Program : **B.Tech**

Subject Name: **Thermodynamics**

Subject Code: **ME-302**

Semester: **3rd**

NOTES- UNIT-III

Reciprocating Machines: Steam engines, hypothetical and actual indicator diagram; Carnot cycle and ideal efficiency; Otto and diesel cycles; working of two stroke & four stroke petrol & diesel IC engines

INTRODUCTION:

Any type of Engine or a Machine which derives Heat Energy from the combustion of fuel or any other source and converts this energy into mechanical work is termed as a **Heat Engine.**

Heat Engine may be classified into two main classes as follows:

1. External Combustion Engine
2. Internal Combustion Engine

1. External Combustion Engine:-

In this case, combustion of fuel takes place outside the cylinder as in case of **STEAM ENGINES,** where the heat of combustion is employed to generate steam which is used to move a piston in the cylinder.

2. Internal Combustion Engine:-

In this case, combustion of the fuel with the oxygen of the air occurs within the cylinder of the engine. Internal Combustion Engine is a machine that converts Chemical Energy into Mechanical Work. Fuel is burnt in a combustion chamber, releases it's chemical energy in form of heat, which is further converted into Mechanical Energy with the help of Reciprocating Piston and Crank Mechanism.

CLASSIFICATION OF I. C. ENGINES:-

The I. C. Engines are usually reciprocating type. The reciprocating I. C. Engines are classified on the basis on the following:

1. According to piston strokes in the working cycle:
i) Four Stroke Engine, ii) Two Stroke Engine
2. According to the Fuel used in the cycle:
i) Petrol Engine, ii) Diesel Engine, iii) Gas Engine, and
iv) Multi-Fuel Engine
3. According to Method of Ignition:
i) Spark Ignition, ii) Compression Ignition
4. According to the Fuel-Feeding System:
i) Carbureted Engine, ii) Engine with Fuel Injection
5. According to Charge Feeding System:
i) Naturally aspirated Engine, ii) Supercharged Engine
6. According to Cooling System:
i) Air-Cooled Engine, ii) Water-Cooled Engine
7. According to the Number of Cylinders:
i) Single Cylinder Engine, ii) Multi-Cylinder Engine
8. According to Speed of Engine:
i) Low Speed Engine, ii) Medium Speed Engine, and iii) High Speed Engine
9. According to Position of Engine:
i) Horizontal Engine, ii) Vertical Engine, and iii) V- Engine

COMPONENTS OF I. C. ENGINES:-

The essential Parts of Otto-cycle and Diesel-cycle Engines are same. Actually an internal combustion consists of a large number of parts and each has its own function. A few of them are shown in fig.3.1

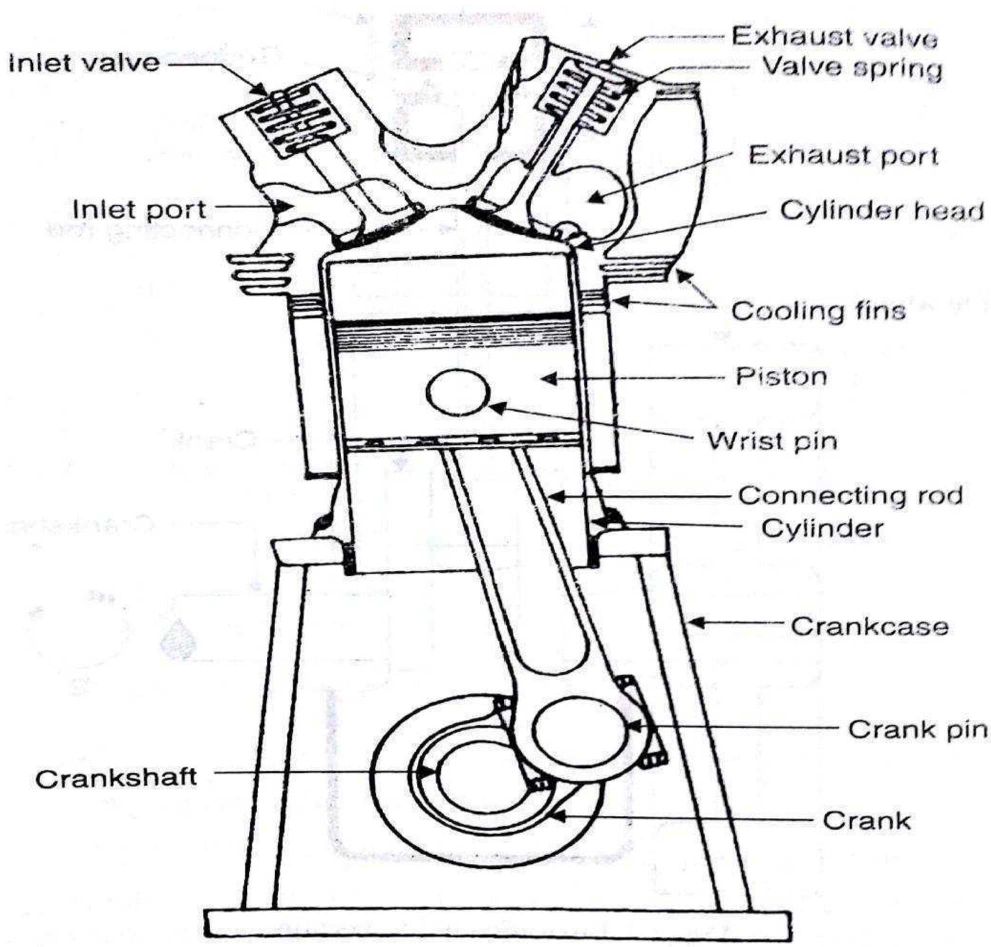

Fig.3.1 Main Components of an Internal Combustion Engine

1. **Cylinder: -** It is the heart of the engine. The piston reciprocates in the cylinder..
2. **Cylinder Head:-** The top cover of the cylinder, towards TDC (Top Dead Centre) is called Cylinder Head. It houses the spark plug in petrol engines and fuel injector in Diesel Engines.
3. **Piston: -** It is reciprocating number of engine. It reciprocates in the cylinder. It is made of usually Cast Iron or Aluminum alloys. Its top surface is called Piston Crown and bottom surface is piston skirt. Its top surface is made flat for four stroke engines and deflected for two stroke engines.
4. **Piston Rings: -** The two or three piston rings are provided on piston. The piston rings seal the space between cylinder liner and piston in order to prevent leakage (blow by losses) of high pressure gases, from cylinder to crank case.
5. **Crank: -** It is rotating member. It makes circular motion in the crank case (its housing). Its one end is connected with shaft called Crank-Shaft and other end is connected with connecting rod.
6. **Crank-Case: -** It is housing of the crank and body of the engine to which cylinder and other engine parts are fastened. It also acts as a ground for lubricating oil.
7. **Connecting Rod: -** It is a link between piston and crank. It s connected at its one end with crank and on other end with piston. It transmits power developed on the piston to crank shaft through crank. It is usually made of medium carbon steel.
8. **Crank Shaft: -** It is shaft, a rotating member, which connects crank and the power developed by the engine is transmitted outside through this shaft. It is made up of medium carbon or alloy steel.
9. **Cooling Fins or Cooling Water Jackets: -** In order to keep the engine parts within safe temperature limits, the cylinder and the cylinder head are provided with cooling arrangement.
10. **Cam Shaft: -** It is provided on four stroke engines. It carries two cams, for controlling the opening and closing of inlet and exhaust valves**.**
11. **Inlet Valve: -** This valve controls the admission of charge into the engine during suction stroke.
12. **Exhaust Valve: -** The removal of exhausted gases after doing work on the piston, is controlled by the valve.
13. **Inlet Manifold: -** It is the passage, which carries the charge from carburetor to engine.

14. **Exhaust Manifold: -** It is the passage which carries the exhaust gases from the exhaust valve to the atmosphere.
15. **A) Spark Plug: -** It is provided on Petrol Engines. It produces a high intensity spark which initiates the combustion process of the charge.
    B) Fuel Injector: - It is provided on Diesel Engines. The Diesel fuel is injected in the cylinder at end of compression through fuel injector under very high pressure.
16. **A) Carburetor: -** It is provided with Petrol Engine for preparation of homogeneous mixture of air and fuel (Petrol). This mixture, as a charge is supplied to engine cylinder through suction valve or port.
    B) Fuel Pump: - It is provided with Diesel Engine. The diesel is taken from fuel tank and its pressure is raised in the fuel pump and then it is delivered to fuel injector.
17. **Fly Wheel: -** It is mounted on the crank shaft. It is made of Cast Iron. It stores energy in the form of inertia, when energy is in excess and it gives back energy when it is deficit. In other words, it minimizes the speed fluctuations on the engine.

INTERNAL COMBUSTION ENGINE TERMINOLOGY

Some of the basic components and generally used terms in internal combustion engines are given as under.

1. Bore: It is nominal inner diameter of the cylinder.

2. Piston area: It is the area of a circle of diameter equal to bore.

3. Stroke: It is the nominal distance travelled by the piston between two extreme positions in the Cylinder.

4. Dead centre: It refers to the extreme end positions inside the cylinder at which piston reverses it's motion. Thus, there are two dead centres in cylinder, called as 'top dead centre' or 'inner dead centre' and 'bottom dead centre' or 'outer dead centre'. Top dead centre (TDC) is the farthest position of piston from crankshaft. It is also called inner dead centre (IDC). Bottom dead centre (BDC) refers to the closed position of piston from crankshaft. It is also called outer dead center (ODC).

5. Swept volume : It is the volume swept by piston while travelling from one dead centre to the other. It may also be called stroke volume or displacement volume. Mathematically,

Swept volume = Piston area × Stroke

6. Clearance volume: It is the volume space above the piston inside cylinder, when piston is at top dead centre. It is provided for cushioning considerations and depends, largely upon compression ratio.

7. Compression ratio: It is the ratio of the total cylinder volume when piston is at BDC to the clearance volume.

$$\text{Compression ratio} = \frac{Swept\,Volume + Clearance\,Volume}{Clearance\,Volume}$$

WORKING OF FOUR STROKE PETROL ENGINE:- The strokes are as follows:-

1. **SUCTION OR INDUCTION STROKE:** During this stroke, the inlet valve stays open and the exhaust valve closed. The piston moves downward from TDC to BDC by means of crankshaft, which is revolved by the momentum of the flywheel or by power, generated by the electric starting motor. This piston movement creates a pressure difference between outside and inside the cylinder and the higher pressure of the atmosphere forces the air fuel mixture from the carburetor into the cylinder through inlet valve.
2. **COMPRESSION STROKE:** The air fuel mixture, sucked during the suction stroke, is compressed in this stroke. Piston moves from BDC to TDC. Just a little before the end of compression stroke, a spark produced by spark plug ignites the compressed mixture. Both the inlet and exhaust valves remain closed during this stroke.
3. **WORKING OR POWER STROKE:** The inlet and exhaust valves remain closed during this stroke. Product of combustion (hot gases) expands due to high temperature and pressure, due to this the piston starts to move downward from TDC to BDC and the power is obtained.
4. **EXHAUST STROKE:** The inlet valve remains closed while the exhaust opens. The major portion of burnt gases escapes due to own expansion. The upward movement of the piston from BDC to TDC pushes the remaining gases out of the open exhaust valve. Only a small quantity of burnt gases stays in the clearance space. This cycle or series of events take place over and over again.

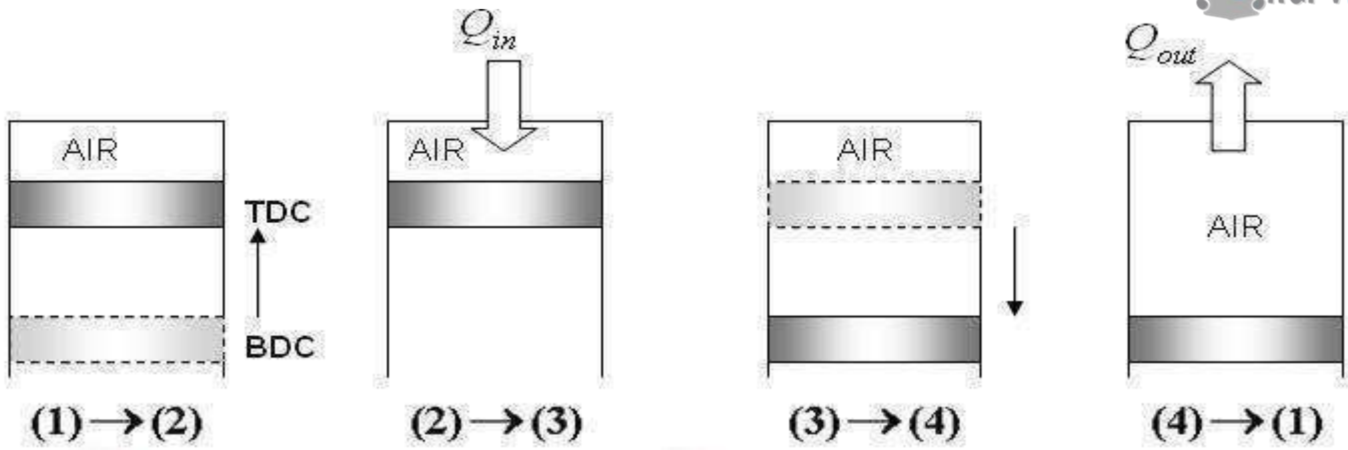

Fig.3.4 Four Stroke Petrol Engine

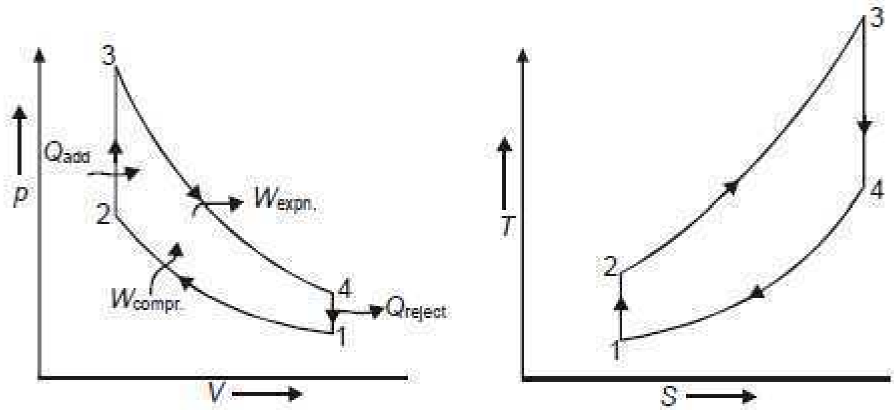

Fig.3.5 P- V And T-S Schematic Diagram Of A Four – Stroke Petrol Engine

WORKING OF FOUR STROKE DIESEL ENGINE:- The strokes are as follows:-

1. **SUCTION OR INDUCTION STROKE:** The piston moves down from the Top Dead Centre (TDC) to Bottom Dead Centre (BDC). The air is drawn into the cylinder through inlet valve, which closes at the end of this stroke. The exhaust valve remains closed during this stroke.
2. **COMPRESSION STROKE:** In a vertical engine the piston moves up towards TDC from BDC position. The inlet valve is now closed. The air drawn in the cylinder in the previous stroke is entrapped inside the cylinder and compressed with the upward movement of the piston. As the compression ratio used in this engine is high (14: 22) the air is finally compressed to a pressure as high as 40 bars at which its temperature is high (as high as 1000^0 C) enough to ignite the fuel. As the piston moves after reaching TDC the fuel is injected into the hot compressed air where it starts burning, maintaining the pressure constant.
3. **WORKING OR POWER STROKE:** Both inlet and exhaust valves remains closed during this stroke. The product of combustion now expands in the engine cylinder pushing the piston down, and hence doing work. The piston finally reaches the BDC position.
4. **EXHAUST STROKE:** The piston now moves up once again. The inlet and fuel valves are closed but the exhaust valve opens. Major part of the burnt gases escape due to their own expansion. The upward movement of the piston pushes the remaining gasses out through the open exhaust valve. The exhaust valve closes at the end of the exhaust stroke. The cycle is thus completed.

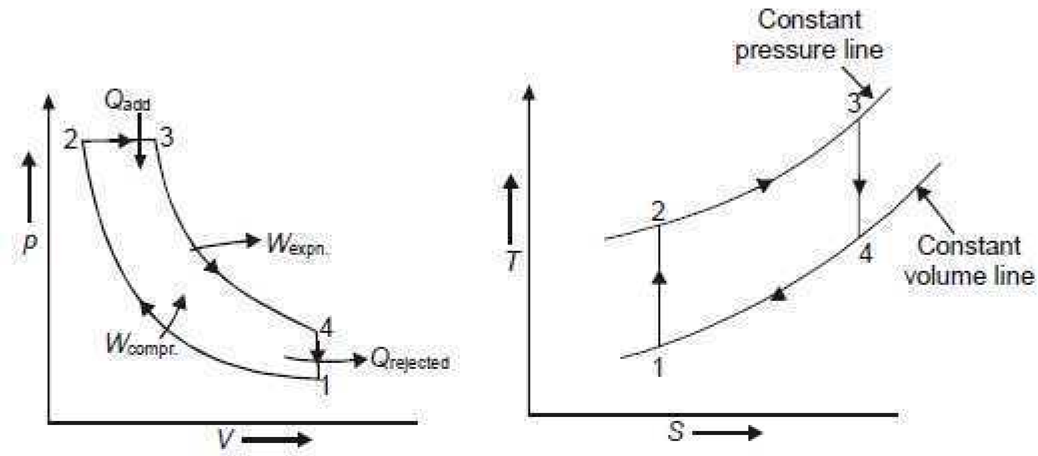

Fig.3.6 P- V Diagram And Schematic Of A Four – Stroke Diesel Engine

CARNOT VAPOUR POWER CYCLE

Carnot cycle has already been defined earlier as an ideal cycle having highest thermodynamic efficiency. Let us use Carnot cycle for getting positive work with steam as working fluid. Arrangement proposed for using Carnot vapour power cycle is as follows.

1 – 2 = Reversible isothermal heat addition in the boiler
2 – 3 = Reversible adiabatic expansion in steam turbine
3 – 4 = Reversible isothermal heat rejection in the condenser
4 – 1 = Reversible adiabatic compression or pumping in feed water pump

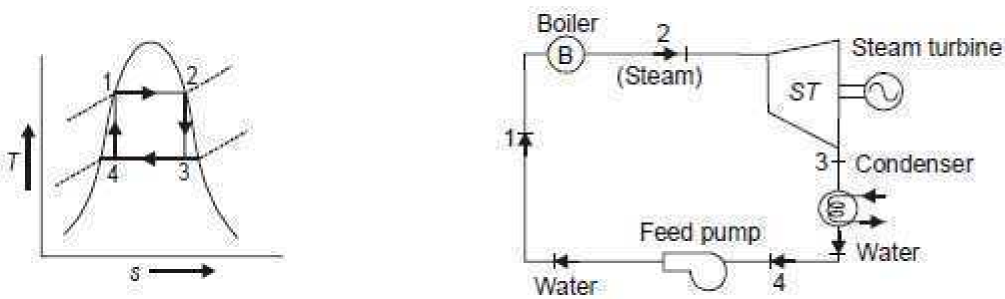

Fig.3.7 Carnot vapor power cycle and A schematic arrangement for Carnot cycle

Assuming steady flow processes in the cycle and neglecting changes in kinetic and potential energies, thermodynamic analysis may be carried out.

Thermal Efficiency = Net Work / Heat Added
Net Work = Turbine Work - Compression/Pumping Work
For Unit Mass flow,
$W = (h_2 - h_3) - (h_1 - h_4)$
Heat Added, $Q_{add} = (h_2 - h_1)$
$\eta_{carnot} = (h_2 - h_3) - (h_1 - h_4) / (h_2 - h_1)$
$\eta_{carnot} = 1 - (h_3 - h_4) / (h_2 - h_1)$
Here, Heat Rejected, $Q_{rejected} = (h_3 - h_4)$
Or, $\eta_{carnot} = 1 - Q_{rejected} / Q_{add}$
Also heat added and rejected may be given as function of temperature and entropy as follows:
$Q_{add} = T_1 \times (S_2 - S_1)$
$Q_{rejected} = T_3 \times (S_3 - S_4)$
Also $S_1 = S_4$ and $S_2 = S_3$

Therefore substituting values :
$\eta_{carnot} = 1 - T_3 / T_1$
Or, $\eta_{carnot} = 1 - T_{minimum} / T_{maximum}$

Efficiency of Otto Cycle

This is a modified form of Carnot cycle in order to make it a realistic cycle. Otto cycle has two constant volume and two adiabatic processes as shown below.

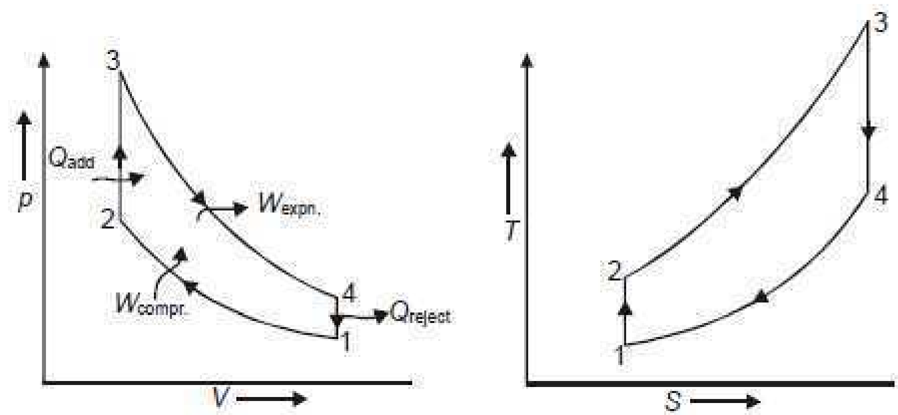

Fig.3.8 P- V And T-S Schematic Diagram Of Otto Cycle

Thermodynamic processes constituting Otto cycle are
1 – 2 = Adiabatic compression process, (–ve work, *W*compr)
2 – 3 = Constant volume heat addition process (+ve heat, *Q*add)
3 – 4 = Adiabatic expansion process, (+ve work, *W*expan)
4 – 1 = Constant volume heat rejection process (–ve heat, *Q*reject)
In order to have an engine based on Otto cycle let us find out the relevance of above processes. Spark ignition type internal combustion engines are based on this cycle.

Process 1 – 2, adiabatic compression process can be realized by piston moving from volume *V*1 to *V*2 and therefore compressing air.

Process 2 – 3, heat addition process can be undertaken in constant volume manner with piston at volume *V*2 and heat added to woking fluid.

Heat addition is practically realized by combustion of fuel and air. As a result of heat addition the compressed air attains state 3 and it is allowed to expand from 3–4 adiabatically. After expansion air is brought back to original state 1 by extracting heat from it at volume *V*1.

Internal combustion engine based on Otto cycle is explained ahead. Let us find air-standard thermal efficiency of Otto cycle.

Compression ratio for the cycle shown can be given by the ratio of volumes of air before and after compression. It is generally denoted by *r*. For unit mass of air and properties at states given with
subscript 1, 2, 3, 4, we can write,

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

Heat added during 2–3, constant volume process

$$q_{add} = c_v \times (T3 - T2)$$

Heat rejected during 4–1, constant volume process

$$q_{rejected} = c_v \times (T4 - T1)$$

Air standard efficiency of Otto cycle

$$\eta_{otto} = \frac{\text{Net work}}{\text{Heat added}}$$

For a cycle,

Net work = Heat added – Heat rejected
$= c_v \{(T3 - T2) - (T4 - T1)\}$

Substituting in the expression for efficiency;

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

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

OR

For perfect gas, by gas laws,

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

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

And

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

From above

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

OR

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

OR

Substituting in the expression for ηotto

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

Efficiency of Diesel cycle

Diesel cycle is modified form of Otto cycle. Here heat addition process is replaced from constant volume type to constant pressure type. In a piston cylinder arrangement heat addition with piston at one position allows very little time for heat supply in Otto cycle. By having heat addition at constant pressure the sufficient time is available for heat supply in Diesel cycle. Compression ignition engines work based on Diesel cycles.

Thermodynamic processes constituting Diesel cycle are as given below.

1 – 2 = Adiabatic compression, (–ve work, W_{compr})

2 – 3 = Heat addition at constant pressure (+ve heat, Q_{add})

3 – 4 = Adiabatic expansion, (+ve work, W_{expn})

4 – 1 = Heat rejection at constant volume (–ve heat, $Q_{rejected}$)

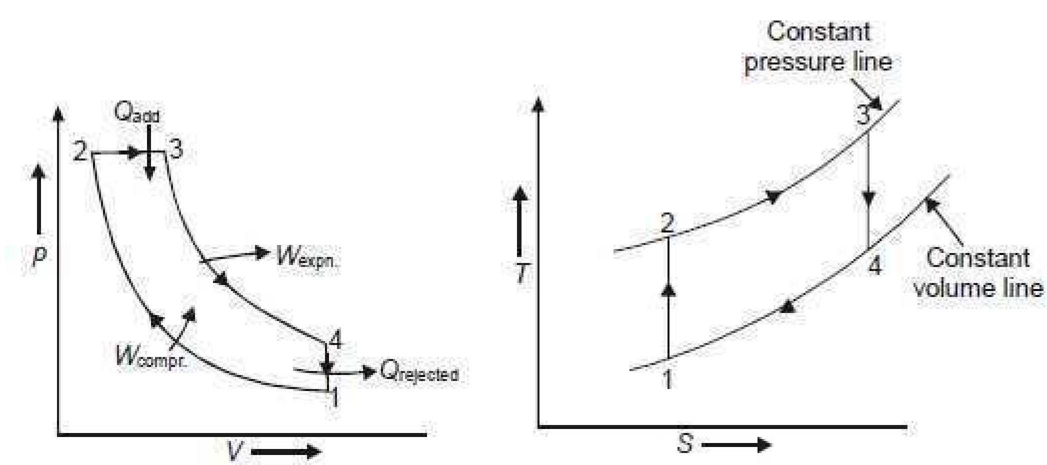

Fig.5.9 P- V Diagram And Schematic Of Diesel Engine

Thermodynamic analysis of the cycle for unit mass of air shows;

Heat added = $c_p (T_3 – T_2)$

Heat rejected = $c_v (T_4 – T_1)$

Let us assume; Compression ratio,

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

$$\text{Cut off ratio, } \rho = \frac{V_3}{V_2}$$

$$\text{Expansion ratio} = \frac{V_4}{V_3}$$

Air standard efficiency for Diesel cycle may be given as,

$$\eta_{\text{diesel}} = \frac{\text{heat added} - \text{heat rejected}}{\text{heat added}}$$

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

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

Using perfect gas equation and governing equation for thermodynamic process 1 –2;

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

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$$

Combining above two, we get

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

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

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

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

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

$$T_3 = T_2 \cdot \rho$$

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

Also for adiabatic process 3 – 4 combining the following:

$$\frac{p_3 V_3}{T_3} = \frac{p_4 V_4}{T_4} \cdot \text{and } p_3 V_3^{\gamma} = p_4 V_4^{\gamma}$$

We get,

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

Or,

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

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

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

$$T_4 = T_1 \cdot \rho \cdot r^{\gamma-1} \times \frac{\rho^{\gamma-1}}{r^{\gamma-1}}$$

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

Substituting T_2, T_3 and T_4 as function of T_1, r, ρ and γ in the expression of air standard efficiency of Diesel

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

Cycle.

Efficiency of Dual cycle:

It is also called 'mixed cycle' or 'limited pressure cycle.' Dual cycle came up as a result of certain merits and demerits associated with Otto cycle and Diesel cycle due to heat addition occurring at constant volume and constant pressure respectively.

Dual cycle is the combination of Otto cycle and Diesel cycle in which heat addition takes place partly at constant volume and partly at constant pressure.

Thermodynamic processes involved in Dual cycle are given as under.

1 – 2 = Adiabatic compression (–ve work, *W*compr)
2 – 3 = Heat addition at constant volume (+ve heat, *Q*add, *v*)
3 – 4 = Heat addition at constant pressure (+ve heat, *Q*add, ρ)
4 – 5 = Adiabatic expansion (+ve work, *W*expn)
5 – 1 = Heat rejection at constant volume (–ve heat, *Q*rejected)

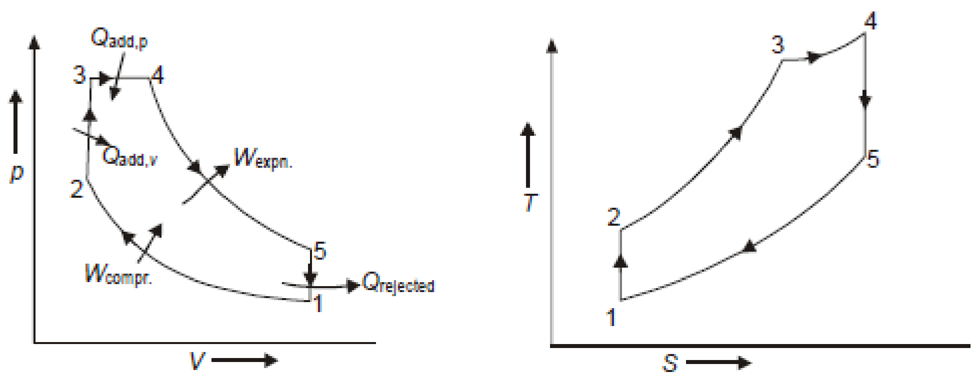

Fig.3.10 P - V and T - S Representations of Dual Cycle

Let us assume for following thermodynamics analysis:
Clearance Volume = Unity

Compression Ratio, $r = V_1/V_2$

Cut-off Ratio, $\rho = V_3/V_4$

Pressure ratio during Heat Addition, α = P3/P2

For unit mass of air as working fluid throughout the cycle.
Total Heat added = Heat added at Constant Volume (2 - 3) + Heat added at Constant Pressure (3 - 4)

$$Q_{add} = C_v\,(T_3 - T_2) + C_p\,(T_4 - T_3)$$

$$Q_{rejected} = C_v\,(T_5 - T_1)$$

Air standard efficiency for Dual Cycle can be given as:

$$\eta_{dual} = \text{(Heat Added - Heat Rejected) / (Heat Added)}$$

$$\eta_{dual} = [\{C_v(T_3 - T_2) + C_p\,(T_4 - T_3)\} - \{C_v\,(T_5 - T_1)\}] \,/\, [C_v(T_3 - T_2) + C_p\,(T_4 - T_3)]$$

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

From gas laws applied to process 2–3,

$$P_3 / T_3 = P_2 / T_2$$
$$\text{Or, } T_2 = (P_2 \times T_3) / P_3$$
$$T_2 = T_3 / \alpha$$

For process 3–4,

$$V_4 / T_4 = V_3 / T_3$$
$$T_4 = (V_4 \times T_3) / V_3$$
$$T_4 = \rho T_3$$

For adiabatic process 4–5,

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

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

$$T_5 = \frac{T_4 \cdot \rho^{\gamma-1}}{r^{\gamma-1}}$$

Substituting T_4

$$T_5 = \frac{T_3 \cdot \rho^{\gamma}}{r^{\gamma-1}}$$

For adiabatic Process 1-2,

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

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

Substituting for T_2

$$T_1 = \frac{T_3}{\alpha \cdot r^{\gamma-1}}$$

Substituting for T_1, T_2, T_4 and T_5 in expression for efficiency,

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

For unity cut off ratio i. e. absence of 3-4 process, cycle becomes equal to Otto Cycle
i. e. For $\rho = 1$, $\eta_{dual} = 1 - 1 / r^{\gamma-1} = \eta_{otto}$
For the pressure ratio α being unity, cycle gets modified to Diesel Cycle,
i. e. for $\alpha = 1$, $\eta_{dual} = 1 - (\rho^{\gamma} - 1) / \gamma \times r^{\gamma-1} \times (\rho - 1) = \eta_{diesel}$

