Thermodynamics

3 E's - energy, entropy, equilibrium

Heat transfer : Transfer of energy (or heat) in transit due to temp difference

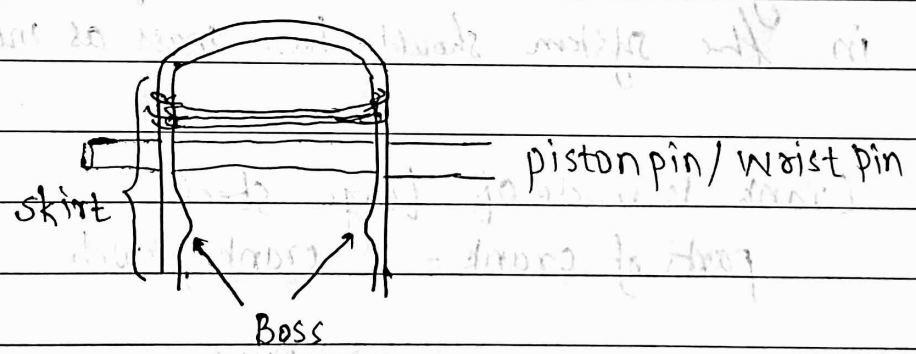
low/high grade energy

Producing (heat) energy by the work done is more efficient than doing the work from the energy produced.

∴ Work is high grade energy

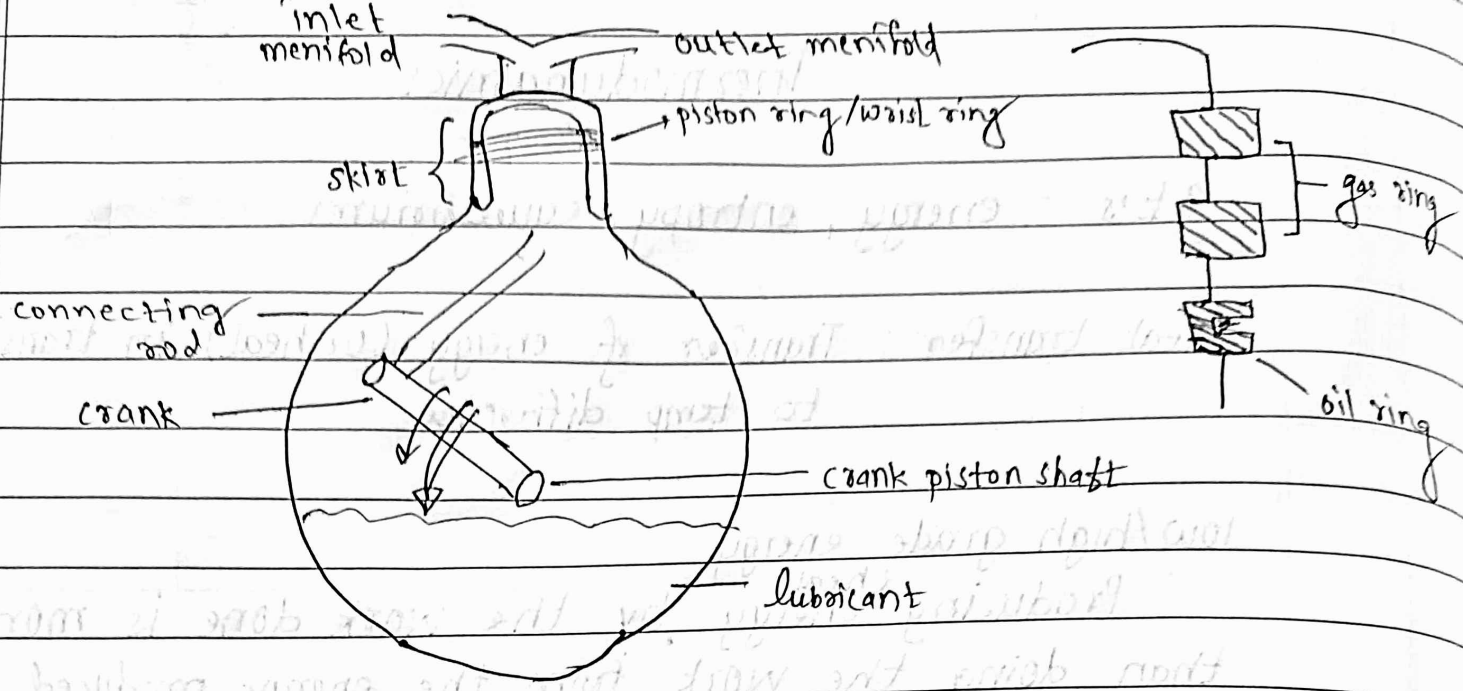
& heat is low grade energy

Piston



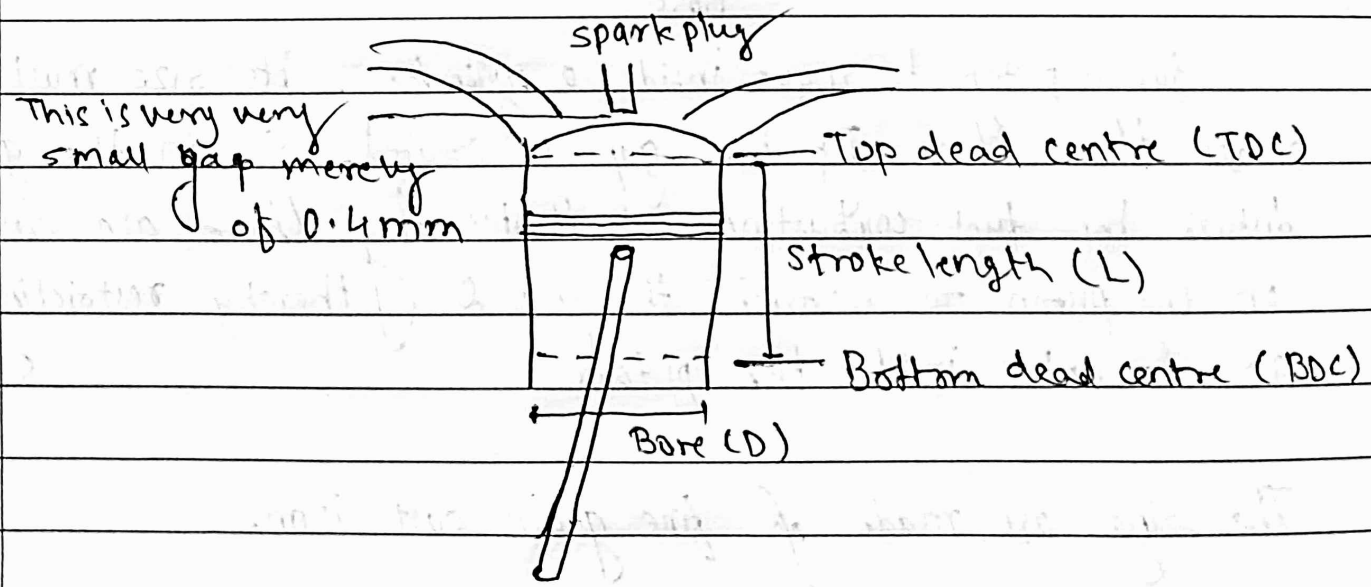
for a piston to move inside a cylinder, its size must be small than that. If the gap is created, air in the gap may disturb the fuel combustion & that's why there are rings present on the piston to restrict the gap & thereby restricting the air to enter inside the piston

The rings are made of fine grain cast iron.



as the speed of the piston is 5000-6000 rpm, it moves with very high speed as a result of which the lubricant splashes out inside it. This results in lubrication of all the parts inside the system. To withstand such high speed, all materials used in the system should have mass as minimum as possible

Crank is made of forge steel
parts of crank - crank, web



Stroke Vol. is area covered by piston while it reciprocates once

V_s = Stroke vol. = $\frac{\pi D^2}{4} L$

Reversible - No collision betⁿ molecules - molecules or molecules - wall of the container i.e. no heat transfer with surroundings.

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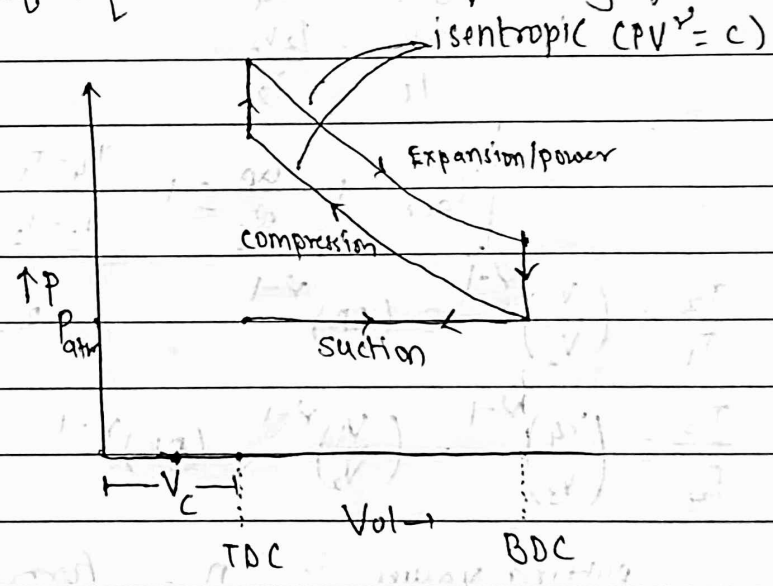
* Combustion Space / Clearance Vol. (V_c)

It is space left for clearance so that piston doesn't collide with topmost side of cylinder. That space is left there for inlet & outlet valve

* Compression Ratio = $CR = \frac{V_s + V_c}{V_c} = \frac{V_s}{V_c} + 1$

in petrol engine, CR → 5 to 11 — 8 - 9 } most widely used CR
diesel engine, CR → 12 to 24 — 18 - 19 }

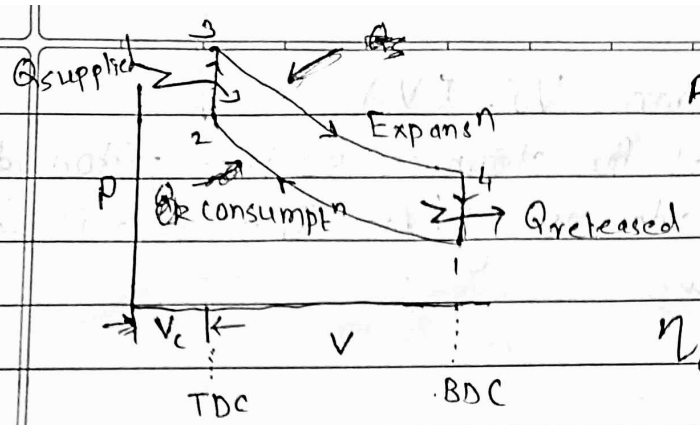
P - pressure of gas inside the piston
V - vol. of liq. betⁿ TDC & reciprocating piston



* Air standard Cycle

1) In order to simplify, air is considered as working fluid
2) No combustion takes place. A heat source & a sink is coming in contact & transferring heat.
3) All the processes are reversible.
4) Compression & ~~adi~~ expansion processes are adiabatic

Reversible & adiabatic means isentropic i.e. same entropy



Air standard Cycle
(Otto cycle)

η_{air} or $\eta_{Thermal}$ i.e. η_{Th}

$$\eta_{air} = \frac{\text{Word done}}{\text{heat supplied}}$$

$$= \frac{Q_S - Q_R}{Q_S} = 1 - \frac{Q_R}{Q_S}$$

$Q_S = C_V (T_3 - T_2) \ldots W = 0$

$Q_r = C_V (T_4 - T_1) \ldots W = 0$

also, $P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$ &

$P_3 V_3^{\gamma} = P_4 V_4^{\gamma}$

& $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

$$\therefore \boxed{\eta_{air} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{T_4 - T_1}{T_3 - T_2}}$$

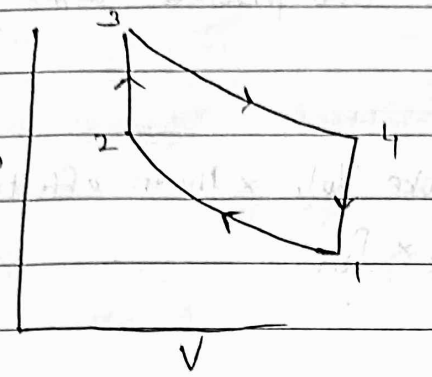
$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1} = (CR)^{\gamma - 1} \qquad CR = \frac{V_1}{V_2}$$

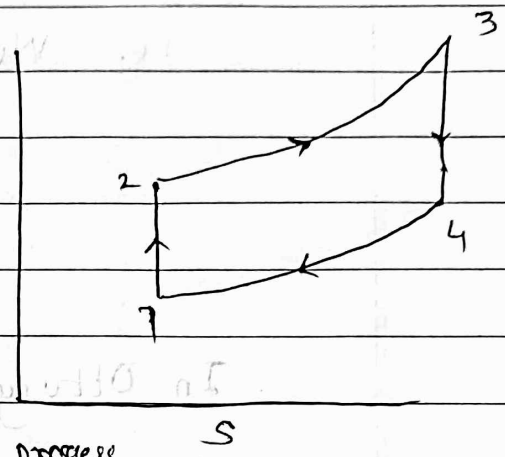
$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma - 1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1} = (CR)^{\gamma - 1}$$

putting values in η_{air} formula,

$$\boxed{\eta_{air} = 1 - \frac{1}{R^{\gamma - 1}}}$$

* Otto cycle for a reversible adiabatic process





for $1 \to 2$ $V\uparrow \Rightarrow T\uparrow$ (adiabatic और isentropic process)

for $2 \to 3$ heat is rising heat rises means entropy rises always Temp is always rising

for $3 \to 4$ $Vol\uparrow \Rightarrow T\downarrow$ isentropic process

for $4 \to 1$ heat $\downarrow \Rightarrow S\uparrow$ T is decreasing

$$W = \int_1^2 PdV + \cancel{\int_2^3 PdV}^{\,0} + \int_3^4 PdV + \cancel{\int_4^1 PdV}^{\,0}$$

$1 \to 2$ & $3 \to 4$ are adiabatic rev process

$$W = \frac{P_2V_2 - P_1V_1}{1-\gamma} + \frac{P_4V_4 - P_3V_3}{1-\gamma}$$

$P_1V_1^{\gamma} = P_2V_2^{\gamma}$ $\frac{V_1}{V_2} = r$

$\therefore \frac{P_1V_1}{P_2V_2} = \frac{1}{r^{\gamma-1}}$

similarly $\frac{P_3V_3}{P_4V_4} = r^{\gamma-1}$

$$= \frac{1}{\gamma-1}\left[P_4V_4\left(\frac{P_3V_3}{P_4V_4} - 1\right) - P_1V_1\left(\frac{P_2V_2}{P_1V_1} - 1\right)\right]$$

$$= \frac{1}{\gamma-1}\left[P_4V_4(r^{\gamma-1} - 1) - P_1V_1(r^{\gamma-1} - 1)\right]$$

$$= \frac{P_1V_1}{\gamma-1}(r^{\gamma-1} - 1)\left[\frac{P_4V_4}{P_1V_1} - 1\right] \quad \because V_4 = V_1$$

$$\boxed{W = \frac{P_1V_1}{\gamma-1}(r^{\gamma-1} - 1)(r_p - 1)}$$

$\frac{P_3}{P_2} = \frac{P_4}{P_1} = r_p$

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* Mean effective pressure is a hypothetical pressure acting on the piston throughout the cycle to produce same ~~power~~ work for the same stroke volume.

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i.e. Workdone = Stroke Vol. × Mean effective pressure

$$= V_s \times P_m$$

$$\therefore \quad P_m = \frac{W}{V_s}$$

In Otto cycle, $V_s = V_1 - V_2$

$$\therefore P_m = \frac{P_1 V_1}{\gamma - 1}\left[(r^{\gamma-1} - 1)(r_p - 1)\right] \times \frac{1}{V_1 - V_2}$$

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

$$P_m = \frac{P_1 V_1}{\gamma - 1}\left[(r^{\gamma-1} - 1)(r_p - 1)\right] \times \frac{r}{V_1(r-1)}$$

$$\boxed{P_m = \frac{r P_1 \left[(r^{\gamma-1} - 1)(r_p - 1)\right]}{(r-1)(\gamma-1)}}$$

1] If compression ratio is 9; what is standard efficiency for petrol engine? $\gamma = 1.4$

$$\eta = 1 - \frac{1}{R^{\gamma-1}} = 1 - \frac{1}{9^{1.4-1}} = 1 - \frac{1}{9^{0.4}} = 58.33$$

2] An engine having bore of 100 mm, stroke of 125 mm, runs on Otto cycle. The clearance volume is 12% of the stroke vol. The initial pressure & temperature are 1 bar & 25°C resp. The max pressure is limited to 25 bar. Find the air standard efficiency of the

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cycle & mean effective pressure.

$V_s = \cancel{125\ mm}$

$D = 100mm \quad L = 125\ mm$

$$V_s = \frac{\pi D^2}{4} L = \frac{\pi}{4} \times 10^4 \times 125$$

Clearance vol. is 12% of stroke vol.

i.e. $\frac{V_c}{V_s} = \frac{12}{100}$ $\quad V_c = \frac{12}{100} \times \frac{\pi}{4} \times 10^4 \times 125$

$$R = \frac{V_s + V_c}{V_c} = \frac{V_s}{V_c} + 1 = 9.33$$

$$\eta_{air} = 1 - \frac{1}{R^{\gamma-1}} = 1 - \frac{1}{9.33^{0.4}} = 59.08\%$$

$$P_m = \frac{\gamma P_1}{(\gamma-1)(\nu-1)} \left[\left(r^{\nu-1} - 1\right)(r_p - 1) \right]$$

$$r_p = \frac{P_3}{P_2} = \frac{P_4}{P_1} \qquad P_1 V_1^{\nu} = P_2 V_2^{\nu}$$

$$\therefore P_2 = P_1 \left(\frac{V_1}{V_2}\right)^{\nu} = P_1 R^{\nu}$$

from Otto cycle we see P_3 is max pressure $= 1 \times (9.33)^{1.4}$

$\therefore P_3 = 25 \qquad = 22.79$ bar

$$r_p = 25 / 22.79$$
$$= 1.09$$

now, $$P_m = \frac{9.33 \times 1}{(1.4-1)(9.33-1)} \left[\left(9.33^{1.4-1} - 1\right)(1.09 - 1) \right]$$

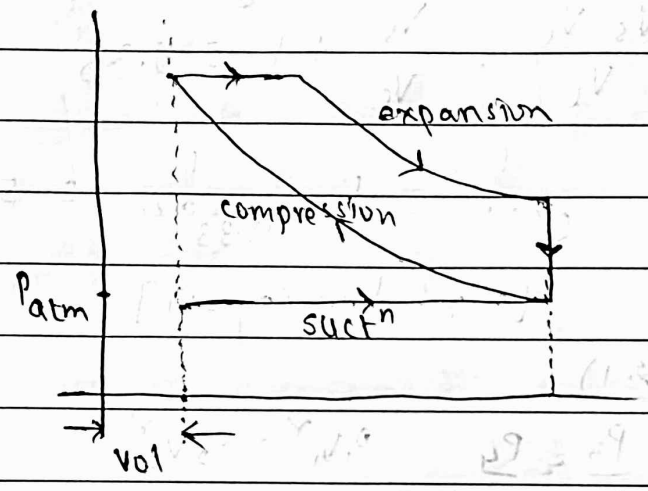
$$= 0.392 \text{ bar}$$

* Diesel engine

Diesel requires higher temperature to burn compared to petrol. $\text{Density}_{diesel} > \text{Density}_{petrol}$

Petrol is more volatile compared to ~~petrol~~ diesel i.e. boiling point of petrol is closer to atmospheric con^n compared to ~~petrol~~ diesel.

To generate higher temperature, greater CR is req in diesel engines than ~~diesel~~ petrol engine (ideally 11-24 & found to be 18-19)



Considerations:

air is working fuel.

No combust^n is taking place.

All processes are reversible

Compression & expansions are adiabatic.

now PV graph will be

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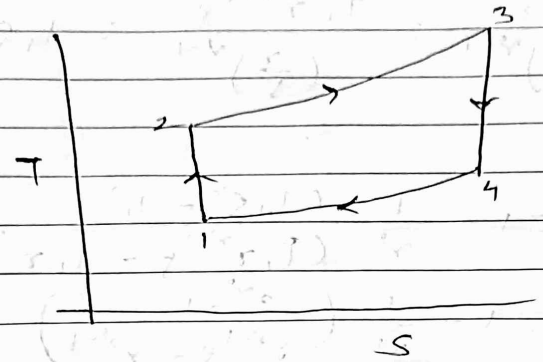

for adiabatic compression, temp rises & vice versa

for 2-3 heat is absorbed
∴ S increases

for 4-1 heat is released
∴ S decreases

area under the curve is heat absorbed

process 2-3 & 4-1 only will count for heat as 3-4 & 1-2 are isentropic, they'll add up to give 0

heat supplied for 2-3 = $Q_s = C_p(T_3 - T_2)$

heat rejected for 4-1 = $Q_r = -C_v(T_1 - T_4)$

$$\text{workdone} = W = Q_s + Q_r$$
$$= C_p(T_3 - T_2) + C_v(T_1 - T_4)$$

$$\eta_{diesel} = \frac{W}{Q_s} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

$\because C_p/C_v = \gamma$

for 1-2, $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r^{\gamma-1}$ $\qquad T_2 = T_1 r^{\gamma-1}$

for 2-3, $\frac{T_3}{T_2} = \frac{V_3}{V_2} = \rho$ (cutoff ratio) $\qquad T_3 = \rho T_2 = T_1 r^{\gamma-1}\rho$

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for 3-4, $\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{V_1}{\rho V_2}\right)^{\gamma-1}$ $\qquad \ldots V_3 = \rho V_2$

$\ldots V_4 = V_1$

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

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

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

$$T_4 = \frac{T_3}{\left(\frac{r}{\rho}\right)^{\gamma-1}} = \frac{T_1 r^{\gamma-1}\rho}{\left(\frac{r}{\rho}\right)^{\gamma-1}} = T_1 \rho^{\gamma}$$

now,

$$\eta_{diesel} = 1 - \frac{1}{\gamma}\frac{(T_1\rho^{\gamma} - T_1)}{(T_1 r^{\gamma-1}\rho - T_1 r^{\gamma-1})}$$

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

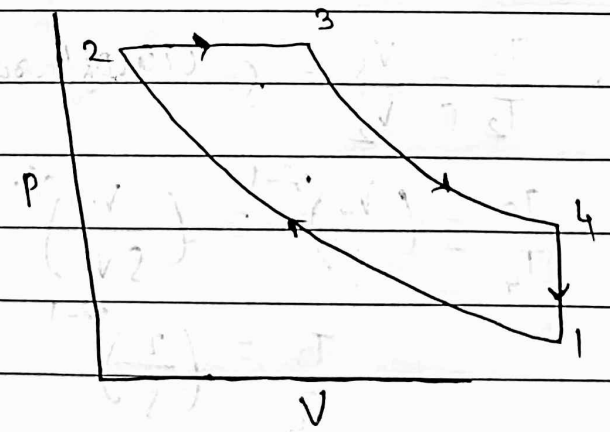
$$\boxed{\eta_{diesel} = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{1}{\gamma}\left(\frac{\rho^{\gamma}-1}{\rho-1}\right)\right]}$$

$\rho > 1$ & $\gamma > 1$

when r is same for petrol & diesel engines,

$$\eta_{diesel} < \eta_{petrol}$$

but in reality r of diesel engine is more & thats why efficiency of diesel engine is found to be higher than petrol engine for trucks, buses



$$\text{Workdone} = W_{12} + W_{23} + W_{34} + W_{41}$$

$$= \frac{P_2V_2 - P_1V_1}{1-\gamma} + P_2(V_3 - V_2) + \frac{P_4V_4 - P_3V_3}{1-\gamma} + 0$$

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$\rho = V_3/V_2 \qquad r = V_1/V_2 \qquad \rho/r = V_3/V_1$

$$P_3V_3^{\gamma} = P_4V_4^{\gamma} \qquad \therefore \frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^{\gamma} \quad \& \quad \frac{P_1}{P_2} = \frac{1}{r^{\gamma}}$$

$$P_2V_2^{\gamma} = P_1V_1^{\gamma}$$

$$V_4 = V_1$$

$$\therefore \frac{P_4}{P_3} = \left(\frac{V_3}{V_1}\right)^{\gamma} = (\rho/r)^{\gamma}$$

now, $$W = P_2(\rho V_2 - V_2) + \frac{P_4 r V_2 - P_3 \rho V_2}{1-\gamma} + \frac{P_2V_2 - P_1 r V_2}{1-\gamma}$$

$$= \frac{V_2}{\gamma-1}\left[P_2(\rho-1)(\gamma-1) + P_3\left(\rho - \frac{P_4}{P_3}r\right) - P_2\left(1 - \frac{P_1}{P_2}r\right)\right]$$

$$W = \frac{P_2V_2}{\gamma-1}\left[(\rho-1)(\gamma-1) + \left(\rho - \frac{\rho^{\gamma}}{r^{\gamma}}\cdot r\right) - \left(1 - \frac{P_1 r}{P_2}\right)\right] \quad \cdots\cdots \; P_3 = P_2$$

$$= \frac{P_2V_2}{\gamma-1}\left[(\rho-1)(\gamma-1) + \rho - \rho^{\gamma}r^{1-\gamma} + r^{1-\gamma} - 1\right]$$

$$= \frac{P_2V_2}{\gamma-1}\left[\gamma(\rho-1) - \rho^{\gamma}r^{1-\gamma} + r^{1-\gamma}\right]$$

$$\boxed{\begin{aligned} W &= \frac{P_2V_2}{\gamma-1}\left[\gamma(\rho-1) - r^{1-\gamma}(\rho^{\gamma}-1)\right] \\ W &= \frac{P_1V_1 r^{\gamma-1}}{\gamma-1}\left[\gamma(\rho-1) - r^{1-\gamma}(\rho^{\gamma}-1)\right] \end{aligned}}$$

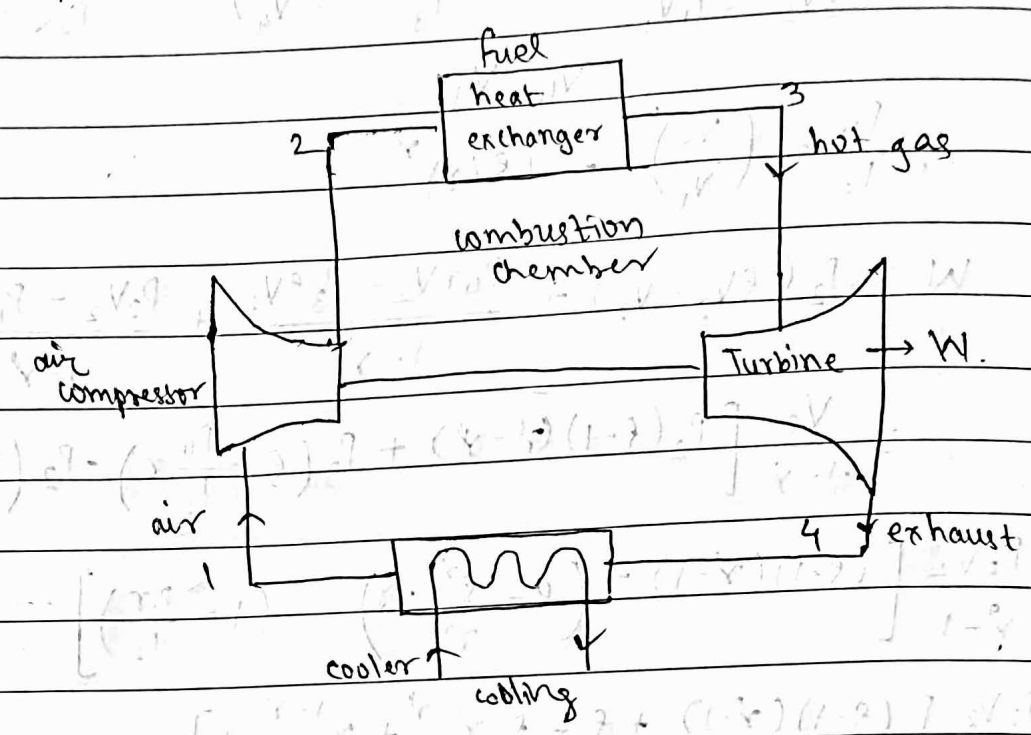
Mean effective pressure $(P_m) = \dfrac{W}{V_s} = \dfrac{W}{V_1 - V_2}$

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

$$= \frac{rW}{V_1(r-1)}$$

$$P_m = \frac{P_1 r^{\gamma}}{(r-1)(\gamma-1)}\left[\gamma(\rho-1) - r^{1-\gamma}(\rho^{\gamma}-1)\right]$$

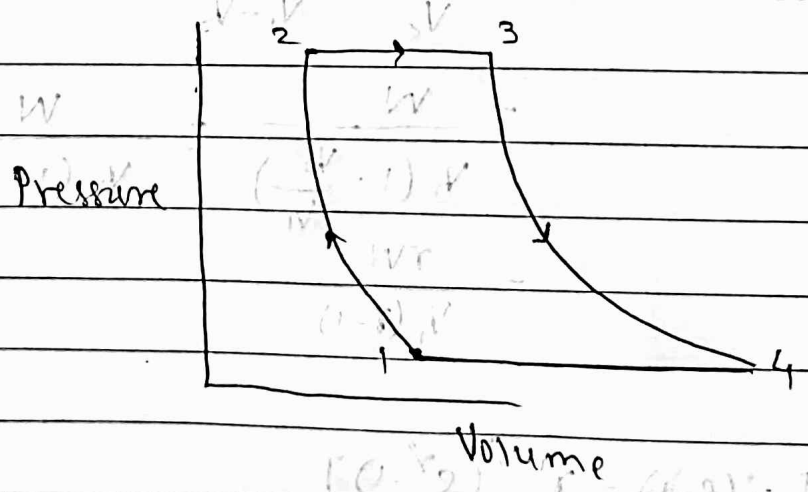
* Brayton cycle
(application found in aeroplane, gas turbine

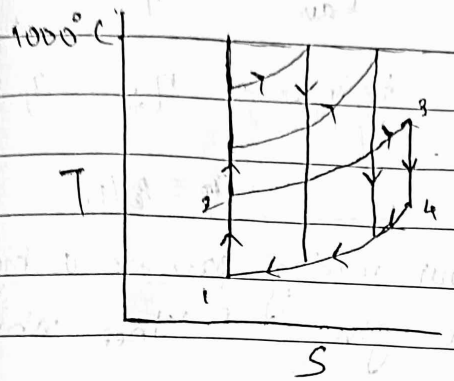


The fuel around the tube is burnt to provide
in combustion chamber

Joule cycle

When the cycle is open i.e. Brayton cycle without cooling part





$$\eta_{air} = \frac{W}{Q_S} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$Q_S = C_p(T_3 - T_2)$ $\quad$ $Q_R = C_p(T_4 - T_1)$

$W = Q_S - Q_R$

1-2 & 3-4 are adiabatic

$$\therefore \frac{T_2}{T_1} = (P_2/P_1)^{\gamma-1/\gamma} \qquad \frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$r_p = P_2/P_1$ $\quad \because P_1 = P_4$, $\cancel{\frac{V_1}{V_4} = \frac{T_1}{T_4}}$ $\quad \because P_2 = P_3$, $\cancel{\frac{V_2}{V_3} = \frac{T_2}{T_3}}$

$= P_3/P_4$

$$T_2 = T_1 (P_2/P_1)^{\gamma-1/\gamma} = T_1 r_p^{\frac{\gamma-1}{\gamma}}$$

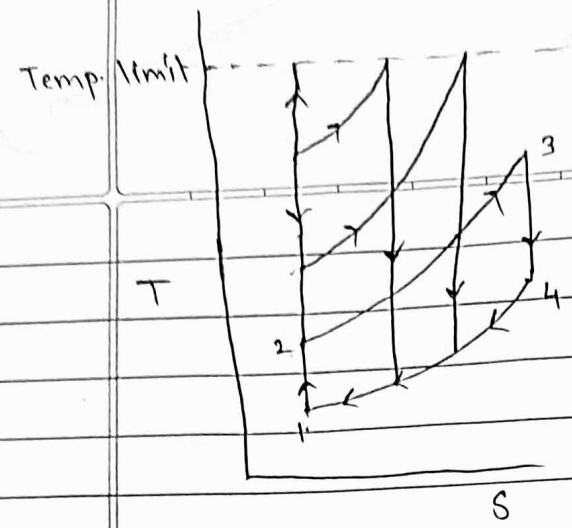
$$T_3 = T_4 (P_3/P_4)^{\gamma-1/\gamma} = T_4 (P_2/P_1)^{\gamma-1/\gamma} = T_4 r_p^{\gamma-1/\gamma}$$

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

$$= 1 - \frac{T_4 - T_1}{r_p^{\gamma-1/\gamma}(T_4 - T_1)}$$

$$\boxed{\eta_{air} = 1 - \frac{1}{r_p^{\gamma-1/\gamma}}}$$

$T_3 < 1000°C$ due to material of gas turbine



$$\eta_{air} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

to increase η_{air}, r_p should increase

$$r_p = P_2/P_1$$

but making pressure as high as the limiting temp value gives 0 W_{net} which is totally undesirable

$\therefore$ We not only have to look after efficiency

Now $W_{net} = W_T - W_c$

$$= C_p(T_3 - T_4) - C_p(T_2 - T_1)$$

$$= C_pT_3\left(1 - \frac{T_4}{T_3}\right) - C_pT_1\left(\frac{T_2}{T_1} - 1\right)$$

$$r_p = \frac{P_2}{P_1} \quad P_1V_1^{\gamma} = P_2V_3^{\gamma} \Rightarrow \frac{T_2}{T_1} = r_p^{\gamma-1/\gamma} \quad \frac{T_3}{T_4} = r_p^{\gamma-1/\gamma}$$

$$W_{net} = \cancel{W_{net}}\ C_pT_3\left(1 - \frac{1}{r_p^{\gamma-1/\gamma}}\right) - C_pT_1\left(r_p^{\gamma-1/\gamma} - 1\right)$$

to maximize W_{net}, $\frac{dW_{net}}{dr_p} = 0$

that gives $\boxed{r_p = \left(\frac{T_3}{T_2}\right)^{\gamma/2(\gamma-1)}}$

$$W_R = \text{work ratio} = \frac{W_{net}}{W_T} = \frac{W_T - W_c}{W_T} = 1 - \frac{W_c}{W_T} = 1 - \frac{C_p(T_2 - T_1)}{C_p(T_3 - T_4)}$$

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

$$= 1 - \frac{T_1}{T_3}\,\frac{r_p^{\gamma-1/\gamma} - 1}{1 - \frac{1}{r_p^{\gamma-1/\gamma}}}$$

$$\boxed{W_R = 1 - \frac{T_1}{T_3}\,r_p^{\gamma-1/\gamma}}$$

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1] The air enters compressor of Brayton cycle at 1 Bar 25°C. r_p is 6 find max temp. if $W_T = 2.5 W_c$. find efficiency also $\gamma = 1.4$

$$C_p (T_3 - T_4) = 2.5 C_p (T_2 - T_1)$$

$$\therefore T_3 \left(1 - \frac{T_4}{T_3}\right) = 2.5 T_1 \left(\frac{T_2}{T_1} - 1\right)$$

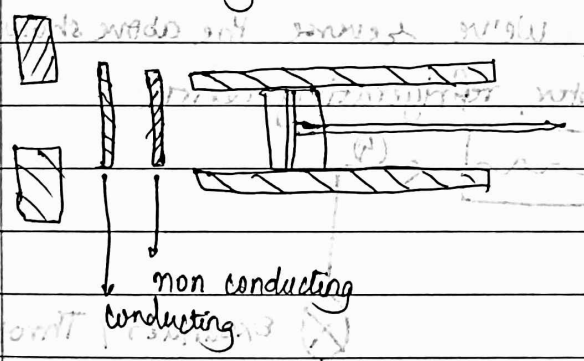
$$\therefore T_3 \left(1 - \frac{1}{r_p^{\gamma-1/\gamma}}\right) = 2.5 T_1 \left(r_p^{\gamma-1/\gamma} - 1\right)$$

max temp is T_3 $T_1 = 25 + 273 = 298K$

we can find T_3

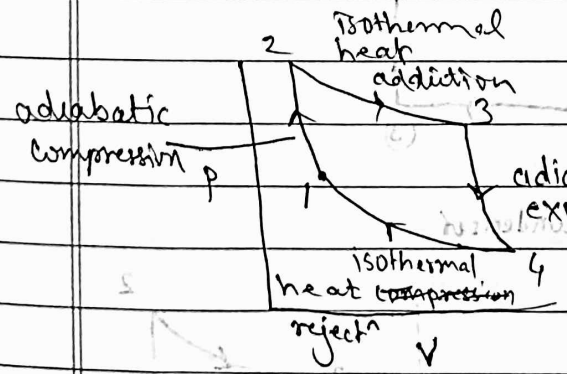
$$\eta = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

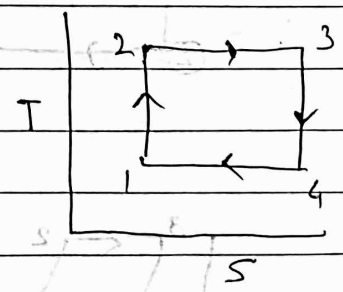
* Carnot cycle



Conducting material comes in contact during heat addition along with source & heat reject^n along with sink

Non conducting material comes in contact during ~~heat~~ adiabatic process since no heat passage is there

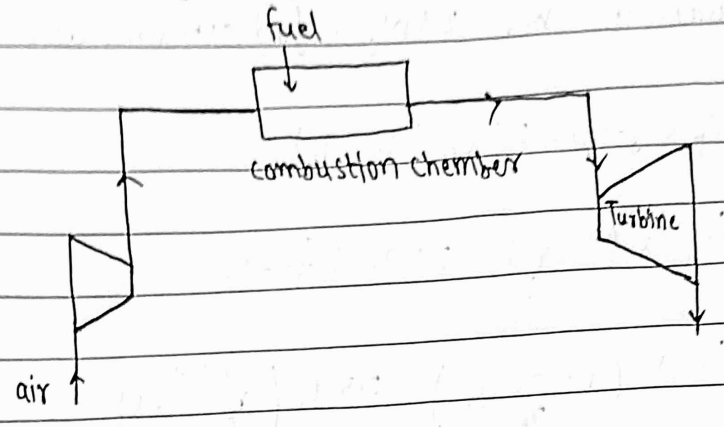




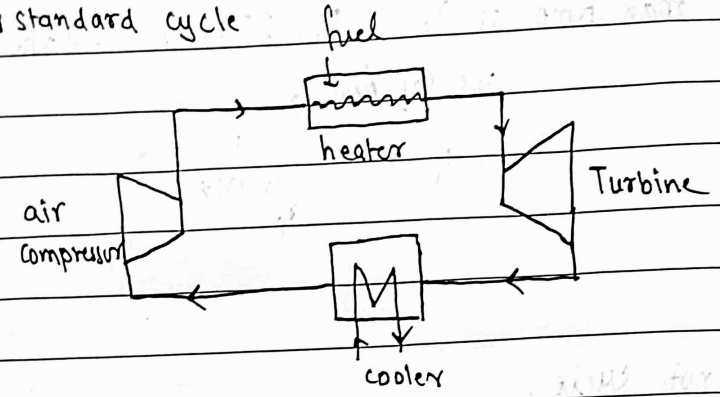
$$\eta_{air} = \frac{Q_s - Q_r}{Q_s} = 1 - \frac{Q_r}{Q_s} = 1 - \frac{T_1 (S_4 - S_1)}{T_2 (S_3 - S_2)}$$

$$\boxed{\eta_{air} = 1 - \frac{T_1}{T_2}} \quad \ldots\ldots T_1 < T_2$$

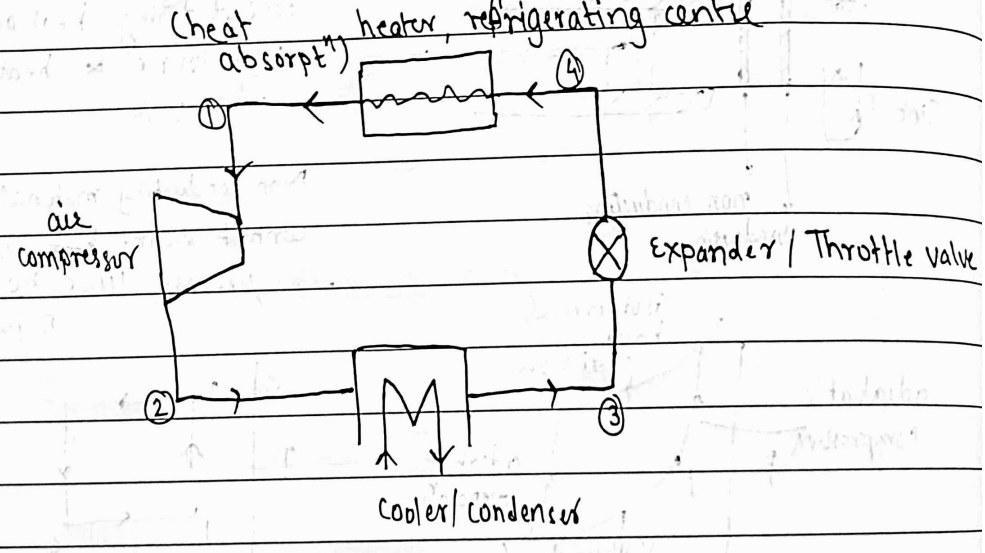
* Reverse Brayton cycle / Bell Coleman cycle

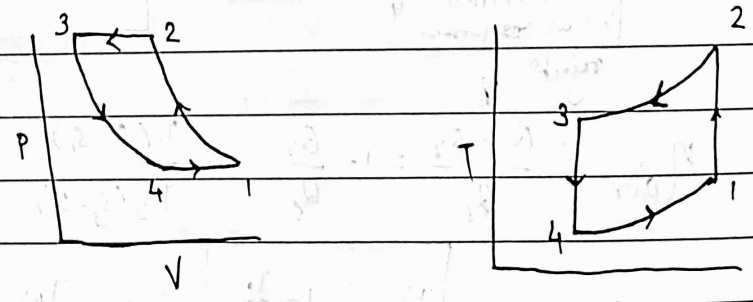


air standard cycle



To make reverse cycle, we've reverse the above shown diagram





1-2 & 3-4 are isentropic

2-3 & 4-1 are isobaric

1. The temperature at the end of heat absorption and heat rejection of a refrigeration system runs on Bell Coleman cycle are 0°C and 30°C respectively. The pressure ratio is 4 and pressure in the cooler is 4 bar. Determine the temperature at all state points and volume flow rates at the inlet to the compressor and at exit of the turbine for 1 TR cooling capacity.

2. A reversed Carnot cycle is used for refrigeration and rejects 1,000 kW of heat at 340 K while receiving heat at 250 K. Determine (a) the COP, (b) the power required, and (c) the refrigerating effect.

3. A reversed Carnot cycle has a refrigerating COP of 4. (a) What is the ratio T_{min}/T_{max} (b) If the work input is 6 kW, what will be the maximum refrigerating effect, kJ/min and tons of refrigeration.

coeff. of power = COP = $\frac{Q_a}{W_c + W_T}$ W_c - compressor work

W_T - Throttle valve work

$$COP = \frac{T_1 - T_4}{T_2 - T_1 + T_4 - T_3} = \frac{T_1 - T_4}{(T_2 - T_3) - (T_1 - T_4)}$$

$$\frac{P_3}{P_4} = \frac{P_2}{P_1} = r_p \qquad \frac{T_2}{T_1} = (P_2/P_1)^{\gamma-1/\gamma} = r_p^{\gamma-1/\gamma}$$

$$\frac{T_3}{T_4} = (P_3/P_4)^{\gamma-1/\gamma} = r_p^{\gamma-1/\gamma}$$

$$COP = \frac{T_1 - T_4}{(T_1 - T_4)\left[r_p^{\gamma-1/\gamma} - 1\right]}$$

$$\boxed{COP = \frac{1}{r_p^{\gamma-1/\gamma} - 1}}$$

Imp

1 tonne AC means in 24 ~~kg~~ hrs, if it is working continuously, it'll absorb heat equal to the heat required to convert 1 tonne (1000kg) of ice at 0°C to 1 tonne water at 0°C.

ex. for 1 Tonne refrigerator i.e. 1 TR,

energy absorbed in 24 hrs = $mL = 1000 \times 336$

" 1 min = $\frac{336000}{24 \times 60}$

= 233.33 kJ/min

normally taken as 210 kJ/min

1] Given : $T_1 = 0°C = 273 K$

$T_3 = 30°C = 303 K$

$r_p = P_3/P_4 = P_2/P_1 = 4$

$P_2 = P_3 = 4$ bar

we know, $T_2 = T_1 r_p^{\gamma-1/\gamma} = 273 (4)^{0.4/1.4} = 405.67 K$

$$T_4 = \frac{T_3}{r_p^{\frac{\gamma-1}{\gamma}}} = \frac{303}{(4)^{\frac{0.4}{1.4}}} = 203.90 K$$

$E = mC_p\Delta T$

$\dot{E} = \dot{m}C_p\Delta T$

$210 = \dot{m} \times 1.005 \times 30$

$\therefore \dot{m} = 6.965 \text{ kg/min}$

$PV = mRT \quad \therefore \quad P\dot{V} = \dot{m}RT$

$\frac{P_2}{P_1} = 4 \quad P_2 = 4 \quad P_1 = 1 \text{ bar} = 10^5 \text{ Pa}$

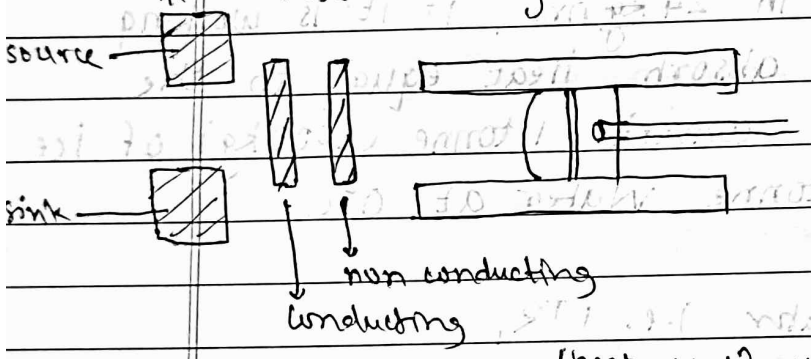
$\therefore P_1\dot{V} = \dot{m}RT_1$

$\therefore 10^5 \dot{V} = 6.965 \times 287 \times 273$

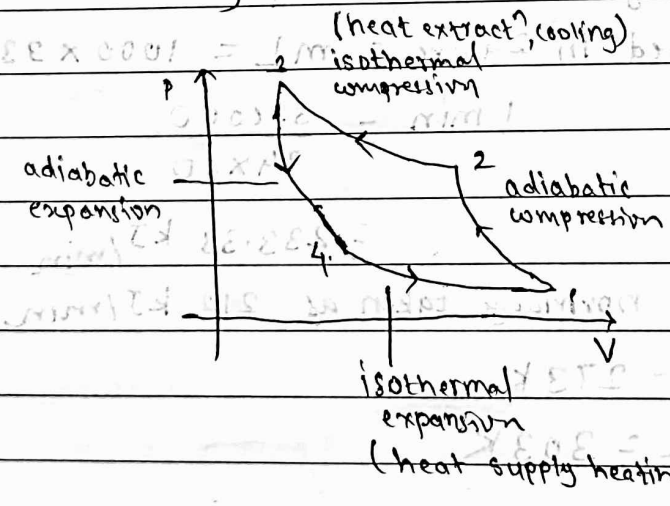
$\dot{V} = 5.4571 \text{ m}^3/\text{min}$

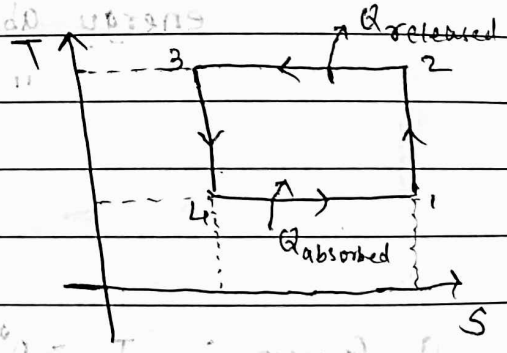
$\therefore$ Vol. flow rate at the inlet is $5.4571 \text{ m}^3/\text{min}$

* Reverse Carnot cycle



conducting material comes in contact during heat addition along with source & during heat extract^n along with sink





$$COP = \frac{Q_a}{Q_r - Q_a} = \frac{T_1(S_1 - S_4)}{T_2(S_2 - S_3) - T_1(S_1 - S_4)} \qquad S_1 = S_2, \; S_3 = S_4$$

$$\boxed{COP = \frac{T_1}{T_2 - T_1}}$$

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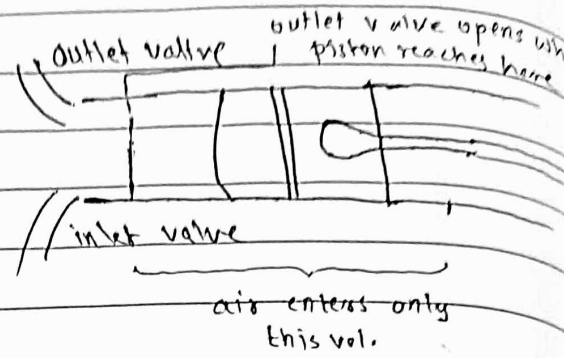
* Reciprocating air compressor

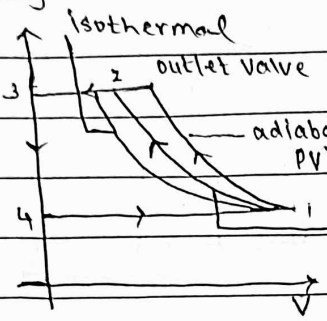
applications:

i. aeroplane engines

ii. Colour spray



neglecting clearance vol.



outlet valve opens at this time, after it opens, still piston moves leftward, vol. decreases but pressure remains the same

adiabatic comp. $PV^{\gamma} = c$

polytropic comp. $PV^{n} = c$ $\boxed{1 < n < \gamma}$

Imp

W = area under curve 1-2-3-4

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

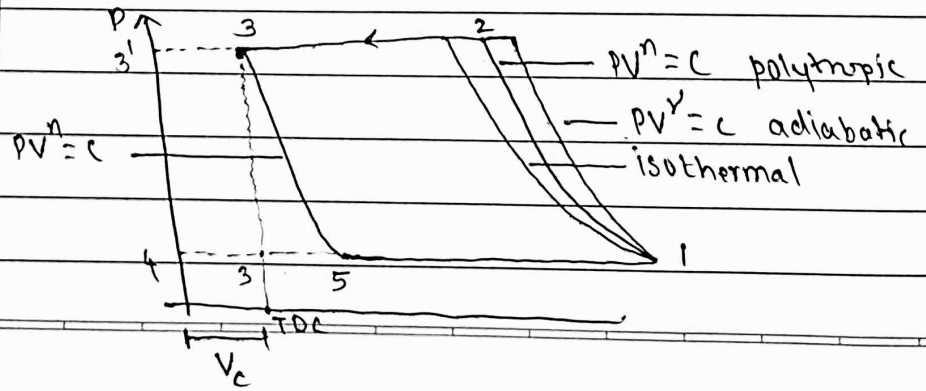
$$W = (P_1V_1 - P_2V_2)\left[1 + \frac{1}{n-1}\right] = \frac{n}{n-1} P_1V_1 \left(1 - \frac{P_2V_2}{P_1V_1}\right)$$

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

$$P_1V_1^{n} = P_2V_2^{n} \quad \therefore \frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{1/n}$$

$$W = \frac{-n}{n-1} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$ — without considering clearance vol.

considering clearance vol.,



now actual workdone = workdone without clearance vol
- area of curve (5-3-3'-4)

The curve 5-3-3'-4 is same like the previous one ∴ it'll have same area under the curve

$$\therefore W = \frac{-n}{n-1} P_1V_1\left[\left(P_2/P_1\right)^{\frac{n-1}{n}} - 1\right] - \frac{-n}{n-1} P_5V_5\left[\left(P_3/P_5\right)^{\frac{n-1}{n}} - 1\right]$$

$P_1 = P_5$, $P_2 = P_3$

$$\therefore W = \frac{-n}{n-1} P_1V_1\left[\left(P_2/P_1\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} P_1V_5\left[\left(P_2/P_1\right)^{\frac{n-1}{n}} - 1\right]$$

$$\boxed{\begin{aligned} W &= \frac{-n}{n-1}\left[\left(P_2/P_1\right)^{\frac{n-1}{n}} - 1\right] P_1(V_1 - V_5) \\ W &= \frac{-n}{n-1}\left[\left(P_2/P_1\right)^{\frac{n-1}{n}} - 1\right] P_1V_a \end{aligned}}$$

.... V_a is actual volume of air absorbed

lesser the value of n, lesser work inputs are needed

Volumetric efficiency : Ratio The mass of air delivered by the compressor to the mass of air that can fill the stroke vol. under NTP or simply ratio of volume of the said entities

$$\eta_{vol} = \frac{V_1 - V_5}{V_1 - V_3} = \frac{V_1 - V_5}{V_s} = \frac{V_s + V_c - V_c\left(P_2/P_1\right)^{1/n}}{V_s}$$

$$\boxed{\eta_{vol} = 1 + k - k\left(P_2/P_1\right)^{1/n}}$$

$V_c/V_s = k$ (% clearance)

$P_3V_3^n = P_5V_5^n$ $\quad V_5 = V_3\left(P_3/P_5\right)^{1/n} = V_c\left(P_2/P_1\right)^{1/n}$

$V_3 = V_c$ $\quad V_1 - V_3 = V_s$ $\quad V_1 = V_s + V_c$

To achieve higher pressures still than this, we use multistage air compressor

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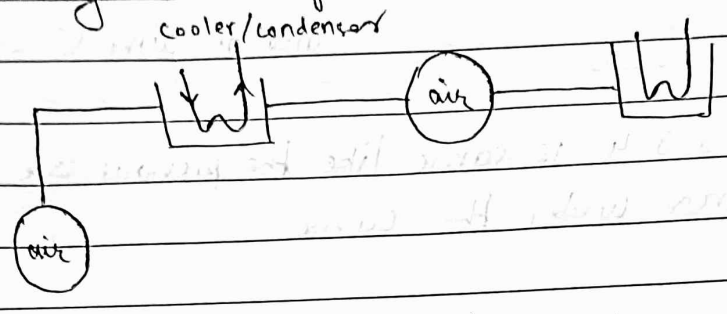
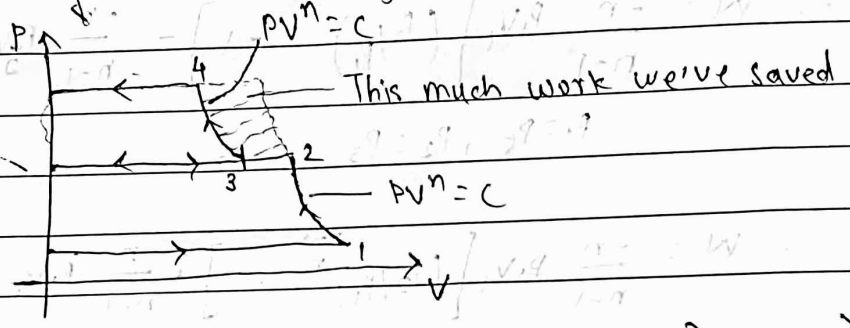
* Multistage air compressor



neglecting % clearance, for 2 stage compressor,



2 to 3 gap Heat vol drop condenser मुळे होतो आहे

W = add^n of area of closed two curves

$$= \frac{-n}{n-1} P_1V_1\left[(P_2/P_1)^{\frac{n-1}{n}} - 1\right] - \frac{n}{n-1}\left[(P_4/P_3)^{\frac{n-1}{n}} - 1\right] P_3V_3$$

$P_1V_1 = mRT_1$ $\quad P_3V_3 = mRT_3$

T_3 is temp of air before entering 2nd cylinder or after getting cooled

$$W = \frac{-n}{n-1} mR_c\left[T_1\left((P_2/P_1)^{\frac{n-1}{n}} - 1\right) + T_3\left((P_4/P_3)^{\frac{n-1}{n}} - 1\right)\right]$$

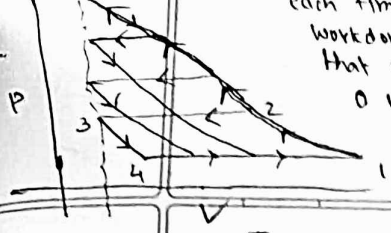
$(T_3 > T_1)$ if T_3 is cooled more & more & made equal to T_1,

$T_3 = T_1$

$$W = \frac{-n mR_cT_1}{n-1}\left[(P_2/P_1)^{\frac{n-1}{n}} + (P_4/P_3)^{\frac{n-1}{n}} - 2\right]$$

Thus P_2 only is variable here

increasing P_2 will increase η ∴



each time we are increasing P_2 efficiency is increasing area under than PV graph is workdone provided for highest achievable P_2, graph traces the same path back that means area under PV is 0 i.e. workdone provided is 0 that means 0 work is provided & compressor is working this is impossible. our goal is to find as minimum workdone to be supplied as possible that'll be done by fin. $\frac{dW}{dP_2} = 0$

To minimize the workdone, $\frac{dW}{dP_2} = 0$

this gives $P_2 = \sqrt{P_1 P_4}$ putting this in eq^n of W gives

$$\boxed{W_{min} = \frac{-2n}{n-1}(mR_cT_1)\left[\left(P_4/P_1\right)^{\frac{n-1}{2n}} - 1\right]}$$

* Advantages of multistaging

i. It requires less power to compress the same amount of air delivered

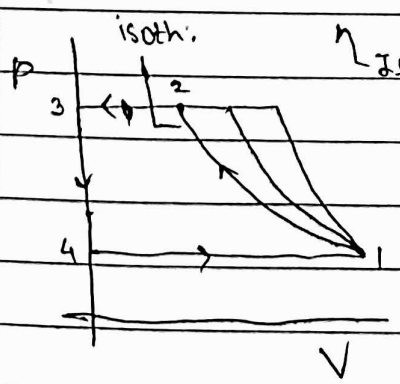
ii. Higher Delivery pressure can be achieved

iii. As we've divided no. of cylinders, better mechanical balance is possible.

iv. The multi stage air compressors have lesser cost of product^n

v. Better lubrication is possible. (low pressure cylinder मा कमी temp bear गरायन असतो ∴ less viscous ~~fluid~~ lubricant वेऊन चालतो high pressure cylinder चा temp खूप जास्त असल्याने त्यांना high viscous lubricants लागतात जे ते temp withstand करतील. जर single stage ठेवले highly viscous lubricant वापरले तर जास्त friction असेल त्याला overcome करण्यासाठी जास्त power loss करावा लागेल)

Isothermal efficiency: Ratio of work req. to compress the air isothermally & actual compression process.



$$\eta_{Iso} = \frac{W_{iso}}{W_{ab}}$$

Clearance vol. is neglected

for isoth., 1-2 is isothermal ∴ $P_1V_1 = P_2V_2$

$$(W_{iso})_{1-2} = P_1V_1 \ln(P_1/P_2) = -P_1V_1 \ln(P_2/P_1)$$

area of (1-2-3-4) $= P_1V_1 - P_1V_1 \ln(P_2/P_1) - P_2V_2$

$= -P_1V_1 \ln(P_2/P_1)$

$$\eta_{Iso} = \frac{-P_1V_1 \ln(P_2/P_1)}{\frac{-n}{n-1} P_1V_1\left[(P_2/P_1)^{\frac{n-1}{n}} - 1\right]}$$

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$$\boxed{\eta_{Iso} = \frac{n-1}{n} \cdot \frac{\ln(P_2/P_1)}{(P_2/P_1)^{\frac{n-1}{n}} - 1}}$$