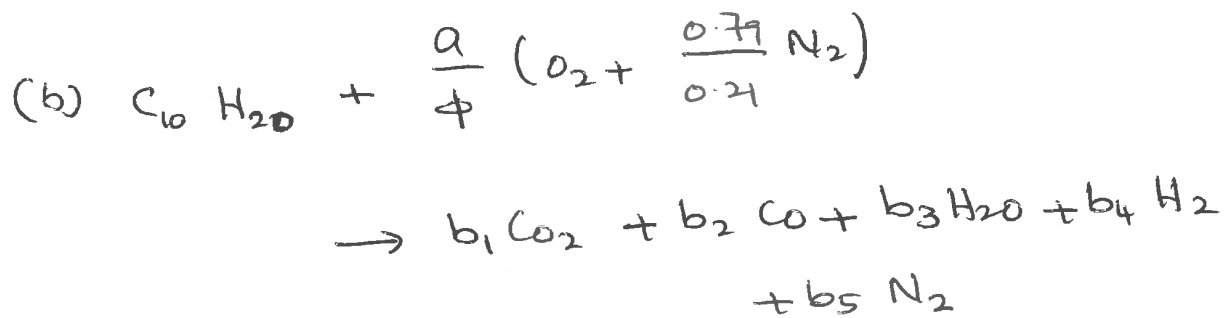


Cribs - 2013.

- 1) (a) In flame chemical kinetics dominate, after the flame chemical equilibrium is approached relatively slowly.



Stoichiometric reaction  $\Rightarrow a = 15$ .

$$\phi = 2$$

C atom balance:  $b_1 + b_2 = 10$

$$O : 2b_1 + b_2 + b_3 = 15 \Rightarrow b_1 + b_3 = 5$$

$$H : 2b_3 + 2b_4 = 20 \Rightarrow b_3 + b_4 = 10$$

$$N : \frac{0.79}{0.21} \times \frac{15}{2} = b_5 \Rightarrow b_5 = 28.25$$

5 unknowns, 4 equations  $\Rightarrow$  1 Kp relation.

fuel-rich combustion,  $\Rightarrow$  use water gas shift reaction.

(2)



$$T = 1800 \text{ K} \Rightarrow \ln(K_p) = -1.329 \text{ from table.}$$

$$\Rightarrow K_p = 0.2647$$

$$K_p = \frac{(p_{\text{CO}_2}/p_0)(p_{\text{H}_2}/p_0)}{(p_{\text{CO}}/p_0)(p_{\text{H}_2\text{O}}/p_0)}$$

$$= \frac{b_1 b_4 (p/p_0)^2}{b_2 b_3 (p/p_0)^2} = 0.2647$$

$$\Rightarrow \frac{b_1(5+b_1)}{(10-b_1)(5-b_1)} = 0.2647$$

after using  
the atom  
balance relations.

$$\Rightarrow b_1 = \frac{-8.9705 \pm \sqrt{119.3267}}{1.4706}$$

$$\Rightarrow b_1 = 1.3303$$

the other root is  
unphysical.

$$\Rightarrow b_2 = 8.6697$$

$$b_3 = 3.6697$$

$$b_4 = 6.3303$$

$$b_5 = 28.2$$

$$\Rightarrow n_{\text{total}} = 48.2$$

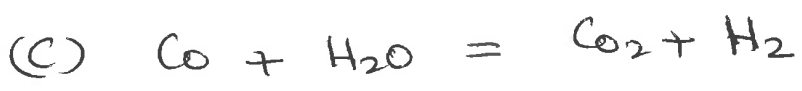
$$x_1 = 0.0276$$

$$x_2 = 0.1799$$

$$x_3 = 0.0761$$

$$x_4 = 0.1313$$

$$x_5 = 0.5851$$

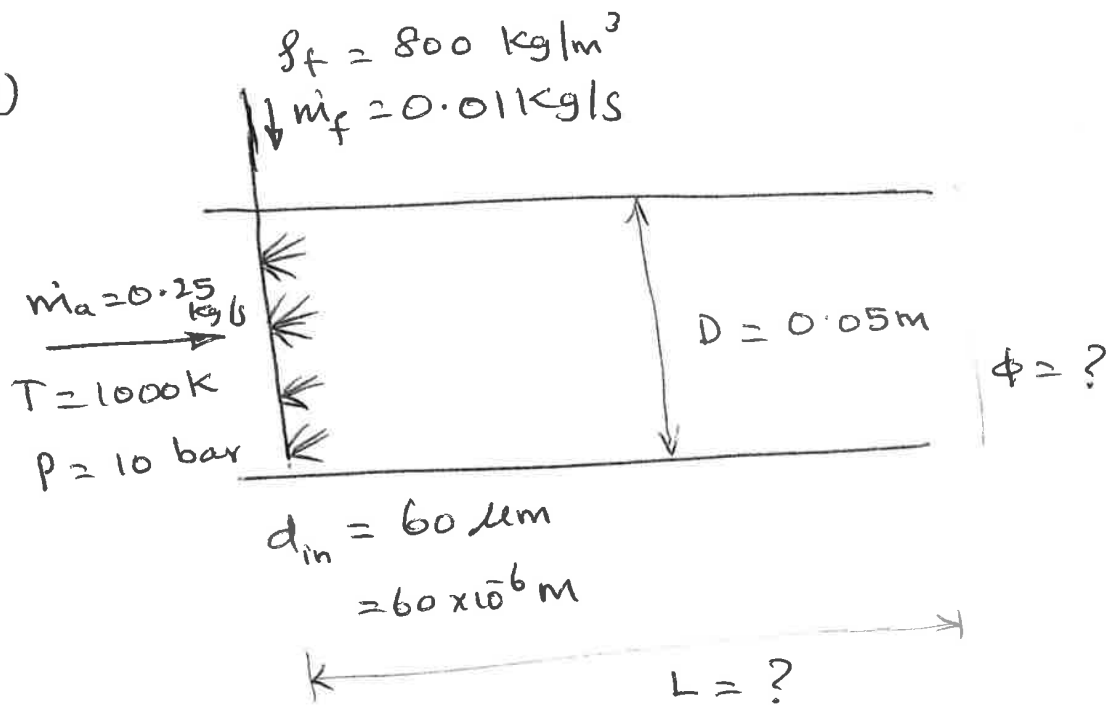


as  $\text{H}_2\text{O} \uparrow$        $\text{H}_2 \uparrow$        $\Rightarrow$  Le-Chatelier principle.

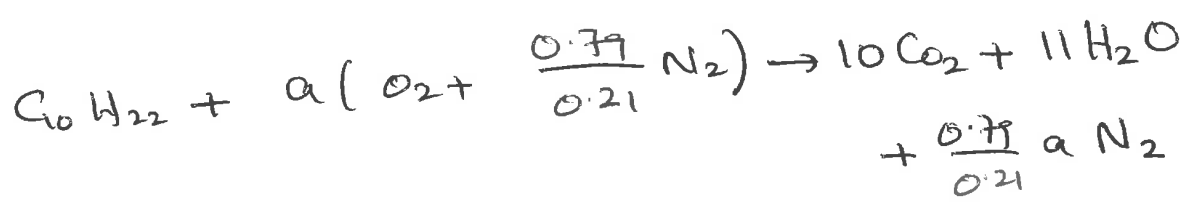
Yes, the suggestion is qualitatively correct.

(d) No, since  $\sum \nu_i \neq 0$  for the water-gas shift reaction used for  $K_p$  relation.

(2)



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



O atom balance: 
$$a = \frac{31}{2}$$

$$\left( \frac{\dot{m}_f}{\dot{m}_{air}} \right)_{st} = \frac{1(10 \times 12 + 22 \times 1)}{\frac{31}{2} \left( 32 + \frac{0.79}{0.21} \times 28 \right)} = 0.0667$$

$$\therefore \phi = \frac{(0.01 / 0.25)}{0.0667} = 0.5997 \approx \underline{\underline{0.6}}$$

(b)



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

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

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

$$\Rightarrow \frac{dd}{dt} = - \frac{B}{2d}$$

$$\int_0^t dt \Rightarrow d^2(t) - d^2(0) = -Bt$$

$$\Rightarrow \boxed{d^2(t) = d_{in}^2 - Bt}$$

$$\text{@ } t_{evap} \quad d = 0 \Rightarrow t_{evap} = \frac{d_{in}^2}{B}$$

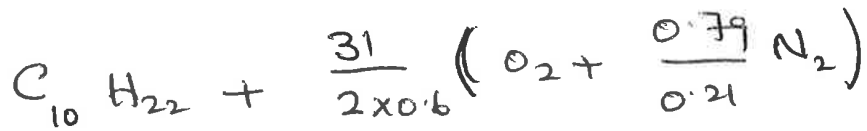
$$t_{evap} = \frac{(60 \times 10^{-6})^2}{1 \times 10^{-6}} = 3.6 \times 10^{-3} \text{ s}$$

$$\therefore L_{evap} = U t_{evap}$$

$$(m_{air} + m_f) = \rho_{mix} U A$$

(6)

To find mixture density.



$$\Rightarrow \rho_f = \frac{1}{\left( 1 + \frac{31}{1.2} + \frac{31 \times 0.79}{1.2 \times 0.21} \right)} = \frac{1}{124.0159}$$

$$\rho_f = 0.0081$$

$$\rho_{O_2} = \frac{31/1.2}{124.0159} = 0.2083$$

$$\rho_{N_2} = 0.7836$$

$$\overline{Mw} = \sum \rho_i Mw_i = 0.0081 \times 142 + 0.2083 \times 32 + 0.7836 \times 28 = 29.757$$

$$\rho_{mix} = \frac{P \overline{Mw}}{RT} = \frac{10 \times 10^5 \times 29.757}{8314 \times 1000} = 3.579 \text{ kg/m}^3$$

$$A = \frac{\pi}{4} D^2 = 0.00196 \text{ m}^2$$

$$U = \frac{(0.25 + 0.01)}{3.579 \times 0.00196} = 37.06 \text{ m/s}$$

$$\therefore L_{evap} = 37.06 \times 3.6 \times 10^{-3} = \underline{\underline{0.133 \text{ m.}}}$$

(c)  $\tau_{ign} \sim e^{+\left(\frac{I_0}{T}\right)}$

$$\frac{\tau_{ign}(1000\text{ K})}{\tau_{ign}(950\text{ K})} = \frac{e^{\left(\frac{15000}{1000}\right)}}{e^{\left(\frac{15000}{950}\right)}} = 0.454$$

$$\tau_{ign}(950\text{ K}) = 2.2 \tau_{ign}(1000\text{ K})$$

$\Rightarrow$   ~~$L_{ign}$~~   $L_{ign} = U \tau_{ign}$ .

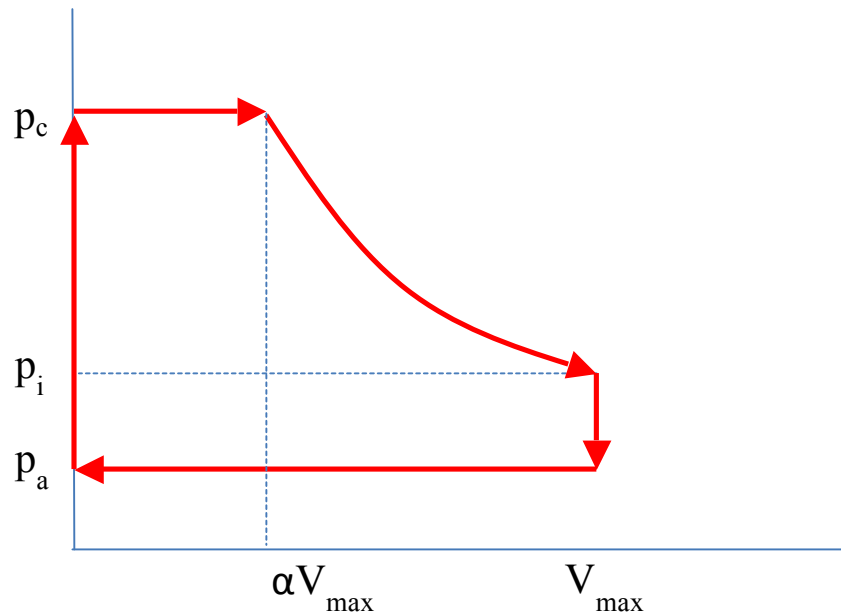
$$\begin{aligned} L_{ign}(950\text{ K}) &= U \tau_{ign}(950\text{ K}) \\ &= 2.2 U \tau_{ign}(1000\text{ K}) \end{aligned}$$

$\Rightarrow$   $L_{ign}(950, K) = 2.2 L_{ign}(1000, K)$

$\Rightarrow$  Ignition at 950 K occurs outside the duct.

Q3

(a)



(b)

$$W = p_c \alpha V_{\max} + \frac{p_c \alpha V_{\max} - p_i V_{\max}}{\gamma - 1} - p_a V_{\max}$$

$$p_i (V_{\max})^\gamma = p_a (\alpha V_{\max})^\gamma, \text{ so } p_i = p_a \alpha^\gamma$$

The air usage will be proportional to  $\alpha V_{\max}$

$$\frac{W}{\alpha V_{\max}} = p_c + \frac{p_c - p_i/\alpha}{\gamma - 1} - \frac{p_a}{\alpha} = p_c + \frac{p_c - p_c \alpha^{\gamma-1}}{\gamma - 1} - \frac{p_a}{\alpha}$$

Differentiating wrt  $\alpha$

$$\frac{d(dW/\alpha V_{\max})}{d\alpha} = -\frac{(\gamma - 1)p_c \alpha^{\gamma-2}}{\gamma - 1} + \frac{p_a}{\alpha^2} = -p_c \alpha^{\gamma-2} + \frac{p_a}{\alpha^2}$$

Which has maximum when  $\alpha = (p_a/p_c)^{1/\gamma}$ , which corresponds to  $p_i = p_a$  as required.

This value should be expected as at this condition there are no irreversibilities associated with a sudden expansion (into or out of the cylinder) when the exhaust valve opens. This is also the reason why starting the process with zero cylinder volume is advantageous – there is no sudden (irreversible) expansion when the inlet valve opens.



(c)

The air mass flow rate is the volume induced times density times the number of cycles per unit time,  $N$ :-

$$\dot{m} = \alpha V_{\max} \frac{P_c}{RT_c} N$$

Also we have from the equation of state,

$$m = \frac{p_c V_c}{RT_c}$$

We are told that the reservoir temperature is constant so we can differentiate this expression to give:-

$$\dot{m} = \frac{V_c}{RT_c} \frac{dp_c}{dt}$$

And equating the two expressions for the mass flow rate we obtain

$$\frac{dp_c}{dt} = p_c \alpha \frac{V_{\max}}{V_c} N$$

(d)

The power output is  $P = WN$ . As the reservoir pressure drops, there will be a minimum value of  $p_c$ ,  $p_{c,\min}$ , at the maximum  $N$ ,  $N_{\max}$ , that will be able to deliver the required power  $P_t$ .

Thus we need to find the value of  $p_{c,\min}$  that satisfies:-

$$P_t = WN_{\max} = \frac{\gamma}{\gamma - 1} V_{\max} p_a \left( \left( \frac{p_{c,\min}}{p_a} \right)^{\gamma-1/\gamma} - 1 \right) N_{\max}$$

Or

$$p_{c,\min} = p_a \left( \frac{P_t}{p_a V_{\max} N_{\max}} \frac{\gamma - 1}{\gamma} + 1 \right)^{\gamma/\gamma-1}$$

**Q4**

(a)

Sketch of basic trends of pollutant levels vs AFR plus justification

uHC sources discussion of :-

crevices (peak pressure effect on packing – spark advance and manifold pressure), oil adsorption/desorption, quenching (surface and bulk (lean/high EGR)), fate of uHC's – oxidation in-cylinder/exhaust port (AFR, spark effects on exhaust gas temp/reactivity), approximate values, small speed effect

CO – discussion of:-

rich chemistry

chemistry during expansion – oxidation mechanisms, relative rates of bimolecular vs trimolecular reactions, freezing out at above equilibrium levels. Any effects increasing uHC tend to increase CO via partial oxidation, small speed effect.

NO<sub>x</sub> – discussion of:-

extended Zeldovich mechanism, relative forward and reverse rates, increasing speed, decreasing time for formation, max temp changes (especially via AFR (though [O<sub>2</sub>] effect too), spark, EGR) lead to [NO<sub>x</sub>] changes, NO<sub>2</sub> insignificant

(b)

plot of trade-off between NO<sub>x</sub> and smoke

NO forms fastest in regions close to stoichiometric. Burned gas temperature is the most important variable, oxygen availability the second most important. – In Diesel always some regions burning at close to stoichiometry. – EGR/late SOI reduce max temps. Speed decreases NO due to lower peak temps and combustion duration. NO<sub>2</sub> significant (up to 30%) due to freezing, EGR reduces NO<sub>x</sub>, by decreasing the heat input per unit mass burning. Leaner AFR's decrease NO<sub>x</sub> mainly due to less fuel burning, and lower peak pressures (temperatures). Late SOI reduces NO<sub>x</sub> due to lower press/temps.

Particulates form in the rich combustion zones that always exist in Diesel combustion. The vast majority of the particles formed (by nucleation (after dehydrogenation, oxidation), surface growth, agglomeration, adsorption/condensation (largely by uHC's)). Smoke rises with engine speed/EGR (dramatically at a certain level), late SOI. Smoke rises very sharply at AFR's approaching stoichiometry due to insufficient oxidation.