4024 THERMAL ENGINEERING

MODULE 2

SALEEM N
LECTURER IN ME, KGPTC

- **MODULE II**
- **2.1.0 Appreciate the air standard cycles**
- 2.1.1 Analyze the Air standard Cycles
- 2.1.2 Define Air standard Cycles
- 2.1.3 State the assumptions made in Air standard cycles.
- 2.1.4 Define Air standard efficiency.
- 2.1.5 Illustrate with P-V, T-S diagrams Carnot cycle, Otto Cycle, Diesel Cycle, Dual combustion Cycle,
- Joule Cycle
- 2.1.6 Derive the expressions for Air standard efficiency of Carnot cycle, Otto Cycle, Diesel Cycle and
- joule cycle.
- 2.1.7 Compute the air standard efficiency using standard expressions.
- **2.2.0 Explain the working of IC Engines with PV, TS, valve timing and port timing diagrams**
- 2.2.1 Review the working of the petrol & diesel engines (both 2 Stroke & 4 Stroke) Explain the
- working of four stroke IC engine with the help of hypothetical P-V diagram.
- 2.2.2 Explain the Valve timing diagrams for the petrol and diesel engines. (both 2 Stroke & 4 Stroke)

AIR STANDARD CYCLE

- An air standard cycle is an idealized cycle in which air is taken as the working fluid.
- The actual combustion process is replaced by a heat transfer process and the exhaust process is replaced by a heat rejection process.
- All the processes are assumed to be reversible.
- A part of heat transferred to the air is converted into useful work and the remainder is rejected.
- Since the workdone by the air is equal to the difference between the heat supplied and heat rejected, if there is no mechanical losses.
- Workdone during a cycle = Heat supplied – Heat rejected

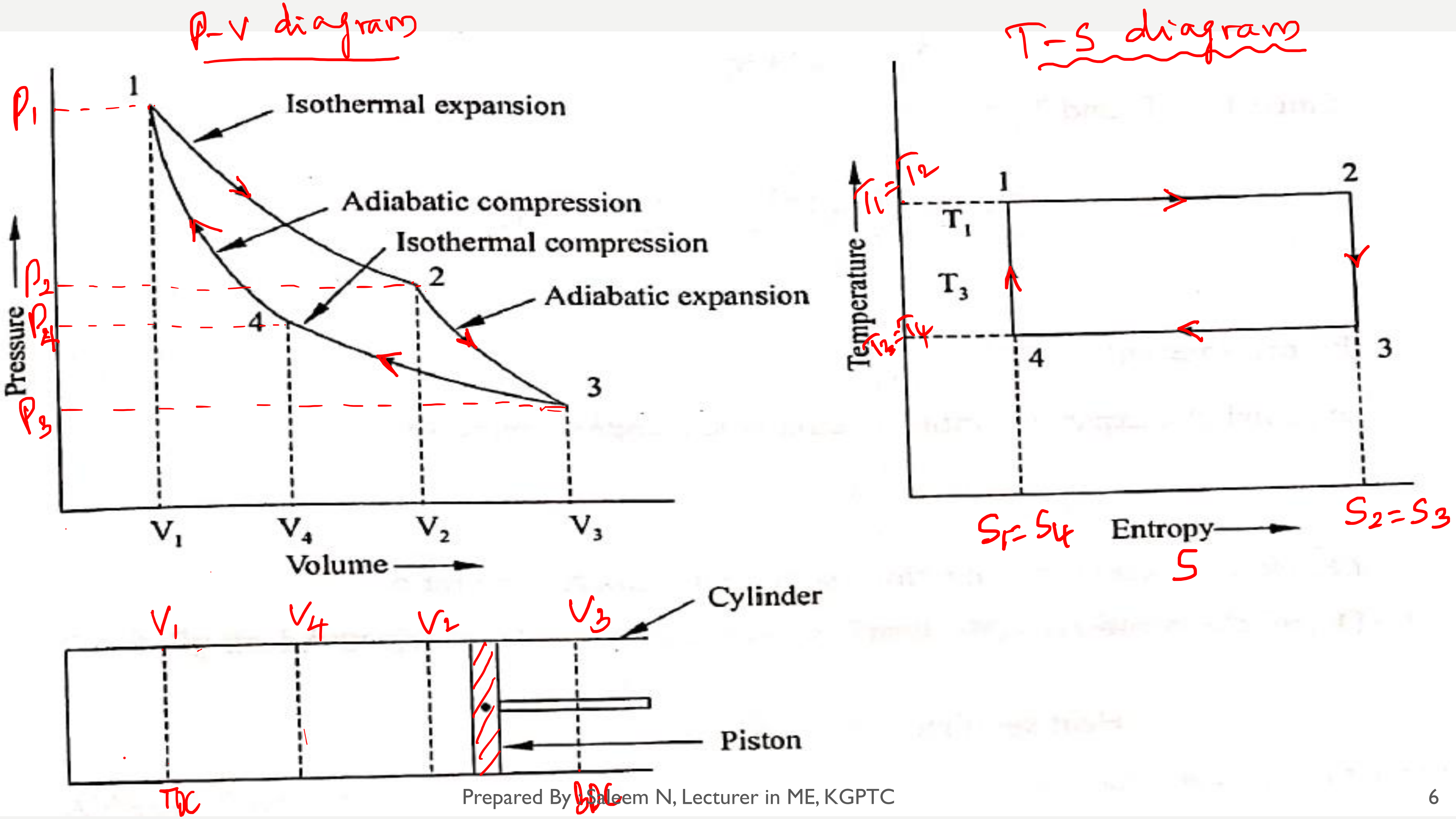
ASSUMPTIONS MADE IN AIR STANDARD CYCLE

- Air is used as a working fluid.
- The air used is a perfect gas. There for it obeys all the gas laws.
- There is no chemical reaction inside the engine cylinder.
- Specific heat at constant pressure and specific heat at constant volume does not change with respect to temperature.
- Mass flow rate of air remains constant throughout the cycle (no loss of air is present). Ie, cycle is considered to be a closed one.

AIR STANDARD EFFICIENCY

- Thermal efficiency of a cycle may be defined as the ratio of the workdone to the heat supplied during the cycle.
- The thermal efficiency obtained with air as the working fluid is known as air standard efficiency.
- Air standard efficiency, $\eta = \dfrac{Workdone}{Heat\ supplied}$
- $= \dfrac{Heat\ supplied - Heat\ rejected}{Heat\ supplied}$
- $\eta = 1 - \dfrac{Heat\ rejected}{Heat\ supplied}$

CARNOT CYCLE



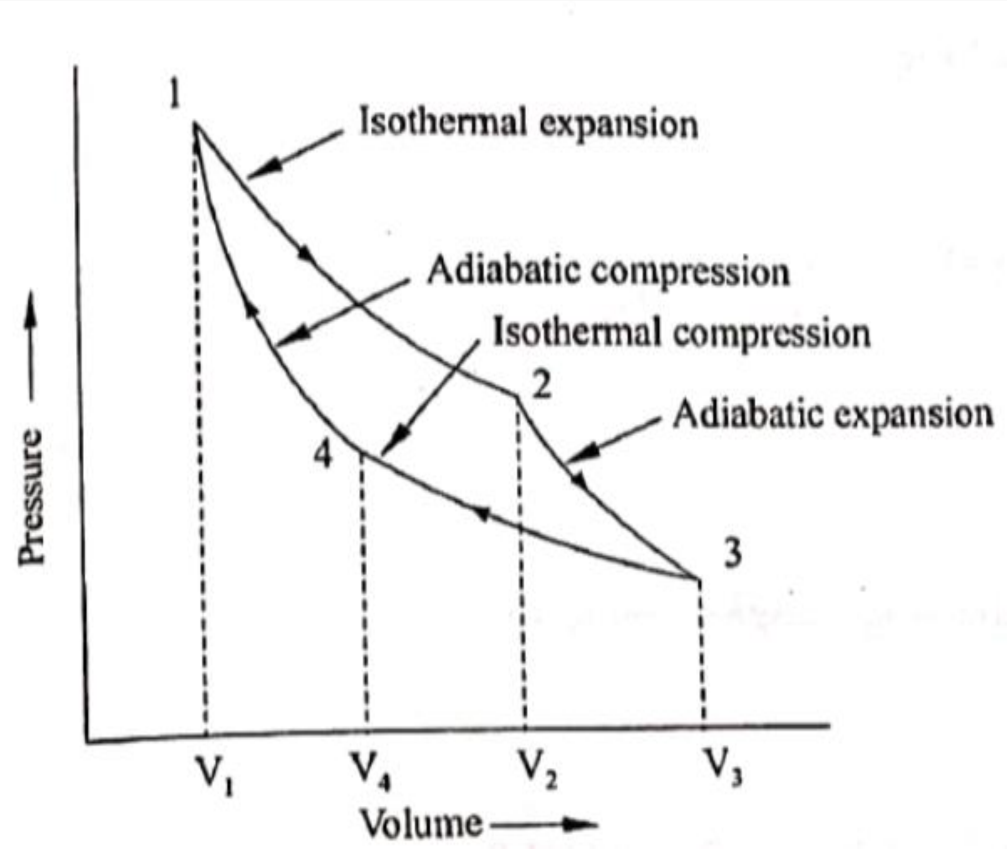
- Carnot cycle is a thermodynamic air cycle consisting of four processes.
- Heat is supplied and rejected isothermally, expansion and compression of air takes place adiabatically.
- Consider a given mass of air in the cylinder, inside which a friction less piston slides.
- Let the pressure, volume and temperature of air at state 1 be p_1, V_1 and T_1 respectively.
- Heat is supplied to this air isothermally from an external hot body.

- The air expands at temperature T_1 till the state 2 is reached.
- This process is represented by curve 1-2 in the p-V diagram and a horizontal line 1-2 in the T-S diagram.
- During this process heat is absorbed from hot body and an equal amount of work is done by the air.
- At state 2, the source of heat is removed and the air is allowed to expand adiabatically till state 3.
- This is represented by curve 2-3 in the p-V diagram and a vertical line 2-3 in the T-S diagram.

- Let the pressure, volume and temperature of the air at state 3 be p_3, V_3 and T_3 respectively.
- During the process 2-3 work is done by the air utilising its internal energy.
- At state 3, an external cold body is brought in contact with the cylinder and heat is rejected isothermally to the cold body at constant temperature T_3.
- This isothermal compression is represented by the curve 3-4 in the p-V diagram and a horizontal line 3-4 in the T-S diagram.
- During this process work is done on the air and an equal amount of heat is rejected to the cold body.
- At state 4, the cold body is removed and the air is compressed adiabatically to the initial state 1.
- In the p-V diagram this adiabatic compression process is represented by curve 4-1 and in the T-S diagram by a vertical line 4-l.
- During this process work is done on the air to bring it to the original state.

EFFICIENCY DERIVATION

- For the adiabatic expansion process 2-3,
- $\frac{V_3}{V_2} = (\frac{T_2}{T_3})^{\frac{1}{\gamma-1}}$……………..(1)
- For the adiabatic compression process 4-1,
- $\frac{V_4}{V_1} = (\frac{T_1}{T_4})^{\frac{1}{\gamma-1}}$
- We know, $T_1 = T_2$ & $T_4 = T_3$ (Isothermal process)
- $\frac{V_4}{V_1} = (\frac{T_2}{T_3})^{\frac{1}{\gamma-1}}$ ……………..(2)
- From (1) and (2), $\frac{V_3}{V_2} = \frac{V_4}{V_1}$



- Ie, Adiabatic expansion ratio = Adiabatic compression ratio
- From this we can say,
- Isothermal expansion ratio = Isothermal compression ratio
- ie, $\frac{V_2}{V_1} = \frac{V_3}{V_4}$
- During the entire cycle heat is supplied during 1-2 and rejected during 3-4
- During the process 1-2,
- Heat supplied, $_1Q_2 = P_1V_1 \ln\left(\frac{V_2}{V_1}\right)$
- $_1Q_2 = mRT_1 \ln\left(\frac{V_2}{V_1}\right)$
- During the process 3-4,
- Heat rejected, $_3Q_4 = -P_3V_3 \ln\left(\frac{V_4}{V_3}\right)$
- $= P_3V_3 \ln\left(\frac{V_3}{V_4}\right)$
- $_3Q_4 = mRT_3 \ln\left(\frac{V_3}{V_4}\right)$

- Air standard efficiency $= \dfrac{Heat\ supplied - Heat\ rejected}{Heat\ supplied}$
- $= \dfrac{mRT_1 \ln\left(\frac{V_2}{V_1}\right) - mRT_3 \ln\left(\frac{V_3}{V_4}\right)}{mRT_1 \ln\left(\frac{V_2}{V_1}\right)}$
- But, $\dfrac{V_3}{V_4} = \dfrac{V_2}{V_1}$
- $= \dfrac{mRT_1 \ln\left(\frac{V_2}{V_1}\right) - mRT_3 \ln\left(\frac{V_2}{V_1}\right)}{mRT_1 \ln\left(\frac{V_2}{V_1}\right)}$
- $= \dfrac{T_1 - T_3}{T_1}$
- $= 1 - \dfrac{T_3}{T_1}$
- $\eta = 1 - \dfrac{Temperature\ of\ cold\ body}{Temperature\ of\ hot\ body}$

- Although Carnot cycle gives maximum possible efficiency, yet no engine can be made to work on this cycle due to the following reasons:

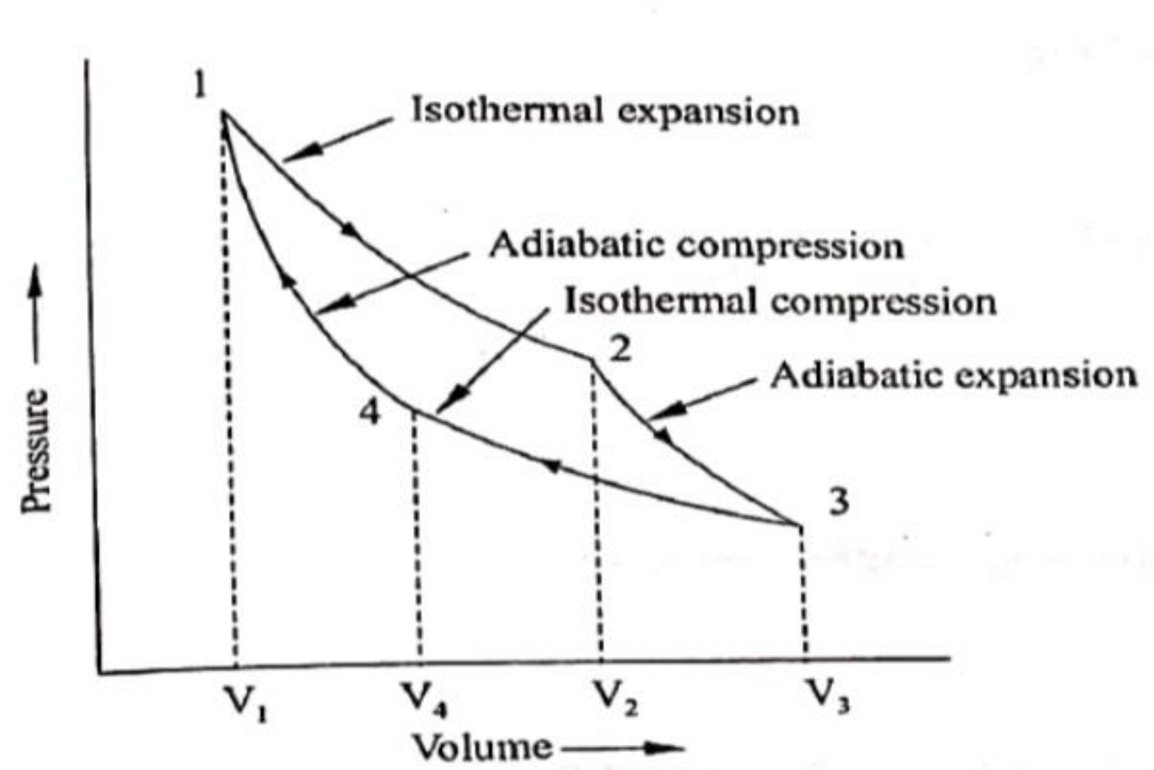
1. The expansion and compression processes are adiabatic and hence the two operations should be carried out as quickly as possible. So that there is hardly any time for the heat exchange to takes place.
2. Heat supply and heat rejection takes place isothermally, which means the operations must be slow to maintain the constant temperature.

- It is obvious that such sudden changes in the speed of an engine in one cycle is not possible in actual practice.

Q.1 A Carnot cycle works with adiabatic compression ratio of 5 and isothermal expansion ratio of 2. The volume of air at the beginning of the isothermal expansion is 0.3 m^3, if the maximum temperature and pressure is limited to 550 K and 21 bar. Determine (i) Minimum temperature in the cycle, (ii) Thermal efficiency of the cycle, (iii) Pressure at all salient points (iv) Workdone per cycle. γ =1.4

Given data:

- Adiabatic compression ratio, $\frac{V_4}{V_1} = \frac{V_3}{V_2} = 5$
- Isothermal expansion ratio, $\frac{V_2}{V_1} = \frac{V_3}{V_4} = 2$
- $V_1 = 0.3\ m^3$
- $T_1 = T_2 = 550$ K
- $P_1 = 21$ bar $= 21 \times 10^5$ N/m^2
- $T_3 = T_4 = ?$, $\eta = ?$,
- $P_2 = ?$, $P_3 = ?$, $P_4 = ?$, ${}_1W_2 = ?$

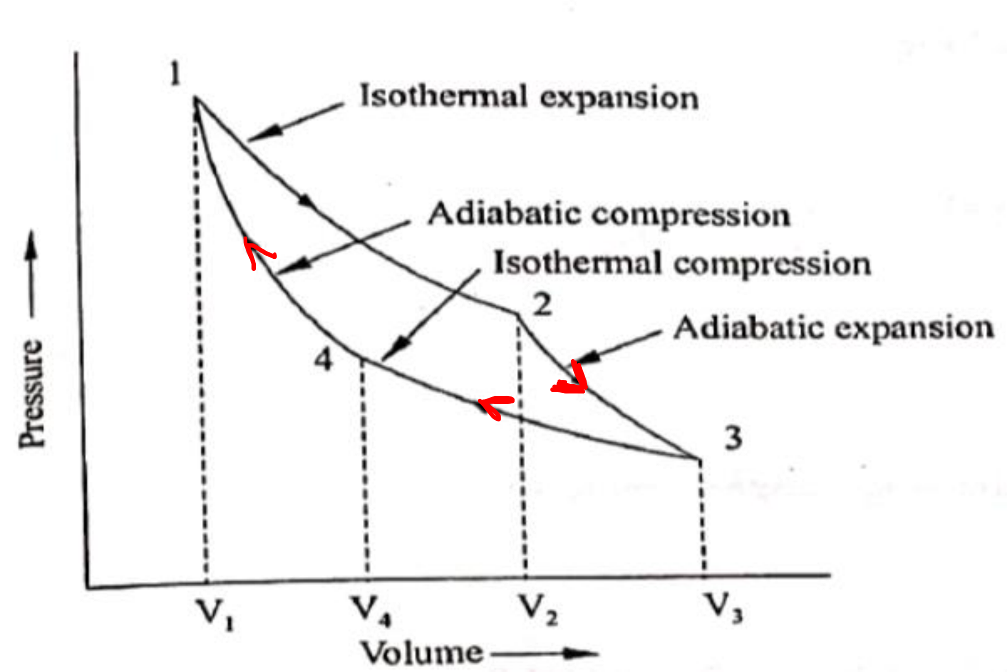


- $\frac{V_2}{V_1} = 2$
- $V_2 = 2\ V_1$
- $= 2 \times 0.3 = 0.6\ m^3$
- $\frac{V_3}{V_2} = 5$
- $V_3 = 5\ V_2$
- $= 5 \times 0.6 = 3\ m^3$
- $\frac{V_3}{V_4} = 2$
- $V_4 = \frac{V_3}{2} = \frac{3}{2} = 1.5\ m^3$
- <u>(i) For the process 4-1</u>
- $\frac{V_4}{V_1} = (\frac{T_1}{T_4})^{\frac{1}{\gamma-1}}$
- $\frac{V_1}{V_4} = (\frac{T_4}{T_1})^{\frac{1}{\gamma-1}}$
- $\frac{T_4}{T_1} = (\frac{V_1}{V_4})^{\gamma-1}$
- $\frac{T_4}{550} = (\frac{0.3}{1.5})^{1.4-1}$
- $T_4 = 550 \times 0.525$
- $= 288.75\ K$
- $T_4 = T_3 = 288.75\ K$
- <u>(ii) Thermal efficiency,</u>
- $\eta = 1 - \frac{T_3}{T_1}$
- $= 1 - \frac{288.75}{550}$
- $= 0.525$
- $\eta = 52.5\ \%$

- (iii) For the process 1-2 (Isothermal)
- $P_1V_1 = P_2V_2$
- $21 \times 10^5 \times 0.3 = P_2 \times 0.6$
- $P_2 = 10.5 \times 10^5$ N/m^2
- $P_2 = 10.5$ bar
- For the process 2-3 (Adiabatic)
- $\frac{P_2}{P_3} = (\frac{V_3}{V_2})^{\gamma}$
- $\frac{P_3}{P_2} = (\frac{V_2}{V_3})^{\gamma}$
- $\frac{P_3}{10.5} = (\frac{0.6}{3})^{1.4}$
- $P_3 = 1.1$ bar
- For the process 3-4 (Isothermal)
- $P_3V_3 = P_4V_4$
- $1.1 \times 3 = P_4 \times 1.5$
- $P_4 = 2.2$ bar
- (iv) Workdone = Heat supplied – Heat rejected
- Heat supplied (HS) = $P_1V_1 \ln(\frac{V_2}{V_1})$
- $= 21 \times 10^5 \times 0.3 \times \ln(2)$
- $= 4.37 \times 10^5$ J = 437 kJ
- Heat rejected (HR) $= -P_3V_3 \ln(\frac{V_4}{V_3})$
- $= P_3V_3 \ln(\frac{V_3}{V_4})$
- $= P_3V_3 \ln(\frac{V_3}{V_4}) = 1.1 \times 10^5 \times 3 \times \ln(2)$
- $= 2.287 \times 10^5$ J = 228.7 kJ
- Workdone = HS –HR = 437 – 228.7
- = 208.3 J

Q.2 0.45 kg of air is taken through a Carnot cycle between temperature of 207^0C and 37^0C. If the highest pressure is 690 kPa and the lowest pressure is 69 kPa. Determine the pressure and volume at the end of each process in the cycle. For air R = 0.287 kJ/kgK and $\gamma = 1.41$

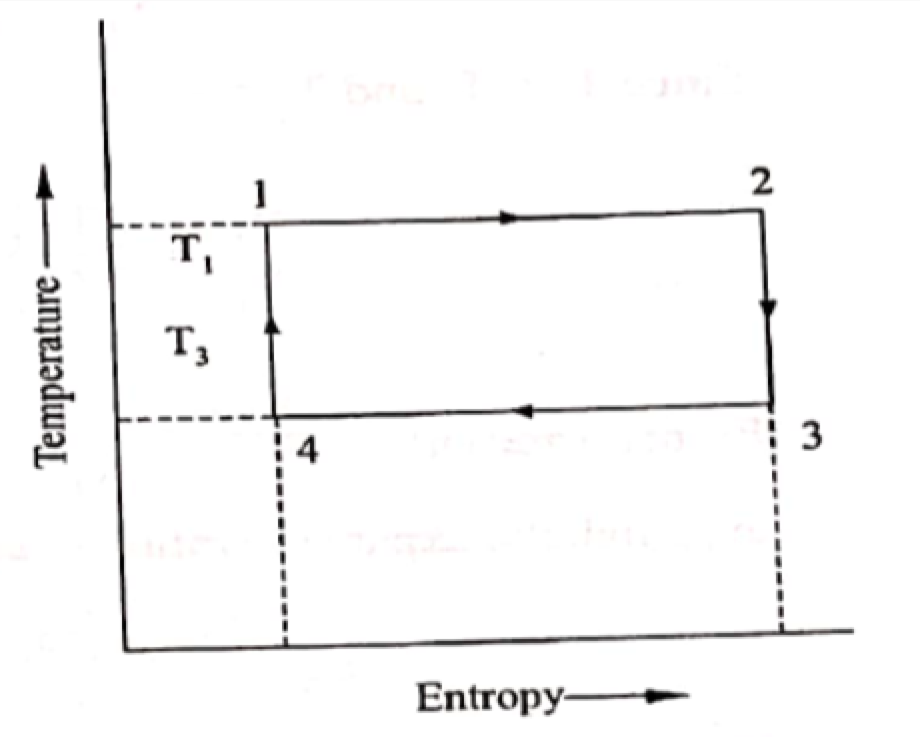
- Given data:
- m = 0.45 kg
- $T_1 = T_2 = 207^0C$
- $= 207 + 273 = 480\ K$
- $T_3 = T_4 = 37^0C$
- $= 37 + 273 = 310\ K$
- $P_1 = 690\ kPa = 690 \times 10^3\ N/m^2$
- $P_3 = 69\ kPa = 69 \times 10^3\ N/m^2$
- $R = 0.287\ kJ/kgK$
- $= 287\ J/kgK$
- $\gamma = 1.41$



- For the process 1-2 (isothermal)
- $P_1V_1 = mRT_1$
- $690 \times 10^3 \times V_1 = 0.45 \times 287 \times 480$
- $V_1 = 0.09\ m^3$
- For the process 3-4 (isothermal)
- $P_3V_3 = mRT_3$
- $69 \times 10^3 \times V_3 = 0.45 \times 287 \times 310$
- $V_3 = 0.58\ m^3$
- For the process 2-3 (adiabatic)
- $\frac{V_3}{V_2} = (\frac{T_2}{T_3})^{\frac{1}{\gamma-1}}$
- $\frac{V_2}{V_3} = (\frac{T_3}{T_2})^{\frac{1}{\gamma-1}}$
- $\frac{V_2}{0.58} = (\frac{310}{480})^{\frac{1}{1.41-1}}$
- $V_2 = 0.19\ m^3$
- For the process 4-1 (adiabatic)
- $\frac{V_4}{V_1} = (\frac{T_1}{T_4})^{\frac{1}{\gamma-1}}$
- $\frac{V_4}{0.09} = (\frac{480}{310})^{\frac{1}{1.41-1}}$
- $V_4 = 0.27\ m^3$
- For the process 1-2 (isothermal)
- $P_1V_1 = P_2V_2$
- $690 \times 10^3 \times 0.09 = P_2 \times 0.19$
- $P_2 = 326.84 \times 10^3\ N/m^2$
- $P_2 = 326.84\ kPa$
- For the process 3-4 (isothermal)
- $P_3V_3 = P_4V_4$
- $69 \times 10^3 \times 0.58 = P_4 \times 0.27$
- $P_4 = 148.22 \times 10^3\ N/m^2$
- $P_4 = 148.22\ kPa$

Q.3. A Carnot engine working between 400^0C and 40^0C produces 130 kJ of work. Determine: i) The engine thermal efficiency ii) The heat added (iii) The entropy changes during heat rejection process.

- Given data:
- $T_1 = T_2 = 400^0C$
- $= 400 + 273 = 673$ K
- $T_3 = T_4 = 40^0C$
- $= 40 + 273 = 313$ K
- W = 130 kJ
- $\eta = ?$
- Heat supplied = ?
- $S_3 - S_4 = ?$



Engine thermal efficiency,

- $\eta = \frac{T_1 - T_3}{T_1}$
- $= \frac{673 - 313}{673} = 0.5349$
- **= 53.5 %**
- Heat supplied
- $\mu = \frac{Workdone}{Heat\ supplied}$
- $0.535 = \frac{130}{Heat\ supplied}$
- Heat supplied = 242.99 kJ
- = 243 kJ

- Entropy change during the heat rejection process ($S_3 - S_4$)
- We know,
- Workdone = Heat supplied – Heat rejected
- 130 = 243 – Heat rejected
- Heat rejected = 243-130
- = 113 kJ
- Change in entropy, $ds = \frac{dQ}{T}$
- $(s_3 - s_4) = \frac{Heat\ rejected}{T_3}$
- $(s_3 - s_4) = \frac{113}{313}$
- = 0.361kJ/K

Q.4 0.23 kg of air is taken through a Carnot cycle between temperature of 300^0C and 50^0C. If the volume ratio of expansion of the isothermals is 2.5, determine (i) air standard efficiency of cycle and (ii) work done per cycle. Take, R = 0.28 kJ/kgK

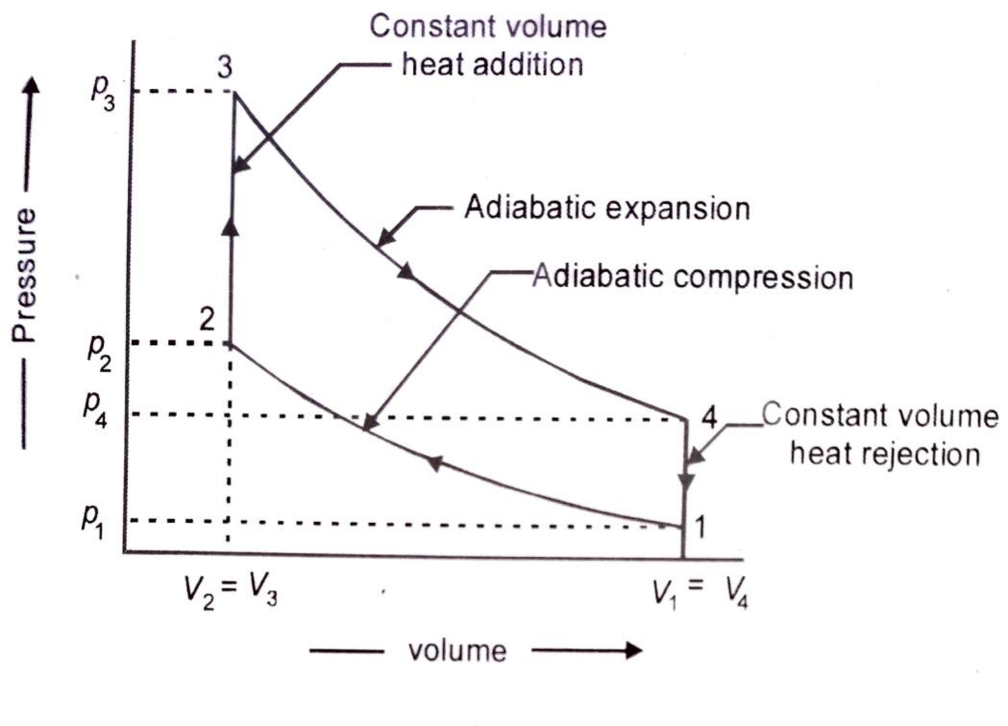
- Given data:
- m = 0.23 kg
- $T_1 = T_2 = 300^0C$
- $= 300 + 273 = 573$ K
- $T_3 = T_4 = 50^0C$
- $= 50 + 273 = 323$ K
- Isothermal expansion ratio = Isothermal compression ratio
- ie, $\frac{V_2}{V_1} = \frac{V_3}{V_4} = 2.5$
- R = 0.28 kJ/kgK
- η = ?, Workdone = ?

<u>Air standard efficiency,</u>

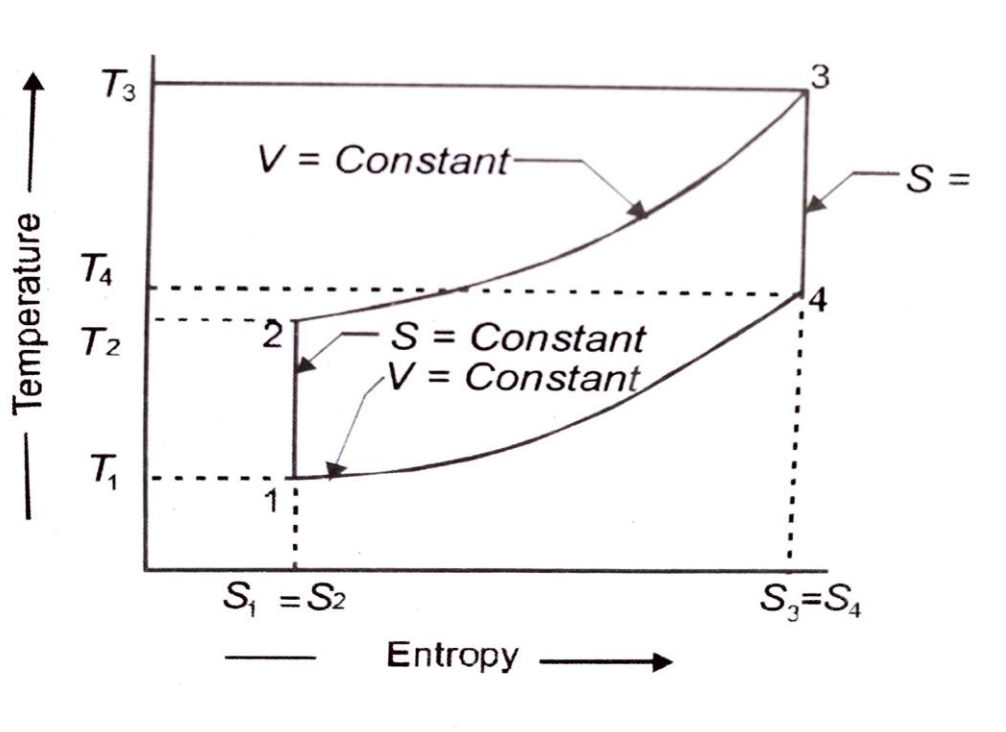
- $\eta = \frac{T_1 - T_3}{T_1}$
- $= \frac{573 - 323}{573} = 0.4363$
- **= 43.63 %**
- <u>Work done</u>
- **Work done = HS – HR**
- **HS** = $mRT_1 \ln\left(\frac{V_2}{V_1}\right)$
- = 0.23 x 0.28 x 573 x ln (2.5)
- = 33.81 kJ

- HR = $mRT_3 \ln \left(\frac{V_3}{V_4} \right)$
- = 0.23 x 0.28 x 323 x ln (2.5)
- = 19.06 kJ
- **Work done = HS – HR**
- **= 33.81 – 19.06**
- **= 14.75 kJ**

OTTO CYCLE (CONSTANT VOLUME AIR CYCLE)



(a) *p . V* Diagram



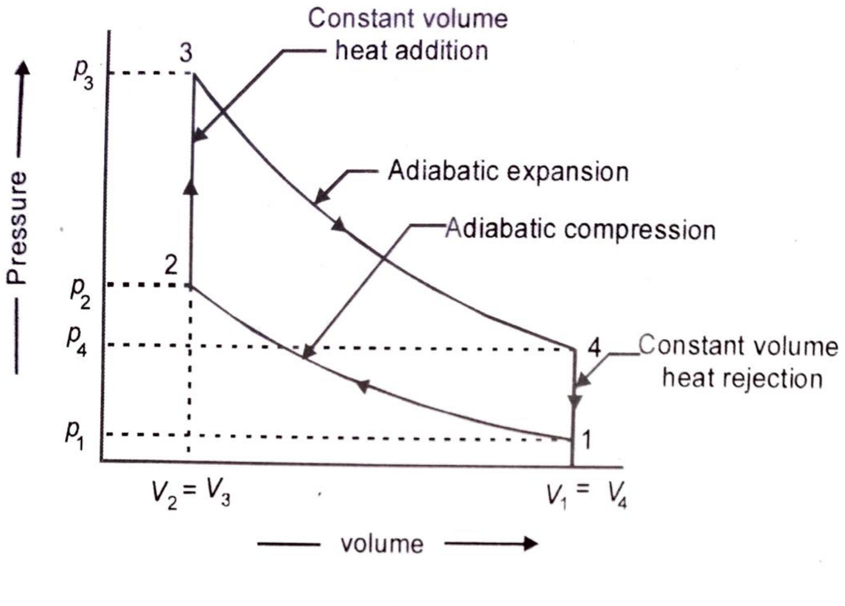
(b) *T -S* Diagram

- Otto cycle is a theoretical cycle consist of four reversible processes.
- Heat is supplied and rejected at constant volume. Expansion and compression of air takes place adiabatically.
- Consider a cylinder containing ‘m’ kg of air.
- Let the pressure, volume, temperature and entropy of air inside the cylinder at state 1 be p_1, V_1, T_1 and S_1 respectively.
- This air is compressed adiabatically to state 2 doing work on the air.
- Now heat is supplied to this compressed air at constant volume from an external hot body till state 3 is reached.

- At state three the hot body is removed and air is allowed to expand adiabatically to state four doing external work.
- Heat is rejected at constant volume to an external cold body till state one is reached.
- Thus air finally returns to its original state after completing a cycle.

Efficiency Derivation

- Heat supplied during constant volume process 2-3,
- $HS = mC_v \, (T_3 - T_2)$
- Heat rejected during constant volume process 4-1,
- $HR = -mC_v \, (T_1 - T_4)$
- $HR = mC_v \, (T_4 - T_1)$



(a) $p \cdot V$ Diagram

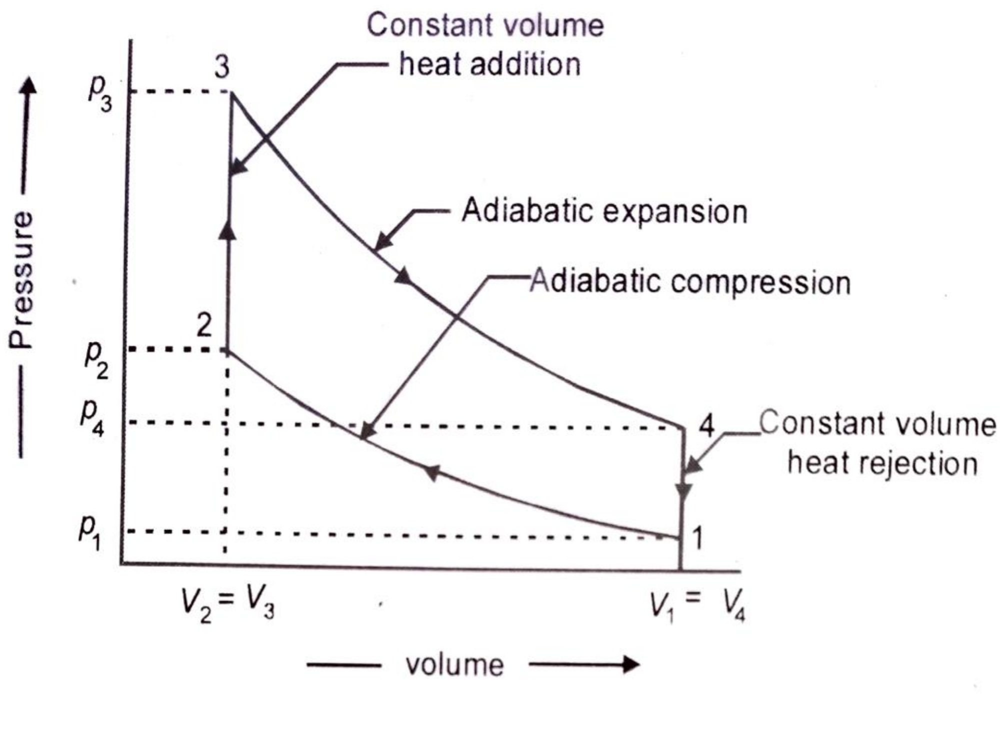
- Air standard efficiency, $\eta = 1 - \dfrac{Heat\ rejected}{Heat\ supplied}$

- $\eta = 1 - \dfrac{mC_v\,(T_4 - T_1)}{mC_v\,(T_3 - T_2)}$
- $\eta = 1 - \dfrac{(T_4 - T_1)}{(T_3 - T_2)}$ ....(1)
- For process 1-2 (adiabatic)
- V-T relation is given by,
- $\dfrac{V_2}{V_1} = \left(\dfrac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}}$
- $\dfrac{V_1}{V_2} = \left(\dfrac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$
- $\dfrac{T_2}{T_1} = \left(\dfrac{V_1}{V_2}\right)^{\gamma-1}$
- Where,
- $\dfrac{V_1}{V_2} = \dfrac{V_4}{V_3} = r =$ compression ratio
- $T_2 = T_1\left(\dfrac{V_1}{V_2}\right)^{\gamma-1}$
- $T_2 = T_1(r)^{\gamma-1}$.................(2)
- For process 3-4 (adiabatic)
- V-T relation is given by,
- $\dfrac{V_4}{V_3} = \left(\dfrac{T_3}{T_4}\right)^{\frac{1}{\gamma-1}}$
- $\dfrac{T_3}{T_4} = \left(\dfrac{V_4}{V_3}\right)^{\gamma-1}$
- $\dfrac{T_3}{T_4} = (r)^{\gamma-1}$
- $T_3 = T_4\,(r)^{\gamma-1}$.................(3)
- Substitute equation (2) and (3) in (1)
- $\eta = 1 - \dfrac{(T_4 - T_1)}{\left(T_4\,(r)^{\gamma-1} - T_1(r)^{\gamma-1}\right)}$

- $\eta = 1 - \frac{(T_4 - T_1)}{((T_4 - T_1)(r)^{\gamma-1})}$
- $\eta = 1 - \frac{1}{(r)^{\gamma-1}}$
- Efficiency of Otto cycle increases with increase in the compression ratio.

Q.1. In an engine working on Otto cycle the measured suction temperature was 100^0C and the temperature at the end of compression was 300^0C. Taking adiabatic index for compression as 1.41. Find the ideal efficiency and compression ratio.

- Given data:
- $T_1 = 100^0C$
- $= 100 + 273 = 373$ K
- $T_2 = 300^0C$
- $= 300 + 273 = 573$ K
- $\gamma = 1.41$
- $\eta = ?$
- $r = ?$

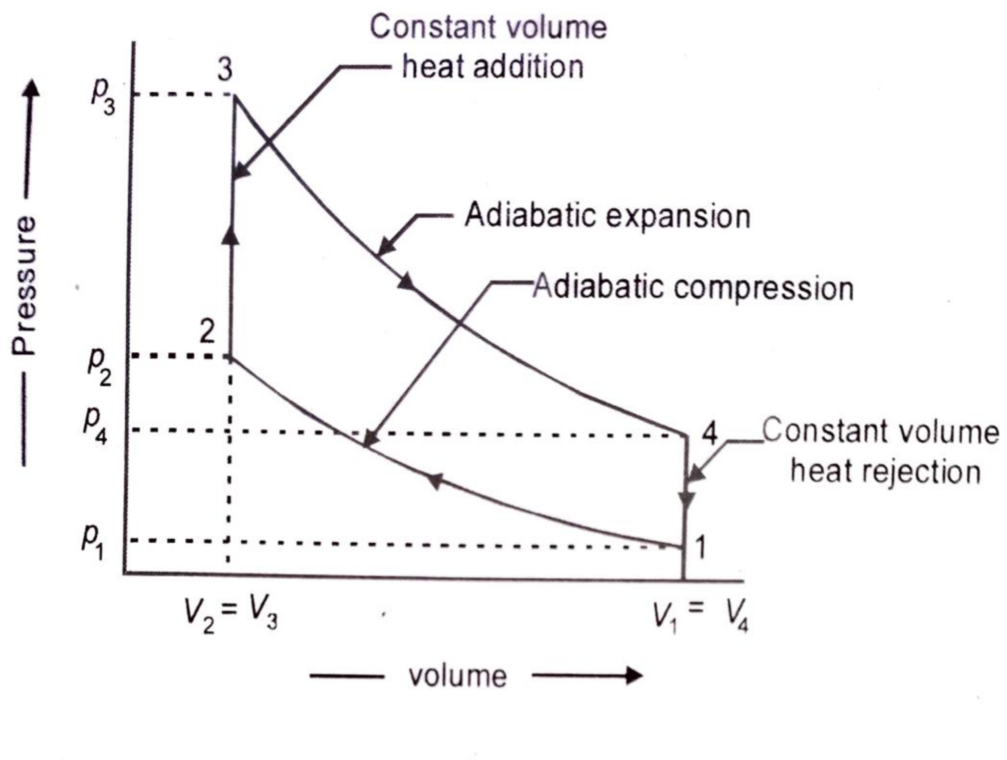


(a) p . V Diagram

- $\frac{V_1}{V_2} = (\frac{T_2}{T_1})^{\frac{1}{\gamma-1}}$
- r = $(\frac{T_2}{T_1})^{\frac{1}{\gamma-1}}$
- $= (\frac{573}{373})^{\frac{1}{1.41-1}}$
- = 2.924
- $\eta = 1 - \frac{1}{(r)^{\gamma-1}}$
- $= 1 - \frac{1}{(2.924)^{1.41-1}}$
- = 0.348
- η = 34.8%

Q.2. In an engine working on the ideal Otto cycle the pressure and temperature at the beginning of compression are 100 kPa and 40^0C respectively. If the air standard efficiency of the engine 50 %. Determine (i) compression ratio (ii) pressure and temperature at the end of adiabatic compression. Assume $\gamma = 1.4$

- Given data:
- $P_1 = 100$ kPa
- $= 100 \times 10^3 \ N/m^2$
- $T_1 = 40^0C$
- $= 40 + 273 = 313$ K
- $\eta = 50$ %
- $r = ?, P_2 = ?, T_2 = ?$
- $\gamma = 1.4$



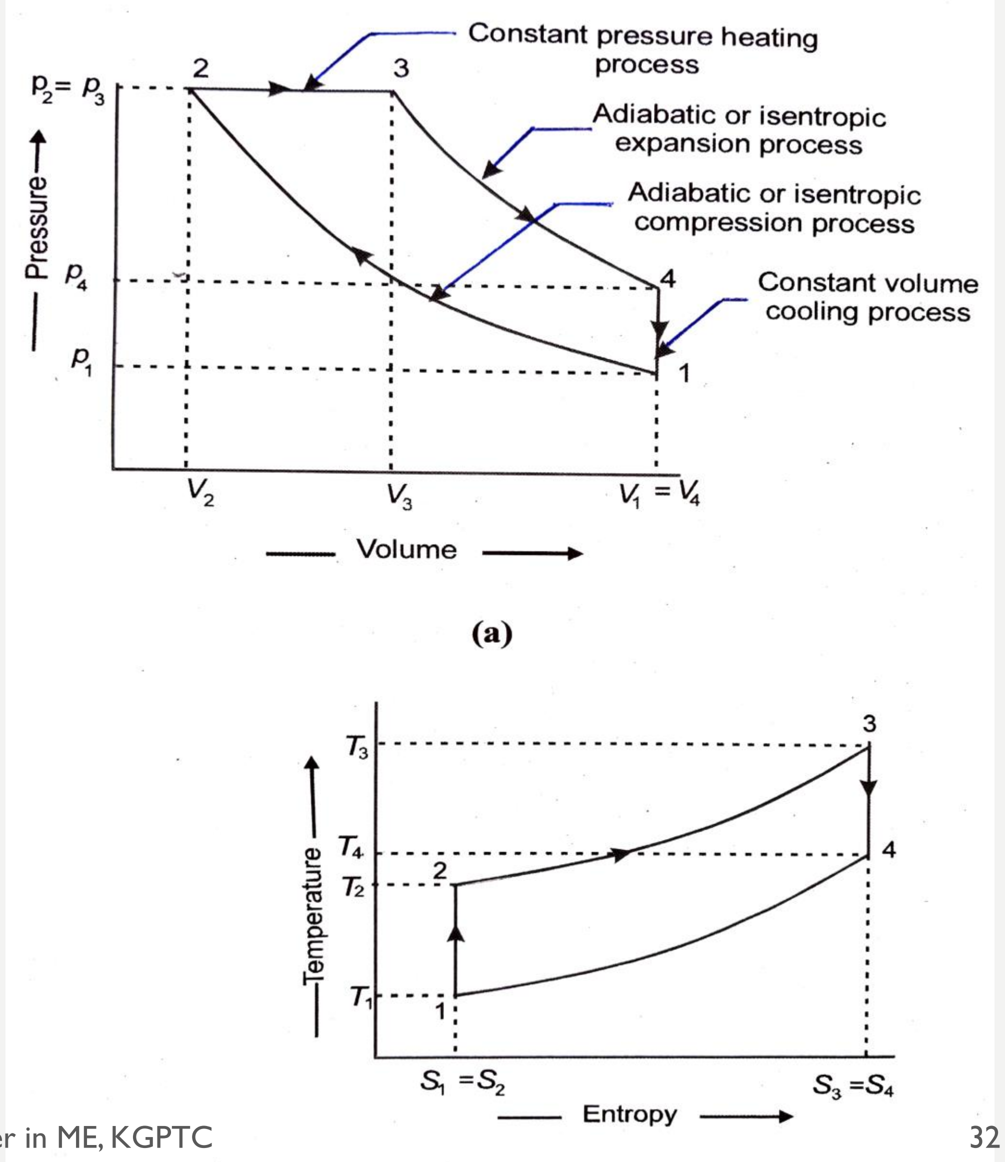
(a) p . V Diagram

- i) $\eta = 1 - \frac{1}{(r)^{\gamma-1}}$
- $0.5 = 1 - \frac{1}{(r)^{1.4-1}}$
- $0.5 = 1 - \frac{1}{(r)^{0.4}}$
- $\frac{1}{(r)^{0.4}} = 1 - 0.5$
- $\frac{1}{(r)^{0.4}} = 0.5$
- $(r)^{0.4} = \frac{1}{0.5}$
- $(r)^{0.4} = 2$
- $r = 5.66$

- (ii) For the process 1-2
- $\frac{V_1}{V_2} = (\frac{T_2}{T_1})^{\frac{1}{\gamma-1}}$
- $\frac{T_2}{T_1} = (\frac{V_1}{V_2})^{\gamma-1}$
- $\frac{T_2}{T_1} = (r)^{\gamma-1}$
- $T_2 = T_1 \times (r)^{\gamma-1}$
- $= 313 \times (5.66)^{1.4-1}$
- $T_2 = 526.1$ K
- $\frac{P_1}{P_2} = (\frac{V_2}{V_1})^{\gamma}$
- $\frac{P_2}{P_1} = (\frac{V_1}{V_2})^{\gamma}$
- $\frac{P_2}{100 \text{ X } 10^3} = (5.66)^{1.4}$
- $P_2 = 1132.2$ kPa

DIESEL CYCLE (CONSTANT PRESSURE CYCLE)

- It is a theoretical cycle consisting of four processes.
- In this heat is supplied at constant pressure and rejected at constant volume.
- Expansion and compression of air takes place adiabatically.



(a)

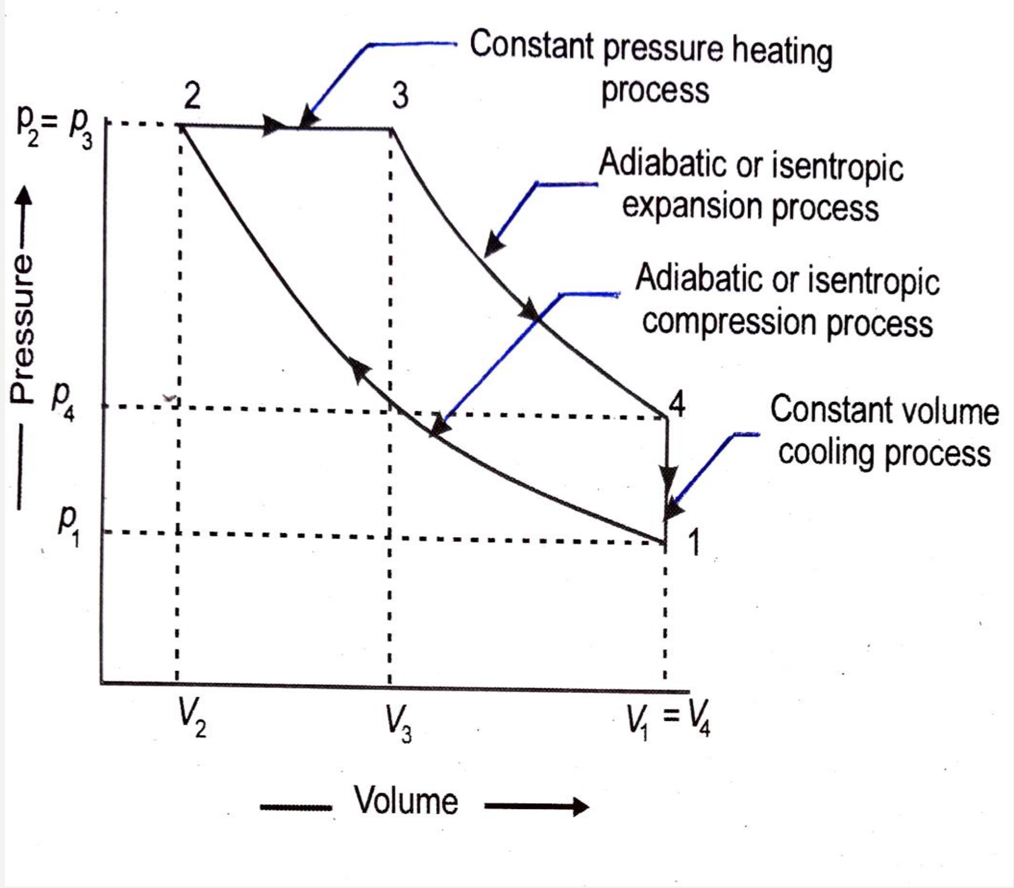
(b)

WORKING

- Consider a cylinder containing ‘m’ kg of air.
- Let the pressure, volume, temperature and entropy of air inside the cylinder at state 1 be p_1, $V_{1,}$ T_1 and S_1 respectively.
- This air is compressed adiabatically to state 2 doing work on the air.
- Now heat is supplied to this compressed air at constant pressure from an external hot body till state 3 is reached.
- At state three the hot body is removed and air is allowed to expand adiabatically to state four doing external work.
- Heat is rejected at constant volume to an external cold body till state one is reached.
- Thus air finally returns to its original state after completing a cycle.

EFFICIENCY DERIVATION

- Heat supplied during constant pressure process 2-3,
- $HS = mC_p\,(T_3 - T_2)$
- Heat rejected during constant volume process 4-1,
- $HR = -mC_v\,(T_1 - T_4)$
- $HR = mC_v\,(T_4 - T_1)$
- Air standard efficiency, $\eta = 1 - \dfrac{\textit{Heat rejected}}{\textit{Heat supplied}}$
- $\eta = 1 - \dfrac{mC_v\,(T_4 - T_1)}{mC_p\,(T_3 - T_2)}$
- $\eta = 1 - \dfrac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$ ....(1)



- For process 1-2 (adiabatic)
- V-T relation is given by,
- $\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}}$
- $\frac{V_1}{V_2} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$
- $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$
- Where,
- $\frac{V_1}{V_2} = r =$ compression ratio
- $T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1}$
- $T_2 = T_1(r)^{\gamma-1}$………………..(2)

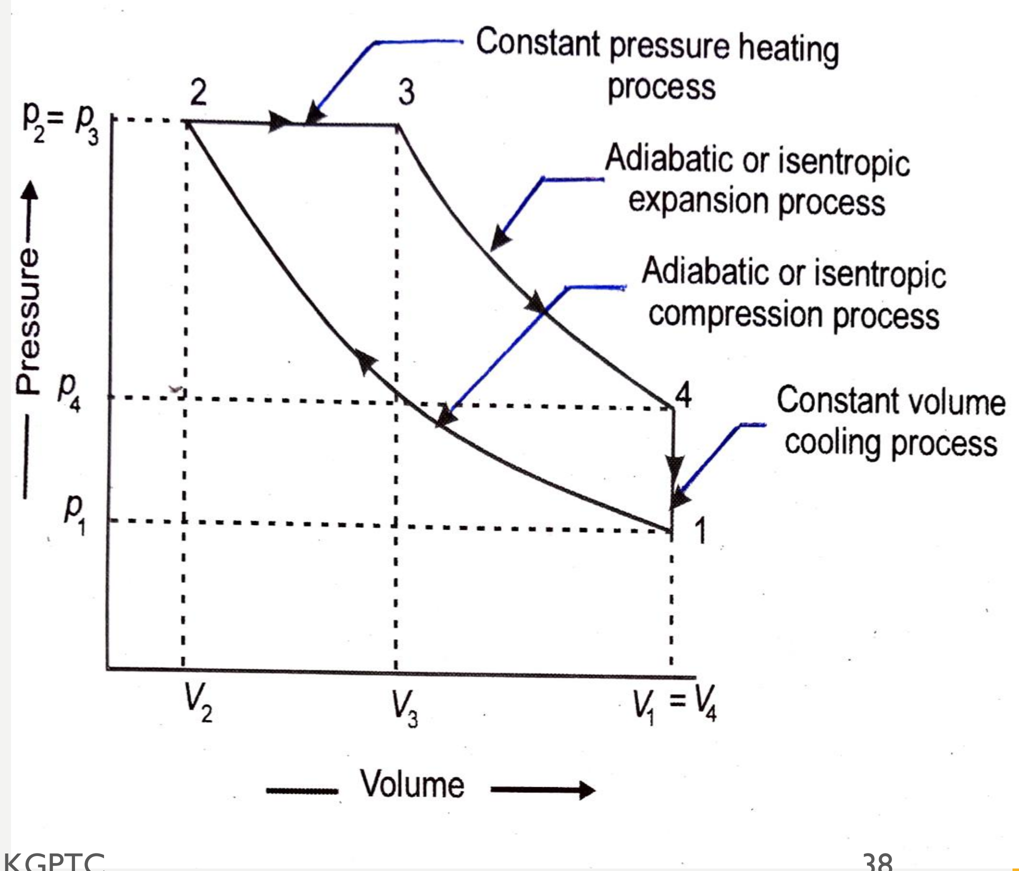
- For process 2-3 (constant pressure)
- $\frac{V}{T} =$ Constant
- $\frac{V_2}{T_2} = \frac{V_3}{T_3}$
- $\frac{T_3}{T_2} = \frac{V_3}{V_2}$
- $\frac{V_3}{V_2} = r_c =$ Cut off ratio
- $T_3 = T_2\,(r_c)$
- Substitute equation (2) in the above equation
- $T_3 = T_1(r)^{\gamma-1}(r_c)$ ………………(3)

- For process 3-4 (adiabatic)
- V-T relation is given by,
- $\frac{V_4}{V_3} = (\frac{T_3}{T_4})^{\frac{1}{\gamma-1}}$
- $\frac{T_3}{T_4} = (\frac{V_4}{V_3})^{\gamma-1}$
- Where, $\frac{V_4}{V_3} = \frac{V_1}{V_3}$ = ρ = Expansion ratio
- $T_3 = T_4(\rho)^{\gamma-1}$……………….(4)
- Also,
- $\frac{V_1}{V_3} = \frac{V_1}{V_3} \text{ x } \frac{V_2}{V_2}$
- $\rho = \frac{V_1}{V_2} \text{ x } \frac{V_2}{V_3}$
- $\rho = r \text{ x } \frac{1}{r_c}$
- Substitute in equation (4)
- $T_3 = T_4 \, (\frac{r}{r_c})^{\gamma-1}$
- Substitute equation (3) in the above equation,
- $T_1(r)^{\gamma-1}(r_c) = T_4 \, (\frac{r}{r_c})^{\gamma-1}$
- $T_4 = \frac{T_1(r)^{\gamma-1}(r_c) \text{ x } (r_c)^{\gamma-1}}{(r)^{\gamma-1}}$
- $T_4 = T_1(r_c)^{\gamma}$……………(5)

- Substitute equation (2), (3) and (5) in equation (1)
- $\eta = 1 - \dfrac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$
- $= 1 - \dfrac{\{T_1(r_c)^{\gamma} - T_1\}}{\gamma\{T_1(r)^{\gamma-1}(r_c) - T_1(r)^{\gamma-1}\}}$
- $= 1 - \dfrac{T_1\{(r_c)^{\gamma} - 1\}}{\gamma T_1(r)^{\gamma-1}\{r_c - 1\}}$
- $\eta = 1 - \dfrac{1}{\gamma(r)^{\gamma-1}} \dfrac{\{(r_c)^{\gamma} - 1\}}{\{r_c - 1\}}$

1. An ideal diesel engine has a bore diameter 150 mm and stroke 200 mm. The clearance volume is 10 % of the swept volume. Determine the compression ratio and air standard efficiency of the engine, if the cut off take place at 6 % of the stroke.

- Given data:
- d =150 mm = 0.15 m
- l = 200 mm = 0.2 m
- Clearance volume, $V_c = V_2$ = 10 % Swept volume
- r = ?
- η = ?
- Cut off = 6 % of stroke

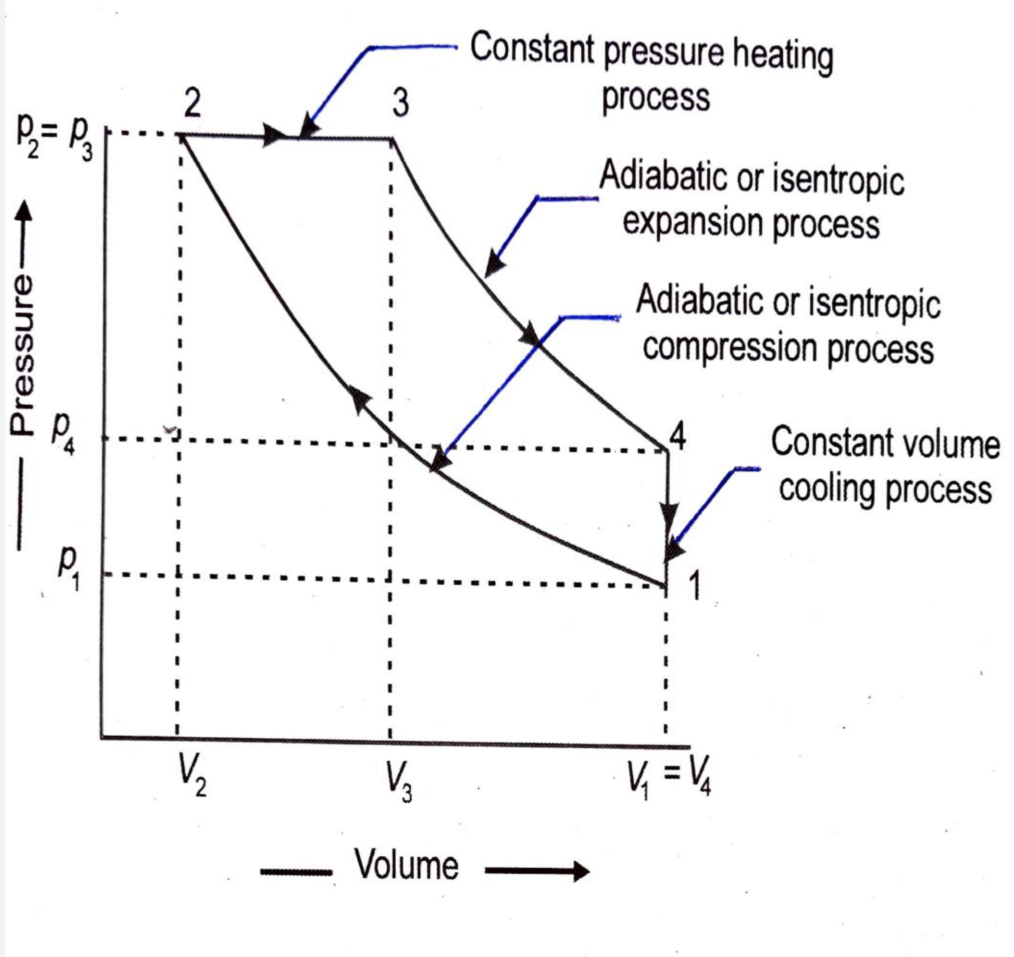


- Area of the cylinder, $A = \frac{\pi}{4} d^2$
- $A = \frac{\pi}{4} (0.15)^2$
- $= 0.0176 \text{ m}^2$
- Swept volume, $V_s = A \times l$
- $V_s = 0.0176 \times 0.2$
- $= 0.0035 \text{ m}^3$
- $V_c = V_2 = 10\ \%\ V_s$
- $V_c = V_2 = 0.1 \times 0.0035$
- $= 0.00035 \text{ m}^3$
- Total cylinder volume, $V_1 = V_c + V_s$
- $V_1 = 0.00035 + 0.0035$
- $V_1 = 0.00385 \text{ m}^3$
- Compression ratio, $r = \frac{V_1}{V_2}$
- $r = \frac{0.00385}{0.00035} = 11$
- Volume at point of cut off, V_3
- $V_3 = V_c + 6\%\ V_s$
- $V_3 = 10\ \%\ V_s + 6\%\ V_s$
- $= 16\ \%\ V_s$
- $= 0.16 \times 0.0035$
- $V_3 = 0.00056 \text{ m}^3$
- Cut off ratio, $r_c = \frac{V_3}{V_2}$
- $r_c = \frac{0.00056}{0.00035} = 1.6$

- $\eta = 1 - \frac{1}{\gamma(r)^{\gamma-1}} \frac{\{(r_c)^{\gamma} - 1\}}{\{r_c - 1\}}$
- Take, $\gamma = 1.4$
- $= 1 - \frac{1}{1.4\,(11)^{1.4-1}} \frac{\{(1.6)^{1.4} - 1\}}{\{1.6 - 1\}}$
- $= 1 - 0.425$
- $= 0.575$
- $\eta = 57.5\ \%$

Q. 2. A diesel engine has a compression ratio of 14 and cut off takes place at 6% of the stroke. Find the air standard efficiency. Take adiabatic index for air as 1.4.

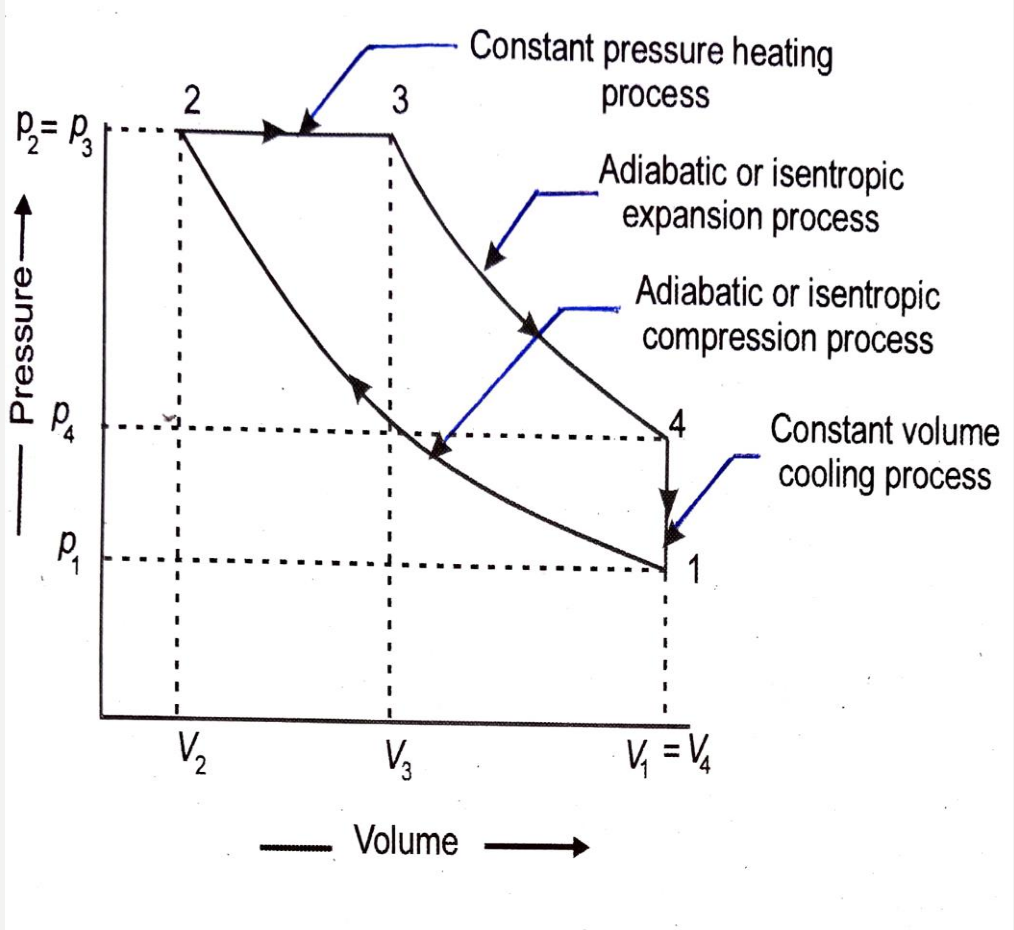
- Given data:
- $r = 14 = \frac{V_1}{V_2}$
- $V_1 = 14\ V_2$
- Cut off = 6 % of stroke
- $\eta = ?$
- $\gamma = 1.4$
- $V_3 - V_2 = 0.06\ (V_1 - V_2)$
- $V_3 = V_2 + 0.06\ (14\ V_2 - V_2)$
- $V_3 = 1.78\ V_2$
- $\frac{V_3}{V_2} = 1.78 = r_c$



- $\eta = 1 - \frac{1}{\gamma (r)^{\gamma-1}} \frac{\{(r_c)^{\gamma} - 1\}}{\{r_c - 1\}}$
- $= 1 - \frac{1}{1.4\ (14)^{1.4-1}} \frac{\{(1.78)^{1.4} - 1\}}{\{1.78 - 1\}}$
- $= 1 - 0.395$
- $= 0.605$
- $\eta = 60.5\ \%$

Q.3. Estimate the air standard efficiency of a diesel engine, having cylinder diameter 250 mm and stroke 400 mm, clearance volume 1.5 liters, fuel cut-off at 5% of stroke.

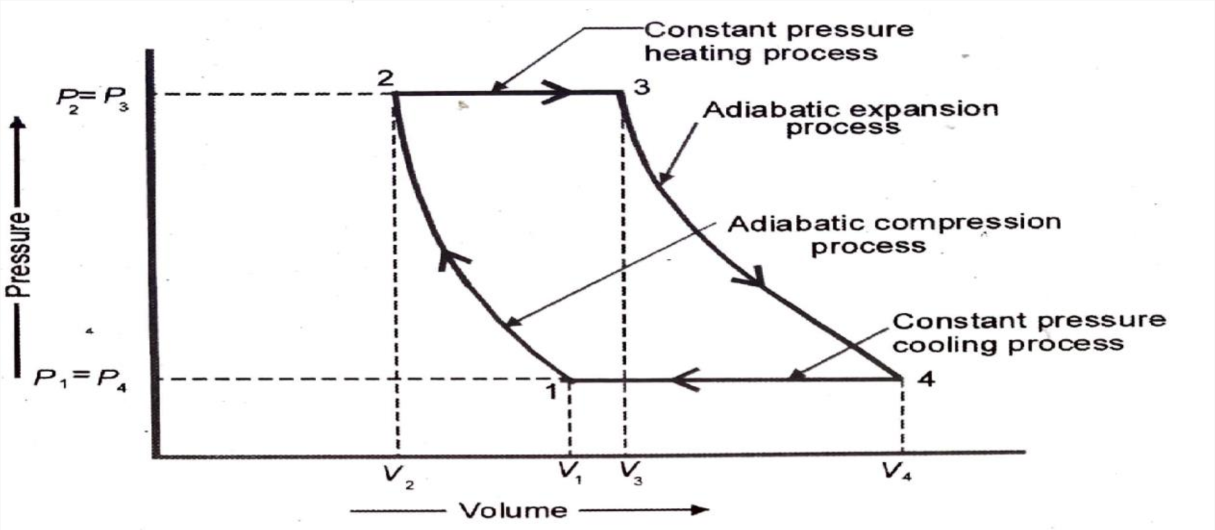
- Given data:
- $d = 250$ mm $= 0.25$ m
- $l = 400$ mm $= 0.4$ m
- $V_c = V_2 = 1.5$ litre
- We know, $1 m^3 = 1000$ litre
- $1 litre = 10^{-3} m^3$
- $V_c = V_2 = 1.5 \times 10^{-3} m^3$
- Cut off = 5 % of stroke
- $\eta = ?$
- Take, $\gamma = 1.4$

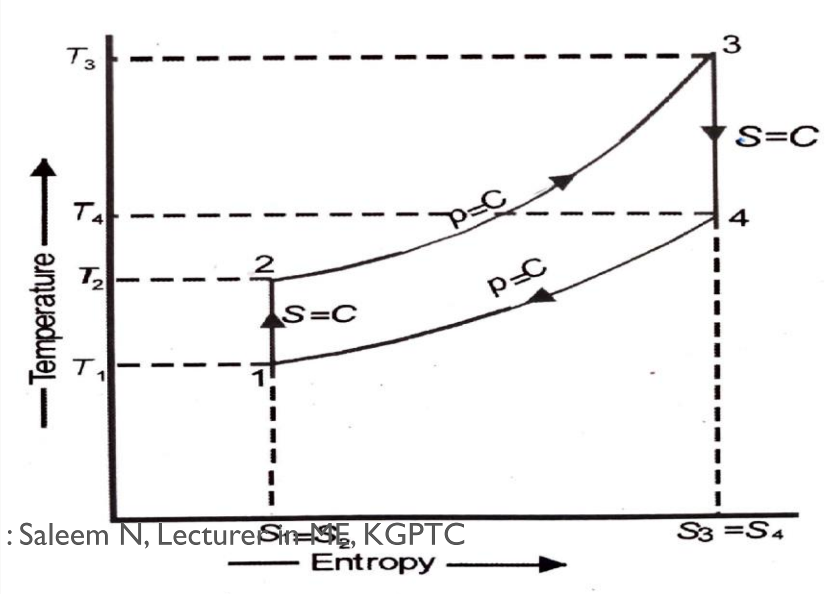


- Area of the cylinder, $A = \frac{\pi}{4} d^2$
- $A = \frac{\pi}{4}(0.25)^2$
- $= 0.049 \text{ m}^2$
- Swept volume, $V_s = A \times l$
- $V_s = 0.049 \times 0.4$
- $= 0.0196 \text{ m}^3$
- Total cylinder volume, $V_1 = V_c + V_s$
- $V_1 = 1.5 \times 10^{-3} + 0.0196$
- $V_1 = 0.0211 \text{ m}^3$
- Compression ratio, $r = \frac{V_1}{V_2}$
- $r = \frac{0.0211}{1.5 \times 10^{-3}} = 14.06$
- Volume at point of cut off, V_3
- $V_3 = V_c + 6\% \, V_s$
- $V_3 = 1.5 \times 10^{-3} + 0.06 \times 0.0196$
- $V_3 = 2.676 \times 10^{-3} \text{ m}^3$
- Cut off ratio, $r_c = \frac{V_3}{V_2}$
- $r_c = \frac{2.676 \times 10^{-3}}{1.5 \times 10^{-3}} = 1.78$
- $\eta = 1 - \frac{1}{\gamma (r)^{\gamma-1}} \frac{\{(r_c)^{\gamma} - 1\}}{\{r_c - 1\}}$
- $= 1 - \frac{1}{1.4\,(14.06)^{1.4-1}} \frac{\{(1.78)^{1.4} - 1\}}{\{1.78 - 1\}}$
- $= 1 - 0.394$
- $= 0.606$
- $\eta = 60.6\ \%$

JOULES CYCLE (BRAYTON CYCLE)

- It is a theoretical cycle for gas turbine consisting of four processes.
- In this heat is supplied and rejected at constant pressure.
- Expansion and compression of air takes place adiabatically.



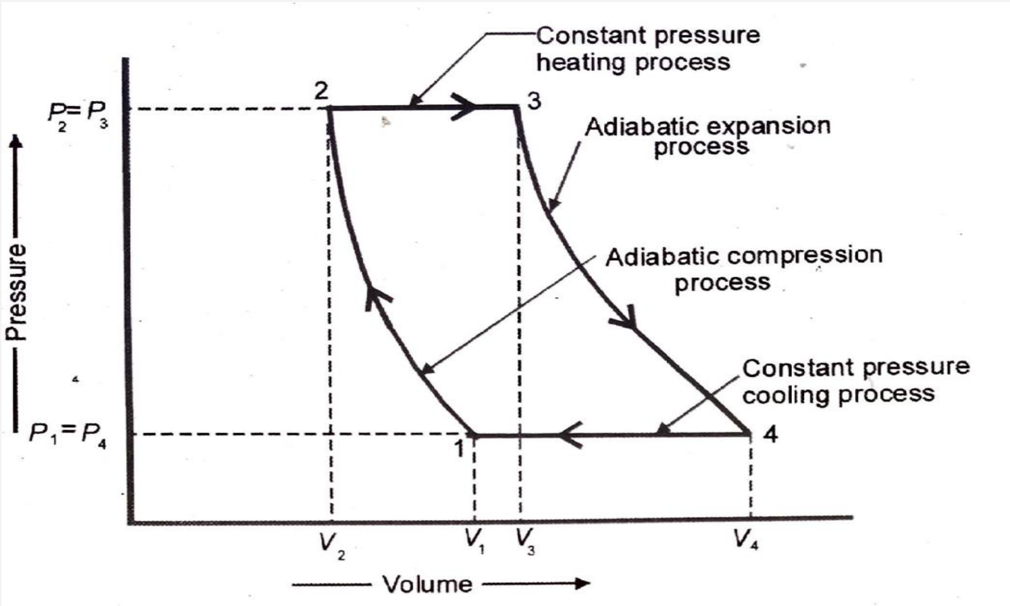


WORKING

- Consider a cylinder containing ‘m’ kg of air.
- Let the pressure, volume, temperature and entropy of air inside the cylinder at state 1 be p_1, V_1, T_1 and S_1 respectively.
- This air is compressed adiabatically to state 2 doing work on the air.
- Now heat is supplied to this compressed air at constant pressure from an external hot body till state 3 is reached.
- At state three the hot body is removed and air is allowed to expand adiabatically to state four doing external work.
- Heat is rejected at constant pressure to an external cold body till state one is reached.
- Thus air finally returns to its original state after completing a cycle.

EFFICIENCY DERIVATION

- Heat supplied during constant pressure process 2-3,
- $HS = mC_p\,(T_3 - T_2)$
- Heat rejected during constant pressure process 4-1,
- $HR = -mC_p\,(T_1 - T_4)$
- $HR = mC_p\,(T_4 - T_1)$
- Air standard efficiency, $\eta = 1 - \dfrac{\textit{Heat rejected}}{\textit{Heat supplied}}$
- $$\eta = 1 - \frac{mC_p\,(T_4 - T_1)}{mC_p\,(T_3 - T_2)}$$
- $$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

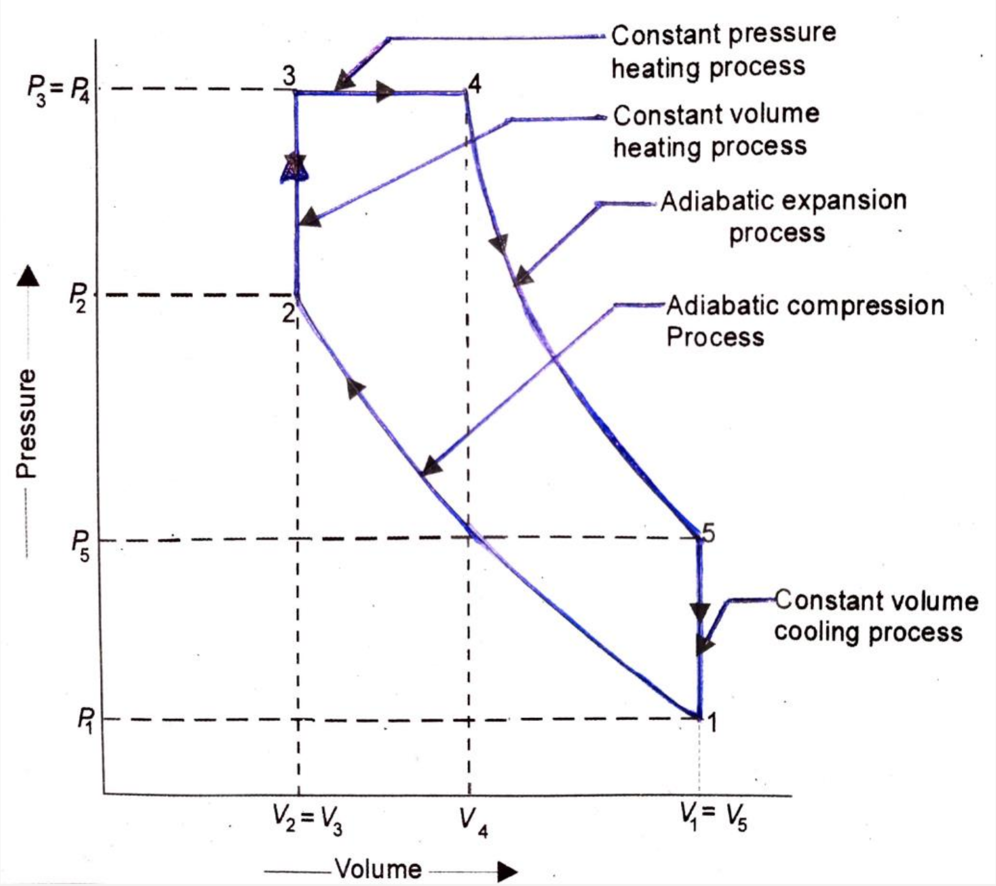


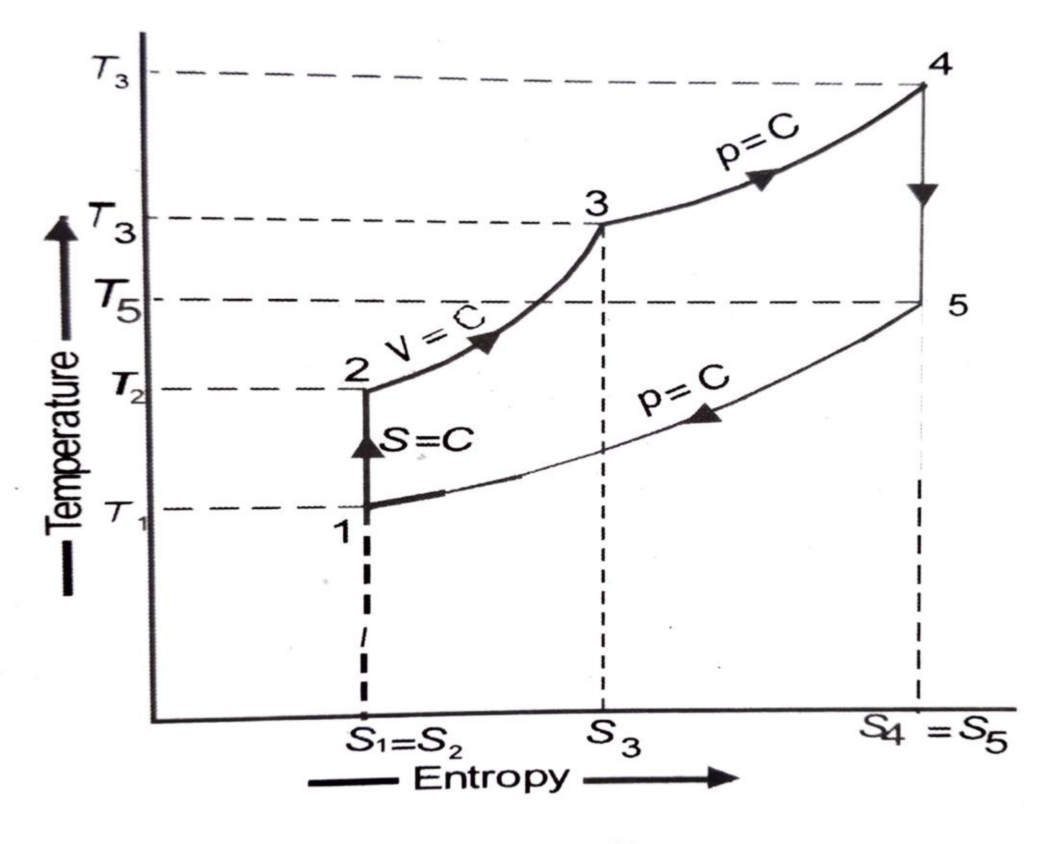
- For process 1-2 (adiabatic)
- P-T relation is given by,
- $\frac{P_1}{P_2} = (\frac{T_1}{T_2})^{\frac{\gamma}{\gamma-1}}$
- $\frac{P_2}{P_1} = (\frac{T_2}{T_1})^{\frac{\gamma}{\gamma-1}}$
- $\frac{T_2}{T_1} = (\frac{P_2}{P_1})^{\frac{\gamma-1}{\gamma}}$
- Where,
- $\frac{P_2}{P_1} = \frac{P_3}{P_4}$ = rp = pressure ratio
- $T_2 = T_1(\frac{P_2}{P_1})^{\frac{\gamma-1}{\gamma}}$
- $T_2 = T_1(r_p)^{\frac{\gamma-1}{\gamma}}$ ……………….(2)

- For process 3-4 (adiabatic)
- P-T relation is given by,
- $\frac{P_3}{P_4} = (\frac{T_3}{T_4})^{\frac{\gamma}{\gamma-1}}$
- $\frac{T_3}{T_4} = (\frac{P_3}{P_4})^{\frac{\gamma-1}{\gamma}}$
- $T_3 = T_4(\frac{P_3}{P_4})^{\frac{\gamma-1}{\gamma}}$
- $T_3 = T_4\,(r_p)^{\frac{\gamma-1}{\gamma}}$ ……………….(3)

- Substitute equation (2) and (3) in equation (1)
- $\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$
- $\eta = 1 - \frac{(T_4 - T_1)}{\{T_4 (r_p)^{\frac{\gamma-1}{\gamma}} - T_1 (r_p)^{\frac{\gamma-1}{\gamma}}\}}$
- $= 1 - \frac{(T_4 - T_1)}{(r_p)^{\frac{\gamma-1}{\gamma}} (T_4 - T_1)}$
- $\eta = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}$
- It shows that the efficiency of Joule cycle increases with increase in pressure ratio.

DUAL COMBUSTION CYCLE (SEMI-DIESEL CYCLE)





(b) T-S diagram

- It is a theoretical cycle having five processes.
- It is used in modern high speed oil engines and is a combination of Otto and Diesel cycle.
- In this cycle heat is supplied at constant volume initially and then heat is supplied at constant pressure.
- Heat is rejected at constant volume process.
- Compression and expansion of air takes place adiabatically.

- Process 1-2 ---- Adiabatic compression
- Process 2-3 ---- Constant volume heat addition.
- Process 3-4 ---- Constant pressure heat addition.
- Process 4-5 ---- Adiabatic expansion
- Process 5-1 ---- Constant volume heat rejection.

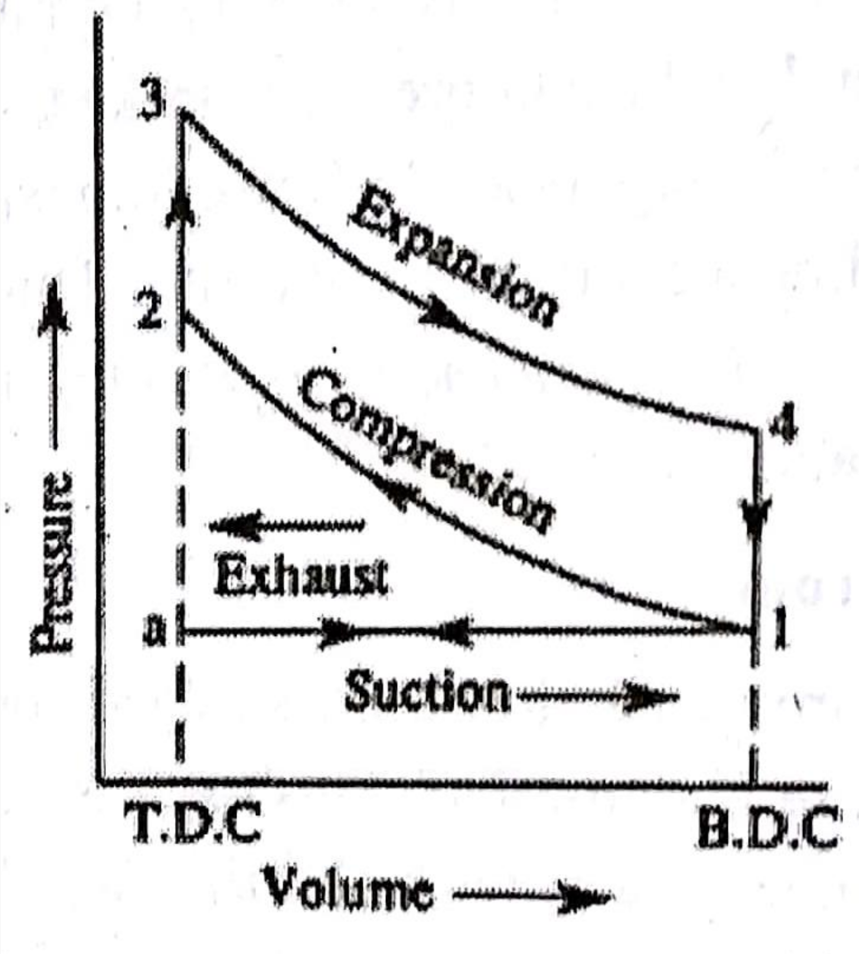
TE ASSIGNMENT NO : 1

1. Explain the working of two stroke Petrol and Diesel engines with the help of P-V diagram.
2. Explain the working of four stroke Petrol and Diesel engines with the help of P-V diagram.

THEORETICAL AND ATUAL P-V DIAGRAM

THEORETICAL P-V DIAGRAM OF FOUR STROKE PETROL ENGINE

- This cycle is also called as otto cycle engine.
- The X-axis indicates the volume and Y-axis indicates the pressure inside the cylinder.
- The point 'a' refers to the clearance volume.
- The line a to 1 refers to the stroke volume.
- The volume at 1 shows the sum of the clearance volume and stroke volume.



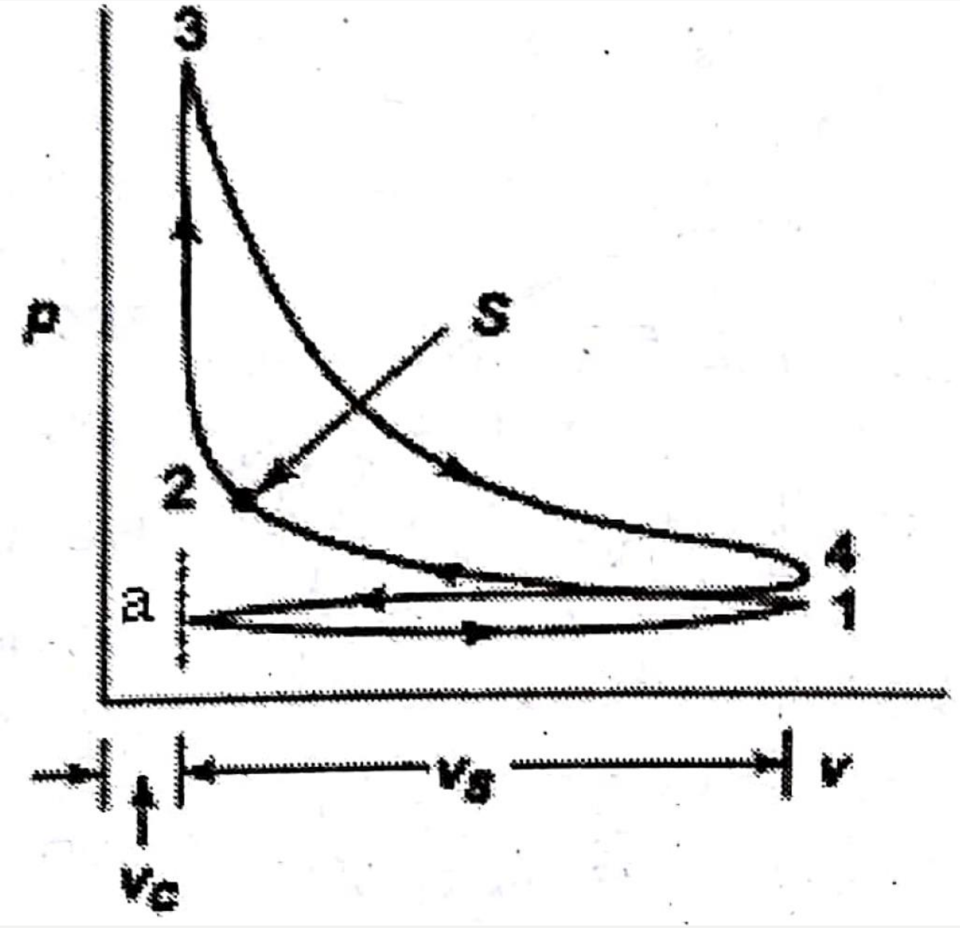
Theoretical P-V. diagram

- During the suction stroke, the air fuel mixture is sucked inside the engine cylinder. The increase in volume takes place and is indicated by the line a-1.
- During the compression stroke, the charge is compressed as indicated from point 1 to 2. The volume has now decreased to point 2 and pressure inside the cylinder rises. This process is adiabatic in nature.
- The compressed charge is ignited at constant volume, accompanied by an increase in pressure as indicated from point 2 to point 3. The line 2-3 is a constant volume line.
- During the power stroke, the volume of the charge increases and pressure decreases. This process is represented by the line 3-4. This process is also adiabatic in nature.

- The exhaust valve opens at the point 4 with the release of exhaust gases, the pressure is suddenly decreased.
- This decrease in pressure is indicated by the line 4-1, which takes place at constant volume.
- During the exhaust stroke, the piston moves inward to the point a. The exhaust gas is pushed out as indicated by the line 1-a.
- The theoretical P-V diagram has sharp edges indicating that the valve opens instantaneously.
- The suction and exhaust stroke takes place at atmospheric pressure.

ACTUAL P-V DIAGRAM OF FOUR STROKE PETROL ENGINE

- The opening and closing of the valves does not takes place instantaneously.
- Each valve takes some time for opening and also for closing.
- According to the actual process, every corner in the P-V diagram is rounded.

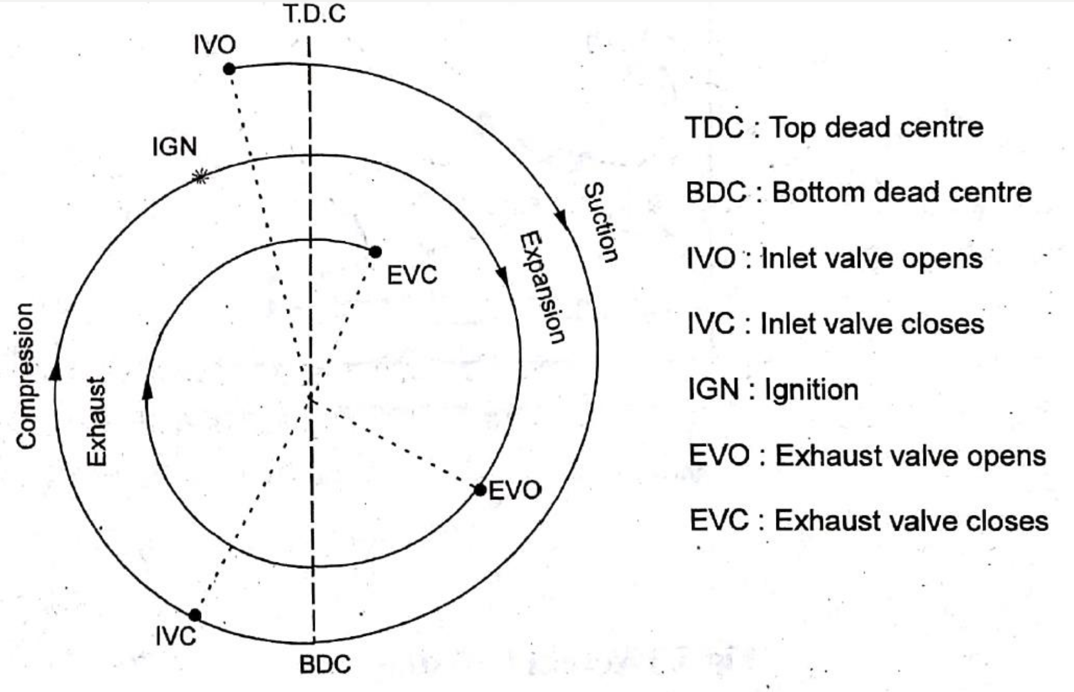


- Actually the suction takes place at a pressure 0.3 bar below the atmospheric pressure.
- This is required to overcome the resistance of the inlet valve to the entering charge.
- During the compression stroke, the mixture is compressed as shown by the line 1-2.
- At the point 's' just before the end of the compression stroke, the ignition of the mixture with electric spark takes place.
- The pressure of the fuel at the point 3 is as high as 60 bars under full load. The temperature also rises to 2000°C to 3000°C.
- The burning gases then expand and power stroke takes place. This is indicated by the line 3-4.

- At the end of the power stroke, the inlet valve remains closed but exhaust valve opens.
- The piston moves towards the top of the cylinder.
- Most of the burnt gases is expelled to the atmosphere at the end of the exhaust stroke.
- The exhaust takes place at a pressure higher than the atmospheric pressure.
- This is indicated by the line 4-a.

VALVE TIMING DIAGRAM OF A FOUR STROKE CYCLE PETROL ENGINE

- The valves of an engine should open and close at the correct intended time during its operation.
- There is a special method to enable the valves to open and close on time. This method is called valve timing.
- The diagram representing the correct opening and closing is called as valve timing diagram.



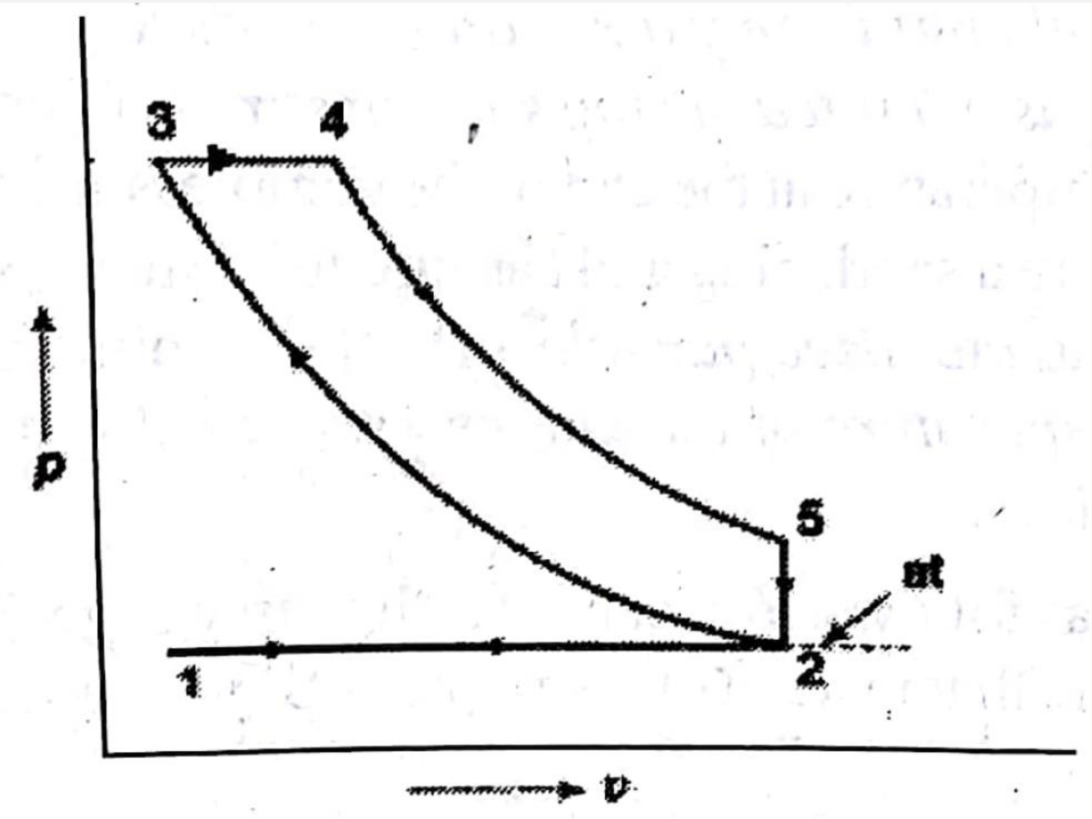
Valve timing diagram of four stroke petrol engine

- One revolution of the crank shaft is equal to 360°. This angle is called crank angle.
- In actual practice, the inlet valve opens a few degrees before the start of the suction stroke because the valve opens and closes slowly, and therefore some time should be provided for the valve to open fully at the beginning of the suction stroke.
- It may be noted that during the suction stroke, there is a possibility that the full amount of air-fuel mixture is not admitted, if the inlet valve is closed at the end of the suction stroke. This insufficient air-fuel mixture will not produce the intended power.
- So it is necessary that the inlet valve should remain open even after the completion of theoretical suction stroke. This helps to admit full amount of air-fuel mixture into the engine cylinder. The inlet valve closes at a crank angle after the BDC as shown in Fig.

- Now the charge is compressed (with both valves closed) and then ignited with the help of a spark plug before the end of the compression stroke(At a crank angle 6° to 20° before the TDC).
- This is done as the charge requires some time to ignite. By the time, the piston reaches TDC, the burnt gases push the piston downwards and the expansion or working stroke takes place.
- Now the exhaust valve opens before the piston again reaches BDC and starts moving up, thus performing exhaust stroke.
- The exhaust valve closes after the crank has moved a little beyond the TDC. This is done as the burnt gases continue to leave the engine cylinder although the piston is moving downwards.
- It may be noted that for a small fraction of a crank revolution, both the inlet and outlet valves are in open condition. This is known as valve overlap.

THEORETICAL P-V DIAGRAM OF FOUR STROKE DIESEL ENGINE

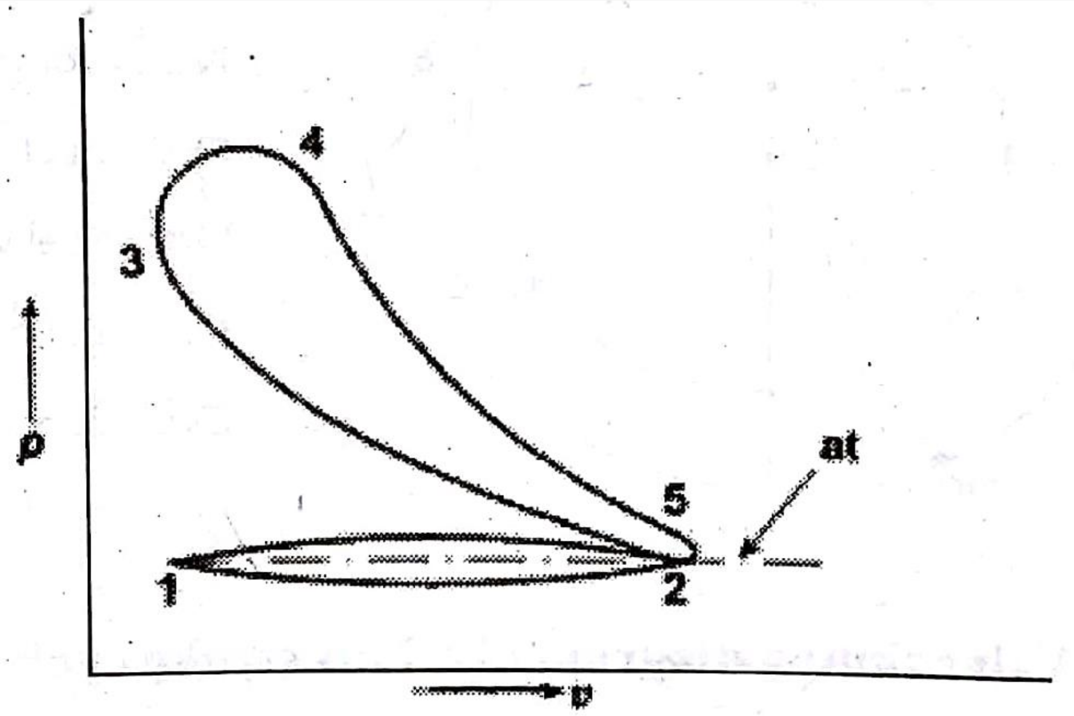
- During the suction stroke, the air is sucked inside the cylinder. The volume increases as shown by the point- 1 to point-2 at atmospheric pressure.
- During the compression stroke, the air is compressed from point-2 to point-3. Volume decreases to point -3(clearance volume) and pressure increases. This process takes place adiabatically.



- The fuel (Diesel) is injected at the end of the compression stroke at point-3. Thus heat is added to the compressed air. Injection of fuel is continued for some time and then cut off. The cut-off is indicated by the point-4.
- The line 3-4 is called constant pressure stroke. The power stroke starts from point-4. The hot gases now expand adiabatically till the piston reaches at the bottom dead centre. Point-5 is the bottom dead centre and the line 4-5 represents the power stroke.
- The line 5-2 is the constant volume line, showing the escape of the gases.
- Then the piston moves up and reaches the top dead centre. During this time, the exhaust gases are pushed out, The line 2-1 represents the exhaust stroke. Exhaust takes place at atmospheric pressure and one cycle is thus completed.
- Here there are two adiabatic processes, namely the constant pressure process during which the heat is added, and the constant volume process where heat is rejected.

ACTUAL P-V DIAGRAM OF FOUR STROKE DIESEL ENGINE

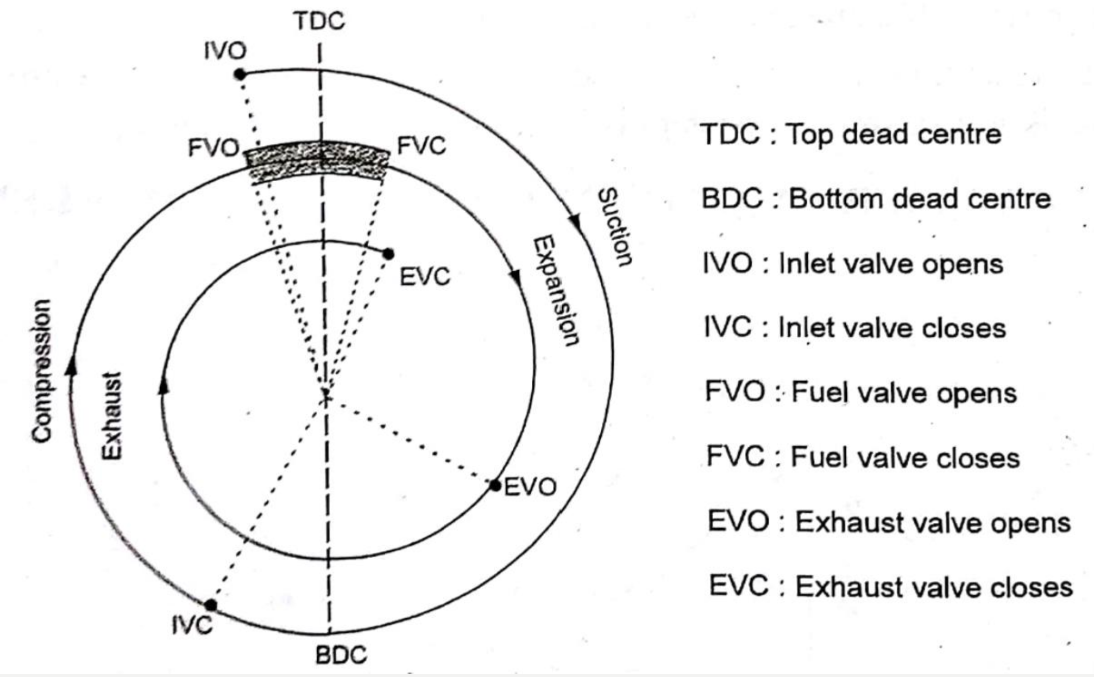
- Actually, during the suction stroke in a diesel cycle engine, the pressure inside the cylinder is slightly less than atmospheric pressure.
- Therefore, atmospheric air is sucked inside the engine cylinder, till the piston reaches the bottom dead centre position. This is shown by the line 1-2.



- Then the piston moves towards the top dead centre, compressing the air to a very high pressure. The temperature of air is also increased.
- Just before the top dead centre, the fuel injection takes place. The injection continues for some time and then cut-off during the power stroke.
- The point-3 shows the point of injection of fuel and point-4 refers the point of cut-off of the fuel.
- The line 4-5 indicates the expansion of the burnt gases during the power stroke. The point-5 shows the position of piston to the bottom dead centre.
- At this point the exhaust valve opens and the burnt gases escape into the atmosphere. The line 5-2 indicates the escape process.
- The line 2-1 indicates the exhaust stroke. During this period, the burnt gases are pushed into the atmosphere by the piston.
- The pressure during this period is slightly higher than the atmospheric pressure. One cycle of operation is thus completed.

VALVE TIMING DIAGRAM OF A FOUR STROKE DIESEL ENGINE

- The actual valve timing diagram of a four stroke cycle diesel engine is shown in the Figure.
- The inlet valve opens before the piston reaches TDC (10 to 25^0).
- Now the piston reaches the TDC and the suction stroke starts.
- The piston reaches the BDC and then starts moving up. The inlet valve closes after the piston passes the BDC (25 to 50°).

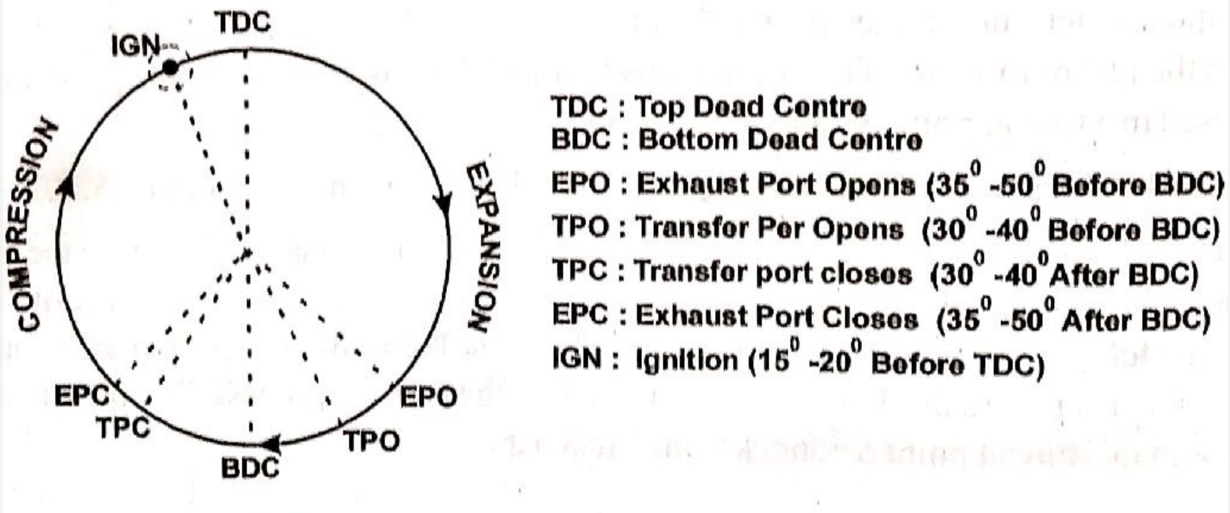


- This is done as the incoming air continues to flow into the cylinder although the piston is moving upwards from BDC.
- Now the air is compressed with the both valves closed.
- The fuel valve opens before the piston reaches the TDC. Now the fuel is injected in the form of very fine spray, into the engine cylinder, which gets ignited due to the high temperature of compressed air.
- The fuel valve closes after the piston has come down a little from TDC. This is done to ensure that the required quantity of fuel is injected into the cylinder.
- The burnt gases pushes the piston downwards, and the working or expansion stroke takes place.
- Now the exhaust valve opens before the piston reaches the BDC and starts moving up thus performing the exhaust stroke.
- The inlet valve opens before the piston reaches TDC to start the suction stroke. This is done as the fresh air helps to push out the burnt gases.
- Now the piston again reaches TDC, and the suction starts.

VALVE TIMING DIAGRAM OF A TWO STROKE PETROL ENGINE

- After igniting the charge, the expansion of the charge starts and the piston moves from TDC to BDC.

- First of all, the exhaust port opens before the piston reaches BDC and the burnt gases start leaving the cylinder.



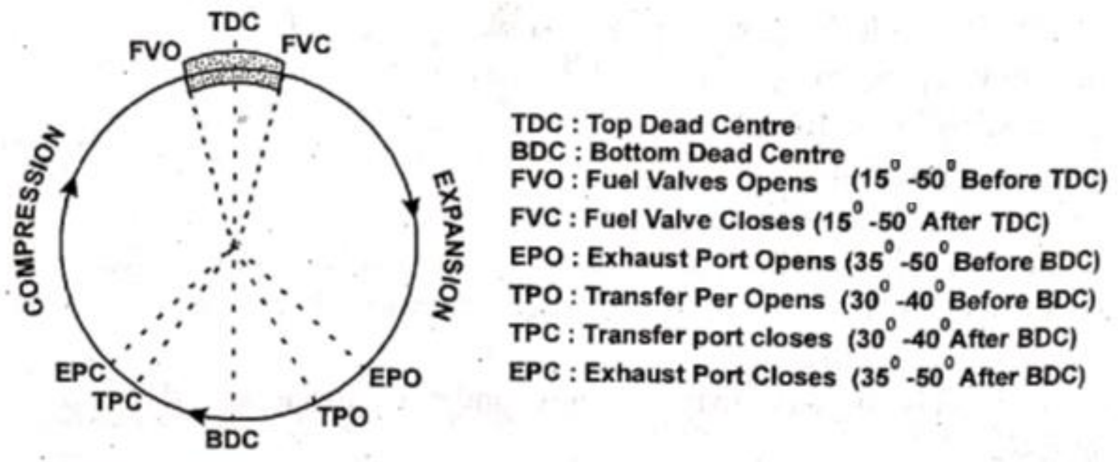
Valve timing-diagram of a two stroke cycle petrol engine.

- After a small fraction of the crank revolution, the transfer port also opens and the fresh air fuel mixture enters into the engine cylinder. This is done as the fresh incoming charge helps in pushing out the burnt gases.
- Now the piston reaches BDC and then starts moving upwards. As the crank moves a little beyond BDC, first the transfer port closes and then the exhaust port also closes.
- This is done to suck fresh charge through the transfer port and to exhaust the burnt gases through the exhaust port simultaneously.
- Now the charge is compressed with both ports closed, and then ignited with the help of a spark plug before the end of compression stroke. This is done as the charge requires some time to ignite.
- By the time the piston reaches TDC, the burnt gases under high pressure and temperature push the piston downwards with full force and expansion of the burnt gases takes place.
- The exhaust and transfer ports open and close at equal angles on either side of the BDC position.

VALVE TIMING DIAGRAM OF A TWO STROKE DIESEL ENGINE

- After igniting he charge, the expansion of the fuel starts and the piston moves from TDC to BDC.

- First of all, the exhaust port opens before the piston reaches BDC and the burnt gases start leaving the cylinder.



Valve timing diagram of a two stroke cycle diesel engine

- After a small fraction of the crank revolution, the transfer port also opens and the fresh air enters into the engine cylinder. This is done as the fresh incoming air helps in pushing out the burnt gases.
- Now the piston reaches BDC and then starts moving upwards. As the crank moves a little beyond BDC, first the transfer port closes and then the exhaust port also closes. This is done to suck fresh air through the transfer port and to exhaust the burnt gases through the exhaust port simultaneously.
- Now the charge is compressed with both the ports closed. Fuel valve opens a little before the piston reaches the TDC. Now the fuel is injected in the form of very fine spray into the engine cylinder, which gets ignited due to high temperature of the compressed air.
- The fuel valve closes after the piston has come down a little from the TDC. This is done as the required quantity of fuel is injected into the engine cylinder.
- Now the burnt gases (under high pressure and temperature) push the piston downwards with full force and expansion of the gases takes place.
- It may be noted that in a two-stroke cycle diesel engine, like two-stroke petrol engine, the exhaust and transfer ports open and close at equal angles on either side of the BDC position.