4A13 – Combustion & Engines

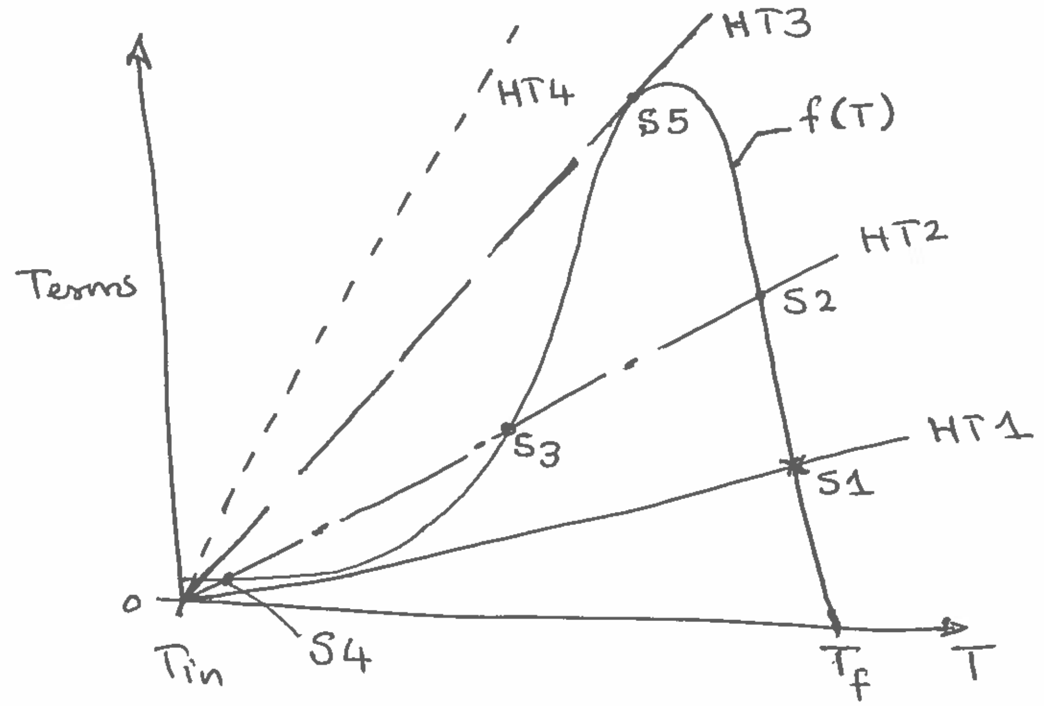
Cribs - 2021

1) (a) The energy balance for a well-stirred reactor is

$$\frac{\dot{m}}{\rho V}(T - T_{in}) = -\dot{\omega}_f \frac{LHV}{c_p} = c\, f(T) \quad \text{— (A)}$$

$\dot{m}$ – mass flow rate c – constant.
ρ – reactant density
V – Volume of the reactor
$f(T)$ – heat generation by chemical reaction

Plot of L.H.S & R.H.S of Eq. (A) is



The L.H.S. is a linear term in T with a slope $(\dot{m}/\rho V) = 1/t_{res}$

⇒ The residence time, t_{res}, is smaller for larger heat loss (larger slope).

For HT1 – larger residence time
⇒ Stable flame @ S1.

HT2 – intermediate residence time
if the reactor temperature is large then one gets a Stable flame @ S2

if T is low, then no flame @ S4, S3 is unstable Solution and it will move to S4.

HT3 – Critical residence time

A Small increase in ṁ leading to a small decrease in t_{res} will extinguish the flame leading to flame blow-off. This depends on reactant temperature, equivalence ratio, fuel, and pressure. This is governed by competing effects of heat generation and heat loss, which can be written as

$$t_{chem} > c\, t_{res}.$$

HT4 – residence time is too short for chemical reactions to occur
⇒ No flame.

(b) At blow-off

$$\frac{\tau_{chem}}{\tau_{res}} = C$$

$\tau_{chem} \sim T_0^{-5/2}$

$\tau_{res} = \frac{L}{U} = \frac{L \rho A}{\dot{m}}$

ideal gas mixture

$\Rightarrow \rho \sim \frac{1}{T_0}$

$\therefore \tau_{res} = \frac{LAPR}{\dot{m} T_0}$

$= B \frac{L}{\dot{m} T_0}$

① ref. condition

② - new condition.

$$\therefore \frac{\tau_{chem,1}}{\tau_{res,1}} = \frac{\tau_{chem,2}}{\tau_{res,2}}$$

$$\frac{\dot{m}_2 T_{0,2} T_{0,2}^{-5/2}}{\cancel{B} L_2} = \frac{\dot{m}_1 T_{0,1} T_{0,1}^{-5/2}}{\cancel{B} L_1}$$

$$\Rightarrow \boxed{\frac{\dot{m}_2}{\dot{m}_1} = \frac{L_2}{L_1} \left(\frac{T_{0,2}}{T_{0,1}}\right)^{3/2}}$$

(i) T_0 is doubled, all others kept const.

$\Rightarrow T_{0,2} = 2 T_{0,1}$ $\quad L_2 = L_1$

$\Rightarrow \frac{\dot{m}_2}{\dot{m}_1} = 2\sqrt{2} = 2.828$

$\dot{m}_2$ is increased by nearly 183%.

(ii) $L_2 = 2L_1$ and other parameters kept const.

$\Rightarrow \frac{\dot{m}_2}{\dot{m}_1} = 2 \Rightarrow$ $\dot{m}_2$ is increased by 100 %

(c) Three mechanisms:

1. <u>Fuel NO</u>: Nitrogen in the fuel contributes to this NO, formed through reactions with hydrocarbon radicals such as CH, CH_3 forming CHN.

2. <u>Prompt NO</u>: Air bound N reacting with hydrocarbon radicals as above. Difficult to control this unless air is replaced with Oxygen.

3. <u>Thermal NO</u>: This is common and major contributor to NO generation in combustion processes. and it is described using Zeldovich mechanism

$$N_2 + O \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O$$

with an overall reaction of $N_2 + O_2 \rightarrow 2NO$. The O-atom is provided by the dissociation of O_2 at $T > 1800K$ and this reaction is typically slow compared to combustion reactions. Thus, the residence time at high temperature plays a vital role for the total amount of thermal NO formed.

Mitigation methods:

S. I. engines: 1) Catalytic reduction
$NO \rightarrow N$ & O_2
2) Lean burning ⇒ reduced peak/flame temperature.
3) EGR - reduced T, reduced N_2, and O_2 levels

Diesel engines:
1) EGR, (2) Selective Catalytic reduction using ammonia.

Gas Turbines:
1) Lean burning. (2) Good fuel-air mixing to avoid Hot Spots and diffusion combustion.

Coal - Power Station: - This could be a thing of the past because of recent outcries to mitigate climate change.
EGR, NOx reburn and Selective catalytic reduction using ammonia can be employed to reduce NOx emissions.

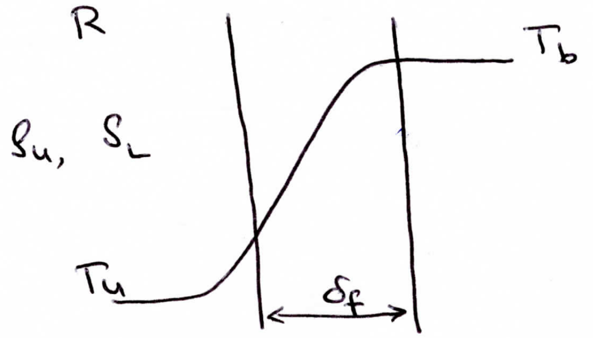
These techniques can also be used for industrial burners and incinerators.

Examiner's comments:

This was a very popular question as it was a straightforward one. Generally, answered very well. Student demonstrated good understanding of flame blow-off mechanisms and their application to the analysis in part (b). The generation routes for NOx were also discussed quite well in part (c). Algebraic errors were found to be common in the analysis required for part (b).

2)

(a)



energy Generated $\approx$ Conducted

$$\dot{\omega}\, c_p (T_b - T_u) A \delta_f \approx \lambda A \frac{(T_b - T_u)}{\delta_f}$$

$$\Rightarrow \boxed{\delta_f^2 \approx \frac{\lambda}{\dot{\omega} c_p}}$$

mass reacted inside the flame $\approx$ mass coming in

$$\dot{\omega} A \delta_f \approx \rho_u S_L A \Rightarrow S_L \approx \frac{\dot{\omega}}{\rho_u} \delta_f$$

$$\Rightarrow \boxed{S_L = \frac{1}{\rho_u}\sqrt{\frac{\lambda \dot{\omega}}{c_p}}}$$

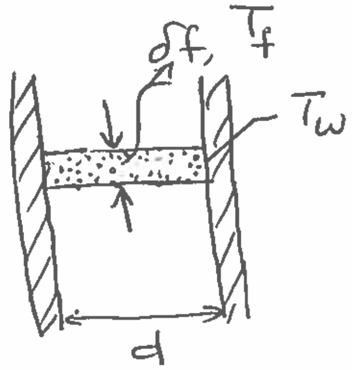
by using the expression above for δ_f.

From the above equations one gets

$$\delta_f S_L \approx \frac{\lambda}{\rho_u c_p} = \alpha$$

thermal diffusivity as required.

(b) Consider one hole with the flame inside



$T_u = 298$ K, $P = 1$ atm.

Heat generated in the flame = Conducted away to the wall.

$$\dot{\omega} C_p (T_f - T_u) \frac{\pi d^2}{4} \delta_f = \pi d \delta_f \lambda \frac{2(T_f - T_w)}{d}$$

Taking $\dot{\omega} = \rho_u \frac{S_L}{\delta_f}$ and rearranging gives

$$d = \left\{ \frac{8 \lambda (T_f - T_w) \delta_f}{\rho_u C_p S_L (T_f - T_u)} \right\}^{1/2}$$

$$\Rightarrow \quad d = \left\{ 8 \left(\frac{\alpha}{S_L}\right) \delta_f \frac{(T_f - T_w)}{(T_f - T_u)} \right\}^{1/2} \qquad \alpha = \left(\frac{\lambda}{\rho C_p}\right)$$

thermal diffusivity.

(i) for flame quenching

heat generated < Conducted away.

& $T_w = T_u$

$$\Rightarrow \quad d \leq 2\sqrt{2} \sqrt{\left(\frac{\alpha}{S_L}\right) \delta_f} \qquad \alpha \sim \delta_f S_L$$

$$\therefore \quad \boxed{d \leq 2\sqrt{2}\, \delta_f}$$

(ii) $S_L \sim p^{-1/2}$; $\alpha = \frac{\lambda}{\rho c_p}$ & for ideal gas $\alpha \sim p^{-1}$

$\alpha \sim \delta_f S_L \Rightarrow \delta_f \sim \frac{\alpha}{S_L}$

$\therefore \boxed{\delta_f \sim p^{-1/2}}$

$\Rightarrow \frac{d_5}{d_1} = \frac{\delta_{f,5}}{\delta_{f,1}} \sim \frac{1}{\sqrt{5}} \Rightarrow \boxed{d_5 = 0.447 d_1}$

$\Rightarrow$ The hole diameter decreases by nearly 55 %

(iii) $\alpha = \frac{\lambda}{\rho c_p}$

$\lambda \sim T_u^{1/2}$ $\rho \sim T_u^{-1} \Rightarrow \alpha \sim T_u^{3/2}$
& $S_L \sim T_u^{2}$

$\therefore \delta_f \approx \frac{\alpha}{S_L} \sim T_u^{-1/2}$

$\Rightarrow \frac{d_{400}}{d_{298}} = \left(\frac{298}{400}\right)^{1/2} \Rightarrow \boxed{d_{400} = 0.863 d_{298}}$

The hole diameter decreases by 13.7 %

Examiner's comments:

The popular question had correct answer to part (a), demonstrating a good understanding of laminar premixed flame and its structure. The second part was also answered quite well but a common error was in identifying the correct area for conductive heat loss from the flame to the metal plate. This led to incorrect hole diameter and some students showed difficulty to rearrange inequality relations with fractional powers.

Q3 (a)
Here we compare the work output from the throttled and unthrottled cycles. The ratio of these work outputs represents the fraction of the time that the start/stop engine must run to supply the same average power demand. The fuel consumption is proportional to the average air flow.

For an inlet manifold pressure of p_1, $W_{12} = p_1V_1(1 - 9^{0.4}) = -1.408\, p_1V_1$. The mass of air induced is $m = \frac{p_1 v_1}{RT_1}$. The temperature at the end of compression is given by
$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1} = 2.408$, and, $T_2 = 722.4$ K, $T_3 = 2522.4$ K. Now $p_3V_3 = mRT_3$, so
$p_3 = \frac{p_1 v_1}{RT_1}\frac{RT_3}{V_3} = \frac{9*2522.4*p_1}{300} = 75.672\, p_1$.

Thus, the work done during the expansion is
$W_{34} = p_3V_3(1 - 1/9^{0.4}) = 75.672 p_1 \frac{V_1}{9} 0.5848 = 4.917 p_1 V_1$

The pumping work is given by $W_p = (p_1 - p_{amb})(V_1 - V_2) = 0.89 p_1 V_1 \left(1 - \frac{p_{amb}}{p_1}\right)$.

The net work per working cycle is

$$W_{net} = \left[4.917 - 1.408 + 0.89\left(1 - \frac{p_{amb}}{p_1}\right)\right] p_1 V_1.$$

For unthrottled running $W_{net} = 3.509 p_1 V_1$, and for throttled running, $p_1 = 0.35$ bar, $W_{net} = 1.856 p_1 V_1$. Thus, the stop/start engine runs (100)(1.856)(0.35/3.509) = 18.5% of the time. As the AFR is the same, the fuel consumption is proportional to the air flow multiplied by the time running. The ratio of the fuel usage is therefore 1.856/3.509= 0.53, corresponding to a 47% fuel saving. (Calculations at other levels of throttling show that the benefit is very pronounced at highly throttled conditions, but falls off rapidly for higher manifold pressures.)

(b) Potential advantages:

1) By preventing fuel consumption during idle in slow moving traffic, start/stop allows greater overall efficiency, at a small penalty of electrical losses.
2) For the same engine power rating, highway performance is little affected by start/stop.

Potential disadvantages:

1) The electric transmission (generator and motor) has to handle the whole engine power, the electrical machines and battery can be large and heavy, adding weight to the vehicle and thus detrimental to overall efficiency.
2) The battery size has to be increased (adding further weight penalty), and frequent cycling may lead to shorter battery lifetime.

Examiner's comments:

This was second most popular question with good answers to both parts (a) and (b). The students demonstrated a good understanding of the workings of the two engines, setup the correct relations for the net work per working cycle. Many students did not recognise that keeping p1 and V1 as they were simplifies the analysis and also there were errors in obtaining the pumping work for throttled (standard) engine. These issues lead to incorrect estimates of fuel saving and the fraction of time the hybrid engine was running.

4. (a) Starting with the energy equation, for a constant volume, constant mass system, we have:

$$\begin{aligned} dE = d(me) &= d(m_u e_u + m_b e_b) \\ d(mc_v T) &= md((1-x)e_u + xe_b) \\ \frac{mc_v}{\rho R} dp = mc_v d[(1-x)T_u + xT_b] &= mc_v d[T_u + x(T_b - T_u)] \\ \frac{1}{\rho R} dp = dT_u + d[(T_b - T_u)x] &= dT_u + xd(T_b - T_u) + (T_b - T_u)dx \end{aligned}$$

(b) We start from the equation in the previous item, and assume that $\Delta T = (T_b - T_u)$ is constant, so that:

$$\frac{1}{\rho R} dp = dT_u + d[(T_b - T_u)x] = dT_u + \Delta T dx$$

This can be integrated if dT_u can be expressed as a function of pressure. For an isentropic process,

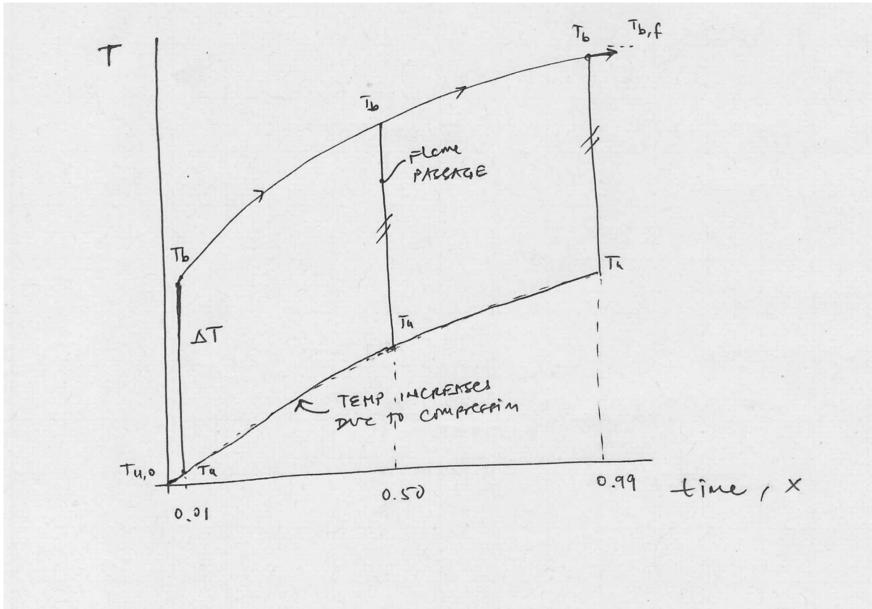
$$\begin{aligned} Tds = dh - \frac{1}{\rho} dp = c_p dT - \frac{RT}{p} dp &= 0 \\ \frac{\gamma}{\gamma - 1} \frac{dT}{T} &= \frac{dp}{p} \\ \frac{T_u}{T_{u0}} &= \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} \\ dT_u = \frac{\gamma - 1}{\gamma} T_u \frac{dp}{p} = T_{u0} \frac{\gamma - 1}{\gamma} \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} &\frac{dp}{p} \end{aligned}$$

Substituting:

$$\begin{aligned} \frac{1}{\rho R} dp &= dT_u + \Delta T dx \\ \frac{1}{\rho R} dp = \frac{\gamma - 1}{\gamma} T_{u0} \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} &\frac{dp}{p} + \Delta T dx \\ \Delta T dx = \frac{1}{\rho R} dp - T_{u0} \frac{\gamma - 1}{\gamma} \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} &\frac{dp}{p} \\ dx = \frac{1}{\rho R \Delta T} dp - \frac{T_{u0}}{\Delta T} \frac{\gamma - 1}{\gamma} \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} &\frac{dp}{p} \end{aligned}$$

Integrating between the initial pressure p_0 and p:

$$\begin{aligned} x &= \frac{1}{\rho R \Delta T} (p - p_0) - \frac{T_{u0}}{\Delta T} \left[\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \\ x &= \frac{T_{u0}}{\Delta T} \left[\left(\frac{p}{p_0} - 1\right) - \left[\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right] \end{aligned}$$



(c)

(d) The maximum pressure is reached when the reaction is complete. Under those conditions, $x = 1$, and the final pressure is reached, which can be extracted from the transcendental equation below:

$$1 = \frac{T_{u0}}{\Delta T}\left[\left(\frac{p_f}{p_0} - 1\right) - \left[\left(\frac{p_f}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right]$$

In order for the assumption to be valid, the value of p_f/p_0 must equal the value obtained from the overall energy conservation given by $m\,q = \int_i^f dE$. This leads to

$$\frac{p_f}{p_0} = 1 + (\gamma - 1)\frac{q}{RT_{u0}}.$$

Examiner's comments:

This least popular question was answered reasonably well. The students were able to setup the energy balance required for part (a) but unable to carry out the integration required for part (b) because they did not recognise that dp and dT could be related using isentropic relations. Some of these 9 candidates couldn't attempt parts (c) and (d) as they ran out of time.