4A13 - Combustion & IC Engines

Cribs - 2019

1) $T = 1600K$; $\phi = 2.0$

Fuel is $C_{17}H_{32}O_4$

(a) No, the chemical kinetics play dominant role in the flame.

(b)

$$C_{17}H_{32}O_4 + \frac{a}{\phi}\left(O_2 + \frac{0.79}{0.21}N_2\right)$$

$$\rightarrow b_1 CO_2 + b_2 CO + b_3 H_2O + b_4 H_2 + \cancel{\left(\frac{a}{\phi}\frac{0.79}{0.21}\right)} N_2 . \rightarrow b_5$$

for $\phi = 1$; Stoichiometric mixture

$$C_{17}H_{32}O_4 + a\left(O_2 + \frac{0.79}{0.21}N_2\right) \rightarrow 17\,CO_2 + 16\,H_2O + \left(a\,\frac{0.79}{0.21}\right)N_2$$

The balance of O atom gives $\boxed{a = 23}$

for $\phi = 2$.

$C: \quad b_1 + b_2 = 17 \quad \Rightarrow \quad b_2 = 17 - b_1$

$H: \quad 2(b_3 + b_4) = 32 \quad \Rightarrow \quad b_3 + b_4 = 16$

$O: \quad 2b_1 + b_2 + b_3 = 27$

$b_1 + b_3 = 10 \quad \Rightarrow \quad b_3 = 10 - b_1$

$b_4 = 6 + b_1$

4 unknowns, 3 equations

$\Rightarrow$ 1 K_p relation.

Fuel rich combustion, so consider water gas shift reaction.

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

$$K_p = \frac{(P_{CO_2}/P_0)(P_{H_2}/P_0)}{(P_{CO}/P_0)(P_{H_2O}/P_0)} = \frac{b_1 b_4}{b_2 b_3} \frac{(P/P_0)^2}{(P/P_0)^2}$$

$$\therefore K_p = \frac{b_1 b_4}{b_2 b_3} = \frac{b_1(6+b_1)}{(17-b_1)(10-b_1)}$$

$T = 1600$ K; from data book for Rxn. 8

$$\ln(K_p) = -1.091 \Rightarrow K_p = 0.3359$$

$$\Rightarrow 0.6641 b_1^2 + 15.0693 b_1 - 57.103 = 0$$

$\Rightarrow \quad b_1 = 3.3073$

Taking the +ve root on physical reasonings grounds,
No. of moles can't be -ve.

$b_1 = 3.3073$

$b_2 = 13.6927$

$b_3 = 6.6927$

$b_4 = 9.3073$

$b_5 = 43.2619$

Sum $= 76.2619$

mole fractions:

$X_{CO_2} = 0.0434$

~~$X_{CO} = 0.107$~~

$X_{CO} = 0.1795$

$X_{H_2O} = 0.0878$

$X_{H_2} = 0.1220$

$X_{N_2} = 0.5673$

Sum $= 1.0000$ ✓

(c) The chamber pressure does not affect the product composition, because sum of the mole numbers is zero for the Kp relation.

(d) There are two ways to increase the hydrogen yield.

1) if T is decreased Kp increases (See the data book)

for $CO + H_2O \rightleftharpoons CO_2 + H_2$.

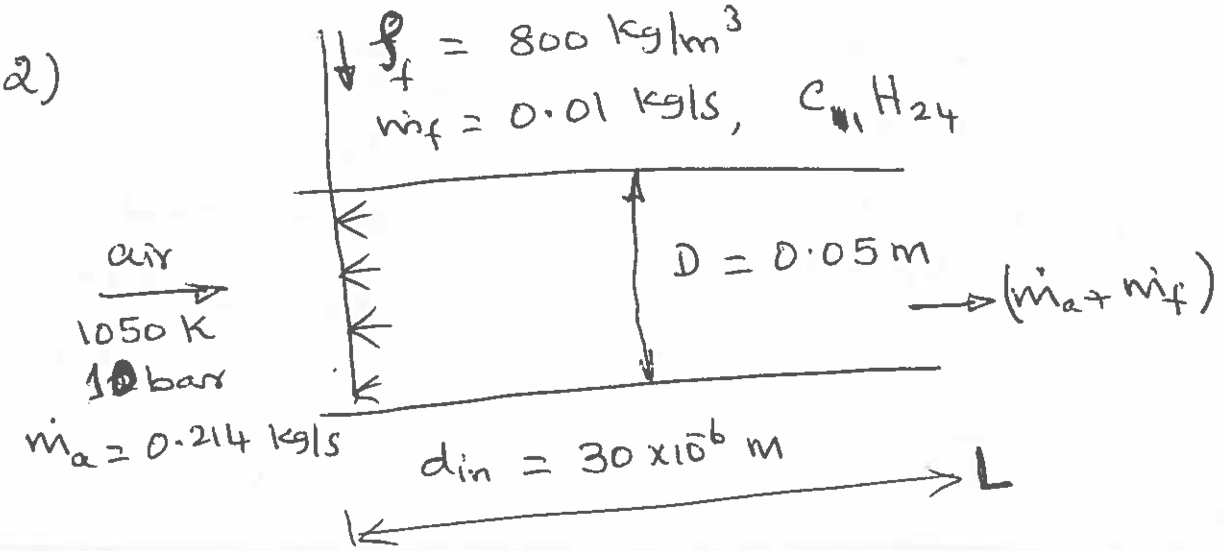
$\Rightarrow K_p = \frac{b_1 b_4}{b_2 b_3}$; So $K_p \uparrow$ means $b_4 \uparrow$ & also $b_1 \uparrow$

(2) one can use H_2O (spray water vapour) So, the water gas shift reaction shifts to the right.

$H_2O \uparrow \Rightarrow H_2 \uparrow$ by Le-chartelier principle.

This was a very popular question as it was a straightforward one. Generally, answered very well. Student demonstrated good understanding of chemical equilibrium and its limitations required to answer major parts of this question. The candidates were able to setup the required equations clearly. There were algebraic errors while finding the required solution by solving 4 simultaneous algebraic equations, but the candidates were not penalised heavily for that. Part (d) required some extended thinking and there were some good and also many correct answers.

2)



(a) $$\phi = \frac{(\dot{m}_f/\dot{m}_a)}{(\dot{m}_f/\dot{m}_a)_{st.}}$$

$$C_{11}H_{24} + a\left(O_2 + \frac{0.79}{0.21}N_2\right) \rightarrow 11\,CO_2 + 12\,H_2O + \left(a\,\frac{0.79}{0.21}\right)N_2$$

O atom balance gives

$$\boxed{a = 17}$$

$$\left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{st} = \frac{1\,(11\times12 + 24\times1)}{17\left(32 + \frac{0.79}{0.21}\times28\right)} = 0.0668$$

$$\therefore\ \phi = \frac{(0.01/0.214)}{0.0668} = 0.6995 \approx \underline{0.7}$$

$$\boxed{\phi = 0.7}$$

(b) 

$$m = \rho_f \frac{4}{3}\pi\left(\frac{d}{2}\right)^3$$

$$\frac{dm}{dt} = -\dot{m}'' A = \frac{\rho_f B}{4d} 4\pi\left(\frac{d}{2}\right)^2$$

$$\rho_f \frac{4}{3}\pi\frac{3}{2}\left(\frac{d}{2}\right)^2 \frac{dd}{dt} = \frac{\rho_f B}{4d} 4\pi\left(\frac{d}{2}\right)^2$$

$$\Rightarrow \quad \frac{dd}{dt} = -\frac{B}{2d} \quad \Rightarrow \quad \boxed{d^2(t) = d_{in}^2 - Bt}$$

@ t_{evap} $d = 0$

$$\Rightarrow \quad t_{evap} = \frac{d_{in}^2}{B} = \frac{(30\times10^{-6})^2}{3\times10^{-7}} = 3\times10^{-3}\,s$$

$$\boxed{t_{evap} = 3\,ms}$$

$$L_{evap} = U\,t_{evap}.$$

$$\dot{m}_t = (\dot{m}_a + \dot{m}_f) = \rho U A \qquad A = \frac{\pi}{4}D^2 = 0.00196\,m$$

$$0.224 = \rho U A.$$

The mixture is $C_{11}H_{24} + \frac{17}{0.7}\left(O_2 + \frac{0.79}{0.21}N_2\right)$

$$x_f = \frac{1}{\left(1 + \frac{17}{0.7} + \frac{17}{0.7}\frac{0.79}{0.21}\right)} = 0.0086$$

$$x_{O_2} = \frac{(17/0.7)}{116.6462} = 0.2[illegible]82$$

$$x_{N_2} = 0.7832 \quad ; \quad \overline{W} = \Sigma x_i W_i = x_f 156 + x_{O_2}32 + x_{N_2}28 = 29.9336$$

$$\therefore \quad \rho = \frac{p\overline{W}}{RT}$$

$$\rho = \frac{10\times10^{5} \times 29.9336}{8314 \times 1050} = 3.4289 \ \text{kg/m}^3$$

$$\therefore \ U = \frac{0.224}{3.4289 \times 0.00196} = 33.33 \ \text{m/s}$$

$$L_{evap} = U t_{evap} = 33.33 \times 3\times10^{-3} = 0.09999 \ \text{m}$$

$$\boxed{L_{evap} = 0.1 \ \text{m}}$$

(c) Tests indicated $L_{ign} \sim 0.5 L$

$$\tau_{ign} \sim e^{(Ta/T)}$$

$$\frac{\tau_{ign}(1050)}{\tau_{ign}(980)} = \frac{e^{(15000/1050)}}{e^{(15000/980)}} = \frac{1.6\times10^{6}}{4.4398\times10^{6}}$$

$$= 0.3604$$

$$\therefore \ \tau_{ign}(980) = 2.77 \ \tau_{ign}(1050)$$

$$L_{ign}(980) = U_{980}\tau_{ign}(980) = 2.77 \ U_{980}\tau_{ign}(1050)$$

$$= 2.77 \frac{U_{980}}{U_{1050}} \left[U_{1050}\tau_{ign}(1050) \right]$$

$$= 2.77 \frac{U_{980}}{U_{1050}} L_{ign}(1050)$$

$$\frac{U_{950}}{U_{1050}} = \frac{\cancel{\dot{m}}/\rho_{950}\cancel{A}}{\cancel{\dot{m}}/\rho_{1050}\cancel{A}} = \frac{\rho_{1050}}{\rho_{980}} = \frac{980}{1050}$$

$$= 0.9333$$

$$\therefore \boxed{L_{ign}(980) = 2.585\, L_{ign}(1050)}$$

$$L_{ign}(1050) \approx 0.5\, L$$

$$\therefore L_{ign}(980) \approx 1.293\, L.$$

$\Rightarrow$ ignition is outside the duct length L.

So, the suggestion is sensible.

The most popular question with correct answer to part (a). The second part was also answered well but a common error was in calculating the gas mixture density (some answers were as high as 35 kg/m3!) which led to wrong length (of the order of few mm, while the correct answer was 0.1 m) required for complete evaporation. Part (c) was answered well but many students assumed the flow velocities to be constant although the temperature varied between the two cases.

3)

(a) Modern SI engines use three-way catalyst to control emissions of unburnt hydrocarbons (HC), Carbon monoxide (CO), and oxides of nitrogen. The catalyst converts these pollutants into H_2O, CO_2, & ~~or~~ N_2. The conversion efficiency is maximum when the engine runs at Stoichiometric condition. This is because of the O_2 coming out of reduction of NO_x and that required to oxidise HC and CO, and the temperature of the exhaust, for the Stoichiometric mixture correspond to the maximum efficiency requirement for the catalyst.

(b) 4 Stroke engine,

$r_c = 10.5$

bore; $d = 86$ mm

Stroke $L = 86$ mm

$N = 2000$ rpm

$= \left(\frac{2000}{60}\right)$ rps

IMEP = 11.1 bar

$\Rightarrow$ Swept volume $= \frac{\pi d^2}{4} \times L = \frac{\pi \times 86^2 \times 86}{4} \times 10^{-3} = 499.56$ cc

$V = 499.56 \text{ cm}^3$

$LHV = 43.1 \times 10^3$ kJ/kg ;

$T = 39.5$ N·m

$\dot{m}_a = 35.4$ kg/h

$\dot{m}_f = \frac{35.4}{14.56}$ ε kg/h

$\rho_a = 1.23 \text{ kg/m}^3$

$\gamma = 1.4$

(9)

(i) $$\eta_{otto} = 1 - \frac{1}{r_c^{(r-1)}} = 1 - \frac{1}{(10.5)^{0.4}} = 60.96\%$$

$$\boxed{\eta_{otto} = 60.96\%}$$

(ii) $$\eta_{vol.} = \frac{\text{actual air flow rate}}{\text{ideal air flow rate}}$$

ideal = V x No. of cycles per min

$$= V \times \frac{RPM}{2} = 499.56 \times 1000$$

$$= 4.9956 \times 10^5 \text{ cc/min}$$

$$\text{actual} = \frac{35.4}{1.23} \times \frac{1}{60} \times 10^6 = 4.7967 \times 10^5 \text{ cc/min}$$

$$\therefore \eta_{vol} = \frac{4.7967}{4.9956} = 96\% \qquad \boxed{\eta_{vol} = 96\%}$$

(iii) $$\dot{m}_f \text{ per cycle} = \dot{m}_f \left(\text{g/min}\right) \times \left(\frac{\text{min}}{\text{cycle}}\right)$$

$$= \frac{35.4}{14.56} \; \frac{10^3}{60} \; \frac{1}{1000} = \underline{\underline{0.04052 \text{ g/cycle}}}.$$

(iv) $$BSFC = \frac{\dot{m}_f \text{ per cycle}}{\text{break energy per cycle}}$$

$$\text{Break Power} = 2\pi\left(\frac{N}{60}\right)T \quad W$$

$$\text{Break energy per cycle} = \frac{2\pi NT}{60} \left(J/s\right) \times \left(s/\text{cycle}\right)$$

$$= \frac{2\pi \times 2000 \times 39.5}{60} \times \frac{60}{1000} = 496.3716 \text{ J/cycle}$$

$$\therefore \text{BSFC} = \frac{0.04052}{496.3716} = 8.1632 \times 10^{-5} \text{ g/J}$$

~~BSFC~~ BSFC in g/Kwh   Kwh = 3.6×10^{6} J

$$= 293.877 \text{ g/kwh}$$

(V) BMEP: $= \dfrac{\text{Brake energy in J per cycle}}{\text{Swept Volume in } m^3}$

$$= \frac{496.3716}{499.56 \times 10^{-6}} = 9.936 \times 10^{6} \text{ N/m}^2$$

$$\therefore \boxed{\text{BMEP} \approx 9.94 \text{ bar}}$$

(vi) $\eta_{B.F} = \dfrac{\text{Brake energy|cycle}}{\text{Fuel energy|cycle}} = \dfrac{496.3716 \text{ J/cy}}{43.1 \times 10^{3} \frac{J}{g} \times 0.04052 \text{ g/cy}}$

$$= 28.42\,\%$$

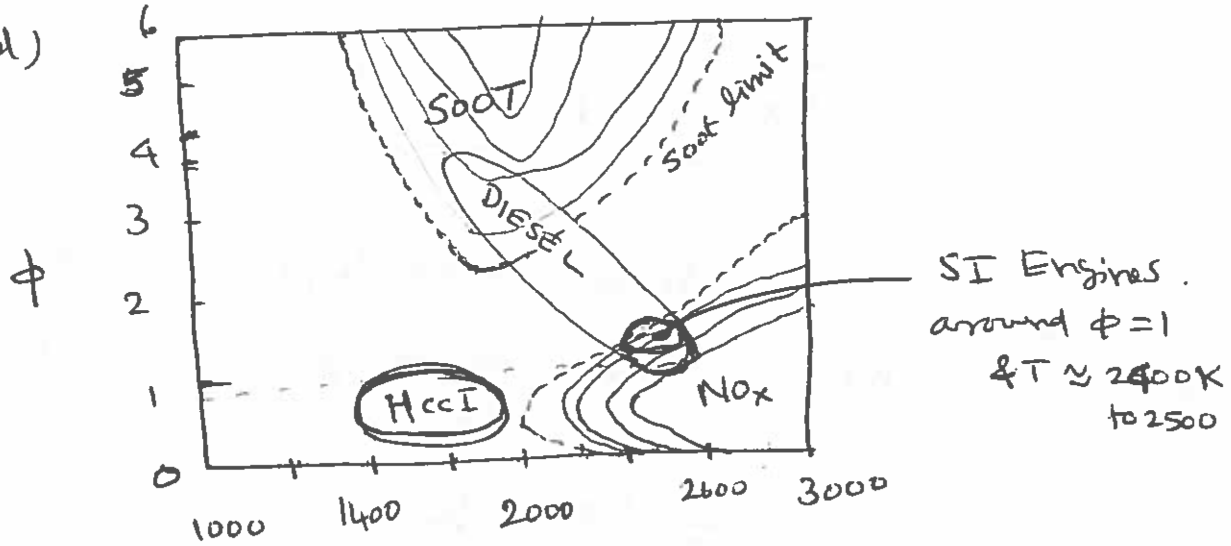
(vii) $\eta_{mech} = \dfrac{\text{BMEP}}{\text{IMEP}} = \dfrac{9.94}{11.1} = 89.55\,\%$

(c) (1) Diesel engines have higher compression ratio and thus higher efficiency.

(2) They compress mostly air ~~during the compression stroke~~, rather than a mixture of fuel and air, during the compression stroke, which brings the cycle nearer to the ideal cycle.

(3) Diesel engines can run at part load by reducing the amount of fuel injected rather than through throttling. Thus, the throttling losses at part loads are ~~reduced~~ elemincted.

(d)



SI Engines around $\phi = 1$ & $T \approx 2400K$ to 2500

main features: (1) Soot level increases as $\phi\uparrow$ with peak around 2000 K, which also increase with ϕ

(2) NOx level increases with T for $\phi = 1$ & lean mixtures, it starts to form around 1800 K, but it increases dramatical after this T.

The part (b) involved calculations of various parameters related to SI engine performance and was answered well in general. The other three parts of this question needed descriptive answers and students demonstrated good understanding the operational characteristics of the Spark Ignition (gasoline) and Compression Ignition (diesel) engines.

4)

(a) Knock is an abnormal combustion event in SI engines, caused by autoignition of the fuel-air mixture ahead of the expanding flame front initiated by the spark. The mixture ahead of the flame is also known as the "end gas."

The knock can lead to high rates of pressure rise in the cylinder and can damage the engine. Hence this undesirable event needs to be avoided.

The knock limits engine efficiency.

(b) RON ~~are defined~~ by comparing the fuel
& MON
for knocking in the ~~CRF~~ CFR (Co-operative Fuel Research) engine to the mixtures of iso-octane and n-heptane, which are known as Primary reference fuels (PRFs). The testing procedure is set by ASTM. RON (or MON) is the volume percent of iso-octane in the iso-octane and n-heptane mixture that matches the test fuel for knocking in the RON (or MON) tests.

(c) Octane Sensitivity is the difference between RON & MON.

i.e $OS = S = RON - MON$

Yes, the fuel composition or compounds can affect the OS. The non-paraffin compounds such as aromatics, olefins, and oxygenates increase the octane Sensitivity.

By definition PRFs ~~the~~ (Primary reference fuels) have $S = 0$ ⇒ S indicates how different the fuel composition is compared to PRFs.

(d) $OI = (1-K)\,RON + K\,MON$

$= RON - K(RON - MON) = RON - KS$

⇒

				OI	
Fuel	RON	MON	$K = -0.6$	-0.1	0.5
A	95	85	101	96	90
B	98	88	104	99	93
C	92	84	96.8	92.8	88
D	98	95	99.8	98.3	96.5
iso-octane	100	100	100	100	100

Oc. 1 : Fuel C, D iso-octane, A and B.

Oc. 2 : Fuel C, A, D, B and iso-octane.

Oc. 3 : Fuel C, A, B, D and iso-octane.

To get adequate anti-knock quality one must have OI $\geq$ OR

$\Rightarrow$ Oc. 1 has OR = 101, $\Rightarrow$ Fuel A & B

Oc. 2 has OR = 93 $\Rightarrow$ Fuel - all except C.

Oc. 3 has OR = 85 $\Rightarrow$ All fuels have adequate anti-knock quality.

(e) Preignition occurs when a flame is initiated in a SI engine before the spark fires.

The necessary conditions for it are

1) There should be an initial hot spot.

(2) An initial hot spot has to be of a size larger than the critical size required for a laminar flame to self-sustain its propagation. This size would be the laminar flame thickness (δ_f). If the size is smaller than this then there will be quenching of

the initial flame.

The laminar burning velocity (S_L) of the fuel-air mixture is the important property.

if $S_L \uparrow \Rightarrow \delta_f \downarrow$

$\Rightarrow$ The hot spot size can be smaller for preignition to occur.

$\Rightarrow$ probability for preignition ↑

(f) Super knock are detonation created when the pressure wave set off by the autoignition ~~is~~ couples to the autoignition wave. This coupling strengthens the pressure wave.

When the temperature and pressure of the autoigniting mixture (developing hot spots) is large, the detonation can develop. Engine operating conditions are chosen so that no autoignition and hence no knock occur in SI engines. However, if preignition occurs, the pressure and temperature of the end gas can be high enough for the detonation to ensue.

Hence, as pressure increases because of turbocharging, the probability of preignition and detonation increase and hence the probability of the superknock increases.

Superknock is a Stochastic process, depends on the probability for a number of chain events leading to it. Thus, it is less likely to occur in every cycle, but its likelihood increases as the cylinder pressure increases.

This topic was introduced for this year. The students attempted this question showed good understanding of Octane Number, its definition, requirement to avoid knock in engines. There were some good answered to explain knock, preignition and superknock required for Parts (a), (e) and (f) of this question. Part (d) required some calculations and there were few correct answers. In general, the students showed a good understanding of the fuel requirement for smooth engine operation.