UNIT II

DIESEL, GAS TURBINE AND COMBINED CYCLE POWER PLANTS

INTRODUCTION TO GAS POWER CYCLES :-

Thermodynamic cycle is defined as the series of operations or processes performed on a thermal system so that the system attains its original state. The cycles which use air as the working fluid are known as gas power cycles. The sources of heat supply and the sink for the heat rejection are assumed to be external to the air. The cycle can usually be represented on P-V and T-S diagrams.

The following assumptions are made in the analysis of gas power cycles.

through out i.e.) It follows the law $pv = mRT$

2. The working Medium has constant specific heats.
3. Kinetic and potential energies of the working fluid are neglected.

SOME IMPORTANT PARAMETERS :-

(i) Air standard efficiency (η) :-

It is the ratio of work done to the heat supplied during the process.

$$\text{Air standard Efficiency } \eta = \frac{\text{Workdone}}{\text{Heat supplied}} = \frac{W}{Q_S}$$

where Workdone = Heat supplied - Heat rejected

$$W = Q_S - Q_R$$

(ii) Mean Effective pressure (P_m) :-

The average pressure developed throughout a cycle of operation is called mean effective pressure. In other words, it is the ratio of work done to the swept volume.

$$\text{Mean Effective pressure } (P_m) = \frac{\text{Workdone}}{\text{Swept volume}} = \frac{W}{(V_1 - V_2)}$$

$$\text{Also, Mean effective pressure } (P_m) = \frac{\text{Area of the p-V diagram}}{\text{Length of the diagram}}$$

(iii) Power (P) :-

It is defined as the amount of workdone for the unit mass flow rate of the working substance.

power = work done × Mass flow rate of working substance

$$P = W \times m_f$$

OTTO CYCLE :-

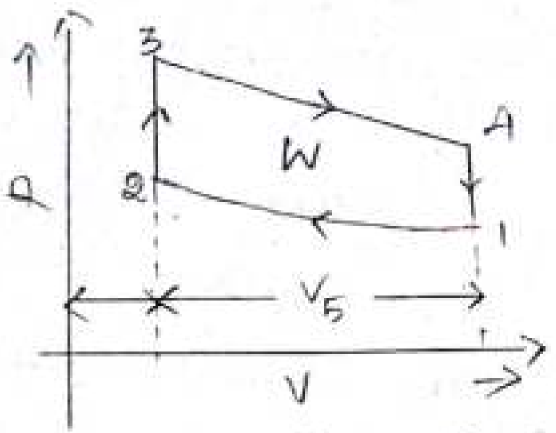
The cycle which was introduced by Dr. A.N. Otto, a German scientist is called ... Generally, petrol and gas engines follows [illegible]

following four processes.

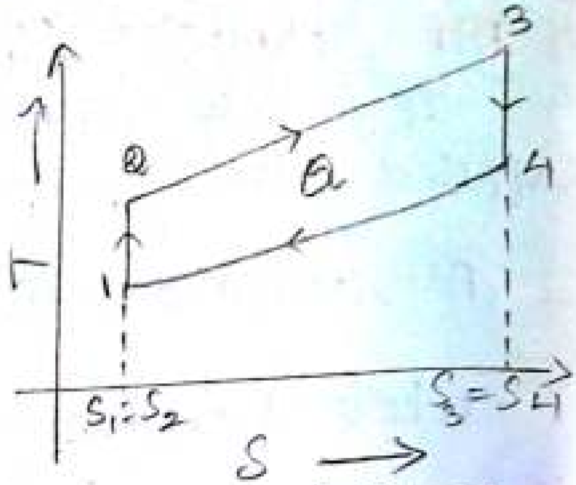
1. Two reversible adiabatic or isentropic processes, and

2. Two constant volume processes.

p-V and T-s diagrams are as shown as



p-V diagram



T-s diagram

process 1-2 :-

process 1-2 is the isentropic compression process. During this process, pressure increases from p_1 to p_2 and temperature increase from T_1 to T_2. But, the volume decreases from V_1 [illegible] and the entropy remains constant

(ie) $S_1 = S_2$

process 2-3 :-

process 2-3 is a constant volume heat addition process. During this process, pressure increases from p_2 to p_3; temperature increases from T_2 to T_3 and entropy increases from S_2 or S_1 to S_3 (since $S_1 = S_2$). But the volume remains constant (ie) $V_2 = V_3$

process 3-4 :-

process 3-4 is an isentropic expansion process. During this process, pressure decreases from p_3 to p_4, temperature decreases from T_3 [illegible] and volume increase from V_3 to V_4. But, the entropy remains constant (ie) $S_3 = S_4$

constant volume heat rejection process. During this process, pressure decreases p_4 to p_1, temperature decreases from T_4 to T_1, and entropy decreases from S_4 to S_1 or S_3 to S_1 (since $S_3 = S$). But the volume remains constant (ie) $V_4 = V_1$)

Heat is rejected during 4-1 process,

$$Q_R = m \times C_V (T_4 - T_1) \text{ in KJ}$$

workdone during cycle W } = Heat supplied - Heat rejected

$$= Q_S - Q_R$$

$$= m \times C_V (T_3 - T_2) - m \times C_V (T_4 - T_1)$$

Efficiency; $\eta_{otto} = \frac{Q_S - Q_R}{Q_S}$

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

$$\eta_{otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

This expression is in terms of temperature only. If the temperatures at all points of the cycle are known, then only the above equation can be used. Hence, the efficiency equation is simplified in terms of volume ratio

From p-V diagram

Total cylinder volume $= V_1 = V_4$

Clearance volume $= V_C = V_2 = V_3$

stroke volume $= V_S = V_1 - V_2 = V_4 - V_3$

Compression ratio (r) :-

compression ratio (r) is the ratio between the total cylinder volume and clearance volume

$$\text{compression ratio } r = \frac{V_1}{V_2}$$

Adiabatic compression ratio

Total cylinder volume

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

During the adiabatic process, the compression ratio is equal to expansion ratio.

Consider the process 1-2 :-

The adiabatic relation between T and v is given by

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

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

Consider the process 3-4 :-

The adiabatic relation between T and v is given by

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

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

Substituting T_2 and T_3 values in equation

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

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

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

from above equation, the efficiency of otto cycle increase with increase in compression ratio and viceversa.

Mean effective pressure (P_m) :-

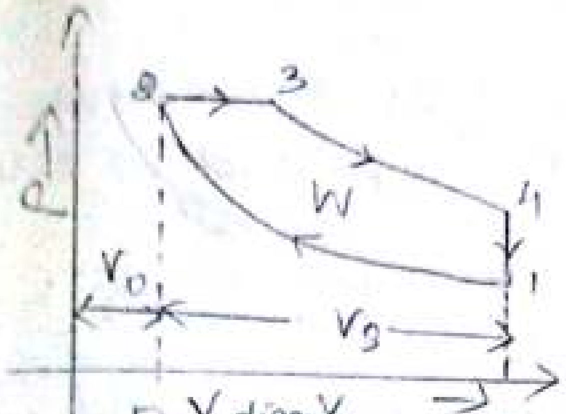
$$P_m = P_1 r \left(\frac{k-1}{\gamma-1}\right)\left(\frac{r^{\gamma-1}-1}{r-1}\right)$$

DIESEL CYCLE :-

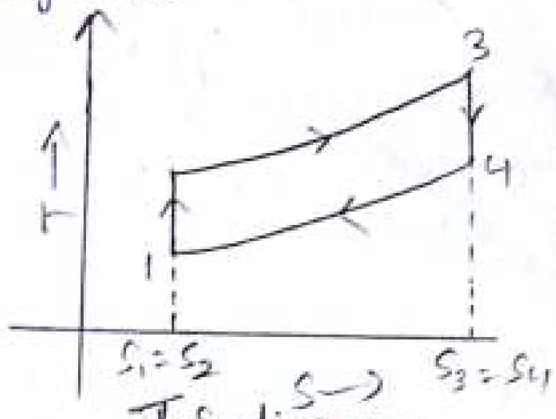
This is the cycle which was introduced by Rudalph Diesel. This cycle is used in Diesel engines. It consists of the follo four processes.

1. Two reversible adiabatic or isentropic
2. One constant volume, and
3. One constant pressure processes.

p-V and T-s diagrams



P-V diagram



T-S diagram

process 1-2 :- Isentropic Compression process :-

During the process, the air is isentropically compressed from P_1 to P_2. But the entropy remains constant ($S_1 = S_2$)

process 2-3 :- Constant pressure head addition process :-

During the process, the air is heated from T_2 to T_3 but the pressure remains constant ($P_2 = P_3$)

Heat supplied during the process

$$Q_S = m \times C_p (T_3 - T_2)$$

process 3-4 : Isentropic expansion process :-

During this process, the air Isentropically expands from P_3 to P_4. But the temperature decreases from $T_3 - T_4$

process 4-1 :- constant volume heat rejection process :-

During this process, the heat is rejected from air but the volume remains constant. Thus, the temperature decreases from T_4 to T_1

Heat rejected $Q_R = m \times C_V (T_4 - T_1)$

Efficiency of Diesel cycle.

$$\eta = \frac{Q_S - Q_R}{}$$

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

$$= 1 - \frac{mC_v(T_4-T_1)}{mC_p(T_3-T_2)} \qquad \left[\because \frac{C_p}{C_v} = \gamma\right]$$

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

The efficiency is in terms of temperature only. Hence, the equation is simplified in terms of volume ratio

Compression ratio $= \frac{\text{Total cylinder volume}}{\text{clearance volume}} = \frac{V_1}{V_2} = r$

Cut-off ratio is the ratio between the volume at the point of cut off and clearance volume. It is denoted by 'ρ'

Cut-off ratio $\rho = \frac{\text{cut-off volume}}{\text{clearance volume}} = \frac{V_3}{V_2}$

Expansion ratio $= \frac{V_4}{V_3} = \frac{V_1}{V_3} = \frac{V_1}{V_2} \times \frac{V_2}{V_3} = r \times \frac{1}{\rho} = \frac{r}{\rho}$

Consider process 1-2 :-

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

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

Consider process 2-3 :-

Process 2-3 is a constant pressure process.

so, $\frac{V}{T} = C$

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

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

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

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

Consider process 3-4 :-

using adiabatic equation

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

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

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

$$T_4 = T_1 \rho^{\gamma}$$

substituting T_2, T_3 and T_4 values in η_{Diesel} equation

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

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

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

from above equation

1. If the compression ratio increases, the efficiency of Diesel cycle is increased and vice versa
2. The efficiency of Diesel cycle decreases with increase in cutoff ratio and vice versa

Mean effective pressure (P_m) :-

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

DUAL CYCLE :-

In earlier otto and Diesel cycles, the heat addition takes place at both constant volume and constant pressure processes. Dual cycle is the combination of above two cycles because the heat addition takes place partially at constant volume and remaining at constant pressure. Therefore, it is also called as mixed cycle or limited pressure cycle. This cycle consists of the following processes.

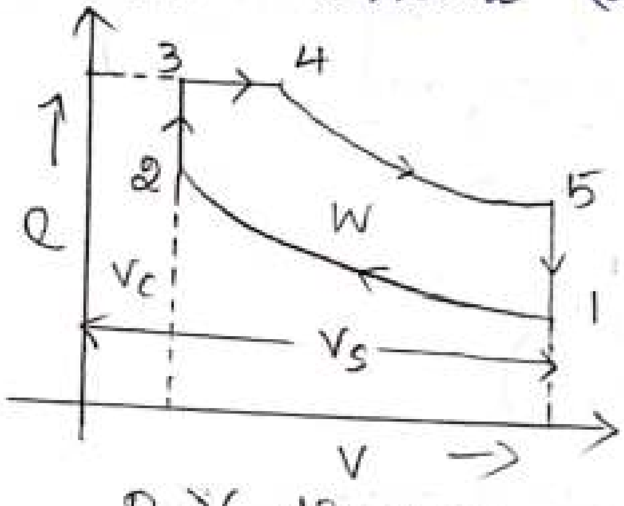
1. Two reversible adiabatic or isentropic processes

2. One constant pressure process

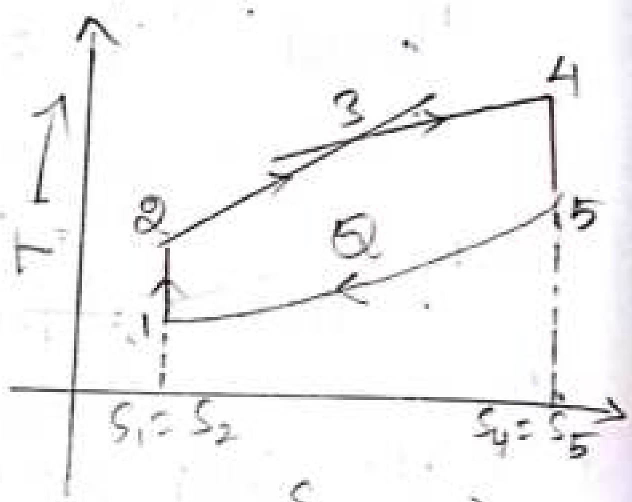
p–V and T–S diagrams

Process 1-2 :- Isentropic compression process :-

During the process, the air is isentropically compressed from P_1 to P_2. But, the entropy remains constant (i.e) $s_1 = s_2$



P–V diagram



T–S diagram

Process 2-3 :- Constant volume heat addition process :-

During the process, the compressed air is partially heated by constant volume process (i.e) $V_2 = V_3$. Both temperature and entropy increase from T_2 to T_3 and S_2 to S_3 respectively.

Heat supplied during the process

$$Q_{S_1} = m \times C_V (T_3 - T_2)$$

Process 3-4 :- Constant pressure heat addition process

During the process, the partially heated air is again heated by constant pressure process (i.e) $P_3 = P_4$. Both temperature and entropy increase from T_3 to T_4 and S_3 to S_4 respectively.

Heat supplied during the process,

$$Q_{S_2} = m \times C_p (T_4 - T_3)$$

decreases from P_4 to P_5 and the temperature decreases from T_4 to T_5.

process 5-1 :- Constant Volume heat rejection process :-

During the process, the heat is rejected from the air and the volume remains constant (ie) $V_5 = V_1$. Thus temperature decreases T_5 to T_1 and entropy decreases S_5 to S_1.

$$Q_R = m \times C_v (T_5 - T_1)$$

The total heat supplied during heat addition is the sum of the heat supplied at Constant volume and constant pressure processes

$$Q_s = Q_{s1} + Q_{s2} = m \times C_v (T_3 - T_2) + m \times C_p (T_4 - T_3)$$

Air standard efficiency

$$\eta = \frac{W}{Q_s} = \frac{Q_s - Q_R}{Q_s}$$

$$= \frac{mC_v (T_3 - T_2) + mC_p (T_4 - T_3) - mC_v (T_5 - T_1)}{mC_v (T_3 - T_2) + mC_p (T_4 - T_3)}$$

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

The above efficiency equation is in terms of temperatures.

compression ratio, $r = \frac{V_1}{V_2}$

pressure ratio, $K = \frac{P_3}{P_2}$

cut-off ratio, $\rho = \frac{V_4}{V_3}$

Expansion ratio, $\frac{V_5}{V_4} = \frac{V_1}{V_4} = \frac{V_1}{V_2} \times \frac{V_2}{V_4} \quad \left(\because V_5 = V_1,\ V_3 = V_2\right)$

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

Consider process 1-2 :- $T_2 \ldots \left(\frac{V_1}{\ldots}\right)^{\gamma-1} = (r)^{\gamma-1}$

Consider process 2-3

Constant volume process, $\frac{P_2}{T_2} = \frac{P_3}{T_3}$

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

Consider process 3-4 :-

constant pressure process, $\frac{V_3}{T_3} = \frac{V_4}{T_4}$

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

Consider process 4-5 :-

Isentropic process,

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

$$T_5 = \frac{T_4}{\left(\frac{r}{\rho}\right)^{\gamma-1}} = \frac{T_4\,\rho^{\gamma-1}}{(r)^{\gamma-1}} = \frac{T_1(r)^{\gamma-1}K.\rho.\rho^{\gamma-1}}{(r)^{\gamma-1}}$$

$$T_5 = T_1 K.\rho^{\gamma}$$

Note :-

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

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

$T_4 = \rho.K.T_1(r)^{\gamma-1}$

$T_5 = T_1 K.\rho^{\gamma}$

Substituting T_2, T_3, T_4, T_5 in η equation

$$\eta = 1 - \frac{T_1K\rho^{\gamma} - T_1}{[T_1(r)^{\gamma-1}K - T_1(r)^{\gamma-1}] + \gamma[T_1(r)^{\gamma-1}K\rho - T_1(r)^{\gamma-1}K]}$$

$$= 1 - \frac{T_1[K\rho^{\gamma}-1]}{T_1(r)^{\gamma-1}[(K-1)+\gamma K(\rho-1)]}$$

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

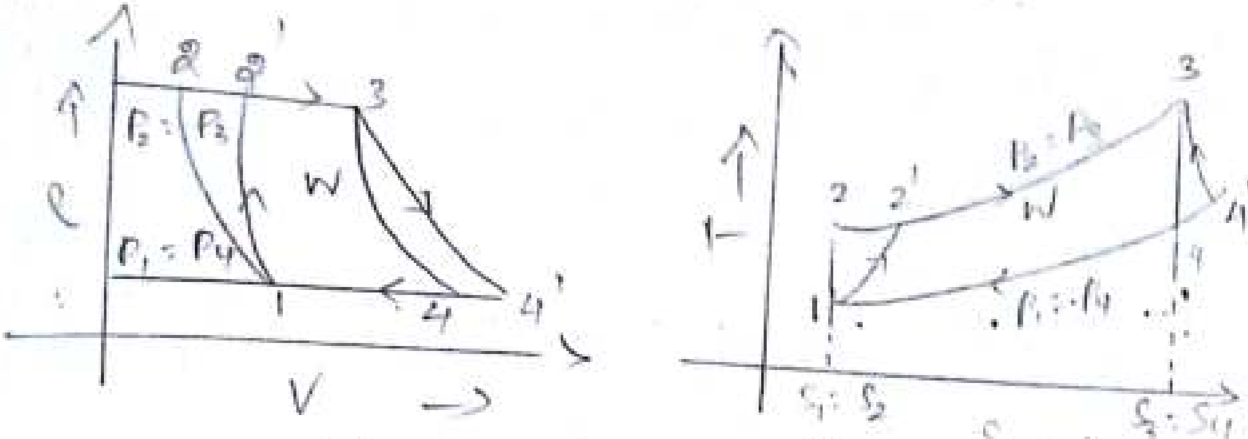
Mean effective pressure (P_m) :-

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

ANALYSIS OF BRAYTON CYCLE :-

In an ideal cycle, both compression and expansion processes are reversible adiabatic. But in actual practice it is not possible to achieve a reversible process because of friction and unaccounted heat loses in both turbine and compressor

Therefore, an actual gas turbine plane differs from ideal one



p-V diagram T-s diagram

In above diagram the ideal process is represented by 1-2-3-4 lines and the actual process is represented by 1-2'-3-4' lines

work required by compressor, $W_C = m \times C_p (T_2' - T_1)$

work done by the turbine, $W_T = m \times C_p (T_3 - T_4')$

$\therefore$ Net work available $W = W_T - W_C$

$$= m \times C_p [(T_3 - T_4') - (T_2' - T_1)]$$

Net heat supplied $Q_S = m \times C_p (T_3 - T_2')$

Thermal efficiency for actual cycle.

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

Isentropic efficiency of the

compressor $\eta_C = \frac{T_2 - T_1}{T_2' - T_1}$,

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

The net output of the cycle is reduced by the amount $[(h_4' - h_4) + (h_2' - h_2)]$ and the heat supplied is reduced by the amount $(h_2' - h_2)$

The efficiency of the cycle is less than the ideal cycle

OPTIMISATION OF BRAYTON CYCLE:

The pressure ratio at which the work is known as optimum the optimum pressure ratio of the [illegible]

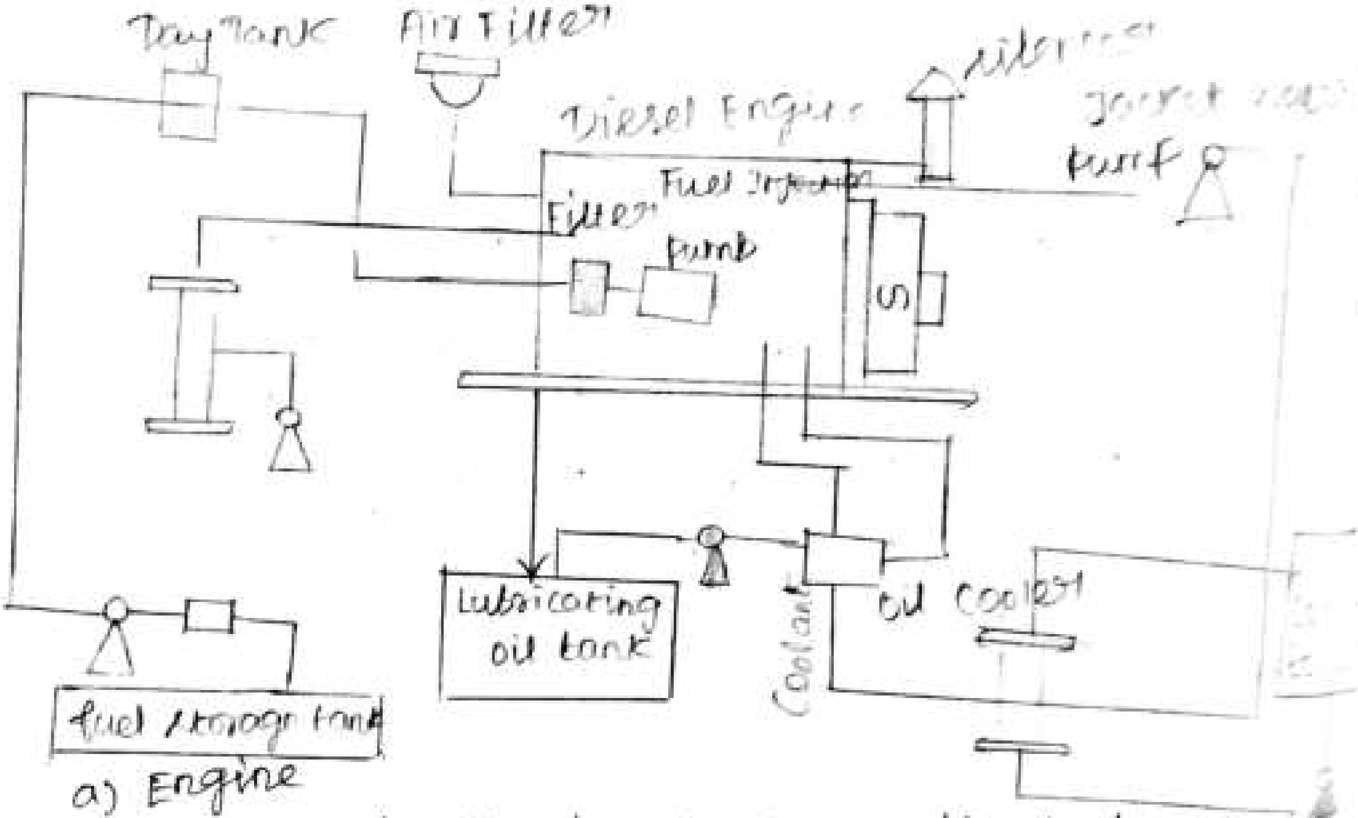
$$\left(\frac{P_2}{P_1}\right) = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$(R_p)_{opt} = \left[\frac{(T_1 \times T_3)^{1/2}}{T_1}\right]^{\frac{\gamma}{\gamma-1}}$$

$$(R_p)_{opt} = \left[\frac{T_3}{T_1}\right]^{\frac{1}{2} \times \frac{\gamma}{\gamma-1}}$$

The optimum pressure can also be obtained by differentiating the network output with respect to the pressure ratio and putting the derivative equal to zero.

DIESEL POWER PLANT :-



a) Engine

Engine is the heart of a diesel power plant. Engine is directly connected through gear box to the generator. Generally two-stroke engines are used for power generation. Now a days advanced super & turbo charged high speed engine are available for power production.

b) Air supply system :

Air Inlet is arranged outside the engine filter and conveyed to the inlet manifold of engine. In Large plants supercharger/turbo charger is used for increasing the pressure of input air which increase the power output.

c) Exhaust system :-

This includes the silencers and connecting ducts. The heat content of the exhaust gas is utilized in a turbine in a turbo charger to compress the air input to the engine.

d) fuel system :-

fuel is stored in a tank from where it flows to the fuel pump through a filter. fuel is injected to the engine as per load requirement.

e) Cooling system :-

This system includes water circulating pumps, cooling towers, water filter etc. cooling water is circulated through the engine block to keep the temperature of the engine in the safe range.

f) Lubricating system :-

Lubrication system includes the air pumps, oil tanks, filters, coolers and pipe lines. Lubricant is given to reduce friction of moving parts and reduce the wear and tear of the engine parts.

g) Starting system :-

There are three commonly used starting systems.

1) A petrol driven auxiliary engine
2) use of electric motors
3) use of compressed air from an air compressor at a pressure of 20 kg/cm²