ET IIB

PROF S HOCHGREB
PROF N COLLINGS

Module 4A13 – Combustion and IC Engines 2011

Q1

(a) [5%]

$$\tau = \rho V/\dot{m} = \frac{pWV}{RT_o\dot{m}}$$

(b) The concentration change in the oxidiser will be proportional to that in the pollutant. Since we do not know the concentration of the pollutant, we can bound the maximum change as the case in which all the pollutant reacts: [20%]

$$\nu\, dY_R = dY_O$$
$$\nu(Y_{R,i} - 0) = \Delta Y_O$$
$$\frac{\Delta Y_O}{Y_{O,o}} = \nu\frac{Y_{R,i}}{Y_{O,o}}$$

Therefore, the maximum change in the oxidiser concentration $\Delta Y_O/Y_{O,o} = \nu Y_{R,i}/Y_{O,o}$. Even for heavy hydrocarbons with 20 or more carbons, C_nH_m require $\nu = n + m/4 \approx 20$ oxygen moles per unit mol, or 32 x 20 g/12 g carbon $\approx$ 53 (we are neglecting $m/4$). So as long as the concentrations of pollutants x 50 is still small relative to the oxygen concentration in the mixture, the concentration of oxygen will still remain unchanged.

(c) (i) The species balance for the pollutant in the reactor is: [30%]

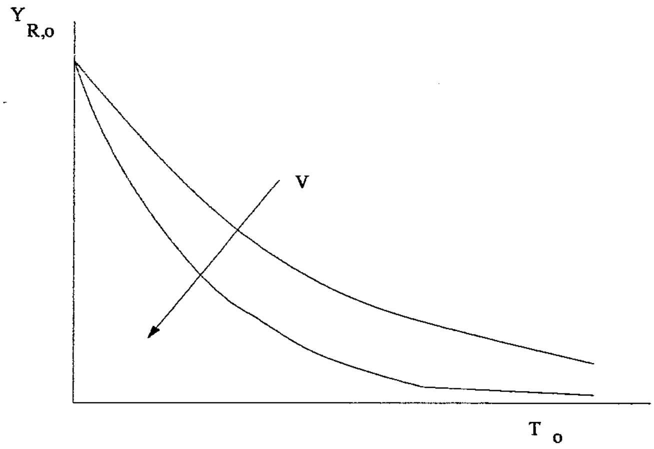
$$\dot{m}(Y_{R,o} - Y_{R,i}) = -AY_{R,o}Y_{O,o}\rho^2\exp(-\theta/T)V$$
$$Y_{R,o}[\dot{m} + AY_{O,o}\rho^2\exp(-\theta/T_o)V] = \dot{m}Y_{R,i}$$
$$Y_{R,o} = \frac{Y_{R,i}}{1 + AY_{O,o}\rho^2\exp(-\theta/T_o)V/\dot{m}}$$
$$Y_{R,o} = \frac{Y_{R,i}}{1 + AY_{O,o}p^2\exp(-\theta/T_o)V/(\dot{m}(RT_o)^2)}$$

(ii)

(d) The energy balance without pollutant is: [30%]

$$\dot{m}c_p(T_o - T_i) = -\dot{m}Y_{F,i}\Delta H_F$$

where ΔH_F is the enthalpy of reaction of methane.



The energy balance including the pollutant is:

$$\dot{m}c_p(T_o - T_i) = -\dot{m}Y_{F,i}\Delta H_F - \underbrace{\dot{m}(Y_{R,i} - Y_{R,o})\Delta H_R}_{\text{negligible, by assumption}} \approx -\dot{m}Y_{F,i}\Delta H_F$$

For the case in which the mass flow rate of pollutant is higher, we have an additional load $\dot{m}'_R$ as well as an additional heat release contribution:

$$(\dot{m} + \dot{m}'_R)c_p(T'_o - T_i) = -\dot{m}\,Y_{F,i}\Delta H_F - w'_R\Delta H_R V$$

We take the ratio of the two expressions above to yield:

$$\frac{T'_o - T_i}{T_o - T_i} = \frac{-\dot{m}\,Y_{F,i}\Delta H_F - w'_R\Delta H_R V}{-\dot{m}\,Y_{F,i}\Delta H_F}\frac{\dot{m}}{\dot{m} + \dot{m}'_R}$$
$$= \frac{1 + w'_R\Delta H_R V/(\dot{m}\,Y_{F,i}\Delta H_F)}{1 + \dot{m}'_R/\dot{m}}$$

Therefore, the rise or fall in temperature will depend on the ratio of the extra heat release provided by the increased concentration of pollutants to the higher flow thermal capacity created by the larger mass flow rate.

(e) If the mass flow rate of fuel increases from a very fuel-lean condition, the temperature will increase and the pollutant reaction rate will increase, up to the point where the reaction starts being limited either by the availability of oxygen or of the reactant itself. [15%]

Examiner's comment: Straightforward question, but not popular The question looked long, but required only straightforward application of basic species and energy conservation.

Q2

(a) Reaction (1) is an *initiation* reaction, typically with high activation energies. Reaction (2) is a molecule-radical reaction, typically fast with low activation energies. It is also a *branching* reaction. Reaction (3) is a *termination* reaction, as it removes the radical from the pool. [10%]

(b) Steady state for X: [30%]

$$\frac{d[\mathrm{X}]}{dt} = k_1[\mathrm{A}][\mathrm{M}] + k_2(\alpha-1)[\mathrm{A}][\mathrm{X}] - k_3[\mathrm{A}][\mathrm{X}][\mathrm{M}] = 0$$

$$[\mathrm{X}] = \frac{k_1[\mathrm{A}][\mathrm{M}]}{k_3[\mathrm{A}][\mathrm{M}] - k_2(\alpha-1)[\mathrm{A}]} = \frac{k_1[\mathrm{M}]}{k_3[\mathrm{M}] - k_2(\alpha-1)}$$

$$\frac{d[\mathrm{A}]}{dt} = -k_1[\mathrm{A}][\mathrm{M}] - k_2[\mathrm{A}][\mathrm{X}] - k_3[\mathrm{A}][\mathrm{X}][\mathrm{M}]$$

$$\frac{1}{[\mathrm{A}]}\frac{d[\mathrm{A}]}{dt} = -k_1[\mathrm{M}] - (k_2 + k_3[\mathrm{M}])\left\{\frac{k_1[\mathrm{M}]}{k_3[\mathrm{M}] - k_2(\alpha-1)}\right\}$$

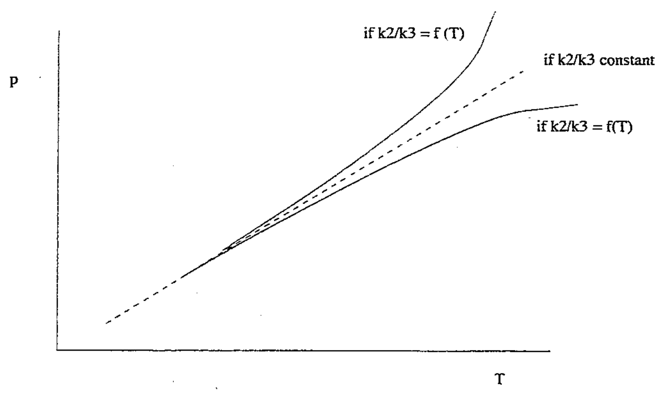
$$= -k_1[\mathrm{M}]\left[1 + \frac{k_2 + k_3[\mathrm{A}]}{k_3[\mathrm{M}] - k_2(\alpha-1)}\right]$$

(c) If the denominator of the second term in brackets is zero (or smaller), the rate of growth will blow up: [20%]

$$k_3[\mathrm{M}] = k_2(\alpha-1)$$

Since $[\mathrm{M}] = p/RT$, we have an explosive limit given on the $p-T$ plane as:

$$p/T = (\alpha-1)Rk_2/k_3$$



(d) Integrating the expression for [A], we have: [15%]

$$\frac{[A]}{[A]_o} = \exp(-Kt)$$

where $K = k_1[M]\left[1+\frac{k_2+k_3[M]}{k_3[M]-k_2(\alpha-1)}\right]$. [25%]

(e) For the temperature, we have:

$$\rho c_v \frac{dT}{dt} = -w_A q V \qquad \text{where} \qquad w_A = W_A \frac{d[A]}{dt}$$

$$\frac{dT}{dt} = -\frac{w_A q V}{\rho c_v} = -\frac{q V W_A}{\rho c_v}\frac{d[A]}{dt}$$

$$= \frac{[A] W_A q V K}{\rho c_v} = \frac{W_A q V K [A]_o \exp(-Kt)}{\rho c_v}$$

For the pressure, we have:

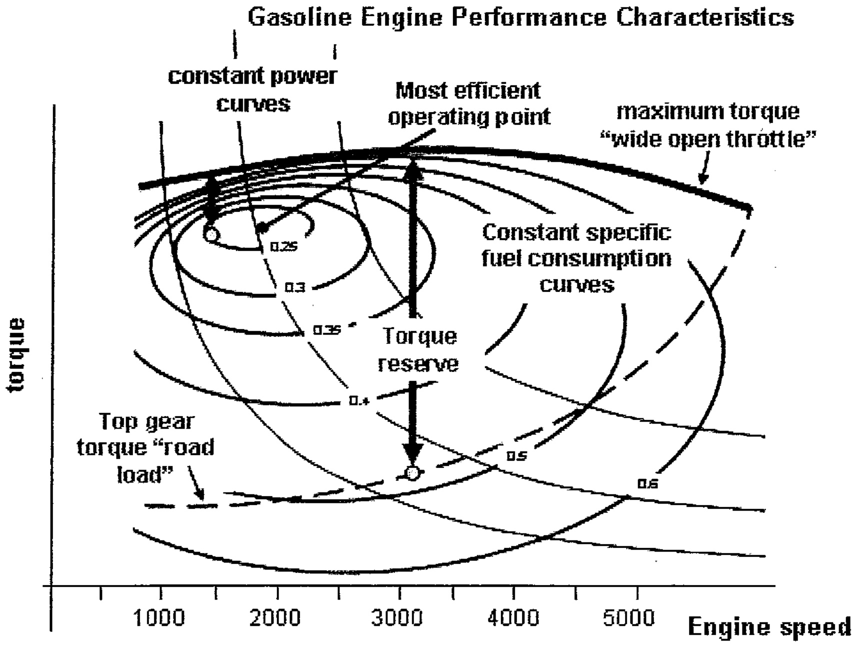
$$\frac{dp}{dt} = \frac{d\rho RT}{dt} = \rho R \frac{dT}{dt}$$

which is given above.

The explosion can take place simply due to the chemical kinetic rates at constant temperature. The heat release can move the reaction away or into the explosive region, depending on the trajectory of the p, T history. An example is found in the case of H2 explosion, which can move out of the explosive regime for higher pressures. Ultimately, the heat release will typically have an impact on the reaction rates and the reaction will go to completion.

Examiner's comment: Simple application of steady-state assumption for a radical, as illustrated in examples. The main difficulty was in clearly identifying explosive regime in (c). Most reasonable answers for that were accepted. Few candidates got as far as item (e) correctly, which required application of energy conservation.

Q3 Solution



(a) On a plot torque vs engine speed sketch the following [5%]

(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

$C_d = \dfrac{Drag}{1/2\,\rho v^2}$, 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

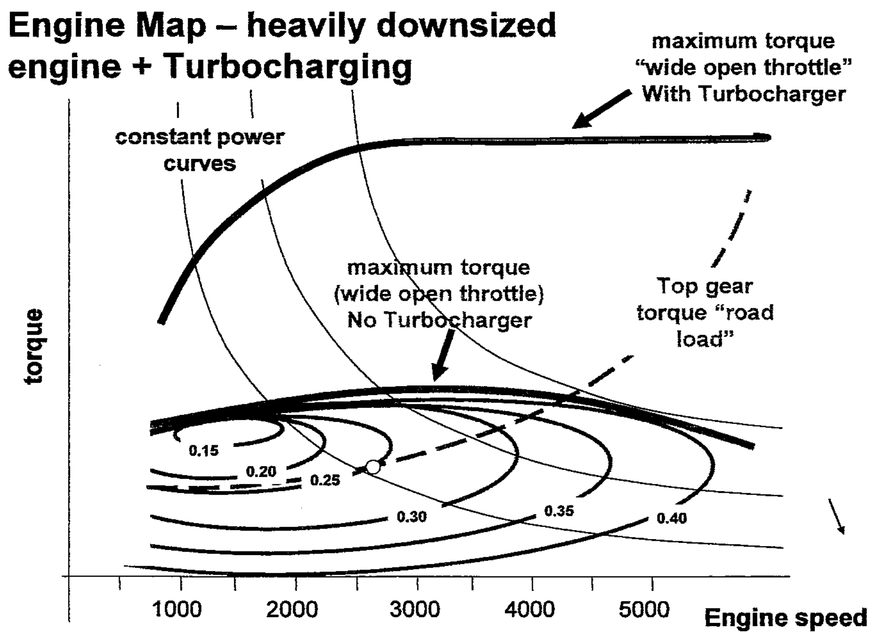
Power is proportional to torque*rpm – so the constant power curves are rectangular hyperbolae.

(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) Discuss, with, as appropriate, alternative versions of the figure generated in part (a), the benefits, and drawbacks, of:- [50 %]

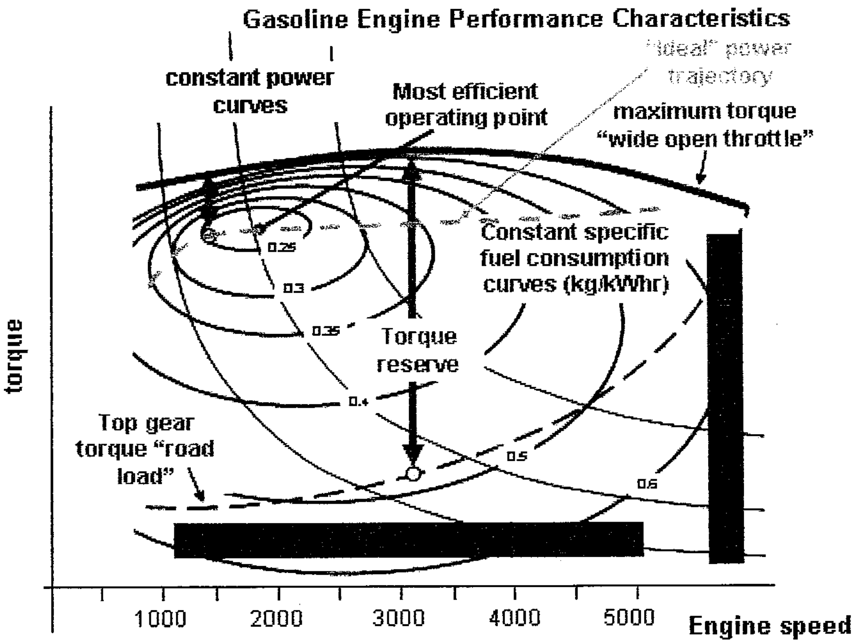
(i) down-sized turbocharged engines



The figure illustrates the benefits, and some of the drawbacks of downsized turbocharged engines. Because the base engine is smaller, the sfc numbers are significantly better when the T/C is doing relatively little boosting – which is the case for most driving conditions. When high powers are required, the T/C supplies the boost required to get 2 to 3 times more air into the cylinder – even though the engine may have to operate with retarded ignition to avoid knock, the extra power is very significant. One of the problems is illustrated however – the torque available at very low engine speeds is limited so there is "launch" problem.

A big advantage of T/C's over other boosting methods (battery, flywheel…) is that the extra power is available continuously.

(ii) hybrid powertrains and continuously variable transmissions (CVT's)



With reference to the figure, it is seen that a CVT or hybrid transmission can allow the engine to be run at a much lower sfc, while delivering the same power. Effectively, much higher gear ratios are available. The hybrid has the additional advantage of start-stop operation, and a certain all-electric range, which has a big effect on city driving fuel consumption.

Downsides include cost, and that for "motorway cruise", there may actually be a fuel economy penalty.

Examiner's comment: Popular essay question requiring comprehensive view of engine performance. Mostly well handled.

Q4 Solution

(a) from the definition of mep:- [40%]

$$mep = W/V_d = \eta_f m_f Q_{LCV} = \eta_f \eta_V \rho_{a,i} Q_{LCV} / AFR$$

So

$$bmep = \eta_m \eta_{f,i} \eta_V \rho_{a,i} Q_{LHV} / AFR$$

Now $\rho_{a,i} = p_{a,i} / (RT_{a,i})$

So $$\frac{p_{a,i}}{AFR} = \frac{bmep\, RT_{a,i}}{\eta_m \eta_{f,i} \eta_v Q_{LCV}}$$

(b) [30%]

For a four stroke engine

$$P_b = \frac{bmep\, V_d N}{2}$$

$$V_d = n_{cyl} \pi \frac{B^2 L}{4}$$

$$N_{max} = S_{p\,max} / 2L$$

At the max rated condition

$$P_{b,ax} = \frac{bmep_{max} (n_{cyl} \pi B^2 L/4)(S_{p,max}/2L)}{2} = 400E3 = \frac{12E5 * n_{cyl} \pi B^2 12}{2*4*2}$$

Hence

$$n_{cyl} B^2 = 0.1415 m^2$$

For 6 cylinders, B= 0.154 m

For 8 cylinders B = 0.133 m

Assuming stroke = bore, then

$N_{max} = 39$ rev/s (6 cyl)

$N_{max} = 45$ rev/s (8 cyl)

(c) $p_{a,i} = 2E5$ Pa. [30%]

$\eta_m = 0.9,\ \ \eta_{f,i} = 0.42,\ \eta_v = 0.9$ (Any sensible values are acceptable.)

Q_{LCV} = 42 MJ/kg, R_{air} = 287 J/kgK, $T_{a,i}$ = 325 K

So, $$\frac{2E5}{AFR_{max}} = \frac{900E3 * 287 * 325}{0.9 * 0.42 * 0.9 * 42E6} = 5875$$

And thus $AFR_{max} = 34.0$

Examiner's comments: This question unusually required candidates to make reasonable assumptions, drawing on material from lecturers.