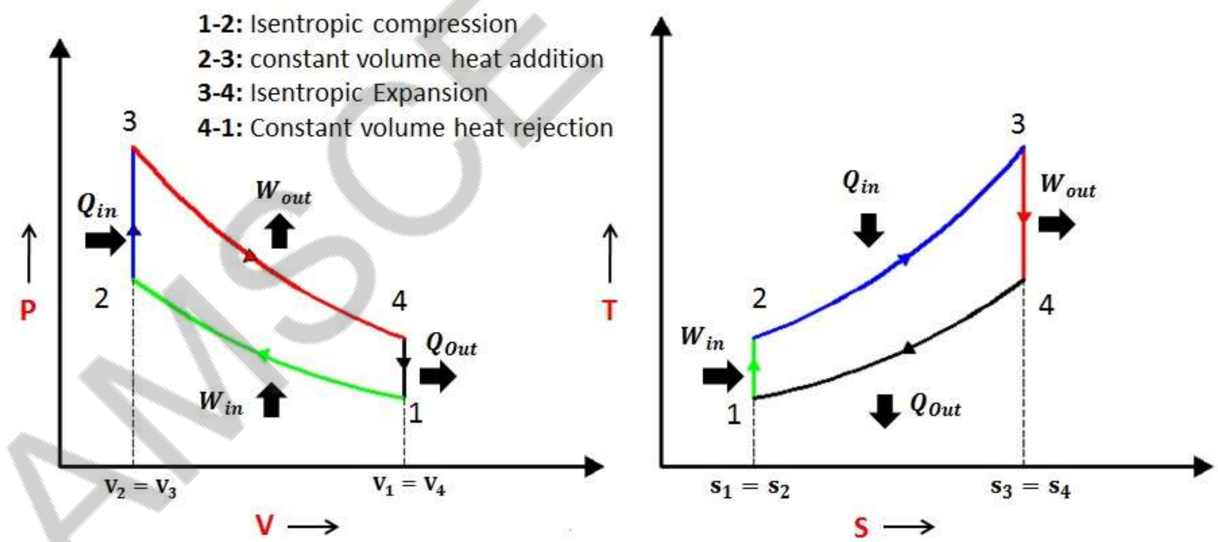
13. Define compression ratio.

It is defined as the ratio of total cylinder volume to the clearance volume.

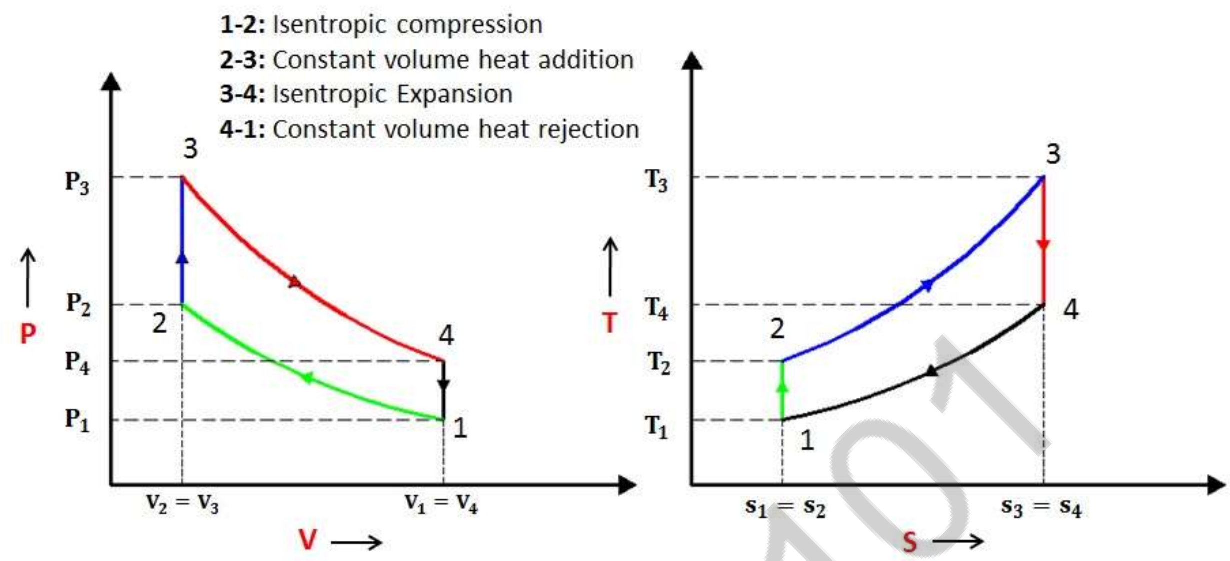
14. Define mean effective pressure. (April/May 2019)

It the constant (or) average pressure acting on the piston during the working stroke. It is defined as the ratio of work done to the swept (or) stroke volume.

15. Draw the P-V and T-S diagram of Otto cycle and name the process involved.

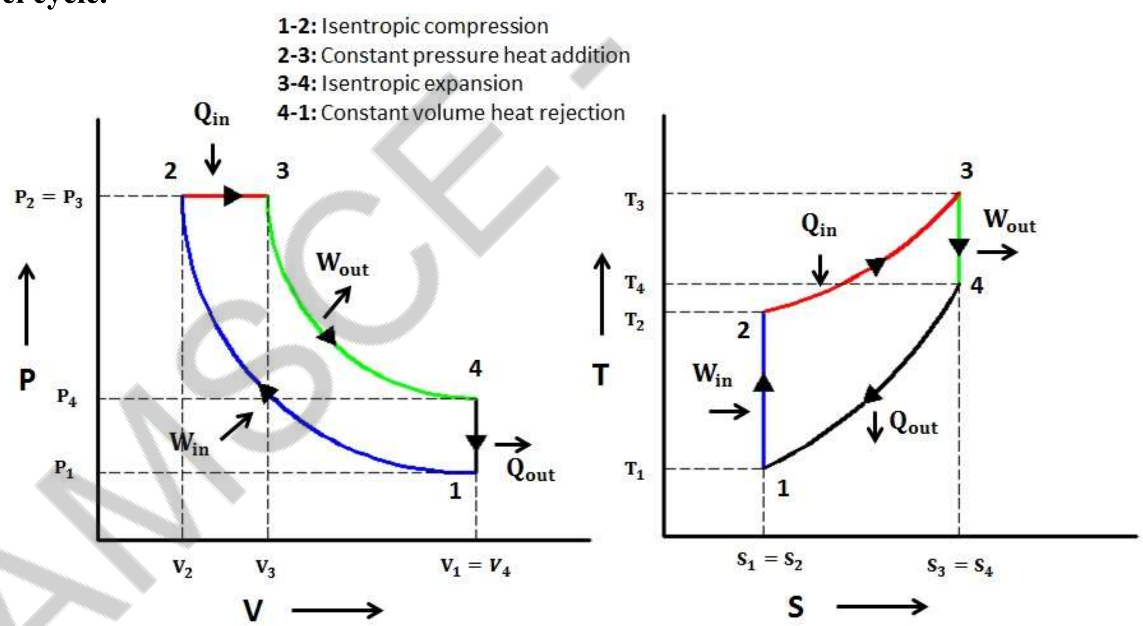


P-V and T-S Diagram of Otto Cycle



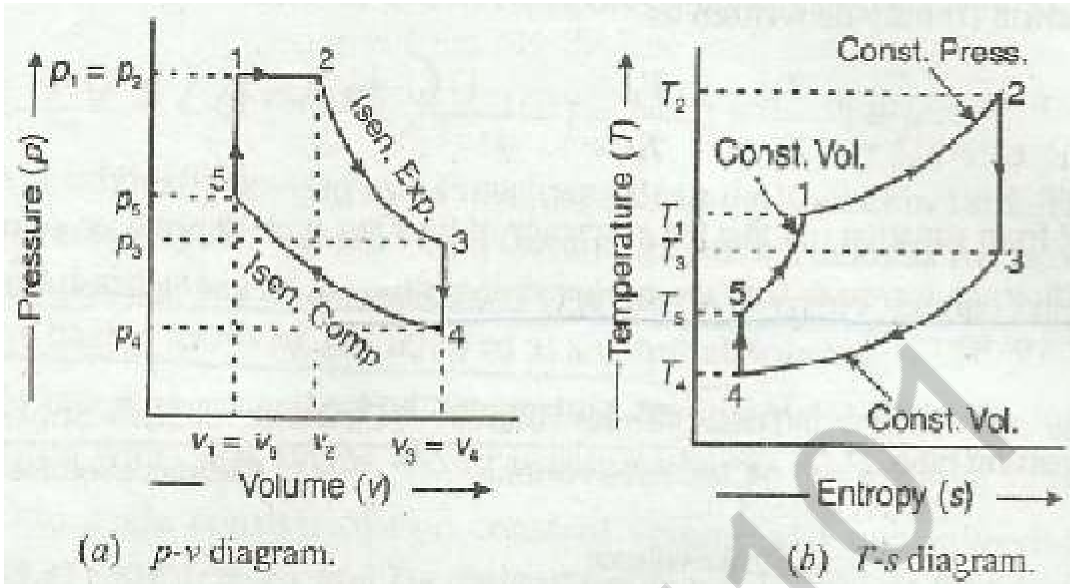
P-V and T-S Diagram of Otto Cycle

16. **Plot the Diesel engine cycle on P-V and T-S diagram. Name the various process of the diesel cycle.**



P-V and T-S Diagram of Diesel Cycle

17. **Sketch the dual cycle on p-V and T-S diagram. Name the various process of the dual cycle.**



18. What is the effect of compression ratio on air standard efficiency of an ideal Otto cycle?

The efficiency of Otto cycle increases with the increase in compression ratio.

19. What is gas turbine?

Gas turbine is an axial flow rotary turbine in which gas is used as working medium.

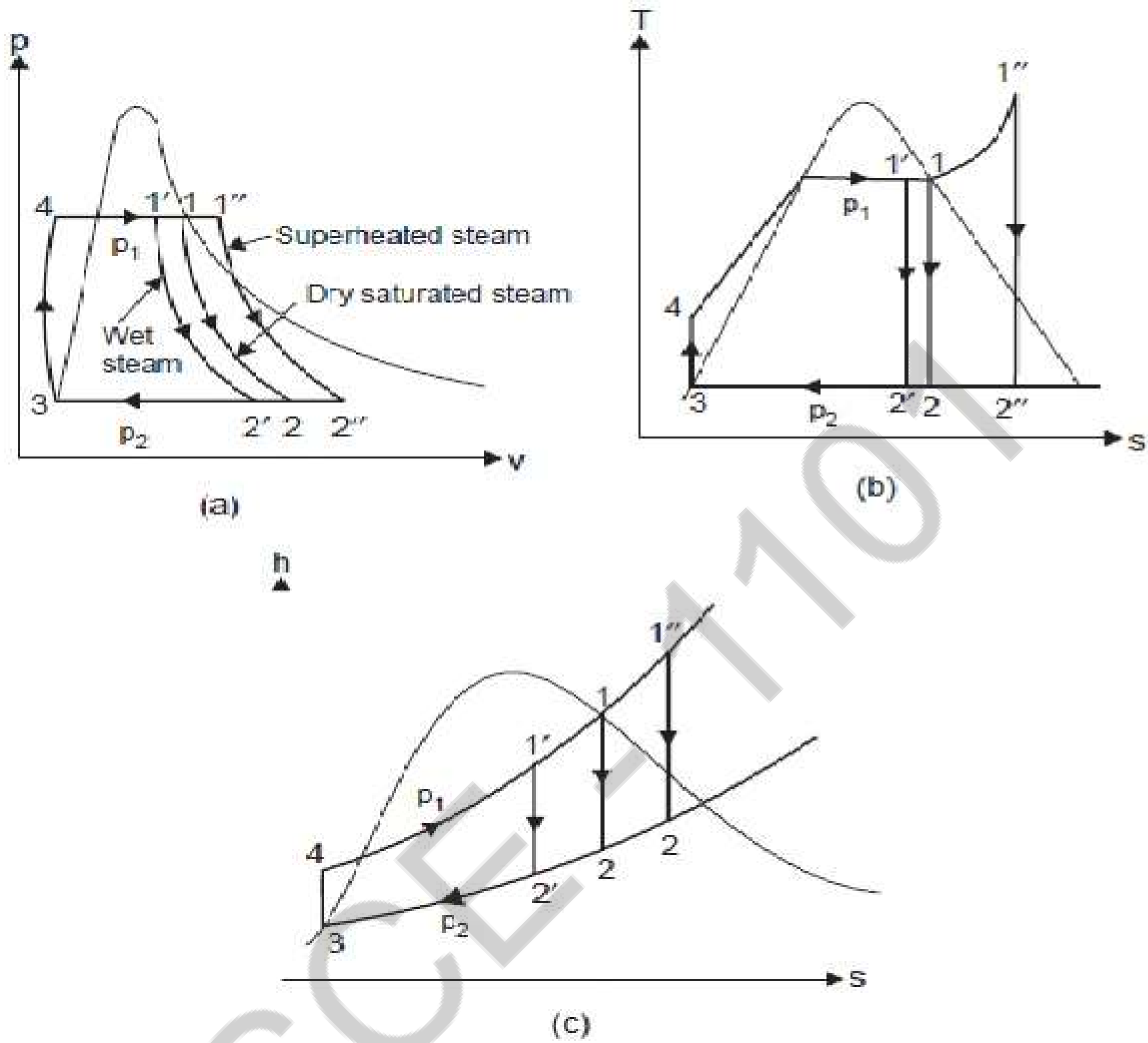
20. Differentiate open and closed cycle gas turbine?

Open cycle gas turbine	Closed cycle gas turbine
• Gas is exhausted to the atmosphere after each cycle	• Gas is recirculated again and again
• Size is small	• Size is large
• Weight is less	• Weight is high
• High quality fuels are used	• Low quality fuels are used
• Intercooler is not required	• Intercooler is required to cool the exhaust gas to the original temperature

21. What is meant by steam (or) vapour power cycles?

The cycle used to convert heat into work are called the power cycle. If the working fluid in the cycle is vapour, it is called as vapour power cycle.

22. Plot p-V and T-S and h-S diagram of Rankine cycle and name the various processes involved in it.



23. Define heat rate.

It is defined as the rate of heat input required to produce unit work output (1 kW)

$$heat\ rate = \frac{heat\ input\ in\ kJ\ /\ s\ x\ 3600\ s\ /\ h}{net\ power\ output\ in\ kW}$$

24. Define the term relative efficiency (or) efficiency ratio.

It is defined as the ratio of the actual thermal efficiency of steam power plant to the Rankine efficiency.

Relative efficiency = actual thermal efficiency / Rankine efficiency

25. Why Carnot cycle is not practical for a vapor power plant?

- The steam at exit of the turbine is of low quality (ie) high moisture content when strikes the blades causes erosion and wear of the turbine blades.
- It is impossible to maintain the quality of steam during the condensation process in the condenser.
- The steam after the condensation process is both in the liquid and the vapor state. So it is very difficult to fabricate and maintain a pump with large work to convert it to saturated liquid.

- The superheating of steam in a boiler at constant temperature is impossible.
- The vapor has a large specific volume and to accommodate greater volumes, the size of the compressor becomes quite large.

26. Explain the Reheat rankine cycle.

The Reheat Rankine cycle is used to prevent liquid-droplet formation in the turbine exit. In the reheat cycle, steam is reheated after expanding partially in the high-pressure turbine. This is done by the partial expansion of steam in the high-pressure turbine.

The steam is then sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the high-pressure turbine. Steam then supplied to the low pressure turbine in which it expands isentropically to the condenser pressure.

27. What are the advantages of Reheat Rankine cycle?

- It increases the thermal efficiency of the cycle when the cycle works at optimum values of the boiler pressure and the reheat pressure.
- It increases the net work output.
- It decreases the moisture content of the steam at the low pressure turbine exit, reducing the turbine blade erosion.
- It increases the average temperature of the heat addition.

28. What is Regenerative cycle?

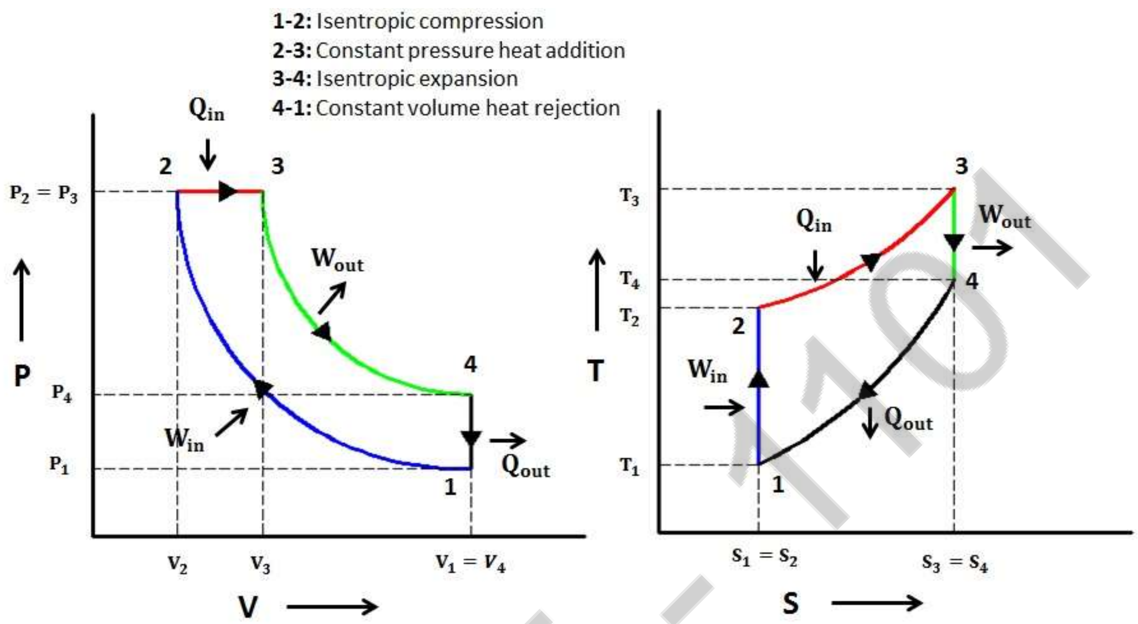
Regeneration is a process in which the certain quantity of heat extract from the steam is utilized to heat the feed water. The cycle that utilizes this type of heating is called a regenerative cycle.

29. What are the advantages of the regenerative cycle?

- ✓ It increases the thermal efficiency of the cycle
- ✓ Water particles escape with the bled steam through extraction belts. This reduces the moisture content in the steam, thus decreasing the turbine blade erosion.
- ✓ Feed heating by bled steam decreases the quantity of steam reaching the condenser. Thus in turn reduces the size of the condenser and the cooling water requirements.
- ✓ Steam extraction for feed heating reduces the flow rate significantly in the low pressure stages, thus allowing the blades to be shorter. This is a great advantage in large units where the designing long turbine blades is very critical.

Part – B

1. **Derive the expression for the efficiency of diesel cycle in terms of cycle parameters. (May 2019)**



P-V and T-S Diagram of Diesel Cycle

1-2 Isentropic compression
2-3 Constant pressure Heating
3-4 Isentropic expansion
4-1 Constant volume Cooling

Since combustion takes place at constant pressure the Diesel cycle is also called as **Constant Pressure Cycle**.

Heat Supplied $= C_p (T_3 – T_2)$ -------(1)

Heat Rejected $= C_v (T_4 – T_1)$ -------(2)

$\therefore$ Work done = Heat Supplied – Heat Rejected

$= C_p (T_3 – T_2) - C_v (T_4 – T_1)$

$$\eta_{cycle} = \frac{workdone}{Heat\ Supplied} = \frac{C_p\ (T_3 - T_2) - C_v\ (T_4 - T_1)}{C_p\ (T_3 - T_2)}$$

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

$$\eta_{cy} = 1 - \left[\frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}\right]$$

$$\because \frac{C_p}{C_v} = \gamma = ratio\ of\ specific\ Heats$$

$$\eta_{cy} = 1 - \frac{T_1\left[\frac{T_4}{T_1} - 1\right]}{\gamma T_2\left[\frac{T_3}{T_2} - 1\right]} = 1 - \frac{\left[\frac{T_4}{T_1} - 1\right]}{\gamma r^{\gamma-1}\left[\frac{T_3}{T_2} - 1\right]} \quad \text{--------(3)}$$

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

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

$$= \left(\frac{V_3}{V_4}\right)^{\gamma-1} \times \frac{T_3}{T_2} \times \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$= \left(\frac{V_3}{V_2}\right)^{\gamma-1} \times \frac{T_3}{T_2} \qquad [\because V_4 = V_1]$$

$$= \left(\frac{V_3}{V_2}\right)^{\gamma-1} \times \frac{V_3}{V_2}$$

$$\left[\because \frac{T_3}{T_2} = \frac{V_3}{V_2}, \text{2-3 constant pressure process}\right]$$

$$= \left(\frac{V_3}{V_2}\right)^{\gamma} = r_c^{\gamma}$$

$$where \quad r_c = \frac{V_3}{V_2} = cutoff \ ratio$$

substituting $\frac{T_4}{T_1} = r_c^{\gamma}$ and $\frac{T_3}{T_2} = r_c$ in equation (3),

$$\eta_{cy} = \left\{1 - \frac{\left[r_c^{\gamma} - 1\right]}{\gamma r^{\gamma - 1}\left[r_c - 1\right]}\right\}$$

2. **In an SI engine working on the ideal Otto cycle, the compression ratio is 5.5. the pressure and temperature of compression are 1 bar and 27°C, respectively. The peak pressure is 30 bar. Determine the pressure and temperature at the salient points, the air-standard efficiency and the mean effective pressure. Assume ratio of specific heats to be 1.4 for air. (Nov/Dec 2019)**

   Given:

Given data:

Compression ratio $r_k = 5.5$

$P_1 = 1 \text{ bar} = 1 \times 10^5 \ N/m^2$

$P_3 =$ Peak (or) Max. Pressure $= 30 \text{ bar} = 30 \times 10^5 \ N/m^2$

Ratio of specific heat of air $\gamma = 1.4$

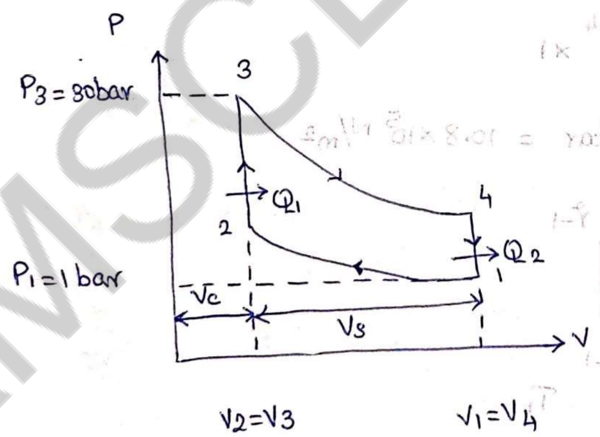
To find:

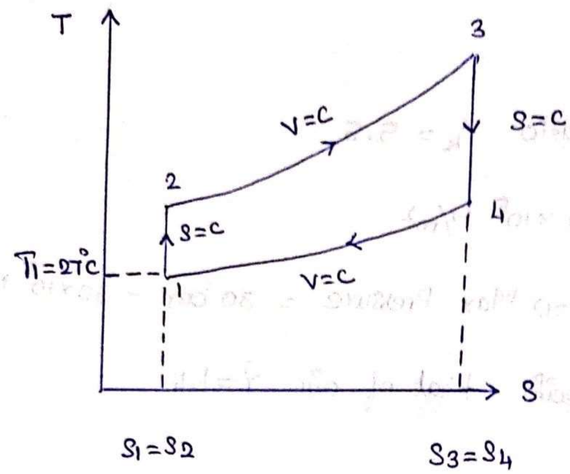
i) Pressure, Temperature at all salient points
$[P_2, P_4, T_2, T_3, T_4]$

ii) Air standard efficiency (η_{air})

iii) Mean effective pressure (P_m).

Solution:





Process 1-2: Isentropic compression $[PV^{\gamma}=C]$

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$\frac{P_2}{P_1} = \left[\frac{V_1}{V_2}\right]^{\gamma}, \quad \frac{P_2}{P_1} = (r_K)^{\gamma}$$

$$P_2 = (r_K)^{\gamma} \cdot P_1$$

$$P_2 = (5.5)^{1.4} \times 1$$

$$P_2 = 10.8 \text{ bar} = 10.8 \times 10^5 \text{ N/m}^2$$

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

$$T_2 = [r_K]^{\gamma-1} \cdot T_1$$

$$T_2 = [5.55]^{1.4-1} \times 300$$

$$T_2 = 593.28 \text{ K}$$

Process : 2-3 : Constant Volume Heat Addition (v=c)

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

$$T_3 = \frac{P_3}{P_2} \times T_2 \Rightarrow T_3 = \frac{30}{10.88} \times 593.28$$

$$T_3 = 1635.88\ K.$$

Process 3-4 : Isentropic Expansion

$$P_3 V_3^{\gamma} = P_4 V_4^{\gamma}$$

$$\frac{P_4}{P_3} = \left[\frac{V_3}{V_4}\right]^{\gamma} \quad V_3 = V_2 \ ; \ V_4 = V_1 \text{ from P-V diagram}$$

$$\frac{P_4}{P_3} = \left[\frac{V_2}{V_1}\right]^{\gamma} \Rightarrow P_4 = \left[\frac{1}{r_k}\right]^{\gamma} \times P_3$$

$$P_4 = \left[\frac{1}{5.5}\right]^{1.4} \times 30$$

$$P_4 = 2.758 \text{ bar} = 2.758 \times 10^5\ N/m^2$$

$$\frac{T_4}{T_3} = \left[\frac{V_3}{V_4}\right]^{\gamma-1} \Rightarrow \frac{T_4}{T_3} = \left[\frac{V_2}{V_1}\right]^{\gamma-1}$$

$$\frac{T_4}{T_3} = \frac{1}{[r_k]^{\gamma-1}} \Rightarrow T_4 = \frac{1}{[r_k]^{\gamma-1}} \times T_3$$

$$T_4 = \frac{1635.88}{[5.5]^{0.4}} \quad T_4 = 827.19\ K$$

Air standard efficiency

$$\eta_{air} = 1 - \frac{1}{[r_k]^{\gamma-1}}$$

$$= 1 - \frac{1}{[5.5]^{1.4-1}}$$

$$\eta_{air} = 49.43\,\%$$

Mean Effective Pressure $P_m = \dfrac{\text{Network done}}{\text{Swept (or) stroke volume}}$

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

Work done $= \eta_{air} \times$ Heat supplied

Heat supplied per kg of air

$$Q_s \text{ (or) } Q_1 = C_v\,[T_3 - T_2]$$

$$= 0.718\,[1635.88 - 593.28]$$

$$= 748.58 \text{ kJ/kg}$$

$$\text{Workdone} = 0.4943 \times 748.58$$

$$= 370.02 \text{ kJ/kg}$$

$$P_m = \frac{W}{V_1 - V_2} = \frac{W}{V_1\left[1 - \frac{V_2}{V_1}\right]} = \frac{W}{V_1\left[1 - \frac{1}{r_k}\right]}$$

$$P_1 V_1 = R T_1 \Rightarrow V_1 = \frac{0.287 \times 300}{100} = 0.861 \text{ m}^3/\text{kg}$$

$$P_m = \frac{W}{V_1\left[1-\frac{1}{r_k}\right]} = \frac{370.02}{0.861\left[1-\frac{1}{5.5}\right]}$$

$P_m = 525.25$ kPa (or) 5.25 bar $= 5.25\times10^5\ N/m^2$

3. In an air standard dual cycle, the pressure and temperature at the beginning of the compression are 1 bar and 57°C respectively. The heat supplied in the cycle is 1250 kilo Joule/kg, two-third of this being added at constant volume and rest a constant pressure. If the compression ratio is 16, determine the maximum pressure and temperature in the cycle thermal efficiency and MEP. (April/May 2019)

Given:

$P_1 = 1$ bar. $T_1 = 57°C = 273+57 = 330K$

$r = 16$

$Q_s = 1250$ kJ/kg

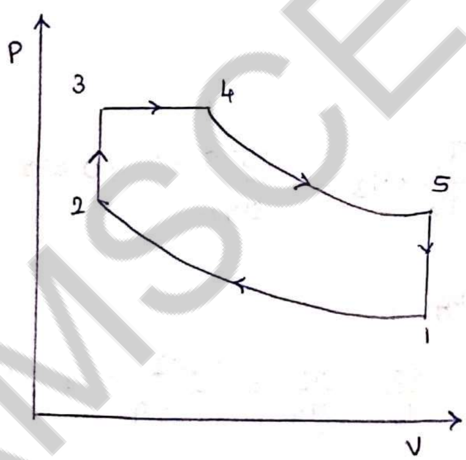
$Q_{s1} = \frac{2}{3} \times Q_s = \frac{2}{3} \times 1250 = 833.33$ kJ/kg

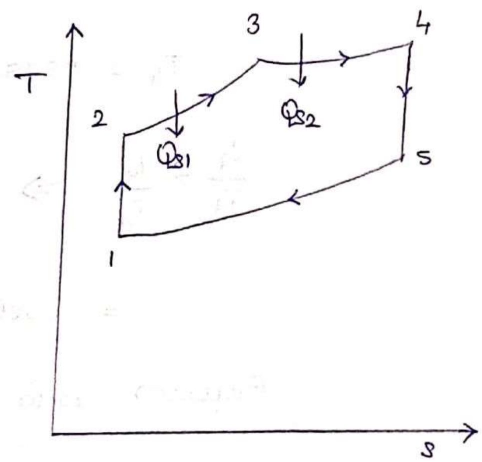
$Q_{s2} = \frac{1}{3} \times Q_s = \frac{1}{3} \times 1250 = 416.67$ kJ/kg

solution:

specific volume $v_1 = \frac{RT_1}{P_1} = \frac{287 \times 330}{1 \times 10^5} = 0.9471$ m³/kg

$r = \frac{V_1}{V_2} = 16 \Rightarrow V_2 = \frac{V_1}{16} = \frac{0.92}{16} = 0.058$ m³/kg.





Process 1-2 ⇒ Isentropic compression process

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

$$= (16)^{1.4} \times 1 = 48.5 \text{ bar}$$

$$\frac{T_2}{T_1} = \left[\frac{V_1}{V_2}\right]^{\gamma-1} = (r)^{\gamma-1} \Rightarrow T_2 = (16)^{1.4-1} \times 330 = 1000.372 \text{ K}$$

Process 2-3 ⇒ Constant volume heat addition.

$$Q_{S1} = C_v [T_3 - T_2]$$

$$833.33 = 0.718 [T_3 - 1000.372]$$

$$T_3 = 2160.9 K$$

$$\frac{P_3}{T_3} = \frac{P_2}{T_2} \Rightarrow P_3 = \frac{T_3}{T_2} \times P_2 = \frac{2160.9}{1000.372} \times 48.5$$

$$P_3 = 104.74 \text{ bar}$$

Process 3-4 ⇒ Constant pressure heat addition.

$$Q_{S2} = C_p [T_4 - T_3]$$

$$416.67 = 1.005 (T_4 - 2160.9)$$

$$T_4 = 2575.49 K$$

$$\frac{V_3}{T_3} = \frac{V_4}{T_4} \Rightarrow V_4 = \frac{T_4}{T_3} \times V_3 = \frac{2575.49}{2160.9} \times 0.058$$

$$= 0.069 \, m^3/kg .$$

Expansion ratio $r_e = \frac{V_5}{V_4} = \frac{V_1}{V_4} = \frac{0.92}{0.069} = 13.33$

Process 4-5 ⇒ Isentropic expansion process.

$$\frac{T_4}{T_5} = \left[\frac{V_5}{V_4}\right]^{\gamma-1} = \left[\frac{V_1}{V_4}\right]^{\gamma-1} = (r_e)^{\gamma-1}$$

$$T_5 = \frac{T_4}{(r_e)^{\gamma-1}} = \frac{2575.49}{(13.33)^{0.4}} = 913.96 \, K$$

Heat rejected $Q_R = C_v [T_5 - T_1]$

$$= 0.718 [913.96 - 330]$$

$$= 419.28 \text{ kJ/kg}.$$

Work done $W = Q_S - Q_R$

$$= 1250 - 419.28$$

$$= 830.72 \text{ kJ/kg}.$$

Cycle efficiency $\eta = \frac{\text{Work output}}{\text{Heat supplied}} = \frac{830.72}{1250} = 0.66$ (or) 66%.

Mean effective pressure

$$P_m = \frac{W}{V_1 - V_2} = \frac{830.72}{0.92 - 0.058}$$

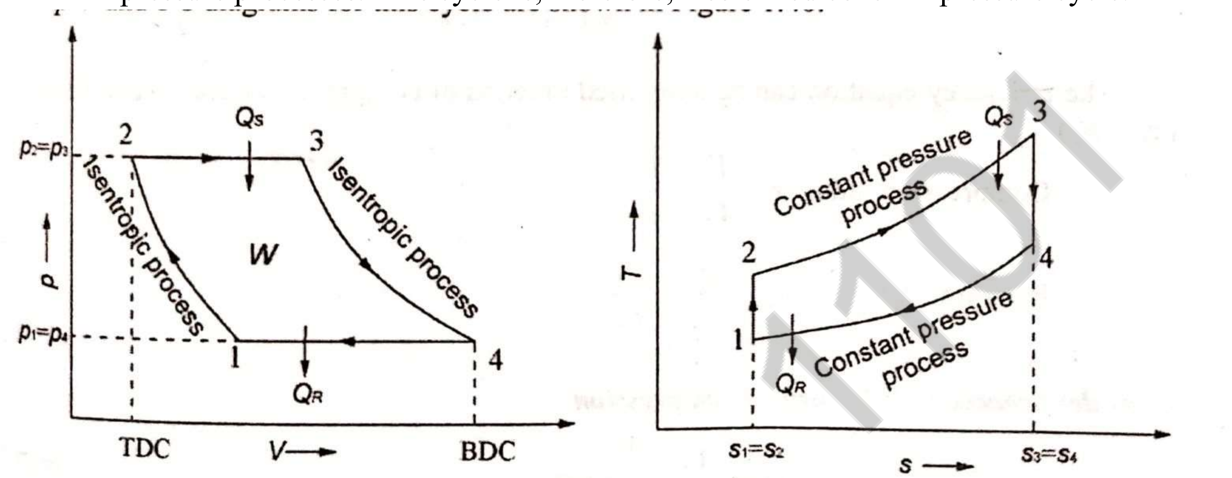
= ~~963.7 m~~

= 9.63 bar.

4. Derive the expression for the efficiency of Brayton cycle in terms cycle parameters. (April/May 2019)

Brayton cycle is the theoretical cycle for the gas turbines. The two major application areas of gas turbine engines are aircraft propulsion and electric power generation.

Brayton cycle consist of two reversible adiabatic processes and two constant pressure processes. This cycle is, therefore, also called constant pressure cycle.



p-V diagram *T-s diagram*

Process 1-2: isentropic compression process

The air is isentropically compressed in the compressor from p_1 to p_2. During the process, pressure increases from p_1 to p_2 and temperature increases from T_1 to T_2. But the volume decreases from V_1 to V_2.

$compressor\ work\ W_c = mC_p(T_2 - T_1)$

$process\ 2-3:$ constant pressure heat addition process

the compressed air is passed through the combustion chamber where the fuel is injected and burned at constant pressurer p_2 *and temperature increases from* T_2 *to* T_3

$heat\ added\ Q_s = mC_P(T_3 - T_2)$

$process\ 3-4:$ *isentropic expansion process*

the high temperature air is then expanded isentropically in the turbine to the ambient pressure. the temperature falls from $T_3 - T_4$

$Turbine\ work = W_T = mC_p(T_3 - T_4)$

Process 4-1: Constant pressure heat rejection:

The air is then returned to its original position after passing through the cooler where it cools at constant pressure process.

$$heat\,rejected\; Q_R = mC_p(T_4 - T_1)$$

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

$$= \frac{mC_p(T_3 - T_2) - mC_P(\mathrm{T}_4 - T_1)}{mC_p(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

The efficiency equation can be simplified in terms of compression ratio (r) *and pressure ratio* (R_P)

$$Comprerssion\,ratio = r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$$

$$\mathrm{Pr}\,essure\,ratio = R_p = \frac{p_2}{p_1} = \frac{p_3}{p_4}$$

consider process : 1 − 2 : *isentropic compression*

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

$$T_2 = T_1[r]^{\gamma-1}$$

$$\frac{T_2}{T_1} = \left[\frac{p_2}{p_1}\right]^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_1[R_P]^{\frac{\gamma-1}{\gamma}}$$

consider process 3 − 4 : *isentropic* exp*ansion*

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

$$T_3 = T_4[r]^{\gamma-1}$$

$$\frac{T_3}{T_4} = \left[\frac{p_3}{p_2}\right]^{\frac{\gamma-1}{\gamma}}$$

$$T_3 = T_4[R_p]^{\frac{\gamma-1}{\gamma}}$$

$$\eta_{Brayton} \text{ in terms of pressure ratio}$$

$$\eta_{Brayton} = 1 - \frac{1}{[R_P]^{\frac{\gamma-1}{\gamma}}}$$

$$\eta_{Brayton} \text{ in terms of compression ratio}$$

$$\eta_{Brayton} = 1 - \frac{1}{[r]^{\gamma-1}}$$

5. **Steam power plant runs on a single regenerative heating process. The steam enters he turbine at 30 bar and 400^{o}C and steam fraction is withdrawn at 5 bar. The remaining steam exhausts at 0.10 bar to the condenser. Calculate the efficiency and steam rate of the power plant. Neglect the pump works. (April/May 2019)**

Given:

$P_1 = 30$ bar $\quad T_1 = 400^\circ C$

$P_2 = 5$ bar $\quad P_3 = 0.1$ bar

To find:

1) η_{rege} 2) SSC 3) T_{mean}.

Solution:

Properties of steam, at 30 bar and $400^\circ C$

$h_1 = 3232.5$ kJ/kg , $s_1 = 6.925$ kJ/kg K

At 5 bar

$T_{sat} = 151.8^\circ C$

$h_f = 640.1$ kJ/kg $\quad h_{fg} = 2107.4$ kJ/kg

$s_f = 1.86$ kJ/kg K $\quad s_{fg} = 4.959$ kJ/kg K

$s_g = 6.8191$ kJ/kg

At 0.1 bar

$T_{sat} = 45.83^\circ C$

$h_f = 191.8$ kJ/kg $\quad h_{fg} = 2392.9$ kJ/kg $\quad s_f = 0.649$ kJ/kg K.

$s_{fg} = 7.402$ kJ/kg K $\quad s_g = 8.151$ kJ/kg

process 1-2: Isentropic expansion.

$s_1 = s_2 = 6.925$ kJ/kg K , $s_2 > s_g$ at 5 bar

So, the steam is at super heated condition.

By interpolation the entropy and super heated temp

At 5 bar is 173°C

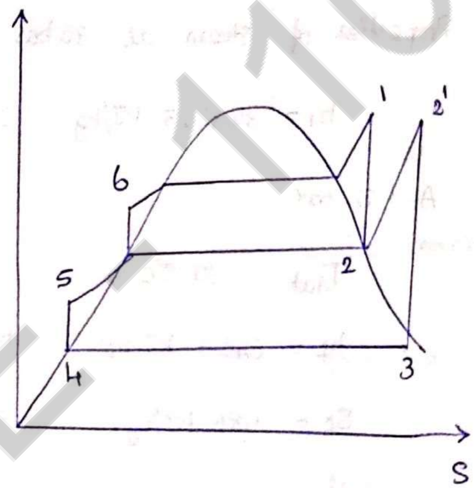
$h_2 = 2794.83$ kJ/kg

Process 3-2: Isentropic expansion

$S_2 = S_3 = 6.925$ kJ/kgK. $S_3 < S_g$ at 0.1 bar

steam is wet condition.

$S_3 = S_{f3} + x_3 S_{fg3}$



$$x_3 = \frac{6.925 - 0.649}{7.502}$$

$x_3 = 0.84$

$h_3 = h_{f3} + x_3 h_{fg3}$

$h_3 = 191.8 + 0.84(2392.9)$

$= 191.8$ kJ/kg

Mass of steam bled

$$m = \frac{h_{f2} - h_4}{h_2 - h_4} = \frac{640.1 - 191.8}{2794.83 - 191.8}$$

$= 0.1722$ kg/kg of steam

Work done by the turbine with regeneration.

$W_{reg} = (h_1 - h_2) + (1-m)(h_2 - h_3)$

$= (3232.5 - 2794.83) + (1 - 0.1722)$
$(2794.83 - 2201.836)$

$= 928.55$ kJ/kg

Efficiency of cycle with regeneration.

$$\eta_{reg} = \frac{W}{h_1 - h_{f2}} = \frac{928.55}{3232.5 - 640.1} \times 100 = 35.82\%$$

Steam rate with regeneration

$$SSC_{reg} = \frac{3600}{W_{reg}} = \frac{3600}{928.55} = 3.877 \text{ kg/kW-hr}$$

Mean temperature of heat addition with regeneration.

$$(T_{mean})_{reg} = \frac{h_1 - h_{f2}}{s_1 - s_{f2}} = \frac{3232.5 - 640.1}{6.925 - 1.86}$$

$$= 511.83 K = 241.83^\circ C$$

Mean temperature of heat addition without regeneration

$$T_{mean} = \frac{h_1 - h_{f3}}{s_1 - s_{f3}}$$

$$= \frac{3232.5 - 191.8}{6.925 - 0.649} = 484.49 K = 214.49^\circ C$$

Increase in mean temp of heat addition due to regeneration

$$= 241.83 - 214.49$$

$$= 27.33^\circ C$$

6. **The swept volume of a diesel engine working on dual cycle is 0.0053m³ and clearance volume is 0.00035m³. Fuel injection ends at 5 percent of the stroke. The temperature and pressure at the start of the compression are 80°C and 0.9 bar. Determine the air standard efficiency of the cycle. Take γ for air as 1.4. (May 2016)**

Given data

$V_s = 0.0053 m^3$

$V_c = 0.00035 m^3$

$p_3 = 65$ bar

Cut off = 5% of V_s

$p_1 = 0.9$ bar

$T_1 = 80°C = 273+80 = 353k$

$\gamma = 1.4$

Solution:

Compression ratio, $r = \frac{V_s + V_c}{V_c} = \frac{0.0053 + 0.00035}{0.00035} = 16.14$

$V_3 = V_2 = V_c = 0.00035 m^3$

$V_4 - V_3 = 0.05 V_s$

$V_4 - 0.00035 = 0.05 \times 0.0053$

$\therefore \quad V_4 = 0.00062 m^3$

Cut off ratio, $\rho = \frac{V_4}{V_3} = \frac{0.00062}{0.00035} = 1.77$

Process 1.2 $\Rightarrow$ Isentropic compression process

$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r)^{\gamma}$$

$$\therefore \quad p_2 = (r)^{\gamma} \times p_1 = (16.14)^{1.4} \times 0.9 = 44.19 \text{ bar}$$

Pressure ratio, $k = \left(\frac{p_3}{p_2}\right) = \frac{65}{44.19} = 1.47$

Cycle efficiency

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{(kp^{\gamma}-1)}{(k-1)+k\times\gamma\times(p-1)}\right]$$

$$= 1 - \frac{1}{(16.14)^{1.4-1}}\left[\frac{(1.47\times(1.77)^{1.4}-1)}{(1.47-1)+1.4\times1.47\times(1.77-1)}\right]$$

$$= 63.69\%$$

7. **In a gas turbine power plant working on Brayton cycle, the inlet air temperature is 30° C and pressure is 1.0 bar, the pressure ratio is 6.25 and the maximum temperature is 827° C. Find (a) the compression work (b) the turbine work, (c) the cycle efficiency and (d) the work ratio Compared the efficiency with Carnot cycle operating between the same temperature limits. (Nov 2016)**

Given data:

$$T_1 = 30°C = 303\ K$$
$$p_1 = 1\ bar = 100\ kN/m^2$$
$$\text{Pressure ratio}\ \ R_p = 6.25$$
$$T_3 = 827°C = 1100\ K$$

Solution:

Consider the process 1-2

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

$$T_2 = (6.25)^{\frac{1.4-1}{1.4}} \times 303 = 511.48\ K$$

Consider the process 3-4

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

$$T_4 = \left(\frac{1}{6.25}\right)^{\frac{1.4-1}{1.4}} \times 1100 = 651.62\ K$$

Compressed work,

$$W_C = C_p(T_2 - T_1)$$

$$= 1.005 \times (511.48 - 303)$$

$$=209.5\ kJ/kg$$

Turbine work $\quad W_r = C_P(T_3 - T_4)$

$$=1.005\times(1100-651.62)$$

$$=450.62 \text{ kJ/kg}$$

Cycle efficiency $\eta = 1-\frac{1}{(R_p)^{\frac{\gamma-1}{\gamma}}}$

$$=1-\frac{1}{(6.25)^{\frac{1.4-1}{1.4}}}$$

$$= 0.4076 = 40.76\%$$

$$\text{Work ratio} = \frac{\text{Net work}}{\text{Gross work}}$$

$$=\frac{450.62-209.5}{450.62}$$

$$= 0.535$$

Carnot cycle efficiency,

$$=1-\frac{T_1}{T_2}=1-\frac{303}{1100}=0.7245=72.45\%$$

($\because$ here the maximum temperature is T_2=1100 K)

Therefore % increase in efficiency,

$$\frac{72.45-40.76}{72.45} = \mathbf{43.74\ \%}$$

8. An engine with 200 mm cylinder diameter and 300 mm stroke works on theoretical Diesel cycle. The initial pressure and temperature of air used are 1bar and 27°C. T-he-eut-off is 8% of the stroke. Determine : _:.

(i) Pressures and temperatures at all salient points *1.*

(ii) Theoretical air standard efficiency

(iii) Mean effective pressure

(iv) Power of the engine if the working cycles per minute are 380 Assume that compression ratio is 15 and working fluid is air. (May 2015)

Given data:

$d = 0.2$
$L = 0.3$
$P_1 = 1$ bar
$T_1 = 27 + 273 = 300$ K
$\text{Cut off} = \frac{8}{100} V_s = 0.08\ V_s$

Solution:

(i) Pressure and temperature

Swept volume

$$V_s = \frac{\pi d^2}{4} \times L = \frac{\pi}{4} \times 0.2^2 \times 0.3 = 0.00942\ m^3$$

$$V_1 = V_g + V_c = V_s + \frac{V_s}{r-1} = V_s\left[1 + \frac{1}{r-1}\right] = \frac{r}{r-1} V_s$$

$$V_1 = \frac{15}{15-1} \times 0.00942 = 0.0101\ m^3$$

also $P_1V_1 = mRT_1$

$$m = \frac{P_1V_1}{RT_1} = \frac{1 \times 10^5 \times 0.0101}{28 \times 300} = 0.0116\ \text{kg / cycle}$$

Process 1-2

$$P_1V^{\gamma}{}_1 = P_2V^{\gamma}{}_2 \text{ or } P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = P_1(r)^{\gamma} = 1 \times 15^{1.4} = \mathbf{44.31}$$

P_2= 44.31 bar.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1} = (15)^{1.4-1} = 2.954$$

$$\therefore T_2 = 2.954 \times 300 = \mathbf{887\ K}$$

$$V_2 = V_C = \frac{V_S}{r-1} = \frac{0.00942}{15-1} = \mathbf{0.00673\ m^3}$$

$$P_2 = P_3 = 44.31 \text{ bar}$$

% cut off $= \frac{\rho - 1}{r - 1} = \frac{8}{100}$

$$\frac{\rho-1}{15-1} = \frac{8}{100} \text{ or } \rho = 2.12$$

$$V_3 = \rho V_2 = 2.12 \times 0.000673 = 0.001428\ m^3$$

$\therefore$ **V_3 = 0.001428 m^3.**

ii) air standard efficiency

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

$$= 1 - \frac{1}{(1.4)(15)^{1.4-1}}\left[\frac{(2.12)^{1.4}-1}{2.12-1}\right] = 0.597$$

η_{diesel} = **59.7 %**

iii)Mean effective pressure (Pm)

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

$$= \frac{1\times 15^{1.4}\left[1.4(2.12-1)-(15)^{1.4}\left(2.12^{1.4}-1\right)\right]}{(1.4-1)(15-1)}$$

P_m = 7.424 bar

iv) Power of engine

Work done (W) = $P_m V_s$ = $\frac{7.424\times 10^5 \times 0.00942}{10^3}$

W = 70 kJ/cycle

Power = $7\times\frac{380}{60} = 44.28$ kJ/s or kW

Process 2-3

$$T_3 = T_2 \times \frac{V_3}{V_2} = 887\times\frac{0.001426}{0.000673} = \mathbf{1878\ \ K}$$

Process 3-4

$$P_3 V^{\gamma}{}_3 = P_4 V^{\gamma}{}_4 \text{ or } P_4 = P_3\left(\frac{V_3}{V_4}\right)^{\gamma} = 44.31\left(\frac{0.001428}{0.0101}\right)^{1.4}$$

$\therefore P_4$ =**2.846 bar** $[\because V_4 = V_1]$

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{\gamma-1} = T_3\times\left(\frac{0.001428}{0.0101}\right)^{1.4-1} = 1878\times 0.457 = 859\text{ K}$$

$\therefore T_4$ = **859 K**

$V_4 = V_1$ = 0.0101 m^3

9. Air enters the compressor of a gas turbine plant operating on Brayton cycle at 1 bar, 27°C. The pressure ratio in the cycle is 6. If Wt = 2.5 Wc where Wt and Wc are the turbine a:nd compressor work respectively, calculate the maximum temperature and the cycle efficiency. (May 2015)

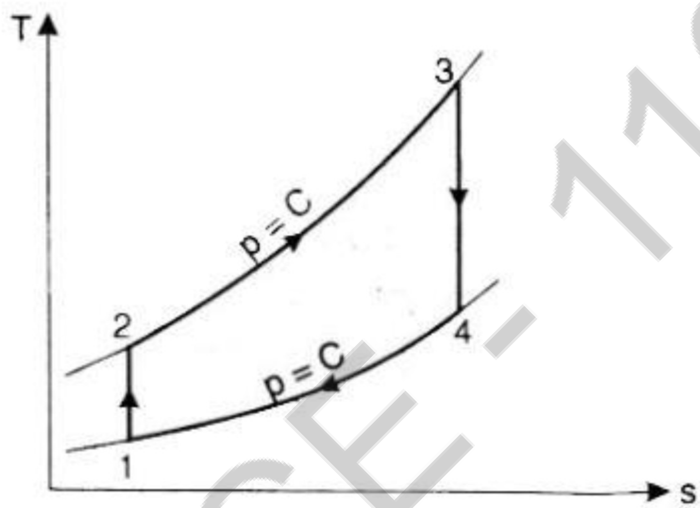
Given data:

Pressure of intake air p_1 = 101.325 kPa

Temperature of intake air, T_1=27+273 = 300 K

The pressure ratio in cycle r_p = 6

i) Maximum temperature in the cycle T_3:



$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = (r)^{\frac{\gamma-1}{\gamma}} = (6)^{\frac{1.4-1}{1.4}} = 1.668$$

$\therefore \quad T_2 = 1.668\ T_1 = 1.668 \times 300 = 500.4$

But $W_r = 2.5\ W_c$

$$mc_p(T_3 - T_4) = 2.5mc_p(T_2 - T_3)$$

$$T_3 - \frac{T_3}{1.668} = 2.5(500.4 - 300) = 501 \text{ or } T_3\left(1 - \frac{1}{1.668}\right) = 501$$

$$T_3 = \frac{501}{\left(1 - \frac{1}{1.668}\right)} = \mathbf{1251\ K\ \ or\ \ 978^\circ\ C}$$

ii) cycle efficiency , η_{cycle} :

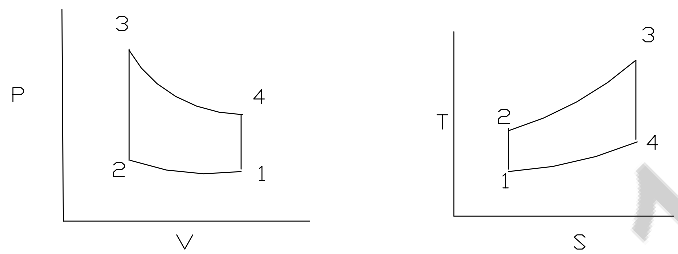
now, $$T_4 = \frac{T_3}{1.668} = \frac{1251}{1.668} = 750\text{ K}$$

$$\eta_{cycle} = \frac{\text{Net work}}{\text{Heat added}} = \frac{mc_p(T_3 - T_4) - mc_p(T_2 - T_1)}{mc_p(T_3 - T_2)}$$

$$= \frac{(1251-750)-(500.4-300)}{(1251-500.4)} = \mathbf{0.4 \text{ or } 40\%.}$$

10. Brief the working of Otto cycle with the help of p-v diagram and T-s diagram and derive the air standard efficiency of the cycle. (Nov 2018)

PETROL AND GAS ENGINES – CONSTANT VOLUME CYCLE:



1-2 Isentropic compression
2-3 Constant Volume Heating
3-4 Isentropic Expansion
4-1 Constant Volume Cooling

Since combustion takes place at constant volume the Otto cycle is also called as **Constant Volume Cycle**.

Heat Supplied $= C_v (T_3 – T_2)$ ------- (1)

Heat Rejected $= C_v (T_4 – T_1)$ ------- (2)

Work done = Heat Supplied – Heat Rejected

$= C_v (T_3 – T_2) - C_v (T_4 – T_1)$

$$\eta_{cycle} = \frac{workdone}{Heat\ Supplied} = \frac{C_p\ (T_3 - T_2) - C_v\ (T_4 - T_1)}{C_p\ (T_3 - T_2)}$$

$$\eta_{cycle} = 1 - \left[\frac{T_4 - T_1}{T_3 - T_2}\right]$$

$$= 1 - \left[\frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}\right] \quad \text{------- (3)}$$

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

$$\frac{T_4}{T_1} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} \times \frac{T_3}{T_2} \times \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \qquad [\because V_3 = V_2\ \ \& V_4 = V_1]$$

Substituting $\frac{T_4}{T_1} = \frac{T_3}{T_2}$ in equation (3)

$$\eta_{cy} = 1 - \frac{T_1}{T_2}$$

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

11. An air standard diesel cycle has a compression ratio of 18, and the heat transferred to the working fluid per cycle is 1800 kilo joule/kg. at the beginning of compression stroke, the pressure is 1 bar and the temperature is 300K. calculate (i) the thermal efficiency, (ii) the mean effective pressure (April/May 2019)

Given:

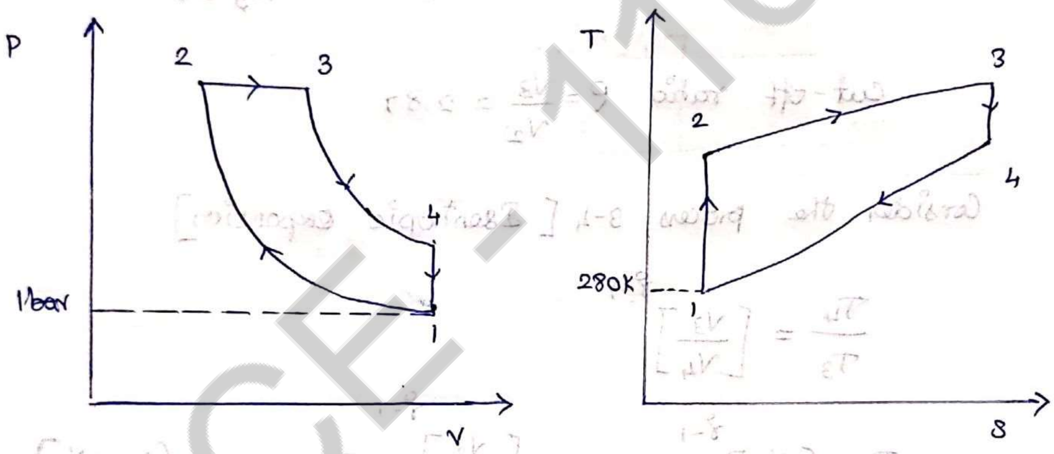
$r = 18$

$Q_s = 1800$ kJ/kg

$T_1 = 300K$

$P_1 = 1 bar = 100$ kN/m².

Solution:



Consider the process 1-2 [Isentropic compression]

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

$$T_2 = \left[\frac{V_1}{V_2}\right]^{\gamma-1} \times T_1 = [18]^{0.4} \times 300 = 953.30 K$$

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma}$$

$$P_2 = \left[\frac{T_2}{T_1}\right]^{\gamma/\gamma-1} \times P_1 = \left[\frac{953.30}{300}\right]^{1.4/0.4} \times 100$$

$= 5719.77$ kN/m²

Consider the process 2-3 [constant Pressure heat addition]

$$Q_s = mC_p [T_3 - T_2] = 1800 \text{ kJ/kg}$$

$$1800 = 1 \times 1.005 \times [T_3 - 953.30]$$

$$T_3 = 2744.34 \text{ k}.$$

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \Rightarrow \frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{2744.34}{959.30} = 2.87$$

$$\text{cut-off ratio } \rho = \frac{V_3}{V_2} = 2.87$$

Consider the process 3-4 [Isentropic expansion]

$$\frac{T_4}{T_3} = \left[\frac{V_3}{V_4}\right]^{\gamma-1}$$

$$T_4 = \left[\frac{V_3}{V_4}\right]^{\gamma-1} \times T_3 = \left[\frac{V_3}{V_1}\right]^{\gamma-1} \times T_3 \qquad (V_4 = V_1)$$

$$= \left[\frac{V_3}{V_2} \times \frac{V_2}{V_1}\right]^{\gamma-1} \times T_3 = \left[\frac{2.87}{18}\right]^{0.4} \times 2744.34$$

$$= 1316.6 \text{ K}.$$

$$\frac{T_4}{T_3} = \left[\frac{P_4}{P_3}\right]^{\gamma-1/\gamma}$$

$$P_4 = \left[\frac{T_4}{T_3}\right]^{\gamma/\gamma-1} \times P_3$$

$$= \left[\frac{1316.6}{2744.34}\right]^{\frac{1.4}{0.4}} \times 5719.97$$

$$P_4 = 437.45 \ KN/m^2$$

Air standard efficiency

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

$$= 1 - \frac{1}{1.4(18)^{0.4}} \left[\frac{(2.87)^{1.4}-1}{2.87-1}\right]$$

$$= 1 - \frac{1.8051}{4.4487}$$

$$= 0.594 \ (\text{or}) \ 59.4\ \%$$

Mean effective pressure

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

$$= \frac{100(18)^{1.4}\left[1.4(2.87-1) - (18)^{-0.4}((2.87)^{1.4}-1)\right]}{(1.4-1)(18-1)}$$

$$= 1064.13 \ KN/m^2.$$

12. **In a otto cycle air at 17^{o}C and 1 bar is compressed adiabatically until the pressure is 15 bar. Heat is added at constant volume until the pressure rises to 40 bar. Calculate the air standard efficiency, the compression ratio and the mean effective pressure for the cycle. Assume C_v=0717 kilo joule/kg K and R=8.314 Kilo joule/kmol K. (April/may 2018)**

Given:

$P_1 = 1$ bar

$T_1 = 17°C = 273 + 17 = 290K$

$P_2 = 15$ bar

$P_3 = 40$ bar

$C_v = 0.717$ kJ/kgK

$R = 8.314$ kJ/kmol K.

Solution:

Consider process 1-2 [Adiabatic compression process]

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

$$r = \left[\frac{P_2}{P_1}\right]^{1/\gamma} = \left[\frac{15}{1}\right]^{1/1.4} = 6.92$$

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

$$T_2 = (r)^{\gamma-1} \times T_1 = (6.92)^{0.4} \times 290$$

$$T_2 = 628.7K.$$

Air standard efficiency

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(6.92)^{0.4}}$$

$$= 53.87\ \%$$

Pressure ratio $k = \frac{P_3}{P_2} = \frac{40}{15} = 2.67$

Mean effective pressure $P_m = P_1 r \left[\frac{k-1}{\gamma-1}\right]\left[\frac{(r)^{\gamma-1}-1}{r-1}\right]$

$= 100 \times 6.92 \left[\frac{2.67-1}{1.4-1}\right]\left[\frac{(6.92)^{0.4}-1}{6.92-1}\right]$

$= 569.97 \text{ kN/m}^2$

Alternatively,

Consider process 2-3 [constant volume heat addition]

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

$$T_3 = \frac{P_3}{P_2} \times T_2 = \frac{40}{15} \times 628.7 = 1676.53 \text{ K}$$

Heat supplied $Q_s = m C_v [T_3 - T_2]$

$= 1 \times 0.718 [1676.53 - 628.7]$

$= 752.34 \text{ kJ/kg}$

Thermal efficiency $\eta = \frac{W}{Q_s}$

$W = \eta \times Q_s$

$= 0.5387 \times 752.34$

$= 405.29 \text{ kJ/kg}$.

$$v_1 = \frac{RT_1}{P_1}$$

$$= \frac{0.287 \times 290}{100}$$

$$= 0.83 \ m^3/kg.$$

compression ratio $r = \frac{v_1}{v_2} = 6.92$

$$v_2 = \frac{0.83}{6.92} = 0.12 \ m^3/kg$$

Mean effective pressure $P_m = \frac{W}{v_1 - v_2}$

$$= \frac{405.29}{0.83 - 0.12}$$

$$= 570.83 \ kN/m^2.$$

13. The mean effective pressure of an ideal diesel cycle is 8 bar. If the initial pressure is 1.03 bar and the compression ratio is 12. Determine the cut-off ratio and the air standard efficiency. Assume ratio of specific heat for air to be 1.4. (April/may 2018)

Given:

$P_m = 8\ bar = 800\ kPa$

$P_1 = 1.03\ bar = 103\ kPa$

$r = 12$

$\gamma = 1.4$

solution:

1) Mean effective pressure.

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

$$= \frac{103 \times (12)^{1.4}\left[1.4(\rho-1) - (12)^{(1-1.4)}(\rho^{1.4}-1)\right]}{(0.4)(11)}$$

$$0.973 = 1.4\rho - 1.4 - 0.37\rho^{1.4} + 0.37$$

$$1.4\rho - 0.37\rho^{1.4} - 2.003 = 0.$$

By trial and error method.

$\rho = 0$	error = -2.003
$\rho = 1$	error = -0.973
$\rho = 2$	error = -0.179
$\rho = 2.5$	error = 0.163
$\rho = 2.3$	error = 0.0295

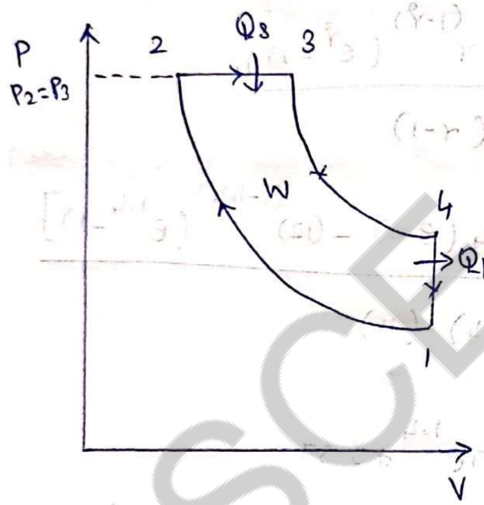
$\rho = 2.27$ error $= 0.00917$

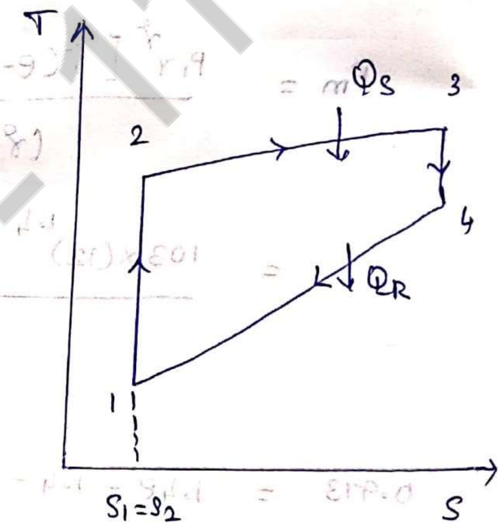
$\rho = 2.26$ error $= 0.0024$

$\rho = 2.255$ error $= -0.0011$

$\rho = 2.257$ error $= 0.0003 \simeq 0$

So cut-off ratio $\rho = 2.257$





2) Air standard efficiency

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

$$= 1 - \frac{1}{1.4 (12)^{0.4}} \left[\frac{(2.257)^{1.4} - 1}{2.257 - 1} \right]$$

$$= 55.29\ \%$$

14. A gas turbine works on an air standard brayton cycle. The initial condition of the air is 25 ^{o}C and 1 bar. The maximum pressure and temperature are limited to 3 bar and 650 ^{o}C. determine the following (i) cycle efficiency (ii) heat supplied and heat rejected per kg or air (iii) work output (iv) exhaust temperature. (Nov/Dec 2018)

Given:

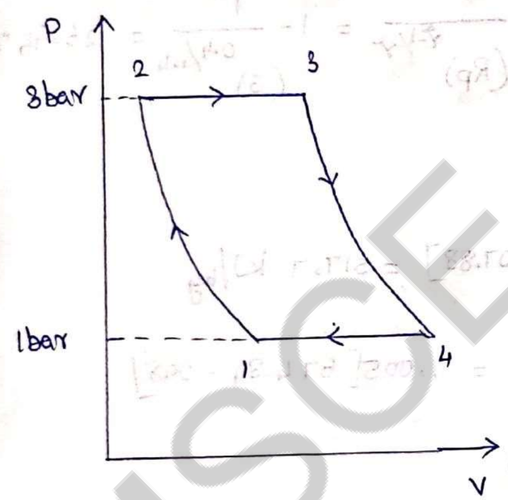
$P_1 = 1$ bar

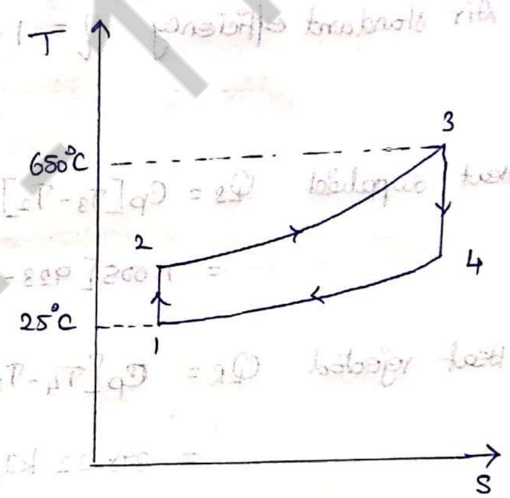
$T_1 = 25^\circ C = 273 + 25 = 298K.$

$P_2 = 3$ bar.

$T_3 = 650^\circ c = 273 + 650 = 923K.$

Solution:





Consider the process 1-2 : adiabatic compression.

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma}$$

$$T_2 = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma} \times T_1 = \left[\frac{3}{1}\right]^{0.4/1.4} \times 298$$

$$= 407.88K.$$

Consider the process 3-4 : adiabatic expansion.

$$\frac{T_4}{T_3} = \left[\frac{P_4}{P_3}\right]^{\gamma-1/\gamma}$$

$$T_4 = \left[\frac{P_4}{P_3}\right]^{\gamma-1/\gamma} \times T_3 = \left[\frac{1}{3}\right]^{0.4/1.4} \times 923$$

$$= 674.34K.$$

Air standard efficiency $\eta = 1 - \frac{1}{(R_p)^{\gamma-1/\gamma}} = 1 - \frac{1}{(3)^{0.4/1.4}} = 26.94\%.$

Heat supplied $Q_S = C_p[T_3 - T_2]$

$$= 1.005[923 - 407.88] = 517.7 \text{ kJ/kg}$$

Heat rejected $Q_R = C_p[T_4 - T_1] = 1.005[674.34 - 298]$

$$= 378.22 \text{ kJ/kg}$$

compressor work $W_c = C_p[T_2 - T_1] = 1.005[407.88 - 298] = 110.43 \text{ kJ}$

Turbine work $W_T = C_p[T_3 - T_4] = 1.005[923 - 674.34] = 249.9 \text{ kJ}$

Work output $W = W_T - W_c$

$$= 249.9 - 110.43 = 139.47 \text{ kJ/kg}$$

Temperature of air leaving the turbine

$$T_4 = 674.34K.$$

15. **An oil engine works on the dual cycle, the heat liberated at constant pressure being twice that liberated at constant volume. The compression ratio of the engine is 8 and the expansion ratio is 5.3. but the compression and expansion processes follow the law of $pv^{1.3}=C$. the pressure and temperature at beginning of compression are 0.93 bar and 27 ^oC. assuming Cp=1.005 kilo joule/kg K and Cv = 0.718 Kilo joule/kg K. (NOV/DEC 2017)**

Given:

$P_1 = 1 bar$

$T_1 = 15°c = 273+15 = 288 K$

$P_2 = 5 bar$

$Q_s = 2500 kJ/kg.$

solution:

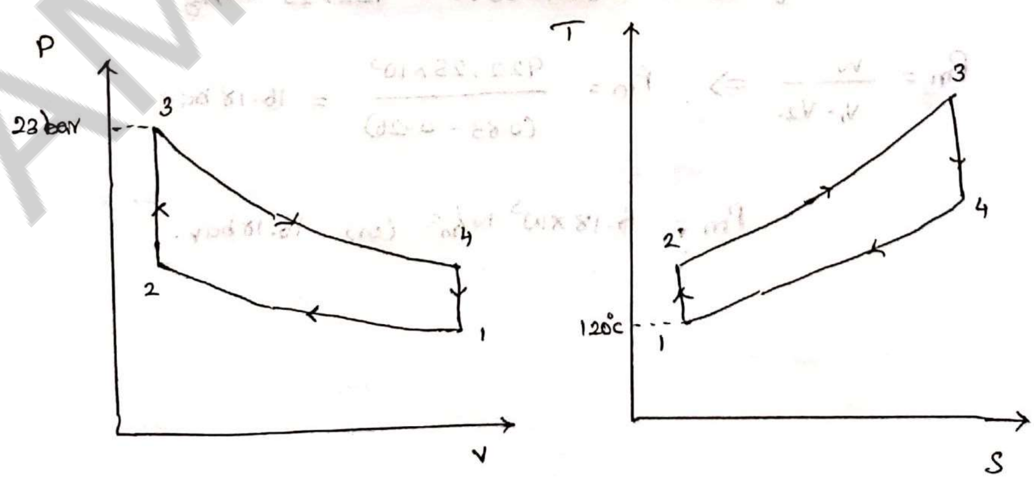
From the ideal gas equation $pv = RT$

$$v_1 = \frac{RT_1}{P_1} = \frac{287 \times 288}{1 \times 10^5} = 0.83 \; m^3/kg$$

From Process 1-2: Isentropic compression.

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma}$$

$$T_2 = T_1 \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma} = 288 \times \left[\frac{5}{1}\right]^{0.4/1.4} = 456.14 K.$$



From the relation $Q_S = C_v [T_3 - T_2]$

$$T_3 = T_2 + \frac{Q_s}{C_v} = 456.14 + \frac{2500}{0.718} = 3938.03\,K$$

From Process 2-3: Constant volume process

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

$$P_3 = \frac{P_2}{T_2} \times T_3 = \frac{5}{456.14} \times 3938.03$$

$$P_3 = 43.17\ bar$$

Peak Pressure $P_3 = 43.17$ bar

compression ratio $r = \frac{V_1}{V_2} = \left[\frac{P_2}{P_1}\right]^{1/\gamma} = \left[\frac{5}{1}\right]^{1/1.4} = 3.16$

Ideal cycle efficiency $\eta = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(3.16)^{0.4}} = 36.89\%$.

Work done $= \eta \times Q_S = 0.3689 \times 2500 = 922.25\ kJ/kg$

$$P_m = \frac{W}{V_1 - V_2} \Rightarrow P_m = \frac{922.25 \times 10^3}{(0.83 - 0.26)} = 16.18\ bar$$

$$P_m = 16.18 \times 10^5\ N/m^2 \text{ (or) } 16.18\ bar.$$

16. A gas engine operating on the ideal Otto cycle has a compression ratio of 6:1. The pressure and temperature of the commencement of compression are 1 bar and 15 ^{o}C. Pressure at the end of compression is 5 bar. heat added during the constant volume combustion process is 2500 kilo joule/kg. determine the peak pressure and temperature, work output per kg of air and air standard efficiency. Take Cp=1.004 kilo joule/kg K and Cv= 0.718 kilo joule/kg K, gamma = 1.4 for air. (Nov/Dec 2017)

Given:

$Q_{S_2} = 2 \times Q_{S_1}$, $r = 8$

$k = \frac{V_5}{V_4} = \frac{V_1}{V_4} = 5.3$

$P_1 = 0.93$ bar

$T_1 = 27°C = 273+27 = 300K$

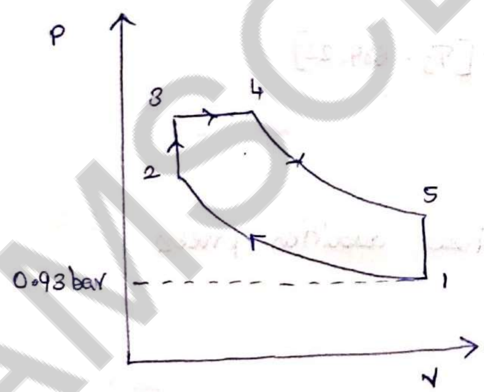
$C_p = 1.005$ kJ/kg K , $C_v = 0.718$ kJ/kg K.

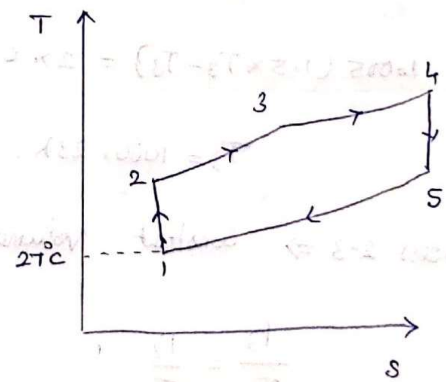
Solution:

Specific volume $V_1 = \frac{RT_1}{P_1} = \frac{287 \times 300}{0.93 \times 10^5} = 0.93\ m^3/kg$.

$v_2 = \frac{v_1}{r} = \frac{0.93}{8} = 0.12\ m^3/kg$

$v_3 = v_2 = 0.12\ m^3/kg$.





Process 1-2 ⇒ adiabatic compression process.

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

$$P_2 = (r)^{\gamma} \times P_1 = (8)^{1.4} \times 0.93 = 17.09 \text{ bar}$$

$$\frac{T_2}{T_1} = \left[\frac{V_1}{V_2}\right]^{\gamma-1} = (r)^{\gamma-1} \Rightarrow T_2 = (r)^{0.4} \times T_1 = (8)^{0.4} \times 300 = 689.22\ K.$$

Process 4-5 ⇒ Adiabatic Expansion Process

$$\frac{V_5}{V_4} = 5.3 \Rightarrow V_5 = 5.3 \times v_4$$

$$v_4 = \frac{V_5}{5.3} = \frac{v_1}{5.3} = \frac{0.93}{5.3} = 0.18 \ m^3/kg.$$

Process 3-4: Constant Pressure heat addition process

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

$$T_4 = \left[\frac{V_4}{V_3}\right] \times T_3 = \left[\frac{0.18}{0.12}\right] \times T_3 = 1.5 \times T_3$$

Heat supply to the system

$$Q_{S2} = 2 \times Q_{S1}$$

$$C_p [T_4 - T_3] = 2 \times C_v [T_3 - T_2]$$

$$1.005 (1.5 \times T_3 - T_3) = 2 \times 0.718 [T_3 - 689.22]$$

$$T_3 = 1060.23 K.$$

Process 2-3 ⇒ Constant volume heat addition process

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

$$P_3 = \frac{T_3}{T_2} \times P_2 = \frac{1060.23}{689.22} \times 17.09 = 26.3 \ bar$$

$$T_4 = 1.5 \times T_3 = 1.5 \times 1060.23 = 1590.35 K$$

Cut-off ratio $\rho = \frac{V_4}{V_3} = \frac{0.18}{0.12} = 1.5$

Pressure ratio $k = \left[\frac{P_3}{P_2}\right] = \frac{26.3}{17.09} = 1.54$

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

$= 1 - \frac{1}{(8)^{0.4}}\left[\frac{1.54 \times 1.5^{1.4} - 1}{(1.54-1) + 1.54 \times 1.4(1.5-1)}\right]$

$= 53.82\%.$

Net heat supplied to the cycle.

$Q_s = C_v[T_3 - T_2) + C_p[T_4 - T_3]$

$= 0.718[1060.23 - 689.22] + 1.005[1590.35 - 1060.23]$

$= 799.16$ kJ/kg.

Net work output $W = \eta \times Q_s = 0.5382 \times 799.16$

$= 430.11$ kJ/kg.

Mean effective pressure

$P_m = \frac{W}{V_1 - V_2} = \frac{430.11}{(0.93 - 0.12)} = 5.31$ bar.

17. An air-standard Dual cycle has a compression ratio of 10. The pressure and temperature at the beginning of compression' are 1 bar and 27°C. The maximum pressure reached is 42 bar and the maximum temperature is 1500 °C. Determine (i) the temperature at the end of constant volume heat addition (ii) cut-off ratio (iii) work done per kg of air and (iv) the cycle efficiency. Assume Cp = 1.004 kJ/kg K and Cv = 0.717 kJ/kg K for air.

Given data:

$$r = 10$$
$$p_1 = 1\,\text{bar}$$
$$T_1 = 27°C = 273 + 27 = 300\,K$$
$$p_3 = 42\,\text{bar}$$
$$T_4 = 1500°C = 1500 + 273 = 1773\,K$$
$$c_p = 1.004\ kJ/kgK$$
$$c_v = 0.717\,kJ/kgK$$

Solution:

Specific volume, $v_1 = \frac{RT_1}{p_1} = \frac{287 \times 300}{1 \times 10^5} = 0.86\,m^3/kg$

But $$r = \frac{v_1}{v_2} = 10$$

$$\therefore\ v_2 = \frac{v_1}{10} = \frac{0.86}{10} = 0.086\ m^3/kg$$

Process 1-2 $\Rightarrow$ Isentropic compression process

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = (r)^{\gamma}$$

$$\therefore p_2 = (r)^{\gamma} \times p_1 = (10)^{1.4} \times 1 = 25.12\ \text{bar}$$

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

$$\therefore\ T_2 = (r)^{\gamma-1} \times T_1 = (10)^{1.4-1} \times 300 = 753.57\ K$$

Process 2-3 $\Rightarrow$ constant volume heat addition process

$$\frac{p_3}{T_3} = \frac{p_2}{T_2}$$

$$\therefore\ T_3 = \left(\frac{p_3}{p_2}\right) \times T_2 = \frac{42}{25.12} \times 753.57 = 1259.95\ K$$

$$Q_{s_1} = c_v\left(T_3 - T_2\right)$$
$$= 0.718\left(1259.95 - 753.57\right) = 363.58\ kJ/kg$$

Process 3-4 $\Rightarrow$ constant pressure heat addition

$$Q_s = c_p(T_4 - T_3)$$
$$Q_s = 1.005(1773 - 1259.95) = 515.62 \text{ kJ/kg}$$
$$\frac{v_3}{T_3} = \frac{v_4}{T_4}$$
$$v_4 = \frac{T_4}{T_3} \times v_3 = \frac{1773}{1259.95} \times 0.086 = 0.12\, m^3/kg$$

Cut off ratio, $\rho = \frac{v_4}{v_3} = \frac{0.12}{0.086} = 1.4$

`Pressure ratio, $k = \left(\frac{p_3}{p_2}\right) = \left(\frac{42}{25.12}\right) = 1.67$

Cycle efficiency,
$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{(k\rho^{\gamma} - 1)}{(k-1) + k \times \gamma \times (\rho - 1)}\right]$$
$$= 1 - \frac{1}{(10)^{1.4-1}}\left[\frac{(1.67 \times (1.4)^{1.4} - 1)}{(1.67 - 1) + 1.4 \times 1.67 \times (1.4 - 1)}\right]$$

= **58.46 %**

Net heat supplied to the cycle
$$Q_s = Q_{s_1} + Q_{s_2} = 363.58 + 515.62 = 879.2 \text{ kJ/kg}$$

Net work done of the cycle,
$$W = Q_s \times \eta = 879.2 \times 0.5846 = \textbf{513.98 kJ/kg.}$$

18. In an air standard dual cycle, the compression ratio is 12 and the maximum pressure in the cycle is 70 bar. The lowest pressure and temperature of the cycle are 1 bar and 300k. Heat added during constant pressure process is up to 3% of the stroke. Taking diameter as 25cm and stroke as 30cm, determine the (i) pressure and temperature at the end of compression, (ii) thermal efficiency and (iii) mean effective pressure.

Take C_p = 1.005 kJ/kgK; c_v = 0.718kJ/kgK; γ = 1.4

Given data:

P1 = 1 bar

T1 = 300 k

P3 = 70 bar

r = 12

k = 3% of V_5 = 0.03V_5 i.e. $(V_4-V_3) = 0.03\,(V_1-V_2)$

d = 25 cm

l = 30 cm

Solution:

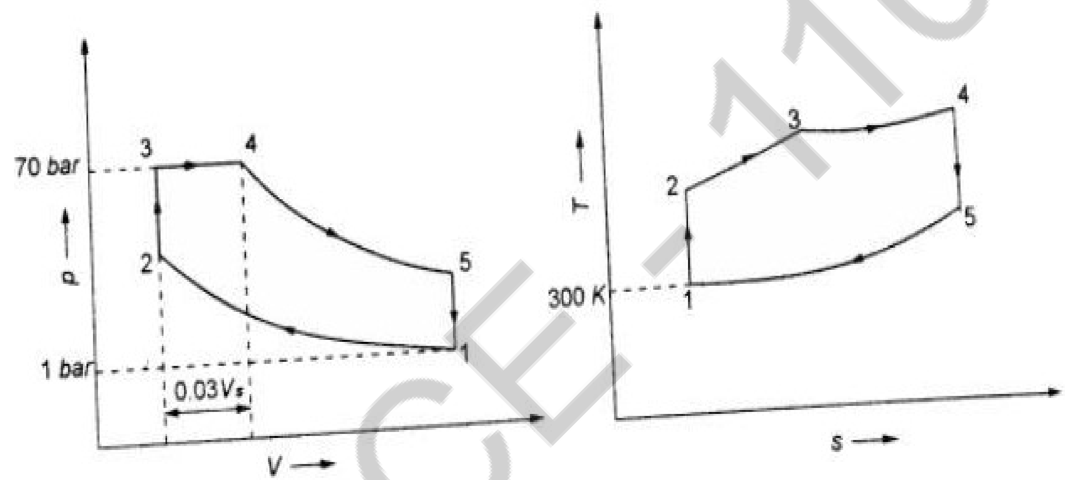
Swept volume, $V_5 = \frac{\pi}{4} d^2 l = \frac{\pi}{4} \times 0.25^2 \times 0.3 = 0.02 m^3$

Compression ratio, $r = \frac{V_5 + V_5}{V_5}$

$$12 = \frac{V_5}{V_5} + 1$$

$$12 - 1 = \frac{V_5}{V_5}$$

$$\therefore \quad V_5 = \frac{0.02}{11} = 0.0018 m^3$$



p-V diagram T-s diagram

We know that $V_1 = V_1 + V_3 = 0.02 + 0.0018 = 0.0218 m^3$

From ideal gas equation,

$$p_1 V_1 = mRT_1$$

$$m = \frac{p_1 V_1}{RT_1} = \frac{100 \times 0.0218}{0.287 \times 300} = 0.025 kg$$

Then $V_3 = V_2 = V_c = 0.0018 m^3$

$$V_4 = V_3 = 0.03(V_1 - V_2)$$

$$V_4 - 0.0018 = 0.03(0.0218 - 0.0018)$$

$$\therefore \quad V_4 = 0.0024 m^3$$

Cut of ratio, $p = \frac{V_4}{V_3} = \frac{0.0024}{0.0018} = 1.33$

Process 1.2 $\Rightarrow$ Isentropic compression process

$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r)^{\gamma}$$

$$\therefore \quad p2 = (r)^{\gamma} \times p_1 = (12)^{1.4} \times 1 = 32.42 \text{ bar}$$

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

$$\therefore \quad T_2 = (r)^{\gamma-1} \times T_1 = (12)^{1.4-1} \times 300 = 810.58K$$

Process 2.3 $\Rightarrow$ Constant volume heat addition process

$$\frac{p_3}{T_3} = \frac{p_2}{T_2}$$

$$\therefore \quad T_3 = \left(\frac{p_3}{p_2}\right) \times T_2 = \left(\frac{70}{32.42}\right) \times 810.58 = 1750.17K$$

Process 3.4 $\Rightarrow$ Constant pressure heat addition process

$$\left(\frac{V_3}{T_3}\right) = \left(\frac{V_4}{T_4}\right)$$

$$T_4 = \left(\frac{V_4}{V_3}\right) \times T_3 = 1.33 \times 1750.17 = 2327.73K$$

Pressure ratio, $k = \left(\frac{p_3}{p_2}\right) = \frac{70}{32.42} = 2.16$

Net heat supplied to the cycle,

$$Q = m\left[c_v(T_3 - T_2) + c_p(T_4 - T_3)\right]$$

$$= 0.025\left[0.718(1750.17 - 810.58) + 1.005(2327.73 - 1750.17)\right]$$
$$= 31.38kW$$

Efficiency of the cycle,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{(k \times p^{\gamma} - 1)}{(k-1) + k\gamma(p-1)}\right]$$

$$= 1 - \frac{1}{(12)^{1.4-1}}\left[\frac{\left(2.16\times(1.33)^{1.4}\right)}{(2.16-1)+2.16\times(1.33-1)}\right]$$

$$= 61.93\%$$

Net work done by the cycle, $W = \eta \times Q_s = 0.6193 \times 31.38 = 19.44$

Mean effective pressure,

$$p_m = \frac{W}{V_1 - V_2}$$

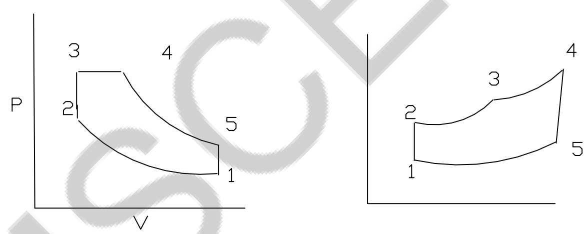
$$= \frac{19.44}{0.0218 - 0.0018}$$

$$= 972\text{kPa} = 9.72 \text{ bar}$$

19. **Derive the expression for air standard efficiency of an DUAL CYCLE**

SEMI DIESEL CYCLE OR DUAL CYCLE

CRUDE OIL ENGINE - LIMITED PRESSURE CYCLE



1-2 Isentropic Compression
2-3 Constant Volume Heating
3-4 Constant Pressure Heating
4-5 Isentropic Expansion
5-1 Constant Volume Cooling

Since part of the combustion takes place at constant volume and part of the combustion takes place at constant pressure the semi diesel cycle is also called as **Dual Cycle**.

Heat Supplied = $[C_v(T_3 - T_2) + C_p(T_4 - T_3)]$ ------(1)

Heat Rejected = $C_v(T_5 - T_1)$ ------(2)

Work Done = $[C_v(T_3 - T_2) + C_p(T_4 - T_3)] - C_v(T_5 - T_1)$

$$\eta_{cy} = \frac{[C_v(T_3 - T_2) + C_p(T_4 - T_3)] - C_v(T_5 - T_1)}{[C_v(T_3 - T_2) + C_p(T_4 - T_3)]}$$

$$\eta_{cy} = 1 - \frac{C_v(T_5 - T_1)}{[C_v(T_3 - T_2) + C_p(T_4 - T_3)]}$$

$$= 1 - \frac{(T_5 - T_1)}{[(T_3 - T_2) + \gamma(T_4 - T_3)]}$$

$$= 1 - \frac{T_1\left[\frac{T_5}{T_1} - 1\right]}{T_2\left[\frac{T_3}{T_2} - 1\right] + \gamma T_3\left[\frac{T_4}{T_3} - 1\right]} \quad \text{------(3)}$$

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

$$= 1 - \frac{\left[\frac{T_5}{T_1} - 1\right]}{\left\{r^{\gamma-1}\left[\frac{T_3}{T_2} - 1\right] + \gamma\frac{T_3}{T_1}\left[\frac{T_4}{T_3} - 1\right]\right\}}$$

$$\left[\because \frac{T_2}{T_1} = \left[\frac{V_1}{V_2}\right]^{\gamma-1} = r^{\gamma-1}\right]$$

$$\frac{T_5}{T_1} = \frac{T_5}{T_4} \times \frac{T_4}{T_3} \times \frac{T_3}{T_2} \times \frac{T_2}{T_1}$$

$$= \left[\frac{V_4}{V_5}\right]^{\gamma-1} \times \frac{V_4}{V_3} \times \left[\frac{V_1}{V_2}\right]^{\gamma-1} \times \frac{P_3}{P_2} \qquad [\because V_3 = V_2; V_5 = V_1]$$

$$= \frac{V_4^{\gamma}}{V_3^{\gamma}} \times \frac{P_3}{P_2} = r_c^{\gamma} r_p$$

$$\text{where } r_p = \frac{P_3}{P_2} = \text{Pressure ratio}$$

$$\eta_{cy} = \left\{1 - \frac{\left[r_c^{\gamma} r_p - 1\right]}{r_c^{\gamma-1}\left(r_p - 1\right) + \gamma \dfrac{T_3}{T_1}\left[r_c - 1\right]}\right\}$$

$$\frac{T_3}{T_1} = \frac{T_3}{T_2} \times \frac{T_2}{T_1} = r_p r^{\gamma-1}$$

$$\eta_{cy} = \left\{1 - \frac{\left[r_c^{\gamma} r_p - 1\right]}{r_c^{\gamma-1}\left(r_p - 1\right) + \gamma r_p r^{\gamma-1}\left[r_c - 1\right]}\right\}$$

$$\eta_{cy} = \left\{1 - \frac{\left[r_c^{\gamma} r_p - 1\right]}{r^{\gamma-1}\left\{\left(r_p - 1\right) + \gamma r_p \left[r_c - 1\right]\right\}}\right\}$$

Pressure ratio (r_p) : It is the ratio of the final pressure to the initial pressure during constant volume combustion.

ME 8493 – THERMAL ENGINEERING – 1

QUESTION BANK

UNIT – 2

RECIPROCATING AIR COMPRESSORS

PART – A

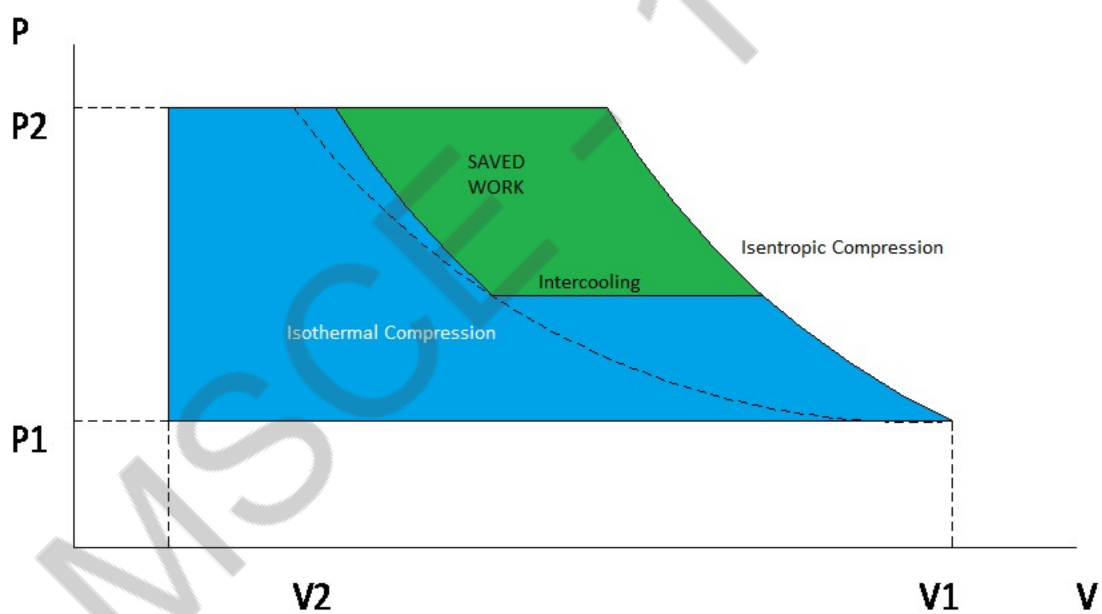
1. **What are the advantages of multi stage compression? (Nov/Dec 2019)**
   - ✓ Volumetric efficiency of compressor increases due to reduced pressure ratio in each stage.
   - ✓ Temperature at the end of compression would be less. As a result, lubrication would be effective. Hence, compressor life is increases.
   - ✓ Leakages past the piston are reduced.
   - ✓ Operating cost is reduced.

   - ✓ **Improved efficiency.** Two-stage compressors perform less work to compress air to a given pressure, which means your operating costs are lower.
   - ✓ **Better reliability**. The intercooling stage of two-stage compression creates less chance of overheating, which in turn means more uptime and better productivity.
   - ✓ **Less moisture buildup.** Cooler air has a lower moisture content. Moisture in compressed air can lead to equipment failure and premature wear. Using a two- or three-stage compressor can potentially save you from having to purchase a separate air dryer.
   - ✓ **Smaller footprint**. For heavy-duty applications, multi-stage compressors deliver greater air pressure (PSI) at higher capacities (CFM) than single-stage machines of a comparable size.
   - ✓ **Few maintenance requirements.** Thanks to smaller components and cooler temperatures, wearable components don't wear out as quickly. As a result, recommended service intervals are longer.
2. **What is a rotary compressor? How are rotary compressor classified? (Nov/Dec 2019)**
   A rotary compressor is a type of gas compressor which uses a rotary type positive displacement mechanism. The mechanism for gas compressor utilizes either a single screw element or counter rotating intermeshed helical screw elements housed within a specially shaped chamber.
   Classification:
   - ✓ Positive displacement compressor
     - ❖ Root blower.
     - ❖ Screw type compressor.
     - ❖ Vane type compressor.
   - ✓ Non-positive displacement compressor
     - ❖ Centrifugal compressor.
     - ❖ Axial flow compressor.
3. **Define the following terms. (i) Mechanical efficiency (ii) Adiabatic or isentropic efficiency (iii) Compressor efficiency (iv) Isothermal efficiency (April/May 2019)**

Mechanical efficiency: it is defined as the ratio of indicated power to the brake power
Adiabatic efficiency: it is defined as the ratio of isentropic work input to the actual work input.
Compressor efficiency: it is defined as the ratio of isothermal work input to the indicated work input.
Isothermal efficiency: it is defined as the ratio of isothermal work input to actual work input during compressor.

4. How is work saving possible in multi stage compressor? (April/May 2019)

In a two-stage compressor, air is partially compressed using isentropic compression, and then cooled in a heat exchanger, called an intercooler. This brings the compression process closer to isothermal (constant temperature) compression, which is more efficient. The blue shaded area below represents the amount of work done to change the air from P1/V1 to P2/V2 in two stages, with an intercooler. The green shaded area represents the savings achieved by two stage compression versus single stage.



We can see that there is a distinct efficiency advantage to multiple stages when intercoolers are used. Without intercooling, however, the savings would not exist, and the efficiency would match a single stage machine.

5. Define clearance ratio. (Nov/Dec 2018)

Clearance ratio is defined as the ratio of clearance volume to swept volume (or) stroke volume.

6. What is purpose of intercooler? (Nov/Dec 2018)

The purpose of intercooler is to minimize the compression work. As the intercooler reduces the intake temperature of high pressure cylinder, the amount of work is reduced.

7. **What is air compressor? State its applications.**
Air compressor is a mechanical device which are used for increasing the pressure by reducing the volume of air.
Compressor air are mostly used in IC engines, pneumatic brakes, spray painting, pneumatic drills, pneumatic jacks etc.
8. **Classify the air compressors.**
   - ✓ According to the principle of operation
     - ❖ Positive displacement compressors (ex: reciprocating, rotary compressor)
     - ❖ Dynamic compressor (ex: centrifugal, axial flow compressor)
   - ✓ According to number of stages
     - ❖ Single stage
     - ❖ Double stage
   - ✓ According to action
     - ❖ Single acting
     - ❖ Double acting
   - ✓ According to prime mover
     - ❖ Electric motor drive (or) IC engine drive
     - ❖ Gas turbine drive
   - ✓ According to pressure limits
     - ❖ Low pressure
     - ❖ Medium pressure
     - ❖ High pressure
   - ✓ According to method of cooling
     - ❖ Air cooled
     - ❖ Water cooled
9. **Define the following terms. (i) Mechanical efficiency (ii) Adiabatic or isentropic efficiency (iii) Compressor efficiency (iv) Isothermal efficiency**
Mechanical efficiency: it is defined as the ratio of indicated power to the brake power
Adiabatic efficiency: it is defined as the ratio of isentropic work input to the actual work input.
Compressor efficiency: it is defined as the ratio of isothermal work input to the indicated work input.
Isothermal efficiency: it is defined as the ratio of isothermal work input to actual work input during compressor.
10. **What is clearance volume? Why it is provided?**
The clearance volume is the space left in the cylinder when the piston reaches the TDC.
It is provided;
    - ❖ To avoid the piston striking the cylinder head
    - ❖ To accommodate the valve's actuation inside the cylinder, because suction and delivery valves are located in the clearance volume.

11. What is the effect of clearance volume in air compressor?

- ❖ The volume of air taken per stroke is less than swept volume, thus the volumetric efficiency decreases.
- ❖ More power input is required to drive the compressor for same pressure ratio, due to increase in volume.
- ❖ The maximum compression pressure is controlled by the clearance volume.

12. What are the methods adopted for improving isothermal efficiency?

- ❖ Water spray
- ❖ Water jacketing
- ❖ External fins
- ❖ Inter cooler
- ❖ Suitable cylinder proportions.

13. Define volumetric efficiency.

It is defined as the ratio of actual volume of air sucked into the compressor to the piston displacement (or) stroke volume.

$$\eta_{vd} = \frac{actual\ volume\ of\ air\ sucked\ \text{into}\ the\ compressor}{piston\ displacement\ or\ stroke\ volume} = \frac{V_a}{V_s}$$

14. List the factors which affect the volumetric efficiency of the compressor.

- ❖ Large clearance volume
- ❖ Obstruction at inlet valve
- ❖ High speed of compressor
- ❖ Heated cylinder walls
- ❖ Leakage past the piston

15. Define FAD (Free Air Delivered)

The Free Air Delivered is the volume of compressed air measured in m^3/min, reduced to atmospheric pressure and temperature.

16. Mention the factors that limits the delivered pressure in a reciprocating compressor?

- ❖ Size of the cylinder
- ❖ Stroke length
- ❖ Pressure and temperature of intake air

17. State the limitations of single stage compressor?

- ❖ Greater expansion of clearance air decreases the suction volume (v1-v4)therefore there is a decrease in fresh air indication.
- ❖ The delivery temperature and specific volume of air in the cylinder increase with high delivery pressure.
- ❖ For high pressure ratio, cylinder size will be large and heavy working parts are needed.
- ❖ For high pressure ratio balancing problem will be more
- ❖ High torque fluctuation will require a heavier flywheel installation.

18. What is meant by intercooler? Why intercooler is provided in multi stage compressor?

Intercooler is a heat exchanger. Is provided to exchange the heat of air from how pressure compressor to the circulating water before entering into high pressure compressor.

19. What do you mean by perfect intercooling?

When the temperature of air leaving the intercooler (T3) is equal to atmospheric air temperature(T1), then the intercooling is called as perfect intercooling.

20. What do you mean by imperfect intercooling?

When the temperature of air leaving the intercooler (T3) is not equal to atmospheric air temperature (T1), then the intercooling is called imperfect cooling.

21. What are the advantages (or) effects of multi stage compressor with intercooling?

- ❖ It improves the volumetric efficiency
- ❖ It gives uniform torque hence smaller size flywheel is required.
- ❖ It reduces the leakage loss
- ❖ The work done per Kg of air is reduced in multi stage compressor with intercooler.
- ❖ The size of cylinders can be adjusted to the required pressure and volume of the air.

22. What is rotary compressor?

Rotary compressor is an air compressor which uses rotor or impeller for driving the air through a curved chamber to compressor the air.

23. What are the types of rotary compressor?

- ✓ Positive displacement compressor
  - ❖ Root blower.
  - ❖ Screw type compressor.
  - ❖ Vane type compressor.
- ✓ Non-positive displacement compressor
  - i. Centrifugal compressor.
  - ii. Axial flow compressor.

24. Write the difference between perfect intercooling and imperfect intercooling.

Perfect intercooling: when the temperature of air leaving the intercooler is equal to the temperature of air entering the compressor, it is said to be perfect intercooling.

Imperfect intercooling: when the temperature of air leaving the intercooling is more than the temperature of air entering the compressor, it is said to be imperfect cooling.

25. Distinguish between rotor and reciprocating compressor.

Reciprocating compressor	**Rotary compressor**
It is a mechanical device which takes atmospheric air into the cylinder at inlet and then compresses it with the help of mechanical energy and delivers it higher pressure at outlet with the help of piston cylinder arrangement is known as reciprocating compressor	An air compressor using a rotary impeller that spins inside a circular housing to compress the air is known as rotary compressor. It is used for low and medium pressures.

26. Differentiate centrifugal and axial flow compressor.

Centrifugal compressor	Axial flow compressor
❖ Area is larger	❖ Area is smaller
❖ Starting torque is low	❖ Starting torque required is high
❖ Upto 400 bar delivery pressure	❖ Delivery pressure is only upto 20bar
❖ Multi staging is slightly difficult	❖ More suitable for multi-staging
❖ More flexible	❖ Flexible
❖ Pressure ratio high	❖ Low pressure ratio

Part – B

1. **Present the comparison between centrifugal and reciprocating compressors. (May 2019)**

Reciprocating compressors	Centrifugal compressors
Higher initial cost	Lower initial cost
Pressure ratio per stage is about 5 to 8	Pressure ratio per stage is about 3 to 4.5
High delivery pressure upto 5000 atm	Medium delivery pressure upto 400 atm
Smaller free air delivered	Greater FAD
High maintenance cost	Lower maintenance cost
Compression efficiency is higher , at compression ratio above 2	Compression efficiency is higher , at compression ratio less than 2
Low speed drive	High speed drive
More operating attention needed	Less operating attention needed
Suitable for low, medium and high pressures and low and medium gas volumes	Suitable for low and medium pressures and large gas volumes
Always a chance of mixing of air with lubricating oil	No chance of mixing of lubricating oil with air.

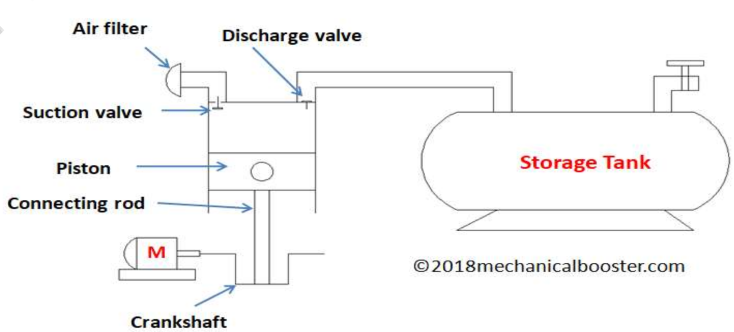
2. **Explain the working of reciprocating compressor using relevant sketch. (May 2019)**

Reciprocating Air Compressor is a positive displacement air compressor in which air is sucked in a chamber and compressed with the help of a reciprocating piston. It is called as positive displacement compressor because air is first sucked in a chamber and then compression is achieved by decreasing area of the chamber. The area is decreased by a piston which does reciprocating motion.

Working principle:

In reciprocating air compressor, as the piston moves towards the BDC, the air is sucked into the cylinder from the atmosphere and when it moves towards the TDC, the compression of the air starts and keeps on going and pressure increases. When the pressure increases upto its design limit it pushes the discharge valve to open and the compressed air is delivered to the storage tank.

Main parts:

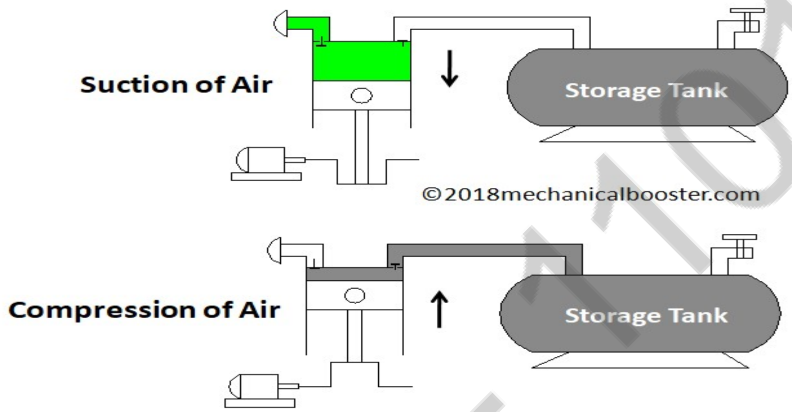


Main Parts of Reciprocating Air Compressor

- ✓ **Piston:** It does reciprocating motion in the cylinder and responsible for the compression of the air.

- ✓ **Cylinder:** It is a chamber in which air is compressed.
- ✓ **Connection Rod:** It connects the piston and crankshaft.
- ✓ **Crankshaft:** It is connected to the shaft of electric motor. And transfers its rotary motion to the piston.
- ✓ **Suction valve:** The air is sucked through suction valve when piston moves to BDC.
- ✓ **Discharge valve:** The compressed air is discharged through the discharge valve to the storage tank.

Working:



Working of Reciprocating Air Compressor

- ✓ As power is On, the electric motor starts rotating and also rotates the crankshaft attached to it. The piston starts doing to and fro motion inside the cylinder.
- ✓ As the piston moves downward (towards BDC), the air from the atmosphere enters into the chamber of the cylinder.
- ✓ Now the piston after reaching at BDC, starts moving upward (i.e. towards TDC), the compression of the air starts and its pressure begins to increase.
- ✓ When the pressure inside the cylinder increases above the pressure of the discharge valve, the discharge valve opens and the compressed air is delivered to a air storage tank from where it is utilized for the work.

3. **a multi stage air compressor is to be designed to elevate the pressure from 1 bar to 125 bar such that stage pressure ratio will not exceed 4. Determine (i) number of stages (ii) exact stage pressure ratios (iii) intermediate pressures. (Nov/Dec 2019)**

Given:

Pressure ratio per stage $\frac{P_{x+1}}{P_x} = 4 = z$

$P_1 = 1 \text{ bar} = 100 \text{ kPa}$

$P_{x+1} = 125 \text{ bar} = 12500 \text{ kPa}.$

To find:

1) Number of stages (x)

2) Exact stage pressure ratio $\left(\frac{P_{x+1}}{P_1}\right)$

3) Intermediate Pressure. (P_2, P_3, P_4)

solution:

For multi-stage compression we know that

$$z = \left[\frac{P_{x+1}}{P_1}\right]^{1/x}$$

x - number of stages

$$4 = \left[\frac{125}{1}\right]^{1/x}$$

Take log on both sides

$$\log 4 = \log\left[\frac{125}{1}\right]^{1/x}$$

$$1.3863 = \frac{1}{x} \log 125$$

$$1.3863 = \frac{1}{x}[4.8283]$$

$$x = \frac{4.8283}{1.3863} = 3.482$$

$x = 4$ (say)

Exact stage pressure ratio

$$\frac{P_{x+1}}{P_x} = \left[\frac{P_{x+1}}{P_1}\right]^{1/x} = \left[\frac{125}{1}\right]^{1/4}$$

$$\frac{P_{x+1}}{P_x} = 3.34$$

Intermediate pressure

$$P_{x+1} = 125 \Rightarrow P_{4+1} = 125$$

$$P_5 = 125 \text{ bar}$$

$$\frac{P_{x+1}}{P_x} = 3.34 \Rightarrow \frac{P_{4+1}}{P_4} = 3.34$$

$$\frac{P_5}{P_4} = 3.34$$

$$P_4 = \frac{P_5}{3.34} = \frac{125}{3.34}$$

$$P_4 = 37.425 \text{ bar}$$

Similarly $\frac{P_4}{P_3} = 3.34$

$$P_3 = \frac{P_4}{3.34} = \frac{37.42}{3.34}$$

$$P_3 = 11.20 \text{ bar}$$

Similarly $\frac{P_3}{P_2} = 3.34$

$$P_2 = \frac{P_3}{3.34} = \frac{11.20}{3.34}$$

$$P_2 = 3.353 \text{ bar.}$$

4. A single stage single acting air compressor running at 800 rpm delivers air at 6 bar, for this purpose, the induction and free air conditions can be taken as 1.013 bar and 20°C and the free air delivery as 10 m^3/min. The clearance volume is 5% of the swept volume and stroke/bore ratio is 1.5:1. Calculate the:

i. Bore and stroke

ii. The volumetric efficiency

iii. The indicated power

iv. Isothermal efficiency of the compressor

Take the index compression and expansion as 1.35 (May 2019)

Given:

Speed $N = 800$ rpm

Delivery pressure $P_2 = 6$ bar

Initial Pressure $P_1 = 1.013$ bar $= 101.3$ KPa

Initial Temp $T_1 = 20°C = 20+273 = 293$ K.

Free air delivery $V_a = 10\ m^3/min$

Clearance volume $V_c = 5\%\ V_s = 0.05 V_s$

Stroke / Bore ratio $\frac{L}{D} = \frac{1.5}{1} \Rightarrow L = 1.5 D$

To find:

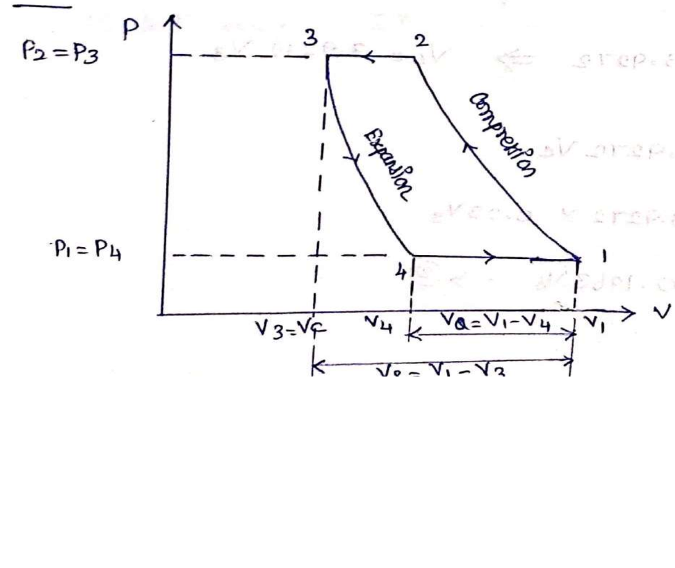
1) volumetric efficiency

2) D and L

3) Isothermal efficiency

4) Power.

Solution:



Free air delivered (FAD) = $V_1 - V_4 = 10\ m^3/min$

$$V_1 - V_4 = \frac{10}{N} m^3 = \frac{10}{800} m^3$$

$$V_1 - V_4 = 0.0125\ m^3$$

Swept volume $V_s = V_1 - V_3 = V_1 - V_c$

$$V_s = V_1 - 0.05 V_s$$

$$V_1 = 1.05 V_s \rightarrow (1)$$

Since index of compression and expansion is given as 1.3 it follows polytropic process

For polytropic process $P_3 V_3^n = P_4 V_4^n$

$$\frac{V_4}{V_3} = \left[\frac{P_3}{P_4}\right]^{1/n} = \left[\frac{P_2}{P_1}\right]^{1/n}$$

$$\frac{V_4}{V_3} = \left[\frac{6}{1.013}\right]^{1/1.3}$$

$$\frac{V_4}{V_3} = 3.9272 \Rightarrow V_4 = 3.9272\ V_3$$

$$V_4 = 3.9272\ V_c$$

$$V_4 = 3.9272 \times 0.05 V_s$$

$$V_4 = 0.1963 V_s \rightarrow (2)$$

Equation ① - ② $\Rightarrow$ $V_1 - V_4 = 1.05 V_s - 0.1963 V_s$

$$V_1 - V_4 = V_s [1.05 - 0.1963]$$

$$V_s = \frac{V_1 - V_4}{(1.05 - 0.1963)} = \frac{0.0125}{1.05 - 0.1963}$$

$$V_s = 0.01464 \, m^3$$

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

$$0.01464 = \frac{\pi}{4} \times D^2 \times 1.5D$$

$$D = 73.18 \, mm$$

$$L = 87.84 \, mm$$

volumetric efficiency $\eta_{vol} = \frac{V_a}{V_s} = \frac{V_1 - V_4}{V_s}$

$$= \frac{0.0125}{0.01464} \times 100$$

$$= 85.3\,\%$$

Indicated power $I.P = \frac{n}{n-1} P_1 V_1 \left[\left[\frac{P_2}{P_1} \right]^{n-1/n} - 1 \right]$

$$= \frac{1.3}{1.3-1} \times 101.3 \times \frac{10}{60}\left[\left[\frac{6}{1.013}\right]^{\frac{1.3-1}{1.3}} - 1\right]$$

$$= 2 \text{ kW}$$

Isothermal efficiency $\eta_{iso} = \dfrac{P_1V_1 \ln\left(\frac{P_2}{P_1}\right)}{I.P}$

$$= 101.3 \times 10 \times \ln\left(\frac{6}{1.013}\right) \times 100$$

$$= 1.353 \text{ kW}$$

$$\eta_{iso} = \frac{1.353}{2} = 0.6765$$

$$= 67.65\%$$

5. A single stage single acting air compressor delivers 0.6 kg of air per minute at 6 bar. The temperature and pressure at the end of suction stroke are 30°C and 1 bar. The bore and stroke of the compressor are 100 mm and 150 mm respectively. The clearance is 3% of the swept volume. Assuming the index compression and expansion to be 1.3, find (i) volumetric efficiency of the compressor (ii) the power required if the mechanical efficiency is 85% and (iii) speed of the compressor. (Nov/Dec 2019)

Given:

$m = 0.6$ kg/min $= \frac{0.6}{60} = 0.01$ kg/s

$P_2 = 6$ bar $= 600$ kPa

$T_1 = 30^\circ C = 30 + 273 = 303$ K

$P_1 = 1$ bar $= 100$ kPa . $D = 100$ mm. $L = 150$ mm.

$V_c = 0.03 V_s$ $n = 1.3$

$\eta_{Mech} = 85\%$ (or) 0.85

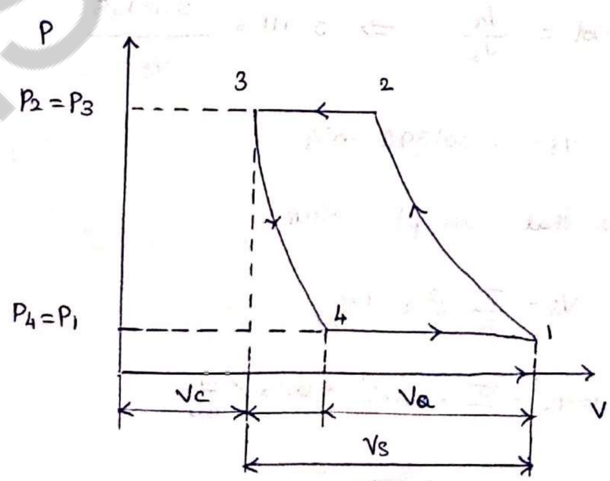
Solution:

C is clearance ratio $\frac{V_c}{V_s} = 0.03$

volumetric efficiency $\eta_{vol} = 1 + c - c\left[\frac{P_2}{P_1}\right]^{1/n}$

$= 1 + 0.03 - 0.03\left[\frac{600}{100}\right]^{1/1.3}$

$= 91.1\%$



From ideal gas equation. $P_a V_a = m R T_1$

$$V_a = \frac{m R T_1}{P_1} = \frac{0.9 \times 0.287 \times 303}{600} = 0.00145 \ m^3/s$$

Workdone on compressor (or) Theoretical power required

$$W = \frac{n}{n-1} P_1 V_n \left[\left[\frac{P_2}{P_1}\right]^{n-1/n} - 1 \right]$$

$$= \frac{1.3}{0.3} \times 100 \times 0.00145 \left[\left[\frac{600}{100}\right]^{0.3/1.3} - 1 \right]$$

$$= 0.322 \ kW$$

Driving power required (or) actual power supplied to the compressor

$$= \frac{\text{Theoretical power}}{\text{Mechanical efficiency}} = \frac{0.322}{0.85} = 0.375 \ kW$$

Swept volume can be calculated from volumetric efficiency

$$\eta_{vol} = \frac{V_a}{V_s} \Rightarrow 0.911 = \frac{0.00145}{V_s}$$

$$V_s = 0.001592 \ m^3/s$$

We know that swept volume

$$V_s = \frac{\pi}{4} D^2 L \ N/60$$

$$0.001592 = \frac{\pi}{4} \times (0.1)^2 \times 0.15 \times \frac{N}{60}$$

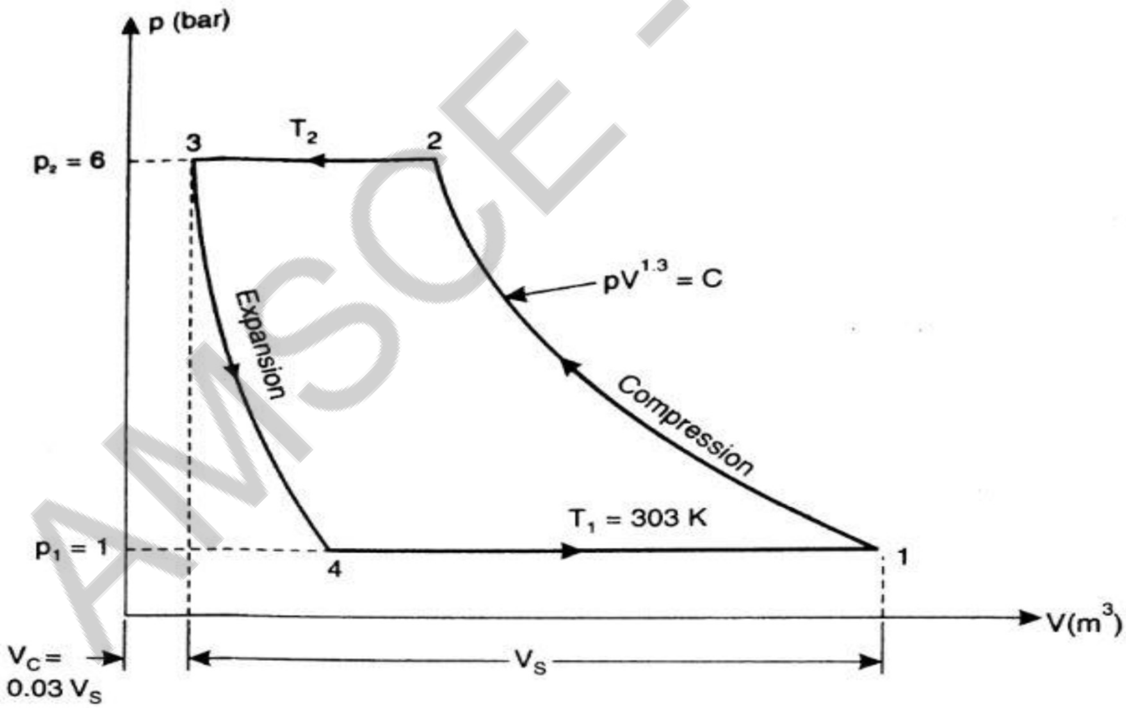
$$N = 81.08 \ rpm$$

6. **A single-stage single-acting air compressor delivers 0.6 kg of air per minute at 6 bar. The temperature and pressure · at the end of suction stroke are 30°C and 1 bar. The bore and stroke of the compressor are 100 mm and 150 mm respectively. The clearance is 3% of the swept volume. Assuming the index of compression and expansion to be 1.3 find:**
(i) Volumetric efficiency of the compressor,

(ii) Power required if the mechanical efficiency is 85%, and
(May 2015)

Solution:

Mass of delivered $m = 0.6$ kg/ min
Delivery pressure $p_2 = 6$ bar
Induction pressure $p_1 = 1$ bar
Induction temperature $T_1 = 30+273 = 303$ K
Bore, $D=100$ mm $= 0.1$ m
Clearance value $L = 150$ mm $= 0.15$ m
Mechanical efficiency $\eta_{mech} = 85\%$



i) volumetric efficiency of compressor $\eta_{vol} = 1 + k - k\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$

where h $= \frac{V_c}{V_s} = 0.03$

$$\therefore \qquad \eta_{vol} = 1 + 0.03 - 0.03\left(\frac{6}{1}\right)\frac{1}{1.3} = \mathbf{0.1096 \text{ or } 91.096\ \%}$$

ii)power required to drive the compressor :

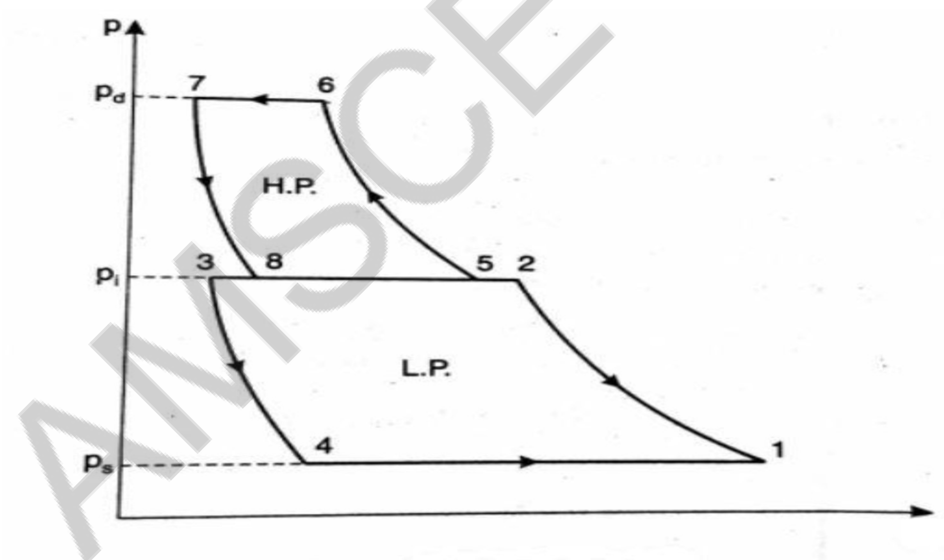
indicted power $$= \frac{n}{n-1} mRT_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} - 1\right]$$

$$= \frac{1.3}{1.3-1} \times \frac{0.6}{60} \times 0.287 \times 303 \left[\left(\frac{6}{1}\right)^{\frac{1.3-1}{1.3}} - 1\right] = \mathbf{1.93\ \ kW}$$

$$\therefore \text{ power required to drive the compressor} = \frac{1.93}{\eta_{mech}} = \frac{1.93}{0.85} = \mathbf{2.27\ kW}$$

7. In a single - acting two - stage reciprocating air compressor 4.5 kg air per min. are compressed from 1.013 bar and 15°C through a pre sure ratio of 9 to 1. Both stags have the system pressure ratio, and the ·law of compression and expansion in both stages is pV1.3• Calculate
(i) The indicated power
(ii) The cylinder swept volumes required
Assume that the clearance volumes of both stages are 5% of their respective swept volumes and that the compressor . runs at 300 r .p.m . (May 2015)

Solution:



Amount of air compressed, m = 4.5 kg/min.
Suction condition, p_s =1.013 bar ,T_s = 15+273=288 K

Pressure ratio, $\frac{p_d}{pl} = 9$

Also, $\frac{p_i}{p_s} = \frac{p_d}{p_i}$

Compression expansion index n = 1.3

Clearance volume in each stage = 5% of swept volume
Speed of compressor, N=300 rpm.
i) Indicated power :

$$\frac{p_i}{p_s} = \frac{p_d}{p_i}$$

$$p_i^2 = p_s \times p_d = p_s \times 9p_s = 9p_s^2$$

$$p_i = 3p_s \quad \text{i.e.,} \frac{p_i}{p_s} = 3$$

Now using the equation, $$\frac{T_i}{T_s} = \left(\frac{p_i}{p_s}\right)^{\frac{n-1}{n}} = (3)^{\frac{1.3-1}{1.3}}$$

$$T_i = T_s \times (3)^{\frac{0.3}{1.3}} = 288 \times (3)^{\frac{0.3}{1.3}} = 371 \text{ K}$$

Now as n, m and temperature difference are the same for both stage, then the work done in each stage is the same.

Total work required per min $= 2 \times \frac{n}{n-1} mR(T_i - T_s)$

$$= 2 \times \frac{1.3}{1.3-1} \times 4.5 \times 0.287(371-288)$$ =**929 kJ/min**

$\therefore$ indicated power $\frac{929}{60} =$ **15.48 kW**

$$\eta_{vol} = 1 + k - k\left(\frac{p_d}{p_i}\right)^{1/n}$$

And since $\frac{V_c}{V_s} = k$ is the same as the low pressure stage and also $\frac{p_i}{p_s} = \frac{p_d}{p_i}$ then η_{vol} is 0.934 as above

Swept volume of H.P stage

$V_{s(H.P)} = \frac{0.0408}{0.934} =$ **0.004367m³**

It may be noted that the clearance ratio $\left(k = \frac{V_c}{V_s}\right)$ is the same in each cylinder ,suction temperature are the same since inter cooling is complete therefore the swept volume in the ratio of suction pressures,

$$V_{s(H.P)} = \frac{V_{L.P}}{3} = \frac{0.0131}{3} = 0.00437 \text{ m}^3$$

8. A single acting air compressor takes in atmospheric air (atm condition 101.325 kPa, 27° C) and delivers it at 1.4 MPa. The compressor runs at 300 rpm and has cylinder diameter of 160 mm and stroke 20.0 mm, clearance volume is 4% of stroke volume . If the pressure and temperature of the air at the end of suction stroke are l00 kPa and 47° C, and law of
compression and expansion is $PV^{1.3}$ = c, determine;
(i) - mass of the air delivered per minute . ·.
(ii) volumetric efficiency.

(iii) driving power required , if η_m =.0.85 . (Nov/Dec 2015)

Given data:

$p_0 = 101.325 \text{ kPa}$

$T_0 = 27°C + 273 = 300K$

$p_2 = 1.4 \text{ MPa} = 1400 \text{ kPa}$

$N = 300 \text{rpm}$

$D = 160 \text{ mm} = 0.16 \text{ m}$

$L = 200 \text{ mm} = 0.2 \text{ m}$

$V_a = 4\% \quad V_s = 0.04 V_s$

$p_1 = 1 \text{ bar} = 100 \text{ kPa}$

$T_1 = 47°C = 47 + 273 = 320 \text{ K}$

$n = 1.2$

$\eta_{mech} = 0.85$

Solution:

Clear ratio, $C = \frac{V_a}{V_s} = \frac{0.04 V_s}{V_s} = 0.04$

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

$$= 1 + 0.04 - 0.04\left(\frac{1400}{100}\right)^{\frac{1}{1.2}}$$

$$\eta_{vol} = 1 + 0.04 - 0.04 \times (1.4)^{\frac{1}{1.2}}$$

$$\eta_{vol} = 0.6793 = 67.93\%$$

Stroke volume, $V_s = \frac{\pi}{4} D^2 L = \frac{\pi}{4} \times (0.16)^2 \times (0.2) = 0.00402 \, m^3$

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

$$0.6793 = \frac{V_a}{0.00402}$$

We know that $p_1 V_1 = mRT_1$

$$m = \frac{100 \times 0.00273}{0.287 \times 320} = 0.00297 \text{ kg}$$

$$m = 0.00297 \times N$$
$$= 0.00297 \times 300 = 0.891 \text{ kg/ min}$$

We know that at free air delivery condition,

$$p_0 V_0 = mRT_0$$

$$V_0 = \frac{mRT_0}{p_0}$$

$$V_0 = \frac{0.00297 \times 0.287 \times 300}{101.325} = 0.002524 \text{ m}^3$$

Volume efficiency at free air delivery,

$$\eta_{vol} = \frac{V_0}{V_s}$$

$$\eta_{vol} = \frac{0.002524}{0.00402}$$

$$\eta_{vol} = 0.6279 = 62.97\%$$

Power supplied to the compressor with clearance volume,

$$P \text{ or } W = \frac{n}{n-1} mRT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$= \frac{1.2}{1.2-1} \times \frac{0.891}{60} \times 0.287 \times 320 \times \left[\left(\frac{1400}{100} \right)^{\frac{1.2-1}{1.2}} - 1 \right]$$

$$= \mathbf{4.52 \text{ kW}}$$

9. A three-stage air compressor with perfect intercooling takes 15 m 3 of air per minute at 95 kPa and 27° C, and delivers the air at 3. 5 MPa. If compression process is polytrophic (= c), determine:

i) power required if mechanical efficiency is 90%.

(ii) heat rejected in the intercoolers per minute.

(iii) · isothermal efficiency,

(iv) Heat rejected through cylinder walls per minute . (Nov/Dec 2016)

Given data:

$$V_{a_1} = 15 \text{ m}^3/\text{min} = \frac{15}{60} = 0.25 \text{ m}^3/\text{s}$$

$$p_1 = 95 \text{ kPa}$$

$$T_1 = 27° \text{ C} = 27 + 273 = 300 \text{ K}$$

$$p_4 = 3.5 \text{ MPa} = 3500 \text{ kPa}$$

$$pV^{1.3} = C$$

$$\eta_{mech} = 0.9$$

Solution:

We know that for perfect intercooling exact stage pressure ratio,

$$\frac{p_2}{p_1} = \frac{p_3}{p_2} = \frac{p_4}{p_3} = \left(\frac{p_4}{p_1}\right)^{\frac{1}{3}}$$

$$\frac{p_2}{p_1} = \left(\frac{3500}{95}\right)^{\frac{1}{3}} = 3.33$$

From ideal gas equation,

$$p_1 V_{a_1} = mRT_1$$

$$\therefore \quad m = \frac{95 \times 0.25}{0.287 \times 300} = 0.276 \text{ kg/s}$$

Power supplied to the compressor for 3 stages,

$$P \text{ or } W = \frac{3n}{n-1} mRT_1 \left[\left(\frac{p_4}{p_1}\right)^{\frac{n-1}{3n}} - 1\right]$$

$$= \frac{3 \times 1.3}{1.3 - 1} \times 0.276 \times 0.287 \times 300 \times \left[\left(\frac{3500}{95}\right)^{\frac{1.3-1}{3 \times 1.3}} - 1\right]$$

$$= \mathbf{98.78 \text{ kW}}$$

Driving power required or actual supplied to the compressor,

$$= \frac{\text{Theoretical power}}{\text{Mechanical efficiency}}$$

`

$$= \frac{98.78}{0.9} = 109.76 \text{ kW}$$

From thermo dynamic relations,

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} = 300 \times (3.33)^{\frac{1.3-1}{1.3}} = \mathbf{395.99 \text{ K}}$$

Heat rejected in one inter cooler,

$$= mc_p(T_2 - T_1)$$

$$0.276 \times 1.005 \times (395.99 - 300) = \mathbf{26.63\ kW}$$

`Since there are three stages, there should be two inter coolers in the compressor and it is given that the inter cooling is perfect, hence the heat rejection in each inter cooler will be the same.

$\therefore$ total heat rejection in two intercoolers,

$$Q = 26.63 \times 2 = \mathbf{53.26\ Kw}$$

Isothermal work of compressor,

$$W_{iso} = mRT_1 \ln\left(\frac{p_1}{p_2}\right)$$

$$= 0.276 \times 0.287 \times 300 \times \ln\left(\frac{95}{3500}\right) = \mathbf{-\ 85.71\ kW}$$

(negative sign indicates the compressor work)

Isothermal efficiency, $\eta = \frac{W_{iso}}{W_{act}} = \frac{85.71}{98.78} = \mathbf{86.77}$ %

Applying steady flow energy equation to each cylinder,

$\therefore$ for one cycle,

Energy in = Energy out

$$h_1 + W = Q + h_2 \quad [\because \text{neglating KE and PE effects}]$$

Heat rejected, $Q = W + (h_1 - h_2)$

$$Q = \frac{n}{n-1} mR(T_1 - T_2) + mc_p(T_1 - T_2)$$

$$= m(T_1 - T_2)\left[c_p \frac{n}{n-1} R\right]$$

Hence, polytropic work of compression in each cylinder is considered.

Heat rejection per minute,

$$= (0.276 \times 60)(300 - 395.99)\left[1.005 - \frac{1.3}{1.3-1} \times 0.287\right]$$

= 376.38 kJ per cylindrical of air

Total heat rejection in all 3 cylinders,

$$= 379.38 \times 3 = \mathbf{1138.14\ kJ}$$

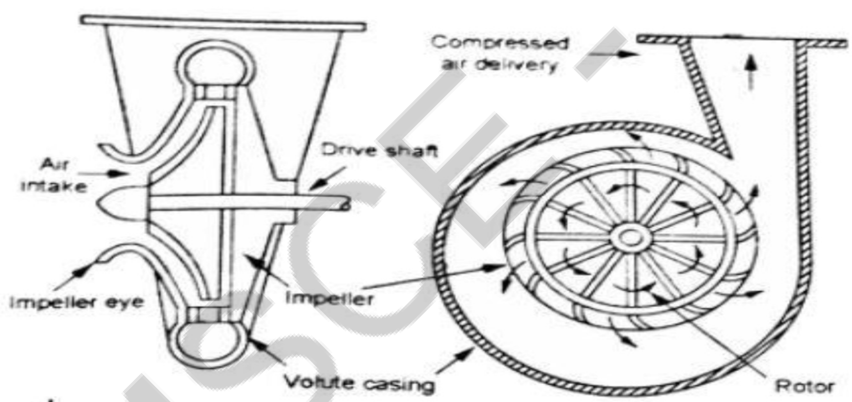
10. Explain the construction and working principle of centrifugal compressor and axial flow compressor with neat sketches. (Nov/Dec 2016)

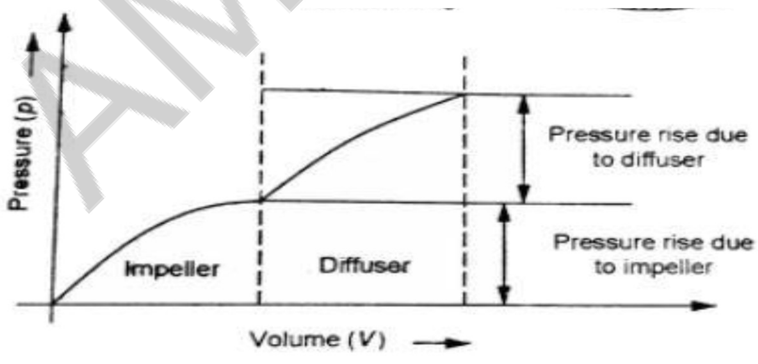
CENTRIFUGAL COMPRESSOR:

In this type of compressor, air enter axially and leaves radially.

Construction:

The arrangement of centrifugal compressor is shown figure. It consists of a rotating impeller, casting and diffuser. The impeller consists of a disc on which radial blades are attached. The impeller is sour rounded by be casing. The diffuser is another important part if the compressor which is used to convert hr kinetic energy of air into pressure energy. The air coming out from the diffuser is collected in the casing and taken out from the outlet of the compressor. The impeller of a centrifugal compressor can be run at the speed of 20,000 to 30,000 rpm.





Centrifugal compressor

Working:

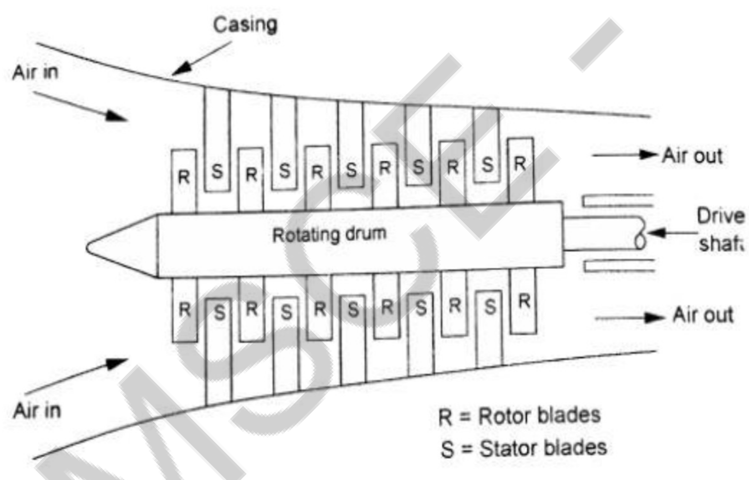
When the power is given to compressor, the impeller rotates and it sucked the air. This air enters axially with low velocity. The velocity and pressure of the air passing through the impeller are partially increased. Then the airs passing through the impeller are partially increased. Then the air is entered into the diffuser. In the diffuser, the kinetic energy is converted into pressure energy. So, the pressure of air is further increased. Finally the air high pressure is delivered to receiver. Nearly, half of the total pressure and velocity of air passing through the impeller and remaining half of the total pressure and velocity of air passing through the impeller and diffuser are shown fig.

Application:

Centrifugal compressors are suitable for super charging I.C engines, refrigerator and low pressure units.

AXIAL FLOW COMPRESSOR

In the type of compressor, air enters axially and hence it is called as axial flow compressor.



Axial compressor

Construction:

The arrangement of axial flow compressor is shown fig. It consists of a casing, a rotating drum, rotor blades and stator blades. The rotor blades are fixed to the casing. The rotor blades are fixed on the rotating drum. The air flow passage area is gradually reduced from the inlet to outlet of the compressor.

Working:

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

Application:

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

11. A single stage single-acting air compressor running at 1000 rpm delivers air at 25 bar, for this purpose the induction and free air conditions can be taken as 1.013 bar and 15°C and the free air delivery as 0.25 m^3/min. the clearance volume is 3% of the swept volume and stroke/bore ratio is 1.2:1. Calculate (i) bore and stroke (ii) the volumetric efficiency (iii) the indicated power (iv) the isothermal efficiency of the compressor. Take the index compression and expansion as 1.3. (April/may2019)

Given data:

Speed $N = 1000$ r.p.m

Delivery pressure $P_2 = 25$ bar

Initial pressure $P_1 = 1.013$ bar $= 101.3$ kPa

Initial temperature $T_1 = 15°C = 15 + 273 = 288$ K

Free air delivery $V_a = 0.25\ m^3/min$

clearence volume $V_c = 3\%\ V_s = 0.03\ V_s$

stroke / Bore ratio $\frac{L}{D} = 1.2 \Rightarrow L = 1.2D$

To find:

Bore, D

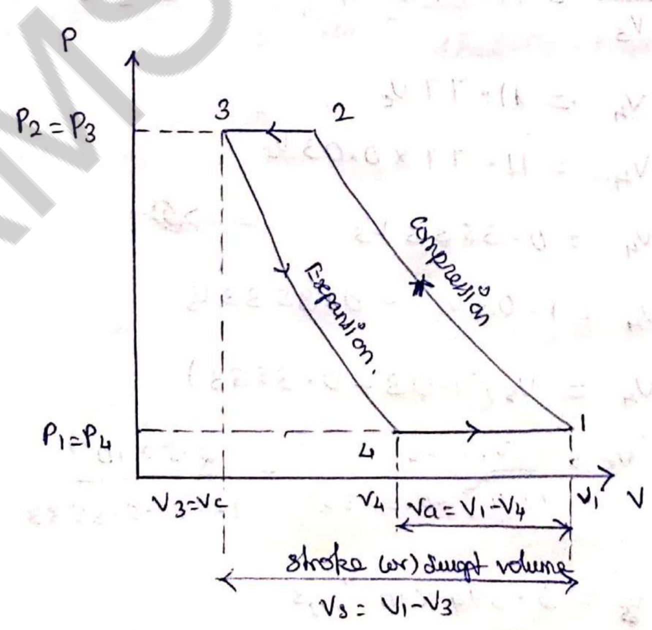
stroke, L

Volumetric efficiency, η_{vol}

Isothermal efficiency, η_{iso}

Indicated power I.P

solution:



Free air delivered (FAD) $= V_1 - V_4 = 0.25\ m^3/min$.

$$V_1 - V_4 = \frac{0.2}{N}\ m^3 = \frac{0.25}{1000}\ m^3.$$

$$V_1 - V_4 = 2.5 \times 10^{-4}\ m^3$$

Swept volume $V_S = V_1 - V_3 = V_1 - V_c$

$$V_S = V_1 - 0.03 V_S \quad [V_3 = V_c \text{ from PV diagram}]$$

$$V_1 = 1.03\, V_S \longrightarrow (1)$$

Since index of compression and expansion is given as 1.3 it follows polytropic process.

For polytropic process; $P_3 V_3^n = P_4 V_4^n$

$$\frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{1/n} = \left(\frac{P_2}{P_1}\right)^{1/n} \quad P_3 = P_2;\ P_4 = P_1$$

$$\frac{V_4}{V_3} = \left(\frac{25}{1.013}\right)^{\frac{1}{1.3}} \quad [\text{From PV diagram}]$$

$$\frac{V_4}{V_3} = 11.77 \Rightarrow V_4 = 11.77\, V_3 \quad [V_3 = V_c \text{ from PV diag}]$$

$$V_4 = 11.77\, V_c$$

$$V_4 = 11.77 \times 0.03\, V_S$$

$$V_4 = 0.3533\, V_S \longrightarrow (2)$$

(1)-(2) $\Rightarrow V_1 - V_4 = 1.03 V_S - 0.3533 V_S$

$$V_1 - V_4 = V_S(1.03 - 0.3533)$$

$$V_S = \frac{V_1 - V_4}{(1.03 - 0.3533)} = \frac{2.5 \times 10^{-4}}{1.03 - 0.3533}$$

$$V_S = 3.694 \times 10^{-4}\ m^3$$

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

$$3.694 = \frac{\pi}{4} \times D^2 \times 1.2D$$

$$D = 0.07318\, m \text{ (or) } 73.18\, mm$$

$$L = 1.2D = 1.2 \times 0.07318$$

$$L = 0.0874\, m \text{ (or) } 87.84\, mm$$

volumetric efficiency $\eta_{vol} = \frac{V_a}{V_s} = \frac{2.5 \times 10^{-4}}{3.694 \times 10^{-4}}$

$$\eta_{vol} = 0.6767 \text{ (or) } 67.67\%$$

Indicated power $I.P = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$

$$= \frac{1.3}{1.3-1} \times 101.3 \times \frac{0.25}{60} \left[\left(\frac{25}{1.013} \right)^{\frac{1.3-1}{1.3}} - 1 \right]$$

$$I.P = 2\, kW$$

Isothermal efficiency $\eta_{iso} = \frac{\text{Isothermal power}}{\text{shaft (or) Indicated power}} = \frac{P_1 V_1 In\left(\frac{P_2}{P_1}\right)}{I.P}$

Isothermal power $= P_1 V_1 In\left(\frac{P_2}{P_1}\right) = 101.3 \times 0.25 \times In\left(\frac{25}{1.013}\right) \times 100$

$$= 1.353\, kW$$

$$\eta_{iso} = \frac{1.353}{2} = 0.6765$$

$$\eta_{iso} = 67.65\%$$

12. A three stage compressor is sued to air from 1.013 bar to 36 bar. The compression in all stages follows the law $pv^{1.25}$=C. the temperature of air at the inlet of compressor is 300K. neglecting the clearance and assuming perfect intercooling, determine: (i) the indicated power required in kW to deliver 15m^3/min measured at inlet conditions and (ii) intermediate temperature. (April/may 2019)

Given data

Initial pressure $P_1 = 1.04$ bar $= 104$ kPa

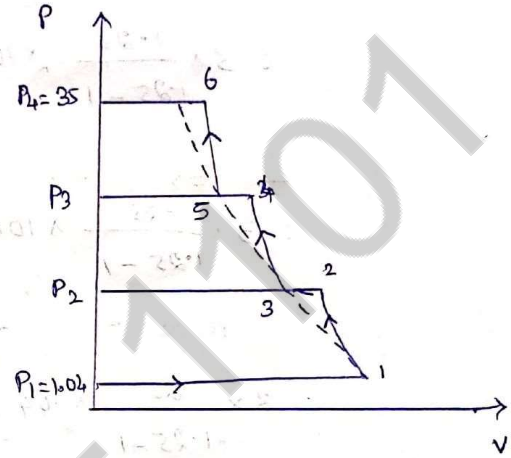
Final pressure $P_4 = 35$ bar $= 3500$ kPa

Inlet Temperature $T_1 = 288$ K

$R = 4125$ J/kg K for H_2

$n = 1.25$

$V_1 - V_4 = 14\ m^3/min = V_a$



To find:

(i) Indicated Power I.P

(ii) Intermediate pressure P_2 & P_3

Solution:

Intermediate pressure

For an x-stage compressor, pressure ratio

$$\frac{P_2}{P_1} = \frac{P_3}{P_2} = \frac{P_4}{P_3} = \left(\frac{P_4}{P_1}\right)^{1/x} \qquad x \rightarrow \text{No. of stages}$$

$$\frac{P_2}{P_1} = \left(\frac{P_4}{P_1}\right)^{1/3} \qquad x = 3$$

$$\frac{P_2}{1.04} = \left(\frac{35}{1.04}\right)^{1/3}$$

$$P_2 = 3.357 \text{ bar.}$$

$$\frac{P_3}{P_2} = \left(\frac{P_4}{P_1}\right)^{1/x}$$

$$\frac{P_3}{3.357} = \left(\frac{35}{1.04}\right)^{1/3}$$

$$P_3 = 10.838 \text{ bar}$$

Indicate power

$$I.P = x \cdot \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_{x+1}}{P_1} \right)^{\frac{n-1}{xn}} - 1 \right]$$

Here $x = 3 \rightarrow$ no. of stages.

$$= 3 \times \frac{1.25}{1.25-1} \times 104 \times \frac{14}{60} \left[\left(\frac{P_{3+1}}{P_1} \right)^{\frac{1.25-1}{3 \times 1.25}} - 1 \right]$$

$$= 3 \times \frac{1.25}{1.25-1} \times 104 \times \frac{14}{60} \left[\left(\frac{P_4}{P_1} \right)^{\frac{1.25-1}{3 \times 1.25}} - 1 \right]$$

$$= 3 \times \frac{1.25}{1.25-1} \times 104 \times \frac{14}{60} \left[\left(\frac{35}{1.04} \right)^{\frac{1.25-1}{3 \times 1.25}} - 1 \right]$$

$I.P = 96.15$ kW

Result:

Indicated power $I.P = 96.15$ kW

Intermediate pressure $P_2 = 3.357$ bar

$P_3 = 10.838$ bar.

13. A single-stage single-acting air compressor delivers 0.6 kg of air per minute at 6 bar. The temperature and pressure · at the end of suction stroke are 30°C and 1 bar. The bore and stroke of the compressor are 100 mm and 150 mm respectively. The clearance is 3% of the swept volume. Assuming the index of compression and expansion to be 1.3 find:
(i) Volumetric efficiency of the compressor,

(ii) Power required if the mechanical efficiency is 85%, and
(Nov/dec 2018)
Refer problem no 6. Same problem asked in may 2015.

14. Explain in detail the working of a multistage compressor with the help of p-v diagram. (Nov/Dec 2018)

MULTI-STAGE AIR COMPRESSOR WITH INTERCOOLING

In a multistage compressor, the compression of air from the initial pressure to the final pressure is carried out in more than one cylinder. It is used to get high-pressure air. In a compressor, when the compression ratio exceeds 5, generally, the multistage compression is adopted.

Type values of maximum delivery pressures generally available from different types of compressors are,

(i) Single stage Compressor - for delivery pressure up to 5 bar
(ii) Two stage Compressor - for delivery pressure between 5 and 35 bar
(iii) Three stage Compressor - for delivery pressure between 35 and 85 bar
(iv) Four stage compressor - for delivery pressure more than 85 bar.

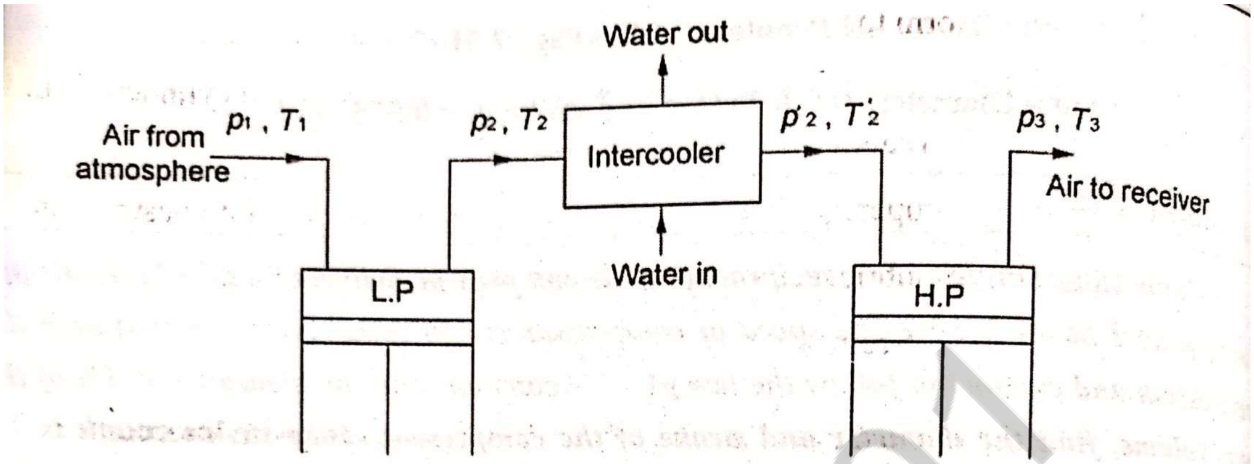


Figure 2.10 (a) Two stage compression with intercooler

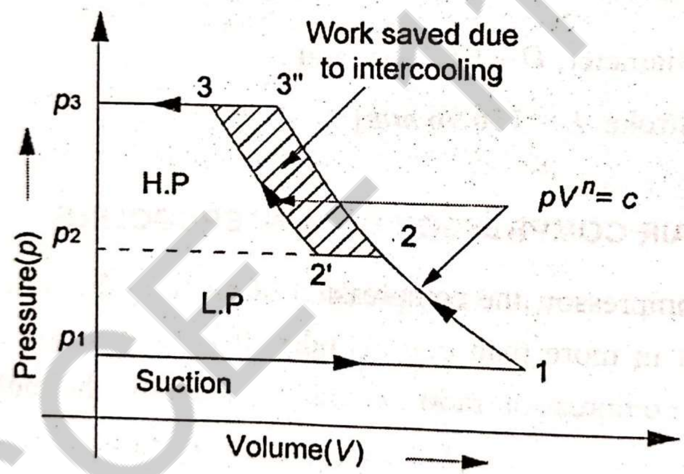


Figure 2.10 (b) p-V diagram

A schematic arrangement for a two-stage reciprocating air compressor is shown in Figure. It consists of a low-pressure cylinder (LP), an intercooler and a high-pressure cylinder (HP). The fresh air is sucked from the atmosphere in the low-pressure cylinder during its suction stroke at intake pressure pi and temperature T. The air after compression in LP cylinder is delivered to the intercooler at pressure p2 and temperature T. In the intercooler, the air is cooled at constant pressure by circulating cold water. The cooled air from the intercooler is then taken to the high-pressure cylinder. In the high-pressure cylinder, air is further compressed to the final delivery pressure (p) and discharged to the receiver.

Assumptions Made in Multistage Compression

1. Both suction and delivery pressures remain constant during each stage,
2. The index of compression is same in each stage.
3. The intercooling in each stage is at constant temperature.
4. The mass of air handled by low pressure and high-pressure cylinders are same

Advantages of Multistage Air Compressor

1.Volumetric efficiency is improved by increasing number of stages.

2. A better mechanical balance can be achieved with multistage compressors.

3. Work done per kg of air is reduced in multistage compression with intercooler as compared to a single stage compression for the same delivery pressure.

4. It reduces the leakage loss considerably.

5. it gives more uniform torque. Hence smaller size flywheel is required

6. it reduces the cost of compressor

15. A single stage single acting air compressor 30 cm and 40 cm stroke runs at 200 rpm. The suction pressure is 1 bar at 15^{o}C and the delivery pressure 5 bar. Determine the indicated mean effective pressure and ideal power required to run it. When (i) compression is isothermal (ii) compression follows the law $pv^{1.25}$=C. (iii) compression is reversible adiabatic. Determine the isothermal efficiency for (ii) and (iii). (Nov/Dec 2017)

Given data:

$D = 30\ cm = 0.3\ m$

$L = 40\ cm = 0.4\ m$

$N = 200\ rpm$

$p_1 = 1\ bar = 100\ kPa$

$T_1 = 15°\ C + 273 = 288\ K$

$p_2 = 5\ bar = 500\ kPa$

☺ ***Solution:***

Stroke or suction volume, $V_s = V_1 = \frac{\pi}{4} D^2 LN$

$$V_1 = \frac{\pi}{4} \times 0.3^2 \times 0.4 \times \frac{200}{60} = 0.0943\ m^3/s$$

Case (i): Work done during isothermal compression [pV = C]

Ideal power, $W = p_1 V_1 \ln\left[\frac{p_2}{p_1}\right]$

$$= 100 \times 0.0943 \times \ln\left[\frac{500}{100}\right] = 15.18\ kW$$

We know that the ideal or indicated mean effective pressure,

$$p_m = \frac{\text{Work done}}{\text{Stroke volume}} = \frac{15.18}{0.0943} = 160.98\ kPa$$

Case (ii): Compression follows the law $pV^{1.25} = C$

$$W = \frac{n}{n-1} p_1 V_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$W = \frac{1.25}{1.25-1} \times 100 \times 0.0943 \times \left[\left(\frac{500}{100} \right)^{\frac{1.25-1}{1.25}} - 1 \right]$$

$W = \mathbf{17.9}\ kW$ **Ans.**

We know that the ideal or indicated mean effective pressure,

$$p_m = \frac{\text{Work done}}{\text{Stroke volume}} = \frac{17.9}{0.0943} = \mathbf{189.82\ kPa}$$ **Ans.**

Also, we know that isothermal work of case (i), $W_{iso} = 15.18\ kW$

Actual work of case (ii), $W_{act} = 17.9\ kW$

Isothermal efficiency, $\eta_{iso} = \frac{W_{iso}}{W_{act}} = \frac{15.18}{17.9} = \mathbf{84.81\%}$ **Ans.**

Case (iii): Compression is reversible adiabatic ($\gamma = 1.4$)

$$W = \frac{\gamma}{\gamma-1} p_1 V_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

$$W = \frac{1.4}{1.4-1} \times 100 \times 0.0943 \times \left[\left(\frac{500}{100} \right)^{\frac{1.4-1}{1.4}} - 1 \right]$$

$= \mathbf{19.27}\ kW$ **Ans.**

We know that the ideal or indicated mean effective pressure,

$$p_m = \frac{\text{Work done}}{\text{Stroke volume}} = \frac{19.27}{0.0943} = \mathbf{204.35\ kPa}$$ **Ans.**

Also, we know that isothermal work of case (i), $W_{iso} = 15.18\ kW$

Actual work of case (iii), $W_{act} = 19.27\ kW$

Isothermal efficiency, $\eta_{iso} = \frac{W_{iso}}{W_{act}} = \frac{15.18}{19.27} = \mathbf{78.78\%}$ **Ans.**

16. **Derive the work done equation for multistage compressor with intercooler. (Nov/Dec 2017)**

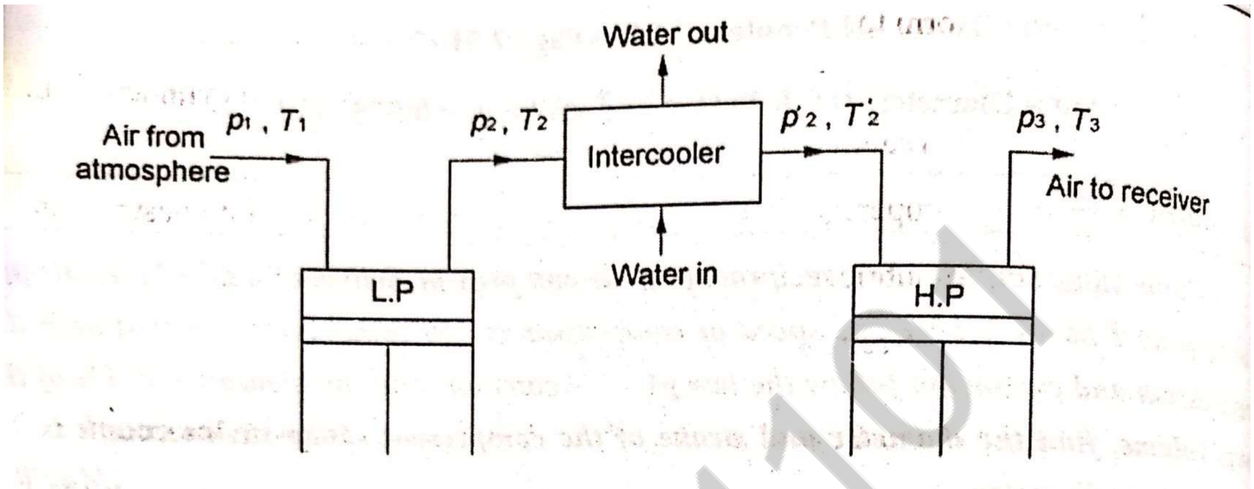


Figure 2.10 (a) Two stage compression with intercooler

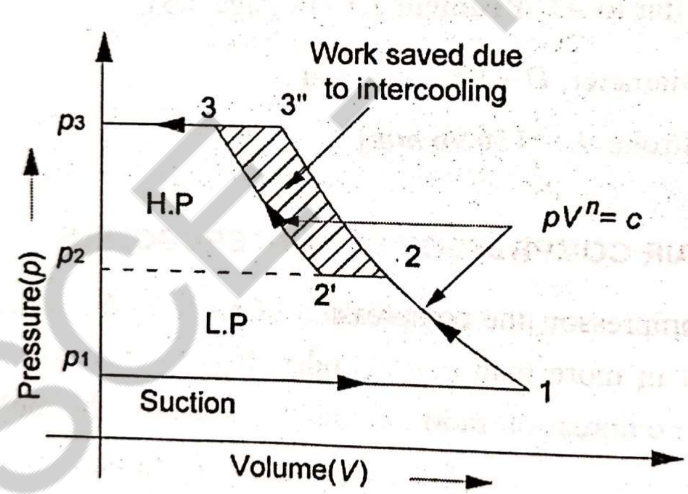


Figure 2.10 (b) p-V diagram

The p-V diagram for two-stage compressor with intercooler is shown in Figure 2.10. Let

p_1, V_1, T_1 are the pressure, volume and temperature of air entering the low-pressure (LP) cylinder.

p_2', V_2', T_2' are the pressure, volume and temperature of air entering the high-pressure (HP) cylinder.

p_3 be the final delivery pressure of air

n be the polytropic index of both the cylinder.

Total work input = Work input to LP compressor + Work input to HP compressor

$$W = \frac{n}{n-1} p_1 V_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] + \frac{n}{n-1} p_2' V_2' \left[\left(\frac{p_3}{p_2'} \right)^{\frac{n-1}{n}} - 1 \right] \qquad \ldots (2.18)$$

We know that $p_2 = p_2'$ and

$p_1 V_1 = p_2' V_2'$ for the perfect cooling

So, the above equation (2.18) can be rewritten as

$$W = \frac{n}{n-1} p_1 V_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] + \frac{n}{n-1} p_1 V_1 \left[\left(\frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$W = \frac{n}{n-1} p_1 V_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} + \left(\frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 2 \right] \qquad \ldots (2.19)$$

17. Discuss the application, working and terminology of reciprocating compressor. (April/may 2018)

2.4. WO...

In a single stage compressor, the compression of air from the initial pressure to final pressure is carried out in one cylinder only. A schematic diagram of a single stage single acting compressor is shown in Figure 2.1.

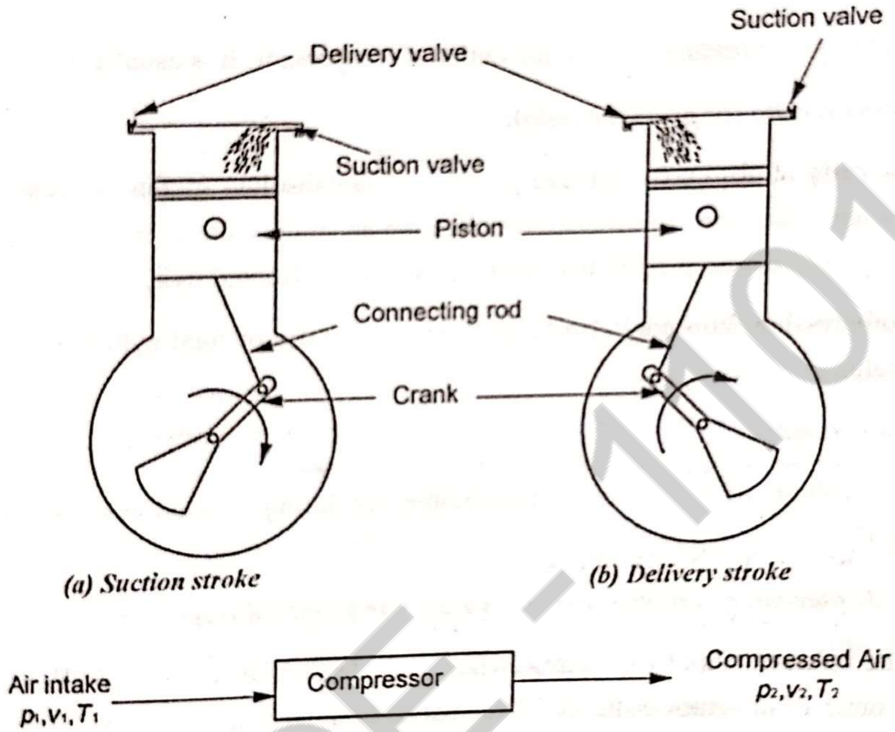


Figure 2.1 Single stage reciprocating air compressor

It consists of a cylinder, piston, connecting rod, crank, inlet and discharge valves. During the suction stroke, the piston moves downward from the top dead centre and the pressure of air inside the cylinder falls below the atmospheric pressure. So, the inlet valve opens and the air from atmospheric is sucked into the cylinder until the piston reaches the bottom dead centre. During this stroke, the delivery valve remains closed.

When the piston moves upwards from the bottom dead centre, both valves are closed. So, the pressure inside the cylinder goes on increasing till it reaches the required discharge pressure. At this stage, the discharge valve opens and the compressed air is delivered through this valve. Thus, the cycle is repeated.

2.5. IMPORTANT TERMS

The following important terms which will be frequently used in this chapter should be clearly understood at this stage.

(a) *Suction pressure:*

It is the absolute pressure of air at the inlet of a compressor. It is usually denoted by p_1.

(b) *Discharge pressure:*

It is the absolute pressure of air at the outlet of compressor. It is usually denoted by p_2.

(c) *Compression ratio (or pressure ratio):*

It is the ratio of absolute discharge pressure to the absolute suction pressure. Since the absolute discharge pressure is always more than the absolute suction pressure, therefore, the value of compression ratio is more than unity. It is usually denoted by r.

The compression ratio may also be defined as the ratio of total cylinder volume to the clearance volume.

(d) *Suction volume:*

It is the volume of air sucked by the compressor during its suction stroke. It is usually denoted by V_1.

(e) *Piston displacement volume or stroke volume or swept volume:*

It is the volume swept by the piston when it moves from its top or inner dead position to bottom or outer dead centre position. Mathematically, piston displacement volume or stroke volume or swept volume is given as follows:

Stroke or swept volume, $V_s = \frac{\pi}{4} D^2 L$

where D = diameter of cylinder

L = length of piston stroke

(f) Compressor capacity:

It is the volume of the actual amount of air passing through the compressor in a unit time. It is equal to the suction volume (V_1). It is expressed in m^3/s.

(g) Clearance space and clearance volume

When the piston reaches top dead centre in the cylinder, there is a dead space between piston top and cylinder head. This space is known as *clearance space* and the volume occupied by this space is known as *clearance volume* (V_c).

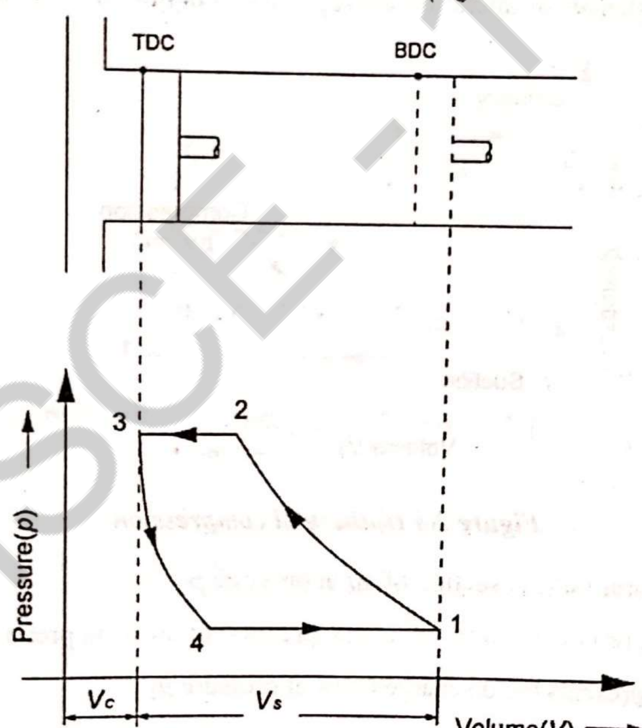


Figure 2.2 Clearance volume

(h) Clearance factor or clearance ratio:

It is the ratio of clearance volume (V_c) to the stroke volume (V_s). It is usually denoted by C. Mathematically, clearance ratio,

$$\text{Clearance ratio, } C = \frac{V_c}{V_s}$$

18. The free air delivery of a single cylinder, single stage reciprocating air compressor is 2.5 m³/min. The ambient air is at STP condition. The delivery pressure is at 7 bar. The clearance volume is 5% of stroke volume. Both compression and expansion are according to the law $PV^{1.25}$ = constant. Stroke length is 20% more than that of the bore. Compressor runs at 150 rpm. Determine the mass of air per second, indicated power, indicated mean efficiency pressure, bore and stroke of cylinder.

Given data:

$$V_a = 2.5\ m^3/\min = 0.042\ m^3/s$$

For STP conmdition the pressure and temprature are

$$p_1 = 1.013\ \text{bar} = 101.3\ \text{kPa}$$
$$T_1 = 15°C = 288\ K$$
$$p_2 = 7\ \text{bar} = 700\ \text{kPa}$$
$$V_c = 5\%,\ V_s = 0.05 \times V_s$$
$$pV^{1.25} = C$$
$$L = 1.2D$$
$$N = 150\ \text{rpm}$$

Solution:

Work done, $$W = \frac{n}{n-1} p_1 v_a \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$W = 1\frac{1.25}{1.25-1} \times 101.3 \times 0.042 \left[\left(\frac{700}{101.3}\right)^{\frac{1.25-1}{1.25}} - 1\right] = 10.04\ kW$$

Clearance ratio $$C = \frac{V_c}{V_s} = \frac{0.05 V_s}{V_s} = 0.05$$

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

$$= 1 + 0.05 - 0.05\left(\frac{700}{101.3}\right)^{\frac{1}{1.25}} = 0.815$$

We know that the free air delivery,

$$V_a = V_s \times \eta_{vol} \times N$$

$$2.5 = V_s \times 0.815 \times 150$$

$$\therefore\ V_s = 0.0205\ m^3$$

We know that swept volume,

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

$$0.0205 = \frac{\pi}{4} \times D^2 \times 1.2D$$

D =0.279 m

L = 1.2D = 1.2 × 0.279 = 0.335 m

19. A two – stage air compressor consist of three cylindrical having the same bore and stroke. The delivery pressure is 7 bar and the free air delivery is 4.2 m^3/min .air is drawn in at 1.013 bar , 15 ° C and an inter cooler cools the air to 38 ° C. The index of compression is 1.3 for all three cylinders. Neglecting clearance calculate the; (i) inter mediate pressure (ii) power required to drive the compressor (iii) isothermal efficiency.

Given data:

P = 7 bar

V_{a_1} = V_1 4.2 m^3/min = 4.2/60 = 0.007 m^3/s

P_1 = 1.013 bar = 101.3 kPa

T_1 = 15 ° C = 15+273 = 288K

T_2'= 38 ° C = 31+273 = 311K

n = 1.3

Solution:

From ideal gas equation,

$p_3 V_e = mRT_1$

$$m = \frac{101.3\left(\frac{4.2}{60}\right)}{0.287 \times 288} = 0.086\,kg/s$$

Optimum pressure ratio condition is assumed, the intermediate pressure.

$p_2 = \sqrt{p_1 p_3}$

$p_2 = \sqrt{1.013 \times 7}$ = 2.66 bar

Since, $T_2 \neq T_1$ its incomplete inter cooling.

We know that $\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$

$$V_2 = \frac{p_1V_1T_2}{p_2T_1}$$

$$= \frac{1.013 \times 4.2 \times 311}{2.66 \times 288} = 1.73\,m^3/\min$$

Work done on the two- stage reciprocating air compression for incomplete inter cooling.

$$W = \frac{n}{n-1}p_1V_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1}p_2V_2\left[\left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 1\right]$$

$$W = \frac{n}{n-1}p_1V_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1}p_2V'_2\left[\left(\frac{p_3}{p_{\leftarrow}}\right)^{\frac{n-1}{n}} - 1\right]\left[\therefore p'_2 = p_2\right]$$

$$W = \frac{1.3}{1.3-1} \times 1.013 \times 100 \times (\frac{4.2}{60})\left[\left(\frac{2.66}{1.013}\right)^{\frac{1.3-1}{1.3}} - 1\right] + \frac{1.3}{1.3-1} \times 2.66 \times 100\left(\frac{1.73}{60}\right)\left[\left(\frac{7}{2.66}\right)^{\frac{1.3-1}{1.3}} - 1\right]$$

W = 7.67 + 8.32 =15.99 kl/s =15.99 kW

Isothermal work of compressor,

$$W_{iso} = mRT_1 In\left(\frac{p_4}{p_1}\right)$$

$$= 0.086 \times 0.287 \times 288 \times \ln\left(\frac{7}{1.013}\right) = 13.74\text{ kW}$$

Isothermal Efficiency,

$$\eta_{iso} = \frac{W_{iso}}{W_{act}} = \frac{13.74}{15.99} = 85.93\%$$

ME 8493 – THERMAL ENGINEERING – 1

QUESTION BANK

UNIT – 3

INTERNAL COMBUSTION ENGINES AND COMBUSTION

PART – A

1. **What are the effects of rich mixtures in petrol engine? (April/May 2019)**
   - ✓ Spark plugs will foul
   - ✓ Reduces the temperature of the engine and combustion speed
   - ✓ Excess fuel, as in rich mixture, cools the engine somewhat, but the effect of unburned fuel as a coolant is generally overrated.
2. **How are SI and CI engine fuels rated? (Nov/Dec 2019)**

   There are two important parameters that rate the engine fuels. Those are Octane number for the petrol, Cetane Number for Diesel. Usually, the rating of the fuels will be done by their antiknock characteristic.

   Rating of Spark-Ignition Engine Fuels
   - ✓ Anti-knocking is one of the major characteristics for the Spark-Ignition Engine Fuel.
   - ✓ The resistance to the knocking is completely depended on the chemical composition of the fuel.
   - ✓ Apart from this, there are other parameters which result in knocking in the spark-ignition engine, those are the air-fuel ratio, ignition timing, engine speed, dilution, the shape of the combustion chamber, compression ratio, ambient conditions.
   - ✓ So before we rate the anti-knock characteristics of the fuel we have to fix those parameters to the standard values.

   Normally fuels are rated for their antiknock characteristics. To determine the antiknock characteristics of any fuel it can be done by comparing its antiknock property with a mixture of two reference fuels. one which is having the high octane number, and another one which will have less octane number.

   In other words, the Octane number can be computed with Performance Number (PN) by using the following formula.

$$Octane\ Number\ (ON) = 100 + \frac{PN - 100}{3}$$

Rating of Compression-Ignition Engine Fuels

- ✓ In the Compression Ignition engines, the antiknock characteristics will depend on the chemical composition an also on the design and operating conditions of the engine.
- ✓ The knock rating is done by comparing the fuel under prescribed conditions of operations in a special engine with the reference fuels.

3. **What is meant by ignition delay? (Nov/Dec 2019)**

An ignition delay in a CI engine is the time taken by the fuel to auto-ignite after being injected into the engine cylinder. It can be called as the preparatory phase during which the fuel prepares to undergo auto-ignition.

Ignition delay can be divided into two parts. Both these occur simultaneously.

- ✓ **Physical delay**, during which the fuel gets mixed and atomized inside the cylinder and is raised to auto-ignition temperature. Heavier viscous fuels have longer delay period. It can be reduced by increasing injection pressure or by increasing the combustion chamber temperature or the turbulence.
- ✓ **Chemical delay**, during which the air fuel mixture undergoes pre-ignition reactions. This is similar to the ignition lag in SI engines.

4. **How is cam shaft speed related to crank shaft speed? And why? (Apr/May 2019)**
   - ✓ On a 4 stroke internal combustion engine the camshaft turns exactly half the speed of the crankshaft. A 4 stroke engine require 2 rotations to complete the entire cycle of intake (down stroke), compression (up stroke), power stroke (down), and exhaust (up).
   - ✓ If the cam shaft speed matched the engine speed, then the intake valve would open twice in the cycle as would the exhaust valve. Any slower than half speed and you would not get air in or out of the engine.
5. **Mention the use of camshaft? (Nov/Dec 2018)**
   - ✓ It is used to convert the rotary motion of the camshaft into linear motion of the follower or lifter. Thus, it operates the inlet and exhaust valves through rocker arms
   - ✓ In addition cam is also provided to drive he fuel pump
6. **Mention the use of carburetor? (Nov/Dec 2018)**
   - ✓ It combines gasoline and air creating a highly combustible mixture
   - ✓ It regulates the ratio of air and fuel
   - ✓ It controls the engine's speed
7. **What is meant by heat engine? Write its classification?**

Heat engine is a machine which converts the heat energy into mechanical work. It can be broadly classified into two types;

- ❖ Internal combustion engines
- ❖ External combustion engines

8. **Give the difference between IC engine and EC engine.**
   In internal combustion engine, the chemical energy of the fuel is released as a heat by the way of combustion inside the engine cylinder where power is produced. By expansion of this hot medium inside the cylinder, heat energy is converted into mechanical work
   In external combustion engine, the chemical energy of the fuel is released as a heat by the way of combustion outside the engine cylinder where power is produced. By expansion of this hot medium inside the cylinder, heat energy is converted into mechanical work.
9. **What are the various components of IC engine?**
   - Cylinder
   - Piston
   - Piston rings
   - Combustion chamber
   - Inlet manifold
   - Exhaust manifold
   - Crank shaft
   - Cam shaft
   - Spark plug
   - Connecting rod
   - Flywheel
10. **Write the function of pushrod?**
    Pushrod is used when the camshaft is situated at the bottom end of the cylinder. It carries the camshaft motion to the valve which are situated at the cylinder head.
11. **State the difference between the spark plug and fuel injection.**
    Spark plug: It is used in spark engine. The main function of a spark plug is to conduct the high potential from the ignition system into the combustion chamber to ignite the compressed air fuel mixture.
    Fuel injector: Injector is usually used in compression ignition engine. It sprays the fuel into the combustion chamber at the end of compression stroke. It is fitted on cylinder head.
12. **State the function of flywheel, connecting rod, piston and crank shaft. (May 2018)**
    Piston : The main function of piston is to give tight seal to the cylinder through bore and slide freely inside of cylinder.
    Connecting rod: Connecting rod connects the piston to crankshaft and transmits the motion and thrust of piston to crankshaft. It converts the reciprocating motion of the piston into rotary motion of crankshaft.
    Crankshaft: The crankshaft of an internal combustion engine receives the efforts or thrust supplied by piston to the connecting rod and converts the reciprocating motion of piston into rotary motion of crankshaft.
    Flywheel: The net torque imparted to the crankshaft during on complete cycle of operation the engine fluctuates causing a change in the angular velocity of the shaft. In order to achieve a uniform torque an inertia mass in the form a a wheel is attached to the output shaft and this wheel is called the flywheel.

13. List the merits and demerits of four stroke engines.

Advantage:

- Thermal efficiency is high
- High compression ratio
- Overall efficiency is high
- Less cooling and lubrication are required
- Wear and tear is less
- Less specific fuel consumption
- Torque is high

Disadvantage:

- More expensive
- Complicated design
- Less powerful

14. What is meant by scavenging?

In a two stroke engine the major problem is scavenging. The removal of exhaust gases from the cylinder is known as scavenging. If the burnt gases remain inside the cylinder they will dilute the strength of the fresh incoming charge, causing lowering of the efficiency.

15. What are the types of scavenging?

- Cross flow scavenging
- Loop scavenging
- Uniflow scavenging

16. List the difference between two stroke and four stroke engines.

Four stroke engine	**Two stroke engine**
For every two revolution of the crank shaft, there is one power stroke.	For every one revolution of the crank shaft, there is one power stroke.
Valves are required – inlet and exhaust valves	Ports are made in the cylinder walls – inlet, exhaust and transfer port
Volumetric efficiency is high due to more time for induction	Volumetric efficiency is low due to lesser time for induction
Lower fuel consumption per horse power	The fuel consumption per horse power is more because of fuel dilution by the exhaust gas
Used in heavy vehicles	Used in light vehicles
The engine cost is more	The engine cost is less

17. List any four differences between SI engines and CI engines.

SI Engines	CI Engines
The fuel used is gasoline (petrol)	Fuel used is diesel
For mixing air and fuel a separate device called carburetor is required	No need of carburetor
Compression ratio is around 6 to 10	Compression ratio is around 15 to 25

Cost is comparatively low	Cost is high
Less maintenance	High maintenance is needed
Thermal efficiency is about 25%	Thermal efficiency is about 35 to 40%
Spark plug needs frequent maintenance	Fuel injector needs less maintenance

18. Define the terms crank radius and crank angle.

Crank radius: it is the distance above the center axis of shaft where the crank is connected to the piston via connecting rod.

Crank angle: it refers to the position of an engine's crankshaft in relation to the piston as it travels inside of the cylinder wall.

19. Define fuel. Give its classification.

Fuel is a combustible substance, containing carbon as main constituent which on proper burning with oxygen liberates large amount of heat, which can be used economically for domestic and industrial purposes.

Natural (or) primary fuels which occur in nature coal, petroleum and natural gas.

Secondary (or) artificial fuels which are derived from the primary fuels. Ex. Coke, gasoline, coal gas etc.

20. Define Octane and Cetane number.

Octane number: The octane number is defined as the percentage of iso-octane in a mixture of iso-octane and n-heptane.

Cetane Number: The cetane number is defined as the percentage of hexa decane present in a mixture of hexa decane and 2-methyl naphthalene, where has the same ignition lag as the fuel under test.

21. List the properties of IC engine fuels.

- ✓ It should have a high calorific value
- ✓ It should have a low ignition point
- ✓ It should be easy to handle
- ✓ It should be free from hazard
- ✓ It must have thermal stability

22. State 3T's of combustion.

- ✓ Temperature high enough to and maintain ignition of the fuel
- ✓ Turbulence (or) initial mixing of the fuel and oxygen
- ✓ Time sufficient for complete combustion

23. Write the difference between lean and rich mixture?

If the air-fuel ratio more than the theoretical air, is called lean mixture.

If the air-fuel ratio is less than the theoretical air, is called rich mixture.

24. What are the stages of combustion in SI engine?

- ✓ Ignition lag (or) delay period
- ✓ Rapid combustion
- ✓ After burning

25. List the stages of combustion in CI engine?

- ✓ Ignition lag (or) delay period
- ✓ Rapid combustion
- ✓ Controlled combustion
- ✓ After burning

26. What is knocking? What are the factors that affects the knocking?

Knocking occurs in SI engine occurs when combustion of the air/fuel mixture in the cylinder does not start off correctly in response to ignition by the spark plug.

27. What is pre-ignition? What are the effects of pre-ignition?

Pre-ignition is the ignition of the homogeneous mixture of charge as it comes in contact with hot surfaces, in the absence of spark.

Effects of pre-ignition:

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

28. What is excess air in combustion?

The amount of air is in excess required for complete combustion is known as the excess air.

29. What are the methods of control diesel knock?

- ✓ Controlling the rate of fuel supply
- ✓ Increasing swirl
- ✓ Knock reducing fuel injector
- ✓ Using a better fuel

Part – B

1. **Describe the advantages and disadvantages of 2-stroke engines. (May 2019)**

Advantages of 2-Stroke Engines

- ✓ Two stroke engines do not have valves which are easy to construct and lowers their weight
- ✓ Two stroke engines fire once every revolution. Power is produced once during 2 strokes of the piston**. This** gives a significant power boost.
- ✓ These two stroke engines lower output in horse power
- ✓ Two stroke engines can work in any position, since oil flow is not a concern with any valves to worry about.
- ✓ 2 stroke engines are lighter comparatively.
- ✓ Since the power produced by the two-stroke engine is higher, these engines are small and compact in size.
- ✓ The torque produced on the crankshaft is more uniform because the power is produced during every alternate stroke of the piston.
- ✓ These Engines often provide high power-to-weight ratio, usually in a narrow range of rotational speeds called the "power band".

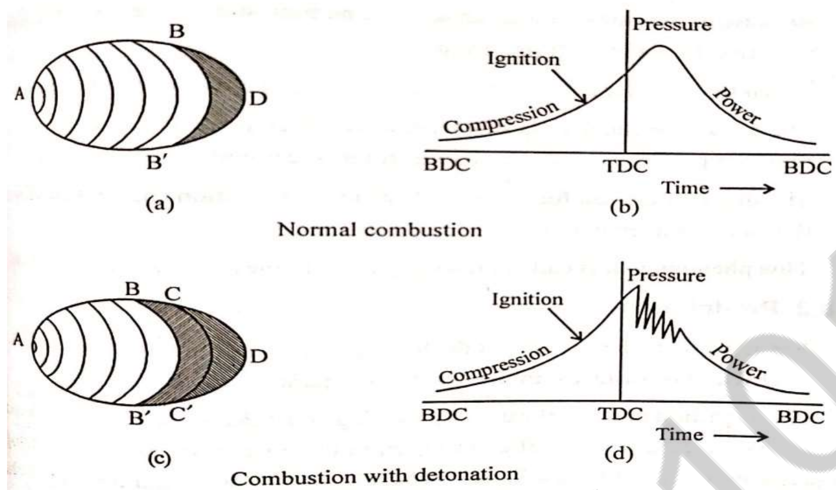
Disadvantages of 2-Stroke Engines

- ✓ Two stroke engines do not last as long as four stroke engines; there is no lubrication system in a two stroke engine so parts wear out a lot faster.
- ✓ Two stroke oil is expensive; you would burn a gallon every 1000 miles if it were in a car
- ✓ Two stroke engines are Less Efficient.
- ✓ Two stroke engines produce a lot of pollution, and the way the engine is designed that part of the air/fuel leaks out of the chamber through the exhaust port.
- ✓ The exhaust gases often get trapped inside the combustion chamber. This makes the fresh charge impure. Therefore maximum power doesn't get delivered because of improper incomplete combustion.
- ✓ Since in two-stroke engines power stroke is produced after every stroke, a large amount of heat is generated within them. To reduce the temperature of the engine and keep the moving parts well-lubricated, good lubrication and cooling systems for the engine are required.

2. **Explain with neat sketches the phenomena of knocking in SI engines. (Nov/Dec 2019)**

If the temperature of an air-fuel mixture is raised high enough, the mixture will self-ignite without the need of a spark plug. This phenomenon is called self-ignition or auto-ignition. The temperature above which self-ignition occurs called self-ignition temperature.

If the temperature of the unburnt mixture exceeds the self-ignition temperature during the ignition delay period, auto-ignition occurs at various locations in the cylinder. It will generate pressure pulses. These high-pressure pulses can cause damage to the engine and quite often are in the audible frequency range. This phenomenon is often called knocking or detonation.



A mixture of fuel and air can react spontaneously and produce heat by chemical reaction without the use of flame to initiate the combustion or self-ignition. It has been found experimentally that the auto-ignitions of the mixtures does not occur instantaneously as soon as its temperature rises above the self-ignition temperature. Auto ignition occurs only when the mixture stays at a temperature equal to or higher than the self ignition temperature for a finite time. This time is known as ignition delay period or reaction time for auto-ignition.

As the compression ratio increases the delay period decreased and this is because of increase in initial (before combustion) pressure and temperature of the charge.

The self-ignition temperature is a characterizing of fuel-air mixture and it varies from fuel to fuel and mixture strength to mixture strength of the same fuel.

Phenomenon of knocking or detonation:

The major requirements of the engine is high thermal efficiency. The thermal efficiency of an SI engine is directly proportional to the compression ratio but there are limitations from practical point of view.

- ✓ The maximum pressure of the cycle increases rapidly with the increase in compression ratio and this requires robust engine which increase the bulk and cost of the engine.
- ✓ As the compression ratio increases, the combustion process rakes place in an abnormal way causing excessive rate of pressure rise, noise and rapid deterioration of engine parts. This abnormal combustion produce a metallic sound by the pressure impact on the piston and it is termed as knocking or pinking of the engine.

Knocking is due to the auto-ignition of the end portion of the unburned charge in the combustion chamber. As the normal flame front proceeds across the chamber, the pressure and temperature of the unburned charge increase due to the compression by the burned portion of the charge. This unburned compressed charge may auto-ignite under certain temperature conditions and release the energy at a very rapid rate compared to normal combustion process in the cylinder. This rapid release of energy during auto-ignition causes a high pressure differential in the combustion chamber and a high pressure wave is released from the auto-ignition region. The motion of high pressure compressed waves inside the cylinder causes vibration of the engine parts and pinking noise and it is known as knocking or detonation.

The localized pressure differences causing the knocking superimposed on the overall pressure rise due to auto-ignition of end charges is shown in fig. The pressure waves created due to auto-ignition travel through the chamber and are reflected back and forth by the combustion chamber walls. The gas in the cylinder is compressed and expanded alternately by the pressure waves until pressure equilibrium is restored.

3. List the desirable properties of IC engine fuels. (April/May 2019)

- ✓ The fuels should have antiknock quality
- ✓ They must have ignition delay
- ✓ They must be enough volatile in the operating range to ensure a proper mixing and complete combustion
- ✓ The smoke in the exhaust should be minimum
- ✓ It should not cause any corrosion and wear problem in the engine components
- ✓ The fuels should be in such a way to handle easily and available.

- ✓ Lower heating value LHV: this property is added in fuel for reducing knocking when engine start
- ✓ Density : density between fuel compound are not high for easy burning and easy to mix with air (nitrogen, sulfer, oxigen)
- ✓ Viscosity: fuel are make more viscous than water because viscosity is depend on temperature.
- ✓ Vapor pressure: The equilibrium **vapor pressure** is an indication of a liquid's evaporation rate. It relates to the tendency of particles to escape from the liquid (or a solid). A substance with a **high vapor pressure** at normal temperatures is often referred to as volatile.
- ✓ Heat of evaporation: the latent heat of vaporization of fluid is not high because this heat required to change the state from liquid to vapour.

4. Compare the relative advantages and disadvantages of four-stroke and two-stroke cycle engines. (Nov/Dec 2019)

Two Stroke Cycle Engine	**Four Stroke Cycle Engine**
Advantages	**Disadvantages**
A cycle is completed in two stroke or one revolution of the crankshaft.	A cycle is completed in four stroke or two revolution of the crankshaft.
It develops twice the number of power strokes than four stroke engine	It develops half the number of power stroke than two stroke engines
Turning moment is more uniform and hence, a lighter flywheel is required	Turning moment is not uniform and hence, a heavier flywheel is required

Initial cost is low due to less complexity in the mechanism	Initial cost is high because of heavier and complicated mechanism
Mechanical efficiency is more	Mechanical efficiency is less
It is easy to start	It requires separate starting motor
It can run in either direction which is useful in marine engines	It can run in only one direction
Disadvantages	**Advantages**
Thermal efficiency is low	Thermal efficiency is high
Volumetric efficiency is low	Volumetric efficiency is more
Greater cooling and lubrication are required	Lesser cooling and lubrication are required
Overall efficiency is less	Overall efficiency is more
Greater rate of wear and tear	Lesser rate of wear and tear
It is used in light vehicles only	Used in heavy vehicles
The sudden release of exhaust gases makes the exhaust noisier	The release of exhaust gas is more uniform and hence, it is noiseless operation
Specific fuel consumption is more because of escaping of the fresh charge with exhaust gases	Specific fuel consumption is less because of the separate exhaust stroke

5. **Write the combustion reaction for methane. Calculate the theoretical air to fuel ratio and composition of the products formed. (April/May 2019)**

When methane burns with O_2, CO_2 and H_2O are produced along with a release of large amount of heat.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Mole basis: 1 mol + 2 mol → 1 mol + 2 mol

Mass basis: 16 kg of CH_4 + 64 kg of O_2 → 44 kg of CO_2 + 36 of H_2O

1 kg of CH_4 + 4 kg of O_2 → $\frac{11}{4}$ kg of CO_2 + $\frac{9}{4}$ kg of H_2O.

The above equation indicates, 1 kg of methane requires 4 kg of oxygen to produce $\frac{11}{4}$ kg of carbondioxide and $\frac{9}{4}$ kg of steam (or) water.

If the combustion process takes place is dry air the above equation can be written as

$$CH_4 + 2(O_2 + 3.76 N_2) \rightarrow 4CO_2 + 2H_2O + 7.52 N_2.$$

Theoretical (or) Minimum air required per m^3 of Gaseous fuel for complete combustion.

Consider $1 m^3$ of a gaseous fuel contains

Volume of methane = $CH_4 \, m^3$

For complete combustion of the gas

1 m^3 of methane requires 2 m^3 of O_2

Therefore CH_4 m^3 of methane requires $2CH_4$ m^3 of O_2

Total volume of oxygen required for complete combustion of 1 m^3 of fuel

$$= 0.5CO + 0.5H_2 + 2CH_4 + 3C_2H_4 \ m^3$$

If some amount of oxygen (O_2 m^3) is already available in the fuel, then total oxygen for the complete combustion of 1 m^3 of fuel.

$$= (0.5CO + 0.5H_2 + 2CH_4 + 3C_2H_4) - O_2 \ m^3$$

Theoretical (or) Minimum air required per m^3 of gaseous fuel for complete combustion

$$= \frac{100}{21}\left[(0.5CO + 0.5H_2 + 2CH_4 + 3C_2H_4) - O_2\right] m^3$$

6. Explain with neat sketches the various stages of combustion in CI engines. (Apr/May 2019)

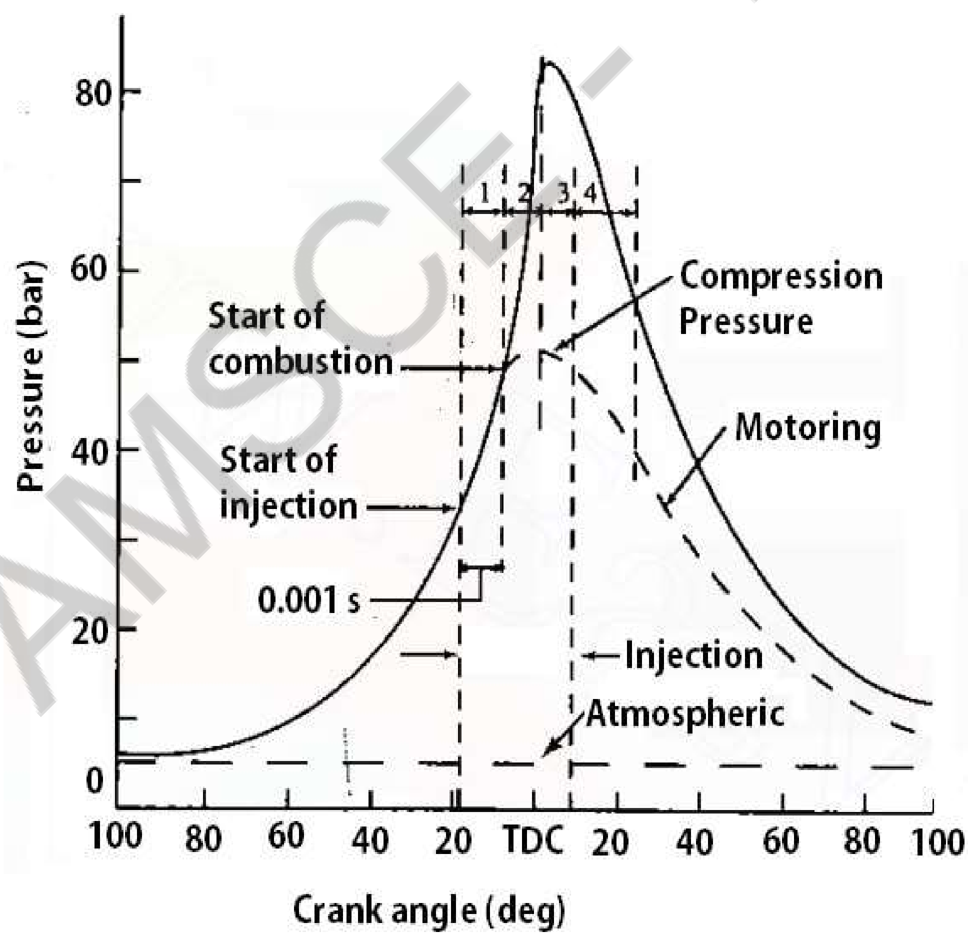
In a thermodynamic cycle, we have the suction, compression, combustion, expansion and exhaust processes. In the spark ignition engines, the fuel mixture is compressed in the cylinder and a spark is introduced to complete the combustion process. But in Compression Ignition Engines, the air is highly compressed in the cylinder and the fuel is directly injected into the cylinder after the compression stroke. Due to the highly compressed air, the fuel will be self-ignited with the elevated temperature caused by mechanical compression.

Usually, the compression ratio of Compression Ignition Engines will be ranging from 16 to 20. Whereas the Spark Ignition Engines will be raging from 6 to 10.

stages of combustion in CI engine

In the Compression Ignition Engine, the combustion process will be completed in the four stages in an actual engine.

1. Ignition Lag
2. Rapid Combustion
3. Controlled Combustion
4. After Burning



1. Ignition Lag

The time interval between the injection of the fuel and the start of the self-ignition of the fuel is known as ignition lag or Ignition delay. It is also referred to as the preparation phase.

The fuel does not ignite immediately upon the injection of fuel into the combustion chamber. There will be a definitely a certain amount of period will be delayed between the first droplet of the fuel injected into the combustion chamber and the time at which it starts the burning phase.

There are two chances that can cause the ignition delay. Physical delay and chemical delay. Physical delay due to the complete injection of fuel, atomization, vaporization and mixing of air and fuel and raised to its self-ignition point. The chemical delay due to the burning slowly starts and then accelerates until the complete ignition takes place.

2. Rapid Combustion

The period of rapid combustion also known as the uncontrolled combustion. This rapid combustion will starts right After the ignition delay period ends. During this period the heat release is maximum.

The pressure released during this period depends on the ignition delay period. If the ignition delay period is more, then the pressure rise is more due to the more fuel will be accumulated during the delay period.

3. Controlled Combustion

The rapid combustion followed by the third stage called the controlled combustion. During the rapid combustion, the cycle reaches its maximum pressure and the temperature. Which means the fuel droplets injected into the combustion chamber during the rapid combustion stage will burn faster with reduced ignition delay as soon as they find the necessary oxygen and any further pressure rise is controlled by the injection.

At the point at where it reaches the maximum cycle pressure the rapid combustion ends and the controlled combustion starts. The period of the controlled combustion is assumed to end at the maximum cycle temperature.

4. After Burning

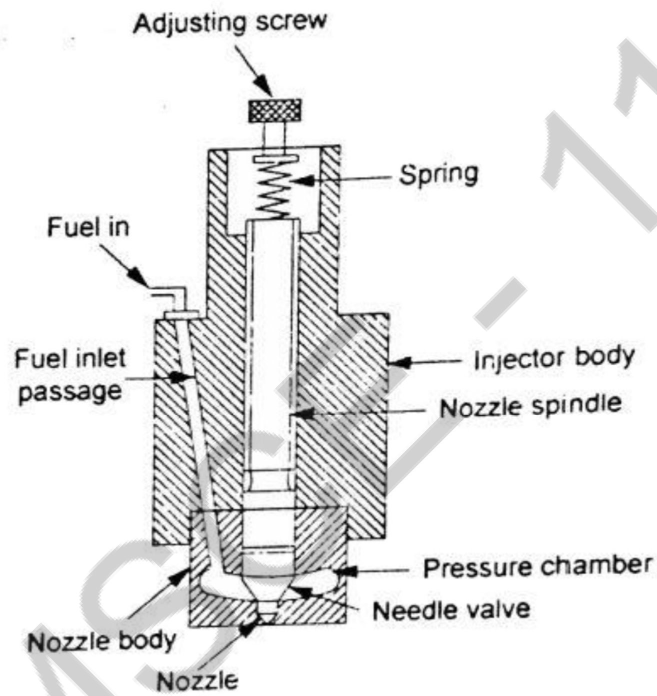
The combustion process will not stop right after the completion of the injection process. The unburnt particles left in the combustion particles will start burning as soon as they get in contact with the oxygen. This process continued for a certain period amount of time called the after burning.

7. **Explain the working principle of diesel injector with a neat sketch.**
FUEL INJECTOR: (May 2016)
Function;

The function of a fuel cell injector is to deliver finally atomized fuel into the combustion chamber. It also assists in bring each droplet of fuel in contact with sufficient oxygen in the air.

Construction;

The injector has housing. A nozzle is connect with the housing by a nozzle cap. There is a plunger with a value. It is connected with a spindle. There is a spring against the spindle, The value is on its seat by this spring force. There is a fuel passage. It connects the nozzle and pump.



Fuel injector

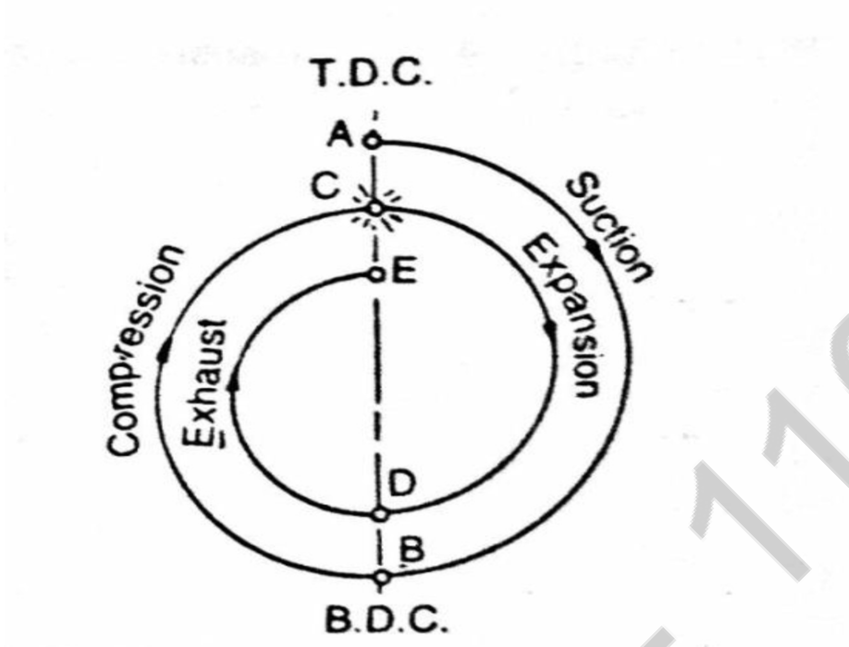
Working:

High pressure fuel from the pump comes to nozzle end through the passage. Due to fuel pressure the valve is lifting up against the spring force. Therefore the hole is nozzle is opened. The fuel is injected into the combustion chamber through the hole and gets atomized.

When the fuel pressure falls the value comes to its seat force. Thus it closes the hole of the nozzle. The injection pressure can be adjusted by adjusting the screw provided above the spring. A small quantity of the fuel is made to leak out through the valve steam for lubricant.

8. Discuss the difference between theoretical and actual valve timing diagrams of a diesel engine. (May 2015)

Theoretical Valve Timing Diagram of Diesel Engine:



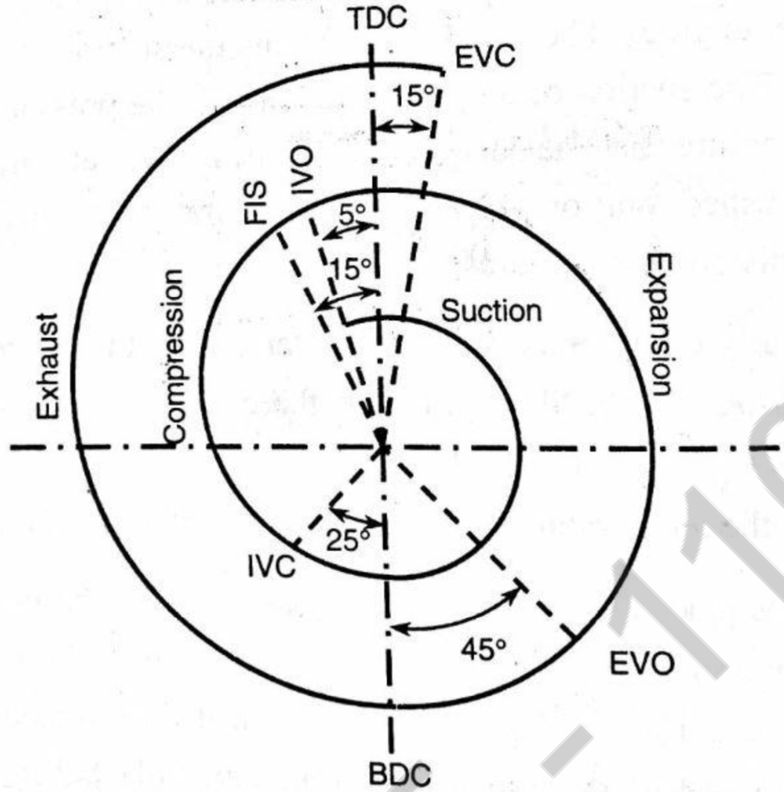
Four-stroke cycle engine.

In this diagram, the inlet valve opens at A and the suction takes place from A to B. The crankshaft resolve through 180° and the piston moves from T.D.C to B.D.C. At B, the inlet valve clo9ses and the compression takes place from B to C. The crankshaft resolves through 180° and the piston mo0ves from to B.D.C to T.D.C. At C, the fuel is fired and the expansion takes place from C to D. The crankshaft revolve through 180° and the piston again moves from T.D.C to B.D.C. At D, the exhaust valve opens and the exhaust takes place from D to E. The crankshaft again resolves through 180° and the piston moves back to T.D.C.

Note ; in four stoke cycle, the crank resolves through two resolutions.

Actual Valve Timing Diagram of Diesel Engine:

The actual valves timing diagram for four stoke diesel CI engine. The inlet valve opens (IVO) 10° to 25° before TDC. Fresh air is sucked into the engine cylinder till the inlet valves closes. The inlet valve closes (IVC) 25° to 50° after BDC. The air is compressed till the fuel is injected. The fuel injection starts (FIS) 5° to 10° before TDC in the compression stoke. The air –fuel mixture burns. Both temperature and pressure increase. The burnt gases are expanded till the exhaust valve opens.



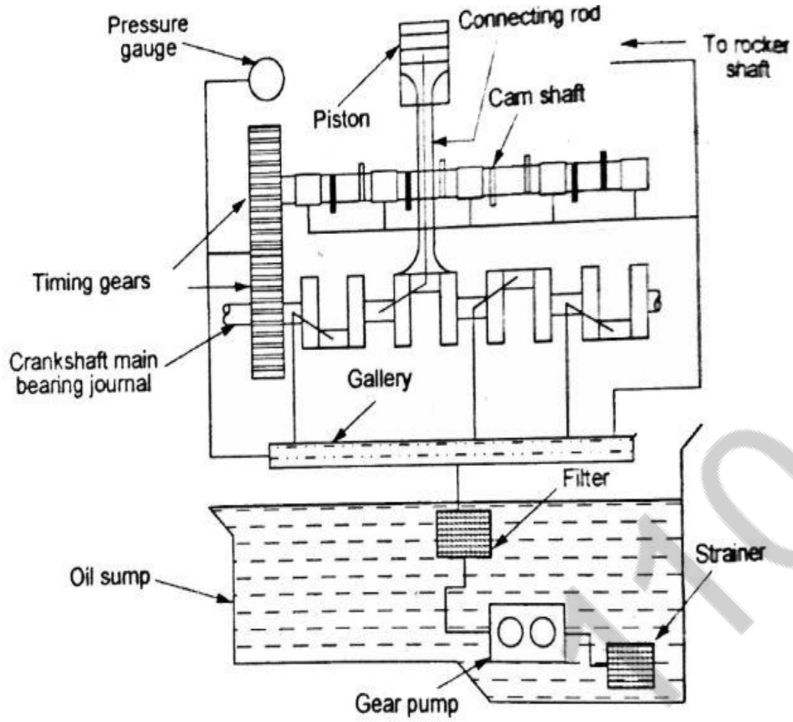
Actual valve timing diagram for four stroke CI engine

The exhaust valve open (EVO) 30°to50°before BDC. The exhaust gases are forced out of the cylinder till the exhaust valve closes.

The exhaust valve closes (EVC) 10° to 15°after TDC. Before closing the exhaust valve, the inlet valve again 10°to25° before TDC. The period when both inlet and exhaust valves are opened is known as valve overlap period. The angle between these two events is known as angle of valve overlap. In fig, the angle of overlap is specified as 5°.

9. Explain the pressure lubrication system with a neat sketch. (Nov 2016)

In this system, the lubricant oil is forced under pressure by a pump at a pressure of 2MPa to 4MPa figure shown as a line diagram of this system. Il consists of the oil sump, oil pump, oil gallery, pressure release valve, oil filter, oil pressure gauge and oil dipstick. The lubricant oil from the sump or pan is sucked by an a oil pump and lifted to the oil main gallery through oil filter and strainer. The oil pump is driven by the camshaft. Oil pump and filter are always immersed in the oil.



Pressure lubrication system

From the oil gallery, the oil is distributed under pressure to various part of the engine to be lubricant by oil tubes. Oil from gallery enter the crank pin bearing through a tapped hole in the crankshaft. A through hole is provided at the center of the connecting rod. The oil from the big end bearing enters the gudgeon pin bearing (small end bearing) through the hole in the connecting rods . separate oil tubes carry oil for lubricant timing gears, rockers arm assembly, camshaft etc.,. Another oil line is connected to the pressure gauge to show the pressure of the oil.

The excess oil supplied drip back into the oil sump. A pressure relief valve is provided to avoid any damage in case of excess oil pressure. An oil dipstick is provided to measure the oil level in the sump. Engine parts lubricant by splash: piston , cylinder wall, cams, piston pin and rings, spring and guide of valve steam, oil pump drive gear etc.,

10. Write a note on lubrication system for an IC engine in detail with relevant sketches of various types. (Nov 2015)

Lubrication in IC Engines

` In IC engine, the moving parts rub against each other causing the frictional force. Due to the frictional force, the heat generated and the engine part wear easily. The power also lost due to friction. To reduced the power is loss and also wear and tear of the moving parts, a foreigner substance called lubricant is introduced in between rubbing surfaces. The lubricant keeps the mating surface apart. Lubricant may be solid(graphite) , or semi-solid (grease) or liquid(oil). The liquid lubricant used is generally mineral oil. Its obtained by refining problem. Grease is also used to lubricant certain parts of the engine.

Methods of lubrication

- ✓ The various method adopted for lubricant of IC engine are
- ✓ Petrol lubricant or mist lubricant.
- ✓ Wet sump system, and
- ✓ Dry sump system,

(i) Petrol or Moist lubricant system :

It is simple of all type of lubricant. This method is used in light vehicles such as motorcycle and scooter. About 3-6%of lubricating oil is mixed with petrol in the fuel tank. Here, there is no separate sump and pump. The oil mixing with petrol acts as a lubricant.

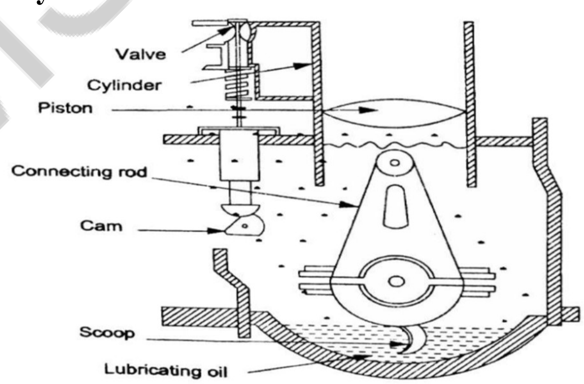
The disadvantages of this method is, if the engine remains idle for a long time, then the oil will get separate and cause clogging of fuel passage in the carburetor thereby resulting starting trouble. If the quality of mixing oil is more, it will release more carbon deposits in the cylinder. So, the engine will produce dark smoke.

(ii) Wet sump system:

In this method, the lubrication oil is stored in the oil sump. From the oil sump, the oil is supplied to various part of the engine. This system may be further classified into

- ✓ Splash lubricant system
- ✓ Gravity lubricant system
- ✓ Pressure lubricant system
- ✓ Semi-pressure lubricant system

a) Splash lubricant system:



Splash lubrication system

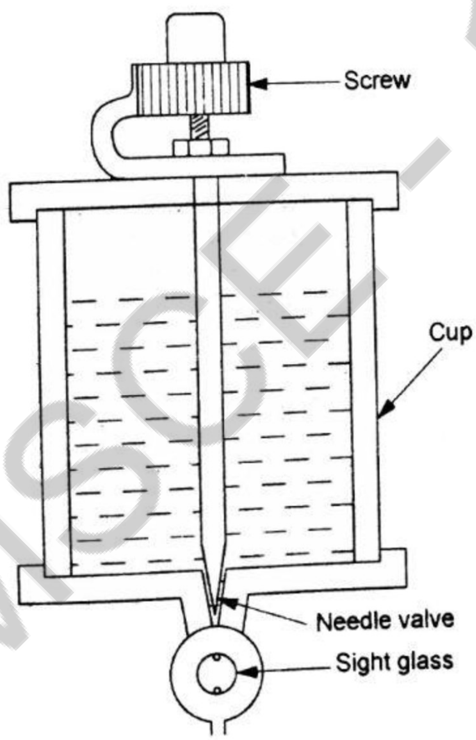
In this system, oil is stored in the crankcase. A small scoop is attached to the big end of connection rods as shown in figure. When the crank is rotated, the scoop dips in the oil and splash the oil. The oil is splashed on the cylinder wall, connecting rod ends and valve mechanisms. This method is used in some motorcycle and single cylinder stationary engines. Greater care should be taken that the oil in the crankcase is filled up to the desired mark. There will be insufficient lubrication when the oil level is low.

Disadvantages:

- ✓ It is not efficient if the bearing loads are heavy.
- ✓ It is very difficult to introduced oil in the minute gap between sliding surface.

b)Gravity lubricant system:

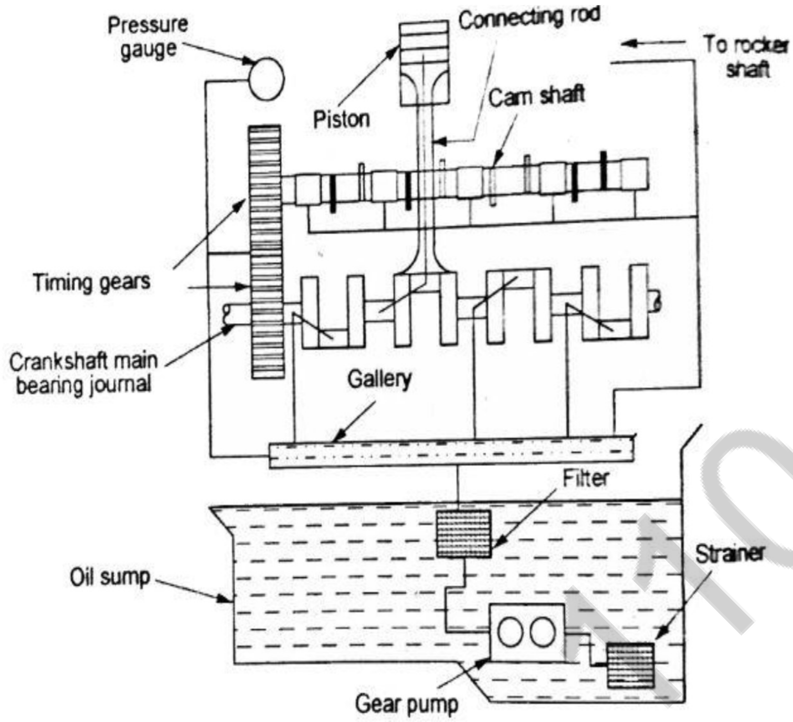
In this method, oil is supplied to the part to be lubricated by means of gravity. This system uses a drop feed oiler shown figure. It consists of a cup and needle value arrangement. The needle valve is operated by means of a screw. The valve is raised to increase the flow of oil and lowered to decrease the oil flow. This system is used for lubricant the external moving part such as bearings, cross head, crank pins of simple steam engine.



Drop feed oiler

c) Pressure lubricant system:

In this system, the lubricant oil is forced under pressure by a pump at a pressure of 2MPa to 4MPa figure shown as a line diagram of this system. Il consists of the oil sump, oil pump, oil gallery, pressure release valve, oil filter, oil pressure gauge and oil dipstick. The lubricant oil from the sump or pan is sucked by an a oil pump and lifted to the oil main gallery through oil filter and strainer. The oil pump is driven by the camshaft. Oil pump and filter are always immersed in the oil.



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The excess oil supplied drip back into the oil sump. A pressure relief valve is provided to avoid any damage in case of excess oil pressure. An oil dipstick is provided to measure the oil level in the sump. Engine parts lubricant by splash: piston , cylinder wall, cams, piston pin and rings, spring and guide of valve steam, oil pump drive gear etc.,

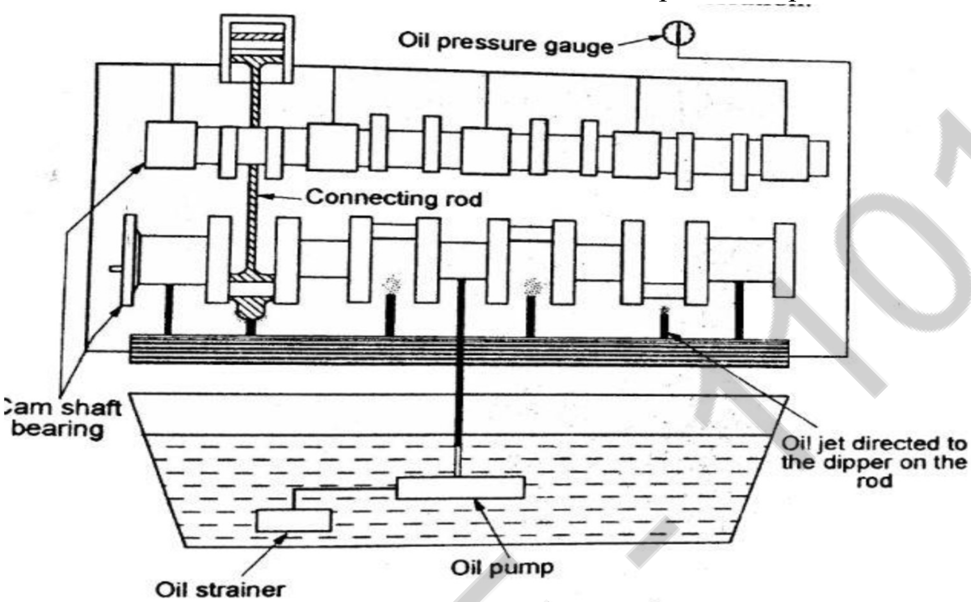
(iii) Dry sump lubricant ion system:

The lubricating oil stored in the oil sump is called wet sump system. But the system in which the lubricating oil is not kept in the oil sump is known as dry sump system. In this system, oil is carried in a separate tank and fed to the engine. The oil which falls into the oil sump after the lubrication is sent back to the oil tank by separate delivery pump. Thus, the system consists of two pumps. One pump is used to feed the oil. The other pump is used to deliver the oil to the oil tank

The main advantage of this system is no change of breakdown in the oil supply during up and down movement of the vehicle.

d) Semi pressure lubrication system:

It is also called partial pressure lubrication system . It is a modification of splash lubrication system. This system is used if the bearing loads are heavy and splash lubrication is not sufficient. It is a combination of splash and pressure lubrication.



Semi pressure lubrication system

This system consists of an oil pump, oil gallery oil filter oil pressure gauge and scoops attached to connecting rod big end. The pump pumps the oil to the main gallery. From the gallery, oil is forced under pressure to be lubricated. Scoops or dippers are attached to the big end of the connecting rod. The lubricant oil is directed through oil jets from gallery to the scoops. The scoop splashed this oil in all direction to the engine part such as the piston, cylinder wall etc.

11. Describe the working of a four stroke diesel engine with neat sketches. (Nov/Dec 2018)

12. Brief the working of battery coil ignition system with neat sketches. (Nov/DEC 2018)
Refer unit 4, part – b, question no: 6.

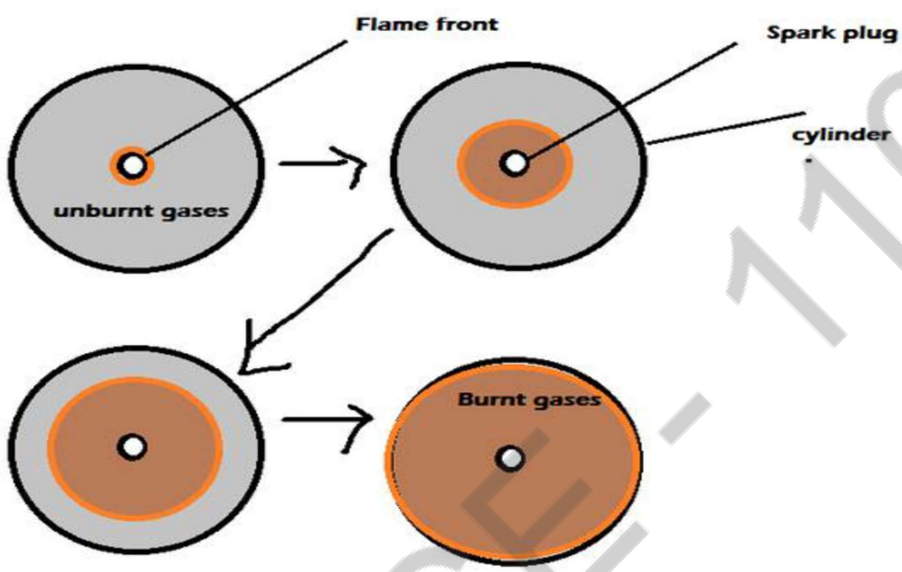
13. Explain the working of multi-point fuel injection system with block diagram. (April/May 2018)
Refer unit 4, part -b, question no 10

14. Explain the construction and working Magneto Ignition system. (April/May 2018)
Refer unit 4, part b, question no 1.

15. Explain the construction and working of battery ignition system. (April/may 2018)
Refer unit 4, part – b, question no: 6.

16. Explain the phenomena of knocking in diesel engines. What are the different factors which influence the knocking?(April/may 2015)

Uncontrolled combustion in Petrol engine is known as knocking and in Diesel engine its called as detonation. This is done in order to reduce the confusion Petrol engine- Knocking Petrol engine is a homogeneous mixture engine , here the fuel will be ignited at one end and there will be definite flame front which progresses to consume all the fuel.



The above images shows the normal combustion process in a petrol engine. There will be one flame front (orange color) which consumes all the fuel. adjacent fuel layers (grey color) ignite due to rise in pressure due to expanding burnt gases (brown color) and due to heat conduction , hence the flame progress like a ripple in water.
Knocking happens when any of the fuel mixture enters combustion before the flame has reached it . This is can be due to increased cylinder wall temperature , low quality fuel (low octane number) , wrong design of combustion chamber (more circumference , hence the flame front will take more time to reach unburnt fuel mixture)

This new flame front will start to propagate and finally ends by clashing with original flame front , so that the charge between two flame front will experience steep increase in pressure and it will consume very fast (sonic or super sonic speeds) , that's when he hear the ping ping noise. Petrol engine may also knock due to preignition , due to hot spots in cylinder or spark plug itself. The air fuel mixture may start to burn before any spark has been applied.

Factors affecting Knocking:

The temperature, pressure, density of the unburned charge and the time factors. Temperature factor includes inlet temperature of the mixture and temperature of the combustion chamber walls. Increase in inlet temperature of the mixture makes the charge more vaporized than the required at the end of compression. This increases the tendency of knocking. Temperature of the combustion chamber walls plays a predominant role in knocking. In order to prevent knocking the hot spot in the combustion chamber should be avoided.

17. Describe with suitable sketches the following system if a modern carburettor:

(i) Main metering system
(ii) Idling system
(iii) Economizer system
(iv) Acceleration pump system
(v) Choke

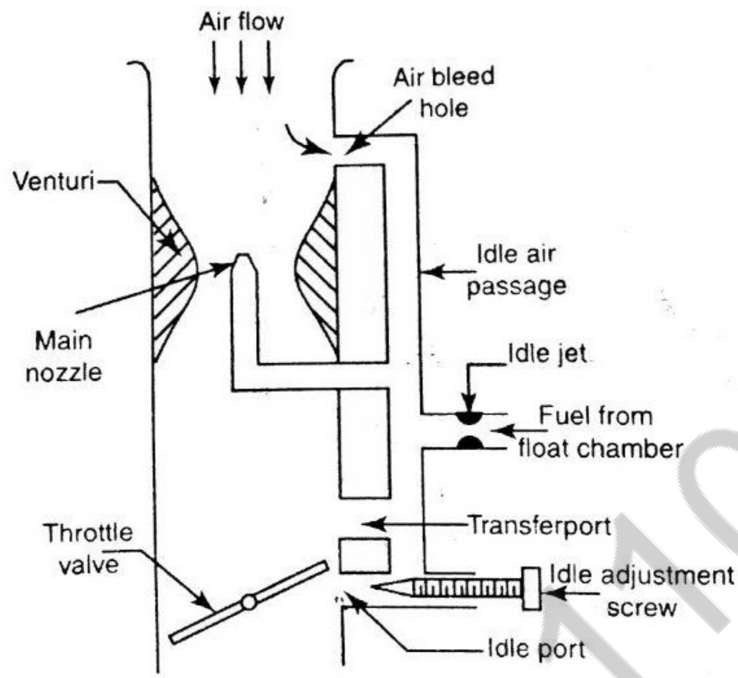
Main Metering System or Compensation System:

A simple carburetor would provide rich mixture at high speed and lean mixture at low speed. The main metering system ensures supply of sufficient amount of fuel for the operation of engine above idle running to a maximum speed when the throttle is almost completely open. Hence, it provides a constant air-fuel ratio at wide range of speeds and loads. It is mainly based upon the best economy at full throttle or high speed.

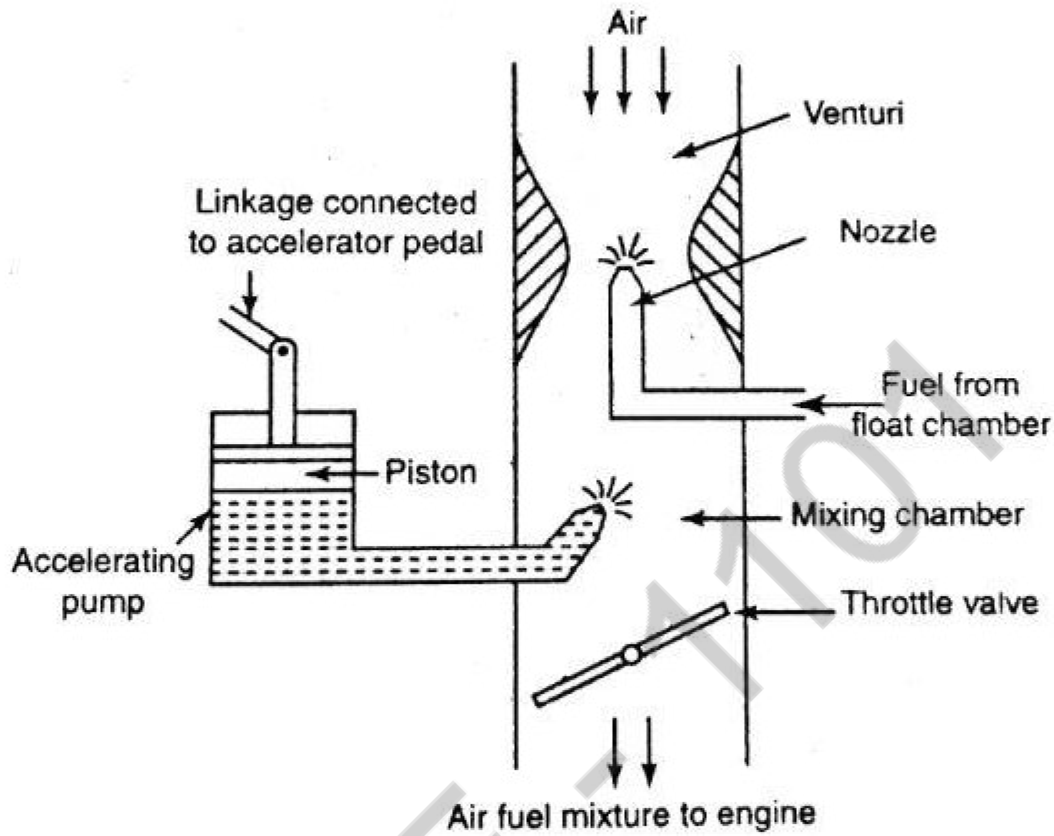
For maintaining the desired mixture proportions at various speeds, automation devices known as compensating devices are provided in modern carburettors.

The process of providing additional air or fuel required to maintain the correct air-fuel mixture is called compensation in carburettor. Automatic compensation systems are provided in latest carburettors to maintain the correct air-fuel mixture at high speed. They are as follows.

(i) Auxiliary or extra air valve compensation system
(ii) Restricted air-bleed compensation system
(iii) Compensating jet system
(iv) Multiple jet system



Acceleration Pump System:
When sudden acceleration is desired, the throttle valve opens suddenly. It results in a maximum amount of air flow with lacking of the fuel which produces a lean mixture. It causes a defect of "engine stumble or hesitation". **Idling circuit**
During idling and slow speed running, a rich mixture is needed by the engine. Although it requires less rich mixture (about 10:1) when compared to a mixture required for starting, the quantity required is more. It is done by providing a separate idle jet and an air bleed hole. With this arrangement, the metered quantity of air-fuel mixture is drawn into the idle passage.

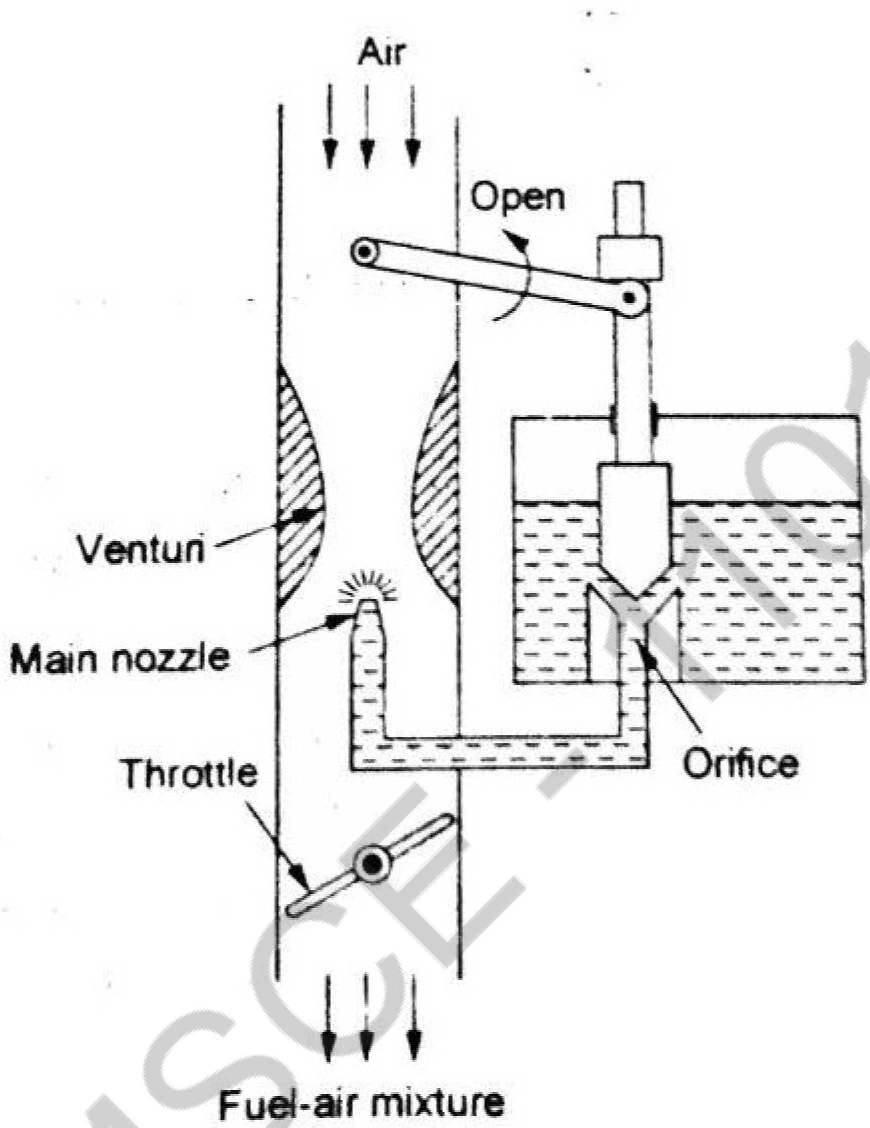


Accelerating system

To remove this defect, a separate pump as shown in Figure is connected through a linkage to the accelerator pedal. It is used to provide the increased fuel momentarily. The fuel is forced out of the acceleration jet when the acceleration pump is pressed to open outlet valve. When the pedal releases, the piston would move up to suck the fuel from the float chamber.

Economizer System or Power Enrichment System:

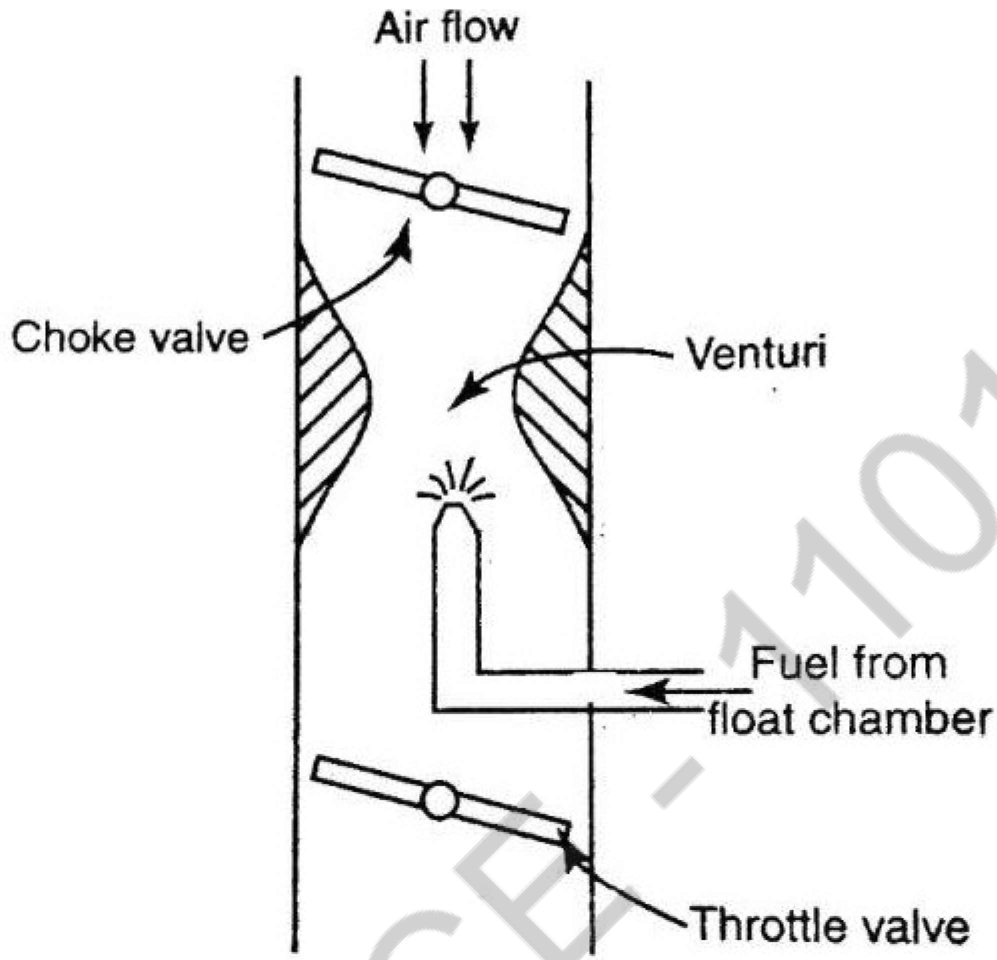
In order to obtain maximum power, the carburettor must supply a rich mixture. This additional fuel required is supplied by a power enrichment system that contains ammeter rod economizer. An economizer is a valve which remains closed at normal cruise operation and get opens only during full throttle operation to supply rich mixture.



Economizer or power enrichment system

Choke:

A choke is a simple butterfly valve (i.e. same as throttle valve) fitted at the top of the air horn as shown in Figure. It may be operated by hand or by automatic. During starting in order to provide a rich mixture, the choke is kept closed so that very small quantity of air passes through it. The suction applied to the nozzle is quite sufficient to deliver a large percentage of fuel.



18. The following details were noted in a test on a four cylinder, four stroke engine diameter= 100mm; stroke = 120mm; speed of the engine =1600 rpm; fuel consumption=0.2 kg/min; fuel calorific value = 44,000 kJ/kg ; difference in the tensions on either side of the brake pulley = 40 kgf ; brake circumference is 300cm. If the mechanical efficiency is 80%, calculate the
Brake thermal efficiency
Indicated thermal efficiency,
Indicated mean effective pressure and
Brake specified fuel consumption.

Given data:

Number of cylinder, k=4
Four stoke engine
Diameter, d = 100 mm =0.1 m
Length, l = 120 mm=0.12 m

$N = 1600\,\text{rpm} = 26.67$ rps

$n = \frac{N}{2} = \frac{26.67}{2} = 13.34$ rps

Mass of fuel $m_f = 0.2\,\text{kg/min} = 0.0033\,\text{kg/s}$

$CV = 44{,}000$ kJ / kg

Different in tension = 40kgf $\quad\quad \therefore W = 40 \times 9.81 = 392.4$ N

Circumference, $2\pi R = 300$ cm = 3 m

Mechanical efficiency, $\eta_{mech} = 80\%$.

Solution:

Break power BP= $2\pi NWR$

$= NW(2\pi R)$

$= 26.67 \times 392.4 \times 3 =$ 31395.92 W = 31.4kW

Break thermal efficiency η_{BT}

$$\eta_{BT} = \frac{BP}{m_f \times CV}$$

$$\eta_{BT} = \frac{31.4}{0.0033 \times 44000} = 0.2163 = 21.63\%$$

Mechanical efficiency,

$$\eta_{mech} = \frac{BP}{IP}$$

$$0.8 = \frac{31.4}{IP}$$

$IP = 39.25$ kW

Indicated thermal efficiency, η_{IT}

$$\eta_{IT} = \frac{IP}{m_f \times CV}$$

$$\eta_{IT} = \frac{39.25}{0.0033 \times 44000} = 0.2703 = 27.03\%$$

Indicated power, IP = $p_m \ell a n k$

$$IP = p_m \ell \frac{\pi}{4} d^2 \frac{N}{2} k$$

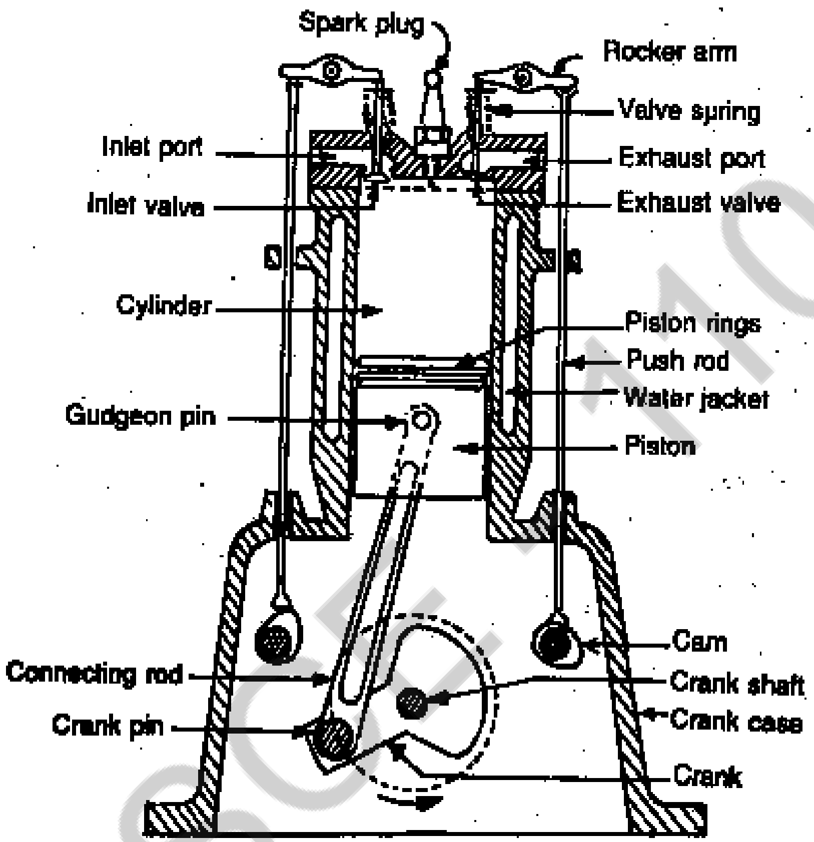
$$39.25 = p_m \times 0.12 \times \frac{\pi}{4} \times 0.1^2 \times 13.34 \times 4$$

pm = 780.46 kPa = 7.18 bar

Brake SFC, $= \frac{m_f}{BP} = \frac{0.2 \times 60}{31.4} =$ 0.38 kg/W-hr

19. Explain the construction details of an IC ENGINES

For effective functioning of the internal combustion engine every components of the engine has to work properly. The following components of the engine are



Cylinder:

It is a cylindrical space (or) container in which piston reciprocates. The working substance contained with in the cylinder is subjected to different thermodynamics processes. The cylinder is supported in cylinder block.

Piston:

It is a reciprocating cylinder component which is fitted in to the cylinder. The power generated by the working substance during the expansion stroke is transmitted into the piston, hence it forms the first link in transmitting the gas force to crankshaft

Piston Ring:

These piston rings are fitted into the slots around the piston, provide a tight seal between piston and cylinder wall, thus preventing leakage of combustion gases.

Combustion chamber:

It is the space enclosed in the upper part of the cylinder, below the cylinder head and above the top of the piston surface during the combustion process. The combustion of the fuel takes place with in this space.

Connecting Rod:

The connecting rod inter connects the piston and the crank-shaft and transmits the gas forces from the piston to the crankshaft. It has two ends called small end and big end. The small end of the connecting rod is connected with piston by using a pin called gudgeon pin. The big end of the connecting rod is connected with crank pin by using a pin called crank pin.

Crankshaft:

It converts the reciprocating motion of the piston in to useful rotary motion of the output shaft. The crankshaft is enclosed within crankcase. The crankshaft is attached with big end of the connecting rod.

Spark plug:

It is usually mounted on the cylinder head. It is a component which initiates the combustion process in spark ignition engines.

Fuel injector:

This component is present in the case of combustion ignition (CI) engines. This component atomizes the fuel into fine droplets, thus injecting it at correct timing, in correct proportion during the working cycle.

Inlet Manifold:

It is a piping system which connects the intake system to the inlet opening. Air, as in the case of CI engine (or) air fuel mixture, as in the case of SI engine, will follow through the inlet manifold.

Inlet Valve:

It is mounted on the cylinder head. It is used to regulate the charge (either air or air fuel mixture) coming into the cylinder.

Exhaust Manifold:

It is a piping system which connects the exhaust system with the exhaust (or) outlet opening. Products of combustion from the cylinder will escape into the atmosphere through this system.

Exhaust Valve:

It is also mounted on the cylinder head. It is used to control and regulate the discharge of combustion products from the cylinder into the atmosphere. In general the exhaust valve is subjected to higher temperature and corrosive atmosphere than the intake or inlet valve.

Cam Shaft:

The cam shaft is driven by crank shaft through timing gears having gear ratio of 2. The cam shaft is used to control the opening and closing of inlet and exhaust valves.

Cam:

These are integral parts of the cam shaft. They are designed in such a way to open the valve at the correct timing and keep them in the same position for necessary duration and to close it.

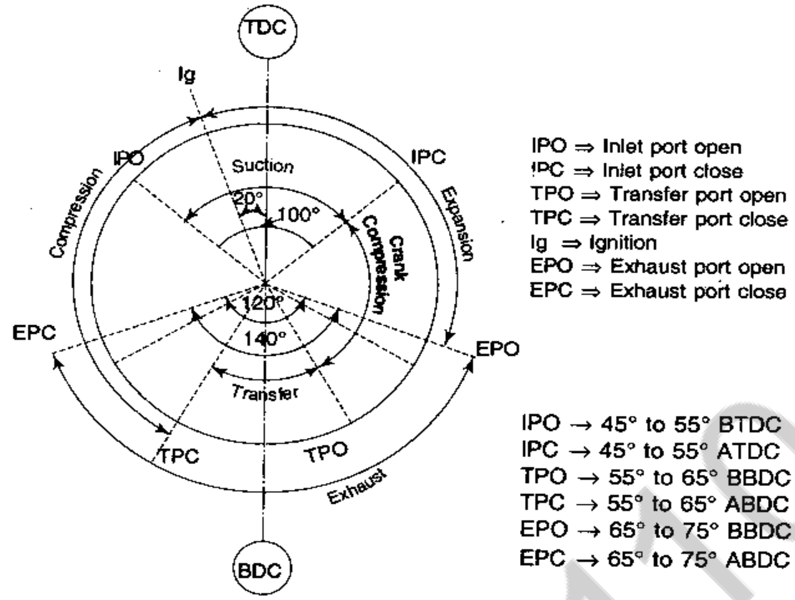
Flywheel:

It is mounted on the crank shaft and its function is to maintain the speed of the engine as a constant. It is done by storing excess energy during the power stroke and is utilized during remaining strokes of operation.

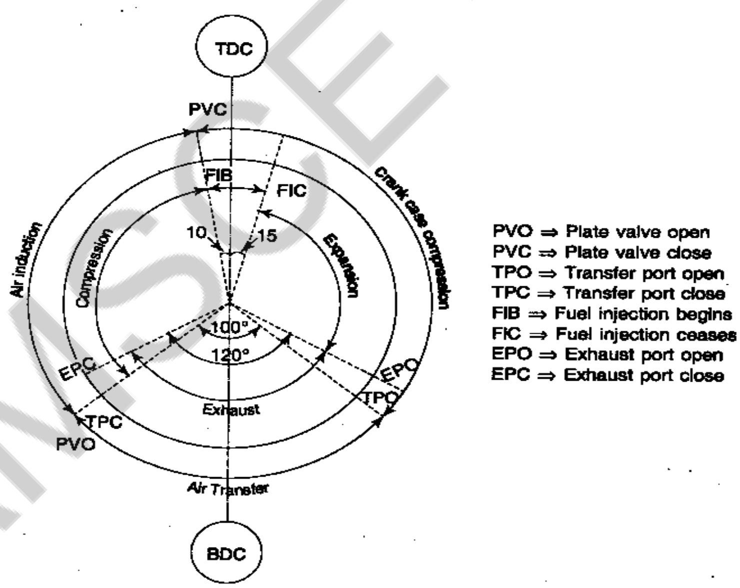
20. Draw the typical PORT TIMING DIAGRAM for SI & CI ENGINES

The timing of sequence of events such as exhaust port opening and closing, transfer port opening and closing, ignition and inlet port opening and closing can be represented graphically in terms of crank angles from dead centre position. This diagram is known as "Port Timing Diagram".

PORT TIMING DIAGRAM FOR TWO STROKE PETROL ENGINE:



Port Timing Diagram for Two Stroke Diesel Engine:



ME 8493 – THERMAL ENGINEERING – 1

QUESTION BANK

UNIT – 4

INTERNAL COMBUSTION ENGINE PERFORAMNCE AND SYSTEMS

PART – A

1. **What is the necessity of cooling in IC engines? (Nov/Dec 2019)**
   When the air-fuel mixture is ignited and combustion takes place at about 2500ºC for producing power inside an engine the temperature of the cylinder, cylinder head, piston and valves, continuous to raise when the engine runs. It these parts are not cooled by some means then they such to get damaged and even melted. The piston may cease inside the cylinder.
   To prevent this, the temperature of the parts around the combustion chamber si maintained as 200ºC to 250ºC. Too much of cooling will lower the thermal efficiency of the engine.
   Hence the purpose of cooling is to keep the engine at its most efficient operating temperature at all engine speeds and all driving conditions.
2. **What is turbocharging? (Nov/Dec 2019)**
   The purpose of forcing induction of an internal combustion engine to increase the density of air entering the engine to produce more power using a gas compressor is called turbocharging.
3. **What are the functions of lubrication system? (Apr/May 2019)**
   - ✓ It reduces friction between moving parts
   - ✓ It reduces wear and tear of the moving parts
   - ✓ It minimizes power loss due to friction
   - ✓ It provides cooling effect: during circulation, it carries heat from the hot moving parts and delivers is to the surrounding through crankcase.
4. **What is the use of Morse test? (Apr/May 2019)**
   - ✓ The purpose of Morse test is to obtain the approximate indicated power of a Multi cylinder engine.
   - ✓ It consist of running the engine against the dynamo-meter at a particular speed, cutting out the firing of each cylinder in turn and noting the fall in BP each time while maintaining the speed constant.
   - ✓ When one cylinder is cut off, power developed is reduced and speed of engine falls. Accordingly the load on dynamo meter is adjusted so as to restore the speed of the engine.
   - ✓ This is done to maintain FP constant, which is considered to be independent of the load and proportional to the engine speed. The observed difference in BP between all cylinder firing and one cylinder cut off is the IP of the cut off cylinder. Summation of IP of the entire cylinder would then give the IP of the engine under test.

5. **Name the various performance parameters of IC engines?**
   - ✓ Friction power
   - ✓ Indicated power
   - ✓ Air-fuel ratio
   - ✓ Brake power
   - ✓ Thermal efficiency
   - ✓ Specific fuel consumption
   - ✓ Volumetric efficiency

6. **Define the terms brake power, indicated power and friction power.**

   Brake power: The net power available at the crankshaft is known as brake power.

$$BP = \frac{2\pi NT}{60}$$

   Indicated power: The power developed inside the engine cylinder is known as indicated power.

$$IP = \frac{MEP \times L \times A \times n}{60}$$

   Friction power: It is defined as the difference between indicated power and brake power.

$$FP = IP - BP$$

7. **Differentiate between the brake thermal efficiency and indicated thermal efficiency.**

   Brake thermal efficiency: It is the ratio of brake power to the heat supplied to an engine.

$$\eta_{bth} = \frac{IP}{heat\,\text{supplied}} = \frac{BP \times 3600}{m_f \times C.V}$$

   Indicated thermal efficiency: It is defined as the ratio of indicated power to the heat supplied to an engine.

$$\eta_{ith} = \frac{IP}{heat\,\text{supplied}} = \frac{IP \times 3600}{m_f \times C.V}$$

8. **What is meant by specific fuel consumption?**

   It is the ratio of the mass of fuel consumed power hour to the power developed in kW

$$SFC = \frac{fuel\ consumed\ in\ kg/h}{power\ developed\ in\ kW}$$

9. **What are the methods used to measure the friction power?**
   - ✓ Willan's line method
   - ✓ Motoring test
   - ✓ Retardation test
   - ✓ Morse test

10. Name the various components of fuel supply of a petrol (or) SI engine.

- ✓ Fuel tank
- ✓ Fuel pump
- ✓ Carburetor
- ✓ Intake manifold
- ✓ Fuel filter

11. What is carburetor?

Carburetor is a device which is used for atomizing and vaporizing the fuel and mixing it with the air in varying proportions to suit the change in conditions of the engine.

12. What do you understand single (or) mono point and multipoint fuel injection system?

In multi-point injection system, the injector is placed on the side of the intake manifold near the intake valve. The injection sprays gasoline into the air, inside the intake manifold. The gasoline mixes with the air in a reasonable manner. This mixture of gasoline and air then passes through the inlet valve and enters into the cylinder.

In single or mono-point injection system, the injector is placed slightly above the throat of the throttle body. The injector sprays gasoline into the air in the intake manifold where gasoline mixes with the air. This mixture then passes through the throttle valve and enters into the manifold.

13. What is meant by ignition system?

Ignition system is a part of electrical system which carries the electrical current to the spark plug to ignite the fuel air mixture in the combustion chambers.

14. State the types of ignition system.

- ✓ Battery (or) coil ignition system
- ✓ Magneto ignition system
- ✓ Electronic ignition system

15. State the advantages and disadvantages of battery ignition system.

Advantages:

- ✓ It offers better sparks at low speeds, starting and for cranking purposes.
- ✓ The initial cost of the system is low
- ✓ It is a reliable system and periodical maintenance required is negligible except for battery
- ✓ The high-speed engine drive is usually simpler than magneto drive

Disadvantages:

- ✓ With the increasing speed, sparking voltage drops
- ✓ Battery, the only unreliable component of the system needs regular attention. Incase battery runs down, the engine cannot be started as induction coil fails to operate.
- ✓ Because of battery, bulk of the system is high.

16. Give the difference between battery ignition and magneto ignition system.

Battery ignition system	Magneto ignition system
✓ Battery is must. Impossible to start the engine when battery is discharged.	✓ No battery is needed hence no problem of battery discharge.
✓ Current for primary circuit is obtained from the battery	✓ The required electric current is generated by the magneto
✓ A good spark is available at spark plug at low speed	✓ During starting quality of spark is poor due to low speed
✓ Starting of engine is easier	✓ Engine starting is rather difficult
✓ Occupies more space	✓ Occupies less space
✓ Mostly employed in petrol cars and buses	✓ Used in racing cars, motor cycles etc

17. List aby four functions of lubrication.

- ✓ It reduces the friction between moving parts
- ✓ It provides sealing action
- ✓ It provides cooling effect
- ✓ It reduces the wear and tear of the moving components

18. How the cooling systems are classified?

- ✓ Air (or) direct cooling system
- ✓ Liquid (or) indirect cooling system
    - ➢ Direct cooling system
    - ➢ Natural circulation system
    - ➢ Forced circulation system
    - ➢ Pressurized water cooling
    - ➢ Evaporative cooling system

19. What is the purpose of fan and radiator in cooling system?

Fan:

- ✓ It draws atmospheric air through the radiator and thus increases the efficiency of the radiator in cooling hot cooling hot water
- ✓ It throws fresh air over the outer surface of the engine, which takes away the heat conducted by the engine parts and thus increases the efficiency of the entire cooling system

Radiator:

The purpose of the radiator is to cool down the water received from the engine

20. What is the function of thermostat in cooling system?

It is a kind of valve which opens and closed with the effect of temperature. It is fitted in the water outlet of the engine. During the warm-up period, the thermostat is closed and the water pump circulates the water only throughout the cylinder block and cylinder head. When the normal operating temperature is reached, the thermostat valve opens and allows hot water to flow towards the radiator.

21. What is meant by supercharging?

Supercharging is a method used for increasing the engine output power without increasing its weight and size by increasing the inlet air density in the engine cylinder.

22. What are the various methods of supercharging?

- ✓ Mechanical supercharging
- ✓ Pressure wave supercharging

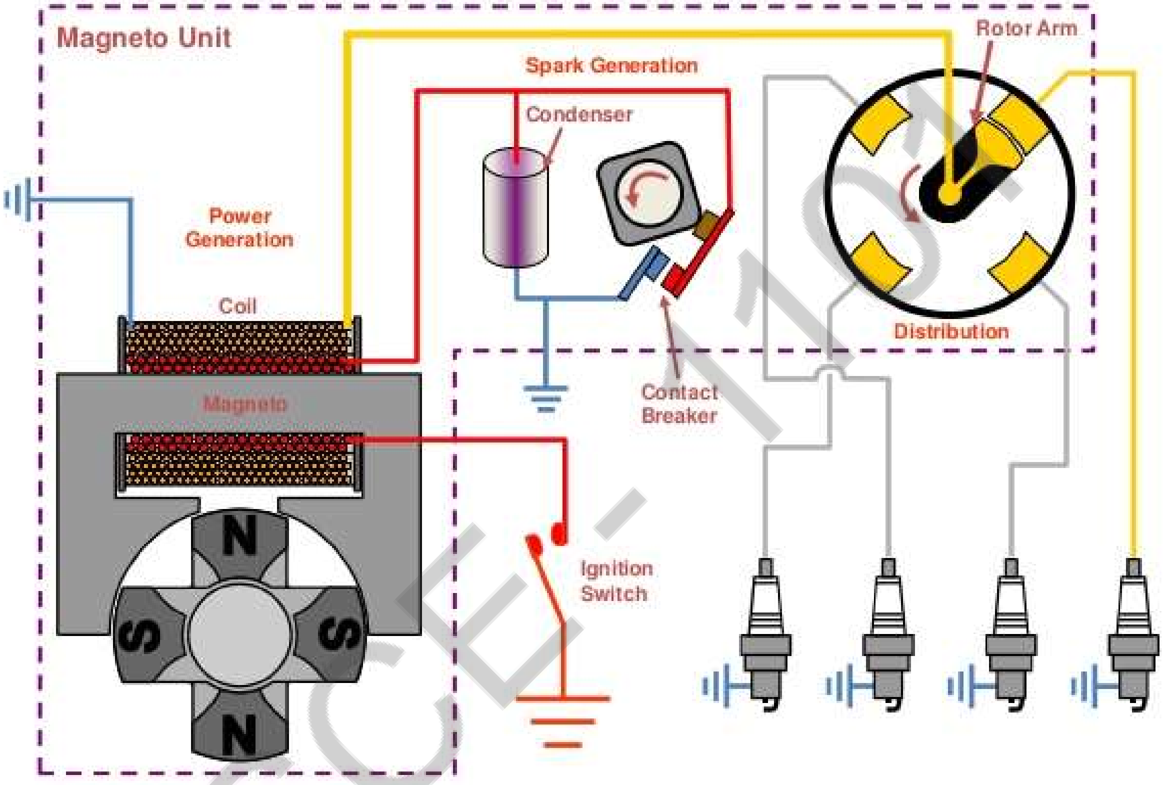
23. What is meant by turbocharger?

Turbocharger is a form of a supercharger which increases the amount of air entering the engine to create more power.

Part – B

1. **Discuss with neat sketches the magneto ignition system. (Nov/Dec 2019)**

The **Magneto Ignition System** is a unique kind of Ignition System which has its own source to generate the necessary amount of energy for an automobile or a vehicle to work.



IGNITION SYSTEM – Magneto System

Here is the list of parts that are used in it

- Magneto
- Distributor
- Spark Plug
- Capacitor

MAGNETO

The source that generates energy in the Magneto Ignition System is the Magneto. Generally, a magneto is a small generator that works on electricity. When magneto is rotated by the engine, it produces the voltage. The higher the rotation, the greater will be the amount of voltage produced by the system. The magneto does not need any external power source such as a battery to kick start it as it itself is a source for generating the energy. There are two types of winding in it. It has a primary binding and a secondary binding.

DISTRIBUTOR

The distributor that is used in the Magneto Ignition System is also used in the multi-cylinder engine. The multi-cylinder engine is used for regulation of spark in a correct sequence in the spark plug. The surge of the ignition is distributed uniformly among the spark plugs. There are two types of distributors

- ✓ Carbon brush type distributor
- ✓ Gap type distributor

In carbon brush type, the rotor arm sliding over the metallic segment carry the carbon brush which is embedded inside the distributor cap or molded insulating material. This help to provide an electric connection with the spark plug. In gap type, the distributor electrode of rotor arm is close to the distributor cap, but no contact is made leading no wear for the electrode.

SPARK PLUG

The spark plug used in the this Ignition System has two electrodes that are parted from each other. A high voltage flows through it which causes the generation of the spark and used to ignite cylinders combustion mixture like oil. The electrode used in it is a steel shell and an insulator. The central electrode is connected to the supply of ignition coil and outer steel shell which is grounded insulating both of them. There is a small air gap that is left between the central electrode and the steel shell where the spark is generated. The central electrode is close when the spark is generated and hence it is made of a high nickel alloy that can withstand high temperature and resistances.

CAPACITOR

The capacitor used in the Magneto Ignition System is a simple electrical capacitor in which two metal plates are separated by an insulating material with a distance. Commonly, air is used as insulating material, but for a particular technical requirement, some high-quality insulating material is used.

Working Principle Of Magneto Ignition System

The working principle of the this ignition System is similar to the working principle of coil or battery ignition system except that in it magneto is used to produce energy but not the battery. Here are the following scenarios that occur in it.

- ✓ When engine in the system starts it help magneto to rotate and thereby producing the energy in the form of high voltage.
- ✓ The one end of the magneto is grounded through contact breaker and ignition capacitor is connected to it parallel.
- ✓ The contact breaker is regulated by the cam and when the breaker is open, current flows through the condenser and charges it.
- ✓ As the condenser is acting like a charger now, the primary current flow is reduced thereby reducing the overall magnetic field generated in the system. This increases the voltage in the condenser.

- ✓ This increased high voltage in the condenser will act as an EMF thereby producing the spark at the right spark plug through the distributor.

At the initial stage, the speed of the engine is low and hence the voltage generated by the magneto is low but as the rotating speed of the engine increases, it also increases the voltage generated by the magneto and flow of the current is also increased. To kick start the engine, we can use an external source such as the battery to avoid the slow start of the engine.

Advantages

- ✓ It is more useful at medium and high speed.
- ✓ It is more useful because no battery is used.
- ✓ It requires less maintenance.
- ✓ The main advantage of the magneto ignition system over other ignition system is it doesn't require any external source to generate energy. It was managed at low tension and high tension. In the high tension, a huge amount of voltage is generated using a step-up transformer which can be used for engines like the airplane engine and low tension can manage this voltage letting it flow in the smallest part of the wiring and this avoid the leakage too.

Disadvantages

- ✓ It has starting problem due to the low rotating speed at starting of the engine.
- ✓ It is more expensive when compared to battery ignition system.
- ✓ There is a possibility of misfire due to leakage because the variation of voltage in the wiring can occur.

Application

- ✓ Here is the partial list of the applications of engines equipped with magneto ignition system.
- ✓ Tractors, Oil Burners, and Outboard Motors
- ✓ Washing Machines
- ✓ Trucks and Cement Mixers
- ✓ Buses
- ✓ Airplane Engines
- ✓ Power Units, Marine Engines and Natural Gas Engines

2. Describe the need for firing order with examples. (April/May 2019)

Firing order in an engine is important because a correct firing order can cause minimum vibrations in the system. Minimum vibration in automobiles is desired as the ride can become smooth and the driver and passengers won't feel the vibrations being transmitted by the engine as it is very less.

Example - A 6 cylinder engine will never have a firing order of 1-2-3-4-5-6 as it causes unbalanced forces in the engine which is the reason for vibrations. Also, odd number of cylinders in an engine cannot be fully balanced i.e. some amount of vibration will be present in the system. Hence most popular engines implement even number of cylinders with a particular firing order so that the system is fully balanced and no vibration is produced in the engine.

The order or the sequence in which the combustion of fuel in the cylinder takes place in a multi cylinder engines is called the firing order of engines.

Example: Considering the example of 4 cylinder inline engine. The firing order is typically 1–3–4–2 or 1–3–2–4.

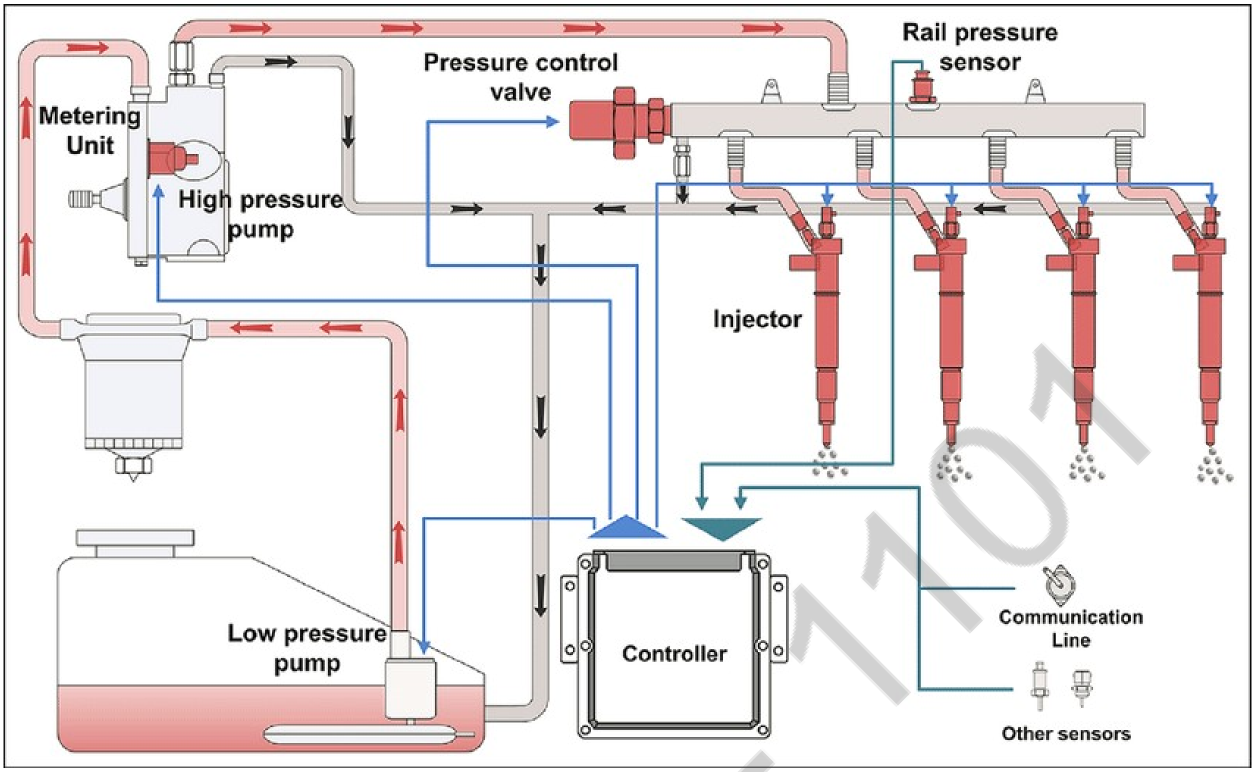
Reason : Many reasons can be stated. Some of them are:

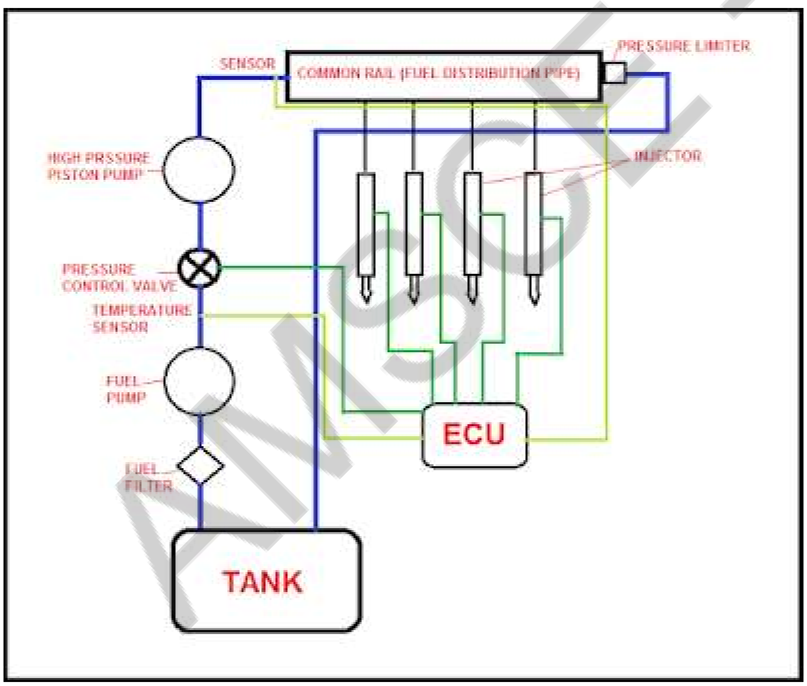
- ✓ When combustion of fuel takes place in cylinder tremendous amount of energy is generated. Some part of the energy is converted into reciprocating motion of piston which in turn rotates the crankshaft and remaining part of it is absorbed by the surrounding (walls and casing). If combustion takes place in the second cylinder immediately after the first cylinder the wall separating them would become extremely hot which is not desired. Similar concept can be applied for the rest.
- ✓ Cylinder firing order improves the distribution of the fresh charge in the manifold to the cylinders and helps the release of the exhaust gases, while at the same time suppresses torsional vibrations
- ✓ The other reason being balancing of the forces acting on the crankshaft.
  If combustion takes place in the sequence 1–2–3–4 it would result in unbalanced forces acting on the crankshaft which leads to damage of bearing and huge loss to the crankshaft itself (viz. in terms of life).

3. Describe the working of common rail direct injection systems. (April/May 2019 & Nov/Dec 2019)

Generally, diesel engines have the specific advantage of good fuel efficiency and low CO_2 emission. Therefore, various new technologies have been developed in order to reduce harmful emissions. One of such technologies is called Common Rail Direct Injection (**CRDI)** system of direct fuel injection. In this system, commencement of combustion takes place directly into the main combustion chamber located in a cavity on the top of the piston crown. This systems injects diesel five times more accurately than the normal injection system by high response injectors with electronic control. It results the grater reduction of particulate matter and NOx thereby improving the fuel efficiency and increasing its torque. So, they lead to reduce engine noise and vibration. Various components of CRDI system are:

- ✓ High pressure fuel pump
- ✓ Common fuel rail
- ✓ Injectors
- ✓ Engine control unit





A common rail system consists of pressure accumulator called common rail (or in simple words, a fuel distribution pipe) which is mounted on the engine block. The rail is fed by a high-pressure multi-cylinder fuel pump. The injectors are activated by solenoid valves. Both solenoid valves and fuel pump are electronically controlled.

In the CRDI system, the injection pressure does not depend on engine speed and load. So, the control of injection parameters is easy. Usually, a pilot injection is introduced in order to reduce engine noise and NOx emissions. The injectors use a needle-and-seat-type valve to control the fuel flow. The fuel pressure is fed to both top and bottom of the needle valve. The pressure at the bottom will push the needle off its seat by bleeding some of the pressure off the top. Thus, the fuel will flow through nozzle holes.

Advantages:

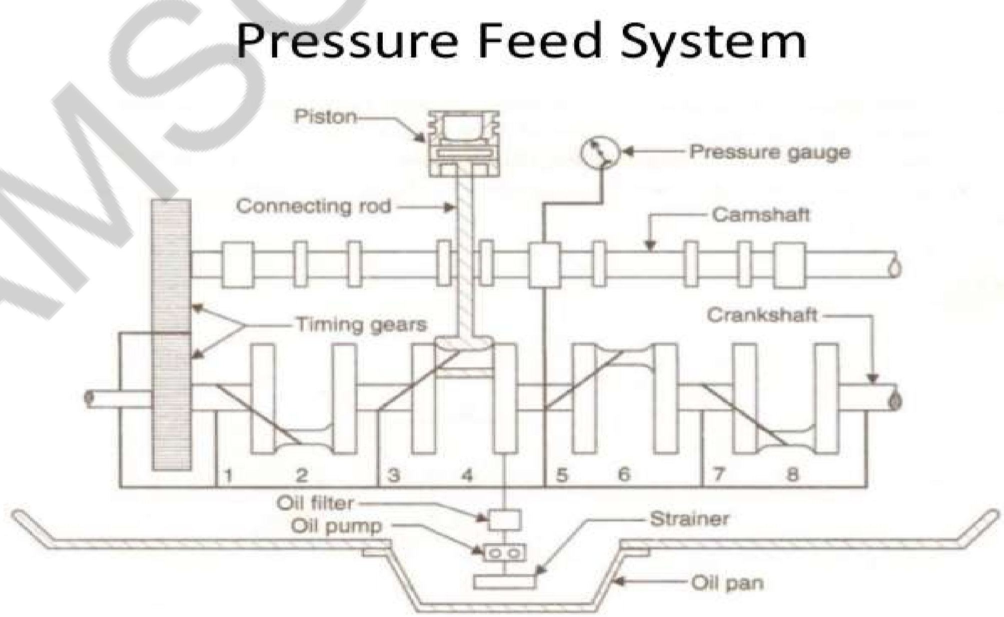
- ✓ It delivers 25% more power and torque than the normal direct injection engine
- ✓ Initial cost is low
- ✓ Superior pick up is possible
- ✓ It maintains lower levels of noise and vibration
- ✓ Higher mileage is obtained
- ✓ Emissions are low
- ✓ Fuel consumption is less
- ✓ Improved performance is obtained

Disadvantages:

- ✓ Many parts involve the complicated design
- ✓ Production cost is high
- ✓ High degree or engine maintenance is required

4. Explain the working of full pressure lubrication system. (April/May 2019)

In this system, lubricating oil is forced under pressure by a pump at a pressure of 2 to 4MPa. It consist of oil sump, oil pump, oil gallery, pressure release valve, oil filter, oil pressure gauge and oil dipstick.



The lubricating oil from the sump or oil pan is sucked by oil pump and lifted to oil main gallery through oil filter and strainer. The oil pump is driven by the camshaft. Oil pump and filter are always immersed in the oil.

From the oil gallery, the oil is distributed under pressure to various parts of the engine to be lubricated by the oil tubes. Oil from gallery enters the crank pin bearing through a taper hole in the crank shaft. A through hole is provided at the centre of the connecting rod. The oil from the big end bearing enters the gudgeon pin bearing (small end bearing) through the hole in the connecting rod.

Separate oil tubes carry oil for lubricating timing gears, rocker arm assembly, cam shaft etc. another oil line is connected to the pressure gauge to show the pressure of the oil

The excess supplied oil drips back into the oil sump. A pressure relief valve is provided to avoid any damages in case of excess oil pressure. An oil dipstick is provided to measure the oil level in the sump.

Advantages:

- ✓ All the parts of the engine are efficiently lubricated
- ✓ The minute gap between the sliding surfaces can be lubricated since the oil is supplied under pressure

5. Describe how turbocharging leads to high power output and the associated effects. (April/May 2019)

- ✓ Turbochargers also appear on large diesel engines. A turbo can significantly boost an engine's horsepower without significantly increasing its weight, which is the huge benefit that makes turbos so popular!
- ✓ In this article, we'll learn how a turbocharger increases the power output of an engine while surviving extreme operating conditions. We'll also learn how wastegates, ceramic turbine blades and ball bearings help turbochargers do their job even better. Turbochargers are a type of **forced induction system**. They **compress** the air flowing into the engine. The advantage of compressing the air is that it lets the engine squeeze more air into a cylinder, and more air means that more fuel can be added. Therefore, you get more power from each explosion in each cylinder. A turbocharged engine produces more power overall than the same engine without the charging. This can significantly improve the power-to-weight ratio for the engine.
- ✓ In order to achieve this boost, the turbocharger uses the exhaust flow from the engine to spin a **turbine**, which in turn spins an **air pump**. The turbine in the turbocharger spins at speeds of up to 150,000 rotations per minute (rpm) -- that's

about 30 times faster than most car engines can go. And since it is hooked up to the exhaust, the temperatures in the turbine are also very high.

- ✓ Keep reading to find out how much more power you can expect from your engine if you add a turbocharger.

Turbocharger lag:

Turbocharger lag (**turbo lag**) is the time required to change power output in response to a throttle change, noticed as a hesitation or slowed *throttle response* when accelerating as compared to a naturally aspirated engine. This is due to the time needed for the exhaust system and turbocharger to generate the required boost which can also be referred to as spooling. Inertia, friction, and compressor load are the primary contributors to turbocharger lag. Superchargers do not suffer this problem, because the turbine is eliminated due to the compressor being directly powered by the engine.

Turbocharger applications can be categorized into those that require changes in output power (such as automotive) and those that do not (such as marine, aircraft, commercial automotive, industrial, engine-generators, and locomotives). While important to varying degrees, turbocharger lag is most problematic in applications that require rapid changes in power output. Engine designs reduce lag in a number of ways:

- ✓ Lowering the rotational inertia of the turbocharger by using lower radius parts and ceramic and other lighter materials
- ✓ Changing the turbine's aspect ratio
- ✓ Increasing upper-deck air pressure (compressor discharge) and improving wastegate response
- ✓ Reducing bearing frictional losses, e.g., using a foil bearing rather than a conventional oil bearing
- ✓ Using variable-nozzle or twin-scroll turbochargers
- ✓ Decreasing the volume of the upper-deck piping
- ✓ Using multiple turbochargers sequentially or in parallel
- ✓ Using an antilag system
- ✓ Using a turbocharger spool valve to increase exhaust gas flow speed to the (twin-scroll) turbine

Sometimes turbo lag is mistaken for engine speeds that are below boost threshold. If engine speed is below a turbocharger's boost threshold rpm then the time needed for the vehicle to build speed and rpm could be considerable, maybe even tens of seconds for a heavy vehicle starting at low vehicle speed in a high gear. This wait for vehicle speed increase is not turbo lag, it is improper gear selection for boost demand. Once the vehicle reaches sufficient speed to provide the required rpm to reach boost threshold, there will be a far shorter delay while the turbo itself builds rotational energy and transitions to positive boost, only this last part of the delay in achieving positive boost is the turbo lag.

6. **Explain with neat sketches of battery ignition system (or) coil ignition system. (Nov/DEC 2018)**

Construction:

It consist of battery, ignition coil, condenser, contact breaker, distributor and spark plugs. Generally, 6 to 12 volts battery is sued. The ignition coil consists of two windings primary and secondary as shown in fig.

The primary windings consist of a thick wire less number of turns. The primary winding is formed of 200-300 turns of wire of #20-gage to produce a resistance of about 1.5 ohms.

The secondary winding located inside the primary winding consist of 21000 turns of thin enameled wire of #38-40 gages with sufficiently insulated to withstand high voltage. It is wound closer to the core with one end connected to the secondary terminal and the other end is wound either to the metal case or the primary coil.

The condense is connected across the contact breaker points. It prevents excess arcing and pitting of contact breaker points. The contact breaker is housed in the distributor itself. It makes and breaks the primary ignition circuits.

The distributor distributes the high voltage to the respective spark plugs having regular intervals in the sequence of firing order of the engine. The sequence in which the firing or power occurs in a multi-cylinder engine is known as firing order. The order of a 4-cylinder in-line engine is 1-3-4-2 or 1-4-3-2.

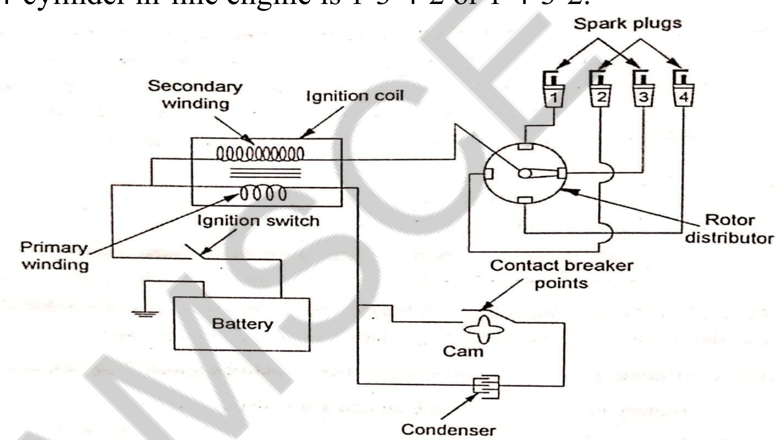
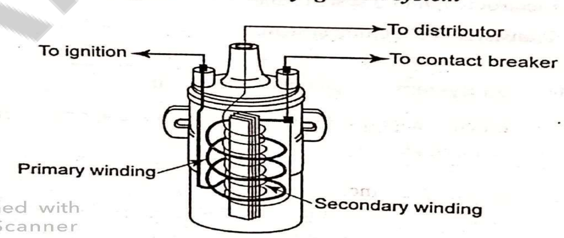


Figure 4.15 Battery ignition system



The spark plug is fitted in the combustion chamber of the engine. It produces spark to ignite the fuel-air mixture. The rotor of the distributor and contact breaker cam are driven by the engine. There are two circuits in this system. One is the primary circuit. It consists of a battery, a primary coil of the ignition coil, condenser and contact breaker. The other circuit is the secondary circuit. It consists of a secondary coil, distributor and spark plugs.

Working:

The ignition switch is switched on when the engine is cranked. The cranking of the engine opens and closes the contact breaker points through a cam.

When the contact breaker points are closed:

- ✓ The current flows from the battery to the contact breaker points through the switch and primary winding and then it returns to a battery through the earth.
- ✓ This current builds up a magnetic field in the primary winding of the ignition coil.
- ✓ When the primary current is at the highest peak, the contact breaker points will be opened by the cam.

When the contact breaker points are opened:

- ✓ The magnetic field sets up in the primary winding which is suddenly collapsed.
- ✓ A high voltage (15000 volts) is generated in the secondary winding of the ignition coil.
- ✓ This high voltage is directed to the rotor of the distributor.
- ✓ The rotor directs this high voltage to the individual spark plugs in the sequence of the firing order of the engine.
- ✓ This high voltage tries to cross the spark plug gap (0.45 to 0.6mm) and the spark is produced. This spark ignites the fuel-air mixture.

Advantages:

- ✓ It provides better sparks at low speeds of the engine during starting and idling due to the availability of maximum current throughout the engine speed range.
- ✓ The initial cost is low as compared with magneto ignition system.
- ✓ The maintenance cost is negligible except the battery
- ✓ Spark efficiency remains unaffected by various positions of the timing control mechanism.

7. Explain in detail the difference between supercharger and turbocharger.

Supercharger	**Turbocharger**
Supercharger are basically compressors	Turbochargers are devices consisting both-turbine and a compressor mounted on same shaft
Extra power is to be supplied	It does not need extra power
They draw power from engine	They extract their power from the exhaust gases
They are connected to the intake manifold of the vehicles	Since they are a combination of turbine and a compressor, the turbine is connected to exhaust pipe while compressor to intake
It is more suitable for engines with smaller displacements	It is more suitable for engines with higher displacements
Supercharger start working as soon as the engine starts	Turbochargers would not start operating until sufficient amount of exhaust gases are produced

It is less efficient since it demands extra power	It is more efficient as it draws its power from the exhaust gases
The cost of supercharger is less	The cost of turbocharger is less
Maintenance is easy	It is difficult to maintain since lot of heat gets generated and it also need frequent lubrication
No lag. Power delivery is immediate	Turbo takes time to spin up to speed. Hence there is a lag
Greater acceleration could be achieved	Higher speeds could be achieved

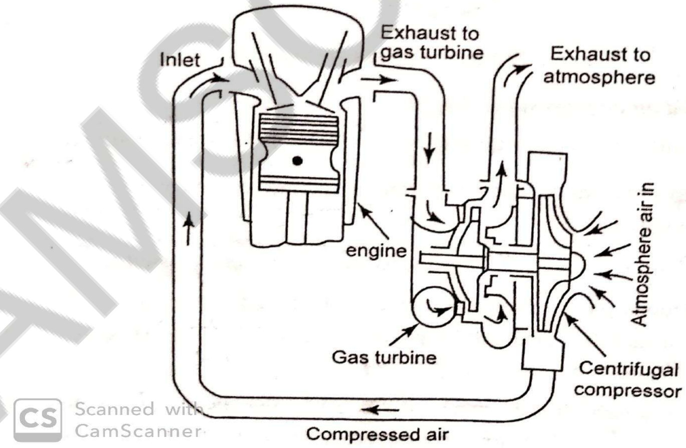
8. Explain with neat sketch of turbocharger.

TURBO CHARGERS

Generally, a centrifugal or axial flow or displacement type supercharger which is driven by the engine crankshaft is used in IC engines. Some superchargers are driven by a gas turbine which derives by using engine exhaust gases. This type of supercharger is called turbocharger.

Purpose of turbocharger:

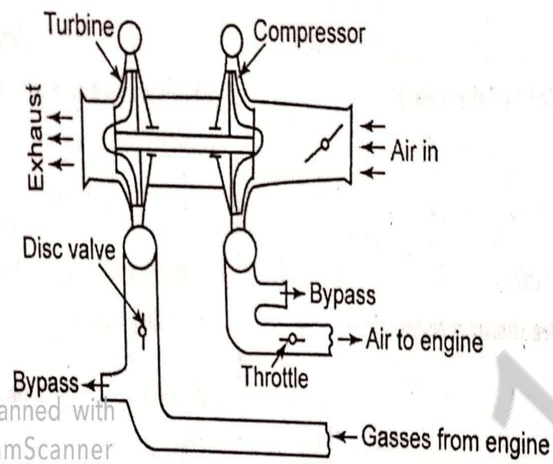
- ✓ To reduce weight per horse power of the engine as required in aero engines
- ✓ To reduce the space occupied by the engine as required in marine engines.
- ✓ To have better turbulence and it ensures more complete combustion giving greater power and low specific fuel consumption.
- ✓ To improve volumetric efficiency of the engine at high altitudes, as in aero engines, and at high speeds as in racing cars.
- ✓ To maintain the power of a reciprocating IC engines even at high altitudes where less oxygen is available for combustion.



Principle of working of a turbocharger:

Exhaust gas from the engine flows along the exhaust manifold and through nozzle box assembly and it enters into the blades of the gas turbine where the mechanical work is done by the gas turbine,

The wheel of the gas turbine and the impeller of the supercharger are mounted on one common shaft. Thus, the supercharger compresses the atmospheric airs in case of diesel engines or air fuel mixture in case of petrol engines and it enters the engine cylinder. By using a turbocharger, the engine fuel economy is improved by the use of the kinetic energy of exhaust gases. The turbocharger output can be controlled for its optimum performance by introducing by pass passage and disc valve on both inlet and outlet passages shown in Figure.



Limitations of turbocharging:

- ✓ Special exhaust manifolds are required for the turbocharging system.
- ✓ In order to inject more fuel per unit time fuel injection needs modification.
- ✓ In contrast to a naturally aspired engine which can digest solid particles in the inlet air without undue stress, a turbocharged engine can pass only the minutest material particles without damage.
- ✓ It is difficult to obtain good efficiency over a wide range of operations since the efficiency of the turbine blades is sensitive to gas velocity.
- ✓ Turbochargers are costly and add complexity. Adding a turbo can often cause a cascade of other engine modifications to cope with the increased power such as exhaust manifold, intercooler, gauges, plumbing, lubrication and pistons.

9. Explain in details – supercharging.

SUPERCHARGING

An engine may not produce the same power output when it is operated at different locations and altitudes. It is due to variation in ambient conditions. Supercharging and trbo charging are used to overcome this problem.

Supercharging is the process of supplying the air fuel mixture to the engine just above the atmosphere pressure. A supercharger increases the pressure of the air fuel mixture from the carburetor before it enters the engine. Supercharger is a pressure boosting device which supplies air in a diesel engine or air-fuel mixture in a petrol engine at high pressure.

Types of Supercharging Methods

Superchargers are broadly classified into the following types according to the method of transfer.

- ✓ **Positive displacement type:**

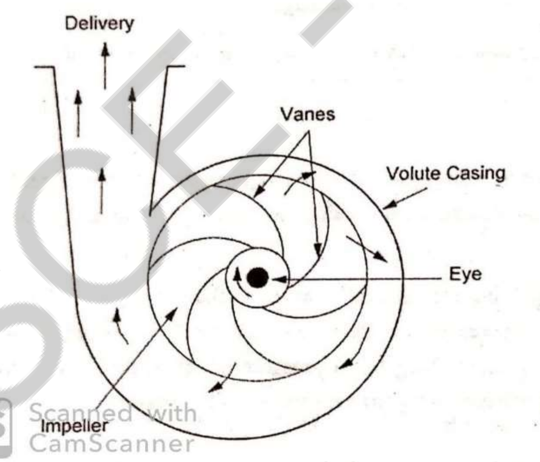
Positive displacement blowers and compressors deliver at constant level of pressure increase at all engine speeds (RPM). Major types of positive-displacement pumps include roots, twin-screw, sliding vane and scroll-type superchargers.

- ✓ **Dynamic compressors type:**

Dynamic compressors do not deliver pressure at low speeds and above a threshold speed, the pressure increases with engine speed. Dynamic compressors rely on accelerating the air to high speed and then exchanging its velocity for the increase in pressure by diffusing or slowing it down. Major types of dynamic compressor are centrifugal and multi-stage axial flow. The following are the most commonly used superchargers.

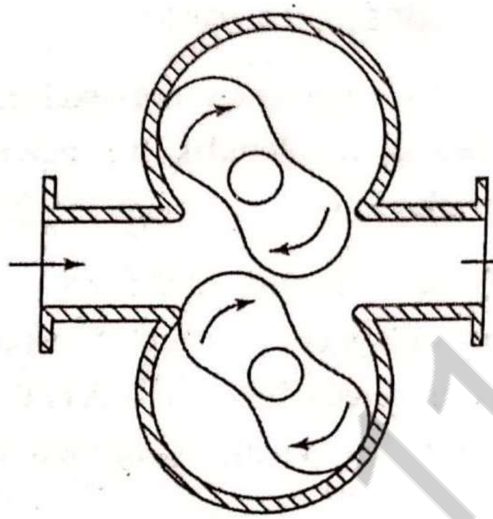
(a) Centrifugal type supercharging:

Centrifugal supercharging compresses the air inside the case of the supercharger using an impeller. Then, it discharges the air out of a scroll to the motor. This design is similar to turbo-charging except for centrifugal superchargers which do not use the exhaust to build pressure. They use a belt driven by the crank pulley to spin the impeller. The ability to change the impeller sizes and spin the impeller at different speeds creates a more inexpensive way to have flexibility.



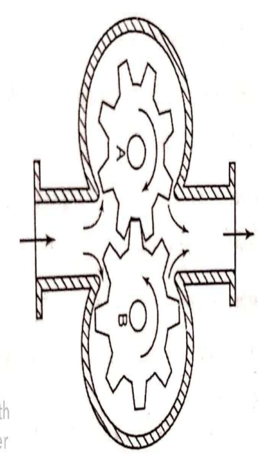
(b) Roots type supercharging:

The roots type supercharger is the first style supercharger and it can be dated back to the 1880s when the roots brothers designed it as an air conveyor for mine shafts. Roots blowers act similar to air pumps (not compressors) and in general, roots blowers have a two or three lobe rotor design depending on the size of the case. Roots blowers will give the positive pressure to the motor from just a crack of the throttle and it will give the pressure at full throttle irrespective of the rpm of the motor. Roots blowers are also extremely reliable and they require very little maintenance which is why Ford, GM, Mercedes, Jaguar and Austin Martin. They have all featured Roots blowers as original equipment on select high performance vehicles.



(c) Screw type supercharging:

Screw type superchargers are derived from roots type concept but with vast improvements for street use. Although from the outside, screw type superchargers may look more similar to roots type superchargers, on the inside, it has a twin-screw design that compresses air unlike roots type superchargers which pump the air into the motor. Screw type superchargers have an axial-flow design that compresses the air as it moves between the screws to create positive pressure without creating the heat which roots type superchargers can create. The screw type supercharger's ability to produce a dramatic increases power from idle and throughout the rest of the power curve make them a great choice for heavy vehicles, towing or commercial use.



Modifications required on engines supercharging:

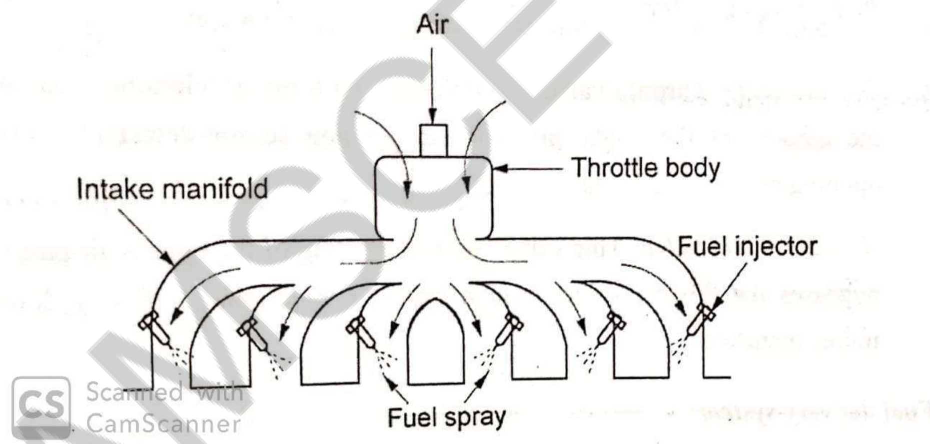
The following modifications make the engine more suitable for supercharging.

- It increases the valve overlap period to permit complete scavenging of the clearance volume.
- It increases the clearance volume by decreasing the compression ratio.
- The injection system of a diesel engine must be modified to supply the increased amount of fuel. It is achieved by providing greater area in nozzle than normally aspirated engines.
- In case of a turbocharged engine, the exhaust valve should open a bit earlier in order to supply more energy to the turbocharger.
- For normally aspired engine the exhaust manifold is water-cooled. But, the exhaust manifold of turbocharged engine is insulated to reduce heat loss.

10. **Explain in detail about multi-point fuel injection system. (MPFI) (April/May 2018)**

Multi-Point Fuel Injection (MPFI) System

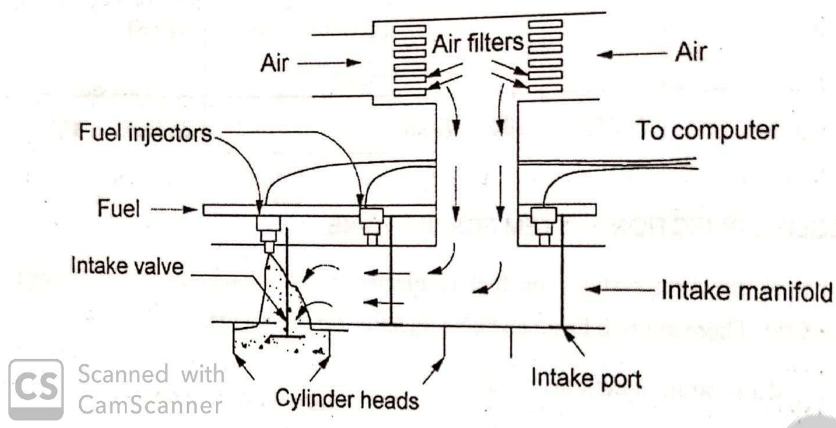
It is also called port injection system. In this system, there is an injection valve for each engine cylinder to supply or spray fuel in the cylinders intake manifold space as shown in Figure. Each injection valve is placed in the intake port near the intake valve. The main advantage of this system is that it allows more time for mixing of air and petrol.



Components of MPFI:

The system has three major components as follows:

(a) Air intake system
(b) Fuel delivery system
(c) Electronic control system



(a) Air intake system:

The air (corresponding to the throttle valve opening) is filtered by the air cleaner and passes through the throttle body. Then it is distributed by the intake manifold and finally drawn into each combustion chamber. Opening and closing of throttle valve is controlled by Electronic Control Unit (ECU) according to demand and necessity with proper calculation with input system. The major components of air intake system are as follows:

(i) Throttle body: Throttle valve is interlocked with the accelerator pedal and controls the amount of the intake air. Throttle position sensor detects the throttle valve opening and sends a signal to ECU.

(ii) Idle air control valve: This valve controls opening of the bypass air passage. The air bypasses the throttle valve through bypass passage and is finally drawn into the intake manifold.

(b) Fuel delivery system:

The fuel in the fuel tank is pumped up by the fuel pump and filtered by fuel filter. It is then fed under pressure to each injector through the delivery pipe. The fuel is injected into the intake port of the cylinder head when the injector opens according to the injection signal form ECU. The major components of fuel delivery system are as follows:

(i)Fuel pump: It is an electric fuel pump and its operation is controlled by ECU. The fuel is drawn through the inlet port with high pressure. It is discharged through the outlet port. The fuel pump also has a check valve to keep some pressure in the fuel feed line even when the fuel pump is stopped.

(ii) Pressure regulator system: The fuel pressure regulator is diaphragm operated relief valve consisting of diaphragm, spring and valve. It keeps the fuel pressure applied to the injector at 2.9 kg/cm at all times. When the fuel pressure rises more than this limit, the fuel pushes the valve in the regulator open and excess fuel return to the fuel tank through the return line.

(iii)Injector: Each cylinder has one injector, which is installed between the intake manifold and delivery pipes. It is an electromagnetic type injection nozzle, which injects fuel into the intake port of the cylinder head according to the signal from ECU.

(c) Electronic Control Unit (ECU);

The electronic control unit consists of various sensors which detect the state of the engine and driving conditions. ECU controls various systems such as fuel injection control system, idle speed control system, fuel pump control system ignition control system etc. according to the signals from the sensors.

The electronic fuel injection system supplies the combustion chambers with air/fuel mixture of optimized ratio under widely varying driving conditions. In this system, ECU controls the time and the timing of the fuel injection according to the signals from the various sensors so that suitable air/fuel mixture is supplied to the engine in each driving condition.

The Idle speed control system controls the bypass airflow by means of ECU and Idle air control valves for the following purposes:

- ✓ To keep the engine idle speed as specified at all times.
- ✓ To improve starting performance of the engine
- ✓ To compensate air fuel mixture ratio when decelerating.
- ✓ To improve drivability while the engine is warmed up.

11. Compare the Magneto ignition and coil ignition system.

- ✓ **Simplicity:**

  A coil ignition system requires a greater attention against possible defects because the wiring is quite complicated. On the other hand, the wiring of a magneto ignition system is comparatively simple and it forms a compact unit.

- ✓ **Cost**

  Due to less precision work, the manufacturing cost in coil ignition system is less than in magneto ignition.

- ✓ **Starting and low speed operation**

  At the time of starting and low-speeds, the strength of the spark in magneto ignition is low while a good spark is given by the coil ignition.

- ✓ **Strength of spark at high speeds**

  With the increase in speed, the strength of spark given by the magneto ignition system increases but it decreases in the case of coil system as shown in gif. Therefore, it is unsuitable for high-speed racing cars and aero planes.

- ✓ **Dependence on battery and charging dynamo:**

  The operation of the coil ignition system is greatly influenced by the condition of the battery and charging dynamo. If a car stands for a few weeks and its battery gets discharged, it becomes difficult to start the engine even by hand cranking. But, there is no such difficulty experienced in magneto ignition system which is more reliable.

12. What is purpose cooling system in CI engines? Explain air cooling and water-cooling systems with neat sketches.

When the air-fuel mixture is ignited, the combustion takes place at about 2500°C for producing power inside an engine. The temperature of the cylinder, cylinder head, piston and valve, continues to raise when the engine runs.

If these parts are not cooled by some means, then they are likely to get damaged and even melted. The piston may cease inside the cylinder. To prevent this, the temperature of the parts around the combustion chamber is maintained at 200°C to 250°C. Too much of cooling will lower the thermal efficiency of the engine. Hence, the purpose of cooling is to keep the engine at its most efficient operating temperature at all engine speeds and all driving Conditions. The cooling system is so designed that it prevents cooling until the engine reaches is normal operating temperature. When the engine warms up the cooling system will begin to function. It cools rapidly when the engine is too hot and it cools slowly or not at all when the engine is cold or warming up. Thus, the duty of the cooling system is to keep the engine from
getting too hot-not to keep it cool.

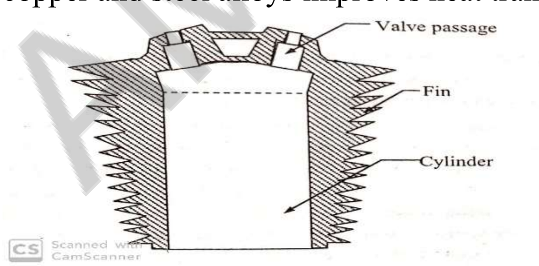
Types of cooling systems:

1. Air cooling or direct cooling
2. Water cooling or indirect cooling
   - ✓ Thermosyphon cooling
   - ✓ Pump circulation cooling
3. Liquid cooling
4. Pressure sealed cooling
5. Steam cooling or evaporative cooling.

Generally, for automobile engines air-cooling and water-cooling are used.

Air Cooling

Method of cooling an engine by the use of atmospheric air is called air-cooling. Generally, the two stroke engines are air-cooled. The heat from inside the cylinder is spread over a large area of the outer surface of cylinder head and cylinder by providing tins as shown in Figure. If a fan is used to supply a continuous air over the large finned surface, heat can be quickly removed. More temperature difference between air and cylinder is due to good heat conductivity of the metal helping the parts to cool by air-cooling. The use of copper and steel alloys improves heat transfer.



Advantages:

(i)Light in weight since there are no radiators, cooling water and pipelines.

(i) No coolant is used and hence, no leak and no anti-freeze required.

(iii) Warming up is faster.

(iv) Maintenance is easy and hence, it is cheaper.

Disadvantages:

(i) It is less efficient since air is a poor conductor of heat compared with water.
(ii) Since it is not possible to maintain, even cooling some time distortion may take place.
(iii) It produces more noise when it is operated.
(iv) It can be used only in small engines.

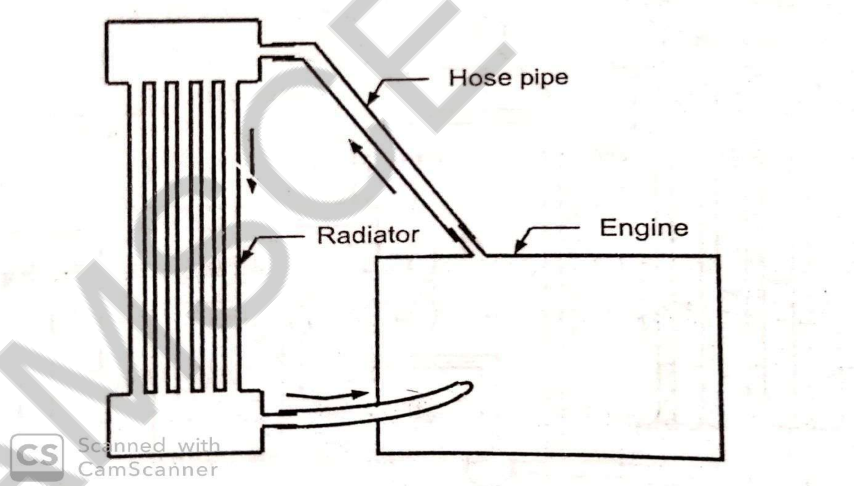
Water Cooling

In water-cooling, water is used for cooling the engine by circulating it through water
jackets around each combustion chamber the cylinder, cylinder head, valve and valve seat. By absorbing heat, water will become hot. When it is again passed through the radiator, it will be cooled by air blast due to the forward motion of the vehicle as well as of this engine to absorb heat. There are two systems of water-cooling.

- ✓ Thermosyphon system
- ✓ Pump circulation system

i Thermosyphon system:

The principle of hot water going up and cold water coming down due to the difference in density is used. There is no pump to circulate water. The light hot water from the engine goes to the top of the radiator by itself and gets cooled by the surrounding air and hence, it goes down to the bottom of the radiator and it again goes to engine cylinder as shown in Figure. It is simple and cheap but cooling is slow. Water should be maintained to a correct level at all time.



ii Pump circulation system:

To make the thermosyphon system more effective and improve water circulation, a water pump is introduced as shown in Figure which is driven by a V-belt from a pulley he engine crankshaft. It is called pump circulation system.

The water cooling arrangement for a 4 cylinder engine is shown in fig. when the hot water in engine passes through the radiator tubes from upper tank to lower tank, it is exposed to a large amount of airflow due to the forward movement of the vehicle as well as the fan rotation and it sufficiently gets cooled. Then, it is pumped to cylinder jackets by the water pump. The automatic thermostat valve is sued to regulate the circulation of water so that very cold water will become hot in short time to improve the efficiency of the engine.

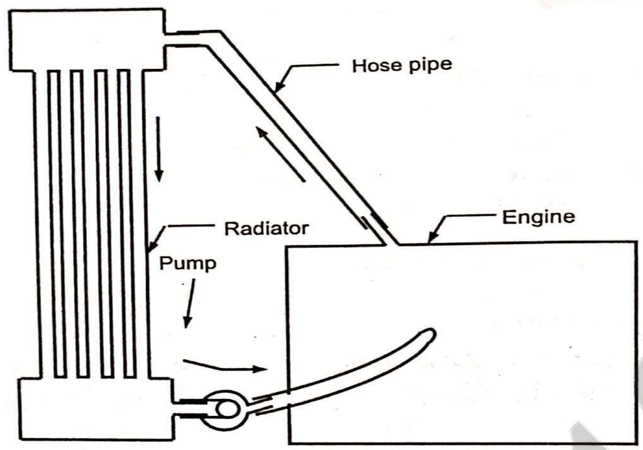
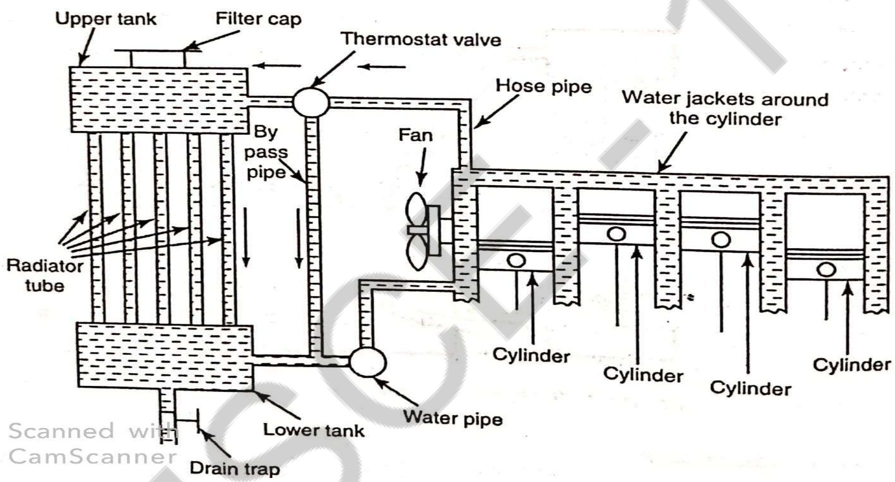


Figure 4.30 Pump circulation system



13. A single cylinder 4-stroke oil engine works on diesel cycle. The following readings were taken when the engine was running at full load. Area of the indicator diagram = 3cm^2, length of the diagram=4cm, spring constant = 10 bar/cm, speed of the engine = 400 rpm, load on the brake = 380 N, spring balance reading = 50 N, diameter of the brake drum = 120 cm, fuel consumption = 2.8 kg/h, calorific valve of the fuel = 42000 kilo joule /kg, diameter of the cylinder = 16 cm, stroke of the piston = 20 cm. find (a) frictional power of the engine (b) mechanical efficiency (c) brake thermal efficiency (d) brake mean effective pressure.

the eng... ...efficiency, (c) brake thermal efficiency and (d) brake mean effective pressure.

[Nov'10]

Given data:

Single cylinder, four stroke engine

Area of indicator diagram, $A = 3\ cm^2$

Length of indicator diagram, $L = 4\ cm$

$S = 10\ bar/mm$

$N = 400\ rpm = 6.67\ rps$

$n = \frac{N}{2} = \frac{6.67}{2} = 3.34\ rps$

$W_1 = 380\ N$

$W_2 = 50\ N$

$D = 120\ cm$

$m_f = 2.8\ kg/h$

$CV = 42000\ kJ/kg$

$d = 16\ cm = 0.16\ m$

$l = 20\ cm = 0.2\ m$

☺ ***Solution:***

Indicated mean effective pressure,

$$p_m = \frac{AS}{L} = \frac{3 \times 10}{4} = 7.5 bar = 750\ kN/m^2$$

Brake drum radius, $R = \frac{D}{2} = \frac{120}{2} = 60\ cm = 0.6\ m$

Brake power, $BP = 2\pi N \times (W_1 - W_2) \times R = 2\pi \times 6.67 \times (380 - 50) \times 0.6$

$= 8927.52\ W = 8.93\ kW$

Area of piston, $a = \frac{\pi d^2}{4} = \frac{\pi}{4} \times 0.16^2 = 0.02 m^2$

Indicated power, $IP = p_m \cdot l \cdot a \cdot n \cdot k$

$= 750 \times 0.2 \times 0.02 \times 3.34 \times 1 = 10.02\ kW$

Frictional power, $FP = IP - BP = 10.02 - 8.93 = \mathbf{1.09\ kW}$ **Ans.**

Mechanical efficiency, $\eta_{mech} = \frac{BP}{IP} = \frac{8.93}{10.02} = 0.8912 = \mathbf{89.12\%}$ **Ans.**

Indicated thermal efficiency,

$$\eta_{IT} = \frac{IP \times 3600}{m_f \times CV} = \frac{10.02 \times 3600}{2.8 \times 42000} = 0.3067 = \mathbf{30.67\%}$$

Brake thermal efficiency,

$$\eta_{BT} = \frac{BP \times 3600}{m_f \times CV} = \frac{8.93 \times 3600}{2.8 \times 42000} = 0.2734 = \mathbf{27.34\%}$$

14. The following details were noted in a test on a four-cylinder, four stroke engine, diameter = 100 mm, stroke = 120 mm; speed of the engine =1600 rpm; fuel consumption = 0.2 kg/min; fuel calorific value = 44000 kilo joule/kg; difference in tension on either side of the brake pulley = 40 kgf; brake circumference is 300 cm. if the mechanical efficiency is 80%. Calculate the; (i) brake thermal efficiency (ii) indicated thermal efficiency (iii) indicated mean effective pressure (iv) brake specific fuel consumption. (May 2017)

Given data:

Number of cylinder, $k = 4$

Four stroke engine

Diameter, $d = 100\ mm = 0.1\ m$

Length, $l = 120\ mm = 0.12\ m$

$N = 1600\ rpm = 26.67\ rps$

$n = \frac{N}{2} = \frac{26.67}{2} = 13.34\ rps$

Mass of fuel, $m_f = 0.2\ kg/min = 0.0033\ kg/s$

$CV = 44{,}000\ kJ/kg$

Difference in tension = 40 kgf $\quad \therefore W = 40 \times 9.81 = 392.4\ N$

Circumference, $2\pi R = 300\ cm = 3\ m$

Mechanical efficiency, $\eta_{mech} = 80\%$

☺ ***Solution:***

Brake power, $BP = 2\pi\, NWR = NW(2\pi R)$

$$= 26.67 \times 392.4 \times 3 = 31395.92\ W = 31.4\ kW$$

Brake thermal efficiency, η_{BT}

$$\eta_{BT} = \frac{BP}{m_f \times CV} = \frac{31.4}{0.0033 \times 44000} = 0.2163 = \mathbf{21.63\%}$$

Mechanical efficiency,

$$\eta_{mech} = \frac{BP}{IP}$$

$$0.8 = \frac{31.4}{IP}$$

$$\therefore \quad IP = 39.25\ kW$$

Indicated thermal efficiency, η_{IT}

$$\eta_{IT} = \frac{IP}{m_f \times CV} = \frac{39.25}{0.0033 \times 44000} = 0.2703 = \mathbf{27.03\%}$$

Indicated power, $IP = p_m\, l\, a\, n\, k = p_m . l . \frac{\pi}{4} d^2 \frac{N}{2} k$

$$39.25 = p_m \times 0.12 \times \frac{\pi}{4} \times 0.1^2 \times 13.34 \times 4$$

$$p_m = \mathbf{780.46\ kPa = 7.81\ bar}$$

Brake *SFC* $= \frac{m_f}{BP} = \frac{0.2 \times 60}{31.4} = \mathbf{0.38\ kg/Wh}$

15. 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/h. the specific gravity of the oil is 0.82 and calorific value of oil is 42000 kilo joule/kg. if the IMEP taken from the indicated diagram is 6.7, find the (i) mechanical efficiency (ii) brake thermal efficiency (iii) brake mean effective pressure (iv) specific fuel consumption in litres on brake power basis. (Nov 2015)

Four stroke engine

$k = 4$

$d = 10\ cm = 0.1\ m$

$l = 15\ cm = 0.15\ m$

$T = 185\ Nm$

$N = 2000 rpm = 33.33\ rps$

$n = \frac{N}{2} = \frac{33.33}{2} = 16.67\ rps$

Volume of fuel consumption, $V_f = 14.5\ lit/h$

$SG = 0.82$

$CV = 42000\ kJ/kg$

$p_m = 6.7\ bar = 670\ kN/m^2$

☺ ***Solution:***

Area, $a = \frac{\pi d^2}{4} = \frac{\pi}{4} \times 0.1^2 = 0.0079 m^2$

Indicated power, $IP = p_m\ l\ a\ n\ k = 670 \times 0.15 \times 0.0079 \times 16.67 \times 4 = 52.94\ kW$

Brake power, $BP = \frac{2\pi NT}{60} = \frac{2\pi \times 2000 \times 185}{60} = 38746.31 W = 38.75\ kW$

Mechanical efficiency,

$$\eta_{mech} = \frac{BP}{IP} = \frac{38.75}{52.94} = \mathbf{73.2\%}$$ **Ans.**

Volume of fuel consumption,

$$V_f = 14.5\ lit/h = \frac{14.5}{1000 \times 3600} = 4.03 \times 10^{-6}\ m^3/s$$

Specific gravity, $SG = \frac{\text{Density of fuel}}{\text{Density of water}} = \frac{\rho_f}{\rho_{water}}$

∴ Density of fuel, $\rho_f = 0.82 \times 1000 = 820\ kg/m^3$ $\left[\because \rho_{Water} = 1000 kg/m^3\right]$

Density of fuel, $\rho_f = \frac{\text{Mass of fuel}}{\text{Volume of fuel}} = \frac{m_f}{V_f}$

∴ Mass of fuel, $m_f = 820 \times 4.03 \times 10^{-6} = 3.31 \times 10^{-3}\ kg/s$

Brake thermal efficiency,

$$\eta_{BT} = \frac{BP}{m_f \times CV} = \frac{38.75}{3.31 \times 10^{-3} \times 42000}$$

$$= 0.2787 = \mathbf{27.87\%}$$

Brake power, $BP = p_m \, l \, a \, n \, k$

$$38.75 = p_m \times 0.15 \times 0.0079 \times 20 \times 4$$

∴ Brake mean effective pressure,

$$p_m = 408.76 \; kPa = \mathbf{4.09 \; bar}$$

Specific fuel consumption on brake power,

$$BSFC = \frac{V_f}{BP} = \frac{14.5}{38.75} = \mathbf{0.37 \; lit/kWh}$$

16. A 2-cylinder CI engine with a compression ratio 13:1 and cylinder dimensions of 200 mm * 250 mm works on two stroke cycle and consumes 14 kg/h of fuel while running at 300 rpm. The relative and mechanical efficiencies of engine are 65% and 76% respectively. The fuel injection is effected up to 5% of stroke. If the calorific value of the fuel used is given as 41800 kilo joule/kg, calculate the mean effective pressure developed. (May 2018)

Given:

Number of cylinders k = 2

Compression ratio r = 13

Piston diameter, $D = 200\ mm = 0.2\ m$

Stroke length, $L= 250\ mm = 0.25\ m$

Fuel consumption, $m_f = 14\ kg/h$

Engine speed, $N = n = 300\ rpm$ (Two stroke)

Relative efficiency, $\eta_{rel} = 65\% = 0.65$

Mechanical efficiency, $\eta_{mech} = 76\% = 0.76$

Cut-off = 5% of stroke

Calorific value, $CV = 41800\ kJ/kg$

☺ ***Solution:***

Stroke volume, $$V_S = \frac{\pi D^2}{4} \times L = \frac{\pi \times 0.2^2}{4} \times 0.25 = 7.854 \times 10^{-3}\ m^3$$

Compression ratio, $$r = \frac{V_C + V_S}{V_C}$$

$$13 = \frac{V_C + 7.854 \times 10^{-3}}{V_C}$$

Clearance volume, $$V_c = 6.545 \times 10^{-4}\ m^3$$

Cut-off ratio, $$\rho = \frac{V_2 + (V_3 - V_2)}{V_2}$$

$$= \frac{V_C + 0.05 V_S}{V_C}$$

$$= \frac{6.545 \times 10^{-4} + 0.05 \times 7.854 \times 10^{-3}}{6.545 \times 10^{-4}} = 1.6$$

Air standard efficiency, $$\eta_{air} = 1 - \frac{1}{\gamma (r)^{r-1}} \left[\frac{\rho^{\gamma} - 1}{\rho - 1} \right]$$

$$= 1 - \frac{1}{1.4 \times 13^{1.4-1}} \left[\frac{1.6^{1.4} - 1}{1.6 - 1} \right] = 0.6028$$

Relative efficiency, $$\eta_{rel} = \frac{\eta_{IT}}{\eta_{air}}$$

$$0.65 = \frac{\eta_{IT}}{0.6028}$$

∴ Indicated thermal efficiency, $\eta_{IT} = 0.3918$

Indicated thermal efficiency,

$$\eta_{IT} = \frac{IP}{m_f \times CV}$$

$$0.3918 = \frac{IP}{\frac{14}{3600} \times 41800}$$

$$\therefore \quad IP = 63.69\ kW$$

Area of the piston, $A = \frac{\pi D^2}{4} = \frac{\pi \times 0.2^2}{4} = 0.0314\ m^3$

Indicated power, $IP = \frac{p_{IP\,m} LAn}{60}$

$$63.69 = \frac{p_{IP\,m} \times 0.25 \times 0.0314 \times 300 \times 2}{60}$$

$\therefore \quad p_{mIP} = 811337.58\ Pa = \mathbf{811.34\ kPa}$ **Ans.**

Mean effective pressure can also be calculated on the basis of brake power.

We know that mechanical efficiency,

$$\eta_{mech} = \frac{BP}{IP}$$

$$0.76 = \frac{BP}{63.69}$$

$$\therefore \quad BP = 48.4\ kW$$

Brake power, $BP = \frac{p_{BP\,m} LAn}{60}$

$$48.4 = \frac{p_{BP\,m} \times 0.25 \times 0.0314 \times 300 \times 2}{60}$$

$p_{mBP} = 616560.51\ Pa = \mathbf{616.56\ kPa}$ **Ans.**

17. At test on a single cylinder 4 stroke oil engine having bore of 180 mm and stroke of 360 mm gave the following results. Speed = 290 rpm, brake torque = 392 Nm, IMEP = 7.2 bar, oil consumption = 3.5 kg/h, coolant flow = 270 kg/h, cooling water temperature rise = 36°C, air-fuel ratio by weight = 25, exhaust gas temperature = 415 °C, room temperature = 21 °C. the fuel has a calorific value 45200 kilo joule/kg. take the specific heat of the exhaust gases as 1.005 kilo joule/kg K. Calculate the: (i)

indicated thermal efficiency and (ii) draw up a heat balance sheet in kilo joule/min basis.

Given data:

Four stroke engine, $k = 1$

Bore, $D = 180\ mm = 0.18\ mm$

Stroke, $L = 360\ mm = 0.36\ mm$

Speed, $N = 290\ rpm = 4.83\ rps$

$n = \frac{N}{2} = \frac{4.83}{2} = 2.42\ rps$

Brake torque, $T = 392\ N\text{-}m$

IMEP, $p_m = 7.2\ bar = 720\ kN/m^2$

Oil consumption, $m_f = 3.5\ kg/h = \frac{3.5}{60} = 0.058\ kg/min$

Coolant flow, $m_w = 270\ kg/h = \frac{270}{60} = 4.5\ kg/min$

Cooling water temperature rise $= 36°\ C$

Air-fuel ratio by weight, $\frac{m_a}{m_f} = 25$

Exhaust gas temperature $= 415°\ C$

Room temperature $= 21°\ C$

Calorific value, $CV = 45200\ kJ/kg$

$C_g = 1.005\ kJ/kgK$

Solution:

Indicated power, $IP = \frac{p_m.l.a.n.k}{60}$

$$= 720 \times 0.36 \times \frac{\pi}{4} \times (0.18)^2 \times 4.83 \times 1 \quad \left[\because n = \frac{N}{2}\right]$$

$$= 31.86\ kW$$

Indicated thermal efficiency, $\eta_{IT} = \frac{IP \times 3600}{m_f \times CV} = \frac{31.86 \times 3600}{3.5 \times 45200}$

$$= 0.725 = 72.5\% \quad \textbf{Ans.}$$

Air-fuel ratio by weight, $\frac{m_a}{m_f} = 25$

$\therefore$ $m_a = 25 \times m_f = 25 \times 0.058 = 1.46\ kg/min$

(i) Heat supplied by the fuel (Q_S):

$$Q_S = m_f \times CV = 0.058 \times 45200 = 2621.6 \ kJ/min$$

(ii) Heat absorbed in BP produced (Q_{IP}):

Brake power, $BP = 2\pi NT = 2 \times \pi \times 290 \times 392$

$$= 714272.51 \ J/min = 714.27 \ kJ/min$$

% heat loss in BP $= \frac{\text{Heat loss}}{Q_S} \times 100 = \frac{714.27}{2621.6} \times 100 = 27.35\%$

(iii) Heat rejected to the cooling water (Q_w):

$$Q_w = m_w C_w (T_2 - T_1) = 4.5 \times 4.2 \times 36 = 680.4 \ kJ/min$$

% heat loss in cooling water $= \frac{\text{Heat loss}}{Q_S} \times 100 = \frac{680.4}{2621.6} \times 100 = 25.95\%$

(iv) Heat carried away by exhaust gas (Q_g):

$$Q_g = m_g C_g (T_g - T_a)$$

$$= 1.458 \times 1.005 \times (415 - 21) \qquad [\because m_g = m_a]$$

$$= 577.32 \ kJ/min$$

% heat loss in exhaust gas $= \frac{\text{Heat loss}}{Q_S} \times 100 = \frac{577.32}{2621.6} \times 100 = 22.00\%$

(v) Unaccounted heat losses (Q_{ua}):

$$Q_{ua} = Q_S - [Q_{BP} + Q_w + Q_g + \dots]$$

$$= 2621.6 - [714.27 + 680.4 + 577.32] = 649.61 \ kJ/min$$

% Unaccounted heat loss $= \frac{\text{Heat loss}}{Q_S} \times 100 = \frac{649.61}{2621.6} \times 100 = 24.7\%$

Heat balance sheet

Credits	*kJ/min*	*%*	*Debits*	*kJ/min*	*%*
Heat supplied by the fuel (Q_S).	2621.6	100	1. Heat equivalent to BP.	714.27	27.35
			2. Heat carried away by cooling water (Q_w).	680.4	25.95

			3. Heat carried away by exhaust gas (Q_g).	577.32	22.00
			4. Unaccounted heat loss (Q_{ua}).	649.61	24.7
	2621.6	**100**	***Total***	**2636.67**	**100**

ME 8493 – THERMAL ENGINEERING – 1

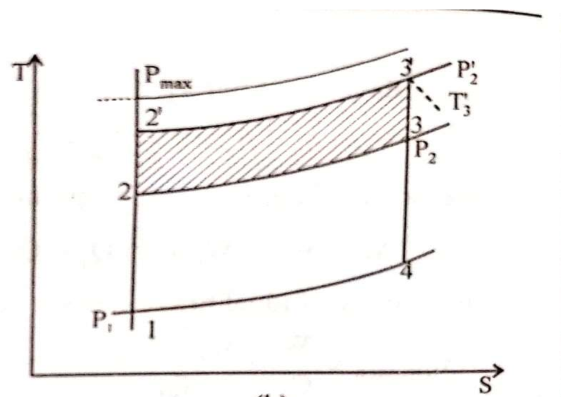
QUESTION BANK

UNIT – 5

GAS TURBINES

PART – A

1. **How are gas turbine classified? (Nov/Dec 2019)**
   i. According to the cycle of operation
      - ✓ Open cycle gas turbine
      - ✓ Closed cycle gas turbine
      - ✓ Semi closed cycle gas turbine
   ii. According to the process
      - ✓ Constant pressure gas turbine
      - ✓ Constant volume gas turbine
   iii. According to the use
      - ✓ Industrial gas turbine
      - ✓ Air craft gas turbine
   iv. According to the application
      - ✓ Marine
      - ✓ Transport
      - ✓ Aircraft
2. **What fuel does a gas turbine use? (April/May 2019)**
   One further advantage of gas turbines is their fuel flexibility. They can be adapted to use almost any flammable gas or light distillate petroleum products such as gasoline (petrol), diesel and kerosene (paraffin) which happen to be available locally, though natural gas is the most commonly used fuel. Crude and other heavy oils and can also be used to fuel gas turbines if they are first heated to reduce their viscosity to a level suitable for burning in the turbine combustion chambers.
3. **Depict the influence of pressure ratio on the efficiency of a Brayton cycle?(Nov/Dec 2019)**
   After the isentropic compression the pressure increase from P_2 to P_2' a shown in fig. the heat supplied Q_1 and net work down W increases by an amount equal to the area $2\text{-}2'\text{-}3'\text{-}3\text{-}2$ whereas the heat rejection Q_2 remains unchanged. Hence, the thermal efficiency of the cycle increases with increase in pressure ratio.



(b)

4. **What is the effect of reheat on the Brayton cycle efficiency? And why? (Apr/May 2019)**
   A reheater is a heat exchanger that increase the power output without increasing the maximum operating temperature but it does not increase the efficiency of the cycle.
5. **What is a gas turbine?**
   A gas turbine is a rotary machine that convers the thermal energy of gas into mechanical work.
6. **List the major components of gas turbine.**
   - ✓ Compressor
   - ✓ Combustion chamber
   - ✓ Turbine
7. **What are the classification of gas turbine?**
   - ✓ Open cycle gas turbine
   - ✓ Closed cycle gas turbine
8. **Define back work ratio.**
   It is defined as the ratio of the compressor work to the turbine work.

$$BWR = \frac{Compressor\ work}{Turbine\ work} = \frac{W_C}{W_T} = \frac{T_2 - T_1}{T_3 - T_4}$$

9. **Define work ratio.**
   It is defined as the ratio of the net work output to the turbine work.

$$WR = \frac{Network\ output}{Turbine\ work} = \frac{W_{net}}{W_T}$$

10. **List the factors which affects the performance of gas turbine.**
    - ✓ Thermal efficiency
    - ✓ Regeneration
    - ✓ Fuel consumption
11. **What are the working fluids used in gas turbine?**
    - ✓ Air
    - ✓ Helium
    - ✓ Carbon dioxide

12. State the difference between open and closed cycle gas turbine.

Open cycle gas turbine	Closed cycle gas turbine
✓ The exhaust gas from turbine is exhausted to atmosphere and fresh air is taken into the compressor for every cycle	✓ The same working fluid is recirculated again and again
✓ Inter cooler is not required	✓ Intercooler is required to cool the exhaust gas to the original temperature
✓ High quality fuels are used	✓ Low quality fuels are used
✓ Low maintenance cost	✓ High maintenance cost

13. How can we increase the efficiency of the gas turbine?

The efficiency of the gas turbine can be increases by providing intercooler, reheater along with heat exchangers.

14. What is function of intercooler and where it is placed in gas turbine?

The intercooler is placed between L.P and H.P compressor. It is used to cool the air coming out from the L.P compressor to its original temperature.

15. What is the function of regenerator in gas turbine?

The function of regenerator is to exchange the heat from the exhaust gas to the compressed air for preheating before sending it to the combustion chamber. It increases fuel economy and thermal efficiency.

16. Why reheat is necessary in gas turbines?

The reheater is necessary to increase the enthalpy of the exhaust gas coming from high pressure turbine. The reheater is placed between the H.P and L.P.

17. State the advantages of gas turbine over IC engine.

- ✓ Mechanical efficiency is high
- ✓ Weight per unit power is low
- ✓ It can be operated at very high speed
- ✓ It can be operated at high altitudes
- ✓ Less pollution
- ✓ It operates at very low pressure

18. State the disadvantages of gas turbine over IC engines.

- ✓ Thermal efficiency is low
- ✓ Poor part load efficiency
- ✓ It is very difficult to start

19. List out any four applications of gas turbine.

It is used for electric power generation

It is used in aircrafts

It is used for supercharging for heavy duty diesel engines

It is used for locomotive propulsion and ship propulsion

20. Define compressor and turbine efficiency.

Compressor efficiency is defined as the ratio of isentropic increase in temperature to the actual increase in temperature.

$$\eta_C = \frac{(\Delta T)_{isentropic}}{(\Delta T)_{actual}} = \frac{T_{2s} - T_{1}}{T_2 - T_1}$$

Turbine efficiency is defined as the ratio of actual decrease in temperature to the isentropic decrease in temperature.

$$\eta_T = \frac{(\Delta T)_{actual}}{(\Delta T)_{isentropic}} = \frac{T_3 - T_4}{T_3 - T_{4s}}$$

21. On which cycle the gas turbine operates.

The gas turbine operates on Brayton cycle

22. Name the various process involved in Brayton cycle.

- ✓ 1-2 isentropic compression
- ✓ 2-3 constant pressure heat addition
- ✓ 3-4 isentropic expansion
- ✓ 4-1 constant pressure heat rejection

Part – B

1. **In a closed gas turbine there is a two stage compressor and a two stage turbine. All the components are mounted on the same shaft. The pressure and temperature at the inlet of the first stage compressor are 1.5 bar and 20°C. The maximum cycle temperature and pressure are limited to 750 °C and 6 bar. A perfect intercooler is used between the two stage compressors and a reheater is used between the two turbines at 3 bar pressure. Gases are heated in the reheater to 750 °C before entering into the L.P turbine. Assuming the compressor and turbine efficiencies as 0.82. calculate,**
   i. **The efficiency of the cycle without regenerator**
   ii. **The efficiency of the cycle with a regenerator whose effectiveness is 0.70. The working fluid used in the cycle is air: for air: specific heat ratio = 1.4 and C_p=1.005 Kilo/Joule/kg K (April/May 2019)**

Given:

$T_1 = 20 + 273 = 293\,K$

$T_5 = T_7 = 750 + 273 = 1023\,K$

$P_1 = 1.5\,bar$

$P_2 = 6\,bar$

$\eta_{compressor} = \eta_{Turbine} = 0.82$

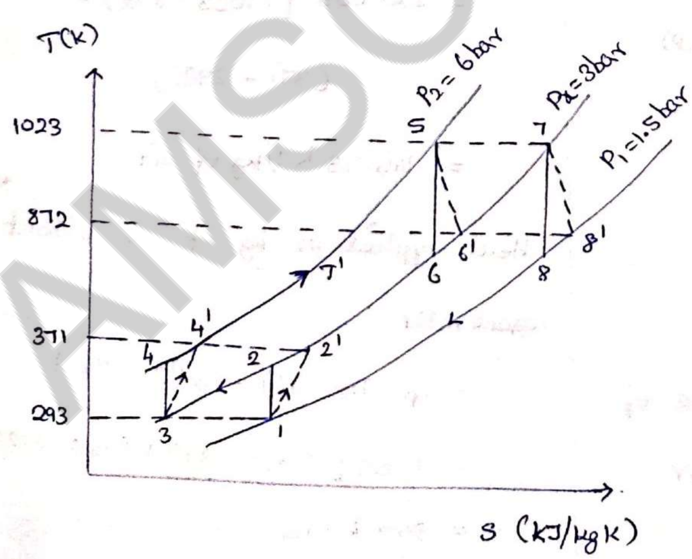
Effectiveness of regenerator $\varepsilon = 0.70$

Power Developed $P = 350\,kW$

For air $C_p = 1.005\,kJ/kg\,K$

$\gamma = 1.4$

Solution:



As per given conditions

$T_1 = T_3\,,\ T_2' = T_4'$

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma}$$

$P_x = \sqrt{P_1 P_2} = \sqrt{1.5 \times 6}$

$= 3\,bar$

Now $T_2 = T_1 \times \left[\frac{P_2}{T_1}\right]^{\gamma-1/\gamma}$

$= 293 \times \left[\frac{3}{1.5}\right]^{0.4/1.4}$

$= 357\,K.$

$$\eta_{compressor\,(I.P)} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.82 = \frac{357 - 293}{T_2' - 293}$$

$T_2' = 371\,K.$

$T_2' = T_4' = 371\,K$

Now $\frac{T_5}{T_6} = \left[\frac{P_5}{P_6}\right]^{\gamma-1/\gamma} = \left[\frac{P_2}{P_x}\right]^{1.4-1/1.4}$

$\left\{ \begin{array}{l} P_5 = P_2 \\ P_6 = P_x \end{array} \right\}$

$\Rightarrow \frac{1023}{T_6} = \left[\frac{6}{3}\right]^{0.286}$

$T_6 = 839\,K.$

$\eta_{Turbine\,(H.P)} = \frac{T_5 - T_6'}{T_5 - T_6}$

$0.82 = \frac{1023 - T_6'}{1023 - 839}$

$T_6' = 1023 - 0.82(1023 - 839)$

$= 872\,K$

$T_8' = T_6' = 872\,K$ as $\eta_{Turbine(HP)} = \eta_{Turbine\,(LP)}$

$T_7 = T_5 = 1023\,K.$

Effectiveness of regenerator

$\varepsilon = \frac{T' - T_4'}{T_8' - T_4'}$

where T' is the temperature of air coming out of regenerator

$0.70 = \frac{T' - 371}{872 - 371}$

$T' = 722\,K$

Network available

$W_{net} = [W_{T(HP)} + W_{T(LP)}] - W_C[HP] + W_C[L.P]]$

$= 2[W_{T(LP)} - W_{C\,(LP)}]$ as the work developed by each turbine is same and work absorbed by each compressor is same.

$W_{net} = 2C_p[(T_5 - T_6') - (T_2' - T_1)]$

$= 2 \times 1.005\,[(1023 - 872) - (371 - 293)]$

$= 146.73\,kJ/kg$ of air

Heat supplied per kg of air without regenerator

$= C_p(T_5 - T_4') + C_p(T_7 - T_6')$

$= 1.005\,[(1023 - 371) + (1023 - 872)]$

$= 807\,kJ/kg$ of air

Heat supplied per kg of air with regenerator

$$= C_p [T_5 - T_1'] + C_p [T_7 - T_6']$$

$$= 1.005 [(1023 - 722) + (1023 - 872)]$$

$$= 454.3 \text{ kJ/kg}$$

$\eta_{Thermal}$ (without regenerator)

$$= \frac{146.73}{807}$$

$$= 0.182 \text{ (or) } 18.2\%$$

$\eta_{Thermal}$ (with regenerator)

$$= \frac{146.73}{454.3}$$

$$= 0.323 \text{ (or) } 32.3\%$$

2. In a gas turbine the compressor takes in air at a temperature of 15°C and compresses it to four times the initial pressure with an isentropic efficiency of 82%. The air is then passed through a heat exchanger heated by the turbine exhaust before reaching the combustion chamber. In the heat exchanger 78% of the available heat is given to the air. The maximum temperature after constant pressure combustion is 600°C, and the efficiency of the turbine is 70%. Neglecting all losses except expect those mentioned, and assuming the working fluid throughout the cycle to have the characteristics of air find the efficiency of the cycle. Assume R = 0.287 kilo joule/kg K and gamma = 1.4 for air and constant specific heats throughout. (Nov/Dec 2019)

Given:

$T_1 = 15 + 273 = 288\,K$

Pressure ratio

$$\frac{P_2}{P_1} = \frac{P_3}{P_4} = 4$$

$\eta_{compressor} = 82\%$

Effectiveness of the heat exchanger } $\epsilon = 0.78$

$\eta_{Turbine} = 70\%$.

Maximum temp $T_3 = 600 + 273$

$= 873\,K$.

Solution:

Considering the isentropic compression 1-2, we have

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma} = (4)^{0.4/1.4}$$

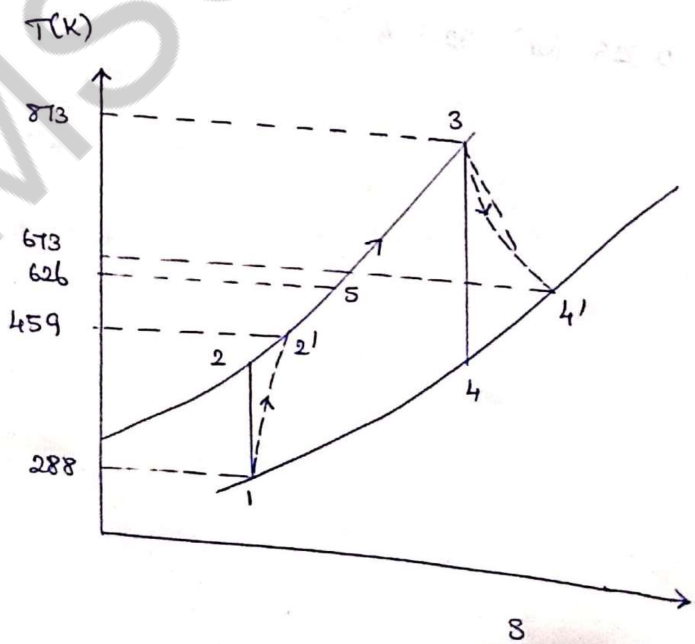
$T_2 = 1.486 \times T_1 = 1.486 \times 288$

$T_2 = 428\,K$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.82 = \frac{428 - 288}{T_2' - 288}$$

$T_2' = 459\,K$



Considering the isentropic expansion process 3-4. we have

$$\frac{T_3}{T_4} = \left[\frac{P_3}{P_4}\right]^{\gamma-1/\gamma} = (4)^{0.4/1.4} = 1.486$$

$$T_4 = \frac{T_3}{1.486} = \frac{873}{1.486}$$

$$= 587.5 \text{ K}$$

$$\eta_{Turbine} = \frac{T_3 - T_4'}{T_3 - T_4} = \frac{873 - T_4'}{873 - 587.5}$$

$$0.70 = \frac{873 - T_4'}{873 - 587.5}$$

$$T_4' = 673 \text{ K.}$$

$$W_{compressor} = C_p [T_2' - T_1]$$

But $C_p = R \times \frac{\gamma}{\gamma - 1} = 0.287 \times \frac{1.4}{0.4}$

$$= 1.0045 \text{ kJ/kg K}$$

$$W_{comp} = 1.0045 (459 - 288)$$

$$= 171.7 \text{ kJ/kg}$$

$$W_{Turbine} = C_p (T_3 - T_4')$$

$$= 1.0045 (873 - 673)$$

$$= 200.9 \text{ kJ/kg}$$

Network = $W_{Turbine} - W_{compressor}$

$$= 200.9 - 171.9 = 29.2 \text{ kJ/kg}.$$

Effectiveness of heat exchanger

$$\epsilon = \frac{T_5 - T_2'}{T_4' - T_2'}$$

$$\Rightarrow 0.78 = \frac{T_5 - 459}{673 - 459}$$

$$T_5 = (673 - 459) \times 0.78 + 459$$

$$= 626 \text{ K}$$

Heat supplied by fuel per kg

$$= C_p [T_3 - T_5] = 1.0045 [873 - 626]$$

$$= 248.1 \text{ kJ/kg}$$

$$\eta_{cycle} = \frac{\text{Network done}}{\text{Heat supplied by fuel}}$$

$$= \frac{29.2}{248.1}$$

$$= 0.117 \text{ (or) } 11.7\%$$

3. **The pressure ratio of an open-cycle gas turbine power plant is 5.6. Air is taken at 30°C and 1 bar. The compression is carried out in two stages with perfect intercooling. The maximum temperature of the cycle is limited to 700°C. Assuming the isentropic efficiency of each compressor stage as 85% and that of turbine as 90%, determine the power developed and efficiency of the power plant, if the air flow is 1.2 kg/s. Assume C_p= 1.005 kilo joule/kg K and gamma = 1.4 (Nov/Dec 2019)**

Given:

Pressure ratio of the open cycle gas turbine = 5.6

Temp of intake air $T_1 = 30 + 273$

$= 303K$

Pressure of intake air $P_1 = 1$ bar

Max. temp of the cycle $T_5 = 700 + 273$

$= 973K$

Isentropic efficiency of each compressor $= \eta_{comp} = 85\%$

Isentropic efficiency of turbine

$\eta_{turbine} = 90\%$.

Rate of air-flow $\dot{m}_a = 1.2$ kg/s.

$c_p = 1.02$ kJ/kgK and $\gamma = 1.41$.

Solution:

Assuming that the pressure ratio in each stage is same, we have

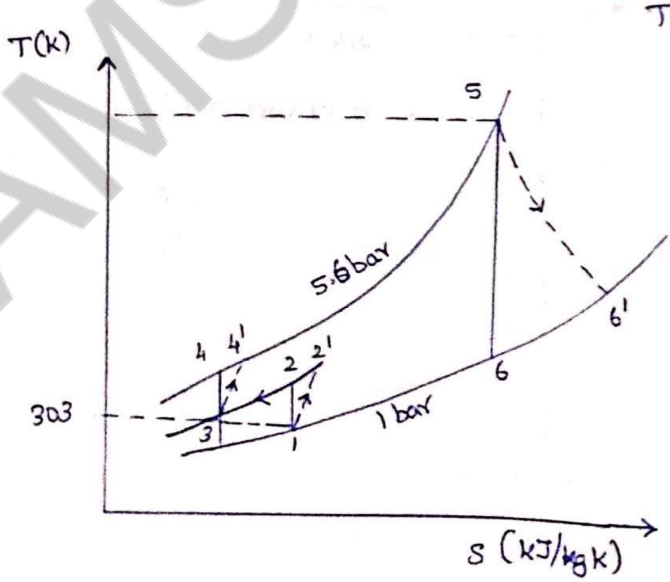
$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \sqrt{\frac{P_4}{P_1}} = \sqrt{5.6} = 2.366$$

Since, the pressure ratio and the isentropic efficiency of each compressor the same then the work input required for each compressor is the same since both the compressors have the same inlet temp (perfect intercooling) $T_1 = T_3$ and $T_2' = T_4'$

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma} = (2.366)^{\frac{1.4-1}{1.4}} = 1.2846$$

$T_2 = 1.2846 \times 303$

$T_2 = 389.23$ K



$$\eta_{comp} = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow$$

$$0.85 = \frac{389.23 - 303}{T_2' - 303}$$

$$T_2' = 404.44\ K$$

Work input to 2-stage compressor

$$W_{comp} = 2 \times m \times C_p [T_2' - T_1]$$

$$= 2 \times 1.2 \times 1.02 [404.44 - 303]$$

$$= 248.32\ kJ/s$$

For turbine we have.

$$\frac{T_5}{T_6} = \left[\frac{P_5}{P_6}\right]^{\gamma - 1/\gamma}$$

$$= [5.6]^{0.4/1.4} = 1.65$$

$$T_6 = \frac{T_5}{1.65} = \frac{973}{1.65} = 589.7\ K.$$

$$\eta_{Turbine} = \frac{T_5 - T_6'}{T_5 - T_6}$$

$$0.9 = \frac{973 - T_6'}{973 - 589.7}$$

$$T_6' = 628\ K$$

Work output of turbine

$$W_T = m \times C_p (T_5 - T_6')$$

$$= 1.2 \times 1.02 (973 - 628)$$

$$= 422.28\ kJ/s$$

Network output $W_{net} = W_T - W_C$

$$= 422.8 - 248.32$$

$$= 173.96\ kJ/s \text{ or } kW$$

Hence power developed = 173.96 kW

Heat supplied

$$Q_s = m\ C_p (T_5 - T_4')$$

$$= 1.2 \times 1.02 [973 - 404.44]$$

$$= 695.92\ kJ/s$$

Power plant efficiency

$$\eta_{th} = \frac{W_{net}}{Q_s} = \frac{173.96}{695.92}$$

$$= 0.25 \text{ (or) } 25\%.$$

4. **Show that the optimum pressure ratio for maximum is equal to the square root of the maximum pressure ratio for the given minimum and maximum temperatures. (Apr/May 2019)**

T_1 = Minimum temperature at inlet of a compressor in the Brayton cycle. $= T_{min}$

T_3 = Maximum temperature at inlet of a turbine in the Brayton cycle $T_3 = T_{max}$.

Process 2-3 : Heat supplied at $P = C$

$$Q_{2-3} = m C_p (T_3 - T_2)$$

For unit mass flow rate

$$Q_{2-3} = C_p (T_3 - T_2)$$

Process 4-1 : Heat rejected at $p = C$

$$Q_{4-1} = m C_p (T_4 - T_1)$$

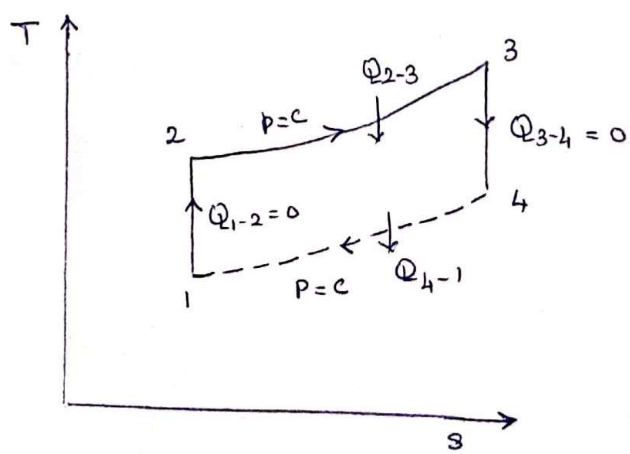
For unit mass flow rate

$$Q_{4-1} = C_p (T_4 - T_1)$$

Net work output W.D = Heat supplied - Heat rejected

$$= Q_{2-3} - Q_{4-1} = C_p (T_3 - T_2) - C_p (T_4 - T_1)$$

$$W.D = C_p [T_3 - T_2 - T_4 + T_1] \longrightarrow (1)$$



Process 1-2:

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

where $r_p = \frac{P_2}{P_1}$, pressure ratio

$$z = \gamma-1/\gamma \Rightarrow \frac{T_2}{T_1} = r_p^{z}$$

$$T_2 = T_1 r_p^{z}$$

Process 3-4:

$$\frac{T_3}{T_4} = \left[\frac{P_2}{P_1}\right]^{\gamma-1/\gamma} = (r_p)^{z}$$

$$T_4 = \frac{T_3}{r_p^{z}} \Rightarrow T_4 = T_3 r_p^{-z}$$

Substituting the values of $T_2 = T_1 r_p^{z}$ and $T_4 = T_3 r_p^{-z}$ in equ ①

$$W.D = c_p (T_3 - T_1 r_p^{z} - T_3 r_p^{-z} + T) \rightarrow ②$$

For given values of T_1 and T_3, equation ② can be optimized.

Thus for maximum work output

$$\frac{dW.D}{dr_p} = 0$$

$$\frac{d}{dr_p}\left[c_p (T_3 - T_1 r_p^{z} - T_3 r_p^{-z} + T_1)\right] = 0$$

$$c_p (0 - T_1 z r_p^{1} - T_3 (-z) r_p^{-z-1} + 0) = 0$$

$$-T_1 z r_p^{z-1} + z T_3 r_p^{-z-1} = 0$$

$$T_3\, r_p^{-z-1} = T_1\, r_p^{z-1}$$

$$\frac{T_3}{T_1} = \frac{r_p^{z-1}}{r_p^{-z-1}} = r_p^{z-1+z+1} = r_p^{2z}$$

$$\frac{T_3}{T_1} = (r_p)^{2(\gamma-1)/\gamma}$$

The maximum work output condition for ideal cycle

$$\frac{T_{max}}{T_{min}} = \frac{T_3}{T_1} = (r_p)^{2(\gamma-1)/\gamma}.$$

5. **Explain with neat sketch – the gas turbine plant and its components.**

A gas turbine unit consist of the following essential parts.

(i) Compressor:

The air compressor used in gas turbine is of a rotary type mainly axial flow turbines. It draws air from the atmosphere and compressed to the required pressure. This compressed air is then transferred to the combustion chamber.

(ii) Combustion chamber:

The compressed air from the air compressor is drawn to combustion chamber. The fuel is injected to the air it is then ignited in the combustion chamber. It instantaneously increase both pressure and temperature of the air.

Constructional details of combustion chamber:

The combustion chamber of gas turbine should secure a steady and stable flame inside it because it has to function under various operating conditions. Four steps in the combustion process are as follows.

a) Formulation of reactive mixture

b) Ignition

c) Flame propagation

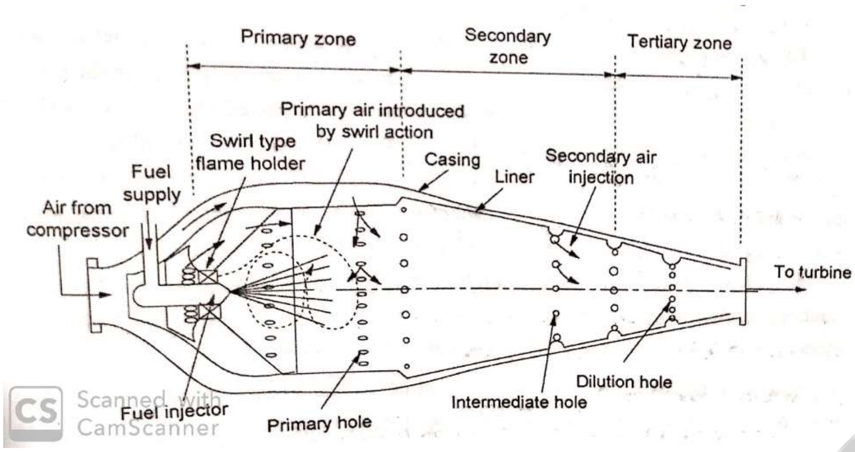
d) Cooling of combustion product with air.

i) Case:

It is an outer shell which covers the whole combustion chamber. It needs a periodic maintenance. The chamber is protected by thermal loads. It acts as a pressure vessel to withstand high pressure inside the chamber and low pressure outside.

ii) Diffuser:

The function of a diffuser is to reduce high pressure and high speed of air n the combustion chamber. So, the velocity gets reduced. The reduced velocity minimizes unavoidable losses in the total pressure of fuel. At the same time, the diffuser design should limit the flow distortion. It helps to avoid the boundary layer separation of fuel particles.



(iii) Liner:

The liner allows the airflow to initiate the combustion process in the combustion zone. The design of liner should withstand high temperature produced during combustion process. Mainly, super alloys are used to make liner.

(iv)Snout

The snout is an extension of the dome which acts as an air splitter to separate the primary air flow from the secondary air flow.

(v) Dome and swirler:

They are the parts of the combustion chamber in which the primary air first enters the combustion chamber without creating any turbulence. The swirl acts as a local low pressure zone which forces some of the combustion products to recirculate for creating high turbulence. It results the high pressure loss in the combustion chamber. So, these are designed to minimize the pressure loss.

(vi) Fuel injector:

It injects the fuel to introduce the fuel in the combustion zone along the swirl to mix the air and fuel.

Working of combustion chamber:

The primary zone handles almost 15 to 20 % of the total air around the jet of fuel to provide rich mixture for better combustion. This mixture is continuously burnt in the primary zone. It produces high temperature gases. The primary air is passed through the swirler to produce a vortex motion which creates a low-pressure zone along the axis of the chamber. This vortex motion will cause the reversal of flow. Almost 30% of the total air is supplied in the secondary zone around the flame to obtain the complete combustion. If the secondary air is not admitted at the right point in the combustion chamber, the cold injected air may chill the flame. It will reduce the rate of reaction. The secondary air is used for completing the combustion process and cooling the flame tube. The remaining 50 % air is mixed with burnt gases in the "tertiary zone" to cool the gases down to the temperature.

Sufficient turbulence and uniform mixing of hot and cold bases are needed in all three zones of combustion to give uniform temperature gas stream at the outlet of the combustion chamber.

3. Turbine:

The air with high pressure and temperature is expanded in the turbine. Turbine is also of a rotary type. During expansion, the heat energy in the gas is converted into mechanical energy. This mechanical energy is again converted into electrical energy by using a generator.

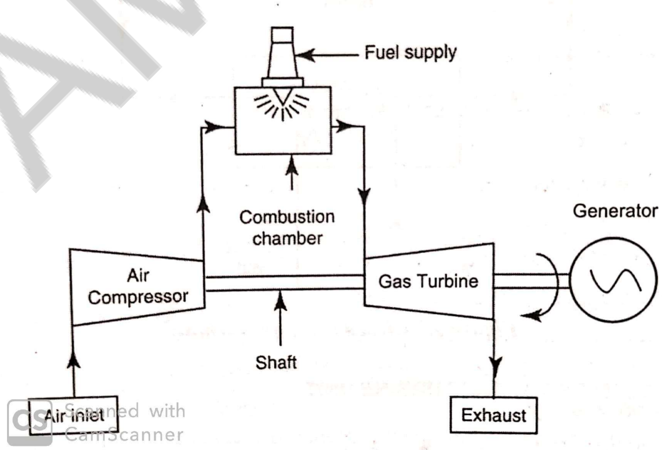
6. **Explain the various types of gas turbine plant.**

Types of gas turbine plants:

- ✓ Open cycle gas turbine
- ✓ Closed cycle gas turbine
- ✓ Semi-closed gas turbine

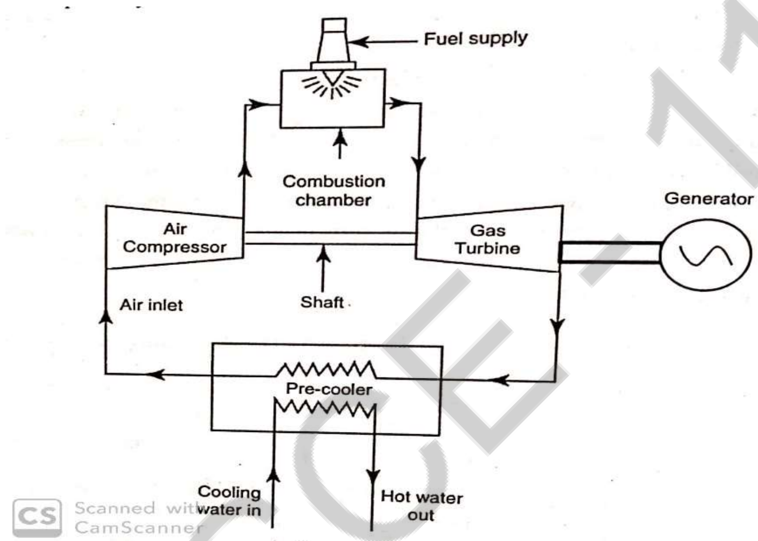
WORKING OF OPEN CYCLE GAS TURBINE UNIT

The most basic gas turbine unit is one operating on the basis of open cycle in which a rotary compressor and turbine are mounted on a common shaft shown in Figure. Air is drawn from the atmosphere into the compressor and it is compressed to a pressure of 300 to 400 kN/m. The compressed air is then entered into the combustion chamber where the energy is supplied by spraying the fuel into the air and it is ignited to produce hot gases. The hot gases expand through the turbine to produce the mechanical power. Then, the burnt gases are exhausted to the atmosphere. After that, the fresh air is drawn into the compressor for the next cycle. The process is repeated again and again. Here, the compressor is driven by a turbine itself. In order to achieve the net work output from the unit, the turbine must develop more gross work output than required work to drive the compressor and it overcomes mechanical losses in the drive.



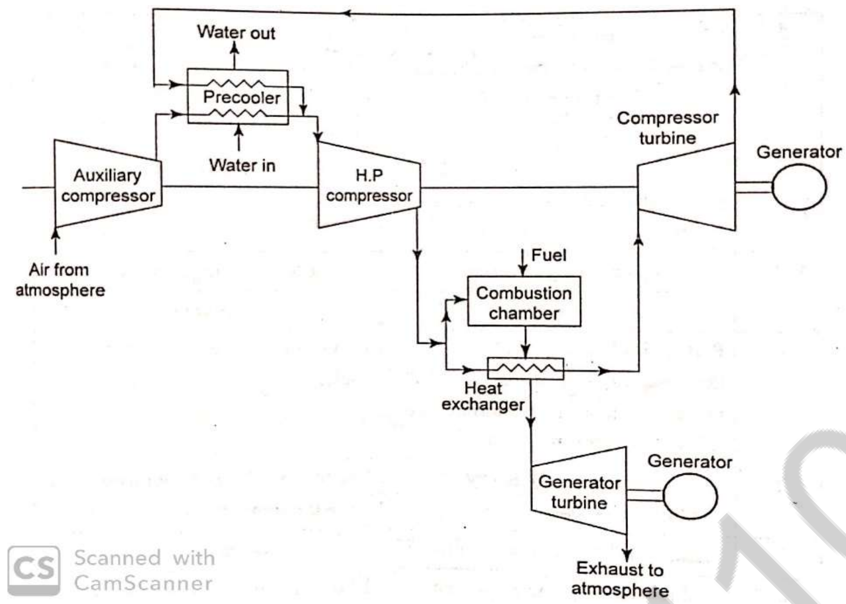
WORKING OF CLOSED CYCLE GAS TURBINE UNIT

It consists of a compressor, combustion chamber, gas turbine and pre-cooler. The schematic diagram of a closed cycle gas turbine plant is shown in Figure. In a closed cycle gas turbine, the air is isentropically compressed in air compressor to a required pressure and then it is passed through a combustion chamber where the fuel injects to the air and ignited. The high temperature air from combustion chamber expands through a gas turbine where the heat energy is converted into mechanical energy. Then, the exhaust gas from the gas turbine is passed through a pre-cooler where it is cooled at constant pressure with the help of circulating water to its original pressure. Then, the same air is passed through the compressor again and again. Therefore, in a closed cycle gas turbine, the same air is continuously and repeatedly circulated throughout the system.



SEMI-CLOSED CYCLE GAS TURBINE UNIT

A semi-closed cycle gas turbine plant combines the advantages of open cycle plant such as quick and ease of starting and closed cycle plant such as constant efficiency at all loads. A higher unit rating permits the use of more back pressure. In this semi-closed cycle gas turbine plant, the part of compressed gas is preheated by exhaust gases of combustion chamber and it is expanded in a gas turbine. The gas turbine drives the compressor. Therefore, it is operated in a closed cycle. The remaining air is used in the combustion chamber to burn the fuel. The combustion products after heating the air expand in a gas turbine to drive the generator before exhausting it to the atmosphere.



7. Compare – open cycle and closed cycle gas turbine plant.

Open cycle gas turbine	Closed cycle gas turbine
Advantages	**Disadvantages**
No pre-cooler is required because of burnt gas from gas turbine exhausted to atmosphere	A separate pre-cooler arrangement is necessary
For the same power developed, the size of and weight of the open cycle gas turbine unit are less	The size and weight are more
Initial cost and maintenance cost of the plant are less	Initial cost and maintenance cost are more
Combustion efficiency is more	Combustion efficiency is less
Coolant is not required .therefore, it is used for moving the vehicles such as aircraft, jet propulsion	Coolant is required for precooler. Therefore, it is used for stationary applications such as power generation, etc.
The response to load variation is greater than the closed cycle gas turbine	The response to load variation is less
Disadvantages	**Advantages**
Part load efficiency rapidly decreases for the considerable % of power developed by the turbine and it is used to drive the compressor	Efficiency is same throughout the cycle
Turbine blades are fouled by combustion products	The turbine blades do not wear away since the combustion is external
Starting of the plant is difficult	Starting of the plant is easy
As direct heating is used in open cycle plant, high quality fuels are required	Low quality fuels can be used since the combustion is external
Thermal stresses are high	Thermal stresses are low

Frequent internal cleaning of the system is necessary	It does not need for internal cleaning

8. Compare the gas turbine plant with IC engine plant.

Gas turbine power unit	IC engine (Diesel) power plant
It is an external combustion engine in which the fuel is burnt outside the engine to obtain the heat energy from fuel	It is an internal combustion engine in which the fuel is burnt inside the engine cylinder to obtain the heat energy from fuel
Only particular fuel should be used	The fuel of different qualities can be used in this plant
The expansion of the flue gas takes place in the turbine	The expansion takes place within the engine cylinder itself
The efficiency of the plant is 20% to 25%	The efficiency of the diesel power plant is 35 % to 42 %
The net work output is high	The net work output is less
The running of power plant will be continuous	The running of power plant is intermittent
Both installation cost and operating cost are high	Both installation cost and operating cost are comparatively less
Maintenance duration and cost of the power plant will be more	It is easy to maintain
Capacity of the plant is higher than diesel plant	The plant capacity is limited
Lubrication cost is less	Lubrication cost is high

9. Write brief note on starting systems of gas turbine.

STARTING SYSTEMS OF GAS TURBINE

Gas turbine engines are started by rotating the high-pressure compressor. To start a gas turbine engine, the compressor should be accelerated to provide sufficient air to support combustion in the combustion section or burners. Once ignition and fuel has been supplied and the lite-off has occurred, the starter must continue to assist the engine until the engine reaches a self-sustaining speed. The torque supplied by the starter should be more than the torque required to overcome compressor inertia and the friction loads of the engine's compressor. As soon as the starter has accelerated the compressor sufficiently to establish airflow through the engine, the ignition is turncd on followed by the fuel.

Several methods are used mostly electric or air turbine starters. An air impingement starting system is sometimes used on small engines consisting of jets of compressed air piped to the inside of the compressor or turbine case so that the jet air blast is directed onto the compressor or turbine rotor blades by causing them to rotate.

A typical pneumatic turbine engine starter may be operated as an ordinary air turbine starter from a ground operated air supply or an engine cross-bleed source. It may also be operated as a cartridge starter.

The fuel/air combustion starter was used in earlier days to start gas turbine engines by using the combustion energy of jet. The starter consists of a turbine-driven power unit and auxiliary fuel, air and ignition systems. Operation of this type starter is fully automatic by actuating a single switch to start to fire and accelerate the engine from rest to starter cutoff speed.

Hydraulic pumps and motors have also been used for some smaller engines. Many of these systems are not often used on modern commercial aircraft due to high power demands required to turn the large turbofan engines during the starting cycle on transport aircraft.

10. **Explain in detail about gas turbine fuels and gas turbine materials.**

FUELS FOR GAS TURBINE PLANT

The advantages of gas turbine such as increases combustion temperatures i.e. increased efficiency, power and reduced fuel consumption are partially negated by increasing the cost of fuels normally used gas turbines.

Residual liquid fuels are used in gas turbines. The residue left after the profitable light fractions is extracted from the crude. The following properties are identified for residual liquid fuels.

(1) It is viscous in nature.

(ii) It tends to polymerize when overloaded.

(iii) Their high carbon content leads to excessive carbon deposits in the combustion chamber.

(iv) The contents of alkali metals such as sodium combine with Sulphur to form sulphates which are corrosive.

(v) They have other metals such as vanadium with compounds. They form corrosion during combustion.

(vi) They have relatively high ash content which deposits mostly on fixed blades. They reduce gas flow and power output.

The rate of corrosion increases with increase in gas temperature. Early turbines designed for residual fuel are operated at the temperature below 900 K to avoid corrosion problem. Ash deposition is not a problem with intermittent operation because of successive expansion and contraction but it is a serious problem with steady operation.

The ideal fuel for the gas turbine unit is natural gas for the efficient energy conversion and good pollution control. The clean fuel will not foul the gas turbine blades and the availability of the unit would be the highest. It is always recommended to use a gas turbine unit designed for multi-fuels (Gaseous as well as liquid fuels such as LPG, Kerosene, landfill gas, or oil). It will help the power plant for the operation of power station in case or non-availability one type of fuel due to some reasons.

The light distillates such as light Diesel oil, high speed Diesel, naptha etc., would be the next preferred gas turbine fuels. These fuels can be used without treatment because of minimal contaminates. The gas turbine can also use heavy residual fuel oils as furnace oil and low Sulphur heavy stock. The furnace oil has the viscosity of about 170 mm 2/s at 50° C with maximum Sulphur content of 4.5 % whereas low Sulphur heavy stock is waxy in nature and it has a viscosity of about 500 mm 2/s at 50° C with maximum Sulphur content of 1.5 % and it has a pour point of 72° C. The low Sulphur heavy stock has higher calorific value of 3.5 % more compared to furnace oil. Also, it is cheap about 15% and it has lower asphaltenses, ash and carbon residue. Both furnace oil and low Sulphur heavy stock can be used in the gas turbine if it is pretreated properly to reduce contaminants within the acceptable limits.

GAS TURBINE MATERIALS

The gas turbines are to be operated at high turbine inlet temperature to achieve high efficiency and output. It means the higher pressure ratio because the optimum pressure increases with increase in turbine inlet temperatures in both efficiency and power. The components which suffer due to a combination of high temperature, high stress and chemical attack are of the turbine first-stage fixed blades i.e, nozzles and moving blades. They must be weldable and castable and must resist corrosion, oxidation and thermal fatigue. Heat resistance materials and precision casting are two recent advances, largely attributed to aircraft engine developments, Cobalt-based alloys are used for the first stage fixed blades which are subjected to the highest temperature of moving blades. These alloys are supplemented by vacuum-cast-nickel based alloys which are strengthened through solution and precipitation-hardening heat treatment. For moving blades, cobalt-based alloys with high chromium content are used

Ceramic materials are especially developed for the turbine inlet fixed blades. The development and it raises uncertainties about the mechanical properties of ceramic materials.

11. When the intercooling is required in Brayton cycle? What is the benefit of employing intercooler? Explain in the Brayton cycle with intercooler with neat sketches.

The thermal efficiency of Brayton cycle may further be improved by providing multistage compression with intercooler between compressors and multistage expansion with reheater between turbines. The work required during ,multistage compression with intercoolers is less than single stage compression.

Similarly, the work output from the turbine is increased by multistage expansion with reheating. As a result, the net work output from the plant increases. Figure shows as ideal gas turbine plant operated by Brayton cycle with two-stage compression.

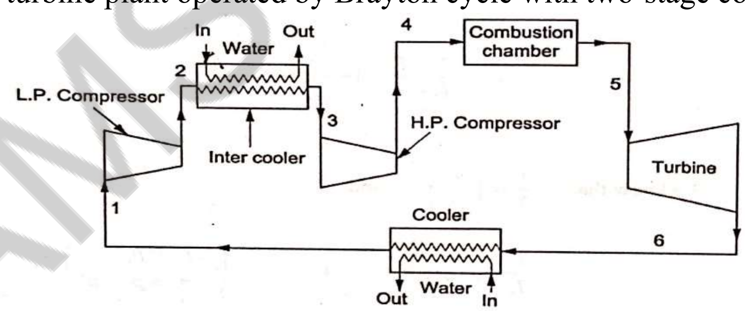
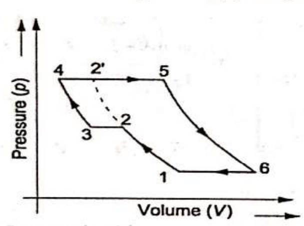
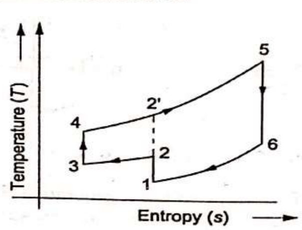


Figure 5.6(a) Brayton cycle with intercooler



p-V diagram



T-s diagram

Initially, the air is compressed in a low pressure (LP) compressor and then it is passed to an intercooler which reduces the temperature of the air to its original temperature at constant pressure. After that, the compressed air is again compressed in a high pressure (HP) compressor. Then, the compressed air is passed through the heating chamber where the heat is added to the air. Now, the air is expanded through the turbine. Finally, the air is cooled in the cooling chamber to its original temperature.

In figure, the ideal cycle without intercooling is represented by 1-2'-5-6-1 and the cycle with intercooler is represented by 1-2-3-4-5-6-1. The area under p-v diagram is increased by the amount of 2-3-4-2'-2. Therefore, the net work output is increased.

$$\text{workdone by the turbine per kg of air}$$
$$W_T = C_P(T_5 - T_6)$$
$$\text{work required by the two compressors per kg of air}$$
$$W_C = C_P(T_2 - T_1) + C_P(T_4 - T_3)$$
$$\text{net work output } W = W_T - W_C$$

12. A 4.5 MW gas turbine generating set operates with two compressor stages. The overall pressure ratio is 9:1. The high pressure turbine drives the compressor while the low pressure turbine drives the generator. The temperature of gases at entry to the HP turbine is 625°C. The exhaust gases leaving the LP turbine are passed through a heat exchanger to heat the air leaving the HP stage compressor. The compressors have equal pressure ratios and intercooling is complete between the stages. The air inlet temperature is 20 °C. the isentropic efficiency of each compressor stage is 0.8 and that of each turbine stage is 0.85. the heat exchanger thermal ratio is 0.8. assume a mechanical efficiency of 93 % for both power shaft and compressor turbine shaft. Neglecting their losses, compute the (i) thermal efficiency (ii) work ratio of the plant (iii) mass flow rate. Take Cp = 1.0 kilo joule.kg K, gamma = 1.4, Cp =1.15 koli joule/kg K and gamma =1.33 for exhaust gases. (Dec 2017)

Given:

Power P=4500 kW

$Rp=9=P_4/P_1=P_6/P_9$

Perfect intercooling, $T_1 = T_3$; $T_2' = T_4'$

Equal pressure ratio = $\frac{p_2}{p_1} = \frac{p_4}{p_3}$

$T_6 = T_8 = 625°C = 898\ K$

$T_1 = T_3 = 20°C = 293\ K$

$\eta_C = 0.8$

$\eta_T = 0.85$

$\epsilon = 0.8$

$\eta_{mech} = 93\% = 0.93$

☺ ***Solution:***

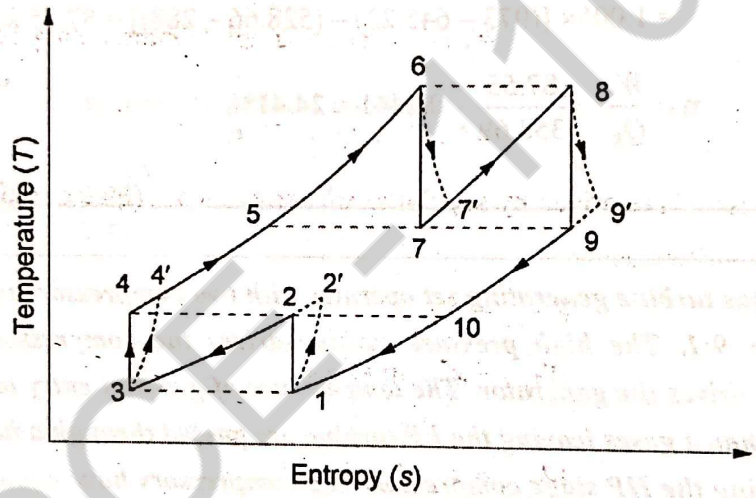


Figure 5.21 T-s diagram for AU Problem 5.5

From process 1-2: Isentropic compression

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

Since $$p_2 = p_3 = \sqrt{p_1 p_4} = \sqrt{9p_1^2} = 3p_1$$

$$\therefore T_2 = 293 \times \left(\frac{3}{1}\right)^{\frac{1.4-1}{1.4}} = 401.04\,K = T_4$$

We know that L.P compressor efficiency,

$$\eta_C = \frac{\text{Ideal work}}{\text{Actual work}} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{401.04 - 293}{T_2' - T_1}$$

$$T_2' - T_1 = 135.05 K$$

$$T_2' = 428.05 K$$

$$T_4' = T_2' = 428.05\ K$$

∴ Actual work of L.P compressor,

$$W_{C_{L.P}} = C_p (T_2' - T_1) = 1.005 \times 135.05 = 135.73\ kJ/kg$$

Total work of compressor, $W_C = W_{C_{L.P}} + W_{C_{H.P}}$

$= 2W_{C_{L.P}}$ since complete intercooling between compressor stages

$= 2 \times 135.73 = 271.46\ kJ/kg$

Both compressors are driven by supplying HP turbine work (Stated in the problem).

So, it can be written as

$$W_{T_{H.P}} = W_C$$

$$W_{T_{H.P}} = 271.46\ kJ/kg$$

We know that

$$W_{T_{H.P}} = C_p (T_6 - T_7')$$

$$\therefore \quad 271.46 = C_p (T_6 - T_7')$$

$$271.46 = 1.005 \times (898 - T_7')$$

$$\therefore \quad T_7' = 627.89 K$$

Efficiency of H.P. turbine, $\eta_T = \frac{T_6 - T_7'}{T_6 - T_7}$

$$0.85 = \frac{898 - 627.89}{898 - T_7}$$

$$T_7 = 580.22\ K$$

From process 6-7,

$$\frac{T_6}{T_7} = \left(\frac{p_6}{p_7}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{p_6}{p_7} = \left(\frac{T_6}{T_7}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{p_6}{p_7} = \left(\frac{898}{580.22}\right)^{\frac{1.4}{1.4-1}} = 4.61$$

Overall pressure ratio, $R_p = \frac{p_6}{p_9} = 9$

Also, $\frac{p_6}{p_9} = \frac{p_6}{p_7} \times \frac{p_8}{p_9}$ $[\because p_7 = p_8]$

$$9 = 4.61 \times \frac{p_8}{p_9}$$

$$\therefore \quad \frac{p_8}{p_9} = 1.95$$

$$\frac{T_8}{T_9} = \left(\frac{p_8}{p_9}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \quad T_9 = \frac{T_8}{\left(\frac{p_8}{p_9}\right)^{\frac{\gamma-1}{\gamma}}} = \frac{898}{(1.95)^{\frac{1.4-1}{1.4}}} = 742.01\ K$$

Efficiency of L.P turbine, $\eta_T = \frac{T_8 - T_9'}{T_8 - T_9}$

$$0.85 = \frac{T_8 - T_9'}{898 - 742.01}$$

$$T_8 - T_9' = 132.59\ K$$

$$\therefore \quad T_9' = 765.41\ K$$

$\therefore$ Actual work of L.P turbine, $W_{T_{L.P}} = C_p\left(T_8 - T_9'\right) = 1.005 \times 132.59 = 133.25\ kJ/kg$

Work done by turbines, $W_T = W_{T_{H.P}} + W_{T_{L.P}} = 271.46 + 133.25 = 404.71\ kJ/kg$

Thermal ratio of heat exchanger, $\in = \frac{T_5 - T_4'}{T_9' - T_4'}$

$$0.8 = \frac{T_5 - 428.05}{765.41 - 428.05}$$

$$\therefore \quad T_5 = 697.94\ K$$

We know that the power generated by H.P turbine is fully utilized to run compressor. So, the net work output is only work produced by L.P turbine.

Ideal net work, $W_{ideal} = W_{T_{L.P}} = 133.25\ kJ/kg$

Mechanical efficiency, $\eta_{mech} = \frac{\text{Actual net work output}}{\text{Ideal net work output}}$

$$0.93 = \frac{\text{Actual net work output}}{133.25}$$

$\therefore$ Actual net work, $W_{net} = 123.92\ kW$

Heat supplied, $Q_S = C_p\,[(T_6 - T_5) + (T_8 - T_7')]$

$$= 1.005\,[(898 - 697.94) + (898 - 627.89)]$$

$$= 472.52\ kJ/kg$$

Thermal efficiency, $\eta = \frac{W_{net}}{Q_S} = \frac{123.92}{472.52} = 0.2623 = \mathbf{26.23\%}$ **Ans.**

Work ratio $= \frac{\text{Actual net work output}}{\text{Trubine output}}$

$$= \frac{123.92}{404.17} = \mathbf{0.307}$$ **Ans.**

Power, $P = \text{Mass flow rate} \times \text{Net work output}$

$$4500 = m \times 123.92$$

$m = \mathbf{36.32\ kg/s}$ **Ans.**

13. In air standard Brayton cycle, the enters the compressor at 1 bar and 15°C. the pressure leaving the compressor is 5 bar and the maximum temperature in the cycle is 900°C. find the following: (i) compressor and expander work per kg of air (b) the cycle efficiency . if an ideal regenerator is incorporated into the cycle, determine the percentage change in efficiency.

Given data:

$p_1 = p_4 = 1\ bar = 100\ kN/m^2$

$T_1 = 15°C = 15 + 273 = 288\ K$

$p_2 = p_3 = 5\ bar = 500\ kN/m^2$

$T_3 = 900°\ C = 900 + 273 = 1173\ K$

☺ ***Solution:***

Case (i): Without using regenerator

Consider the process 1-2 isentropic compression

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

$$\therefore \quad T_2 = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \times T_1 = \left(\frac{500}{100}\right)^{\frac{1.4-1}{1.4}} \times 288 = 456.14K$$

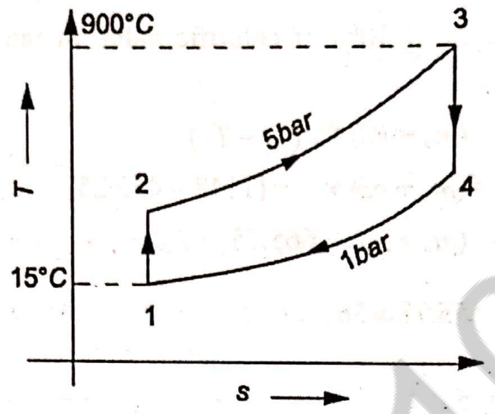


Figure 5.18 T-s diagram for AU Problem 5.1

Consider the process 3-4 isentropic expansion

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

$$T_4 = \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} \times T_3 = \left(\frac{100}{500}\right)^{\frac{1.4-1}{1.4}} \times 1173 = 740.62K$$

Work done by the compressor when it operates isentropically is given by

$W_C = C_P (T_2 - T_1) = 1.005 \times (456.14 - 288) =$ **168.98 *kJ*** **Ans.**

Similarly for expander,

$W_e = C_P \times (T_3 - T_4) = 1.005\ (1173 - 740.62) =$ **434.54 *kJ*** **Ans.**

Air standard efficiency,

$$\eta = 1 - \frac{1}{(R_p)^{\frac{\gamma-1}{\gamma}}} = 1 - \frac{1}{(5)^{\frac{1.4-1}{1.4}}} = 0.3686 = \mathbf{36.86\%}$$ **Ans.**

Case (i): Using regenerator

When ideal regenerator is incorporated,

$$T_3 = T_5 \text{ and } T_2 = T_6$$

Heat supplied, $Q_S = C_p\,(T_4 - T_3)$

Heat rejected, $Q_R = C_p\,(T_6 - T_1)$

$T_1 = 288\ K$

$T_2 = T_6 = 456.14\ K$

$T_3 = T_5 = 740.62\ K$

$T_4 = 1173\ K$

$Q_S = 1.005\,(1173 - 740.62) = 434.54\ kJ/kg$

$Q_R = 1.005\,(456.14 - 288) = 168.98\ kJ/kg$

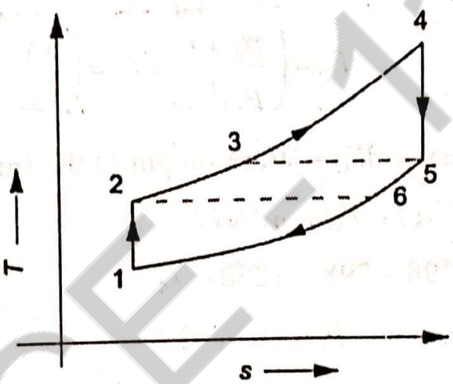


Figure 5.19 T-s diagram with ideal regenerator for AU Problem 5.1

Efficiency, $\eta = 1 - \dfrac{Q_r}{Q_S} = 1 - \dfrac{168.98}{434.54} = 0.6111 = 61.11\%$

% change in efficiency $= \dfrac{61.11 - 36.86}{61.11} = 39.68\%$ **Ans.**

14. A gas turbine generating set has a power output of 2500 kW operates with two stage compressor with perfect intercooling and equal pressure ratios. The overall pressure ratio is 9. The expansion also takes place in two stages each of having pressure ratio is 2.8. the temperature of gases at entry to HP turbine is 670°C and the gases are reheated to 670 °C after expansion in the first turbine. The exhaust gases leaving LP turbine are passes through a heat exchanger to heat the air leaving HP stage compressor. The air inlet temperature to the unit is 20 °C. The isentropic efficiency of each compressor stage is 0.78 and the isentropic efficiency of each turbine stage is 0.82. the heat exchanger thermal ratio is 0.75. calculate the thermal efficiency, work ratio of the plant and the mass flow rate.

Given data:

Power, $P = 2500\ kW$

$$R_p = 9 = \frac{p_4}{p_1}$$

Perfect intercooling, $T_1 = T_3$ and $T_2' = T_4'$

Equal pressure ratio $= \frac{p_2}{p_1} = \frac{p_4}{p_3}$

$T_6 = T_8 = 670°C = 943K$

$T_1 = T_3 = 20°C = 293K$

Turbine stage pressure ratio $= \frac{p_6}{p_7} = \frac{p_8}{p_9} = 2.8$

$\eta_C = 0.78$

$\eta_T = 0.82$

Thermal ratio or effectiveness, $\in = 0.75$ of heat exchanger

☺ ***Solution:***

From process 1-2: Isentropic compression

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

Since $p_2 = p_3 = \sqrt{p_1 p_4} = \sqrt{9p_1^2} = 3p_1$

$$\therefore T_2 = 293 \times \left(\frac{3}{1}\right)^{\frac{1.4-1}{1.4}} = 401.04\,K = T_4$$

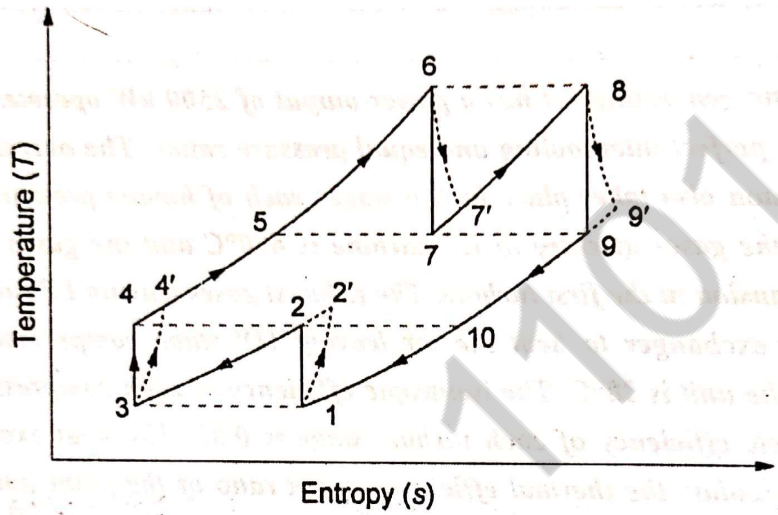


Figure 5.14 T-s diagram for Problem 5.4

We know that L.P. compressor efficiency

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

$$0.78 = \frac{401.04 - 293}{T_2' - 293}$$

$$\therefore \quad T_2' = 431.5\,K = T_4'$$

From process 6-7

$$\frac{T_6}{T_7} = \left(\frac{P_6}{P_7}\right)^{\frac{\gamma-1}{\gamma}} = (2.8)^{\frac{1.4-1}{1.4}} = 1.342$$

$$\therefore \quad T_7 = \frac{T_6}{1.342} = \frac{943}{1.342} = 702.68\,K$$

Efficiency of H.P. turbine,

$$\eta_T = \frac{T_6 - T_7'}{T_6 - T_7}$$

$$0.82 = \frac{943 - T_7'}{943 - 702.68}$$

$$T_7' = 745.94\,K$$

For equal pressure ratio,

$$T_7 = T_9 = 702.68\ K$$

$$T_7' = T_9' = 745.94\ K$$

Thermal ratio of heat exchanger,

$$\in = \frac{T_5 - T_4'}{T_9' - T_4'}$$

$$0.75 = \frac{T_5 - 431.5}{745.94 - 431.5}$$

$$T_5 = 667.33\ K$$

Work done by turbines,

$$W_T = C_p[(T_6 - T_7') + (T_8 - T_9')]$$

$$= 1.005\ [(943 - 745.94) + (943 - 745.94)] = 396.09\ kJ/kg$$

Work required by compressors,

$$W_C = C_p[(T_2' - T_1) + (T_4' - T_3)]$$

$$= 1.005\ [(431.5 - 293) + (431.5 - 293)] = 278.39\ kJ/kg$$

Net work, $W = W_T - W_C = 117.7\ kJ/kg$

Heat supplied,

$$Q_S = C_p\ [(T_6 - T_5) + (T_8 - T_7')]$$

$$= 1.005\ [(943 - 667.33) + (943 - 745.94)] = 475.09\ kJ/kg$$

Thermal efficiency,

$$\eta = \frac{W}{Q_S} = \frac{117.7}{475.09} = 0.2477 = \mathbf{24.77\%}$$ **Ans.**

Work ratio $= \frac{\text{Net work output}}{\text{Turbine output}} = \frac{117.7}{396.09} = \mathbf{0.297}$ **Ans.**

Power, P = mass flow rate × net work out put

$$2500 = m \times 117.7$$

$$m = \mathbf{21.24\ kg/s}$$ **Ans.**