ENGINEERING TRIPOS PART IIB

Thursday 12 May 2011 2.30 to 4

Module 4A13

COMBUSTION AND IC ENGINES

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

There are no attachments.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

sh05

1 An incinerator of volume V is used to destroy a hydrocarbon pollutant from a chemical stream. The incinerator contents can be considered to be perfectly mixed, and the system operates adiabatically and at constant pressure, p. The unit is fired with a mixture of air and methane, starting from ambient temperature T_i and reaching a final temperature, T_o. The inlet fuel-air mixture is overall lean, with an incoming fuel and oxygen mass fraction $Y_{F,i}$ and $Y_{O,i}$, respectively. The total reactant mass flow through the system is $\dot{m}$, and the outgoing mass fraction of fuel and oxygen are $Y_{F,o} = 0$ and $Y_{O,o}$, respectively. The pollutant mass fraction at inlet is $Y_{R,i}$, and its reaction can be represented on a mass basis as $\mathrm{R} + \nu\ \mathrm{O} \rightarrow \mathrm{P}$, where the oxidiser O is molecular oxygen and ν the stoichiometric coefficient. The pollutant mass reaction rate is given by $w = A\rho_R\rho_O \exp(-\theta/T_o)$, where ρ_R and ρ_O are the mass concentrations of the pollutant and oxidizer, respectively, and A and θ are constants. The molecular weight of the mixture in the reactor can be considered fixed as W, and the specific heat of all species, c_p, is constant. The enthalpies per unit of mass reaction of the fuel and pollutant are ΔH_F and ΔH_R, respectively.

(a) Express the mean residence time of the reactant mixture in the incinerator, τ, as a function of the given parameters and any other constants. [5%]

(b) Show that if $Y_{R,i}/Y_{O,o} \ll 1$, the change in mass fraction of oxygen in the outlet mixture due to the addition of the pollutant to the incinerator is negligible. [20%]

(c) (i) Determine the outlet mass fraction of the pollutant, $Y_{R,o}$, as a function of the initial mass fraction and the parameters given, assuming negligible change in oxygen mass fraction.

(ii) Sketch the outlet pollutant mass fraction as a function of outlet temperature, T_o, as well as the incinerator volume.

[30%]

(d) Consider now a case in which the original air and fuel mass flow rates are kept fixed, but the pollutant mass flow rate is increased to $\dot{m}'_R$. The incinerator temperature changes from the original T_o to T'_o . Assume that the original reactant mass fraction contributes negligibly to the original outlet temperature of the incinerator, T_o . Determine the ratio of temperature rise in the new case, $T'_o - T_i$, to the original rise, as a function of the parameters given and the new rate of reaction w'_R . Under what conditions does the temperature increase or decrease? Provide an interpretation for your result. [30%]

(e) Discuss what would happen to the incinerator temperature and final pollutant mass fractions if the fuel flow rate is increased, and state what an optimal flow rate might be. Justify your answers using any necessary equations. [15%]

2 Consider the reaction of a species A, given by the sequence below:

$$\begin{array}{llll} A + M & \rightarrow & B + X & (1) \\ A + X & \rightarrow & \alpha\, X & (2) \\ A + X + M & \rightarrow & P + M & (3) \end{array}$$

where M is any colliding species, X is a radical, P and B are products, and $\alpha > 1$. The reaction takes place in a vessel of constant volume V at uniform temperature T and pressure p.

(a) Determine what type of reactions (1) to (3) are, and describe typical characteristics of their reaction rate constants. [10%]

(b) Assume that species X is in steady state, and that the reverse reaction rates are negligible. Show that the reaction rate for A is given as:

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

[30%]

where k_i are reaction rate constants for the reactions (1) to (3) above, and the brackets represent molar concentrations.

(c) Under what conditions does an explosive reaction arise? Discuss the limits as a function of pressure, temperature and the parameters given. [20%]

(d) Obtain an expression for the concentration of A as a function of time and the parameters given for an initial concentration of A equal to $[A]_o$. Sketch the evolution of $[A]/[A]_o$ as a function of time. [15%]

(e) Consider now that the reaction is exothermic, so that q energy units are released per mass of reactant A consumed. The specific heat per unit mass of the mixture is constant and equal to c_v, and the molecular weight of A is W_A. Obtain differential equations for the temperature and pressure as a function of time. Discuss how the heat release in the reaction affects the evolution of the reaction and explosion limits. Use any necessary equations, and justify your answers. [25%]

3 For a typical normally aspirated gasoline engine:

(a) On a plot of torque *vs.* engine speed sketch the following:

(i) the variation of maximum torque;

(ii) the top gear road load;

(iii) constant power contours;

(iv) contours of constant specific fuel consumption.

Justify the main features of the figure you have generated. [50%]

(b) Discuss the benefits and drawbacks of:

(i) down-sized turbocharged engines;

(ii) hybrid and continuously variable transmissions (CVTs).

Describe and justify your answers using alternative versions of the figure generated in (a). [50%]

4 You wish to do a preliminary design study of a turbocharged four stroke diesel engine. Due to mechanical stress considerations, the maximum *bmep* is to be limited to 12 bar, and the maximum mean piston speed to 12 m s^{-1}. Assume the ambient pressure is 1 bar, and that the temperature after the compressor is 325 ^{o}C. Make appropriate estimates as necessary as you work through the following calculations:

(a) Derive an equation relating the compressor exit pressure to the air/fuel ratio at the maximum rated power condition. Other engine parameters (e.g. volumetric efficiency, fuel conversion efficiency, *bmep* , etc.) will appear in this equation. [40%]

(b) The maximum rated power requirement is 400 kW. Make sensible estimates of the number of cylinders, the bore, the stroke, and determine the maximum rated engine speed. [30%]

(c) If the pressure ratio across the compressor is 2, estimate the overall air to fuel ratio at the maximum rated power. You may assume the lower heating value for diesel fuel is 42 MJ kg^{-1}. Make appropriate estimates for mechanical, fuel conversion and volumetric efficiencies. [30%]

END OF PAPER