MODULE - I

I.C. ENGINES

Introduction

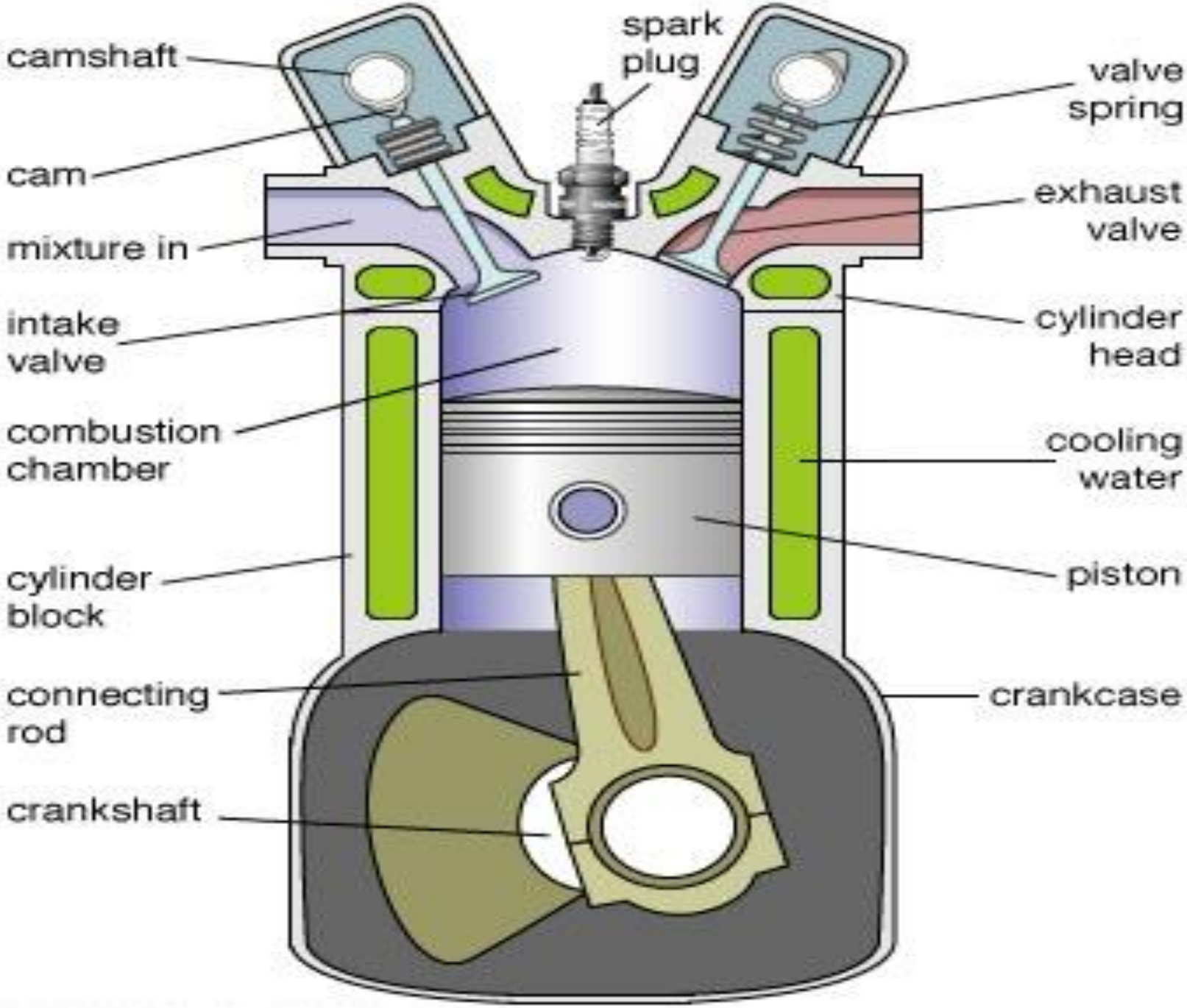
Heat engine : Defined as any engine that converts thermal energy to mechanical work output. Examples of heat engines include: steam engine, Diesel engine, and Petrol engine.

- In an **Internal combustion engine**, combustion takes place within working fluid of the engine, thus fluid gets contaminated with combustion products.
  - Petrol engine is an example of internal combustion engine, where the working fluid is a mixture of air and fuel.

- In an **External combustion engine**, working fluid gets energy using boilers by burning fossil fuels or any other fuel, thus the working fluid does not come in contact with combustion products.
  - Steam engine is an example of external combustion engine, where the working fluid is steam.

- Internal combustion engines may be classified as :
  - Spark Ignition engines.
  - Compression Ignition engines.
- **Spark ignition engine (SI engine):** An engine in which the combustion process in each cycle is started by use of an external spark.
- **Compression ignition engine (CI engine):** An engine in which the combustion process starts when the air-fuel mixture self ignites due to high temperature in the combustion chamber caused by high compression.
  - Spark ignition and Compression Ignition engine operate on either a four stroke cycle or a two stroke cycle.

COMPONENETS AND ITS FUNCTIONS OF I.C. ENGINE


camshaft
spark plug
valve spring
cam
exhaust valve
mixture in
intake valve
cylinder head
combustion chamber
cooling water
cylinder block
piston
connecting rod
crankcase
crankshaft

TERMINOLOGIES RELATED TO ENGINE

Top Dead Center (TDC)

Bottom Dead Center (BDC)

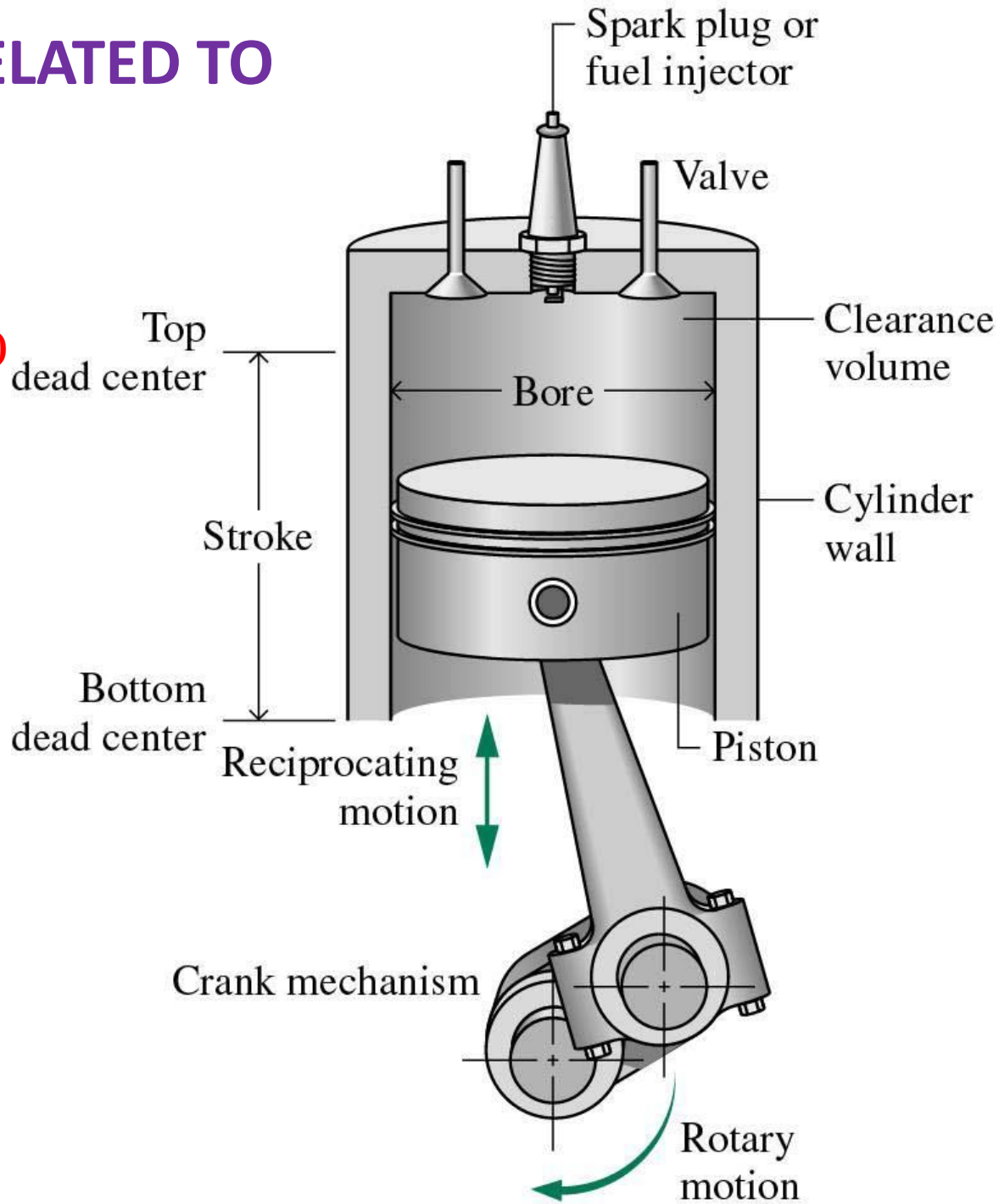
Stroke

Bore

Displacement volume

Clearance volume

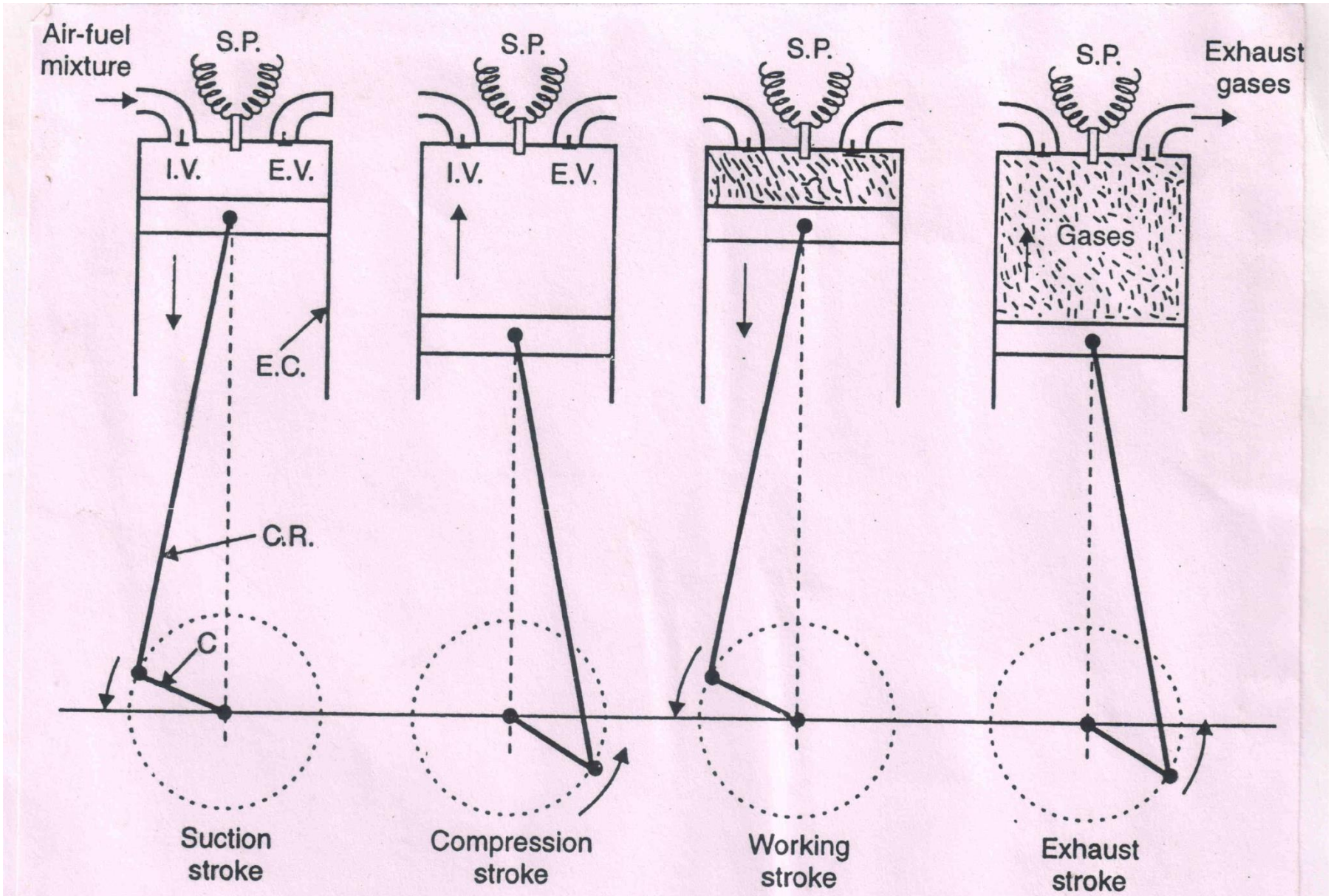
Compression ratio



- **Top Dead Center (TDC):** Position of the piston when it stops at the farthest point away from the crankshaft.
- **Bottom Dead Center (BDC):** Position of the piston when it stops at the point closest to the crankshaft.
- **Stroke :** Distance travelled by the piston from one extreme position to the other : TDC to BDC or BDC to TDC.
- **Bore : d**efined as **c**ylinder diameter or piston face diameter; piston face diameter is same as cylinder diameter (minus small clearance).

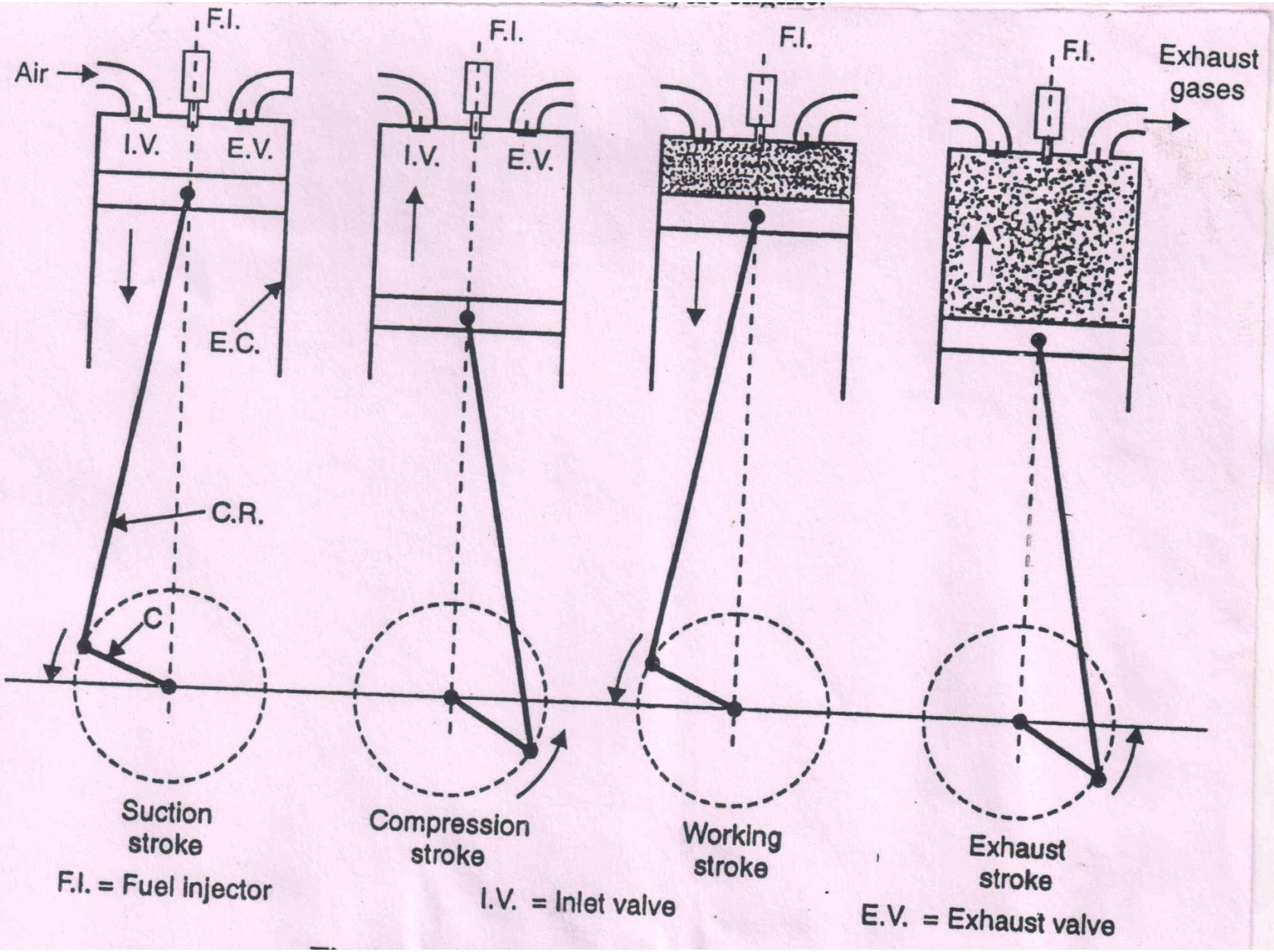
- **Swept volume/Displacement volume :** Volume displaced by the piston as it travels through one stroke.
- **Clearance volume :** It is the minimum volume of the cylinder available for the charge (air or air fuel mixture) when the piston reaches at TDC during compression stroke of the cycle.
  - Minimum volume of combustion chamber with piston at TDC.
- **Compression ratio :** The ratio of total volume to clearance volume of the cylinder is the compression ratio of the engine.
  - Typically compression ratio for SI engines varies form 8 to 12 and for CI engines it varies from 12 to 24

Four Stroke Petrol Engine

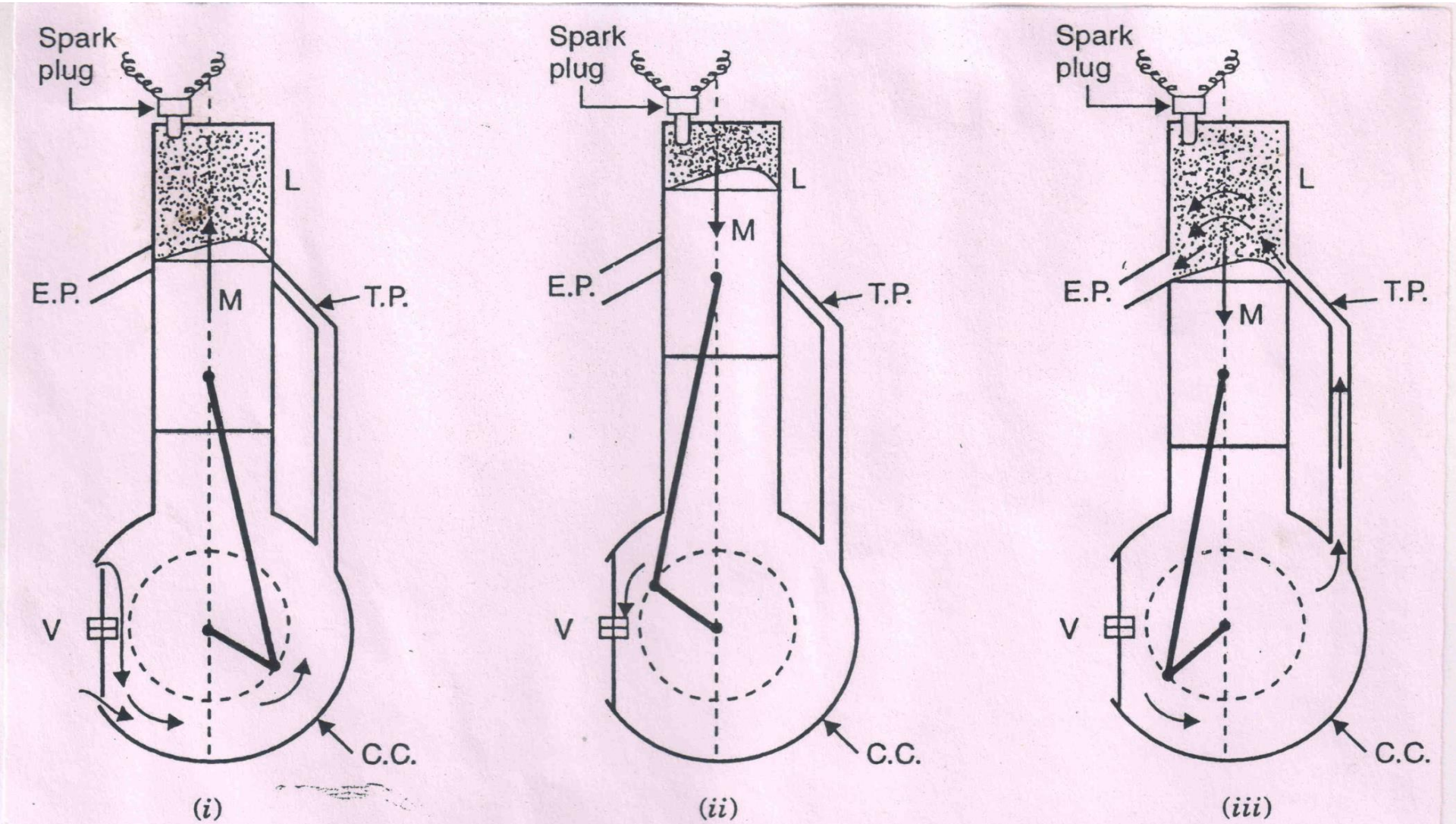


I.V = Intel valve, E.V. = Exhaust valve, E.C. = Engine cylinder, C.R. = Connecting rod
C = Crank, S.P. = Spark plug.

Four Stroke Diesel Engine

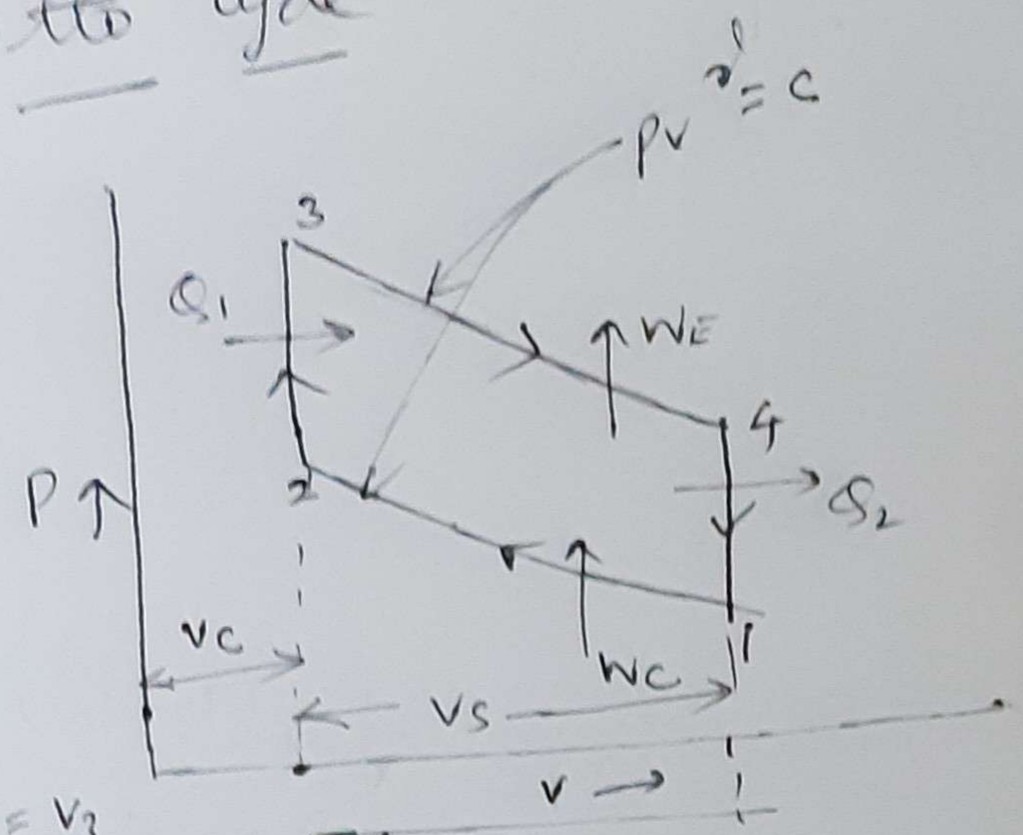


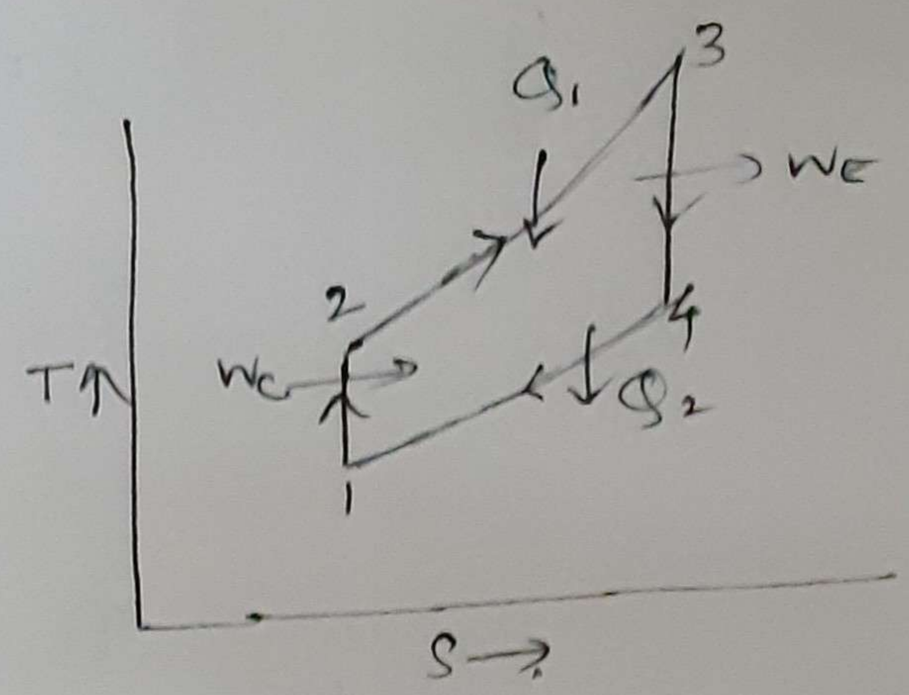
Two Stroke Petrol Engine



L = Cylinder E.P. = Exhaust port T.P. = Transfer port V = valve, C.C = Crank chamber

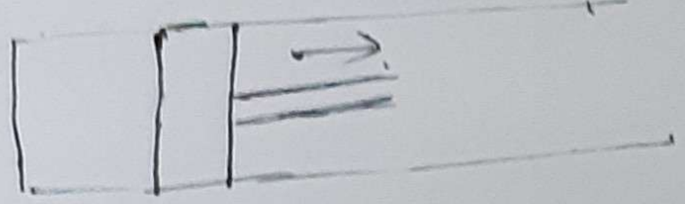
Otto cycle





$V_c = V_2 = V_3$

$V_s = V_1 - V_2$.



1-2 - Adiabatic compression

2-3 - Heat addition at constant volume

3-4 - Adiabatic expansion

4-1 - Heat rejected at constant volume.

$$\eta = \frac{\text{net workdone}}{\text{Heat supplied}} = \frac{H.S - H.R}{H.S.}$$

$$\eta = \frac{Q_1 - Q_2}{Q_1} \quad - (1)$$

compression ratio $r = \frac{V_c + V_s}{V_c} = \frac{V_2 + V_1 - V_2}{V_2} = \frac{V_1}{V_2}$

Expansion ratio $= \frac{\text{Volume at the end of expansion}}{\text{Volume at the begining of expansion}} = \frac{V_4}{V_3}$

From p.v diagram.

$V_2 = V_3$ and $V_1 = V_4$

$\therefore \frac{V_1}{V_2} = r = \frac{V_4}{V_3}$: expansion ratio

Heat supplied $Q_1 = C_v(T_3 - T_2)$

Heat rejected $Q_2 = C_v(T_4 - T_1)$

$$\eta = \frac{C_v(T_3 - T_2) - C_v(T_4 - T_1)}{C_v(T_3 - T_2)} = \frac{(T_3 - T_2) - (T_4 - T_1)}{(T_3 - T_2)}$$

$$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \quad - (2)$$

For adiabatic process (1-2)

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

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

$$T_1 = \frac{T_2}{r^{\gamma - 1}} \quad - (3)$$

For adiabatic process (3-4) ②

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r^{\gamma-1}$$

$$T_4 = \frac{T_3}{r^{\gamma-1}} \quad — ④.$$

Subs. ③ and ④ in ②.

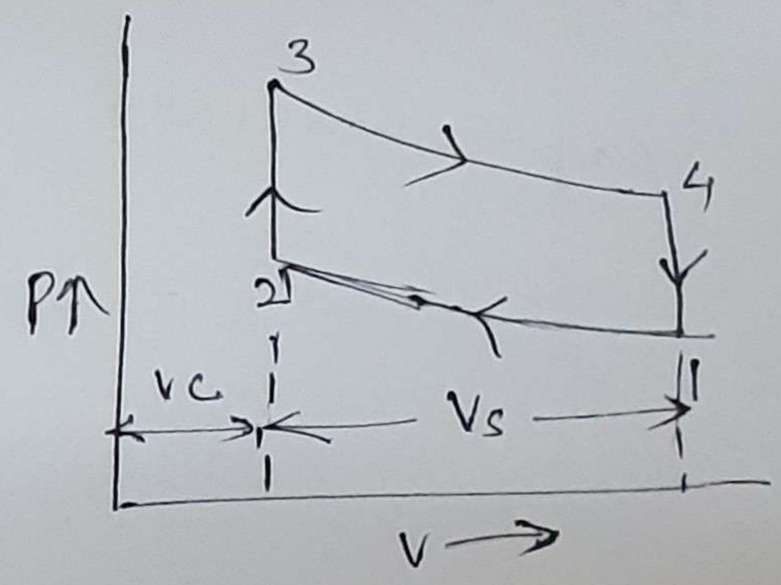
$$\eta = 1 - \frac{\frac{T_3}{r^{\gamma-1}} - \frac{T_2}{r^{\gamma-1}}}{T_3 - T_2} = 1 - \frac{\frac{1}{r^{\gamma-1}}\cancel{(T_3 - T_2)}}{\cancel{(T_3 - T_2)}}$$

$$\boxed{\eta = 1 - \frac{1}{r^{\gamma-1}}}$$

Mean Effective pressure

$$P_m = \frac{\text{Net workdone}}{\text{stroke volume}} = \frac{W_{net}}{V_1 - V_2} = \frac{W_{net}}{d_1 - d_2}.$$

1) Calculate the thermal efficiency of an engine working on the otto cycle. The bore and stroke of the cylinder are 17 cm and 30 cm respectively. The clearance volume is 0.002025 m^3. Take $\gamma = 1.4$.



Given data

$D = 17\,cm = 17 \times 10^{-2}\,m.$

$L = 30\,cm = 30 \times 10^{-2}\,m.$

$V_c = 0.002025\,m^3$

compression ratio $r = \frac{V_1}{V_2} = \frac{V_c + V_s}{V_c}$

Stroke volume $V_s = \frac{\pi}{4} D^2 L = \frac{\pi}{4} \times (17 \times 10^{-2})^2 \times (30 \times 10^{-2})$

$V_s = 0.0068\,m^3.$

$$r = \frac{0.002025 + 0.0068}{0.002025} = 4.36$$

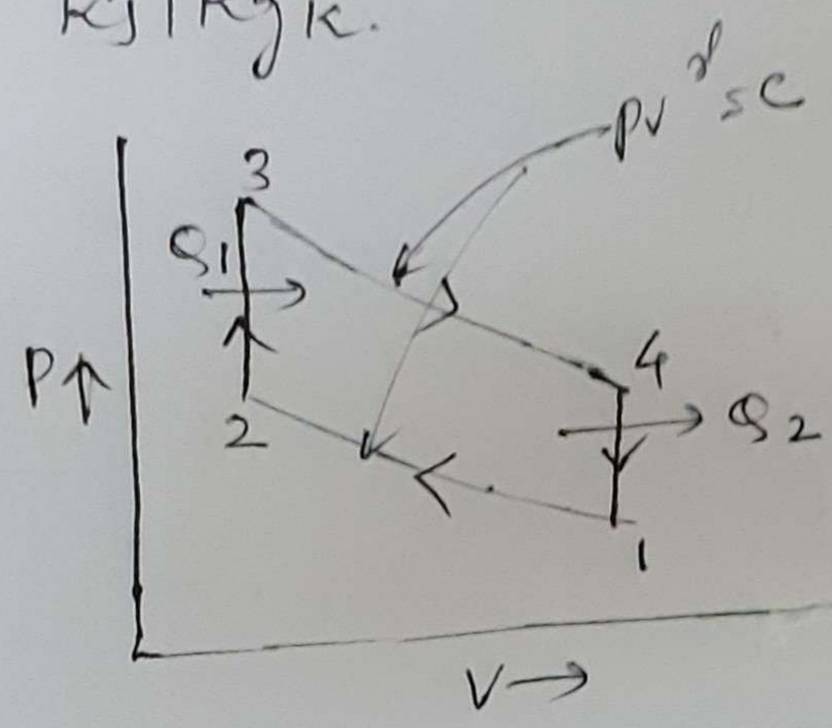
$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

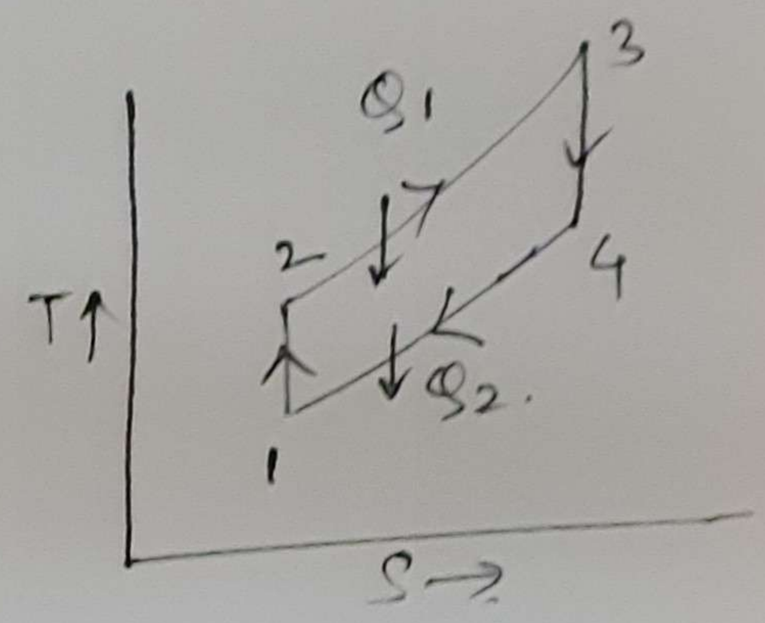
$$= 1 - \frac{1}{(4.36)^{0.4}} = 0.444$$

$\eta = 44.4\%$

(2) An engine working on the Otto cycle is supplied with air at 0.1 MPa, 35°C. The compression ratio is 8. Heat supplied is 2100 kJ/kg. Calculate the maximum pressure and temperature of the cycle. Also Find the cycle efficiency and mean effective pressure. Take for air $C_p = 1.005$ kJ/kgK $C_v = 0.718$ kJ/kgK

$R = 0.287$ kJ/kgK.





Given data

$P_1 = 0.1$ MPa

$P_1 = 0.1 \times 10^6$ N/m^2

$T_1 = 35°C = 308$ K.

$r = \frac{V_1}{V_2} = 8$

$Q_1 = 2100 \times 10^3$ J/kg.

(1) cycle Efficiency (η)

$\gamma = \frac{C_p}{C_v} = \frac{1.005}{0.718} = 1.4$

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

$$\eta = 1 - \frac{1}{8^{0.4}} = 0.565 = 56.5\%$$

(2) To find T_3 and P_3

$$Q = m C_v (T_3 - T_2) \text{ J}$$

$$\frac{Q}{m} = C_v (T_3 - T_2) \text{ J/kg.}$$

For Adiabatic process (1-2)

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

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \Rightarrow \frac{T_2}{308} = (8)^{0.4}$$

$T_2 = 708.4$ K.

$$2100 \times 10^3 = 0.718 \times 10^3 (T_3 - 708.4)$$

$T_3 = 3632.7$ K.

For constant volume process (2-3)

$$\frac{PV}{T} = C$$

$$\frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3}$$

$$\frac{P_2}{P_3} = \frac{T_2}{T_3}$$

$$P_3 = P_2 \times \frac{T_3}{T_2}$$

For adiabatic process (1-2)

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

$$\frac{P_2}{0.1\times10^6} = (8)^{1.4}$$

$$P_2 = 1837.9\times10^3 \ N/m^2$$

$$P_3 = 1837.9\times10^3 \times \frac{3632.7}{708.4}$$

$$P_3 = 9425.1 \ N/m^2$$

$$P_m = \frac{W_{net}}{v_1 - v_2}$$

Also $\eta = \frac{W_{net}}{Q_1} \Rightarrow W_{net} = \eta \times Q_1$

$$W_{net} = 0.565 \times 2100\times10^3 = 1186.5\times10^3 \ J/kg.$$

$$P_1 V_1 = mRT_1 \rightarrow P_1 \frac{v_1}{m} = RT_1$$

$$P_1 v_1 = RT_1 \rightarrow v_1 = \frac{P_1}{RT_1}$$

$$v_1 = \frac{0.1\times10^6}{287\times308} = 1.13 \ m^3/kg.$$

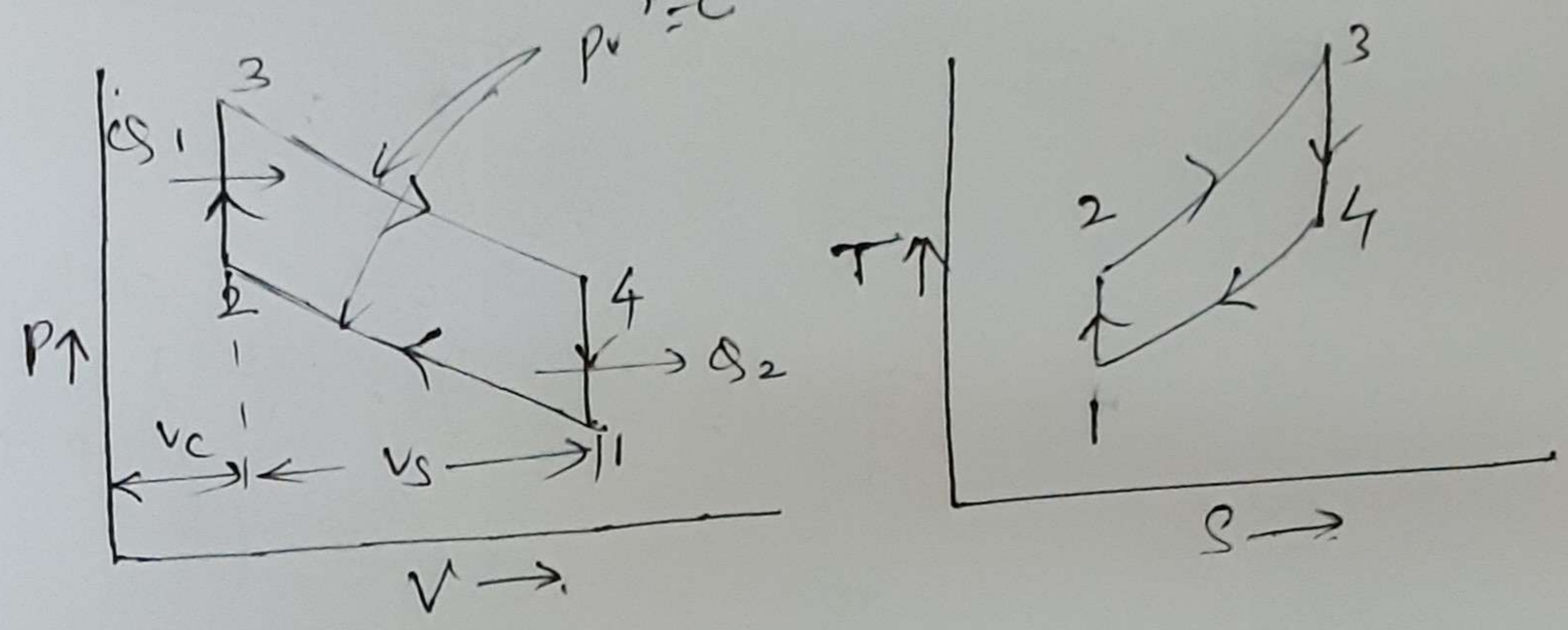
$$\frac{V_1}{V_2} = \frac{v_1}{v_2} = 8$$

$$v_2 = \frac{1.13}{8} = 0.141 \ m^3/kg.$$

$$P_m = \frac{1186.5\times10^3}{1.13 - 0.141}$$

$$P_m = 1.199\times10^6 \ N/m^2$$

3. A Four stroke engine working on Otto cycle has a swept volume of $0.1\ m^3$. The compression ratio is 7. The condition at the start of cycle: pressure 0.1 MPa and temperature 90°C. The heat addition at constant volume is 100 kJ/cycle. Find the ideal efficiency Mean effective pressure and temperature at key points in the cycle. Assume air as working substance.



Given data

$V_s = V_1 - V_2 = 0.1$

$r = \frac{V_1}{V_2} = 7$

$P_1 = 0.1 \times 10^6\ N/m^2$

$T_1 = 90°C = 363\ K$.

$Q = 100 \times 10^3\ J/cycle$

Taking $\gamma = 1.4$ $R = 287\ J/kgK$ $C_v = 718\ J/kgK$ for air.

(1) Efficiency

$$\eta = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{7^{0.4}}$$

$$\eta = 0.541 = 54.1\%$$

(2) Temperature at key points

For adiabatic process 1-2

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

$$\frac{T_2}{363} = (7)^{0.4}$$

$$\boxed{T_2 = 790.5\ K}$$

$$Q = m C_v (T_3 - T_2)$$

$V_1 - V_2 = 0.1$ and $\frac{V_1}{V_2} = 7 \Rightarrow V_1 = 7V_2$.

$7V_2 - V_2 = 0.1$

$6V_2 = 0.1$

$V_2 = 0.0166\ m^3$.

$V_1 = 7 \times 0.0166 = 0.1166\ m^3$

$$P_1 V_1 = m R T_1$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{0.1 \times 10^6 \times 0.1166}{287 \times 363} = 0.111 \text{ kg.}$$

$$Q = m C_v (T_3 - T_2)$$

$$100 \times 10^3 = 0.11 \times 718 (T_3 - 790.5)$$

$$T_3 = 2034.2 \text{ K.}$$

For process 2-3 - Adiabatic process.

1-2

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

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

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma - 1} = \left(\frac{V_2}{V_1}\right)^{0.4}$$

$$T_4 = 2034.27 \times \left(\frac{1}{7}\right)$$

$$T_4 = 934.05 \text{ K}$$

Mean Effective pressure P_m

$$P_m = \frac{W_{net}}{V_1 - V_2} = \frac{Q_1 - Q_2}{V_1 - V_2}$$

$$Q_2 = m C_v (T_4 - T_1)$$

(or) $\eta = \frac{W_{net}}{Q_1}$

$$= 0.111 \times 718 (934 - 363)$$

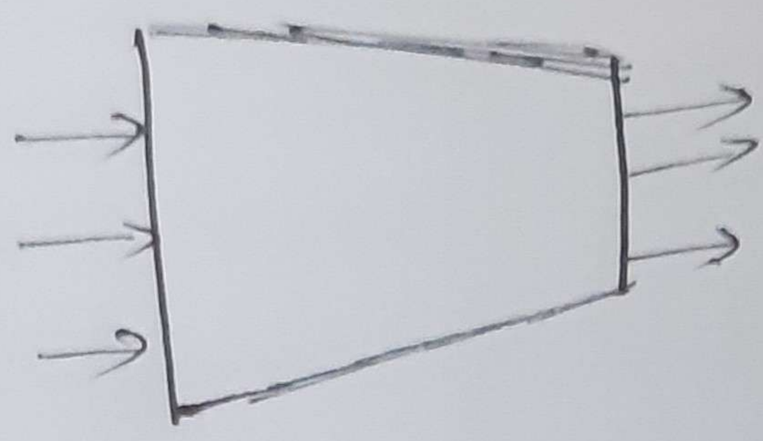
$$Q_2 = 45.88 \times 10^3 \text{ J.}$$

$$P_m = \frac{100 \times 10^3 - 45.88 \times 10^3}{0.1166 - 0.0166}$$

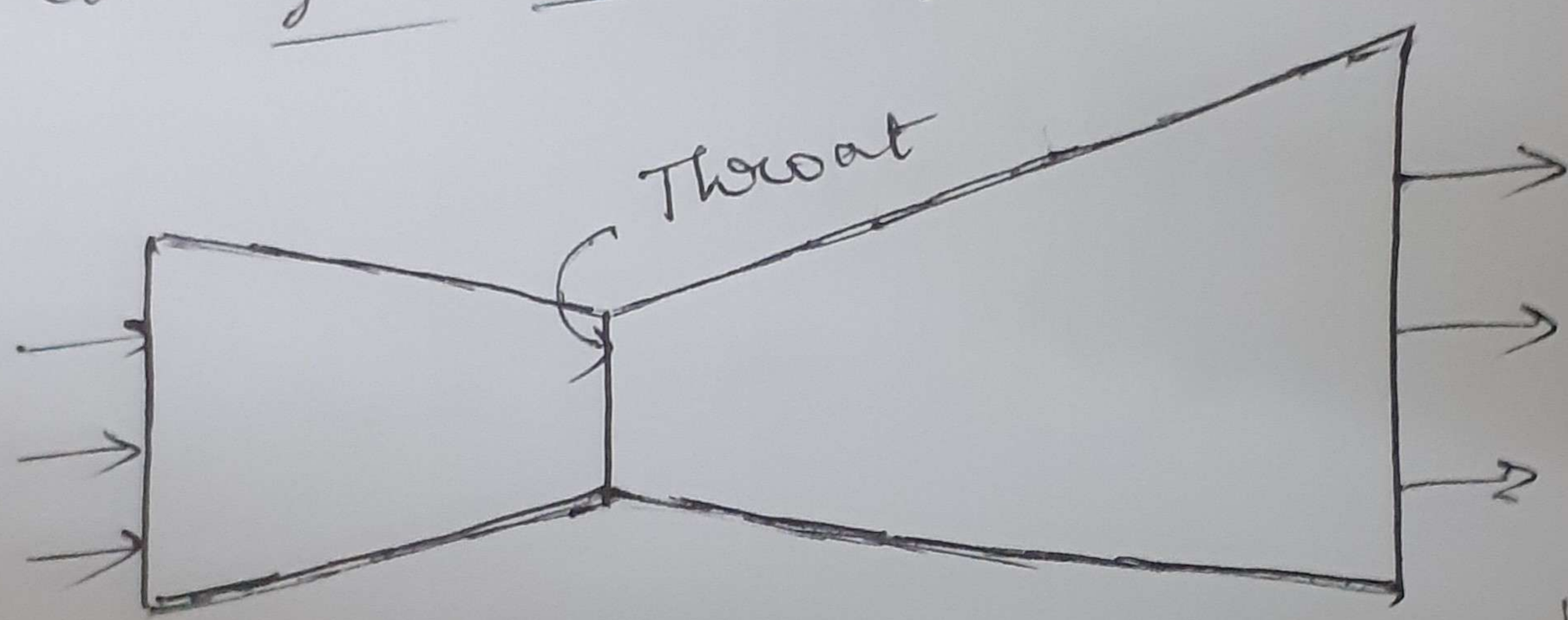
$$P_m = 541.2 \times 10^3 \text{ N/m}^2$$

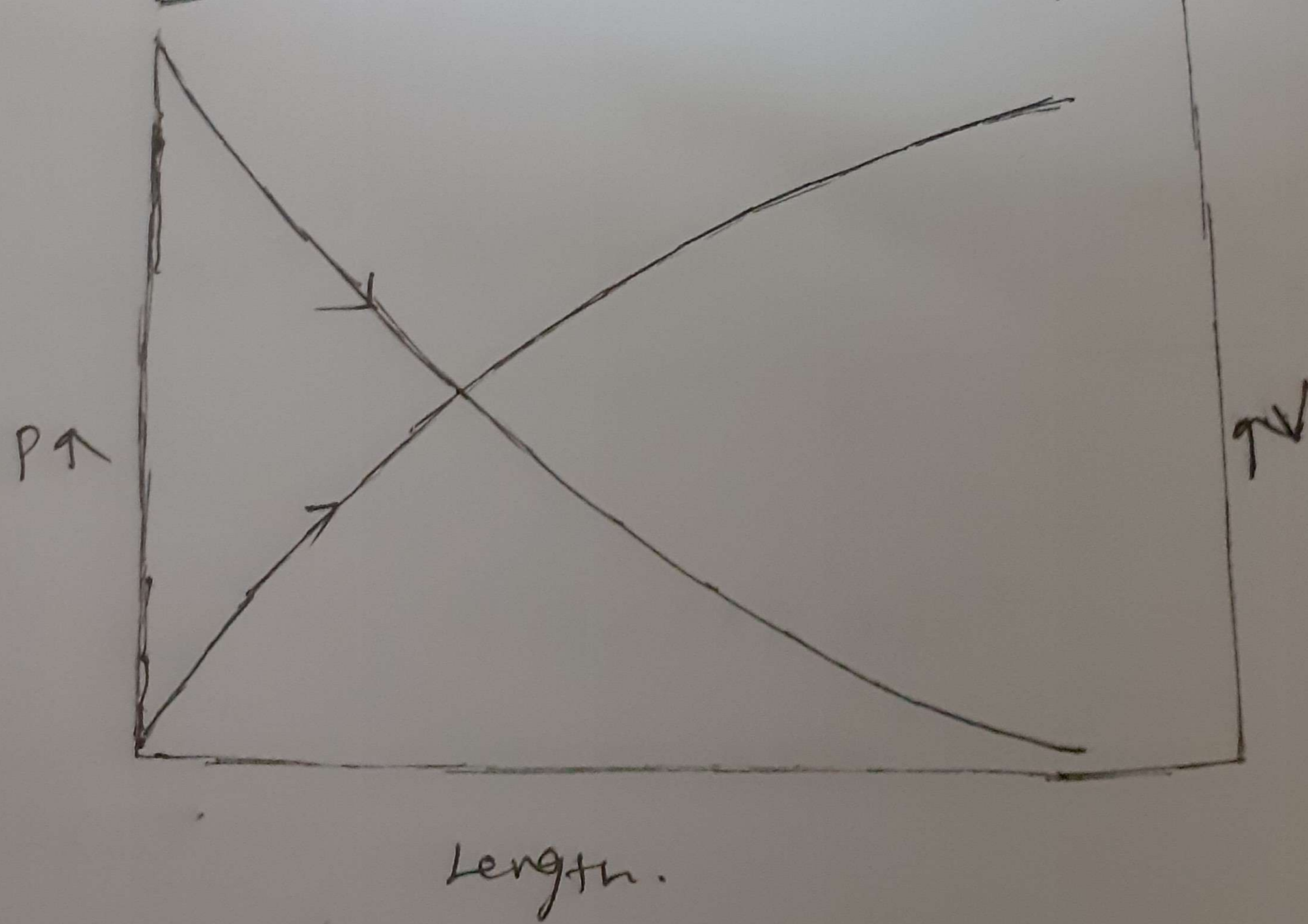
STEAM NOZZLES

convergent nozzle



convergent — divergent nozzle





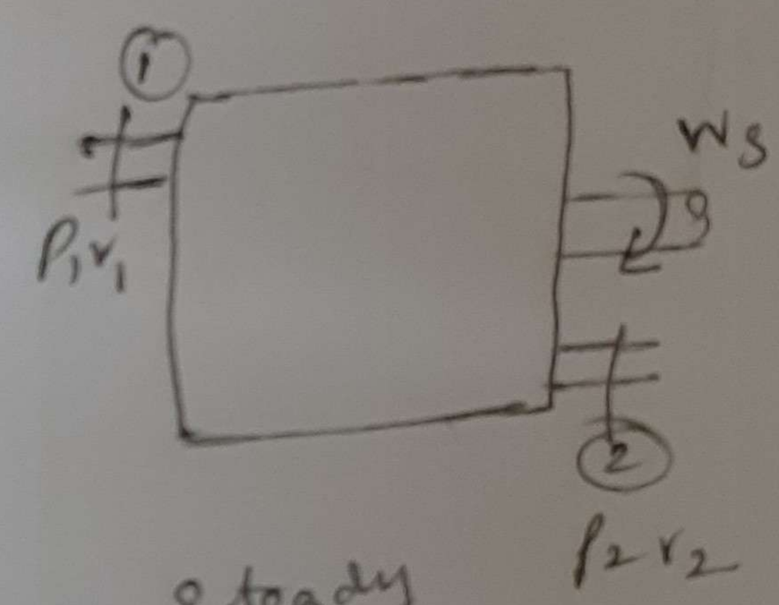
Velocity of Expanding Steam

Expression for velocity of steam nozzle exit.

Using first law of thermodynamics,

$$Q - W = \Delta E \quad \text{— (1)}$$

$$E = U + mgz + \frac{1}{2} m V^2$$



Steady Flow device

$$W = W_s + W_f$$

$$W_f = P_2 V_2 - P_1 V_1$$

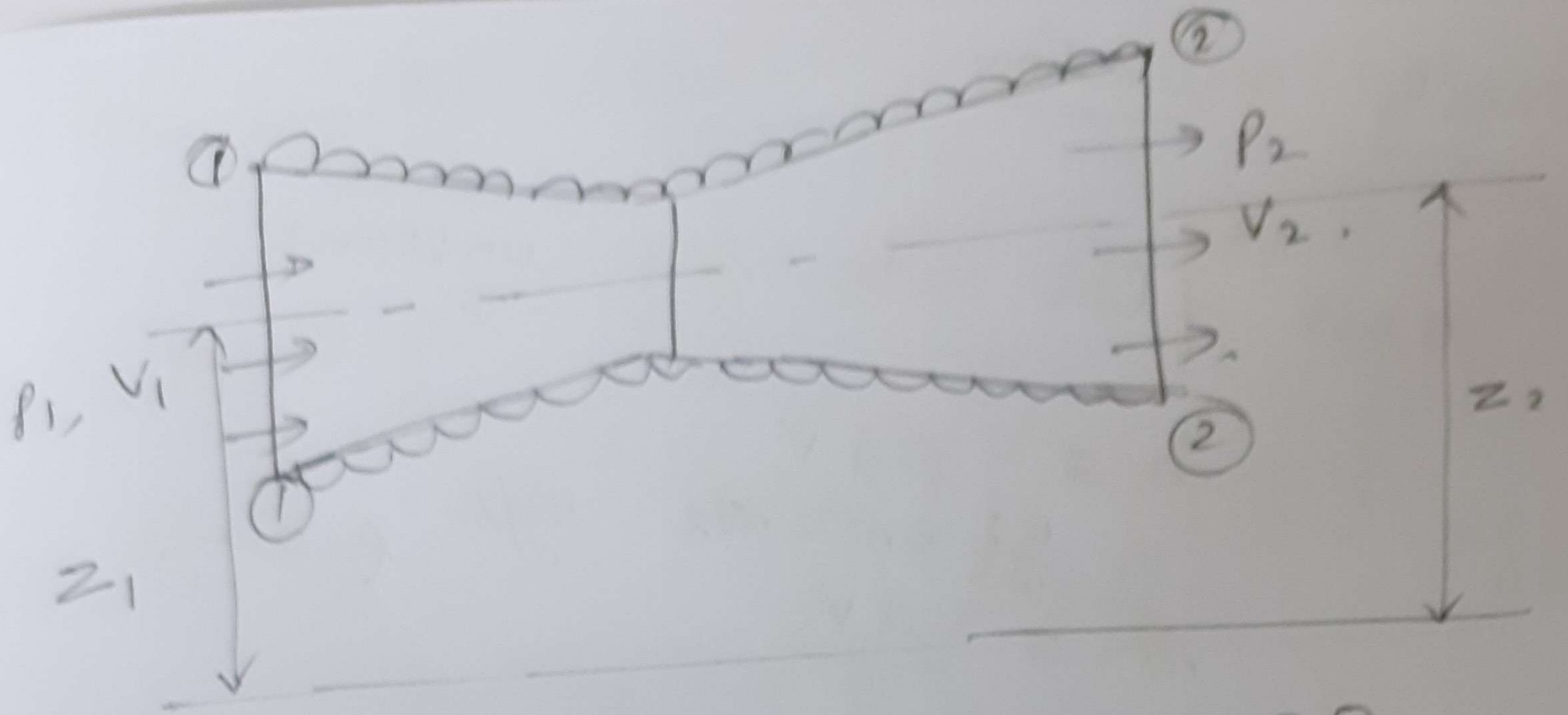
$$W = W_s + P_2 V_2 - P_1 V_1 \quad \text{— (2)}$$

and

$$\Delta E = E_2 - E_1 = U_2 - U_1 + mg(z_2 - z_1) + \frac{1}{2} m (V_2^2 - V_1^2) \quad \text{— (3)}$$

Subs (2) and (3) in (1)

$$Q - W_s - P_2 V_2 + P_1 V_1 = U_2 - U_1 + mg(z_2 - z_1) + \frac{1}{2} m (V_2^2 - V_1^2)$$



$Z_2 - Z_1 = 0$

$Q = 0$ $\quad W_S = 0$

$$P_1V_1 + U_1 = P_2V_2 + U_2 + \frac{1}{2}m(V_2^2 - V_1^2)$$

$$H = U + PV$$

$$H_1 = H_2 + \frac{1}{2}m(V_2^2 - V_1^2)$$

$h = \frac{H}{m}$ J/kg.

$\div$ by m.

$$h_1 = h_2 + \frac{1}{2}(V_2^2 - V_1^2)$$

$$\frac{1}{2}(V_2^2 - V_1^2) = h_1 - h_2$$

$$V_2^2 - V_1^2 = 2(h_1 - h_2)$$

$$V_2^2 = 2(h_1 - h_2) + V_1^2$$

$$V_2 = \sqrt{2(h_1 - h_2) + V_1^2}$$

If V_1 is negligible, $V_1 \simeq 0$

$$V_2 = \sqrt{2(h_1 - h_2)}$$

Continuity Equation

mass flow rate $\dot{m}$ = Constant

$$\dot{m} = \rho A V$$

$$\frac{kg}{m^3} \times m^2 \times \frac{m}{s} \quad \ldots \quad kg/s.$$

$$\dot{m} = \frac{A V}{v_g} \qquad \rho = \frac{1}{v}$$

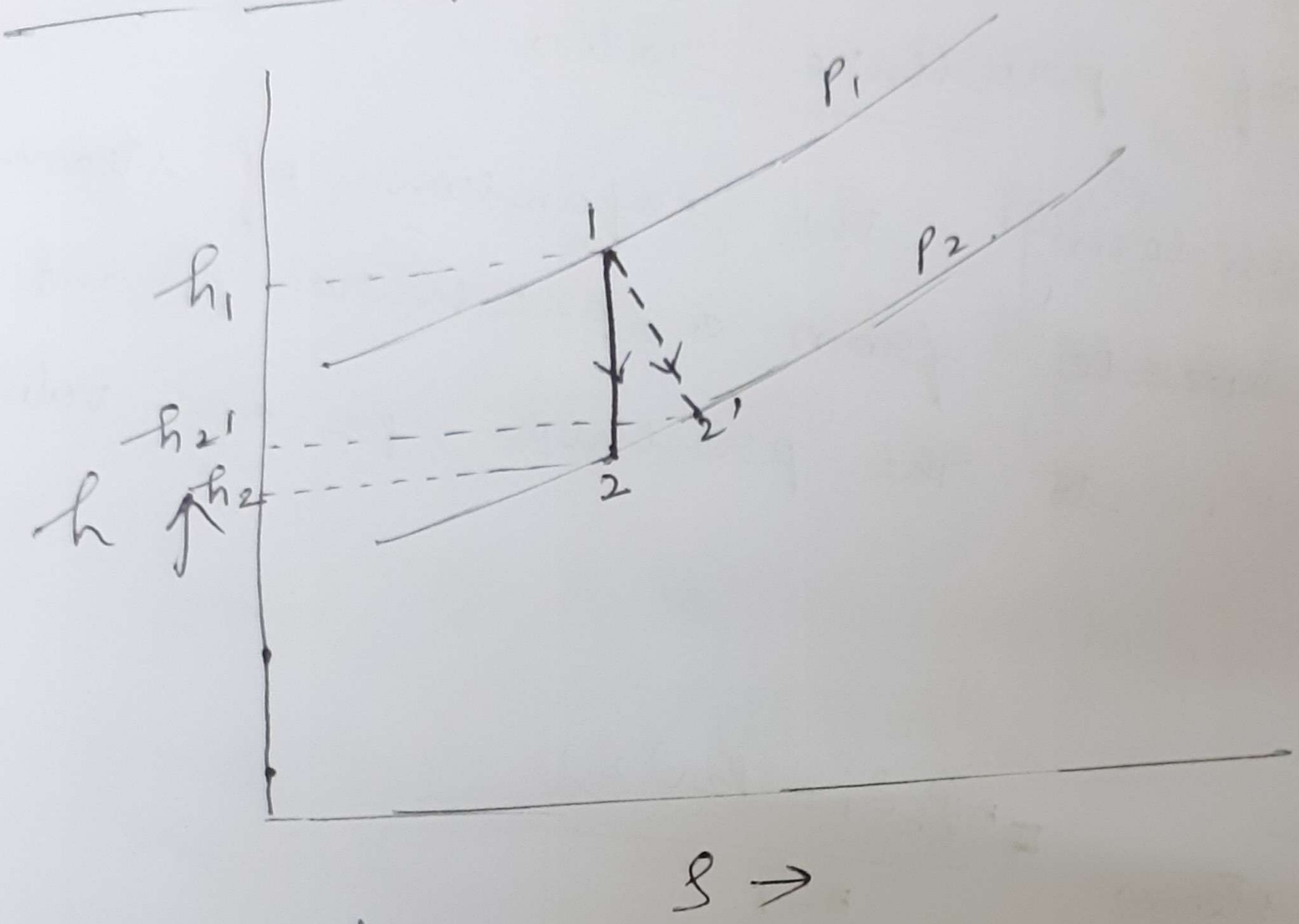
A - cross sectional Area of nozzle, m^2

V - velocity of steam ... m/s.

v_g - specific volume of steam, .. m^3/kg

$$\dot{m} = \frac{A_1 V_1}{v_{g_1}} = \frac{A_2 V_2}{v_{g_2}}$$

Nozzle Efficiency



1-2 - Ideal Expansion

1-2' - Actual Expansion

$$\eta_{nozzle} = \frac{\text{Actual Enthalpy drop}}{\text{Ideal Enthalpy drop}}$$

$$\eta_{noz} = \frac{h_1 - h_2'}{h_1 - h_2}$$

$h_1 - h_2 > h_1 - h_2'$

$$h_1 - h_2' = (h_1 - h_2)\,\eta_{noz}$$

Ideal velocity $V_2 = \sqrt{2(h_1 - h_2)}$ //

Actual velocity $V_2' = \sqrt{2(h_1 - h_2')}$

$$V_2' = \sqrt{2(h_1 - h_2)\,\eta_{noz}}$$ //

Expression for velocity and mass flow rate interms of pressure ratio

considering the expansion of steam in the nozzle from a pressure p_1 and volume v_1 to the pressure p_2 and volume v_2 ..

$$\text{work done per kg of steam} = \frac{n(p_1 v_1 - p_2 v_2)}{n-1} = \text{Work done during Rankine cycle}$$

Also,

$$V_2 = \sqrt{2(h_1 - h_2)}$$

$$V_2^2 = 2(h_1 - h_2)$$

$$\frac{V_2^2}{2} = (h_1 - h_2)$$

Gain in kinetic energy = Heat drop = = Workdone during Rankine cycle

$$\frac{V_2^2}{2} = \frac{n(p_1 v_1 - p_2 v_2)}{(n-1)}$$

$$= \frac{p_1 v_1 \left[1 - \left(\frac{p_2 v_2}{p_1 v_1} \right) \right] n}{n-1} \quad \text{— (1)}$$

$$p_1 v^n = c \implies p_1 v_1^n = p_2 v_2^n.$$

$$\frac{p_1}{p_2} = \left(\frac{v_2}{v_1} \right)^n \implies \frac{v_2}{v_1} = \left(\frac{p_1}{p_2} \right)^{1/n} \quad \text{— (2)}$$

Subs. (2) in (1)

$$= \frac{p_1 v_1 \left(1 - \left(\frac{p_2}{p_1} \right) \times \left(\frac{p_1}{p_2} \right)^{1/n} \right) n}{n-1}$$

$$= \frac{p_1 v_1 \left(1 - \left(\frac{p_2}{p_1} \right) \times \left(\frac{p_2}{p_1} \right)^{-\frac{1}{n}} \right) n}{n-1}$$

$$1 - \frac{1}{n} = \frac{n-1}{n}$$

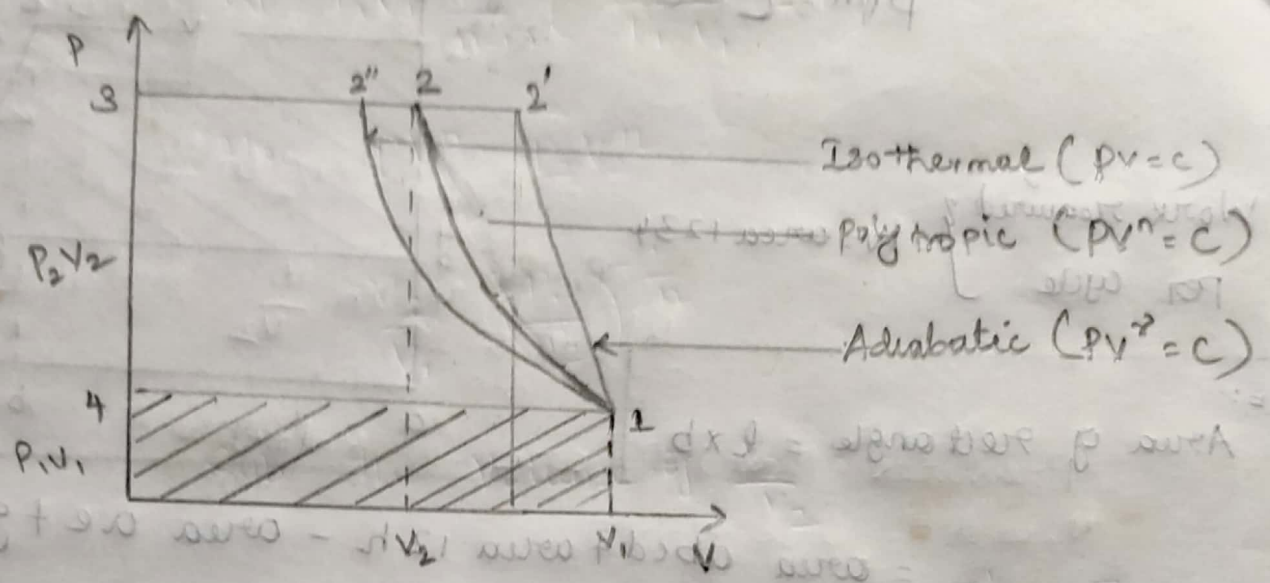
$$= \frac{p_1 v_1 \left(1 - \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \right) n}{n-1}$$

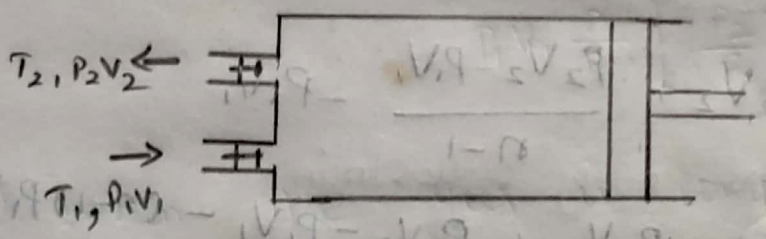
$$= \frac{n}{n-1} p_1 v_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \right]$$

$$V^2 = \frac{2n}{n-1} p_1 v_1 \left(1 - \left(\frac{p_2}{p_1} \right) \right)^{\frac{n-1}{n}}$$

$$V = \sqrt{\frac{2n}{n-1} p_1 v_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \right]}$$

THE IDEAL SINGLE STAGE RECIPROCATING COMPRESSOR



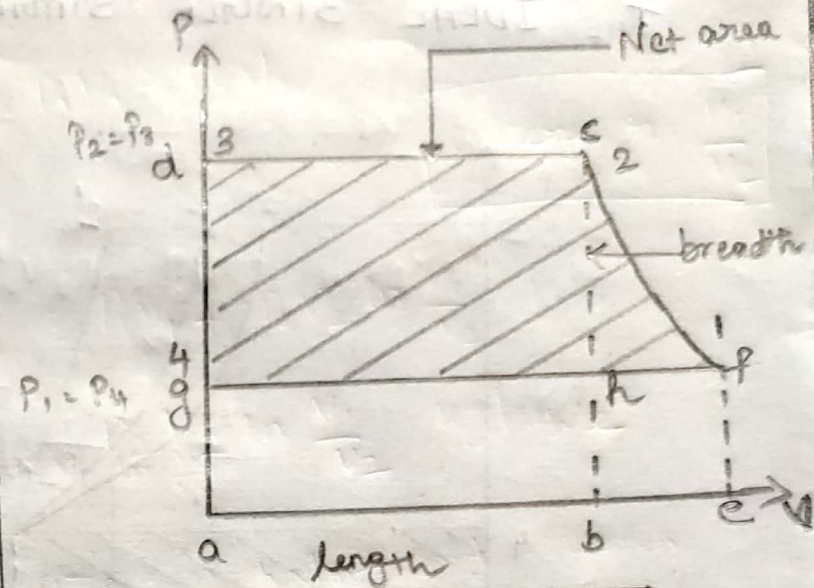


The simplest type of reciprocating compressor is one in which entire compression is carried out in a single cylinder. Such a compressor is called single stage compressor. This may be either single acting or double acting.

Amount of work required to compress the air is less in case of isothermal process. (ie) work done area is less. ∴ Efficiency is more

(1) When the gas is compressed according to the law

$$PV^n = C$$



Work required per cycle = W = area 1234

NOTE:-
Area of rectangle = $l \times b$

$$= \text{area } abcd + \text{area } 12h - \text{area } aefg$$

$$= P_2V_2 + \frac{P_2V_2 - P_1V_1}{n-1} - P_1V_1$$

$$= P_2V_2 + \frac{P_2V_2 - P_1V_1}{n-1} - P_1V_1$$

$$= \frac{(n-1)P_2V_2 + P_2V_2 - P_1V_1 - (n-1)P_1V_1}{(n-1)}$$

$$= \frac{n(P_2V_2 - P_1V_1)}{n-1}$$

It may be noted that expression for the work required per cycle is the work required during the compression following general law $PV^n = C$, multiplied by an index.

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The above equation may be written as

$$W = P_1V_1 \frac{n}{(n-1)}\left(\frac{P_2 V_2}{P_1 V_1} - 1\right)$$

Also $P_1V_1^n = P_2V_2^n$

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{-\frac{1}{n}}$$

Sub the volume of $\frac{V_2}{V_2}$

$$W = P_1V_1 \frac{n}{n-1}\left[\frac{P_2}{P_1} \times \left(\frac{P_2}{P_1}\right)^{-\frac{1}{n}} - 1\right]$$

$$= P_1V_1 \frac{n}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n}{n-1}} - 1\right] \text{ kJ/cycle}$$

(b) When the gas is compressed adiabatically

The expression for work required per cycle $\Big\}$ $W = P_1V_1 \frac{\gamma}{\gamma-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$ kJ/cycle

[This expression is obtained by substituting the γ in the place of n]

(c) When the gas is compressed isothermally

The expression for work required per cycle in this case will be obtained by starting from first principle.

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Work reqd per cycle $= P_2V_2 + P_2V_2 \ln \frac{V_1}{V_2} - P_1V_1$

But $P_1V_1 = P_2V_2$ $\boxed{\text{where } r = \frac{V_1}{V_2}}$

$$= \cancel{P_1V_1} + P_2V_2 \ln \frac{V_1}{V_2} - \cancel{P_1V_1}$$

$$W = P_2V_2 \ln \frac{V_1}{V_2} \text{ kJ/cycle}$$

$$= P_1V_1 \ln \frac{V_1}{V_2}$$

Pressures P_1 and P_2 are in kN/m^2 and volumes V_1 and V_2 are in m^3

Power required to drive the compressor $= \frac{W \times N}{60}$

N = no. of cycles/min

= no. of revs/min if the compressor is single acting

= no. of working strokes/min if the compressor is double acting.

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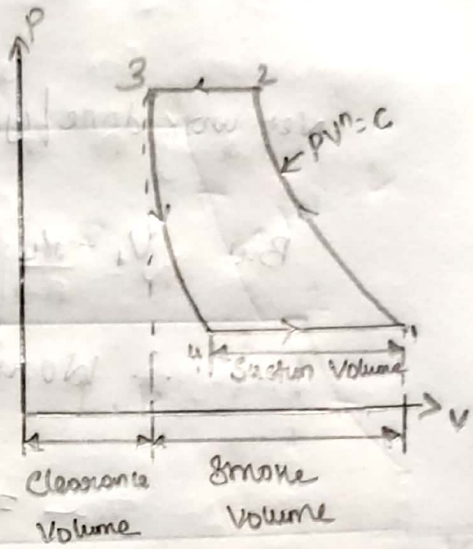
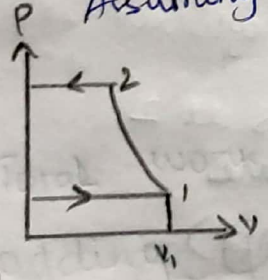
EFFECT OF CLEARANCE VOLUME:-



The displacement volume or the stroke volume is defined as the volume swept by the piston in one stroke. In order to be sure that the piston doesn't stroke the cylinder at the end of the stroke and that there is a room for valves, a clearance volume is essential in reciprocating compressors. The smallest possible clearance are desirable. The ratio of work equal to that done on it during compression. However there is a considerable reduction in the volumetric efficiency due to clearance volume.

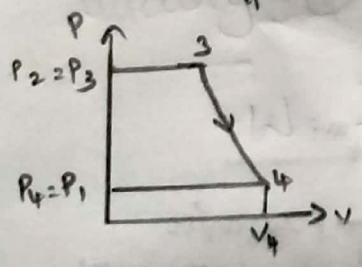
Expression for work done per cycle

Assuming compression and expansion follow the law $PV^n = C$



The work done during compression neglecting clearance $= \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

Before compression

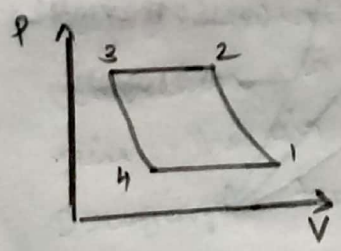


The work done during expansion, assuming the same value of n as for compression

$= \frac{n}{n-1} P_1 V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$ → Before compression

$P_1 = P_4$

$= \frac{n}{n-1} P_4 V_4 \left[\left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}} - 1\right]$ → After compression



Net WD $= \frac{n}{n-1} P_1 V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] - \frac{n}{n-1} P_1 V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

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$$\text{Net work done} = \frac{n}{n-1} P_1 (V_1 - V_4)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$\text{Net work done/cycle} = \frac{n}{n-1} P_1 (V_1 - V_4)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

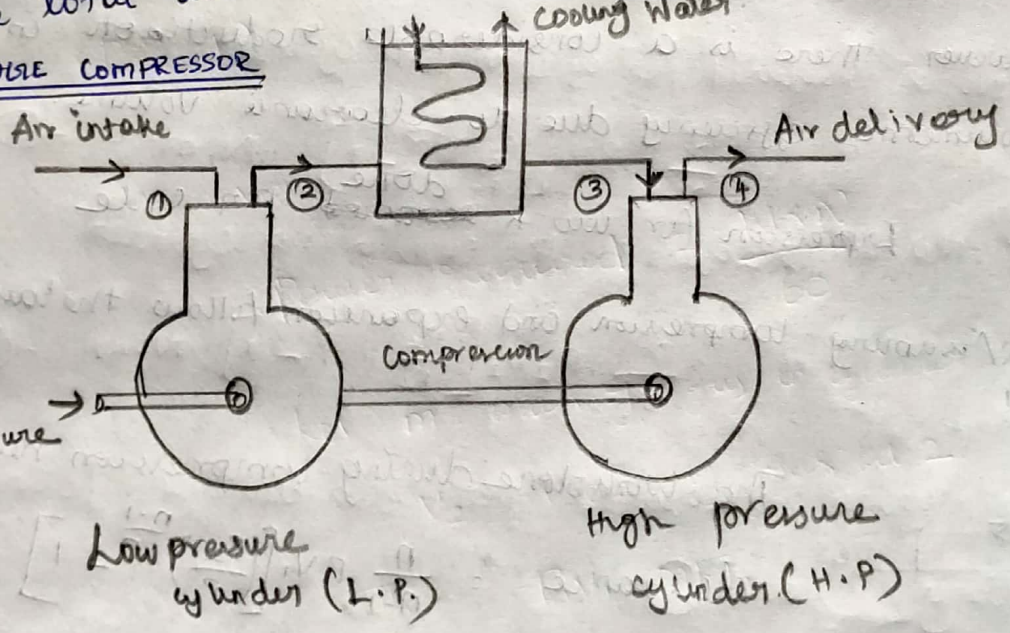
But $V_1 - V_4$ = Suction Volume − eff. Swept Volume

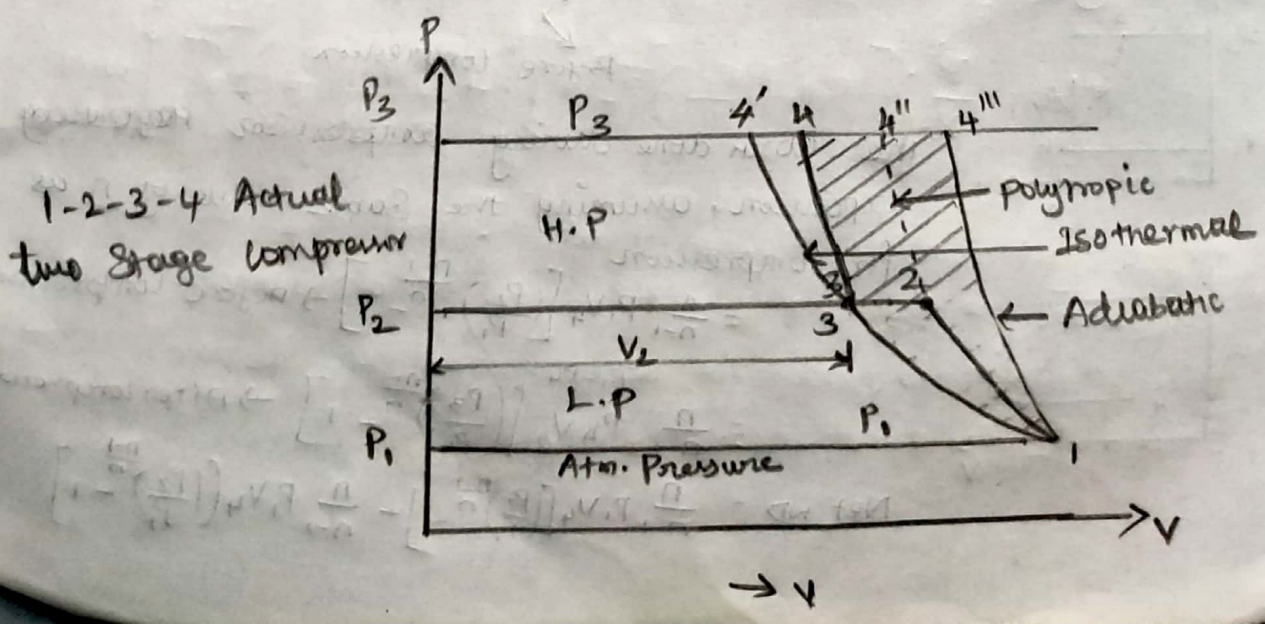
∴ Work done during a comple cycle

$$= \left(\frac{n}{n-1}\right) P_1 \times \text{eff. Swept Volume} \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

In a multi stage compressor this expression must be applied to each stage in order to obtain the total work done in compressor.

TWO STAGE COMPRESSOR





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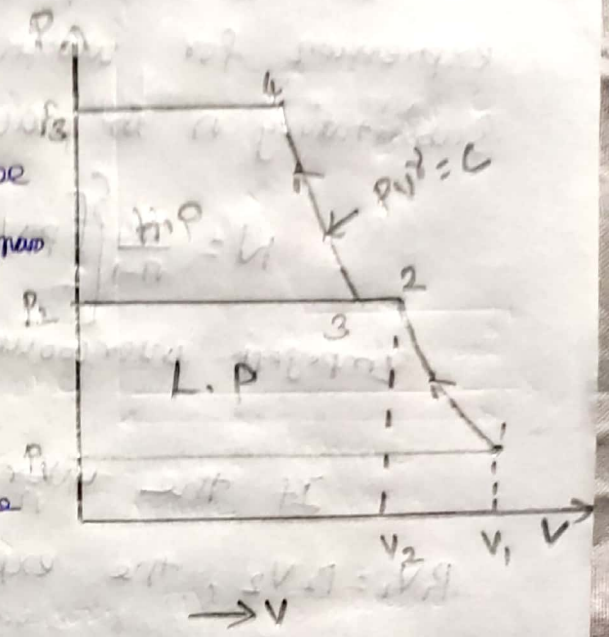
WORKDONE FOR TWO STAGE AIR COMPRESSOR:-



The total work required to drive the compressor per cycle may be calculated from the area of PV diagram

Let P_1 in (N/m^2) and $V(m^3)$ be the condition of gas entering the low pressure cylinder @ P_2, V_2 be the condition of gas entering the high pressure cylinder and P_3 be the final delivery pressure of the gas.

Work required per cycle in L.P cylinder

$$= \frac{\gamma}{\gamma-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \text{ N.m} \quad -(1)$$

III^ly Work required per cycle in H.P cylinder

$$= \frac{\gamma}{\gamma-1} P_2V_2\left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \text{ N-m} \quad -(2)$$

Total work required per cycle can be found by adding (1) and (2)

$$W = \frac{\gamma}{\gamma-1}\left\{\left[P_1V_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right\} + P_2V_2\left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\Bigg\} \text{ N.m}$$

Perfect intercooling means that after the initial compression in the L.P cylinder, which is a constant temp. rise, the air is cooled in an intercooler back to its original temperature (ie) $T_2 = T_1$

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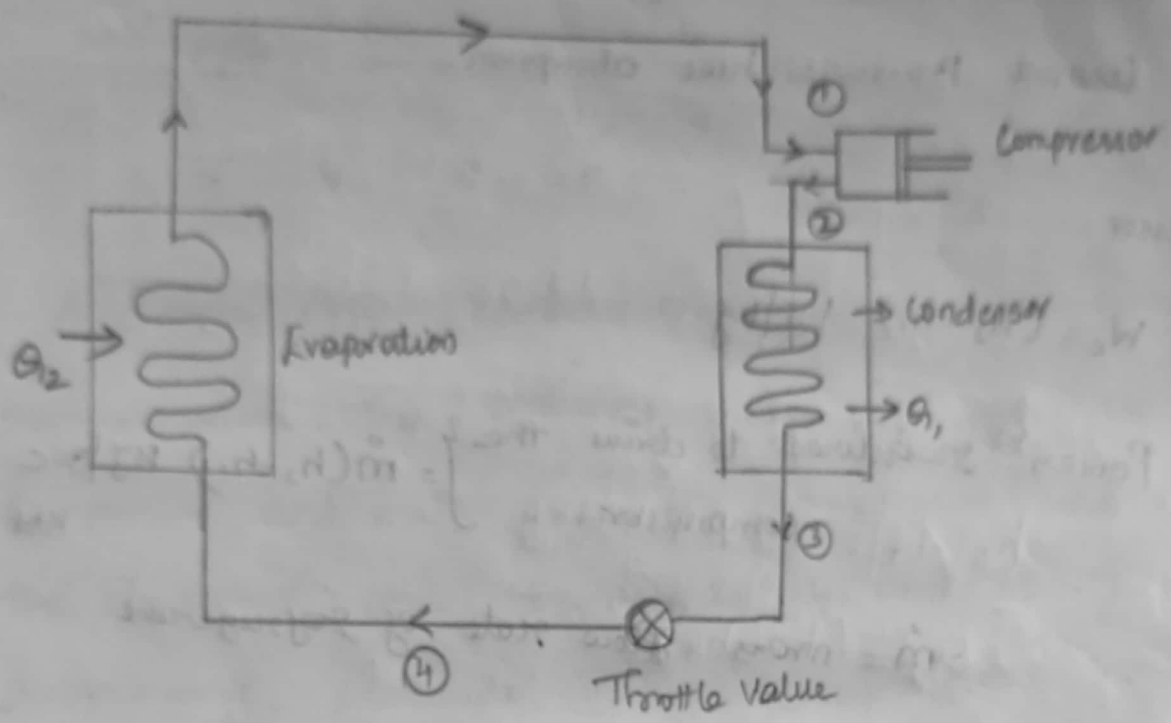
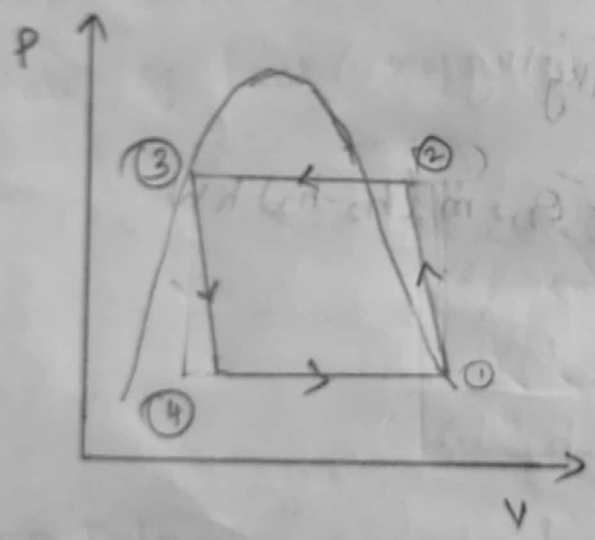
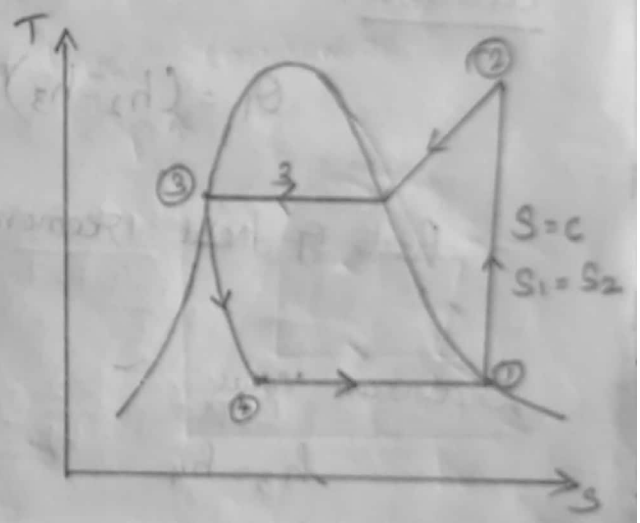
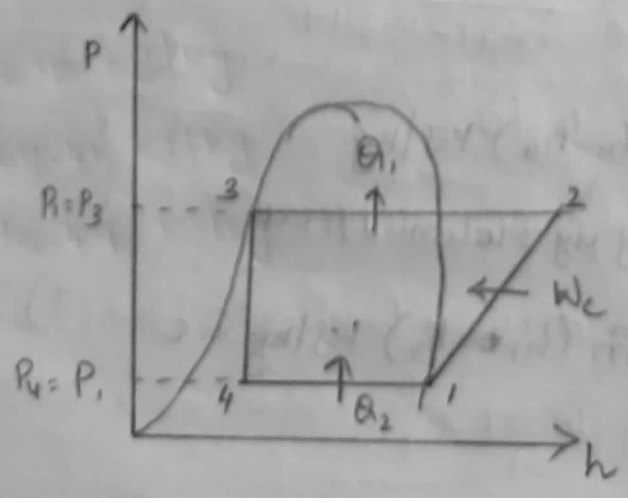
Vapour Compression Refrigeration System:-









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1-2 - Isentropic Compression

2-3 Constant pressure heat rejection

3-4 Expansion (Constant Enthalpy)

4-1 Constant Pressure heat absorption.

Compressor :-

$$W_c = (h_2 - h_1) \text{ kJ/kg}$$

Power required to drive the compressor $= \dot{m}(h_2 - h_1)$ kJ/sec KW

$\dot{m}$ = mass flow rate of refrigerant

Condensor :-

$$Q_1 = (h_2 - h_3) \text{ kJ/kg}$$

Rate of heat removal $= Q_1 = \dot{m}(h_2 - h_3)$ KW

Expansion valve :-

$$h_3 = h_4$$

$$h_g = h_f$$

Evaporator :-

$$Q_2 = (h_1 - h_4) \text{ kJ/kg}$$

→ Refrigeration Effect

$$Q_2 = \dot{m}(h_1 - h_4) \text{ kJ/sec}$$

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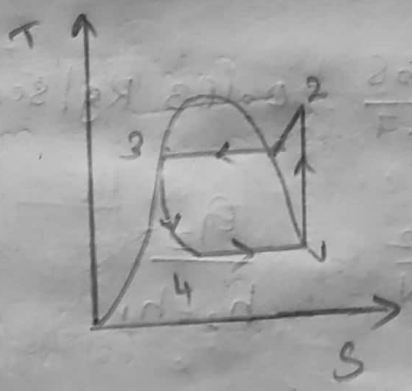
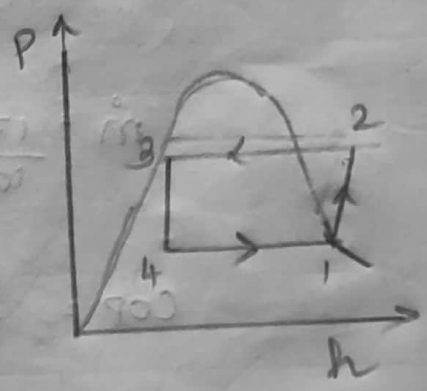
$$\dot{m} = \frac{\text{Refrigeration effect kJ/sec}}{\text{Refrigeration effect kJ/kg}}$$

$$COP = \frac{Q_2}{W_c} = \frac{h_1 - h_4}{h_2 - h_1}$$

① A simple vapour compression plant produces 5 tones of Refrigeration. The enthalpy values at inlet to the compressor and exit from the compressor and exit from the condensor are 183.19, 209.41 and 75.49 kJ/kg. respectively. Estimate ⓐ Refrigerat flow rate ⓑ COP ⓒ Power required to drive the compressor ⓓ Rate of heat rejection to the condensor





Given Data:-

$h_1 = 183.10$ kJ/kg

$h_2 = 209.41$ kJ/kg

$h_3 = 75.49$ kJ/kg

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(1) mass flow rate $= \dfrac{\text{Ref. eff in kJ/sec}}{\text{Ref. eff in kJ/kg}}$

Refrigeration effect = 5 tonnes $\boxed{1\text{ton} = 3.516 \text{ kJ/sec}}$

$= 5 \times 3.516$ kJ/sec

$= 17.58$ kJ/sec.

$h_3 = h_f$

$h_3 = h_4 = 75.49$ kJ/kg

$Q_2 = (h_1 - h_4)$

$= (183.19 - 75.49)$

$= 107.7$ kJ/kg

$\dot{m} = \dfrac{17.58}{107.7} = 0.163$ kg/sec

$COP = \dfrac{Q_2}{W} = \dfrac{Q_2}{h_2 - h_1}$

$= \dfrac{107.7}{209.41 - 183.19} = 4.10$

COP = 4.10

Power $= \dot{m}(h_2 - h_1)$

$= 0.163 \times (209.41 - 183.19)$

Power $= 4.273$ kJ/sec $\Rightarrow 4.273$ kW

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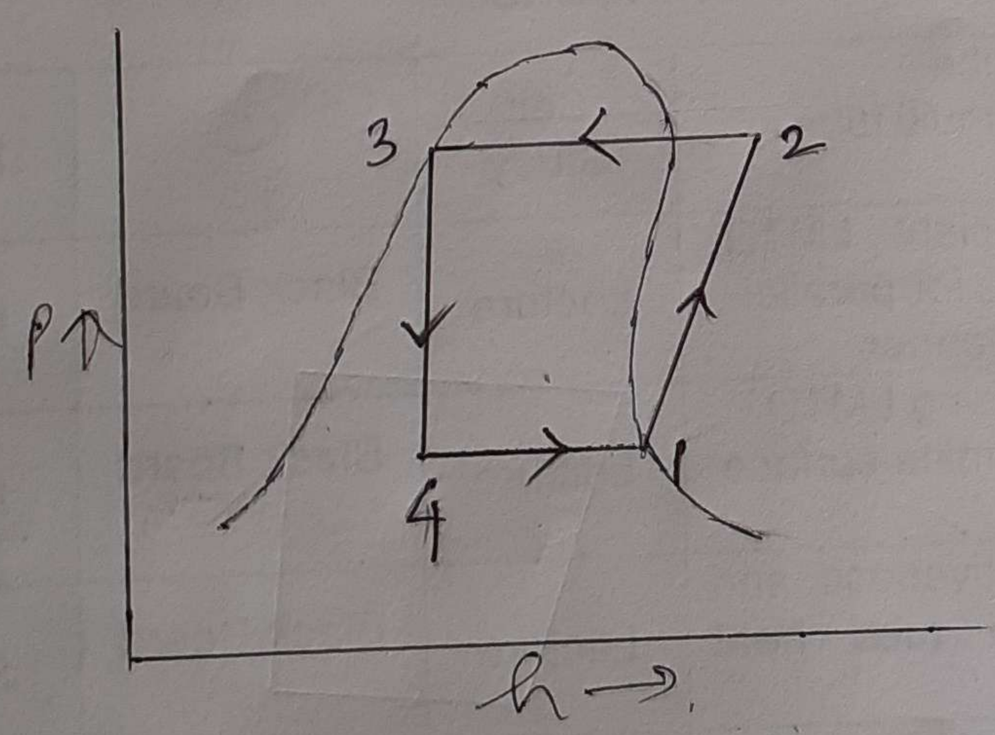
2. The ammonia refrigerator works between -10°C and 38°C. The vapour being at the entry of compressor. There is no under cooling of liquid NH_3 and is expanded through a throttle valve. Calculate power per ton of refrigeration and COP. Sketch the cycle on p-h and T-s planes.

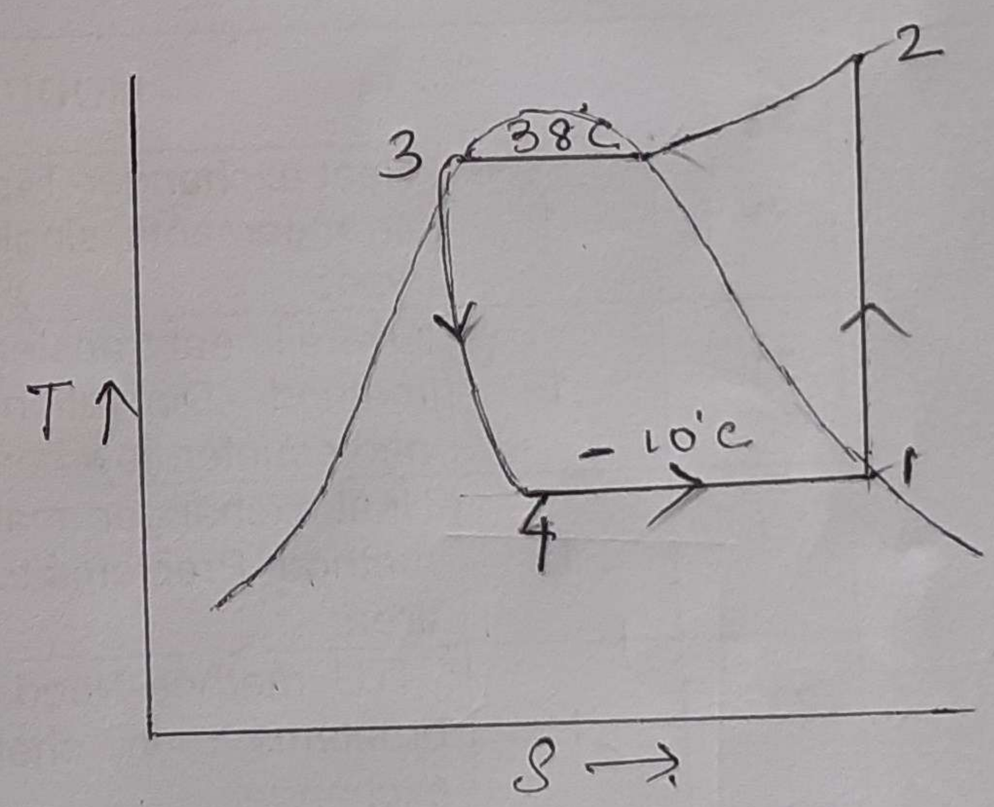
The properties of Ammonia are given below.

	Temp.	Enthalpy KJ/kg			Entropy KJ/kgK			Specific volume m^3/kg
		Liquid (h_f)	latent (h_{fg})	vapour (h_g)	Liquid (s_f)	latent (s_{fg})	vapour (s_g)	v_g
1,4	-10°C	-808.71	1296.41	487.76	5.5257		10.4579	0.41949
2,3	38°C	-587.51	1108.34	526.79	6.311		9.8472	0.08817

C_p for liquid = 4.75 KJ/kgK

C_p for vapour = 3 KJ/kgK.





(1) Power per ton of Refrigeration

$$P = \dot{m}(h_2 - h_1)$$

$$h_1 = h_{g_1} = 487.76 \text{ KJ/kg}$$

$$h_2 = h_{g_2} + C_{pg}(T_{sup} - T_{sat})$$