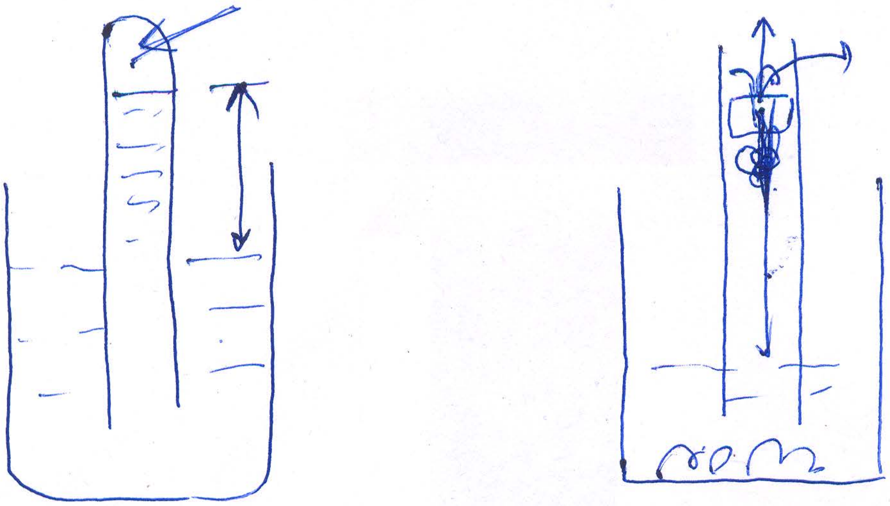
Applied Thermo-Fluids I ME30608
Part- Internal Combustion Engine Spring 2016-2017
3 - 1 - 0: 4 Credits
Indian Institute of Technology Kharagpur
Department of Mechanical Engineering

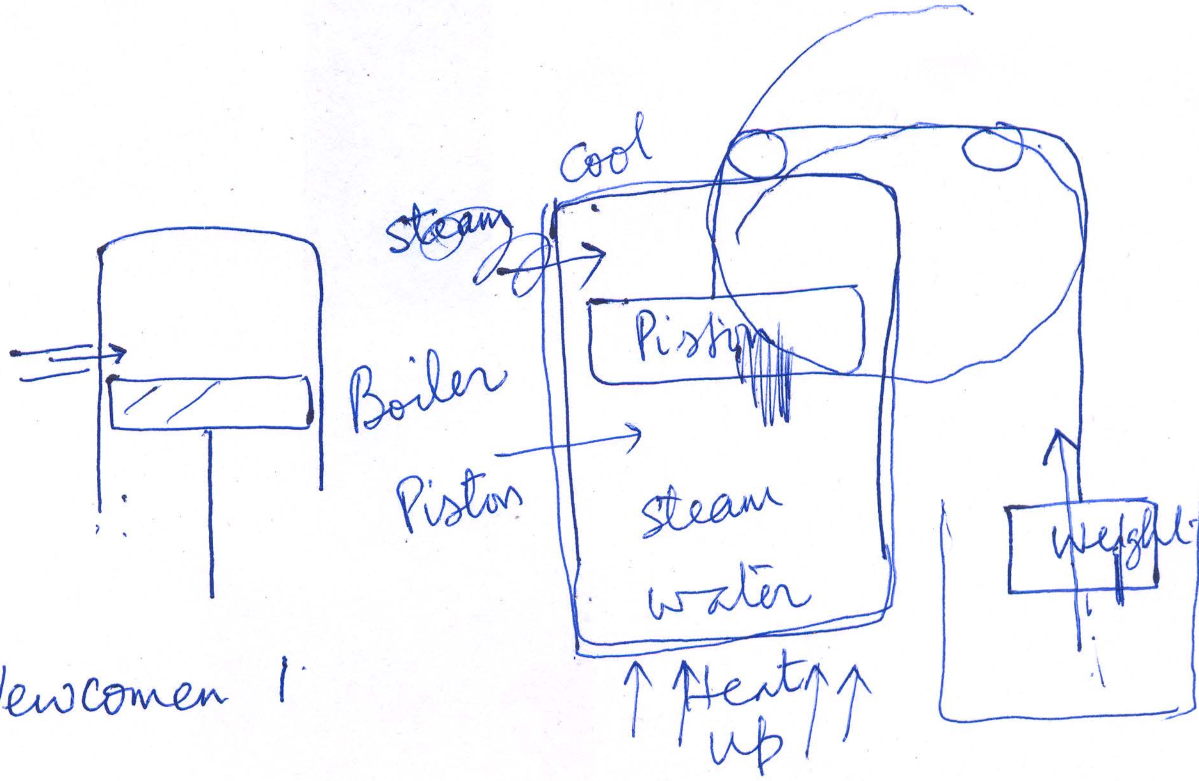
1. *Introduction*: Engine classifications; components of an engine; some useful definitions; engine operation.
2. *Basic cycles*: four stroke SI and CI engine cycles; two stroke SI engine cycle; comparisons.
3. *A detailed classification of engines*; fuels used; arrangement of cylinders; cooling type; application areas.
4. *Operating parameters*; various terminology; compression ratio; torque; power, mean effective pressure.
5. *Engine efficiencies*; bsfc; thermal and mechanical efficiencies; combustion efficiency; volumetric efficiency;
6. *Valve timing diagrams* for SI and CI engines; actual and ideal cycle; effect of speed, part- throttle, supercharger
7. *Air standard cycles*; Otto, Diesel and Dual cycles; comparison of efficiencies.
8. *Fuel air cycles*; assumptions; effects of various parameters.
9. *Actual cycles*; various losses and their effects on performance.
10. *Carburetion*; factors affecting carburetion; different types of carburetor; drawbacks and their remedy.
11. *Fuels*; different types; rating of fuels; octane and cetane number; alternative fuels; environmental characteristics; ignition systems; different types
12. *Combustion in S.I. Engines*; flame speed; stages of combustion; knocking; combustion chamber design; fuel rating.
13. *Combustion in C.I. Engines*; stages of combustion; various factors affecting combustion; cetane number.
14. *Supercharging and turbocharging*; after-coolers and inter-coolers.
15. *Engine heat transfer*; energy distribution; modes of heat transfer; effect of variables on heat transfer; different cooling systems; air cooling; liquid cooling

Required Text:
Ganesan, V., (2003), *Internal Combustion Engines*, Tata McGraw Hill.

Reference:
Pulkrabek, W.W., (1997), *Engineering Fundamentals of the I. C. Engine*, Prentice Hall.
Mathur, M.L. and Sharma, R.P., (2007) Internal Combustion Engine, Dhanpat Rai Publications,
Taylor, C.F., The Internal Combustion Engine in Theory and Practice: Vol. 1 – 2, MIT Press

Coal



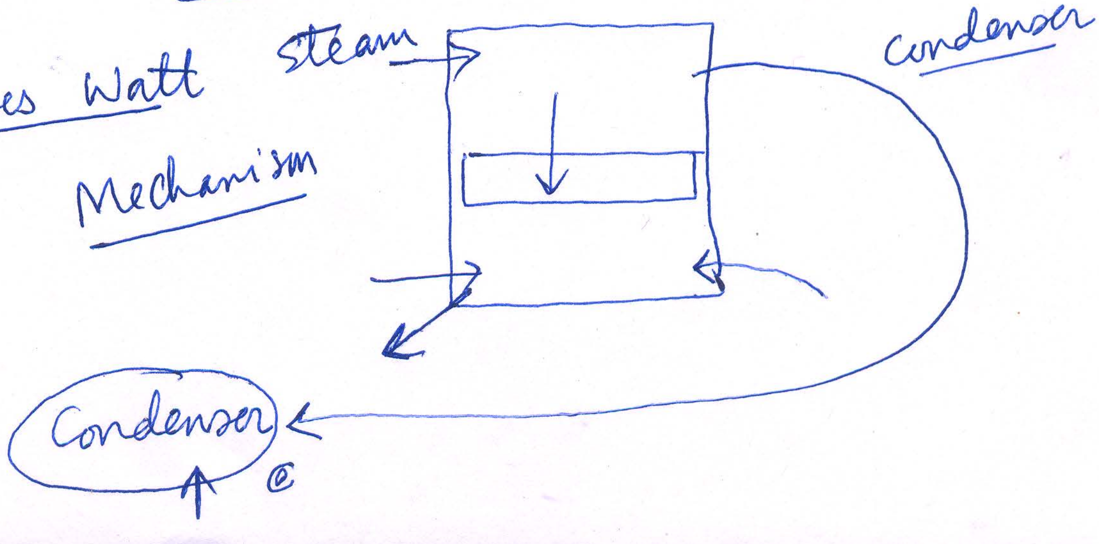


Newcomen 1

~3%-5%

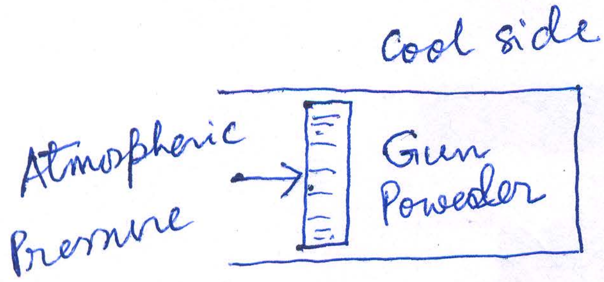
James Watt

Mechanism



~18-20%

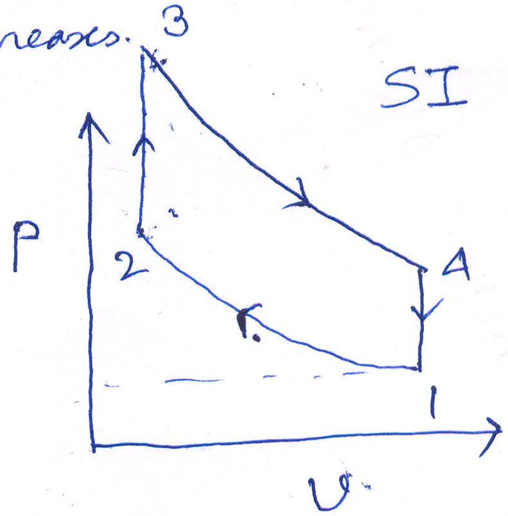
Atmospheric Engine



1859 Petroleum

Pressure increases.

SI

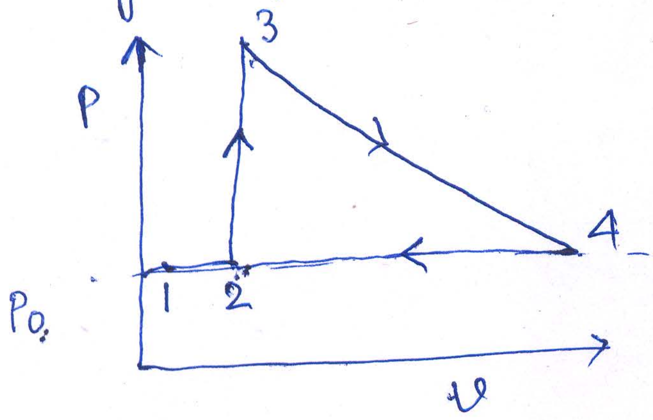


Lenoir Engines

1862

1-2 was absent.

Cycle of Lenoir engine



1-2 compression

2-3 Constant ~~temperature~~ volume heat addition

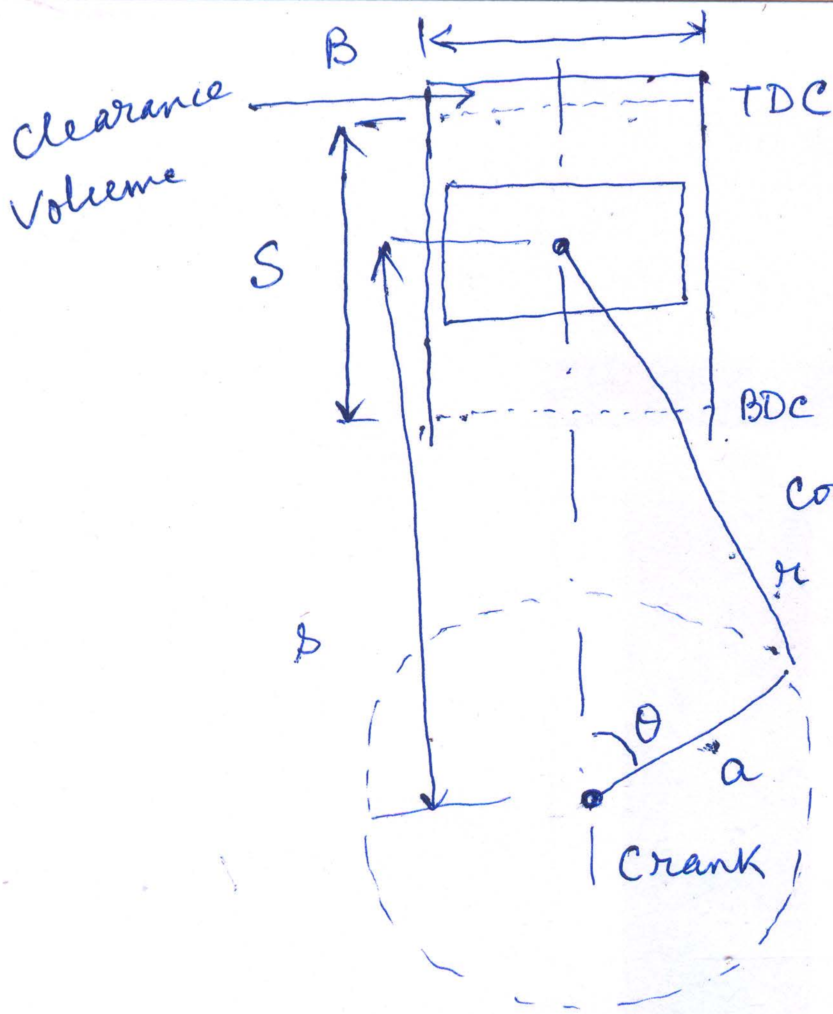
3-4 Expansion process

4-1 constant volume Heat rejection

P_0 = atmospheric pressure

absence of compression process 1-2 reduced the efficiency of the engine.

⇒ Pulse jet engine (One application of Lenoir Engine)



TDC - Top Dead Center

BDC - Bottom Dead Center

B - Engine cylinder bore

S - Engine stroke

Connecting rod length

V_c - Clearance volume

V_{BDC} - Volume of Cylinder at ~~Bot~~ BDC

V_{TDC} - Volume of cylinder at TDC (also V_c)

V_s - Displacement volume (also stroke volume, or swept volume)

$$r_c = \frac{\cancel{V_D}\, V_{BDC}}{V_{TDC}} = \frac{V_c + V_s}{V_c}$$

$$V_s = \frac{\pi}{4} B^2 S$$

$$r_c = 1 + \frac{V_s}{V_c}$$

$$s = a\cos\theta + \sqrt{r^2 - a^2\sin^2\theta}$$

$$= a\left[\cos\theta + \sqrt{R^2 - \sin^2\theta}\right] \qquad R = \frac{r}{a} \sim 3-10$$

$$\frac{ds}{dt} = U_p = a\left[-\sin\theta - \frac{1}{\cancel{2}}\frac{1}{\sqrt{R^2-\sin^2\theta}}\cdot \cancel{2}\sin\theta\cos\theta\right]\omega$$

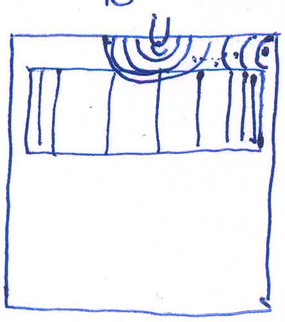
$$= -a\sin\theta\left[1 + \frac{\cos\theta}{\sqrt{R^2-\sin^2\theta}}\right]\omega$$

$$V = V_c + A_p\cdot(r+a-s) \qquad A_p = \text{Piston area} = \frac{\pi}{4}B^2$$

$$\bar{U}_p = \frac{2SN}{60} \text{ m/s} \qquad 5-20 \text{ m/s}$$

B

Clearance volume



S

$\frac{B}{S} > 1$ over square

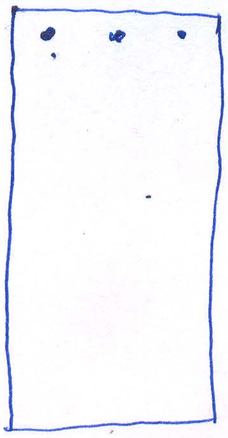
$= 1$ square engine

< 1 under square engine

CI

× SI

B low speed

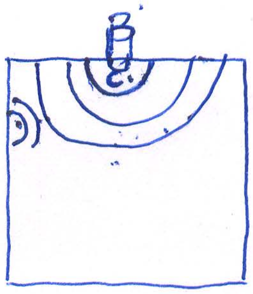


3B

high speed

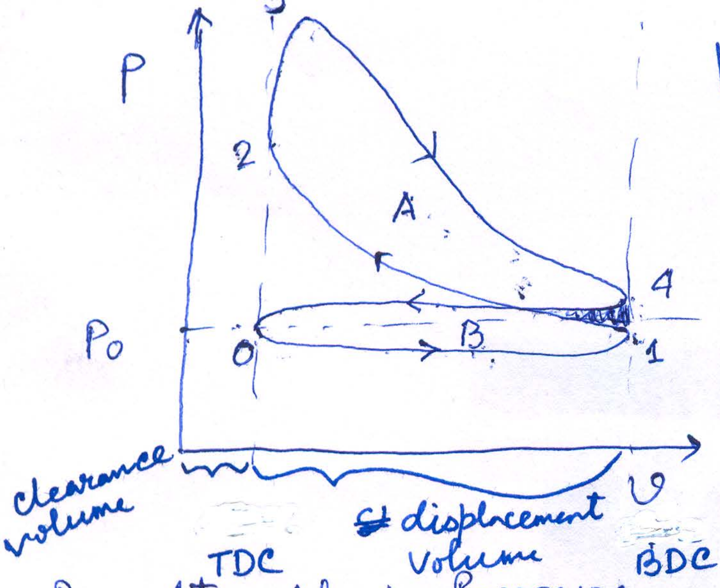
B

C



B

SIT = Self Ignition Temperature



$W \times \frac{N/2}{60}$

Indicator diagram

01 - Suction stroke

12 - Compression "

23 - Heat addition process

34 - Expansion stroke

40 - Exhaust stroke

P_0 = Atmospheric Pressure

$$W_i = W_A - W_B$$

W_A = Work output in loop A

$$w_i = w_A - w_B$$

W_B = Work input in loop B

$$w_b = w_i - (\text{frictional + parasitic load})$$

AC

W_i = Indicated power

w lower case are specific

indicated thermal efficiency

$$\eta_{ith} = \frac{w_i}{Q}$$

$W_i = kW = m w_i$

$w_i = \frac{kW}{kg/sec} = \frac{kJ}{kg}$

$$\eta_{bth} = \frac{w_b}{Q}$$

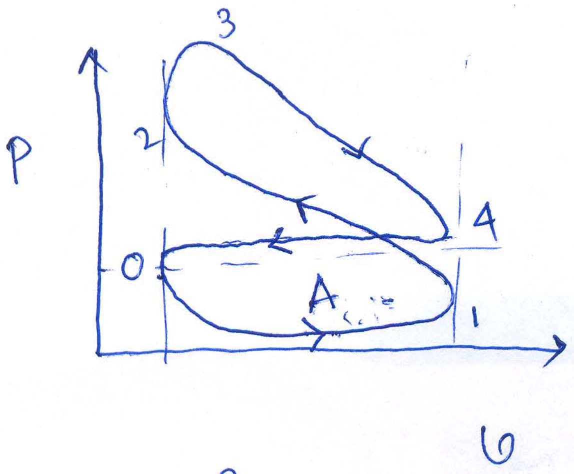
m_f = mass of fuel added per cycle, kg

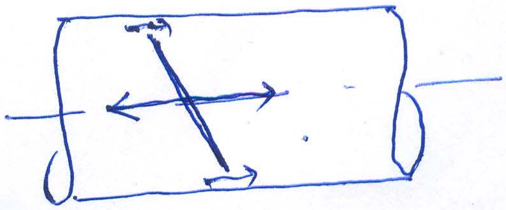
$$\eta_m = \frac{\eta_{bth}}{\eta_{ith}} = \frac{w_b}{w_i}$$

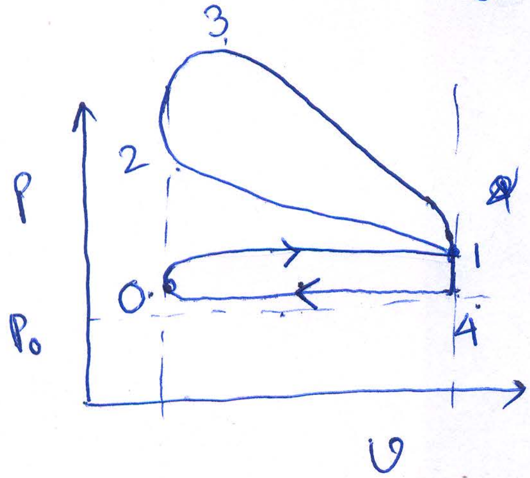
Q_{cv} = Calorific value of fuel, $\frac{kJ}{kg}$

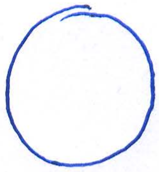
WOT → Wide open Throttle

η_c = Combustion efficiency ~ 98% - 98.5%


3
2
4
0
A
1
P
v




3
2
4
1
0
A
P
P_0
v



mep = Mean effective pressure kPa

V_d = Displacement volume (m^3)

$V_d \times mep = W$ W = Work output, kJ

$$mep = \frac{W}{V_d}$$

bmep = brake mean effective pressure

imep = indicated " " "

$$bmep = \frac{W_b}{V_d}, \quad imep = \frac{W_i}{V_d}$$

fmep = friction mean effective pressure

friction power, $\dot{W}_f = \dot{W}_i - \dot{W}_b$

" work, $W_f = W_i - W_b$

$$\therefore fmep = \frac{W_f}{V_d}$$

~~Mep~~ Mean effective pressure is an indicator how the engine is loaded. or stressed.

sfc = specific fuel consumption $\frac{gm \text{ of fuel}}{KWh}$

$$= \frac{\dot{m}_f}{\dot{W}}$$ $\dot{m}_f$ = mass flow rate of fuel burned.

$\dot{m}_f$ = kg/sec

bsfc = brake specific fuel consumption

isfc = indicated " " "

$$A/F \text{ ratio} = \frac{\dot{m}_a}{\dot{m}_f}$$

$$A/F \text{ ratio, stoichiometric} = \left(\frac{\dot{m}_a}{\dot{m}_f}\right)_{stoich}$$

$$A/F \text{ " , actual} = \left(\frac{\dot{m}_a}{\dot{m}_f}\right)_{actual}$$

$$(F/A)\text{ratio} = \frac{1}{\cancel{A/}(A/F)\text{ratio}}$$

ϕ = equivalence ratio

$$= \frac{(F/A)_{act}}{(F/A)_{stoich}}$$

>1 rich mixture

<1 lean " .

<u>Torque</u> (N-m)

$$\omega\tau = \dot{W}$$

$$\tau = \frac{\dot{W}}{\omega}$$

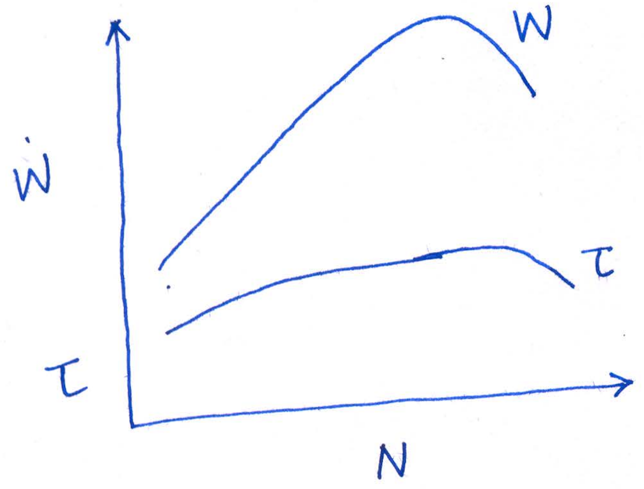
$$\cancel{\omega = \frac{2\pi(N/2)}{60}}$$ N = rpm.

$$\omega = \frac{2\pi N}{60} \text{ rad/sec}$$

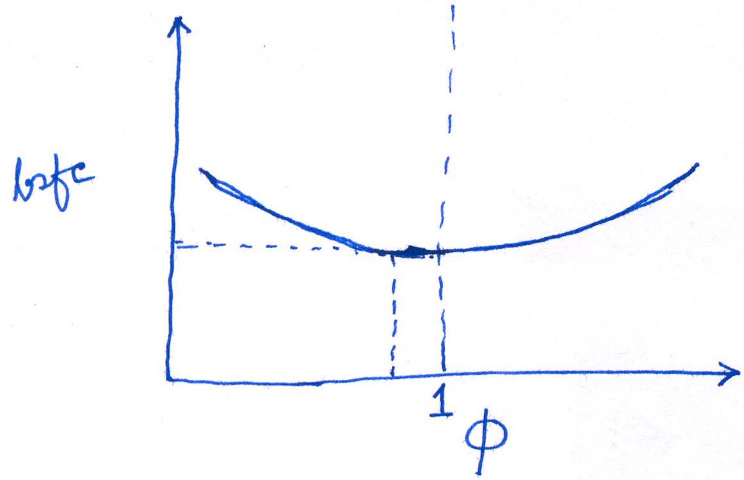
W = Energy from each cycle.

$$\dot{W} = W \times \frac{N}{60} \times \frac{1}{2}$$

$$\dot{W} = W \times \frac{N}{60}$$



ϕ = equivalence ratio



lower ~~bs~~ bsfc means better engine fuel economy

$\phi < 1$ lean mixture

$\phi > 1$ rich mixture

lean mixture is kept at the engine cruising speed ~55 km/hr

$\phi > 1$ for accelerating

for idling

Volumetric efficiency

$$\eta_v = \frac{m_a}{\rho_a V_d}$$

m_a = mass of air inducted kg

ρ_a = Density at standard pressure and temperature 101 kPa and 27°C

V_d = Stroke volume

η_v = an ~~d~~ indication of how much air that can be inducted inside the cylinder in the suction stroke.

A 1500-cm³, four-stroke cycle, four-cylinder CI engine, operating at 3000 RPM, produces 48 kW of brake power. Volumetric efficiency is 0.92 and A/F ratio = 21:1.
Calculate: (a) Rate of air flow into engine [kg/sec]
(b) Brake specific fuel consumption [gm/kW-hr],
(c) Mass rate of exhaust flow [kg/hr]

A 1500-cm^3, four-stroke cycle, four-cylinder CI engine, operating at 3000 RPM, produces 48 kW of brake power. Volumetric efficiency is 0.92 and air-fuel ratio AF=21:1.

Calculate:

(a) Rate of air flow into engine. [~~kW~~ kg/sec]

(b) Brake specific fuel consumption. [gm/kW-hr]

(c) Mass rate of exhaust flow. [kg/hr]

(d) Brake output per displacement. [kW/L]

Ans: $\eta_v = 0.92 = \dfrac{\dot m_a}{\rho_a V_d \frac{N}{120}}$

$\rho_a = \dfrac{P_a}{RT_a} = \dfrac{101\times10^3}{287\times300}$

$= 1.173\ kg/m^3$.

Here, P_a = Atm. pressure $= 101$ kPa

T_a = Atm. temp. $= 27^\circ c = 300K$

ρ_a = Density at atm. condition.

$$0.92 = \frac{\dot m_a}{1.173\times1500\times10^{-6}\times\frac{3000}{120}}$$

where $\dot m_a$ = mass flow rate of air in kg/sec

$\dot m_a = 0.04$ kg/sec. ←

$A/F = \dfrac{\dot m_a}{\dot m_f}$ where $\dot m_f$ = mass flow rate of fuel in kg/sec.

$$\dot m_f = \frac{\dot m_a}{21} = \frac{0.04}{21} = 1.93\times10^{-3}\ kg/sec.$$

$$bsfc = \frac{\dot m_f \times \frac{1000}{\cancel{3600}}\times3600}{kW}\left(\frac{gm}{kWhr}\right)$$

$$= \frac{1.93\times10^{-3}\times\frac{1000}{\cancel{3600}}\times3600}{48}$$

$$= 144.75\ \frac{gm}{kWhr}. \leftarrow$$

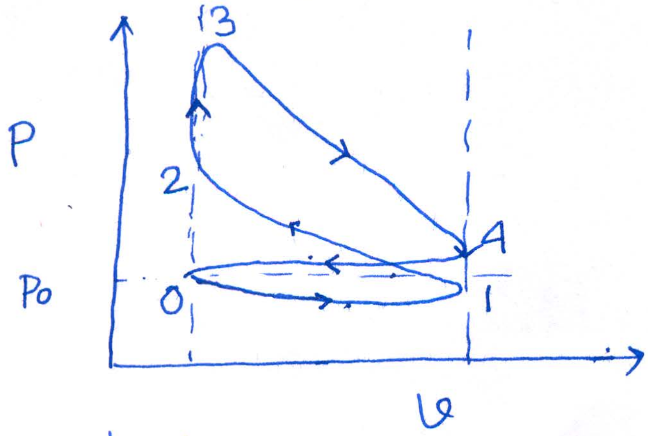
Exhaust flow $= (\dot m_a + \dot m_f) = (0.04 + 1.93\times10^{-3})\times3600\ \frac{kg}{hr}$

$= 151$ kg/hr. ←

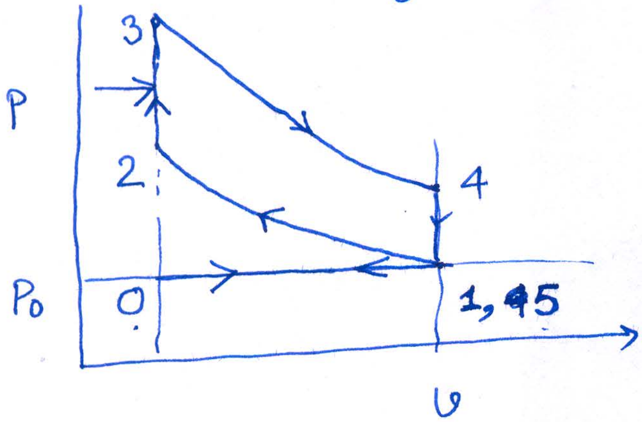
brake output per displacement $= \dfrac{48}{1500\times10^{-3}}\ kW/L = 32$ ←

AIR STANDARD CYCLE

17/1/17



01 - Suction stroke
12 - Compression "
23 - Heat addition
34 - Expansion stroke
40 - Exhaust stroke



Suction and exhaust stroke are removed.

WOT.
Part load or supercharge.

12 - isentropic process
reversible, adiabatic
friction is very small.
heat transfer " " "

2-3 Heat transfer
Pure air cannot combust
Temperature rise will be very high

3-4 Expansion stroke
Isentropic
reversible, adiabatic

4-1 Heat rejection Exhaust Blow-down process

Air is working fluid.

- Ideal gas equation
- Pv^{γ} = constant

where P = Pressure
v = specific volume
γ = ratio of specific heat.

- Working fluid is air.

air + fuel + 7% exhaust gas in CV — S I

air + " — C I

only air specific heat constant

$c_p = 1.005$ kJ/kg K
$c_v = 0.718$ "
$R = 0.287$ "
$\gamma = 1.4$

$\gamma = 1.3$ at ~ 3000-3200 K

$c_p = \frac{\gamma R}{\gamma - 1}$

$c_v = \frac{R}{\gamma - 1}$

$\gamma = 1.35$

$$\cancel{\int_1 \delta q} - \int_1 \delta w = \int_1 du$$

$$-{}_1w_2 = u_2 - u_1$$

$$= c_v (T_2 - T_1)$$

$$\boxed{-{}_1w_2 = \frac{R}{\gamma-1}(T_2 - T_1)}$$

$T_2 > T_1$

negative work

$$-{}_1w_2 = \frac{(RT_2 - RT_1)}{\gamma - 1}$$

$$= \frac{(P_2 v_2 - P_1 v_1)}{\gamma - 1}$$

$${}_1w_2 = \cancel{P_0} \int_1^2 P\,dv$$

$\cancel{P_2, v}$ P_2, T_2

P_3, T_3

P_4, T_4

$$c_p - c_v = R$$

$$c_v\left(\frac{c_p}{c_v} - 1\right) = R$$

$$c_v(\gamma - 1) = R$$

$$c_v = \frac{R}{\gamma - 1}$$

$$\boxed{q_{in} = \frac{Q_{in}}{m_m} = \frac{m_m c_v (T_3 - T_2)}{m_m} = \frac{m_f Q_{cv} \eta_c}{m_m}}$$

$${}_2q_3 = \frac{m_f}{m_m} Q_{cv} \eta_c$$

$Pv = RT$

$P_2 v_2 = RT_2$

$P_1 v_1 = RT_1$

$Q_{cv} =$ KJ/kg of fuel

$m_f =$ kg of fuel

$${}_3w_4 = c_v (T_3 - T_4)$$

$${}_4q_1 = c_v (T_4 - T_1)$$

$$\eta = \frac{w_{net}}{q_{in}}$$

$$= \frac{q_{in} - q_{out}}{q_{in}}$$

$Pv^\gamma = C$, $Pv = RT$

$$Tv^{\gamma-1} = C$$

$$T_2 v_2^{\gamma-1} = T_1 v_1^{\gamma-1}$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = \cancel{\left(\frac{1}{r_c}\right)^{\gamma-1}} r_c^{\gamma-1}, \quad \frac{T_1}{T_2} = \left(\frac{1}{r_c}\right)^{\gamma-1}$$

$$T_3 v_3^{\gamma-1} = T_4 v_4^{\gamma-1}$$

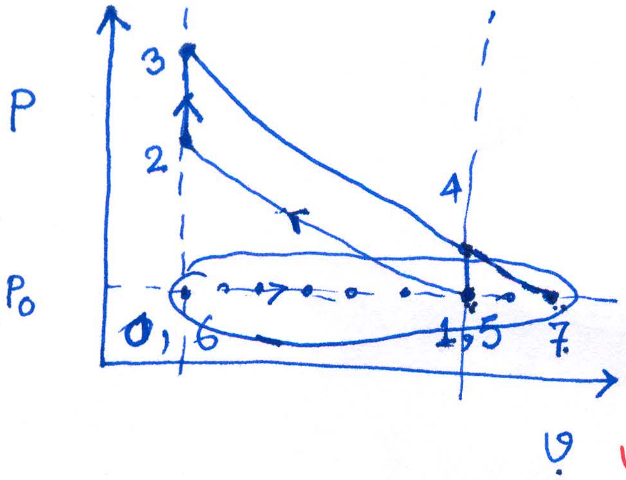
$$\cancel{\frac{T_3}{T_4}} \therefore \frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \left(\frac{1}{r_c}\right)^{\gamma-1}$$

$$\cancel{\frac{T_2}{T_1} = \frac{T_4}{T_3}} \qquad \frac{T_1}{T_2} = \frac{T_4}{T_3} \Rightarrow \frac{T_3}{T_2} = \frac{T_4}{T_1}$$

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

$$\boxed{\eta_{ith} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{1}{r_c}\right)^{\gamma-1}}$$

$$\boxed{\eta_{bth}/\eta_{ith} = \eta_m}$$



0-1
1-2
2-3
3-4
4-5 →
5-6

v_7 remains same for $7 \to 6$

V_7 fictitious volume

4-7 isentropic expansion process substituting 4-5

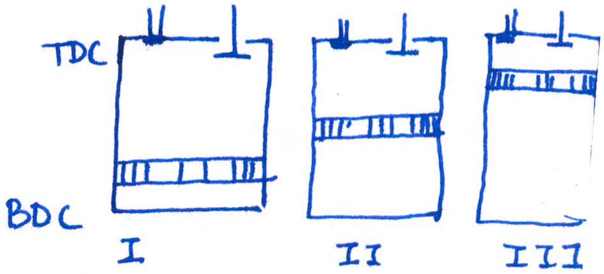
4-7 ~ isentropic process

$$m_m = \underbrace{\frac{V_1}{v_1} = \frac{V_2}{v_2} = \frac{V_3}{v_3} = \frac{V_4}{v_4}}. = \frac{V_7}{v_7}$$

$$P_4 v_4^{\gamma} = P_7 v_7^{\gamma} = P_3 v_3^{\gamma}$$

$$T_4 P_4^{\frac{1-\gamma}{\gamma}} = T_7 P_7^{\frac{1-\gamma}{\gamma}} = T_3 P_3^{\frac{1-\gamma}{\gamma}}$$

$$T_4 v_4^{\gamma-1} = T_7 v_7^{\gamma-1} = T_3 v_3^{\gamma-1}$$



$\frac{V_4}{v_7}$ $\frac{V_2}{v_7}$ ✓

$m_I > m_{II} > m_{III}$

$V_I > V_{II} > V_{III}$

$$m_{ex} h_{ex} + m_a h_a = \underbrace{(m_{ex} + m_a)}_{= m_m} h_m$$

$v_I = \frac{m_I}{V_I}$

v_{II}

v_{III}

v_7

$$m_{ex} T_7 + m_a T_a = m_m T_1$$

$$x_r = \frac{m_{ex}}{m_m},$$

$$\frac{m_a}{m_m} = \frac{m_m}{m_m} - \frac{m_{ex}}{m_m}$$

$$\boxed{x_r T_7 + (1 - x_r) T_a = T_1}$$

Cylinder conditions at the start of compression in an SI engine operating at WOT on an air-standard Otto cycle are 60°C and 98 kPa. The engine has a compression ratio of 9.5:1 and uses gasoline with AF = 15.5. Combustion efficiency is 96% and it can be assumed that there is no exhaust residual.

Calculate:

(a) Temperature at all states in the cycle. [°C]

(b) Pressure at all states in the cycle. [kPa]

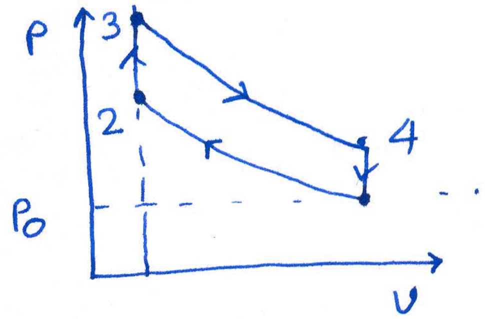
(c) Specific work done during power stroke [kJ/kg]

(d) Heat added during combustion. [kJ/kg]

(e) Net specific work done. [kJ/kg]

(f) Indicated thermal efficiency. [%]

Take $\gamma = 1.35$, $R = 0.287$ kJ/kg-K, $Q_{cv} = 44000$ kJ/kg.



$T_1 = 60°C = 60 + 273 = 333$ K

$P_1 = 98$ kPa

$P_1 v_1^{\gamma} = P_2 v_2^{\gamma} \Rightarrow \frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = (9.5)^{1.35} = 20.9$

$P_2 = 98 \times 20.9 = 2048$ kPa

$T_1 v_1^{\gamma-1} = T_2 v_2^{\gamma-1} \Rightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = 9.5^{0.35} = 2.2$

$T_2 = 333 \times 2.2 = 732.6$ K

m_f = mass of fuel

m_a = " " air

$m_m = m_a + m_f$

$m_f Q_{cv} \eta_c = m_m c_v (T_3 - T_2)$

$Q_{cv} \eta_c = \left(\frac{m_f + m_a}{m_f}\right) c_v (T_3 - T_2)$

$= (1 + 15.5) c_v (T_3 - T_2)$

$\frac{R = 0.287 \text{ kJ/kgK}}{}$

$\frac{R_u}{M_m} = R$

$c_v = \frac{R}{\gamma - 1} = \frac{0.287}{1.35 - 1} = 0.82$

$44000 \times 0.96 = 16.5 \times 0.82 \times (T_3 - T_2)$

$3122 = T_3 - T_2$

$T_3 = 3854.6$ K

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} \Rightarrow P_3 = 2048 \times \frac{3854.6}{732.6}$$

$$= 10775.6 \text{ kPa}$$

$$P_3 v_3^{\gamma} = P_4 v_4^{\gamma}$$

$$\frac{P_4}{P_3} = \left(\frac{v_3}{v_4}\right)^{\gamma} = \left(\frac{1}{r_c}\right)^{\gamma} = \left(\frac{1}{9.5}\right)^{1.35} = 0.048$$

$$P_4 = 517 \text{ kPa}$$

$$T_3 v_3^{\gamma-1} = T_4 v_4^{\gamma-1}$$

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \left(\frac{1}{9.5}\right)^{0.35} = 0.455$$

$$T_4 = 1754 \text{ K}$$

$T_2 = 732.6 - 273 = \cancel{44}459.6\,^\circ C$	$P_2 = 2048$ kPa
$T_3 = 3854.6 - 273 = 3581.6\,^\circ C$	$P_3 = 10775.6$ kPa
$T_4 = 1754. - 273 = 1481\,^\circ C$	$P_4 = 517$ kPa

$$\cancel{q_{in} - w} \; \cancel{\delta q} - \delta w = du$$

$${}_3w_4 = c_v (T_3 - T_4) = 0.82 (3854.6 - 1754) = 1722.5 \text{ kJ/kg}$$

$${}_2q_3 = c_v (T_3 - T_2) = 0.82 (3854.6 - 732.6) = 2560 \text{ kJ/kg}$$

$${}_1w_2 = c_v (T_2 - T_1) = 0.82 (732.6 - 333) = 327.7 \text{ kJ/kg}$$

$$w_{net} = 1722.5 - 327.7 = 1394.8 \text{ kJ/kg}$$

$$\eta_{ith} = \frac{w_{net}}{q_{in}} = \frac{1394.8}{2560} = 54.5\%$$

24/1/17 ④

The engine is a three-liter V6 engine operating at 2400 RPM.
At this speed, the mechanical efficiency is 84%.

Calculate:

(a) Brake power. [kW]
(b) Torque [N-m]
(c) Brake mean effective pressure [kPa]
(d) Friction power lost. [kW]
(e) Brake specific fuel consumption [gm/kWh]
(f) Volumetric efficiency [%]
(g) Output displacement [kW/L]

2. The engine in Problem 1 is a three-liter V6 engine operating at 2400 RPM. At this speed the mechanical efficiency is 84%.

Calculate:

(a) Brake power. [kW]

(b) Torque. [N-m]

(c) Brake mean effective pressure. [kPa]

(d) Friction power lost. [kW]

(e) ~~Bos~~ Brake specific fuel consumption. [gm/kW-hr]

(f) Volumetric efficiency. [%]

(g) Output displacement. [kW/L]

Ans: $\frac{V_d + V_c}{V_c} = 9.5$ where V_d = Displacement volume, m^3

V_c = Clearance volume, m^3

$V_d = \frac{3}{6} \times 1000\ cm^3 = 500\ cm^3$ per cylinder

$\frac{V_d}{V_c} + 1 = 9.5$

$\frac{V_d}{V_c} = 8.5 \quad \therefore V_c = \frac{V_d}{8.5} = \frac{500}{8.5} = 58.8\ cm^3.$

$\therefore V_1 = V_d + V_c = (500 + 58.8)\ cm^3 = 558.8\ cm^3$

m_1 = mass of charge $= \frac{V_1}{v_1} = \frac{558.8 \times 10^{-6}}{1.025}\ \cancel{kg}\ m^3/(m^3/kg) = 5.45 \times 10^{-4}\ kg$

Brake power $= w_i \times \eta_m \times m \times \frac{N}{60} \times \frac{1}{2}$ kW where, w_i = indicated work/kg of charge

η_m = mechanical efficiency

m = mass of charge, kg

N = speed of engine, RPM

$= 1395 \times 0.84 \times 5.45 \times 10^{-4} \times \frac{2400}{60 \times 2}$ kW

$= 12.8$ kW/cylinder.

$\therefore$ Total $= 6 \times 12.8$ kW $= 76.8$ kW

Torque, τ (N-m),

$\frac{2\pi N}{60} \times \tau = 12.8 \times 1000$

$\therefore \tau = \frac{12.8 \times 1000 \times 60}{2 \times \pi \times 2400}$ N-m

$= 50.9$ N-m per cylinder.

$\therefore$ Total $= 6 \times 50.9 = 305.4$ N-m

Brake mean effective pressure $= \frac{1395 \times 0.84}{500 \times 10^{-6}}\ \cancel{kPa} \times 5.45 \times 10^{-4}$ kPa

$= 1277$ kPa

Friction power lost $= 6 \times 5.45 \times 10^{-4} \times 1395 \times 0.16 \; \cancel{kW} \times \frac{N}{120}$ kW

$= 14.6$ kW

Brake specific fuel consumption

$$bsfc = \frac{\dot{m}_f \times 1000 \times 3600}{W_b}$$

where $\dot{m}_f$ = kg/sec

$$m_f = \frac{m}{16.5} = \frac{5.45 \times 10^{-4}}{16.5} \text{ kg}$$

$$= 3.3 \times 10^{-5} \text{ kg}$$

$$\dot{m}_f = 3.3 \times 10^{-5} \times \frac{N}{120} \text{ kg/sec}$$

$$= 6.61 \times 10^{-4} \text{ kg/sec}$$

$$= \frac{6.61 \times 10^{-4} \times 1000 \times 3600}{12.8}$$

$$= 186 \text{ gm/kW-hr}$$

Volumetric efficiency

$$= \frac{m_a}{\rho_a V_d}$$

$$= \frac{\cancel{(5.45 \times 10^{-4})/15.5} \; 3.3 \times 10^{-5} \times 15.5}{1.18 \times 500 \times 10^{-6}}$$

$$= 0.867 = 86.7\%$$

output per displacement

$$= \frac{12.8}{500 \times 10^{-3}} \text{ kW/L}$$

$$= 25.6 \text{ kW/L}$$

(a) Brake power = 76.8 kW

(b) Torque = 305.4 N-m

(c) bmep = 1277 kPa

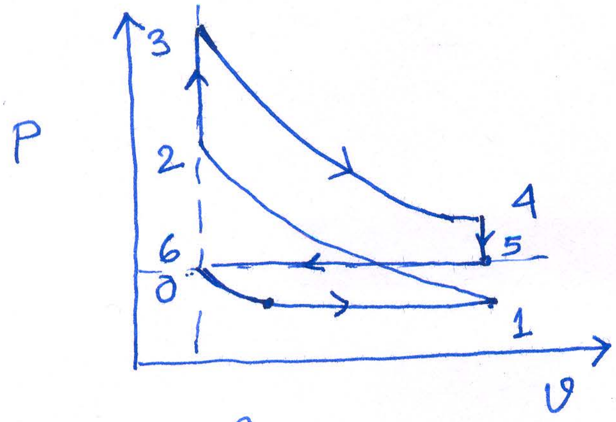
(d) Friction power lost = 14.6 kW

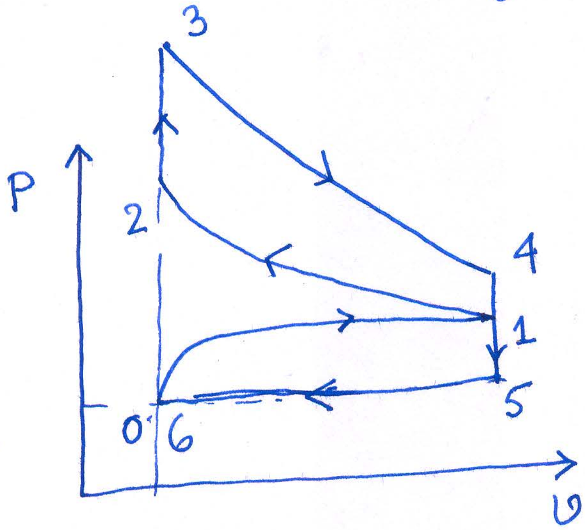
(e) bsfc = 186 gm/kW-hr

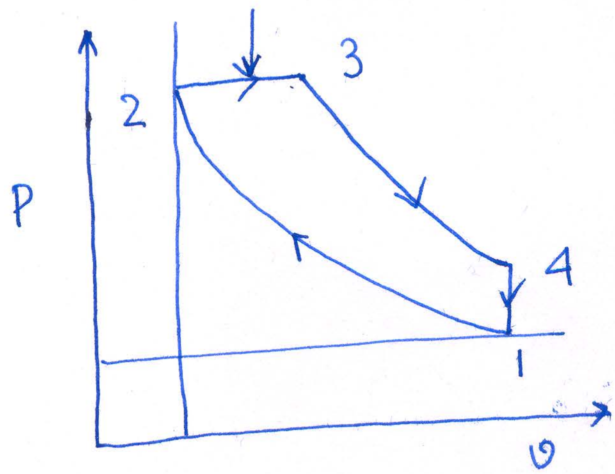
(f) η_v = 86.7%

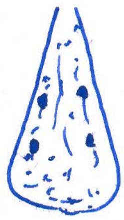
(g) output displacement = 25.6 kW/L

Part load condition









$\cancel{{}_1q_2} - {}_1w_2 = \cancel{0}\; u_2 - u_1$

m_m

${}_1w_2 = -c_v(T_2 - T_1)$

$\cancel{{}_1q_2 - {}_1w_2}$ $\quad {}_1q_2 = 0$

${}_2q_3 - {}_2w_3 = u_3 - u_2 \qquad {}_2w_3 = P_2(v_3 - v_2)$

$${}_2q_3 = u_3 - u_2 + P_2(v_3 - v_2)$$

$$= (u_3 + P_3 v_3) - (u_2 + P_2 v_2)$$

$$= h_3 - h_2 \qquad Q_a \eta_c = (AF+1)\,c_p(T_3 - T_2)$$

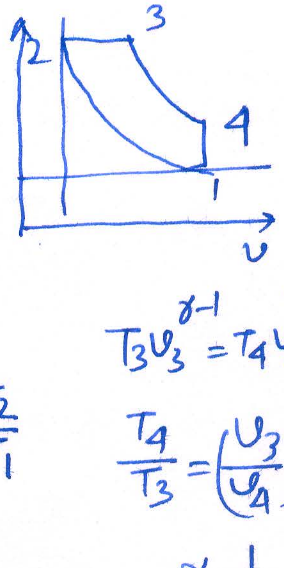
$$= c_p(T_3 - T_2)$$

$${}_3w_4 = c_v(T_3 - T_4)$$

$${}_4q_1 = c_v(T_4 - T_1) \qquad T_1 v_1^{\gamma-1} = T_2 v_2^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)} \qquad \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = r_c^{\gamma-1}$$

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



$$= 1 - \frac{1}{\gamma}\cdot\frac{1}{r_c^{\gamma-1}}\cdot\left(\frac{\beta^\gamma - 1}{\beta - 1}\right) \qquad \frac{v_3}{v_2} = \beta \text{ (cutoff ratio)} = \frac{T_3}{T_2}$$

$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma-1}}$$

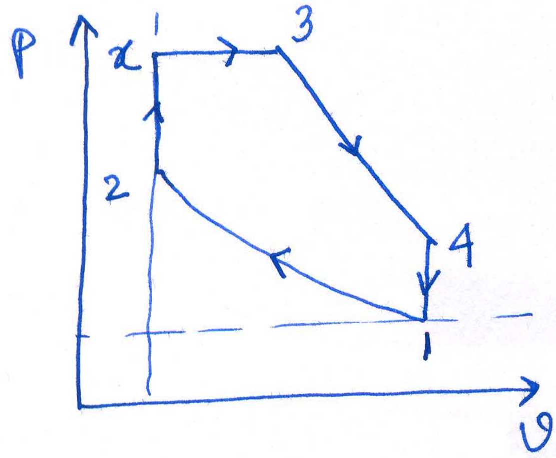
$$T_3 v_3^{\gamma-1} = T_4 v_4^{\gamma-1} \qquad \frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1}$$

$$\frac{T_4}{T_1} = \frac{T_4}{T_3} \times \frac{T_3}{T_2} \times \frac{T_2}{T_1}$$

$$= \cancel{\frac{v_4}{v_3}}\cancel{\left(\frac{v_4}{v_3}\right)}$$

$$= \left(\frac{v_3}{\cancel{v_4}}\right)^{\gamma-1}\cdot\frac{v_3}{v_2}\cdot\left(\frac{\cancel{v_1}}{v_2}\right)^{\gamma-1}$$

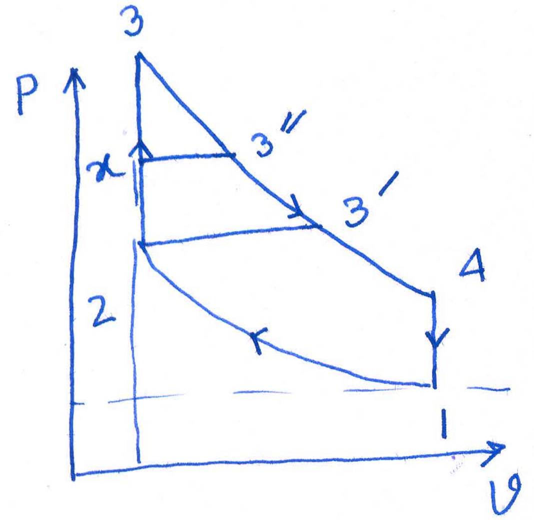
$$= \frac{v_3^{\gamma}}{v_2^{\gamma}} = \beta^{\gamma}$$



Dual Cycle

Limited Pressure Cycle

$$q_{in} = {}_2q_x + {}_xq_3$$



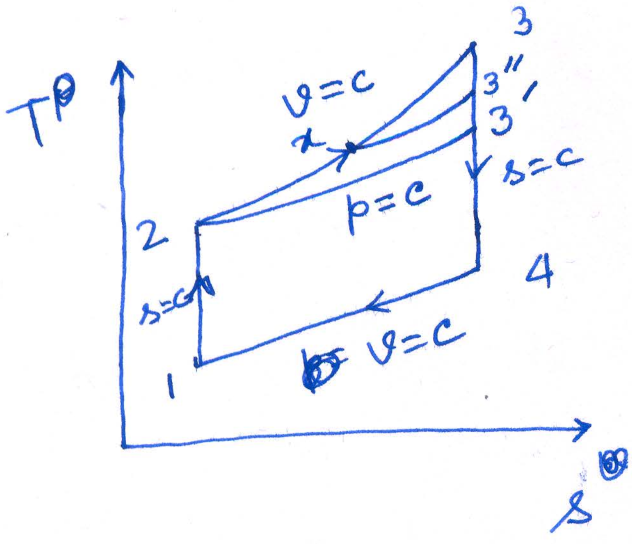
r_c = same

same heat rejection

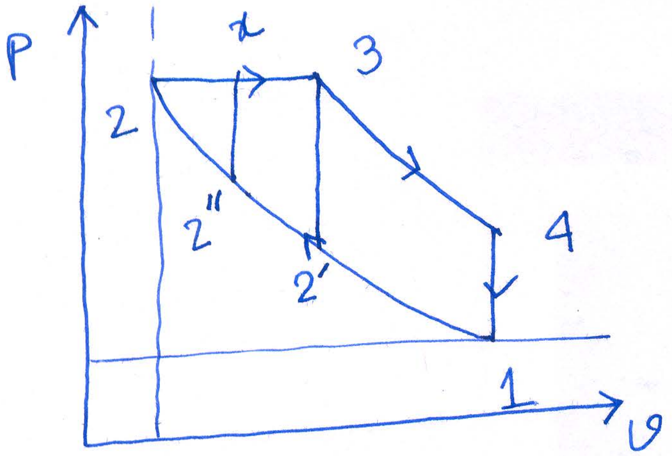
1-2-3-4-1 SI

1-2-3'-4-1 CI

$$\eta_{SI} > \eta_{Dual} > \eta_{CI}$$



Same Peak pressure
Same heat rejection



1-2-3-4-1 Diesel Cycle
1-2'-3-4-1 Otto (SI) "
1-2''-x-3-1 Dual "

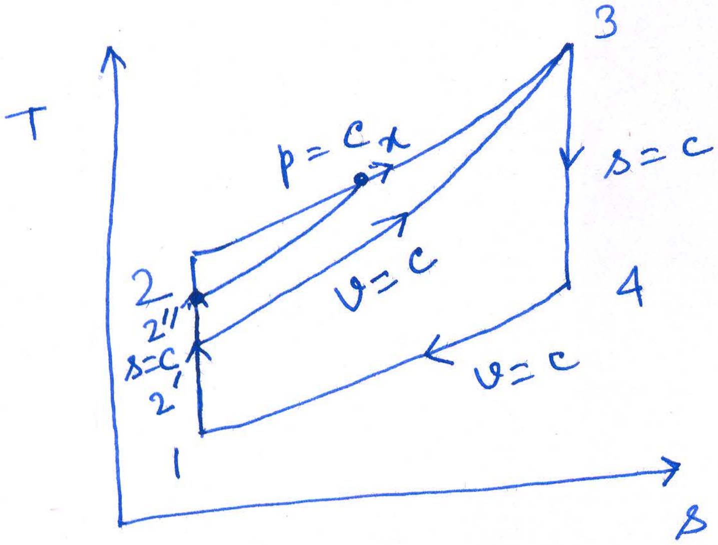


Table 1 page 42 Pulkabrek

First column.

$B = 2.00$

$S = 2.04$

$$\bar{U}_p = 2S\frac{N}{60}$$

$$= 2 \times \frac{2.04}{100} \times \frac{13000}{60}\ \frac{m}{s}$$

$$= \underline{\underline{8.84\ m/s}}.$$

---

3. A four-cylinder 2.4L engine operates on a four-stroke cycle at 3200 ~~rpm~~ RPM. The compression ratio is 9.4:1, the connecting rod length $r = 18$ cm, and the bore and stroke are related as $S = 1.06B$. At this speed, combustion ends at 20° aTDC.

Calculate:

(a) clearance volume ~~on~~ of one cylinder in cm^3.

(b) Bore and stroke in cm.

(c) Average piston speed in m/s.

(d) Piston speed at end of combustion.

(e) distance the piston has travelled from TDC at the end of combustion.

(f) volume in the combustion chamber at the end of combustion.

Ans: Displacement Volume of each cylinder $= \frac{2.4}{4} L = 0.6L$

$$\therefore \frac{\pi}{4}B^2S = \frac{\pi}{4}B^2 \times 1.06B = 0.6\times10^3\ cm^3$$

$$B^3 = \frac{0.6\times10^3\times4}{\pi\times1.06} = 720.7\ cm^3$$

$$\therefore B = 8.96\ cm. \quad \therefore S = 9.5\ cm.$$

r_c = compression ratio $= \frac{V_d+V_c}{V_c}$ where V_d = displacement volume, V_c = clearance volume.

$$9.4 = \frac{0.6\times10^3}{V_c} + 1$$

or, $\frac{0.6\times10^3}{V_c} = 9.4 - 1 = 8.4$,

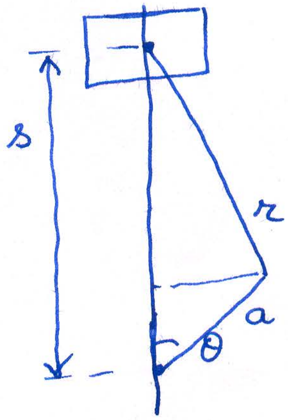
or. $V_c = \frac{0.6\times10^3}{8.4} = 71.4\ cm^3$

②

Average piston speed $= \frac{2SN}{60}$ where $S =$ stroke length, $N =$ RPM

$= \frac{2 \times 9.5 \times 10^{-2} \times 3200}{60}$ m/s

$= \cancel{1.01 \text{ m/s}}$ 10.1 m/s



$s = a\cos\theta + \sqrt{r^2 - a^2\sin^2\theta}$

$= a\left[\cos\theta + \sqrt{R^2 - \sin^2\theta}\right]$ where $R = \frac{r}{a}$.

$U_p =$ Piston speed $= \cancel{d\theta}\ \frac{ds}{dt}$

$U_p = \frac{ds}{dt} = a\left[-\sin\theta - \frac{1}{\cancel{2}} \cdot \frac{1}{\sqrt{R^2 - \sin^2\theta}} \cdot \cancel{2}\sin\theta\cos\theta\right]\frac{d\theta}{dt}$

$= \cancel{(-a\sin\theta)\omega}$

$= -a\omega\sin\theta\left[1 + \frac{\cos\theta}{\sqrt{R^2 - \sin^2\theta}}\right]$

$\bar{U}_p = \frac{2SN}{60} = \frac{S}{\pi} \cdot \frac{2\pi N}{60} = \frac{S\omega}{\pi} = \frac{2a\omega}{\pi}$

$R = \frac{r}{a} = \frac{r}{\frac{S}{2}} = \frac{2r}{S} = \frac{2 \times 18}{9.5} = 3.79$

$\therefore \frac{U_p}{\bar{U}_p} = \frac{-\cancel{a}\cancel{\omega}\sin\theta \times \pi\left[1 + \frac{\cos\theta}{\sqrt{R^2 - \sin^2\theta}}\right]}{2\cancel{a}\cancel{\omega}}$

$= -\frac{\pi}{2}\sin\theta\left[1 + \frac{\cos\theta}{\sqrt{R^2 - \sin^2\theta}}\right]$

$= -\frac{\pi}{2} \times \sin 20 \times \left[1 + \frac{\cos 20}{\sqrt{3.79^2 - \sin^2 20}}\right]$

$= -\frac{\pi}{2} \times 0.342 \times 9.249$

$= \cancel{0.134}$ 0.671 Taking absolute value.

$\therefore U_p = \cancel{1.35 \text{ m/s}}$ 6.78 m/s

$s = \cancel{R + a}\ a\left[\cos\theta + \sqrt{R^2 - \sin^2\theta}\right]$

$= \frac{9.5}{2}\left[\cos 20 + \sqrt{3.79^2 - \sin^2 20}\right]$

$= 22.39$ cm

$x = R + a - s = 18 + \frac{9.5}{2} - 22.39 = 0.36$ cm.

Volume in the combustion chamber

$$= V_c + \frac{\pi}{4} B^2 . x$$

$$= 71.4 + \frac{\pi}{4} \times 8.96^2 \times 0.36 \text{ cm}^3$$

$$= 94 \text{ cm}^3$$

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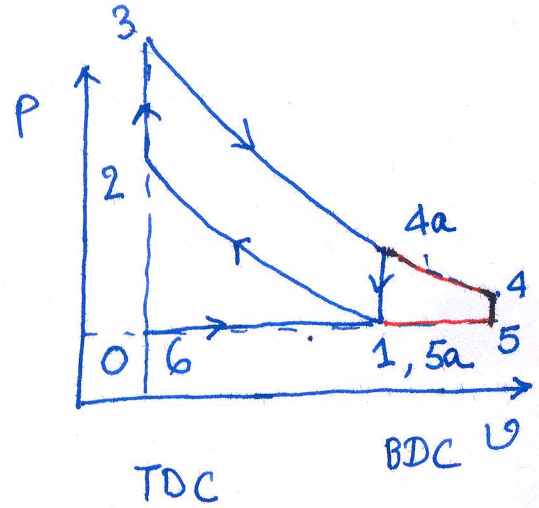


0-1

1-2

3-4a → 3-4

~~4-5~~

5-6

2-3

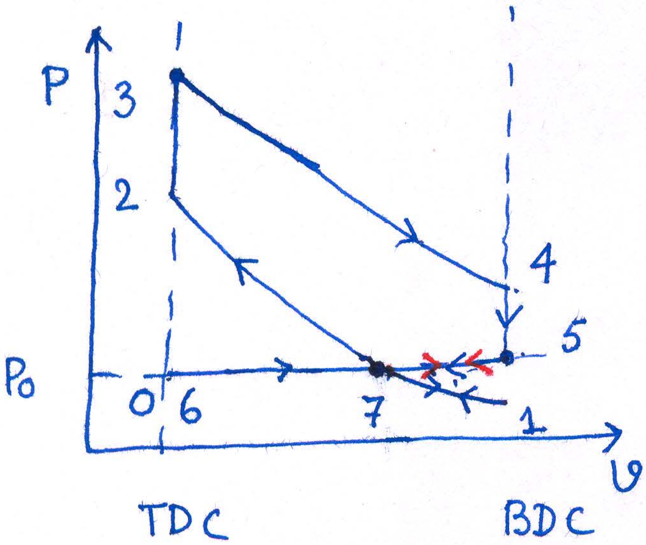
4-5 Exhaust Blow Down

Atkinson Cycle

Over expanded

${}_3W_4$ ✓

${}_1W_2$ ✓



$r_c = \frac{V_7}{V_2}$ $\qquad \frac{V_4}{V_3}$

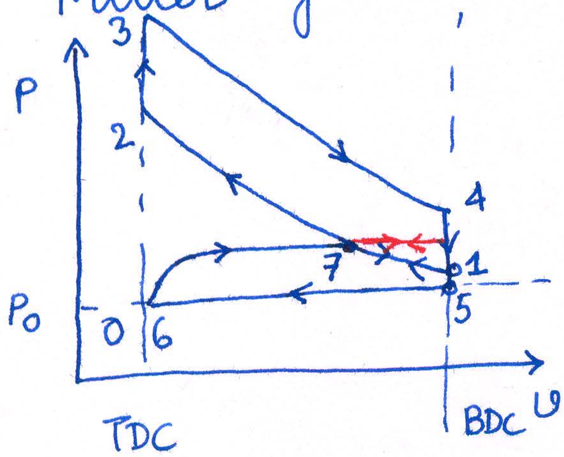
≈ 8 $\qquad \approx 10$

0-7-1-7-2-3-4-5-7-6

Unthrottled

ECS

Miller Cycle



0-7-1-7-2-3-4-5-6

${}_0W_7$

${}_7W_2$

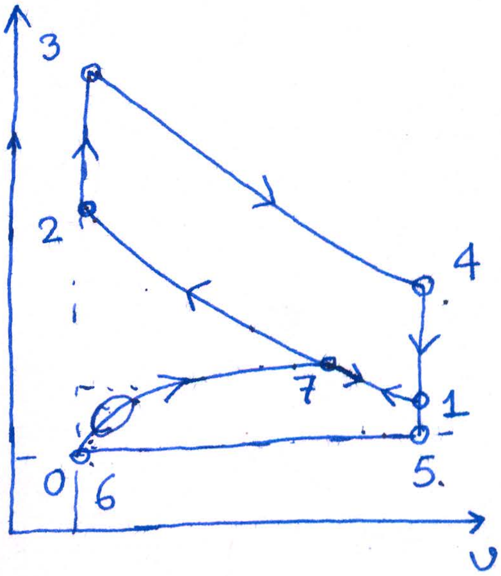
${}_3W_4$

${}_5W_6$

The four-cylinder, 2.5L SI automobile engine is to operate on an air-standard Miller Cycle with early valve closing. It has a compression ratio of 8:1 and an expansion ratio of 10:1. A supercharger is added that gives a cylinder pressure of 160 kPa when the intake valve closes. The temperature is 60°C at this point. The AF ratio is 15 with combustion efficiency $\eta_c = 100\%$. Fuel is isooctane with $Q_{cv} = 44300$ kJ/kg. Exhaust residual is 4% and atmospheric pressure 100 kPa. $\gamma = 1.35$ $R = 0.287$ kJ/kgK.

Calculate:

1. Temperature and pressure at all points in the cycle.
2. Indicated thermal efficiency.
3. " mep.
4. Exhaust temperature.



$\frac{V_7}{V_2} = 8$; $\frac{V_1}{V_2} = 10$

$V_s = \frac{2.5}{4} L = 0.625 L$

$V_7 = 8 \times V_2$

$= 8 \times 0.069 L$

$= 0.552 L$

$\frac{V_s + V_2}{V_2} = 10$

$\frac{V_s}{V_2} + 1 = 10$

$\frac{V_s}{V_2} = 9 \Rightarrow V_2 = \frac{V_s}{9} = \frac{0.625}{9} L = 0.069 L$

$P_7 V_7 = m_m R T_7$

$P_7 = 160$ kPa

$V_7 = 0.552 \times 10^{-3}$ m^3

$T_7 = 60 + 273 = 333$ K

$R = 0.287$ kJ/kg-K

$160 \times 0.552 \times 10^{-3} = m_m \times 0.287 \times 333$

$m_m = 9.24 \times 10^{-4}$ kg

$$\frac{T_2}{T_7} = \left(\frac{V_7}{V_2}\right)^{\gamma-1} = 8^{1.35-1} = 2.07$$

$T_2 = 689.3\,K$

$$\frac{P_2}{P_7} = \left(\frac{V_7}{V_2}\right)^{\gamma} = 8^{1.35} = 16.56$$

$P_2 = 160 \times 16.56 = 2649.6$ kPa.

Procen 2-3 $\quad m_f \times Q_{cv} = m_m \times c_v \times (T_3 - T_2)$

$m_m = m_a + m_f + m_{ex} = 9.24 \times 10^{-4}$

$m_a + m_f = 0.96 \times 9.24 \times 10^{-4}$

$m_f\left(\frac{m_a}{m_f} + 1\right) = 0.96 \times 9.24 \times 10^{-4}$

$m_f\,(15+1) = 0.96 \times 9.24 \times 10^{-4}$

$m_f = 5.544 \times 10^{-5}$ kg

$Q_{in} = 5.544 \times 10^{-5} \times 44300$ kJ

$= 2.456$ kJ

$c_v = \frac{R}{\gamma - 1} = \frac{0.287}{0.35}$

$= 0.82$

$2.456 = 9.24 \times 10^{-4} \times 0.82 \times (T_3 - 689.3)$

$T_3 - 689.3 = \frac{2658}{0.82} = 3241.5$

$T_3 = \cancel{3347.3\,K}.\ 3930.8\,K$

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} = \frac{3930.8}{689.3} = 5.70$$

$P_3 = 15102.7$ kPa

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{1}{10}\right)^{0.35} = 0.447$$

$T_4 = 3930.8 \times 0.447 = 1757\,K$

$$\frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^{\gamma} = \left(\frac{1}{10}\right)^{1.35} = 0.0447$$

$P_4 = 675$ kPa

$$\frac{T_5}{T_4} = \frac{P_5}{P_4} = \frac{100}{675}$$

$T_5 = 260.3\,K$

$\underline{\underline{-13^{\circ}C}}$

An SI engine operates on an air-standard four-stroke Miller cycle with turbocharging. The intake valve closes late, resulting in cycle 6-7-8-7-2-3-4-5-6. Air-fuel enters the cylinders at 70°c and 140 kPa and heat in combustion equals $q_{in} = 1800$ kJ/kg. Compression ratio $r_c = 8$, expansion ratio $r_e = 10$, and exhaust pressure $P_{ex} = 100$ kPa.

Calculate:

(a) Temperature at each state of the cycle. [K]

(b) Pressure . . . . [kPa]

(c) Work produced during expansion stroke. [kJ/kg]

(d) Work of compression stroke. [kJ/kg]

(e) Net pumping work. [kJ/kg]

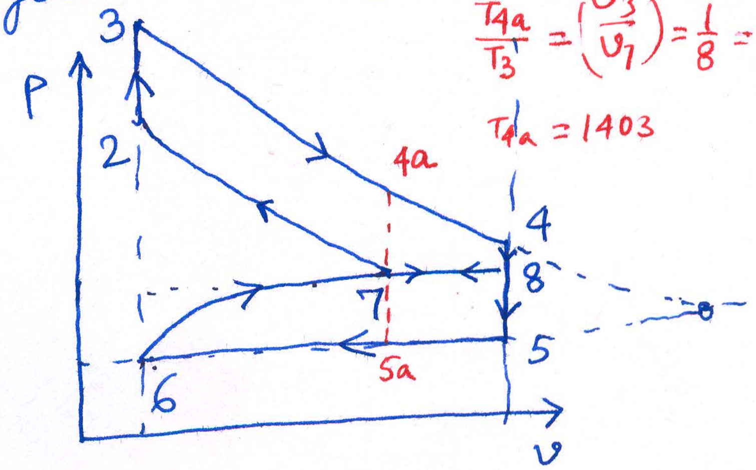
(f) Indicated thermal efficiency. [%]

(g) Compare with SI cycle with $r_c = 8$.

$$\frac{T_{4a}}{T_3} = \left(\frac{v_3}{v_7}\right)^{\gamma-1} = \frac{1}{8}^{1.35-1} = 0.483$$

$$T_{4a} = 1403$$

$\gamma = 1.35$, $R = 0.287$ kJ/kg-K



$$\frac{T_2}{T_7} = \left(\frac{v_7}{v_2}\right)^{\gamma-1}, \quad \frac{P_2}{P_7} = \left(\frac{v_7}{v_2}\right)^{\gamma}$$

$$\frac{T_2}{T_7} = \left(\frac{P_2}{P_7}\right)^{\frac{\gamma-1}{\gamma}}$$

K Kelvin

k kilo

$T_7 = 70 + 273 = 343$ K

$$\frac{T_2}{T_7} = \left(\frac{v_7}{v_2}\right)^{\gamma-1} = 8^{1.35-1} = 2.07 \Rightarrow T_2 = 710\text{K}$$

$$\frac{P_2}{P_7} = \left(\frac{v_7}{v_2}\right)^{\gamma} = 8^{1.35} = 16.56 \Rightarrow P_2 = 140 \times 16.56 = 2318.4 \text{ kPa}$$

$$q_{in} = c_v(T_3 - T_2) \Rightarrow 1800 = 0.82(T_3 - 710) \Rightarrow T_3 = 2905\text{K}$$

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} \Rightarrow P_3 = 2318.4 \times \frac{2905}{710} = 9486 \text{ kPa}$$

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \left(\frac{1}{10}\right)^{1.35-1} = 0.447$$

$$T_4 = 2905 \times 0.447 = 1298 \text{ K}$$

$$\frac{P_4}{P_3} = \left(\frac{v_3}{v_4}\right)^{\gamma} = \left(\frac{1}{10}\right)^{1.35} = 0.0447$$

$$P_4 = 9486 \times 0.0447 = 424 \text{ kPa}$$

$$\frac{T_5}{T_4} = \frac{P_5}{P_4} = \frac{100}{424} = 0.236$$

$$T_5 = 1298 \times 0.236 = 306 \text{ K}$$

$$\frac{T_{ex}}{T_4} = \left(\frac{P_{ex}}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{100}{424}\right)^{\frac{1.35-1}{1.35}} = 0.688$$

$$T_{ex} = 1298 \times 0.688 = 893 \text{ K}$$

$\cancel{P_7 v_7}$ $P_7 v_7 = RT_7$

$$v_7 = \cancel{\frac{P_7}{RT_7} = \frac{140}{0.287 \times 343}}$$

$$= \frac{RT_7}{P_7} = \frac{0.287 \times 343}{140}$$

$$= 0.703 \text{ m}^3/\text{kg}.$$

$$r_c = \frac{v_7}{v_2}$$

$${}_3w_4 = c_v(T_3 - T_4) = 0.82(2905-1403) = 1232$$

$$\cancel{{}_1q_2} - {}_1w_2 = {}_1u_2$$

$$= 0.82(2905-1298) \text{ kJ/kg}$$

$$-{}_1w_2 = u_2 - u_1$$

$${}_1w_2 = u_1 - u_2$$

$$= 1318 \text{ kJ/kg}$$

$${}_7w_2 = c_v(T_7 - T_2)$$

$$= 0.82(343-710) \text{ kJ/kg}$$

$$= -301 \text{ kJ/kg}$$

$$\frac{v_7}{v_2} = 8$$

$$v_2 = \frac{v_7}{8}$$

$$= \frac{0.703}{8} \text{ m}^3/\text{kg}$$

$$= 0.088 \text{ m}^3/\text{kg}$$

$${}_6w_7 = P_7(v_7 - v_6) \text{ kJ/kg}$$

$$= 140(0.703 - 0.088) = 86.1 \text{ kJ/kg}$$

$${}_5w_6 = P_{ex}(v_6 - v_5)$$

$$= 100\,(0.088 - 0.703)\ \text{kJ/kg}$$

0.88

$100\,(0.088 - 0.703) = -61.5$

$$= -79.2\ \text{kJ/kg}$$

$$\frac{v_5}{v_6} = 10$$

$$v_5 = 10\,v_6$$

$$= 0.88$$

$$\text{Net work} = {}_3w_4 + {}_7w_2 + {}_6w_7 + \cancel{{}_5w_6} + {}_5w_6$$

$$= 1318 - 301 + 86.1 - 79.2$$

$1232 - 301 + 86.1 - 61.5$

$$= 1024\ \text{kJ/kg}$$ $= 955.6$

$$\eta_{ith} = \frac{1024}{1800} \times 100\,\%$$

$$= 56.9\,\%$$ 53.1%

An SI engine operates on an air-standard four-stroke Otto cycle with turbocharging. Air-fuel enters the cylinders at 70°C and 140 kPa and heat in ~~by~~ by combustion equals $q_{in} = 1800$ kJ/kg. Take $r_c = 8$ and $P_{ex} = 100$ kPa.

Find out η_{ith} ?=

7/3/17 2

isooctane C_8H_{18} C_8H_{18}

AF ratio.

C	12
H	1
O_2	32
Air	28.97

$3.76 \times 12.5\ N_2$

$C_8H_{18} + \lambda\ 12.5\ O_2 \rightarrow 8CO_2 + 9H_2O + 3.76 \times 12.5\ N_2$

$\frac{79}{21} \simeq 3.76$

$C_8H_{18} = 8 \times 12 + 18 \times 1 = 114$

$3.76 \times 28 + 32 = 137.28$

$3.76 \times 28.01 + 32.02 = \frac{137.33}{4.76} \rightarrow 28.85$

$$\frac{12.5 \times 28.9 \times 4.76}{114} = 15.08 \approx 15.1$$

$C_8H_{18} + 12.5 \times 4.76 \times$

$C_8H_{18} + 12.5 \times (3.76N_2 + O_2) \rightarrow 8CO_2 + 9H_2O + 47\ N_2$

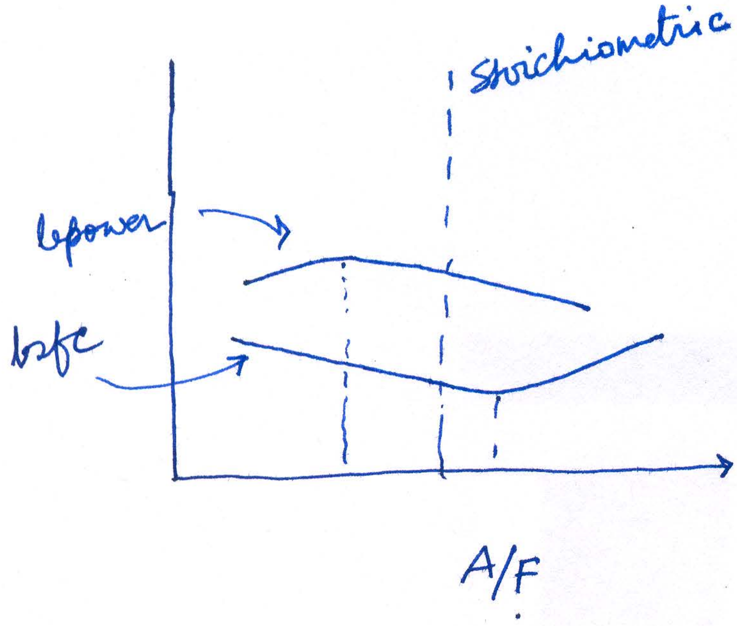
20% excess air

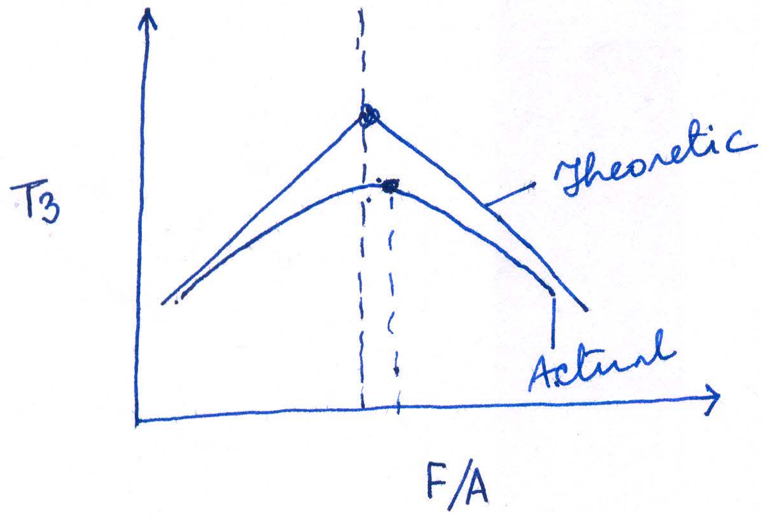
AFT EGR Exhaust Gas Recirculation. $+47N_2 \times$ $\uparrow \times 12.5$

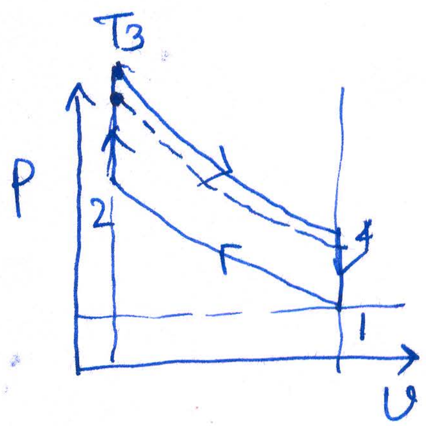
$\phi = ?$

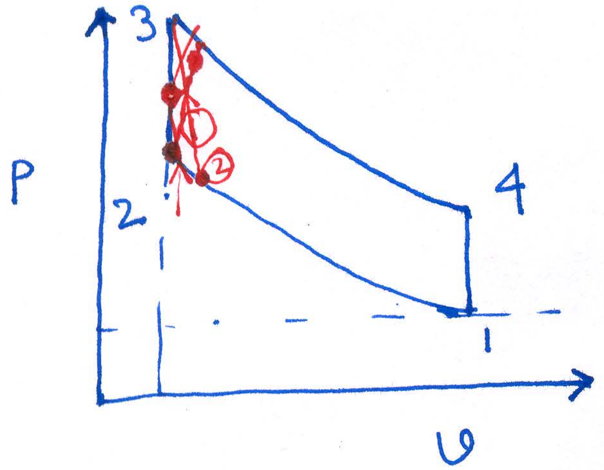
$C_8H_{18} + \cancel{1.2} \times 12.5 \times (3.76N_2 + O_2) \rightarrow 8CO_2 + 9H_2O + 0.2\lambda(3.76N_2 + O_2)$

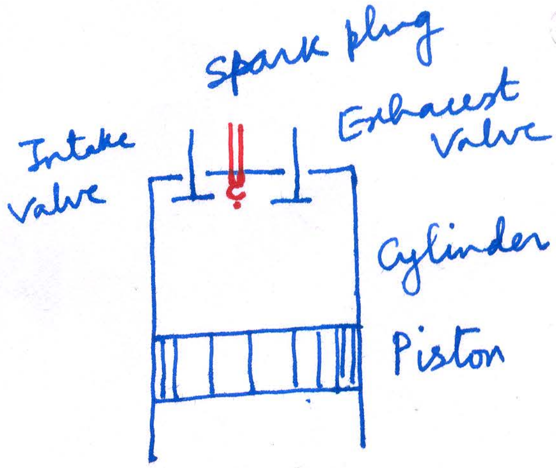
$\phi = (FA)_{act} / (FA)_{stoichiometric} = \frac{1}{1.2}$


Stoichiometric
bpower
bsfc
A/F


T3
Theoretic
Actual
F/A

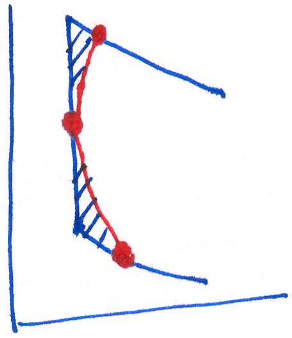

T3
P
2
4
1
V

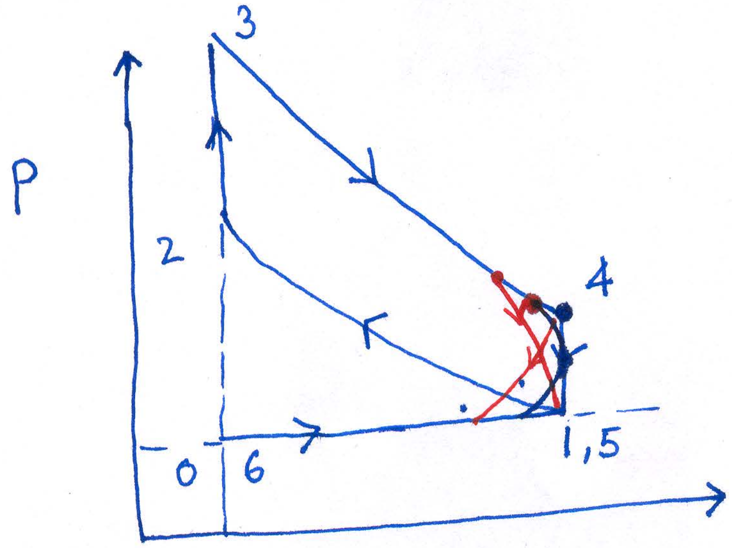




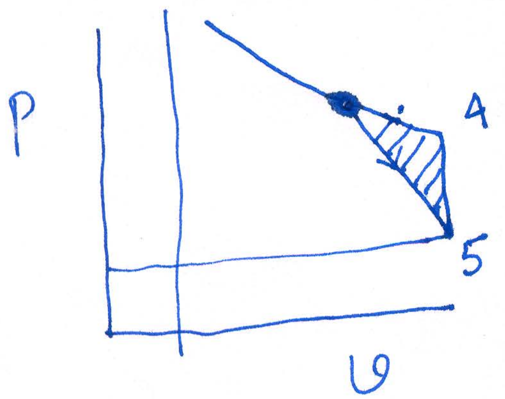
Rate of pressure rise $\frac{dp}{dt}$ or $\frac{dp}{d\theta}$

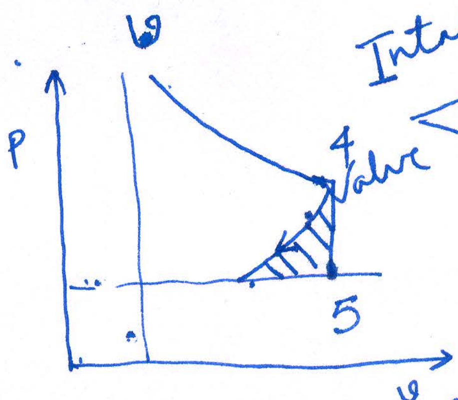
1. Spark initiated at TDC
2. Spark initiated before TDC

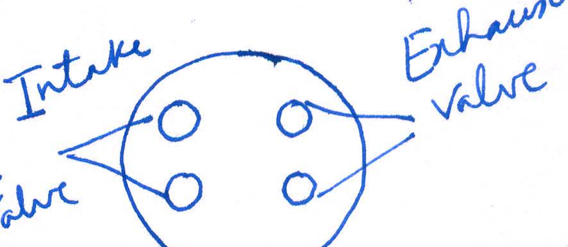


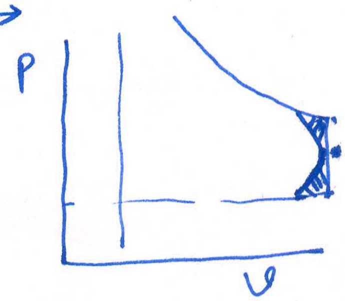


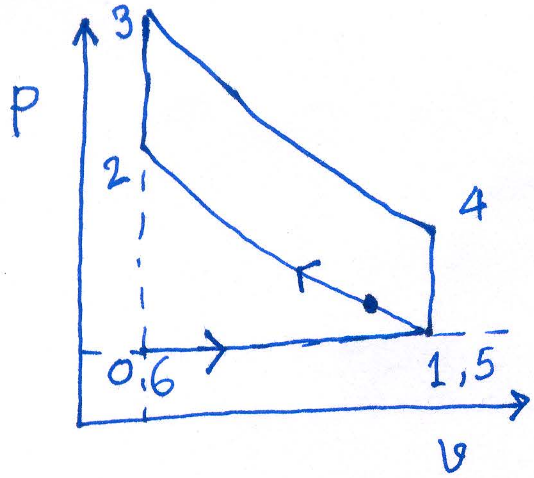
6-1-2-3-4-5-6

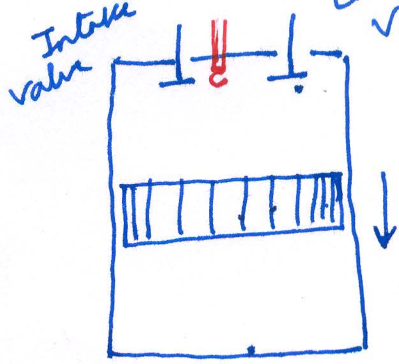






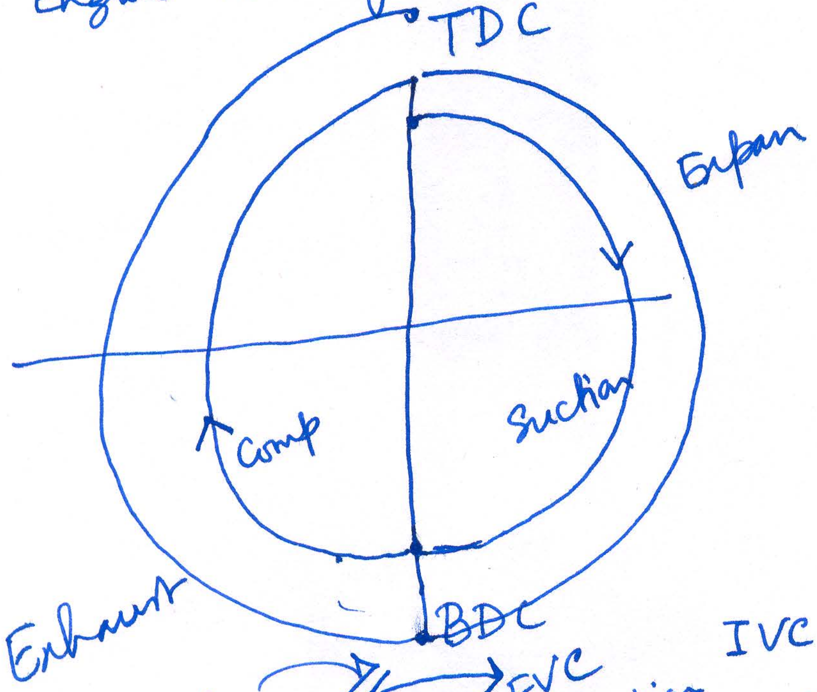


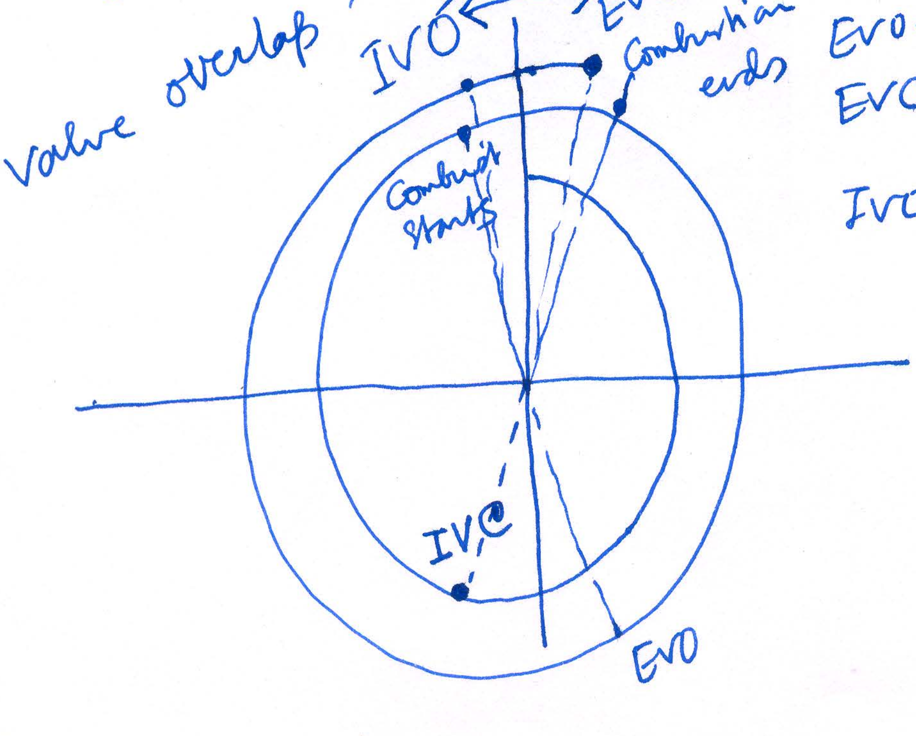




Ram effect

Engine timing





IVC - Intake valve closes

EVO - Exhaust valve opening

EVC - Exhaust valve closes

IVO - Intake valve opens

C_4H_8 is burned in an engine with a fuel-rich air-fuel ratio. Dry analysis of the exhaust gives the volume percents: $CO_2 = 14.95\%$, $C_4H_8 = 0.75\%$, $CO = 0\%$, $H_2 = 0\%$, $O_2 = 0\%$ with the rest being N_2. Higher heating value of this fuel is $Q_{HHV} = 46.9\ MJ/kg$. Write the balanced chemical equation for one mole of this fuel at these conditions:

Calculate: (a) Air-fuel ratio, (b) Equivalence ratio.

$$\frac{17.95}{4} x C_4H_8 + 22.42(O_2 + 3.76N_2) \rightarrow 14.95\, CO_2 + 0.75\, C_4H_8 + 84.3\, N_2 + y\, H_2O$$

4.49   14.96

$$\frac{84.3}{3.76} = 22.42$$

$$14.95 + 0.75 \times 4$$
$$= 17.95$$

$$4.49 \times 8 = 0.75 \times 8 + 2y \qquad y \Rightarrow$$

$$y = 14.96$$

$$C_4H_8 + 5(O_2 + 3.76N_2) \rightarrow 3.33\, CO_2 + 0.167\, C_4H_8 + 18.77\, N_2 + 3.33\, H_2O$$

Air = 28.97 kg/kmole

$$AF = \frac{5 \times 4.76 \times 28.97}{4 \times 12 + 8 \times 1}$$

$$= 12.3$$

$$C_4H_8 + 6(O_2 + 3.76N_2) \rightarrow 4CO_2 + 4H_2O + 22.56\, N_2$$

$$\frac{6}{\phi}$$

$$\phi = \frac{(FA)_{act}}{(FA)_{stoic}} = \frac{(AF)_{stoi}}{(AF)_{act}} = \frac{6 \times 3.76 \times \cdots}{5 \times 3.76 \times \cdots}$$

$$= 1.2$$

21/3/17 (1)

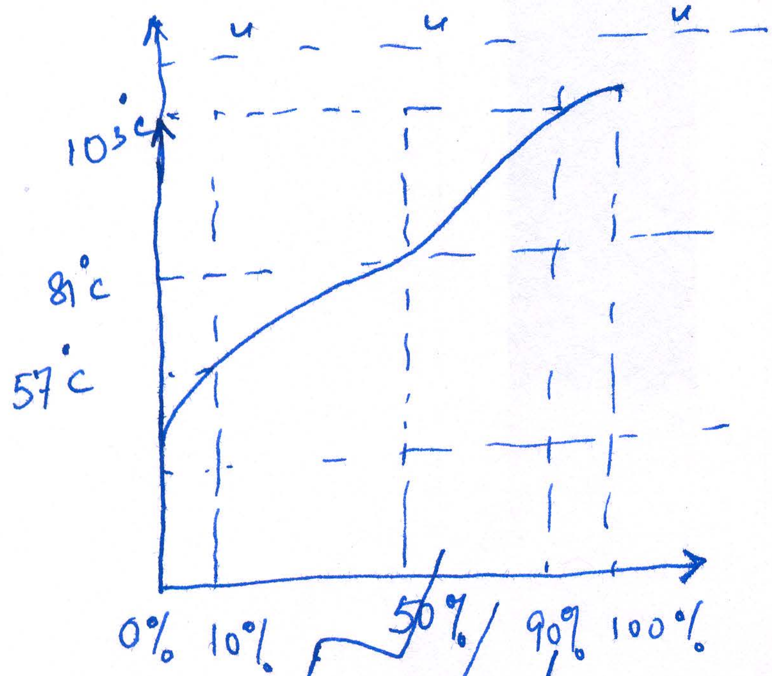
$$\text{Volumetric effy} = \frac{\dot{m}_a}{\rho_a V_d \times \frac{N}{60} \times \frac{1}{2}}$$

$\dot{m}_a$ air + fuel vapour well mixed

some amount of fuel evaporated i.e

" " should get evaporated

" " " be in liquid



57 - 81 - 103

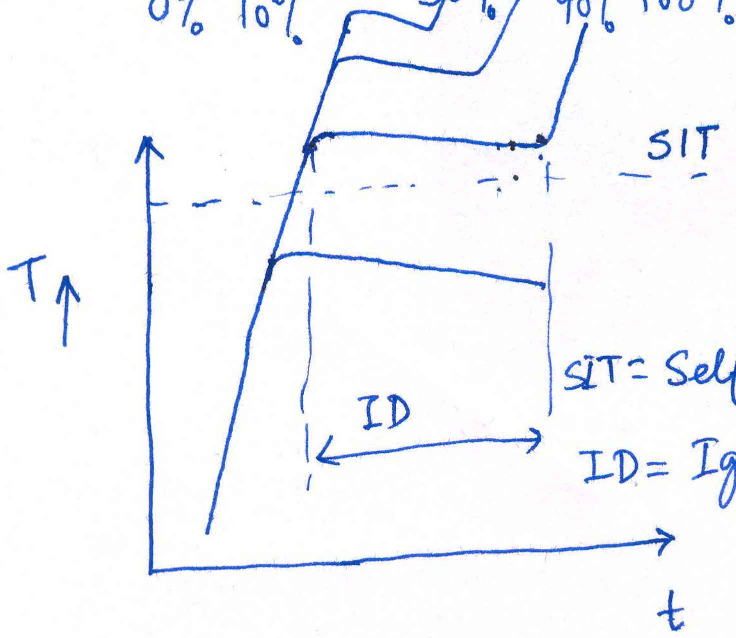
$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = 8^{1.35-1} = 2.07$$

$T_1 = 60 + 273 = 333$

$T_2 = 689\ K$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = 18^{1.35-1} = 2.75$$

$T_2 = 916\ K$

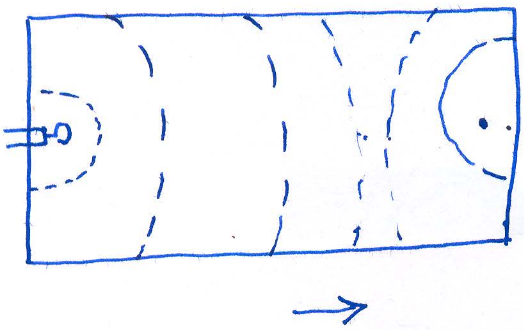


SIT = Self ignition temperature

ID = Ignition delay

$$\frac{A}{V} \sim \frac{4\pi r^2}{\frac{4}{3}\pi r^3} \sim \frac{1}{r}$$

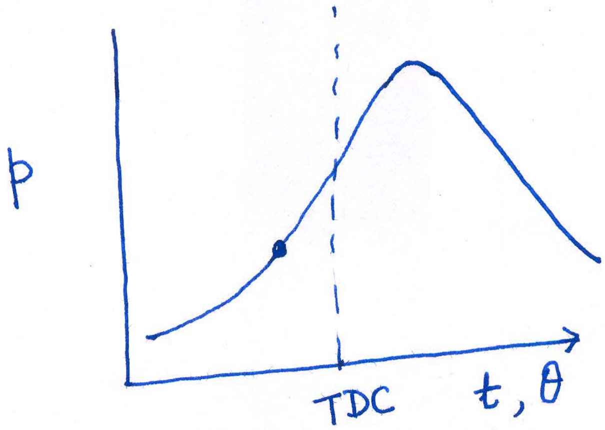
SI engine 21/3/17 2



Flame front

temperature > SIT

Knocking → SI detonation → CI



A four cylinder SI engine with a compression ratio $r_c = 10$ operates on an air-standard Otto cycle at 3000 RPM using ethyl alcohol as fuel. At the start of the compression, temperature and pressure are 60°c and 101 kPa. Combustion efficiency $\eta_c = 97\%$. Write the balanced stoichiometric chemical equation for this fuel. $Q_{HV} = 26950$ kJ/kg.

Calculate:

(a) AF if $\varphi = 1.1$ $\underline{\underline{8.18}}$ C_2H_5OH

(b) Peak temperature [°C] 4218 K $\underline{3945°C}$

(c) Peak pressure. [kPa] 12777 kPa.

$$C_2H_5OH + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 11.28N_2$$

$$(AF)_{Stoich} = \frac{3 \times 4.76 \times 28.97}{2 \times 12 + 6 \times 1 + 16} = 9$$

$$(AF)_{act} = \frac{(AF)_{stoich}}{\varphi} = \frac{9}{1.1} = 8.18$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = (r_c)^{1.35-1} = 10^{0.35} = 2.24$$

$$C_v = \frac{R}{\gamma - 1} = \frac{0.287}{0.35} = 0.82$$

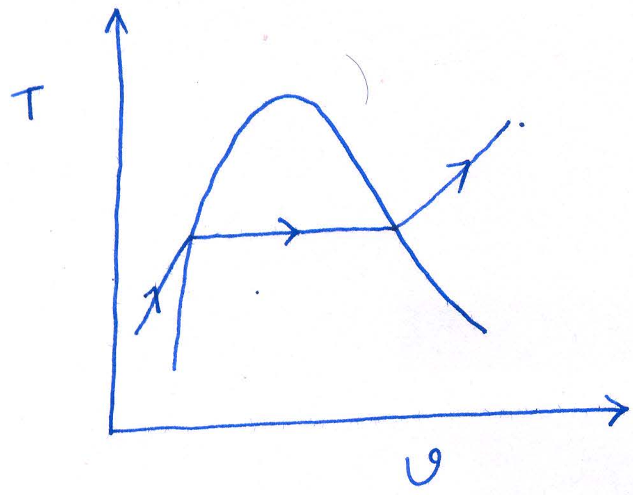
$T_1 = 273 + 60 = 333$

$T_2 = 746$ K

$$m_f \times Q_{HV} \times \eta_c = (m_a + m_f) C_v (T_3 - T_2)$$

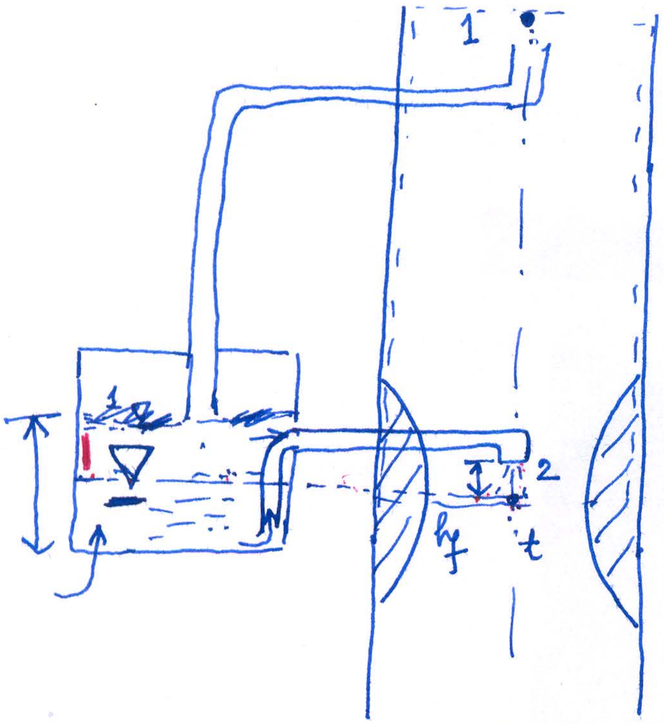
$$Q_{HV} \times \eta_c = (AF + 1) C_v (T_3 - T_2) \quad T_3 =$$

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{\gamma}$$



Air $\frac{PV}{P_{atm}}$

↓ air



1 - up in barrel

t - throat minimum c-s

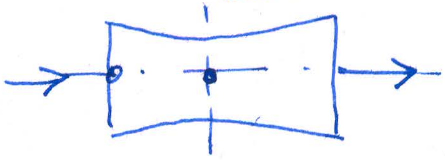
$$\cancel{\dot{Q}} - \cancel{\dot{W}} = \dot{m}\left(h+\frac{V^2}{2}+gz\right)_t - \dot{m}\left(h+\frac{V^2}{2}+gz\right)_1$$

$$h_t + \frac{V_t^2}{2} = h_1 + \frac{V_1^2}{2}$$

$$\frac{V_t^2}{2} = (h_1 - h_t) = c_p(T_1 - T_t)$$

$$V_t = \sqrt{2c_p(T_1 - T_t)}$$

$$c_p = \frac{\gamma R}{\gamma - 1}$$



$$V_t = \sqrt{\frac{2\gamma R T_1}{\gamma-1}\left(1-\frac{T_t}{T_1}\right)}$$

$$= \sqrt{\frac{2\gamma R T_0}{\gamma-1}\left(1-\frac{T_t}{T_0}\right)}$$

T

$$c_p T_0 = c_p T + \frac{V^2}{2}$$

0 → total or stagnation

$$T_0 = T + \frac{V^2}{2c_p}$$

$$\frac{T_0}{T} = 1 + \frac{V^2}{\frac{2\gamma R}{\gamma-1}T} \qquad \gamma R T = a^2 \qquad a = \sqrt{\gamma R T}$$

$$= 1 + \left(\frac{\gamma-1}{2}\right)\frac{V^2}{\gamma R T}$$

$$= 1 + \left(\frac{\gamma-1}{2}\right)M^2 \qquad M = \frac{V}{a}$$

= Mach number

$$= 1 + \frac{\gamma-1}{2}$$

$$= \frac{\gamma+1}{2} = \frac{1.4+1}{2} = \frac{2.4}{2} = 1.2$$

$$\frac{T_0}{T} = \left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{P_1}{P_t}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\dot{m}_a = C_{Dt}\,\rho_t\,A_t\,V_t \qquad \rho$$

$$= C_{Dt}\cdot\frac{P_t}{RT_t}\cdot A_t\cdot V_t$$

$$= C_{Dt}\cdot\frac{P_0\left(\frac{P_t}{P_0}\right)}{RT_0\left(\frac{T_t}{T_0}\right)}\cdot A_t\cdot V_t$$

$$= C_{Dt}\cdot\left(\frac{P_t}{P_0}\right)^{\frac{1}{\gamma}}\cdot\frac{A_t P_0}{\sqrt{RT_0}}\cdot\sqrt{\frac{2\gamma}{\gamma-1}\left(1-\frac{T_t}{T_0}\right)}$$

1 → 0 stagnation condition because velocity is zero.

28/3/17 (2)

For fuel

$$\frac{p_1}{\rho} + \cancel{\frac{v_1^2}{2}} + gz_1 = \frac{p_2}{\rho} + \frac{V_2^2}{2} + gz_2$$

$$\frac{V_2^2}{2} = \frac{p_1 - p_2}{\rho} - gh_f$$

$$= \frac{(p_1 - p_2) - \rho g h_f}{\rho}$$

$$V_2 = \sqrt{\frac{2\left[(p_1 - p_2) - \rho g h_f\right]}{\rho}}$$

ρ = density of fuel.

$p_2 = p_t$

$p_1 = p_0$

$$\boxed{\dot{m}_f = C_{Dc} \rho_f A_f V_2} \leftarrow$$

$$\dot{m}_f = C_{Dc} \rho_f A_c V_c$$

$\rho_f \Downarrow \rho$, $V_c \Downarrow V_2$

$c \rightarrow$ capillary

$C_{Dc} \rightarrow$ Discharge coefficient of capillary

$$= C_{Dc} \cdot \rho_f \cdot A_c \cdot \sqrt{\frac{2p_1}{\rho}\left(1 - \frac{p_2}{p_1} - \frac{\rho_f g h_f}{p_1}\right)}$$

$C_{Dt} \rightarrow$ Discharge coefficient of throat

$A_c = \leftarrow$

28/3/17 (3)

$$V_t = \sqrt{\frac{2 \times 1.4 \times 287 \times 300}{1.4-1}\left(1-\frac{1}{1.2}\right)}$$

$$= 317\ m/s$$

$$0.194 = 0.94\ \frac{101 \times 10^3 \times \cancel{1.89}\,(1/1.89)}{287 \times 300 \times 0.833}\ A_t \cdot 317$$

$$= \cancel{0.658}\ 0.7 \times 317\ A_t$$

$$\frac{T_0}{T_t} = \left(\frac{P_0}{P_t}\right)^{\frac{\gamma-1}{\gamma}}$$

$$1.2 = \left(\frac{P_0}{P_t}\right)^{\frac{1.4-1}{1.4}}$$

$$\frac{P_0}{P_t} = (1.2)^{\frac{1.4}{.4}}$$

$$= 1.89$$

$$A_t = \frac{0.194}{0.7 \times 317} = 8.7 \times 10^{-4}\ m^2$$

Each barrel throat area $= \frac{8.7 \times 10^{-4}}{2}\ m^2$

$$= 4.37 \times 10^{-4}\ m^2$$

diameter of throat d_t

$$\frac{\pi}{4} d_t^2 = 4.37 \times 10^{-4}$$

$$d_t = \frac{4.37 \times 10^{-4} \times 4}{\pi}$$

$$= 0.0236\ m$$

$$= 2.36\ cm$$

$d_c = 1.14\ mm$

Lecture 14/3/17. continuation

(c) Lower heating value (LHV) of fuel. [MJ/kg]

(d) Energy released when one kg of this fuel is burned in the engine with a combustion efficiency of 98%

$$C_4H_8 + 6(O_2 + 3.76N_2) \rightarrow 4CO_2 + 4H_2O + 22.56N_2$$

$Q_{LHV} = Q_{HHV} - \Delta h_{vap}$; $Q_{HHV} = 46.9$ MJ/kg of fuel

$\Delta h_{vap} = h_{fg} = 2442.3$ kJ/kg of water

1 kmole fuel --- 4 kmole of H_2O

$C_4H_8 = 4 \times 12 + 8 \times 1 = 56$ kg/kmole

56 kg --- --- $4 \times 18 = 72$ kg of water

$H_2O = 2 \times 1 + 16 = 18$ kg/kmole

1 .. --- $\frac{72}{56} = \frac{9}{7}$ kg of water

1 . - - $\frac{9}{7} \times 2442.3$ kJ $= 3.1$ MJ

$\therefore$ $Q_{LHV} = (46.9 - 3.1)$ MJ $= 43.8$ MJ/kg of fuel (c)

(d) Heat released

$Q_{in} = 1 \times 43.8 \times 0.98 = 42.9$ MJ~~/kg~~.

Ambient 25°c

C_8H_{18} isooctane 20% excess air.

$$C_8H_{18} + 1.2 \times 12.5 (O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 2.5O_2 + 56.4N_2$$

Paritial pressure of H_2O: Mole fraction $y = \dfrac{9}{8+9+2.5+56.4} = \dfrac{30}{253}$

Total pressure i.e. atmospheric pressure = 101 kPa.

$\therefore \quad P_{H_2O} = \dfrac{30}{253} \times 101 = 11.98$ kPa.

$T_{sat} = 49.1°c$

⇒ Inlet air with relative humidity 55%.

$$\varphi = 55\% = 0.55 = \frac{P_v}{P_g}$$

absolute humidity $\omega = \dfrac{m_v}{m_a}$

$$P_v V = m_v R_v T_m$$

$$P_a V = m_a R_a T_m$$

$$\frac{m_v}{m_a} \cdot \frac{R_v}{R_a} = \frac{P_v}{P_a}$$

$$\omega = \frac{P_v}{P_a} \cdot \frac{R_a}{R_v} = \frac{P_v}{P_a} \cdot \frac{R_u/M_a}{R_u/M_v}$$

$$= \frac{P_v}{P_a} \cdot \frac{M_v}{M_a}$$

$$= \frac{P_v}{P_a} \cdot \frac{18}{28.97}$$

$$= 0.622 \frac{P_v}{P - P_v}$$

$$= 0.622 \times \frac{1.74}{101 - 1.74}$$

$$= 0.0109$$

$m_v = 0.0109 \times 15 \times 4.76 \times 29$

$= 22.57$ kg

$N_v = 1.25$ mole

$P_{sat} @ 25°c = 3.17$ kPa

$$\varphi = 0.55 = \frac{P_v}{P_g} = \frac{P_v}{3.17}$$

$P_v = 1.74$ kPa

$$C_8H_{18} + 1.2 \times 12.5 (O_2 + 3.76N_2) \, \overset{1.25 H_2O}{\wedge} \rightarrow 8CO_2 + 9H_2O + 2.5O_2 + 56.4N_2 + 1.25H_2O$$

$$y_v = \frac{10.25}{8 + 10.25 + 2.5 + 56.4} = 0.133$$

$P_v = 13.42$ kPa.

$T_{sat} = 51.42°c$

Lecture 7/3/17 page 2

$$C_8H_{18} + 12.5 \times (O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 12.5 \times 3.76 N_2$$

Reactant 700K, Product at 1200K

$C_p = 1.7113$ kJ/kg-K. $= 195.1$ kJ/kmol.K

$\bar{h}_f^o$ $C_8H_{18} = -208450$ kJ/kmol. (g)

$$H_{react} = [-208450 + 195.1 \times (700-298)] + 12.5 \times [0 + 12499]$$

$$+ 12.5 \times 3.76 \times [0 + 11937]$$

$$= -130019.8 + 156237.5 + 561039$$

$$= 587256.7 \text{ kJ/}\cancel{\text{kmol}}$$

$$H_{Prod} = 8 \times [-393522 + \overset{44473}{\cancel{17754}}] + 9 \times [-241826 + \overset{34506}{\cancel{14140}}] + 12.5 \times 3.76 \times [0 + 28109]$$

$$= -3337149$$

$\therefore$ $Q_{in} = H_{Prod} - H_{react}$

$$= -3337149 - 587256.7$$

$$= -3924405.7 \text{ kJ/kmol of fuel}$$

P182

A taxicab is equipped with a flexible-fuel four-cylinder SI engine running on a mixture of methanol and gasoline at an equivalence ratio of 0.95. How the air-fuel ratio changes when fuel flow to the engine shifts from M10 (10% methanol) to M85 (85% methanol)?

10% Methanol 90% gasoline by mass

CH_3OH ~~C_8H_{18}~~ C_8H_{15}

32 kg/kmole 111 kg/kmole

Number of mole 3.125×10^{-3} 8.1×10^{-3}

Mole fraction 0.278 0.722

$$0.722\, C_8H_{15} + 0.278\, CH_3OH + 8.9005\,(O_2 + 3.76 N_2) \rightarrow 6.054\, CO_2 + 5.971\, H_2O + 8.9005 \times 3.76\, N_2$$

$$\text{Stoichiometric } A/F = \frac{8.9005 \times 4.76 \times 28.97}{0.722 \times 111 + 0.278 \times 32} = 13.78$$

A/F ratio with $0.95 = \phi$;

$$= \frac{13.78}{0.95}$$

$$= \underline{14.51}$$

M85 85% Methanol 15% gasoline

Number of mole $\frac{0.85}{32} = 0.0266$ 1.35×10^{-3}

mole fraction 0.952 0.048

$$0.952\, CH_3OH + 0.048\, C_8H_{15} + 1.992\,(O_2 + 3.76 N_2) \rightarrow 1.336\, CO_2 + 2.264\, H_2O + 1.992 \times 3.76\, N_2$$

$$\text{Stoichiometric } A/F = \frac{1.992 \times 4.76 \times 28.97}{0.952 \times 32 + 0.048 \times 111}$$

$$= 7.67$$

$$A/F \text{ ratio} = \frac{7.67}{0.95} = \underline{8.08}.$$

P205 Ex.

A 5.6-liter V8 engine with a compression ratio of 10.2:1 is equipped with cylinder ~~cut-out~~ cutout, which converts it to a 2.8 liter four-cylinder engine at low load requirements. The engine operates on an Otto cycle using gasoline, and with eight cylinders at 1800 RPM it has an AF = 14.9, a volumetric efficiency of 57%, a combustion efficiency of 91%, and a mechanical efficiency of 92%. If cylinder cutout occurs, the engine speeds up to produce the same brake power output. Using only four cylinders at this condition, the engine has an AF = 14.2, a volumetric efficiency of 66% and a combustion efficiency of 99%, but a mechanical efficiency of only 90%. ~~At~~ Ambient temperature 27°C, pressure ~~of~~ 101 kPa.

$Q_{HV} = 43\ MJ/kg$

Calculate:

1. percent reduction in fuel consumption operating on four cylinders to produce same brake power output.
2. Engine speed needed to produce same power output using only four cylinders.

Ans $r_c = 10.2$, $\eta_{ith} = 1 - \frac{1}{r_c^{\gamma-1}} = 1 - \frac{1}{10.2^{1.35-1}} = 0.556.$

$$\eta_v = \frac{\dot{m}_a}{\rho_a V_d \frac{N}{60} \cdot \frac{1}{2}} = \frac{\dot{m}_a}{1.17 \times 5.6\times10^{-3} \times \frac{1800}{60}\cdot\frac{1}{2}} = \frac{\dot{m}_a}{0.09828} \qquad \rho_a = \frac{P_a}{RT_a} = \frac{101}{0.287\times300} = 1.17\ kg/m^3$$

$\dot{m}_a = 0.57 \times 0.09828 = 0.056\ kg/sec.$

$\dot{m}_f = \frac{0.056}{AF} = \frac{0.056}{14.9} = 3.76\times10^{-3}\ kg/sec.$

$$W_b = \text{Brake power} = \eta_m \times \underbrace{\left(\dot{m}_f \times Q_{HV} \times \eta_c\right) \times \eta_{ith}}_{\text{indicated power}} = 0.92 \times (3.76\times10^{-3} \times 43000 \times 0.91) \times 0.556 = 75.26\ kW$$

After cutout, $\eta_m = 0.9$, $\eta_c = 0.99$, η_{ith} same.

same power, $75.26 = 0.9 \times (\dot{m}_f \times 43000 \times 0.99) \times 0.556$; $\dot{m}_f = 3.53\times10^{-3}\ kg/sec$

% reduction $= (3.53 - 3.76)\times10^{-3} / 3.76\times10^{-3} = \underline{-6.12\%}$

Engine speed: $\eta_v = \frac{\dot{m}_a}{\rho_a V_d \frac{N}{60}\cdot\frac{1}{2}} \Rightarrow N = \frac{\dot{m}_a}{\eta_v \cdot \rho_a V_d \cdot \frac{1}{60}\cdot\frac{1}{2}} = \frac{3.53\times10^{-3}\times14.2}{0.66\times1.17\times2.8\times10^{-3}\times\frac{1}{120}}$

$= \underline{2782\ RPM}$

A six-cylinder, 3.6-liter SI engine is designed to have a maximum speed of 6000 RPM. At this speed the volumetric efficiency of the engine is 0.92. The engine will be equipped with a two-barrel carburetor, one barrel for low speeds and both barrel for high speeds. Gasoline density can be considered to be 750 kg/m³. $T_a = 27°C$, $P_a = 101$ kPa. AF ratio = 15.2, $h_f = 1.5$ cm

Calculate:

$\gamma = 1.4$, $R = 287$ J/kgK

1. throat diameter for the carburetor ($C_{Dt} = 0.94$)
2. fuel capillary tube diameter ($C_{Dc} = 0.74$)

Ans: $\rho_a = \frac{P_a}{RT_a} = \frac{101}{0.287 \times 300} = 1.17$ kg/m³

$$\dot{m}_a = C_{Dt}\left(\frac{P_t}{P_0}\right)^{\frac{1}{\gamma}} \frac{A_t P_0}{\sqrt{RT_0}} \cdot \sqrt{\frac{2\gamma}{\gamma-1}\left(1-\frac{T_t}{T_0}\right)}$$

$T_0 = T_a$ = Ambient condition

$P_0 = P_a$ = " "

P_t = Pressure at throat

T_t = Temp at throat

$$\frac{T_0}{T_t} = \frac{\gamma+1}{2} = \frac{1.4+1}{2} = \frac{2.4}{2} = 1.2$$

$$\frac{P_0}{P_t} = \left(\frac{T_0}{T_t}\right)^{\frac{\gamma}{\gamma-1}} = 1.2^{\frac{1.4}{1.4-1}} = 1.893$$

$$\eta_v = 0.92 = \frac{\dot{m}_a}{\rho_a V_d \frac{N}{120}} \quad \therefore \dot{m}_a = 0.92 \times 1.17 \times 3.6 \times 10^{-3} \times \frac{6000}{120}$$

$$= 0.194 \text{ kg/sec}$$

$$0.194 = 0.94 \times \left(\frac{1}{1.893}\right)^{\frac{1}{1.4}} \times \frac{A_t \times 101 \times 10^3}{\sqrt{287 \times 300}} \cdot \sqrt{\frac{2 \times 1.4}{1.4-1}\left(1-\frac{1}{1.2}\right)}$$

$$= 0.94 \times 0.634 \times A_t \times 344.2 \times \frac{7}{6}$$

$$= 239.3\ A_t$$

$A_t = 8.1 \times 10^{-4}$ m² $= 8.1$ cm²

Area of each barrel $= \frac{8.1}{2} = 4.05$ cm².

$\frac{\pi}{4} d_t^2 = 4.05$. $\underline{d_t = 2.27 \text{ cm}}$.

$$\dot{m}_f = C_{Dc} A_c \rho_f \sqrt{\frac{2 \rho P_1}{\rho}\left(1 - \frac{P_2}{P_1} - \frac{\rho g h_f}{P_1}\right)}$$

$\rho = 750$, $g = 9.8$, $h_f = 1.5$ cm $= 1.5 \times 10^{-2}$ m

$\frac{P_2}{P_1} = 0.528$,

$\dot{m}_f = \frac{0.194}{15.2} = 0.0128$ kg/sec

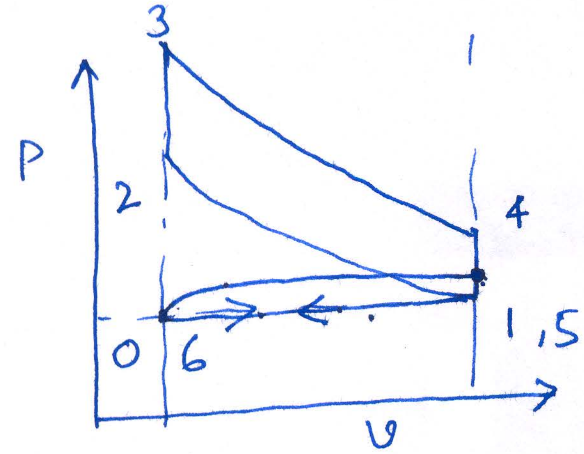
$$0.0128 = 0.74 \times 750 \times A_c \times \sqrt{\frac{2 \times 101 \times 10^3 \cancel{287 \times 300 \times}}{750}\left(1 - 0.528 - \frac{750 \times 9.8 \times 1.5 \times 10^{-2}}{101 \times 10^3}\right)}$$

$A_c = \cancel{6.074 \times 10^{-5}}$ m²
2.05×10^{-6}

$\therefore A_c$ of one $= 1.024 \times 10^{-6}$ m². $d_c = 1.14$ mm.

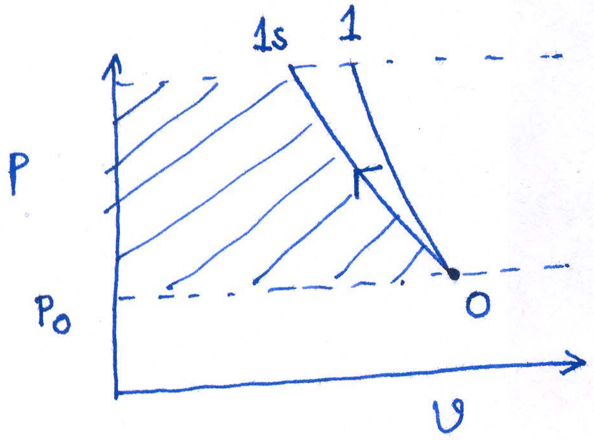
10/4/17 (1)

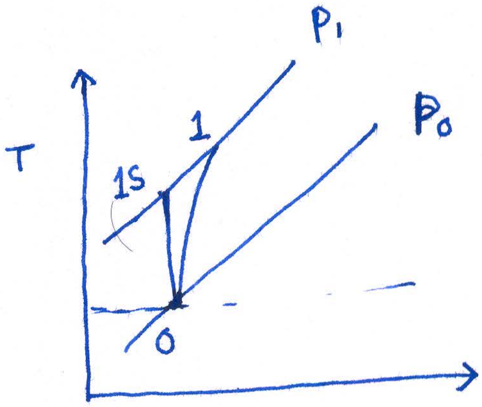
Supercharge or turbocharge



SI

$${}_0\omega_1 = -\int_0^1 v\,dP$$





$$\omega_c = (h_1 - h_0)$$

$$q - w = (h_2 + \cancel{\frac{V_2^2}{2}} + \cancel{gz_2}) - (h_1 + \cancel{\frac{V_1^2}{2}} + \cancel{gz_1})$$

$$V_2 \approx V_1$$

$$\omega_{cs} = (h_{1s} - h_0)$$

$$\eta_c = \frac{h_{1s} - h_0}{h_1 - h_0}$$

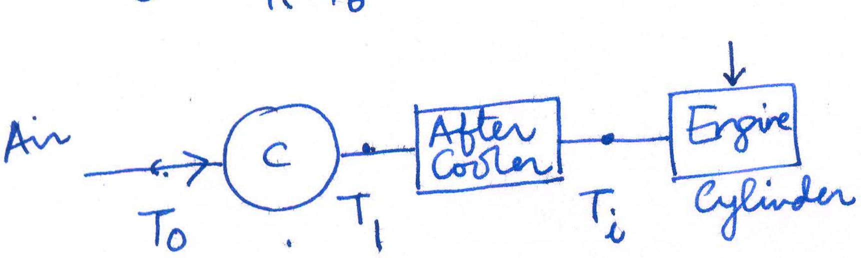
$$-w = (h_2 - h_1)$$

$$h = c_p T$$

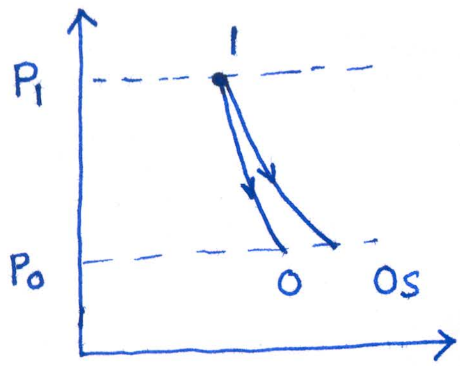
$$\frac{T_{1s}}{T_0} = \left(\frac{P_1}{P_0}\right)^{\frac{\gamma-1}{\gamma}}$$

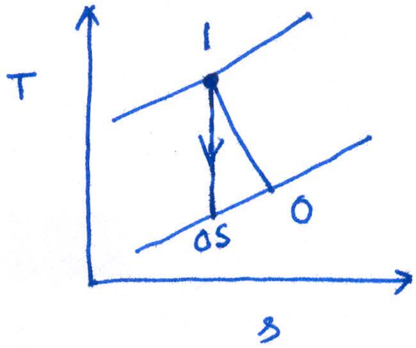
$$\eta_c = \frac{T_{1s} - T_0}{T_1 - T_0}$$

ϵ = Effectiveness



$$= \frac{T_1 - T_i}{T_1 - T_0}$$





$$w_T = (h_1 - h_0)$$

$$w_{Ts} = (h_1 - h_{0s})$$

$$\eta_T = \frac{w_T}{w_{Ts}} = \frac{h_1 - h_0}{h_1 - h_{0s}} = \frac{T_1 - T_0}{T_1 - T_{0s}}$$

<u>Aftercooler</u>

Brake power = 628 kW

Brake efficiency = 40.4%

Compressor efficiency = 57%

Intercooler effectiveness = 0.78

1. A turbocharged six-cylinder Diesel engine has a swept volume of 39 litres. The inlet manifold conditions are 2.0 bar and 53^0C. The volumetric efficiency of the engine is 95% and it is operating at a load of 16.1 bar bmep, at 1200 RPM with an AF ratio of 21.4. The power delivered to the compressor is 100 kW, with entry conditions of 25^0C and 0.95 bar. The fuel has a calorific value of 42 MJ/kg. (c_p=1.01 kJ/kg-K). Calculate:
   a) The power output of the engine
   b) The brake efficiency of the engine
   c) The compressor isentropic efficiency
   d) The effectiveness of the inter-cooler

(3)

Inter-Cooler

Brake power, $W_b = p_b V_b N^* \frac{N}{2\times60}$

$= 16.1\times10^5 \times 39\times10^{-3} \times \frac{1200}{120}$ ~~kW~~

$= 628\ kW \leftarrow$

To find the brake efficiency

$\eta_v = V_a/(V_s N^*)$

$p = \rho RT$

$\rho = \frac{p}{RT}$

$m_a = \rho V_a = \rho \eta_v V_s N^*$

$= \eta_v V_s N^* \frac{p}{RT}$

$= 0.95\times39\times10^{-3}\times\frac{1200}{120}\times2\times10^5/[287\times(287+53)]$

$= 0.792\ kg/s$

$m_f = m_a/AFR = 0.037\ kg/s$

$\eta_b = W_b/(m_f \times CV) = 628\times10^3/(0.037\times42\times10^6) = 40.4\% \Leftarrow$

Compressor efficiency

$W_C = m_a c_p (T_2 - T_1)$

$T_2 - T_1 = \frac{W_C}{m_a c_p} = \frac{100\times10^3}{0.792\times1.01\times10^3}\ K = 125\ K$

$T_{2s} = T_1 (p_2/p_1)^{\frac{\gamma-1}{\gamma}} = (273+25)(2/0.95)^{\frac{1.4-1}{1.4}} = 369\ K$

$\eta_c = \frac{T_{2s}-T_1}{T_2-T_1} = \frac{369-298}{125} = 0.57$ or $57\% \Leftarrow$

Intercooler effectiveness is defined as

$\epsilon = \frac{T_2 - T_3}{T_2 - T_1} = \frac{\cancel{3??}\ \cancel{398}\ 423 - 326}{\cancel{123}\ 423 - 298}$

$= 0.78 \Leftarrow$

$T_3 = 273+53$

$= 326\ K$

$T_2 = 273+125+25$

$\cancel{= 398\ K} = 423\ K$

$423 - 298$

$= 125$