Air Standard Cycles - Reciprocating Internal Combustion Engines

Presentation Outline

- Overview
- Otto Cycle
- Diesel Cycle
- Dual / Mixed Cycle
- Ideal Cycle Efficiency
- Mean Effective Pressure

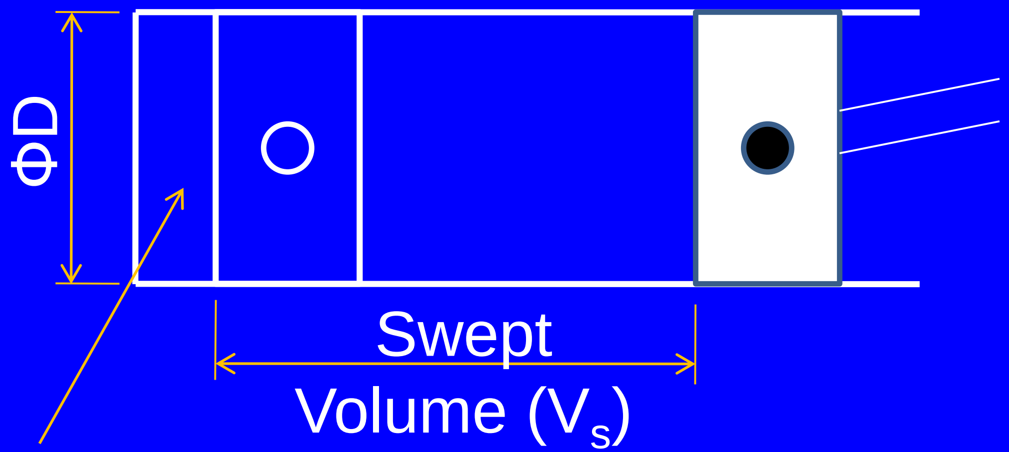
Overview

- Cycles related to reciprocating internal combustion engines are considered in this case.
- A given mass of working fluid can be taken through a series of processes in a cylinder fitted with a reciprocating piston.
- Such processes are much more nearly reversible than the rapid flow processes occurring in a turbine or a rotary compressor.

Overview contd..

- One important advantage of the reciprocating engine is that the maximum permissible temperature of the working fluid is much higher than it is in a turbine plant.
- The main disadvantage is the comparatively low rate at which it can handle the working fluid. This feature makes it excessively bulky and heavy when large power outputs are required.
- In standard cycles the working fluid considered is air.

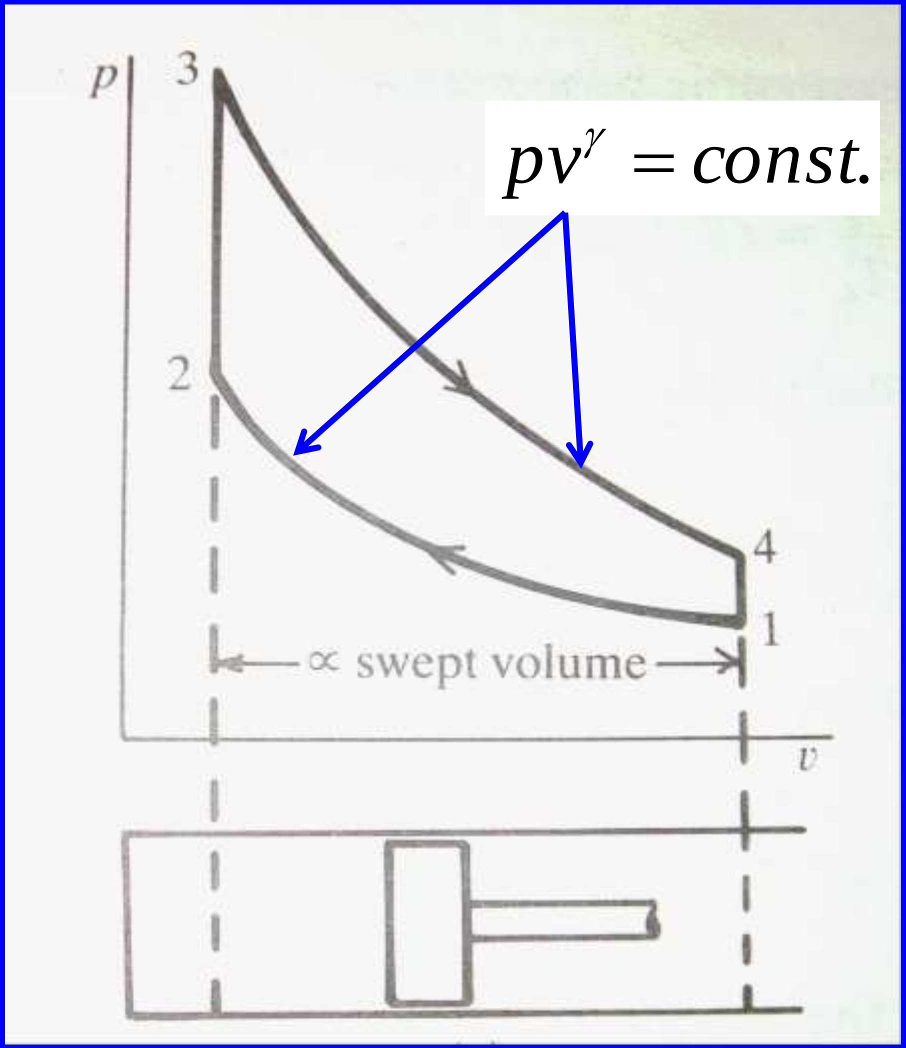
Reciprocating IC Engine Notations



D – Bore Diameter

Total Volume = $V_c + V_s$

Otto Cycle



Otto Cycle contd..

- Otto cycle forms the basis of spark-ignition and high speed compression-ignition engines.
- The processes are as follows
  - 1 – 2 Air is compressed isentropically through a volume ratio v_1/v_2, known as the compression ratio r_v.
  - 2 – 3 A quantity of heat Q_{23} is added at constant volume until it reaches state 3.
  - 3 – 4 Air is expanded isentropically to the original volume.
  - 4 – 1 Heat Q_{41} is rejected at constant volume until the cycle is completed.

Otto Cycle contd..

- The Efficiency of the cycle is

$$\eta = \frac{|W|}{|Q_{23}|} = \frac{|Q_{23}| - |Q_{41}|}{|Q_{23}|}$$

- Assuming constant specific heat capacities for air and considering unit mass of fluid, the heat transfers are:

$$|Q_{23}| = c_v(T_3 - T_2)$$ and $$|Q_{41}| = c_v(T_4 - T_1)$$

- Consequently

$$\eta = 1 - \left(\frac{T_4 - T_1}{T_3 - T_2} \right)$$

Otto Cycle contd..

- For the two isentropic processes

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

- By algebraic manipulation we then have

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

- Hence the Ideal Cycle Efficiency becomes

$$\eta = \frac{T_3-T_4}{T_3}$$

Otto Cycle contd..

- Also $T_3 = T_4 r_v^{\gamma-1}$ and $T_2 = T_1 r_v^{\gamma-1}$

- Hence by substitution

$$\eta = 1 - \left(\frac{T_4 - T_1}{T_3 - T_2} \right)$$

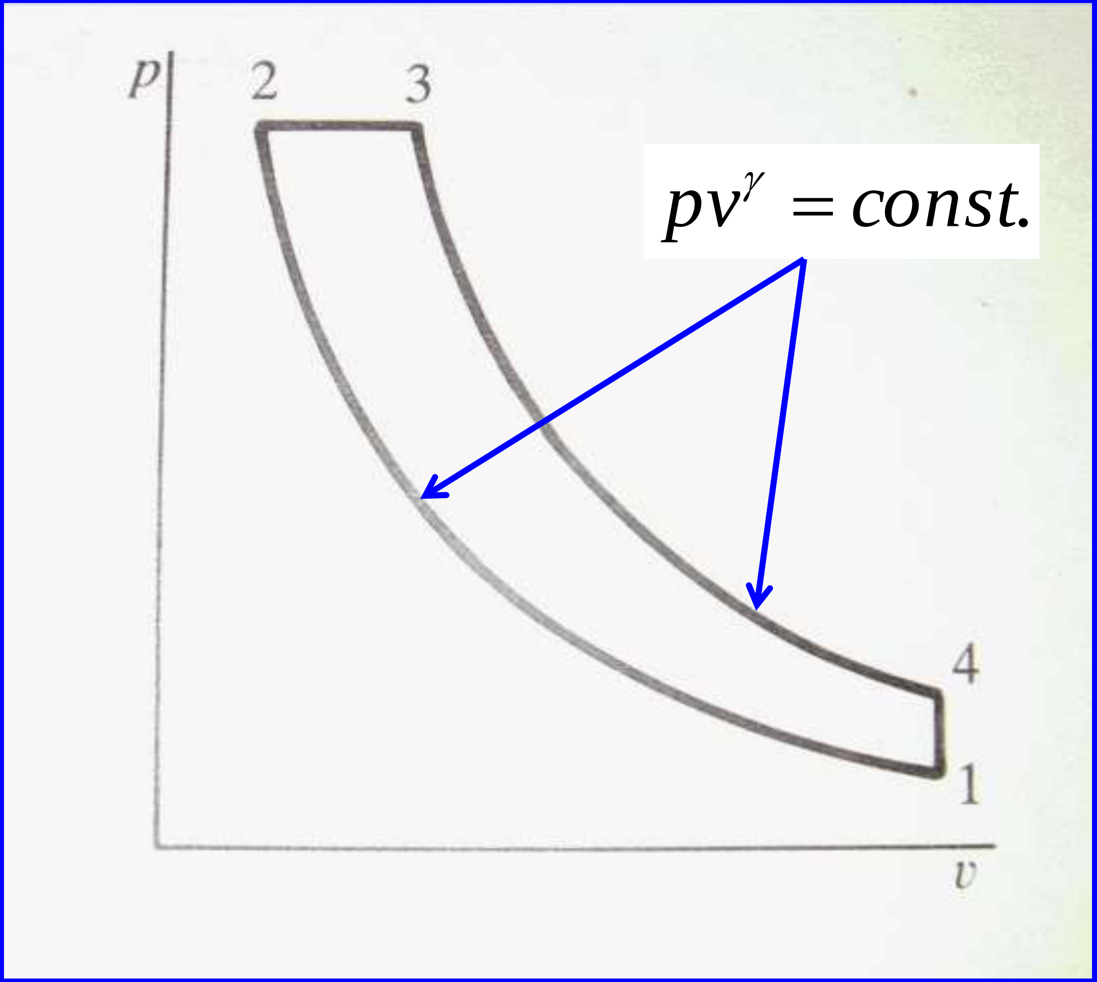
$$\eta = 1 - \left[\frac{T_4 - T_1}{(T_4 - T_1) r_v^{\gamma-1}} \right]$$

$$\eta = 1 - \frac{1}{r_v^{\gamma-1}}$$

Otto Cycle contd..

- The maximum possible efficiency is based upon the maximum and minimum temperatures of the cycle, i.e. Carnot Efficiency is $(T_3 – T_1)/ T_3$.
- The ideal cycle efficiency is less than the Carnot efficiency since the heat addition and rejection do not take place at the upper and lower temperatures.
- Cycle efficiency depends only on the compression ratio.

Diesel Cycle



Diesel Cycle contd..

- Diesel cycle forms the basis of moderate and low speed compression-ignition engines.
- The processes are as follows
  - 1 – 2 Air is compressed isentropically through the compression ratio $r_v = v_1/v_2$.
  - 2 – 3 A quantity of heat Q_{23} is added while the air expands at constant pressure to volume v_3. At state 3 the heat supply is cut off.
  - 3 – 4 Air is expanded isentropically to the original volume.
  - 4 – 1 Heat Q_{41} is rejected at constant volume until the cycle is completed.

Diesel Cycle contd..

- The Efficiency of the cycle is

$$\eta = \frac{|W|}{|Q_{23}|} = \frac{|Q_{23}| - |Q_{41}|}{|Q_{23}|}$$

- Assuming constant specific heat capacities for air and considering unit mass of fluid, the heat transfers are:

$$|Q_{23}| = c_p (T_3 - T_2)$$ and $$|Q_{41}| = c_v (T_4 - T_1)$$

- Consequently

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

Diesel Cycle contd..

- Compression Ratio $$r_v = \frac{v_1}{v_2}$$
- Cut-off Ratio $$r_c = \frac{v_3}{v_2}$$
- Hence $$\frac{T_2}{T_1} = r_v^{\gamma-1}$$ and $$T_1 = T_2\left(\frac{1}{r_v}\right)^{\gamma-1}$$
- For the constant pressure process

$$\frac{T_3}{T_2} = r_c \qquad T_3 = r_c T_2$$

Diesel Cycle contd..

- Also

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \left(\frac{v_3 v_2}{v_2 v_4}\right)^{\gamma-1} = \left(\frac{r_c}{r_v}\right)^{\gamma-1}$$

- Hence

$$T_4 = r_c T_2 \left(\frac{r_c}{r_v}\right)^{\gamma-1}$$

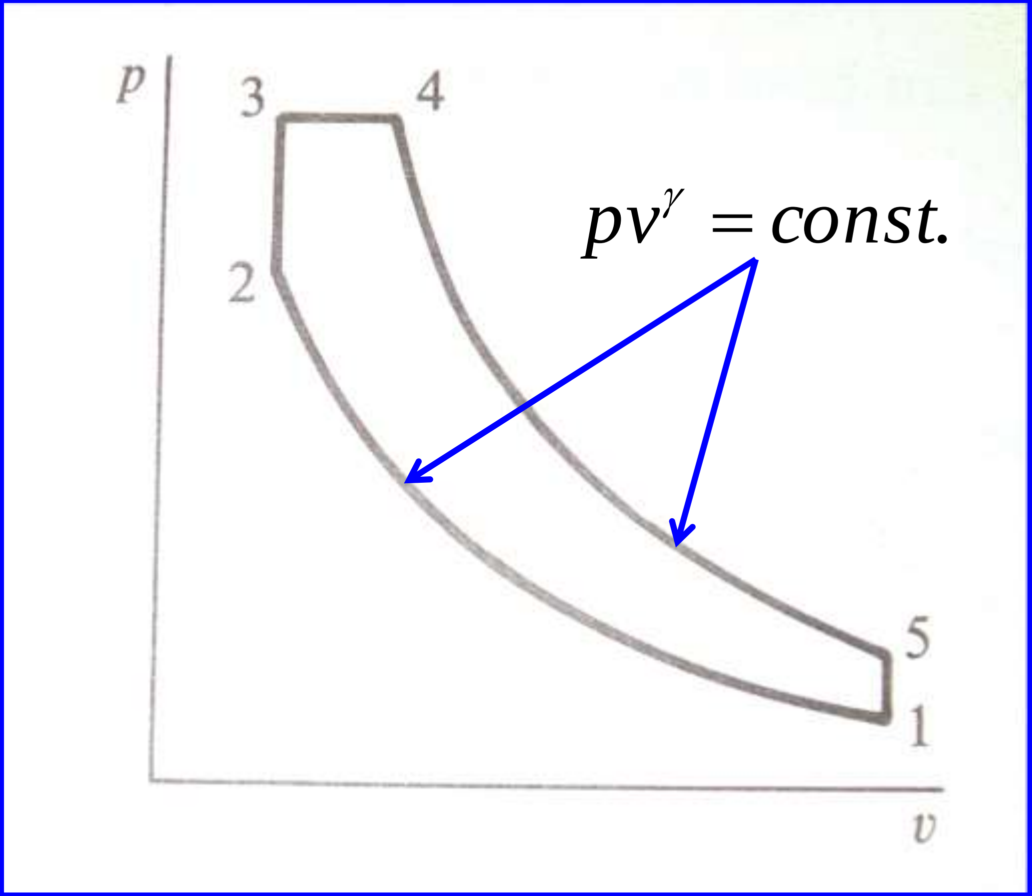
- Substituting for T_1, T_3 and T_4 we have

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

Diesel Cycle contd..

- The efficiency of the Diesel cycle depends upon cut-off ratio (r_c) and hence upon the quantity of heat added, as well as on the compression ratio (r_v).

Dual / Mixed Cycle



Dual / Mixed Cycle contd..

- The behaviour of many reciprocating engines is more adequately represented by the dual or mixed cycle.
- In this cycle part of the heat addition occurs during a constant volume process and the remainder during a constant pressure process.

Dual / Mixed Cycle contd..

- By expressing

$$r_v = \frac{v_1}{v_2} \qquad r_c = \frac{v_4}{v_3} \qquad r_p = \frac{p_3}{p_2}$$

it is possible to show that the cycle efficiency is given by

$$\eta = 1 - \frac{1}{r_v^{\gamma-1}} \left[\frac{r_p r_c^{\gamma} - 1}{\left(r_p - 1\right) + \gamma r_p \left(r_c - 1\right)} \right]$$

Dual / Mixed Cycle contd..

- They have been drawn for the case where both the compression ratios and the heat inputs are the same for each.
- Hence it can be concluded that the air standard cycle efficiencies decrease in the order Otto, Mixed, Diesel.

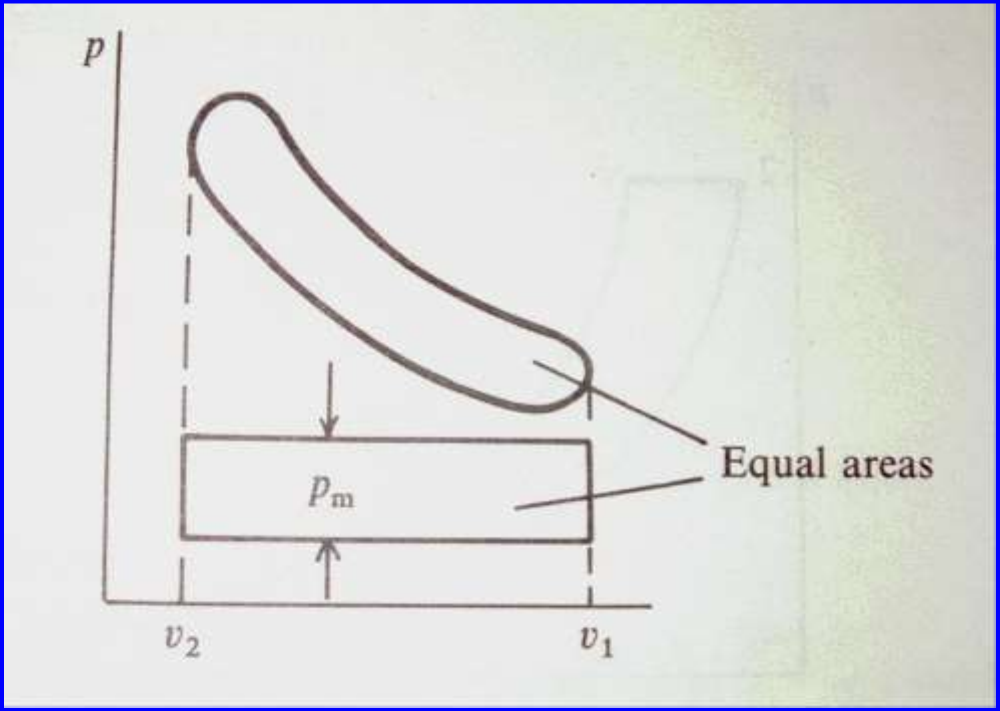
$$\eta_{Otto} > \eta_{Mixed} > \eta_{Diesel}$$

Mean Effective Pressure

- This is defined in order to compare the performance of reciprocating engines

- The Mean Effective Pressure (p_m) is defined as the height of a rectangle on the p-v diagram having the same length and area as the cycle.

Mean Effective Pressure contd..



Hence $$p_m(v_1 - v_2) = \oint p\,dv = |W|$$

W – Net work output per unit mass of fluid

Mean Effective Pressure contd..

- The Mean Effective Pressure gives a measure of the work output per unit swept volume.
- Hence it can be used to compare the performance of reciprocating engines of similar configuration but of different size.