Date ___/___/___ ME321: Applied Thermodynamics

Assignment - ICE

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Ans1 Given:

Swept volume, $V_s = 3 \times 10^{-3} \ m^3$
RPM of Engine, $N = 3600$
number of cylinders, $n = 6$

(a) $V_s = n \times \frac{\pi}{4} B^2 L$ L = Stroke length, B = Bore

Since engine is square, $B = L$

$\rightarrow V_s = \frac{n\pi}{4} B^3$

$$\Rightarrow B = \sqrt[3]{\frac{3 \times 10^{-3} \times 4}{\pi \times 6}} = 0.086 \ m$$

also $L = 0.086 \ m$

(b) Let average piston speed be $\bar{V}_p$

$$\bar{V}_p = 2NL = \frac{2 \text{strokes}}{\text{rev}} \times \frac{0.086 m}{\text{stroke}} \times \frac{3600 \text{ rev}}{60 \text{ sec}}$$

$\underline{\bar{V}_p = 10.32 \ m/s}$

(c) $V_d = \frac{3 \times 10^{-3}}{6} = 0.0005 \ m^3$

V_c = clearance volume of one cylinder

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

$\rightarrow 9.5 = \frac{V_c + 0.0005}{V_c} \Rightarrow V_c = 0.000059 m^3 = 59 cm^3$

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(d) Crank offset, $a = \frac{L}{2} = \frac{0.086}{2} = 0.043$

$R = \frac{r}{a} = \frac{166\,mm}{43\,mm} = 3.86$

To find instantaneous speed of piston

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

$$= \frac{\pi}{2}\sin 20^\circ\left[1 + \frac{\cos 20}{\sqrt{(3.86)^2 - \sin^2 20^\circ}}\right]$$

$= 0.668$

$\Rightarrow V_p = 0.668\,\overline{V_p} = 0.668 \times 10.32 = 6.89\,m/s$

$V_p = 6.89\,m/s$

(e) position of piston, $s = a\cos\theta + \sqrt{r^2 - a^2\sin^2\theta}$

$= 0.043\cos 20^\circ + \sqrt{(0.166)^2 - (0.043)^2\sin^2 20^\circ}$

$= 0.206\,m$

distance from TDC

$x = r + a - s$

$= 0.166 + (0.043) - (0.206)$

$= 0.03\,m$

$x = 0.3\,cm$

(f) instantaneous

$$\frac{V}{V_c} = 1 + \frac{1}{2}(r_c - 1)\left[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}\right]$$

$$= 1 + \frac{1}{2}(9.5 - 1)\left[3.86 + 1 - \cos 20^\circ - \sqrt{3.86^2 - \sin^2 20}\right]$$

$= 1.32$

$\Rightarrow V = 1.32\,V_c \rightarrow V = 1.32 \times 59\,cm^3$

$\boxed{V = 77.9\,cm^3}$

$\boxed{V = 0.0000779\,m^3}$

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Ans2 No. of cylinders $n = 5$

$V_s = 3.5L = 3.5 \times 10^{-3} m^3$

No. of strokes = 4

$N = 2500$ rpm

Mechanical Efficiency $\eta_m = 62\% = 0.62$

Indicated Work = 1000J (per cylinder)

(a) Indicated mean effective pressure

$$IMEP = \frac{\text{Indicated Work}}{\text{Displaced Volume}} = \frac{1000 \times 5}{0.0035} = 1429 \text{ KPa}$$

5 → no. of cylinders

(b) Brake mean effective pressure

$BMEP = \eta_m \times IMEP = 0.62 \times 1429$

$BMEP = 886$ KPa

(c) Friction mean effective pressure

$FMEP = IMEP - BMEP$

$= 1429 - 886$

$FMEP = 543$ KPa

(d) $B.P. = \frac{BMEP \times V_s \times N}{2 \times 1000}$

$$= \frac{886 \times 3.5 \times \frac{2500}{60}}{2 \times 1000}$$

$B.P(KW) = 64.6$ KW

$B.P(HP) = 86.6$ HP [$\because$ 1HP = 0.7457 KW]

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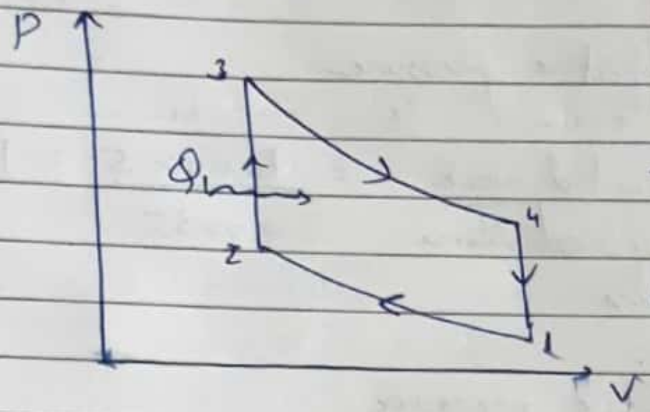
(e) Torque

$$T = \frac{BMEP \times V_s}{4\pi} = \frac{886 \times 0.0035}{4\pi} = 247\ Nm$$

Ans 3

Let $C_v = 0.717\ KJ/kg\,K$
$\gamma = 1.4$ for air



$r = 6$

$P_1 = P_0 = 1\ bar$

$T_1 = T_0 = 27°C = 300K$

$Q_s = 1170\ KJ/kg$

For process 1-2

$$\frac{P_2}{P_1} = r^{\gamma} = (6)^{1.4} = 12.28$$

$\Rightarrow P_2 = 12.28 \times 10^5\ N/m^2$ or 12.28 bar

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1} = 6^{1.4-1} = 6^{0.4} = 2.05$$

$T_2 = 2.05\,T_1 = 2.05 \times 300 = 615\ K$

$\Rightarrow T_2 = 342°C$

For process 2-3

for unit mass flow

$q_s = q_{2-3} = C_v(T_3 - T_2) = 1170\ KJ/kg$

$$\Rightarrow T_3 - T_2 = \frac{1170}{C_v} = \frac{1170}{0.717} = 1631.8$$

$\Rightarrow T_3 = 1631.8 + 615$

Peak Temperature $T_3 = 2246.8K$ or $T_3 = 1973.8°C$

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} = \frac{2246.8}{615} = 3.65$$

Peak pressure $- P_3 = 3.65 \times 12.28 \times 10^5$
$= 44.82 \times 10^5$

$$\boxed{P_3 = 44.82 \text{ bar}}$$

Work output = Area of PV diagram
= area under (3-4) - area under (2-1)

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

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

$R = C_p - C_v = 1.004 - 0.717 = 0.287$ KJ/kg-K

$$\frac{T_3}{T_4} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = r^{\gamma-1} = 6^{0.4} = 2.048$$

$$\Rightarrow T_4 = \frac{T_3}{2.048} = \frac{2246.8}{2.078} = 1097.1 \text{ K}$$

$$\text{Workoutput /kg} = \frac{0.287}{0.4}\left[(2246.8 - (1097.1)) - (615 - 300)\right]$$

$= 598.9$ KJ

$$\eta_{otto} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{6^{0.4}} = 0.5116$$

Air standard efficiency = 51.16 %

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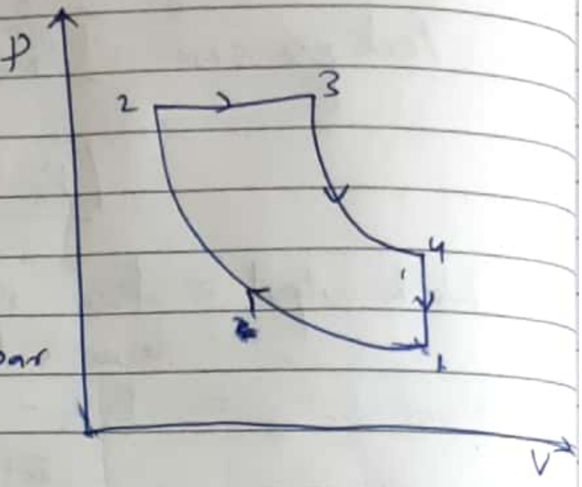
Ans 4

Take $C_p = 1.004$ KJ/kg-K $\quad C_v = 0.717$ KJ/kg-K

$\gamma = 1.4$ for air

$r = 1 + \frac{V_s}{V_c} = 1 + 8 = 9$



Consider the process 1-2

$\frac{P_2}{P_1} = r^{\gamma} = 9^{1.4} = 21.67$

$P_2 = 21.67 \times 1.03 \times 10^5 = 22.32$ bar

$P_2 = 22.32$ bar

$\frac{T_2}{T_1} = r^{\gamma-1} = 9^{0.4} = 2.408$

$T_2 = 308 \times 2.408 = 741.6$ K

$T_2 = 468.6$°C

For process 2-3

$P_2 = P_3 = 22.32$ bar

$T_3 = 1773$ K $= 1500$°C

for process 3-4

$\frac{T_3}{T_4} = r_e^{\gamma-1}$

$r_c = \frac{T_3}{T_2} = \frac{1773}{741.6} = 2.391$

$r_e = \frac{r}{r_c} = \frac{9}{2.391} = 3.764$

$\frac{T_3}{T_4} = 1.7 \Rightarrow T_4 = \frac{1773}{1.7} = 1042.9$ K $= 769.9$°C

$\frac{P_3}{P_4} = r_e^{\gamma} = 3.764^{1.4} = 6.396$

$\Rightarrow P_4 = \frac{P_3}{6.396} = \frac{22.32 \times 10^5}{6.396}$

$P_4 = 3.49 \times 10^5$ N/m² $= 3.49$ bar

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(a) $P_2 = 22.32$ bar $\quad T_2 = 741.6 K = 468.6 °C$

$P_3 = 22.32$ bar $\quad T_3 = 1773 K = 1500 °C$

$P_4 = 3.49$ bar $\quad T_4 = 1042.9 K = 769.9 °C$

(b) Compression ratio, $r = 9$

(c) $\eta_{cycle} = \frac{\text{work output}}{\text{heat added}} = 1 - \frac{\text{heat rejected}}{\text{heat added}}$

$= 1 - \frac{q_{4-1}}{q_{2-3}}$

$q_{4-1} = C_v (T_4 - T_1)$
$= 0.717 (1042.9 - 308)$
$= 526.9$ KJ/kg

$q_{2-3} = C_p (T_3 - T_2)$
$= 1.004 (1773 - 741.6)$
$= 1035.5$ KJ/kg

$\eta_{cycle} = 1 - \frac{526.9}{1035.5} = 0.4912$

$\eta_{cycle} = 49.12\%$

Work output $= q_{2-3} - q_{4-1} = 1035.5 - 526.9$
$= 508.6$ KJ/kg

(d) Power output = work output $\times \dot{m}_a$

$\dot{m}_a = \frac{P_1 V_1}{R T_1} \times \frac{N}{2}$

$R = C_p - C_v = 0.287$ KJ/kgK

$V_1 = V_s + V_c = \frac{9 V_s}{8}$ $\quad \left(\frac{V_s}{V_c} = 8\right)$

$V_s = 6 \frac{\pi}{4} d^2 L = 6 \times \frac{\pi}{4} \times 10^2 \times 12 = 5.65 \times 10^{-3} m^3$

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$V_1 = \frac{9}{8} \times 5.65 \times 10^{-3} = 6.36 \times 10^{-3} m^3$

$\dot{m}_a = \frac{1.03 \times 10^5 \times 6.36 \times 10^{-3} \times 30}{287 \times 308 \times 2} = 0.111$

Power output $= 508.6 \times 0.111$

$\boxed{\text{Power Output} = 56.45 \text{ KW}}$

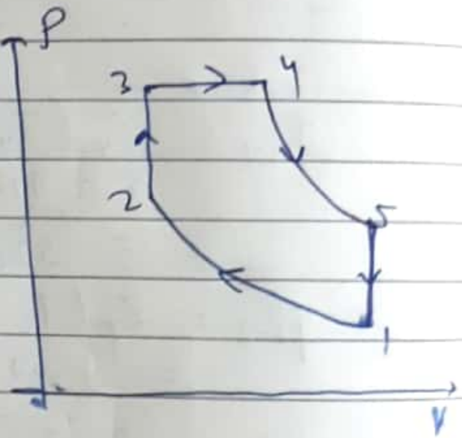
Ans 5

$C_p = 1.004$ KJ/Kg-K

$C_v = 0.717$ KJ/Kg-K

$\frac{V_s}{V_c} = r - 1 = 9 \Rightarrow \boxed{r = 10}$

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



In process 1-2

$\frac{P_2}{P_1} = r^{\gamma} = 10^{1.4} = 25.12$

$P_2 = 25.12 \times 10^5 N/m^2$

$\boxed{P_2 = 25.12 \text{ bar}}$

$\frac{T_2}{T_1} = r^{\gamma - 1} = 10^{0.4} = 2.512$

$T_2 = 2.512 \times 373 = 936.9K$

$\boxed{T_2 = 663.9°C}$

for process 2-3 and 3-4

$\frac{T_3}{T_2} = \frac{P_3}{P_2} = \frac{70}{25.12} = 2.787$

$T_3 = 2.787 \times 936.9 = 2611.1 K$

$\boxed{T_3 = 2338°C}$

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Heat added during constant pressure combustion

$= 1680 - 1200.4$

$= 479.6$ KJ/kg

$= C_p (T_4 - T_3)$

$\Rightarrow T_4 - T_3 = \frac{479.6}{C_p} = \frac{479.6}{1.004} = 477.71K$

$\Rightarrow T_4 = T_3 + 477.7$ K

$= 2611.1 + 477.7$

$= 3088.8K$

$\boxed{T_4 = 2815.8°C}$

$\rho = \frac{V_4}{V_3} = \frac{T_4}{T_3} = \frac{3088.8}{2611.1} = 1.183$

For process 4-5

$\frac{T_4}{T_5} = \left(\frac{r}{r_c}\right)^{\gamma-1} = 8.453^{0.4} = 2.35$

$T_5 = \frac{T_4}{2.35} = \frac{3088.8}{2.35} = 1314.4K$

$\boxed{T_5 = 1041.4°C}$

$\frac{P_4}{P_5} = \left(\frac{r}{r_c}\right)^{\gamma} = 19.85 \Rightarrow P_5 = \frac{P_4}{19.85} = \frac{70\times10^5}{19.85} = 3.533\times10^5 N/m^2$

$\Rightarrow \boxed{P_5 = 3.53 \text{ bar}}$

Heat rejected $= C_v (T_5 - T_1)$

$= 0.717(1314.4 - 373)$

$= 674.98$ KJ/kg

$\eta = \frac{1680 - 674.98}{1680} (100) = 59.82\%$

$\boxed{\eta = 59.82\%}$

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Ans 6 From the given data, 81% volume would be left for nitrogen

$$x C_3H_8 + y(O_2 + 3.76N_2) \longrightarrow 6CO_2 + 10CO + 81N_2 + 3O_2 + zH_2O$$

Conservation of N_2 gives

$$2y(3.76) = 2 \times 81$$
$$\Rightarrow y = \frac{81}{3.76} = 21.54$$

Conservation of C gives $3x = 16$
$$\rightarrow x = \frac{16}{3} = 5.33$$

Conservation of H gives $8x = 2z$
$$8(5.33) = 2(z)$$
$$\Rightarrow z = 21.33$$

$$5.33 C_3H_8 + 21.54(O_2 + 3.76N_2) \rightarrow 6CO_2 + 10CO + 21.33H_2O + 81N_2 + 3O_2$$

Hence

$$C_3H_8 + 4.04(O_2 + 3.76N_2) \rightarrow 1.125CO_2 + 1.875CO + 4H_2O + 15.187N_2 + 0.562O_2$$

(a) Air fuel ratio, $AF_{fuel} = \frac{4.04 \times 4.76 \times 29}{1 \times 44}$
$$= 12.67$$

(b) Stoichiometric reaction:

$$C_3H_8 + 5(O_2 + 3.76N_2) \longrightarrow 3CO_2 + 4H_2O + 5 \times 3.76 N_2$$

$$AF_{stochiometric} = \frac{5 \times 4.76 \times 29}{1 \times 44}$$
$$= 15.887$$

$$\text{Equivalence Ratio} = \frac{AF_{stochiometric}}{AF_{actual}} = \frac{15.837}{12.67} = 1.25$$

(c) Q_{LHV} per mole = $1.125 \times$ heat of formation for CO_2 + $1.875 \times$ heat of formation of CO + $4 \times$ heat of formation

$$= 1.125 \times 393.5 + 1.875 \times 110.5 + 4 \times 286$$
$$= 1792.9375$$

Q_{LHV} per mole $= 648.9375$ MJ

We know that,

molecular weight of propane = 44.097 kg/kmol

$$Q_{LHV} = \frac{1792.9375}{44.097} = 40.66 \text{ MJ/Kg}$$

Lower Heating Value of fuel $Q_{LHV} = 40.66$ MJ/kg

(d) Energy released in 1kg of fuel at 0.98 efficiency

$$= 1 \text{ kg} \times 40.66 \text{ MJ/kg} \times 0.98$$
$$= \underline{39.84 \text{ MJ}}$$

Ans 7 Given hydrogen is used as fuel and with stoichiometric oxygen

$$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$$

(a) We know that, fuel air ratio $= \frac{m_f}{m_a} = \frac{(NM)_f}{(NM)_a}$

$$= \frac{1 \times 2}{0.5 \times 32} = \underline{0.125}$$

(b) the given equation is stoichiometric
So ϕ = equivalence ratio = 1

$$\boxed{\phi = 1}$$

(c) $\sum_{reactant} N_j (h_f^\circ + \Delta h)_j = \sum_{product} N_i (h_f^\circ + \Delta h)_i$

(i) $[(-241826) + \Delta h]_{H_2O} = (1)[0+0]_{H_2} + \frac{1}{2}[0+0]_{O_2}$

(Enthalpy values for water from steam table)
By solving above $\Delta h_{H_2O} = 241.826$ KJ/kg mol

$$\boxed{T_{max} = 4991\ K}$$

(d) Exhaust is all H_2O with $P_{H_2O} = P_{ex} = 101$ KPa

Dew Point Temperature $\boxed{T_{dp} = 100^\circ C}$

Ans 8 Calculate the flame travel distance

$$D_f = \frac{bore}{2} + offset$$

$$= \frac{10.2}{2} + 0.6$$

$$= 5.7\ cm$$

$$= 0.0057\ m$$

Calculate the time for flame front to reach the furthest cylinder wall (time of one combustion process)

$$t = \frac{D_f}{V_f} = \frac{0.057}{15.8} = 3.607 \times 10^{-3}\ sec$$

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(b) Combustion will start at $20° - 6.5° = 13.5°$ bTDC

Calculate the time of combustion in degrees

$$t \times \frac{N}{60} \times 360°/rev$$

$$= 3.607 \times 10^{-3} \times \frac{1200}{60} \times 360°$$

$$= 25.9°$$

Crank position at the end of combustion $= 25.9° - 13.5°$
$= \boxed{12.4° \text{ a TDC}}$

Ans 9 $N = 1850$ rpm
Injection starts at 16° before TDC and lasts for 0.0019 seconds

Total time of injection, $t = \frac{\theta}{6N}$

$\theta \rightarrow$ in degrees
$N \rightarrow$ in RPM
$t \rightarrow$ in seconds

$$0.0019 = \frac{\theta}{6 \times 1850} \Rightarrow \boxed{\theta = 21.09°}$$

(b) Ignition delay = fuel injected − combustion started
$= 16° - 8°$
$= 8°$ of crank rotation

(a) $t = \frac{\theta}{6N} = \frac{8}{6 \times 1850} = 7.2072 \times 10^{-4}$ second

(c) last injection is at $(21.09° - 16°) = 5.09°$ after TDC
Ignition delay is reduced by a factor 2 after combustion starts, ie. $\frac{8°}{2} = 4°$

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Crank angle position = $5.09 + 4 = 9.09^\circ$ after TDC