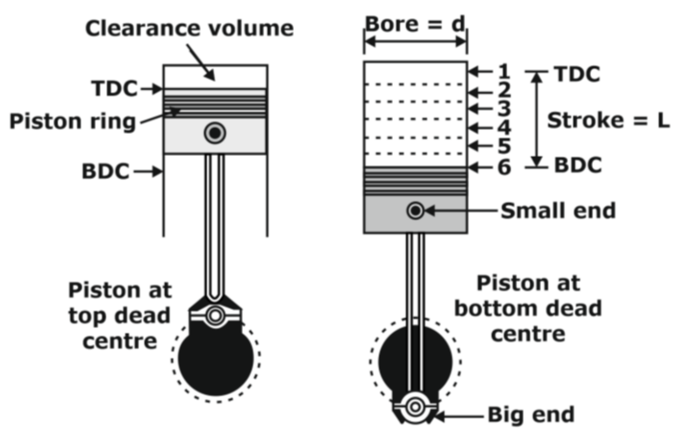
CHAPTER-1 AIR STANDARD CYCLE

NOMANCLATURE OF AN INTERNAL COMBUSTION ENGINE

- **Cylinder Bore(d)-** Nominal inner diameter of the working cylinder.
- **Piston Area (A)-** Cross-sectional area of cylinder $A = \frac{\pi}{4}d^2$
- **Stroke (L)-** Nominal distance b/w Top Dead centre & Bottom Dead centre, piston reciprocates
- **Stroke to Bore Ratio (L/d)**- important parameter in classifying the size of the engine.

  If $\frac{L}{d} > 1 \rightarrow$ under-square engine | If $\frac{L}{d} = 1 \rightarrow$ square engine | If $\frac{L}{d} < 1 \rightarrow$ over-square engine

- **Dead Centre-** Position of piston when direction of piston motion is reversed at either end
  - **Top Dead Centre (TDC) or Inner Dead Centre (IDC) -** when piston is farthest from the crankshaft or nearest to cylinder head.
  - **Bottom Dead Centre (BDC) or Outer Dead Centre (ODC) -** when piston is nearest to the crankshaft or farthest from the cylinder head.

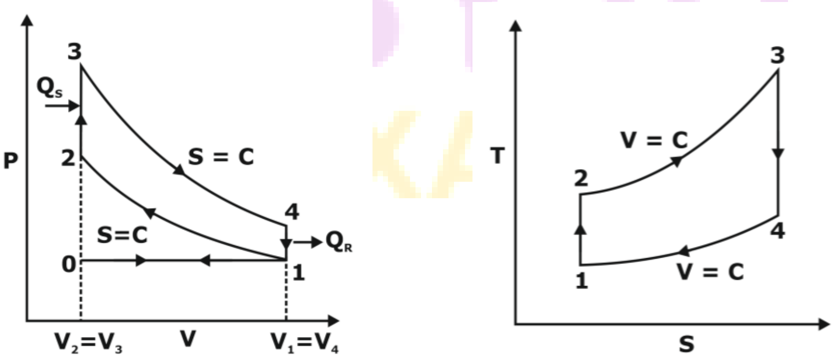


- **Displacement or Swept Volume (V_s)-** Volume swept by piston when travelling b/w TDC and BDC. $Swept\ \text{Volume} = V_s = A \times L = \frac{\pi}{4}d^2L$
- **Engine Capacity**- Displacement volume of a cylinder multiplied by number of cylinders in an engine will give the engine capacity. It is also known as cubic capacity.
- **Clearance Volume (V_c)**- Gap b/w piston (when piston at TDC) & cylinder head.

- **Compression Ratio (r)-** Ratio of the total cylinder volume (when piston at BDC) to clearance volume. $r = \frac{V_{Total}}{V_C} = \frac{V_C + V_S}{V_C} = 1 + \frac{V_S}{V_C}$

CONSTANT VOLUME OR OTTO CYCLE

- Nicolaus Otto (1876), proposed a constant-volume heat addition cycle
- theoretical cycle for the spark-ignition engine or petrol engine or gasoline engine.
- mixture of fuel and air is used as charge at inlet
- Working of otto cycle –
    - **Processes 0→1 and 1→0** Suction and exhaust processes (nullified effect on full throttle)
    - **Process 1→2** isentropic compression of charge
    - **Process 2→3** heat is supplied reversibly at constant volume (corresponds to spark-ignition)
    - **Processes 3→4** isentropic expansion
    - **Process 4→1** constant volume heat rejection



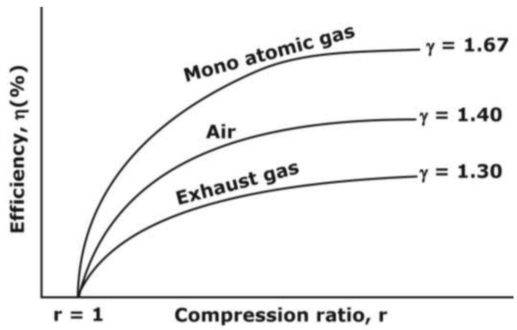
$$\text{Swept volume} = (V_1 - V_2) = V_2\left(\frac{V_1}{V_2} - 1\right) = V_2\,(r-1)$$

Compression ratio $r = \frac{V_S + V_c}{V_C} = \frac{V_1}{V_2}, \Rightarrow \frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{V_1}{V_2}\right)^{(\gamma-1)} = (r)^{(\gamma-1)}$

Expansion ratio $r_e = \frac{V_4}{V_3}, \;\Rightarrow r = r_e$

- **Efficiency** $\eta_{otto} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{C_v\,(T_4 - T_1)}{C_v\,(T_3 - T_2)} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{(\gamma-1)}}$

It is function of compression ratio r and the ratio of specific heats, γ & independent of heat supplied and pressure ratio. The normal range of compression ratio for spark-ignition engines is 6 to 10.



- **Work Output** $W_{net} = W_{1\to2} + W_{3\to4} = \frac{P_1V_1}{\gamma - 1}(r_P - 1)(r^{\gamma-1} - 1)$

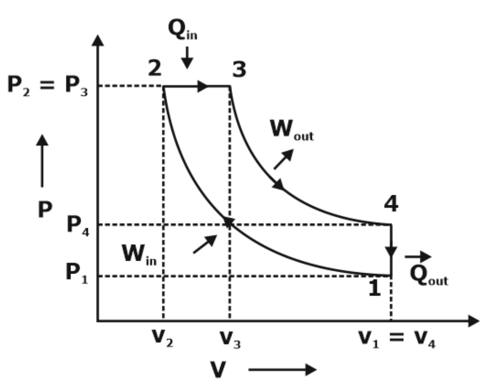
  directly proportional to pressure ratio, r_p.

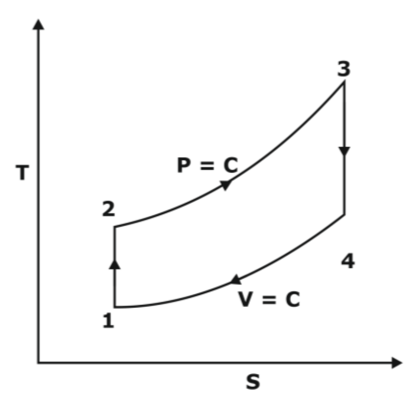
- **Mean effective pressure** $P_{MEP} = \frac{\text{Work output}}{\text{Swept volume}} = \frac{P_1 r(r_p - 1)(r^{\gamma-1} - 1)}{(\gamma - 1)(r - 1)}$

  increase in compression ratio leads to increase in MEP as well as the thermal efficiency.

CONSTANT PRESSURE OR DIESEL CYCLE

- To overcome upper limit of compression ratio in SI engine, air and fuel are compressed separately and brought together at the time of combustion. It is working principal of CI engine.
- Working of Diesel cycle-
  - **Process 1→2** isentropic compression of the air
  - **Process 2→3** heat is supplied reversibly at constant pressure (corresponds to injection of fuel)
  - **Processes 3→4** isentropic expansion
  - **Process4→1** constant volume heat rejection





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

Compression ratio $r = \frac{V_S + V_c}{V_C} = \frac{V_1}{V_2}, \Rightarrow \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{(\gamma-1)} = (r)^{(\gamma-1)}$

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

Cut off ratio, $\rho = \frac{\text{volume after heat addition}}{\text{Volume before heat addition}} = \frac{V_3}{V_2}, \Rightarrow r = \rho \times r_e$

- **Efficiency** $\eta_{Diesel} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{C_v(T_4 - T_1)}{C_P(T_3 - T_2)} = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{\rho^\gamma - 1}{\gamma(\rho - 1)}\right]$

  Value bracketed factor is always greater than unity.

  Fuel cut-off ratio ρ depends on output, thus for maximum output ρ is maximum.

  Unlike the Otto cycle the air-standard efficiency of the Diesel cycle depends on output.

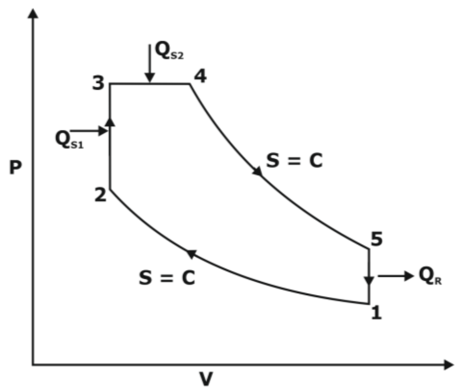
  The normal range of compression ratio for diesel engine is 16 to 20.

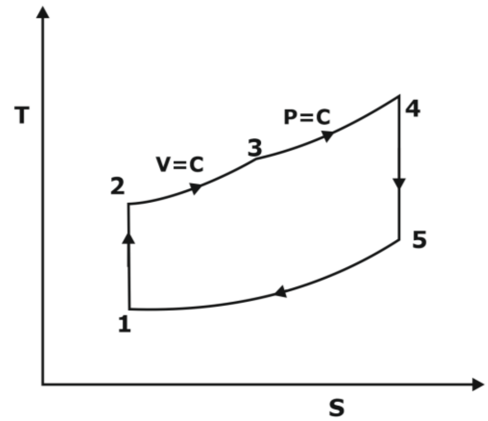
- **Work Output** $W_{net} = W_{1\to2} + W_{2\to3} + W_{3\to4} = \frac{P_1V_1r^{(\gamma-1)}\left[\gamma(\rho-1) - r^{(1-\gamma)}(\rho^\gamma - 1)\right]}{\gamma - 1}$

- **Mean effective pressure** $P_{MEP} = \frac{\text{Work output}}{\text{Swept volume}} = \frac{P_1[\gamma r^\gamma(\rho-1) - r(\rho^\gamma - 1)]}{(\gamma-1)(r-1)}$

DUAL COMBUSTION OR MIXED OR LIMITED PRESSURE CYCLE

- In this cycle, part of the heat addition is at constant volume and remaining at constant pressure
- Heat addition at constant volume tends to increase the efficiency of the cycle whereas switching over to constant pressure heat addition limits the maximum pressure. Hence, this cycle is also called limited pressure cycle.





$$\text{Swept volume} = (V_1 - V_2) = V_2\left(\frac{V_1}{V_2} - 1\right) = V_2\,(r - 1)$$

Compression ratio $r = \dfrac{V_S + V_c}{V_C} = \dfrac{V_1}{V_2},\ \Rightarrow \dfrac{T_2}{T_1} = \left(\dfrac{V_1}{V_2}\right)^{(\gamma-1)} = (r)^{(\gamma-1)}$

Expansion ratio $r_e = \dfrac{V_5}{V_4}$

Cut off ratio, $\rho = \dfrac{\text{volume after heat addition}}{\text{Volume before heat addition}} = \dfrac{V_4}{V_3},\ \Rightarrow r = \rho \times r_e$

Pressure ratio $\alpha = \dfrac{P_3}{P_2}$

- **Efficiency** $\eta_{Dual} = 1 - \dfrac{Q_R}{Q_S} = 1 - \dfrac{C_v\,(T_5 - T_1)}{C_v\,(T_3 - T_2) + C_P\,(T_3 - T_3)} = 1 - \dfrac{1}{r^{\gamma - 1}}\left[\dfrac{\alpha\,\rho^{\gamma} - 1}{(\alpha - 1) + \alpha\,\gamma\,(\rho - 1)}\right]$

  Value of α > 1 results in an increased efficiency for a given value of ρ and γ.

  Thus, efficiency of dual cycle lies between that of Otto cycle and diesel cycle.

  With ρ = 1, it becomes an Otto cycle. With α = 1, it becomes a Diesel cycle.

- **Work Output** $W_{net} = W_{1\to2} + W_{3\to4} + W_{4\to5} = \dfrac{P_1V_1}{\gamma - 1}\left[\gamma\alpha r^{\gamma-1}(\rho - 1) + r^{\gamma-1}(\alpha - 1) - (\alpha\rho^{\gamma} - 1)\right]$

- **Mean effective pressure** $P_{MEP} = \dfrac{Work\ output}{Swept\ volume} = P_1\dfrac{[\gamma\alpha r^{\gamma}(\rho-1) + r^{\gamma}(\alpha-1) - r(\alpha\rho^{\gamma}-1)]}{(\gamma-1)(r-1)}$

COMPARISON OF OTTO, DIESEL, AND DUAL CYCLES

➢ **For same compression ratio and same heat input**

Otto cycle allows working medium to expand more (to lower pressure) compare to Diesel cycle. So, heat energy converted into work is more in otto cycle due to more expansion.

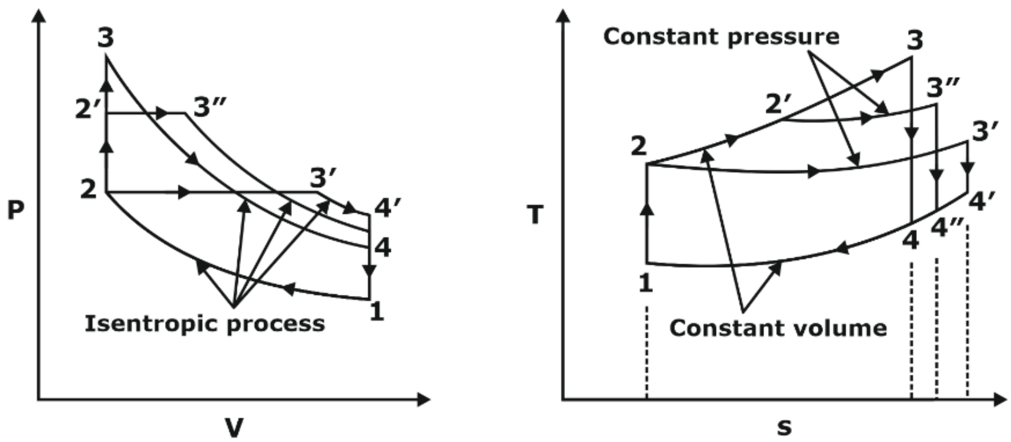
Otto cycle 1→2→3→4→1,

Diesel cycle1→2→3′→4′→1

Dual cycle 1→2→2′→3″ →4″ →1

$\Rightarrow Q_{R_{otto}} < Q_{R_{dual}} < Q_{R_{diesel}}$

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



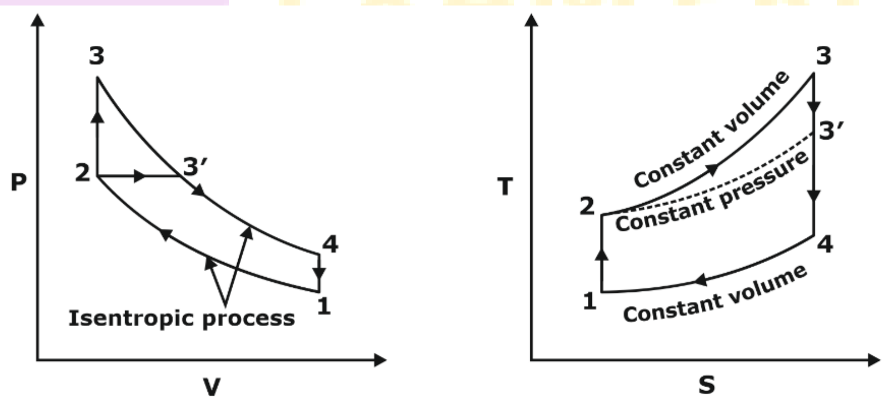
- **Same Compression Ratio and Heat Rejection**

Otto cycle 1→2→3→4→1,

Diesel cycle1→2→3′→4→1

$\Rightarrow Q_{S_{otto}} > Q_{S_{dual}} > Q_{S_{diesel}}$

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



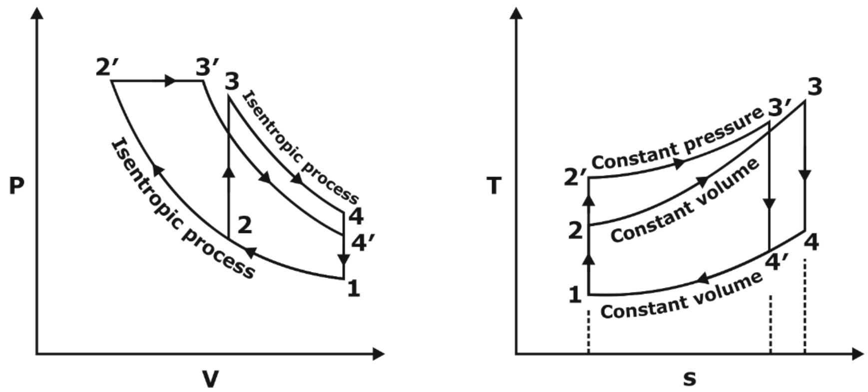
- **For constant maximum pressure and same heat input**

Otto cycle 1→2→3→4→1

Diesel cycle 1→2'→3'→4'→1

$\Rightarrow Q_{R_{otto}} > Q_{R_{dual}} > Q_{R_{diesel}}$

$\Rightarrow \eta_{otto} < \eta_{dual} < \eta_{diesel}$



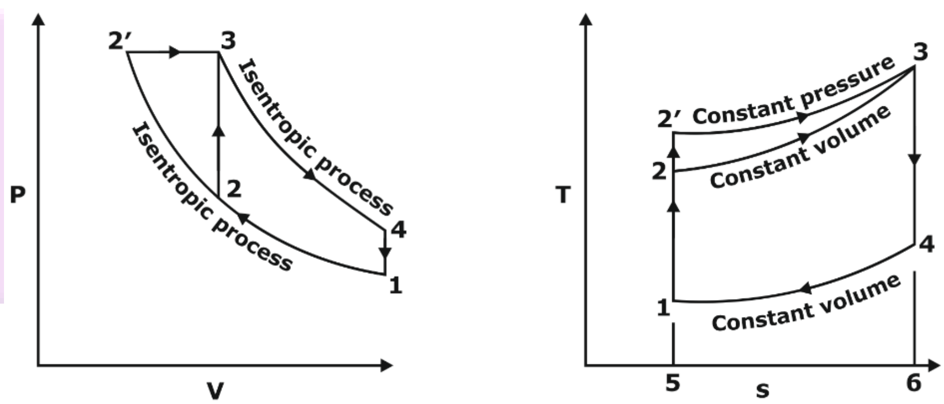
- **Same Peak Pressure, Peak Temperature and Heat Rejection**

  Otto cycle 1→2→3→4

  Diesel cycle 1→2→2′→3→4

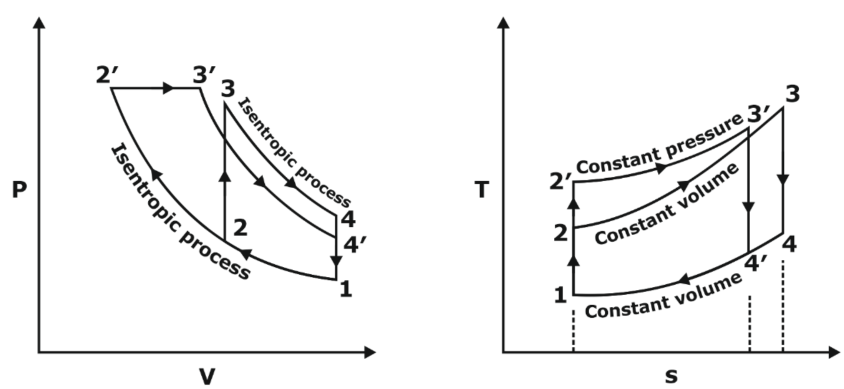
$\Rightarrow Q_{S_{otto}} < Q_{S_{dual}} < Q_{S_{diesel}}$

$\Rightarrow \eta_{otto} < \eta_{dual} < \eta_{diesel}$



- **For same maximum pressure and work output**

$\Rightarrow \eta_{otto} < \eta_{dual} < \eta_{diesel}$



CHAPTER-2 IC ENGINE PERFORMANCE PARAMETERS AND TESTING

INTRODUCTION

- To compare develop engine with other engines in terms of its output & efficiency, we need some parameters that reflect the performance of the engine.
- The performance of engine depends on inter-relationship b/w power developed, speed & specific fuel consumption at each operating condition within the useful range of speed and load.

Indicated Power (IP)

- It tells about the health of the engine. It is conversion of chemical energy of fuel into heat energy.
- Area of the indicator diagram will represent the indicated power of the engine. IP = (GP – PP)
- Indicated power also given by $IP = P_{imep}\dot{V}_s = P_{imep} \times \frac{V_S nk}{60}$

Here P_{imep} = Indicated mean effective pressure, N/m^2

$V_s = A \times L = \frac{\pi}{4} d^2 L$ Swept Volume

L = Length of stroke, (m)

d = inner diameter of piston, (m)

k = number of cylinders

n = number of power strokes per minute

(n = N/2 for a four-stroke engine, n = N for a two-stroke engine)

N= engine speed in revolutions per minute

Brake Power (BP) or shaft power or delivered power

- It is power delivered by engine at output shaft (engine crankshaft) and calculated using torque and angular speed of output shaft.
- Dynamometer is used to measure power output of an engine either by dissipating absorbed power as heat or by transmitting power to the load coupled to the engine.

$$BP = T \times \omega = T \times \frac{2\pi N}{60}$$

Here N= engine speed in revolutions per minute

T = Torque at output shaft in N-m

- Brake power also given by $BP = P_{bmep}\dot{V}_s = P_{bmep} \times \frac{V_S nk}{60}$

  Here P_{bmep} = brake mean effective pressure, N/m^2

  $V_s = A \times L = \frac{\pi}{4} d^2 L$ Swept Volume

  L = Length of stroke, (m)

  d = inner diameter of piston, (m)

  k = number of cylinders

  n = number of power strokes per minute

  (n = N/2 for a four-stroke engine, n = N for a two-stroke engine)

  N= engine speed in revolutions per minute

Frictional power (FP)

- The mechanical losses occur while transmitting work from piston to crank-shaft.

  FP = IP – BP

Indicated thermal efficiency (η_{ith})

- ratio of indicated power (IP) and heat addition by fuel per second

$$\eta_{ith} = \frac{IP}{HA_{/\sec}}$$

Brake thermal efficiency (η_{bth})

- ratio of brake power (BP) to heat addition by fuel per second
- It is also called actual efficiency of engine.

$$\eta_{bth} = \frac{BP}{HA_{/\sec}}$$

Mechanical efficiency

- Ratio of BP to IP
- It takes into account mechanical losses in an engine.
- In general, mechanical efficiency of engines varies from 65 to 85%

$$\eta_{mech} = \frac{BP}{IP} = \frac{P_{bmep}}{P_{imep}} = \frac{\eta_{bth}}{\eta_{ith}}$$

Relative Efficiency

- ratio of actual efficiency obtained from an engine to the theoretical efficiency of air-standard cycle.

$$\text{Relative efficiency},\ \eta_{rel} = \frac{\text{Actual brake thermal efficiency}}{\text{Air-standard efficiency}}$$

- Relative efficiency for most of the engines varies from 75 to 95% with theoretical air and decreases rapidly with insufficient air to about 75% with 90% air.

Specific Fuel Consumption

- It is the mass of fuel consumed in kg/hour per kW of power developed by engine.

$$bsfc = \frac{\dot{m}_f\,(in\ \text{kg/hr})}{BP(in\ \text{kW})}$$

Equivalence ratio

- Ratio of actual fuel-air ratio to stoichiometric fuel-air ratio

$$\text{Equivalence ratio } = \frac{actual\ fuel - air\ ratio}{stoichiometric\ fuel - air\ ratio}$$

Volumetric Efficiency

- it indicates the breathing capacity of the engine.
- ratio of actual mass of air drawn into engine during a given time period to the theoretical mass.

$$\eta_v = \frac{m_{act}}{m_{th}},$$

Where m_{act} = a measured quantity

$m_{th} = \rho_a n V_s$,

n = number of power strokes per minute

(n = N/2 for a four-stroke engine, n = N for a two-stroke engine)

N= engine speed in revolutions per minute

ρ_a = density of the surrounding atmosphere.

$V_s = A \times L = \frac{\pi}{4} d^2 L k$ Swept Volume

L = Length of stroke, (m)

d = inner diameter of piston, (m)

k = number of cylinders

Mean Effective Pressure (P_{mep})

- It is average pressure at which, if engine operates then area under this horizontal line in between TDC and BDC will be equal to the net-work of the system.
- It is a mean value expressed in N/m^2, which, when multiplied by the swept volume V_s gives the same net-work as actually produced with the varying pressures.

$$P_{mep} = \frac{Network\ output}{Swept\ volume}$$

Indicated Mean Effective Pressure (P_{imep})

- It is a mean value expressed in N/m^2, which, when multiplied by the swept volume V_s gives the same indicated net-work as actually produced with the varying pressures.

$$P_{imep} = \frac{Net\ \text{indicated}\ work\ output}{Swept\ volume}$$

BRAKE MEAN EFFECTIVE PRESSURE (P_{bmep})

- P_{imep} may be considered to consist of P_{fmep} and P_{bmep}, two **hypothetical** pressures.
- Fiction mean effective pressure is that portion of P_{imep} which is required to overcome friction losses
- Brake mean effective pressure is the portion which produces useful power delivered by the engine.

$$P_{imep} = P_{fmep} + P_{bmep}$$

MEASUREMENT OF INDICATED POWER- Morse Test

- Let total brake power is B of 4-cylinder engine

  $I_1 = B - B_1$, when engine 1 is cut-off

  $I_2 = B - B_2$, when engine 2 is cut-off

  $I_3 = B - B_3$, when engine 3 is cut-off

  $I_4 = B - B_4$, when engine 4 is cut-off

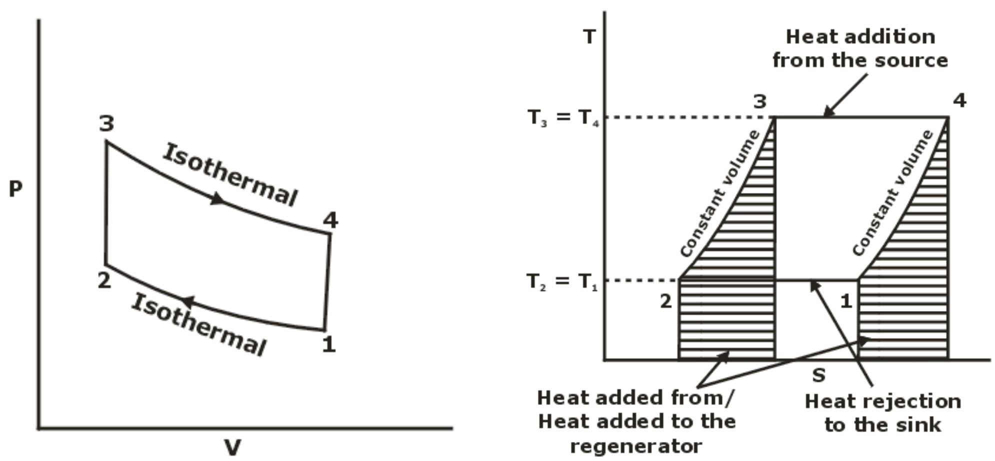
  Then the total indicated power of engine will be equal to $I=I_1+I_2+I_3+I_4$

  And Frictional Power, FP = IP- BP

CHAPTER-3 SPECIAL AIR-STANDARD CYCLE

STIRLING CYCLE

- It consists of two isothermal and two constant volume processes.
- The heat rejection and addition take place at constant temperature.
- from Figure, amount of heat addition and rejection during constant volume processes is same.

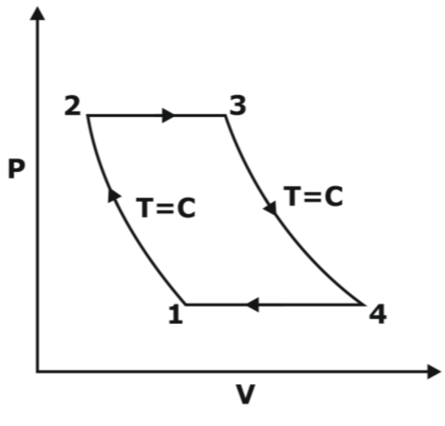


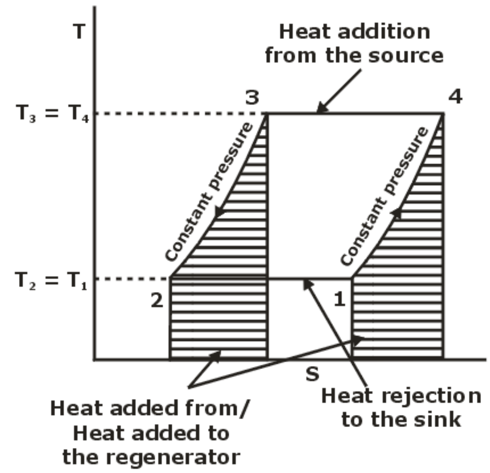
- **Thermal Efficiency** $\eta_{Stirling} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{T_1}{T_3}$

  It is same as Carnot efficiency but work output is more in case of Stirling cycle.

ERICSSION CYCLE

- The Ericsson cycle consists of two isothermal and two constant pressure processes.
- The heat addition and rejection take place at constant pressure as well as isothermal processes.
- from Figure, amount of heat addition and rejection during constant pressure processes is same.





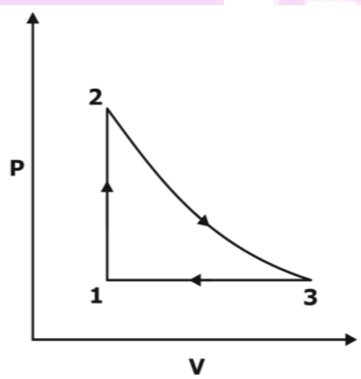
LENOIR CYCLE

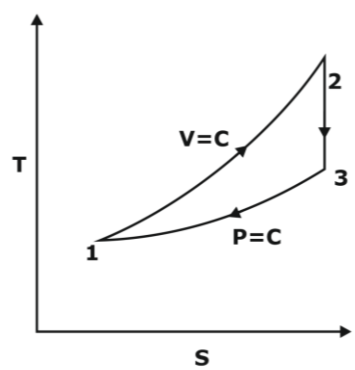
- The Lenoir cycle consists of the 3 processes to complete its cycle.

  Process 1→2 - Constant volume heat addition

  Process 2→3 - isentropic expansion

  Process 3→1 - constant pressure heat rejection





$$\frac{P_2}{P_1} = \frac{P_2}{P_3} = r_p = \frac{T_2}{T_1} \Rightarrow T_2 = r_p T_1$$

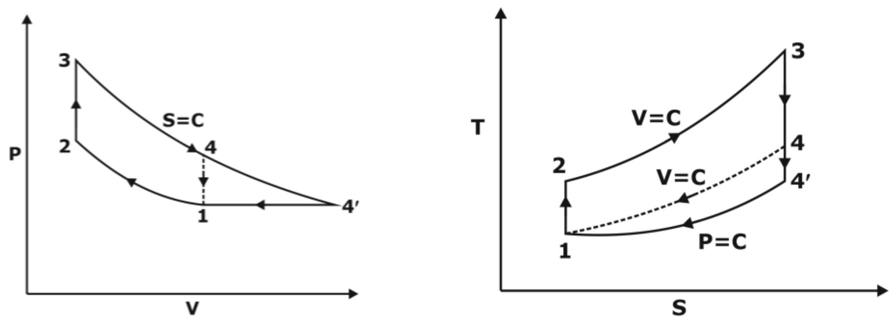
- **Thermal Efficiency**

$$\eta_{Lenoir} = 1 - \frac{Q_R}{Q_S} = 1 - \gamma\left(\frac{T_3 - T_1}{T_2 - T_1}\right) = 1 - \gamma\left(\frac{T_1\,\alpha^{1/\gamma} - T_1}{T_1\,\alpha - T_1}\right) = 1 - \gamma\left(\frac{\alpha^{1/\gamma} - 1}{\alpha - 1}\right)$$

efficiency of Lenoir cycle depends upon the pressure ratio as well as the ratio of specific heats, γ.

ATKINSON CYCLE

- Atkinson cycle is an ideal cycle for Otto engine exhausting to a gas turbine.



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

Expansion ratio $r_e = \frac{V_{4'}}{V_3}$

Thermal Efficiency $\eta_{Atkinson} = 1 - \frac{Q_R}{Q_S} = 1 - \gamma\left(\frac{T_{4'} - T_1}{T_3 - T_2}\right) = 1 - \gamma\left[\frac{r_e - r}{r_e^{\gamma} - r^{\gamma}}\right]$