ENGINEERING TRIPOS PART IIB 2012
4A13 COMBUSTION AND IC ENGINES **Dr N Swaminathan**

(Q1.)

$$A \xrightarrow{k_1} C \qquad (R1)$$

$$A + C \xrightarrow{k_2} \alpha C + \text{Product} \qquad (R2)$$

$$C \xrightarrow{k_w} \text{Product} \qquad (R3)$$

$$C + M \xrightarrow{k_g} M + \text{Product} \qquad (R4)$$

(a) (R1) – is chain initiation as it produces radical

(R2) – is chain branching if $\alpha > 1$
chain carrier if $\alpha = 1$
chain terminator if $\alpha = 0$

(R3) – is wall termination

high energy molecule colliding with the walls of the vessel, looses energy and becomes a stable molecule.

(R4) – is gas ~~[illegible]~~ phase termination.

For gas phase termination reaction, a collision partner is required, but for wall termination, this is not required.

(b)
$$\frac{d[C]}{dt} = k_1[A] + (\alpha - 1)\, k_2 [A][C] - k_w [C] - k_g [M][C]$$

(c) For steady state condition.

$$\frac{d[C]}{dt} = 0 = k_1[A] + [C]\left\{(\alpha-1)k_2[A] - k_w - k_g[M]\right.$$

$$\Rightarrow \quad [C] = \frac{k_1[A]}{(1-\alpha)k_2[A] + k_w + k_g[M]}$$

To have finite [C]

$$(1-\alpha)k_2[A] + k_w + k_g[M] > 0$$

Rearranging this gives

$$\boxed{\alpha < 1 + \frac{k_w + k_g[M]}{k_2[A]}}$$ as required

(d) The radical concentration becomes very large when chemical explosion has occurred.

$$\Rightarrow \quad (1-\alpha)k_2[A] + k_w + k_g[M] = 0$$

rearranging and simplifying gives

$$\alpha = 1 + \frac{k_w + k_g[M]}{k_2[A]}$$

But in the equation for $\frac{d[C]}{dt}$, when k_i's, [M] and [A] are constant, which is acceptable in the early stages of the given reacting system, then [C] will grow exponentially if $\alpha > 1$

Thus the condition for the Chemical explosion becomes

$$\boxed{\alpha \geqslant 1 + \frac{k_w + k_g[m]}{k_2[A]}}$$

(e) Rewrite this condition as

$$\alpha \geqslant 1 + \frac{k_g[m]}{k_2[A]}\left\{1 + \frac{k_w}{k_g[m]}\right\}$$

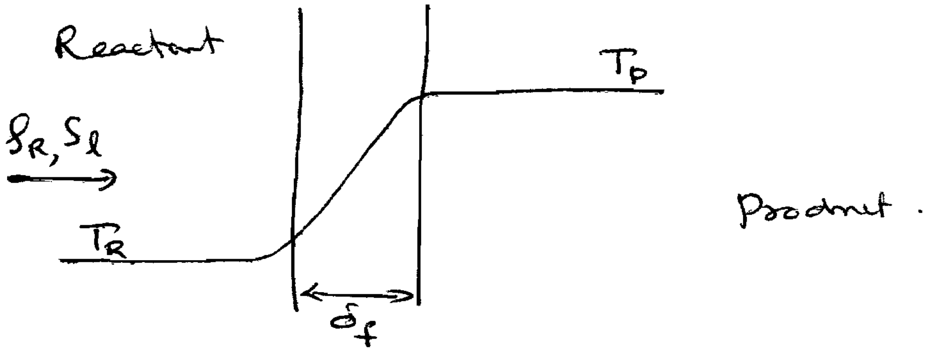
if $k_w << k_g[m]$ then, one gets

$$\boxed{\alpha \geqslant 1 + \frac{k_g[m]}{k_2[A]}}$$

Examiner's note:

The students showed a good understanding of chemical kinetics and able to deduce the condition for chemical explosion. However, few students showed difficulty while carrying out simple algebraic rearrangement of the inequality required for the explosion condition.

(Q2)



(a) Reactive heat flux = Conductive heat flux

$$H\dot{\omega}\delta_f = \lambda\frac{(T_p-T_R)}{\delta_f};$$ H - heat of combustion.

$$C_p(T_p-T_R)\dot{\omega}\delta_f = \lambda\frac{(T_p-T_R)}{\delta_f}$$

$$\Rightarrow \boxed{\delta_f^2 = \frac{\lambda}{C_p\dot{\omega}}}$$

(b) Convective mass flux into the flame = Reactive mass flux

$$\rho_R S_l = \dot{\omega}\delta_f \Rightarrow \boxed{S_l = \frac{1}{\rho_R}\sqrt{\frac{\lambda\dot{\omega}}{C_p}}}$$

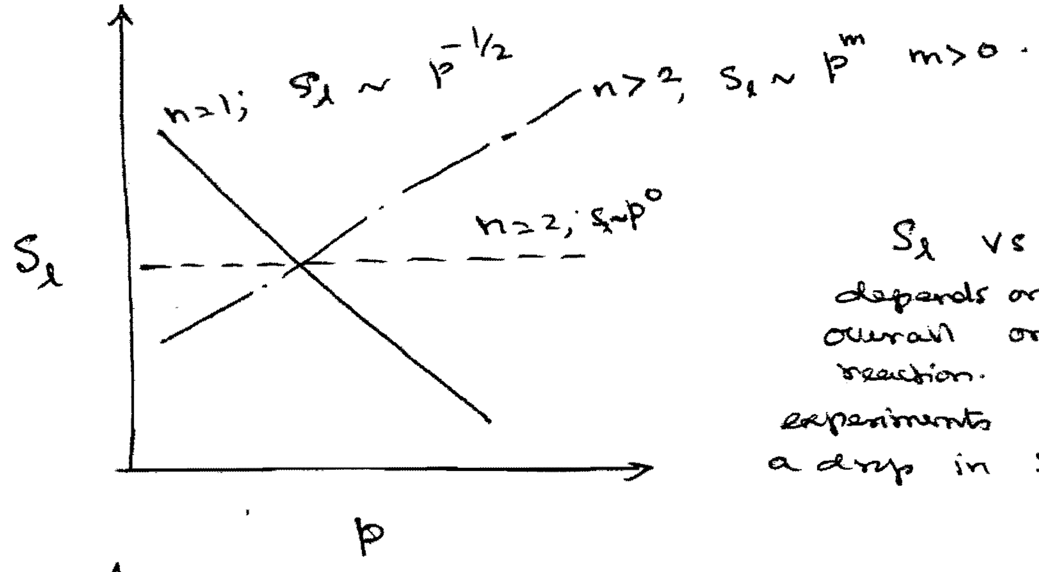
after using the results from (a)

(c) $\dot{\omega} = A_f \, p^n \, Y_R \, \exp\left(-\frac{T_a}{T_p}\right)$

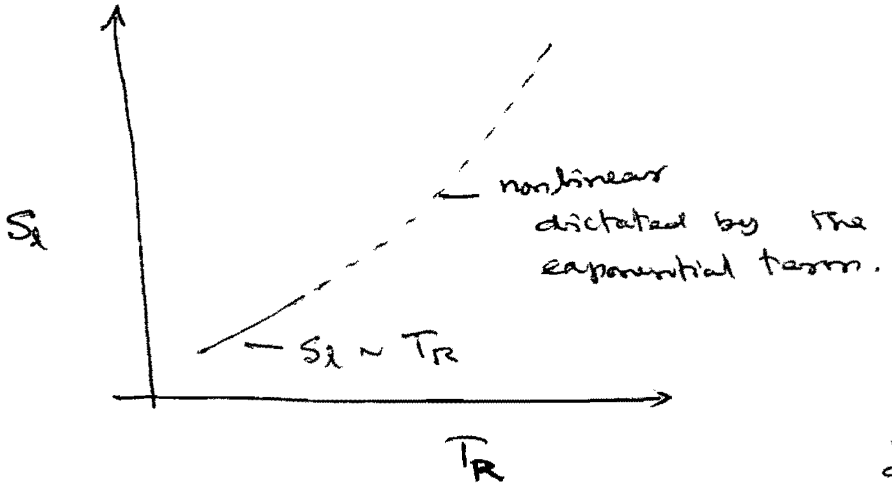
$$\Rightarrow \quad S_l = \frac{1}{\rho_R} \sqrt{\frac{\lambda}{c_p} A_f Y_R} \; p^{n/2} \exp\left(-\frac{T_a}{2T_p}\right)$$

$$\rho_R = \frac{p}{R T_R}$$

$$\Rightarrow \quad S_l = \sqrt{\frac{\lambda}{c_p} A_f Y_R R^2} \; T_R \; p^{\frac{n-2}{2}} \exp\left(-\frac{T_a}{2T_p}\right)$$

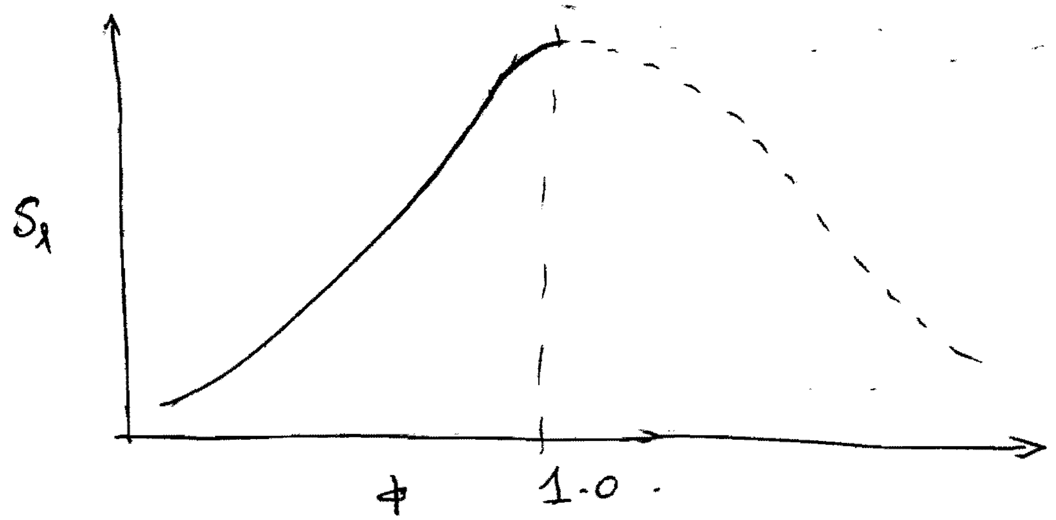


S_l vs p depends on the overall order of the reaction. experiments shows a drop in S_l with p.



As T_R ↑ T_p also increases. The increase in T_p will be small for small change in T_R and thus, the linear term will dominate for small increase in T_R.

For large increase in T_R, the exponential term



As $\phi \left(= \frac{F/air}{(F/air)_{st}}\right)$ increases Y_R will increase and thus S_l will increase if everything else remains constant. But, T_p will also increase as ϕ increases. Thus, the final behaviour of S_l with ϕ will be due to the compounded effects of Y_R, A_f, and T_p in the above expression. Generally, this would give an increase in S_l as ϕ increases.

The behaviour of S_l for $\phi > 1$ is not fairly represented by the above expression, because the ω expression used is good for lean mixtures.

(d) overall mass balance : $\rho_R S_l = \rho_p u_p$

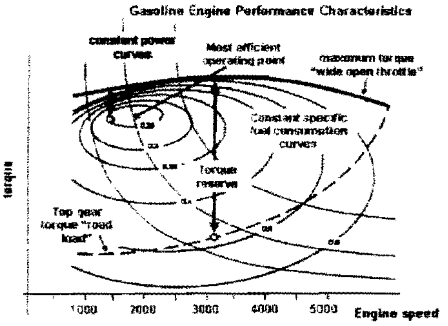
$$\Rightarrow u_p = \frac{\rho_R}{\rho_p} S_l = \frac{T_p}{T_R} S_l$$ if $P =$ const & Mol. wt = const across the flame

$$\Rightarrow u_p - S_l = S_l\left(\frac{T_p}{T_R} - 1\right) = \tau S_l \Rightarrow \boxed{u_p = (1+\tau) S_l}$$

Examiner's note to Q2:

One of the general difficulty was observed to be in setting up the energy balance required to deduce the flame thickness in part (a) of this question. Another common mistake was to treat the reactant density as a constant while answering the pressure dependence of flame speed in part (c). There were few good answers and a good physical understanding was noted.

Q3 Solution



(a) On a plot torque vs engine speed sketch the following

(i) the variation of maximum torque

The shape of the maximum torque characteristic is determined by how much oxygen is in the cylinder when the inlet valve closes. At low engine speeds, even at WOT, a significant quantity of residuals remain in the cylinder (i.e. poor scavenging), as momentum effects, that at higher speeds will largely clear the residuals – explaining the (initially) increasing torque with engine speed – are less effective. At the highest engine speed, frictional effects become dominant, and although scavenging may be effective, the pressure, and hence density of the cylinder contents becomes lower – and hence less torque.

(ii) the top gear road load

At very low vehicle speeds, drag forces are small, but the torque required from the engine is still significant, being required to overcome rolling resistance, engine friction, drive auxiliaries (oil, water and oil pumps). The drag force due to air resistance is given by

$C_d = \frac{Drag}{1/2\,\rho v^2}$, and the drag coefficient is roughly constant as the Reynolds' number is high.

Thus the torque required due to air resistance goes as speed squared, which explains the shape of the road load torque.

(iii) constant power contours

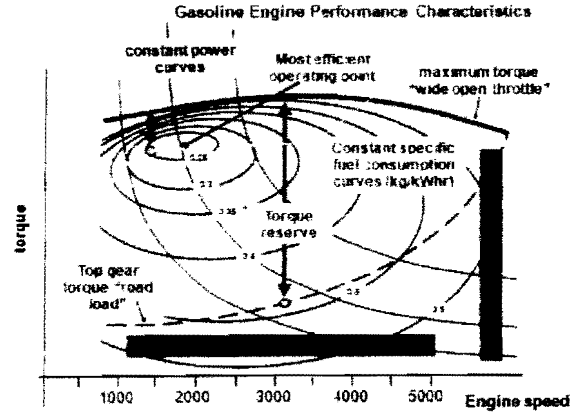
Power is proportional to torque*rpm – so the constant power curves are rectangular hyperbolae.

(iv) contours of constant specific fuel consumption

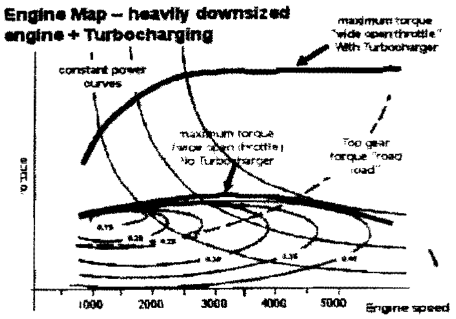
At high engine speed and throttled operation, the proportion of the engine work going to overcome friction increases. Also when throttled, pumping work increases. At the very lowest engine speeds, even when at WOT, combustion rate and stability are impaired, so the sfc increases. At WOT, the engine is richened up to avoid knock and protect the catalyst, so sfc suffers.

(b) The same figure for a diesel engine delivering the same maximum power will have

(i) a higher torque, since the maximum rpm is significantly lower
(ii) less difference between maximum and minimum sfc's as throttling losses are much less (mechanical efficiency arguments still apply)
(iii) sfc tends to improve all the way to the max torque line as richening up is not generally used in diesel engines (due to smoke).



(c), (i) With a CVT, one can in principle operate at the best sfc at each power requirement, as shown in the figure "ideal power trajectory". Actual CVT's are not normally used so "aggressively". Mechanical CVT's tend to suffer from efficiency issues, and reliability. Hybrid transmissions, using electricity as the power transmission, are better in these respects, but are more expensive and heavy.



(c), (ii) Tubochargers enable, for teh same performance, for the engine to be significantly downsized, so that under low to medium load (i.e. most running conditions), the engine is running much less throttled that an equivalent NA engine. Only when maximum troque/power is required does the turbocharger become (very) active, boosting the inlet manifold to 1 to 2 bar above ambient. The figure shows an idealisation of this. Two issues are turbo-lag:- especially when the engine is at very low power output, there is little gas flow through the engine, and even when a large demand is requested by the driver, the spooling up of the TC is much slower that is desirable (essentially relative to the equivalent NA engine). Also it is difficult to get all the desired performance from a single TC because of the very wide range of flow rates.

(d)

Pros:-

No CO2 emitted by the vehicle. Urban air quality beneficially influenced (from noxious emissions). Significant incentives currently exist. "Fuel" is cheap compared to gasoline/diesel, (partly due to the tax structure).

Cons:-

Short range – especially when heating/AC required, or terrain is hilly. Vehicle costs are high, due to battery costs being stuck at ~$1000/kWhr. Battery life is still somewhat of an open issue, but seems unlikely to be anywhere near the vehicle life. Charging infrastructure is not yet significant - though high speed charging is possible (more with some battery technologies than others) this requires significant investment.

Examiner's note:

Most students could describe the Speed vs Torque characteristics well. The influences of CVT and turbocharger were answered quite well.

Q4

The basic idea here is to compare the work output from the throttled and unthrottled cycles. The ratio of these work outputs will represent to fraction of the time that the start/stop engine has to run to supply the same average power demand. The fuel consumption will be proportional to the average air flow.

For an inlet manifold pressure of p_1, $W_{12} = p_1 V_1 \left[1 - 10^{0.4}\right] = -1.512 p_1 V_1$. The mass of air induced is $m = \dfrac{p_1 V_1}{R T_1}$. The temperature at the end of compression is given by

$\dfrac{T_2}{T_1} = \left(\dfrac{V_1}{V_2}\right)^{\gamma - 1} = 2.512$, and $T_2 = 753.6K$, $T_3 = 2753.6K$. Now $p_3 V_3 = mRT_3$, so

$p_3 = \dfrac{p_1 V_1}{R T_1} \dfrac{R T_3}{V_3} = \dfrac{10 * 2753.6 p_1}{300} = 91.79 p_1$.

Thus the work done during the expansion is

$W_{34} = p_3 V_3 \left[1 - 1/10^{0.4}\right] = 91.79 p_1 \dfrac{V_1}{10} 0.602 = 5.525 p_1 V_1$

The pumping work is given by $W_p = (p_1 - p_{amb})(V_1 - V_2) = 0.9 p_1 V_1 \left(1 - \dfrac{p_{amb}}{p_1}\right)$.

So, per working cycle of the engine, the net work is

$W_{net} = (5.525 - 1.512 + 0.9(1 - p_{amb}/p_1))p_1 V_1$.

For unthrottled running $W_{net} = 4.013 p_1 V_1$, and for throttled running $p_1 = 0.3$ bar, $W_{net} = 1.913 p_1 V_1$. Thus the stop/start engine runs $100 * 1.913 * .3 / 4.013 = 14.23\,\%$ of the time. As the AFR is the same, the fuel consumption will be proportional to the air flow multiplied by the time running. Thus the ratio of the fuel usage will be as $1.913/4.013 : 1 = 0.48 : 1$. I.e. roughly a 50% 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)

There are many issues here. On the "plus" side

1) When the vehicle is stationary, or in very slow moving traffic, start/stop has even greater benefits than those suggested here.
2) As the both vehicles have the same engine, highway performance will be little affected – only by the electrical losses which are not large.

On the "negative" side:-

1) As the electric transmission (generator and motor) has to handle the whole engine power, the electrical machines are large, heavy and expensive. This is a big issue.
2) Batteries are also large and expensive, and don't last as long as the rest of the vehicle. This is especially true in this situation where they are being frequently cycled, with significant energy flows. To make the start/stop system really effective, one would like a reasonable battery size – especially when combined with a plug-in capability.
3) It's not easy to make the driver completely unaware of the random starting and stopping of the engine.

Examiner's note:

The students were able to workout the required work outputs accounting for pumping losses and demonstrated a good understanding of the concept required for this question.