

Q1(a) H_2 has no C \Rightarrow no CO_2
Higher flame speed \Rightarrow higher risk of flashback.
Larger flammability limit \Rightarrow better opportunity
to burn lean \Rightarrow low NO_x .

No other pollutants

H_2 leak, however, has greenhouse potential and
has increased safety risks.

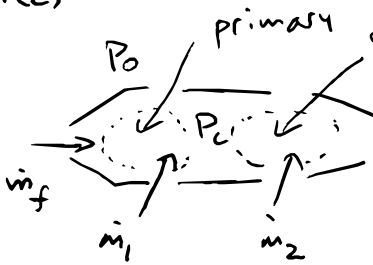
Flame stabilisation is not a problem, but
if injection velocities are not high, flame attachment
might be a problem (too close to the
metal).

(b) If H_2O is added to the air upstream of the
combustor, from a Joule cycle perspective we may
improve things (more mass through turbine; the water
would have been injected in liquid form & allowed
to evaporate, hence smaller penalty to compress
it to the combustor pressure.

From a combustion perspective, the addition
of inert would decrease flame speed. In a
non-premixed system, the flame position would
change little. In a premixed one, the lower
flame speed implies a change in flame angle
relative to the flow, hence anchoring might be
compromised. But unwanted flashback is less risky.

The biggest effect will be a decrease in NO
emission. The inert H_2O will reduce the flame
temperature \Rightarrow NO reduced greatly.

Q1(c)



$\dot{m}_1 + \dot{m}_2 = \dot{m}_a$ total air flow rate
 \dot{m}_f : fuel flow rate

Design point: $\left. \begin{aligned} \left(\frac{\dot{m}_f}{\dot{m}_1}\right) / \text{FAR}_{st} &= 1 \\ \left(\frac{\dot{m}_f}{\dot{m}_1 + \dot{m}_2}\right) / \text{FAR}_{st} &= 0.5 \end{aligned} \right\} \Rightarrow \dot{m}_1 = \dot{m}_2$

$\dot{m}_1 = A_1 \rho V_1$ A_1 : area of primary air inlets
 V_1 : air velocity at primary air inlets

$\Delta P = C_d \frac{1}{2} \rho V_1^2 \Rightarrow V_1 = \left(\frac{2\Delta P}{\rho C_d}\right)^{1/2}$
 $\Rightarrow \dot{m}_1 = \rho A_1 \left(\frac{2\Delta P}{\rho C_d}\right)^{1/2}$ Since $\dot{m}_2 = \dot{m}_1$,
 $A_2 = A_1$

Hence $\dot{m} = (A_1 + A_2) \rho \sqrt{\frac{2\Delta P}{\rho C_d}}$

With manufacturing defect, new area of secondary air inlets is $A'_2 = 2A_2$ & A_1 remains the same. Total air flow remains the same.

$\dot{m}'_1 = A_1 \rho \left(\frac{2\Delta P'}{\rho C_d}\right)^{1/2}$ & $\dot{m}'_2 = 2A_1 \rho \left(\frac{2\Delta P'}{\rho C_d}\right)^{1/2}$

$\Rightarrow \frac{\dot{m}'_1}{\dot{m}'_2} = \frac{1}{2}$ But $\dot{m}'_1 + \dot{m}'_2 = \text{constant} = \dot{m}$

$\Rightarrow \dot{m}'_1 = \frac{1}{3} \dot{m}$ & $\dot{m}'_2 = \frac{2}{3} \dot{m}$

The air distribution along the combustor changed. The overall ϕ did not change; the overall ϕ is equal to the one in the secondary (since the exit of the primary flows into the secondary).

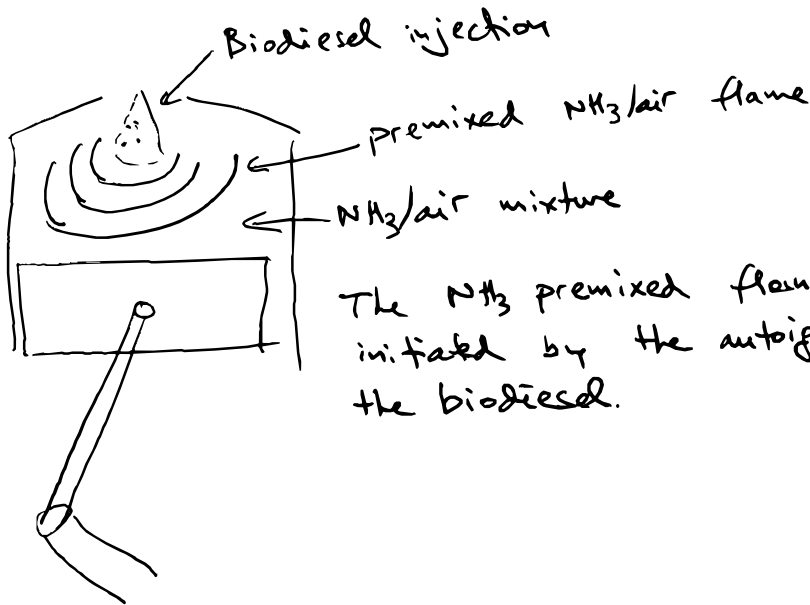
$$\Rightarrow \text{New } \phi_1 = \frac{\dot{m}_f}{\frac{1}{3} \dot{m}} = 3 \times 0.5 = 1.5$$

$$\phi_2 = \text{same} \quad (\text{since total fuel \& air flow rates are unchanged.}) \\ = 0.5$$

The air distribution changed. The primary now is richer.

We may expect lower NO production, since ϕ increased beyond the stoichiometry. We certainly get more soot. Stability would depend on the nature of the flame: if premixed, $\phi > 1.5$ vs $\phi = 1$ implies worse stability limit. If non-premixed, probably little difference. With a primary $\phi = 1.5$ we expect some reactions also to occur at the secondary - perhaps if we don't get that mixing right we may expect more CO.

Q2 (a)



This combustion system must be lean so that the diesel + NH_3 locally at the diesel injection has enough oxygen to autoignite & burnout the diesel completely. Still, we may expect some soot, as in all diesel concepts, to form. Since only small amounts of biodiesel are injected, we expect small soot compared to conventional biodiesel-only engine, but not zero.

NO_x may be higher with NH_3 due to the fuel-bound N. Thermal NO , however, may be a little lower due to the lower flame T from NH_3 . We also have the possibility of N_2O .

We may get NH_3 slip, as for hydrocarbon emissions in SI engines, due to devices (since this is a premixed flame).

Q2-1

Q2(a) Cont'd

To reduce these emissions we need lean operation or to use post-treatment.

Emissions from such engines are the topic of research.

- (b) We expect autoignition time to be delayed relative to the biodiesel case. This is because
- (i) we have less O_2 in our oxidiser due to the presence of the other fuel;
 - (ii) as radicals build-up to take us to the liquid fuel ignition, they may be consumed by the NH_3 , hence delaying the process.

If we increase the biodiesel injection amount, the combustion of this fuel will increase P_{zT} of the unburnt NH_3 /air mixture further than the rise due to a smaller amount. Hence the NH_3 /air flame will be quicker.

A further change will be that the ignition spot will be larger \Rightarrow quicker burn duration in crank angle degrees.

1) Q3

(a) R1: Chain terminating - consumption of radical species to produce H_2O .

R2: chain propagating - the number of radicals does not change despite changing identity.

$$(b) (i) \quad \frac{d[NO]}{dt} = k_{3f}[O][N_2] - k_{3b}[NO][N] + k_{4f}[N][O_2] - k_{4b}[NO][O]$$

(ii) Assume species N is in steady-state, i.e. the net production rate is approximately zero. ($d[N]/dt \approx 0$).

Assume all backward reactions have zero rate.

For reactions R3 and R4, the atom N is in steady state. The reaction R4 is much faster than R3 as N is consumed as soon as some N is produced. The steady-state approximation for N can be written as:

$$\begin{aligned} \frac{d[N]}{dt} &= k_{3f}[N_2][O] - k_{4f}[O_2][N] = 0 \\ \Rightarrow [N] &= \frac{k_{3f}[N_2][O]}{k_{4f}[O_2]} \end{aligned}$$

Substituting this result into the result obtained in (i) and neglecting backward reactions gives:

$$\begin{aligned} \frac{d[NO]}{dt} &= k_{3f}[N_2][O] + k_{4f}[O_2] \frac{k_{3f}[N_2][O]}{k_{4f}[O_2]} \\ &= 2k_{3f}[N_2][O] \end{aligned}$$

Q.E.D.

(c)(i) Three mechanisms for NO production:

- 1) Fuel NO: Nitrogen in the fuel contributes to this NO. It is formed through reactions with hydrocarbon radicals, such as CH or CH_3 , to form CHN .
- 2) Prompt NO: The nitrogen contained in air is attacked by hydrocarbon radicals to form CHN . The NO forms as quickly as the ~~combustion~~ combustion reactions. Difficult to control unless air is replaced by oxygen.
- 3) Thermal NO: The most common and major contributor to NO generation in combustion processes. It is described using the Zel'dovich mechanisms (R3 and R4), with an overall reaction of $\text{N}_2 + \text{O}_2 \rightarrow 2\text{NO}$.

The O atom is provided by the dissociation reaction of O_2 ($\text{O}_2 \rightleftharpoons 2\text{O}$). This occurs at very high temperatures ($T > 1800\text{K}$) and is typically slow compared to combustion reactions. Therefore, the residence time at high temperature plays a vital role for the total amount of thermal NO formed.

Mitigation methods:

SI engines:

- Catalytic reduction: NO to N_2 and O_2 .
- Lean burning: reduces the peak flame temperature.
- Exhaust gas recirculation: reduces the temperature and reduced N_2 and O_2 levels.

Diesel engines:

- EGR
- Selective catalytic reduction using ammonia.

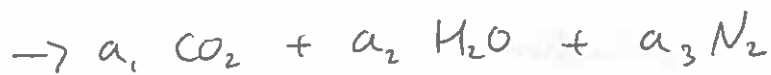
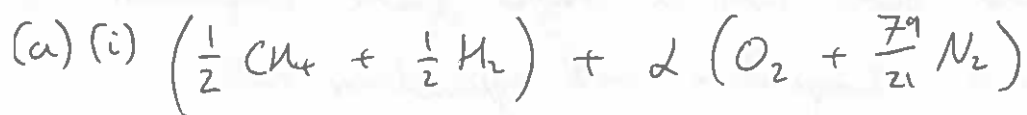
Gas turbines:

- Lean burning.
- Good mixing between fuel and air to prevent hot spots and non-premixed combustion.
- Rich-lean-lean (RLL) concept. Rich flame is used in primary zone of the combustor, rapid mixing with air to lower the temperature and extra fuel burns lean.

EGR and catalytic reduction can also be used in coal power stations, industrial burners and incinerator.

(ii) NO formation is greater in H_2 -air combustion, as H_2 is more reactive and burns with a higher flame temperature for a given pressure, temperature and equivalence ratio as in CH_4 -air combustion.

② Q4



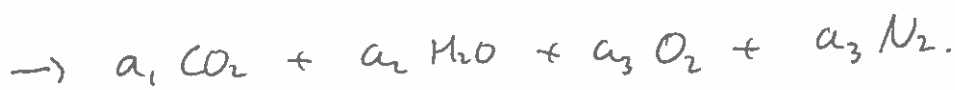
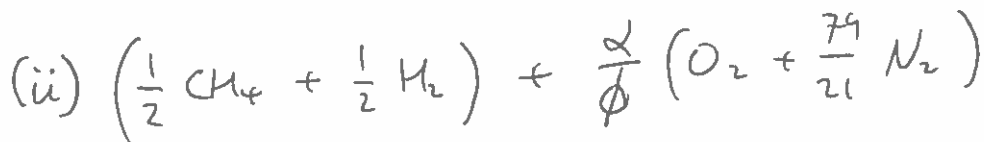
$$\text{C: } 0.5 = a_1$$

$$\text{H: } 0.5 \times 4 + 0.5 \times 2 = 2a_2 = 3 \Rightarrow a_2 = 1.5$$

$$\text{O: } 2\alpha = 2a_1 + a_2 = 2 \times 0.5 + 1.5 = 2.5 \Rightarrow \alpha = 1.25$$

$$\text{N: } a_3 = \alpha \frac{79}{21}$$

$$\phi = \frac{\dot{m}_f / \dot{m}_a}{(\dot{m}_f / \dot{m}_a)_{st}} = \frac{\left(\frac{1}{30} \right)}{\left(\frac{0.5 \times 16 + 0.5 \times 2}{1.25 \left(32 + \frac{79}{21} \times 28 \right)} \right)} = 0.6358$$



$$\text{C: } a_1 = 0.5$$

$$\text{H: } a_2 = 1.5$$

$$\text{O: } 2 \frac{\alpha}{\phi} = 2a_1 + a_2 + 2a_3 \Rightarrow a_3 = \frac{1}{2} \left(2 \frac{\alpha}{\phi} - 2a_1 - a_2 \right)$$

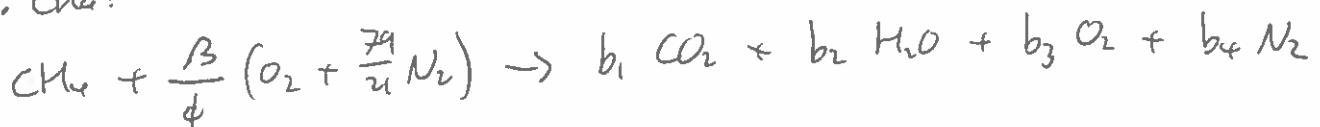
$$= \frac{1}{2} \left(2 \times \frac{1.25}{0.6358} - 2 \times 0.5 - 1.5 \right)$$

$$= 0.71603$$

$$\text{N: } a_4 = \frac{\alpha}{\phi} \frac{79}{21} = 7.39601$$

$$\therefore (X_{\text{CO}_2})_{50\%} = \frac{0.5}{0.5 + 1.5 + 0.71603 + 7.39601} = 0.04945$$

For 100% CH₄:



$$\beta = x + \frac{y}{4} \text{ for } \text{C}_x\text{H}_y \text{ fuel} \Rightarrow \beta = 1 + \frac{4}{4} = 2$$

$$C: 1 = b_1$$

$$H: 4 = 2b_2 \Rightarrow b_2 = 2$$

$$O: 2 \frac{\beta}{\phi} = 2b_1 + b_2 + 2b_3 \Rightarrow b_3 = \frac{1}{2} \left(2 \frac{\beta}{\phi} - 2b_1 - b_2 \right)$$
$$= \frac{1}{2} \left(2 \times \frac{2}{0.6358} - 2 \times 1 - 2 \right)$$
$$= 1.14564$$

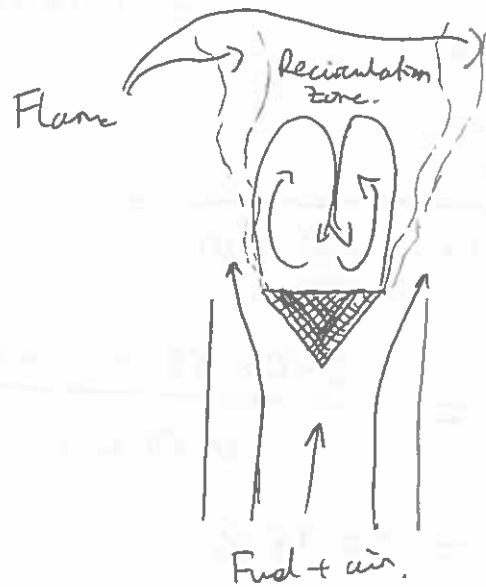
$$N: b_3 = \frac{\beta}{\phi} \frac{79}{21} = 11.83361$$

$$\therefore (X_{CO_2})_{100\%} = \frac{1}{1 + 2 + 1.14564 + 11.83361} = 0.06258$$

$$\therefore \% \text{ reduction in } CO_2 = \frac{0.06258 - 0.04945}{0.06258} \times 100$$
$$= 20.98\%$$

(b) (i) Flame blow-off is considered to be the complete extinction of the flame in a combustion system. In general, the flame will extinguish if the reaction cannot keep up with the supply of reactants. The residence time of the reactants must be long enough compared to the time needed to complete the reactions, i.e. $\tau_{chem} > C \tau_{res}$, where τ_{chem} is the chemical time scale, τ_{res} is the residence time and C is a constant.

(ii) In practical combustion systems, the reactants are supplied at high velocities and therefore, the flow is turbulent and the flame cannot propagate against the reactants. A bluff body flame holder can be used to keep the flame anchored.



The bluff body creates a low-velocity region of recirculating flow. This region contains hot combustion products as they are transported from the flame to the anchoring point to ignite incoming reactants and therefore, the recirculation zone is a constant ignition source.

The recirculation zone is very turbulent and well-mixed, and can therefore be approximately represented by a well-stirred reactor. The flame blow-off limits are therefore determined by the conditions under which the WSR extinguishes.

Bluff body flame holders are typically used for afterburners in military aircraft engines.