ENGINEERING TRIPOS PART IIA

Thursday 6 May 2010 2.30-4.00

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

SH07

1 Consider a laminar flame of a hydrocarbon in an oxygen-carbon dioxide mixture. The reaction of the hydrocarbon in a flame is approximated as a one-step reaction F + O $\rightarrow$ P, where F denotes the fuel, O , the oxidiser, and P the product. Reactants flow from left ($x = -\infty$) to products on the right ($x = +\infty$).

(a) Starting from the one dimensional energy equation for constant specific heat and conductivity:

$$\dot{m}c_p \frac{dT}{dx} - \lambda \frac{d^2T}{dx^2} - wQ = 0$$

where T is the temperature, $\dot{m}$, the mass flow rate per unit area, c_p, the specific heat capacity at constant pressure, x, the streamwise coordinate, λ, the mixture thermal conductivity, w, the mass reaction rate per unit volume and Q, the heat of combustion per unit mass. Show that the temperature gradient at the downstream edge of the preheat zone ($x = 0^-$) is given as:

$$\left(\frac{dT}{dx}\right)_{x=0^-} = \frac{\dot{m}c_p}{\lambda}(T(0^-) - T_R)$$

where T_R is the temperature of the reactants. Explain in detail all assumptions made regarding the different terms, and the appropriate boundary conditions. [20%]

(b) Starting from the same equation, show that at the upstream edge of the the reaction zone ($x = 0^+$), we have:

$$\left(\frac{dT}{dx}\right)^2_{x=0^+} = 2\frac{Q}{\lambda}\int_{T(0^+)}^{T_P} w\, dT$$

where T_P is the temperature of the products. Explain in detail all assumptions made, and the appropriate boundary conditions. [20%]

(c) Show that the premixed laminar flame speed u_L is given by:

$$u_L = \left(\frac{2\lambda}{\rho_R^2 c_p (T_P - T_R)} \int_{T_0}^{T_P} w\, dT\right)^{\frac{1}{2}}$$

where T_0 is the temperature of the interface between the premixed and reaction zone and ρ_R is the density of the reactants. Explain in detail all assumptions made. [20%]

(d) If the reaction rate is given by the expression $w = A\exp(-E/(RT))$, where E and R are constants, explain how a closed form expression can be obtained for the reaction rate as:

$$u_L = \left[\frac{2\lambda A}{\rho_R^2 c_p (T_P - T_R)} \frac{R T_P^2}{E} \exp\left(-\frac{E}{R T_P} \right) \right]^{\frac{1}{2}}$$

[20%]

(e) Using the expression above and physical interpretation, explain how the laminar flame speed of a hydrocarbon/oxygen/carbon dioxide flame should vary with the ratio of oxygen and carbon dioxide in the mixture. Why would one want to use such a mixture in a combustor? [20%]

2 Consider a non-premixed flamelet, which can be characterised parametrically as a strained non-premixed flame. The mixture fraction is defined as $Z = (\beta - \beta_2)/(\beta_1 - \beta_2)$, where $\beta = sY_F - Y_O$, 1 and 2 are the two different streams, Y_F and Y_O the mass fractions of fuel and air, and s the mass stoichiometric coefficient.

(a) Determine the stoichiometric mixture fraction Z_s for (i) streams of methane (CH_4) on one side and pure air on the other, (ii) methane on one side and pure oxygen on the other. [20%]

(b) The simplified balance equation for the mixture fraction balance in a two-dimensional opposed flame along the symmetry axis y is given as:

$$\rho v \frac{\partial Z}{\partial y} = \frac{\partial}{\partial y}\left(\rho D \frac{\partial Z}{\partial y}\right)$$

where Z is the mixture fraction. The diffusion coefficient, D, and the density, ρ, are assumed to be constant. The axial velocity v is given as $v = -ay$, where a is the constant strain rate. The mixture fraction at either boundary is equal to the free stream value. Show that it is possible to reduce the equation to:

$$\frac{\partial^2 Z}{\partial \eta^2} + 2\eta \frac{\partial Z}{\partial \eta} = 0$$

where $\eta = y/\sqrt{(2D/a)}$. [30%]

(c) Show that the solution of the equation for the mixture fraction, subject to the boundary conditions where the fuel stream is on the $y \rightarrow -\infty$ side, and the oxidizer on the $y \rightarrow +\infty$ side, is:

$$Z = \frac{1}{2}[1 - \text{erf}(\eta)]$$

where $\text{erf}(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\eta \exp(-u^2)\,du$, $\text{erf}(-\infty) = -1$ and $\text{erf}(+\infty) = 1$. [20%]

(d) Carefully sketch the mixture fraction profile and the location of the flame as shown in the solution in (c) for methane-air and methane-oxygen flamelets, indicating the respective flame locations. [15%]

(e) Sketch the temperature, fuel and oxygen profile for one of the cases in (d). [15%]

3 Write brief notes which would convey to an engineer not versed in IC engine technology why the following statements are true:

(a) A throttle is required to vary the load of gasoline engines. [15%]

(b) The crank angle over which combustion takes place is roughly independent of engine speed for gasoline engines. [15%]

(c) The bore sizes of most automotive gasoline engines are similar. [20%]

(d) Diesel engines of a similar power output typically have a better sfc than gasoline engines. [20%]

(e) Large cylinder volume diesel engines have a better specific fuel consumption rate than small cylinder volume engines. [15%]

(f) Turbochargers are useful, but have disadvantages. [15%]

4 Automobiles that use a compressed air reservoir as the energy supply are in small scale production. A reciprocating expander is used to extract mechanical work from the reservoir and propel the vehicle. The expander consists of a single piston-in-cylinder arrangement (see Fig. 1), where the maximum cylinder volume is V_{max}.

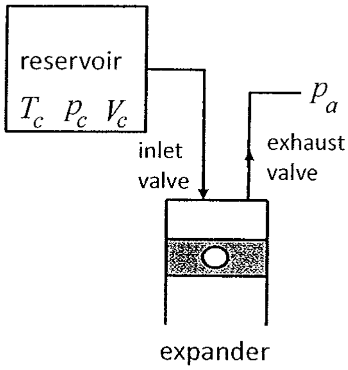

Fig. 1

The cycle proceeds as follows:

Charge: at the minimum cylinder volume, *assumed negligible*, the inlet valve opens which admits compressed air from the reservoir, at a pressure and temperature of p_c , T_c , respectively, into the cylinder, and the inlet valve closes when the volume is αV_{max}.

Expansion: the trapped air, assumed initially to be at p_c , T_c, is expanded adiabatically and reversibly to V_{max} . The value of α can be varied (i.e. the inlet valve closing time), so that whatever the value of p_c, the pressure at the end of the expansion is always p_a, the ambient pressure.

Exhaust: the exhaust valve opens, which allows the air to be ejected to ambient during the return to the minimum volume position. The exhaust valve then closes.

(a) Sketch the cycle on a $p-V$ diagram. [10%]

(b) Show that $\alpha = \left(\frac{p_a}{p_c}\right)^{(1/\gamma)}$. [10%]

(c) Show that the work done during each revolution of the engine, W, is given by:

$$W = p_a V_{max} \frac{\gamma}{\gamma-1}\left[\left(\frac{p_c}{p_a}\right)^{(\gamma-1)/\gamma} - 1\right]$$

[30%]

(d) Find an expression for the air mass flow rate leaving the reservoir if the engine is rotating at N rev/sec as a function of the parameters defined above. [10%]

(e) The engine is required to maintain a constant power output of 5 kW . This means that the engine rotation speed varies from a low value, when p_c (and thus the work per cycle) is high, to the maximum engine speed, N_{max}, when the minimum p_c that will still deliver 5 kW is reached. Assume T_c remains constant at 25 °C , p_a =1 bar, V_{max}= 1 litre and N_{max} =100 rev/s.

(i) What is the minimum value of p_c that will deliver 5 kW? [20%]

(ii) If the compressed air reservoir has a volume V_c of 340 litres and p_c is initially 300 bar, find the maximum trip duration, assuming that the delivered power remains constant.

[20%]

END OF PAPER