ENGINEERING TRIPOS   PART IIB

Wednesday 29 April 2009   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	SPECIAL REQUIREMENTS
Single-sided script paper	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

1 The blow-off limits of a combustor can be captured using a perfectly stirred reactor (PSR) as a model. Consider the energy balance for a PSR with mass flow rate $\dot{m}$, volume V, and constant pressure p, inlet conditions given by temperature T_0, density ρ_0, and reactant mass fraction Y_0. The mass reaction rate per unit volume in the reactor is approximated as a one-step reaction from fuel to products, where $\dot{w} = A\rho Y \exp(-\theta_a/T)$, where ρ is the density, Y is the mass fraction of the reactant, T the temperature, and A and θ_a are constants. The mixture in the reactor can be considered to have constant specific heat capacity c_p, and the enthalpy of reaction per unit mass of reactant is Q.

(a) Using the single step reaction model in the PSR, show that the steady state temperature T in the reactor satifsifes:

$$\frac{\tau_c}{\tau_f}\frac{(T-T_0)}{q} = \frac{T_0}{T}\left(Y_0 - \frac{T-T_0}{q}\right)\exp(-\theta_a/T)$$

where $\tau_c = 1/A$, $\tau_f = \rho_0 V/\dot{m}$ and $q = Q/c_p$. [40%]

(b) Show that the blow-off condition is given by:

$$\frac{\tau_c}{\tau_f} = \frac{qT_0}{T^2}\left((\frac{\theta_a}{T} - 1)(Y_0 - \frac{T-T_0}{q}) - \frac{T}{q}\right)\exp(-\theta_a/T)$$

[30%]

(c) Provide a graphical and commented interpretation for (a)-(b). Use this to illustrate the variation of the steady state temperature with the ratio τ_c/τ_f. [30%]

2 A spherical combustion bomb is used to measure laminar flame speeds. The mixture is ignited at the centre, and a laminar flame propagates spherically through the chamber of radius R. At time t, the radius of the flame is $r_f(t)$. The initial unburned conditions are p_o, $T_{u,o}$ and $\rho_{u,o}$, the initial reactant mass fraction is Y_o, and the specific enthalpy of combustion per unit mass of fuel is Q. The burned and unburned gas mixtures can be assumed to behave as perfect gases with the same properties. The temperatures of the burned and unburned gases are assumed to be uniform, and the pressure is uniform across the chamber. The process is entirely adiabatic, and the burned and unburned gases can be assumed to be compressed isentropically.

(a) Show that the ratio of the final burnt gas temperature to the initial reactant temperature is:

$$T_{b,f}/T_{u,o} = 1 + Y_o Q/(c_v T_{u,o})$$

and sketch the burned and unburned temperatures on a T-p graph. [10%]

(b) Show that the initial density ratio across the flame is given by:

$$\frac{\rho_{b,o}}{\rho_{u,o}} = (1+q)^{-1}$$

where where $\rho_{b,o}$ is density of gas burned at the initial pressure and temperature, and $q = QY_o/(c_p T_{u,o})$. Justify your assumptions. [15%]

(c) Show that the normalized flame radius $\hat{r} = r_f/R$ and pressure $\hat{p} = p/p_o$ are related by: [25%]

$$\left[1 - (1 - \frac{\rho_{b,o}}{\rho_{u,o}})\hat{r}^3\right]\hat{p}^{1/\gamma} = 1$$

(d) Show that under these conditions the normalized rate of flame growth $d\hat{r}/dt$ is related to the pressure rise by: [30%]

$$\frac{d\hat{r}}{dt} = \frac{q+1}{3q\gamma}\hat{p}^{-(\gamma+1)/\gamma}\left[(1-\hat{p}^{-1/\gamma})\frac{q+1}{q}\right]^{-2/3}\frac{d\hat{p}}{dt}$$

(e) Using a volume balance or otherwise, explain how the laminar flame speed can be obtained from the rate of pressure change alone. Justify all assumptions. [20%]

(TURN OVER

3 (a) Show that the work done during the isentropic compression of a perfect gas between states 1 and 2 is given by:

$$W_{12} = \frac{p_1 V_1}{\gamma - 1}\left[1 - \left(\frac{V_1}{V_2}\right)^{\gamma-1}\right] = \frac{p_1 V_1}{\gamma - 1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

[20%]

(b) Fig. 1 shows an idealized four-stroke engine cycle, running under throttled conditions. Assuming that the working fluid is a perfect gas, with ratio of specific heats γ, find expressions for the work done during the compression and expansion strokes (which are assumed isentropic) in terms of p_e, p_i, p_3 and V_c. [20%]

(c) If the compression ratio is 9, γ = 1.4, the manifold inlet temperature is 288 K, the temperature rise on combustion is 1400 K, and the exhaust and inlet manifold pressures are 1 bar and 0.5 bar respectively, determine p_3, and hence the gross imep. [20%]

(d) Determine the pumping work, and hence the pmep and the net imep. [20%]

(e) Sketch the *p-V* diagram of Fig. 1 on your script, and add to this a sketch an unthrottled cycle operating between the same minimum and maximum volumes, which would produce the same net work as the throttled cycle, based on late inlet valve closing. You may assume that the unthrottled inlet pressure is equal to p_e. No calculations are required, but justify clearly with a few comments the sketch you have made. [20%]

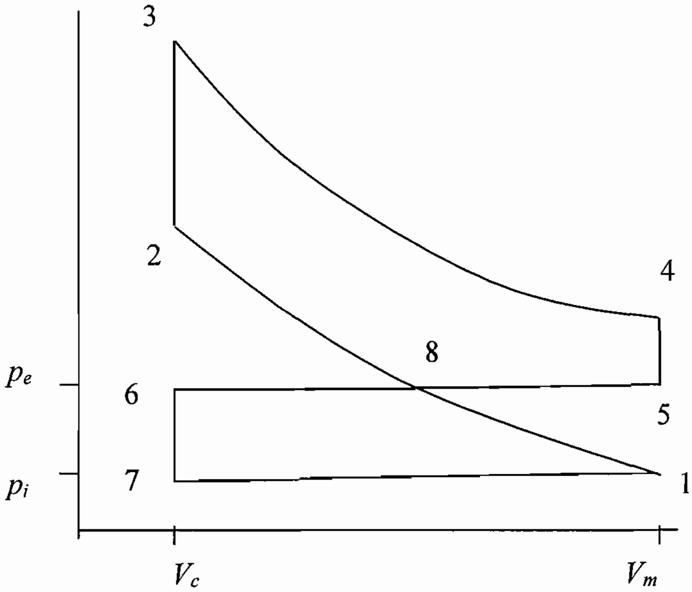

Fig. 1

(TURN OVER

4 A compression-ignition engine is fitted with a turbocharger. The AFR is 18:1, the inlet to the compressor (of isentropic efficiency 70%) is at 0.95 bar abs, 15°C, and the outlet of the compressor is at 2 bar abs. The exhaust gases enter the turbine (of isentropic efficiency 80%) at 1.8 bar abs, 600°C, and leave at 1.05 bar. Assume that for air $c_{p,air}$=1.01 kJ kg^{-1} K^{-1}, γ_{air}=1.4, and that for the exhaust gases, $c_{p,ex}$=1.15 kJ kg^{-1} K^{-1} and γ_{ex}=1.33.

(a) Draw the turbocharger process on a T-s diagram. [25%]

(b) Determine the gas temperature at exit from the compressor and turbine. [25%]

(c) Calculate the mechanical efficiency of the turbocharger. [25%]

(d) If an intercooler of effectiveness 0.5 is fitted at the exit of the compressor, and the AFR, and the compressor delivery pressure and temperature are unchanged, estimate the increase in engine power. (Assume the temperature available for heat exchange is 15°C.) [25%]

END OF PAPER

Part IIB, Module 4A13
2009 Answer Sheet

1. -

2. -

3. -

(a) –

(b) $W_{12} = \frac{p_i V_m}{\gamma - 1}\left(1 - \left(\frac{V_m}{V_c}\right)^{\gamma-1}\right)$, $W_{34} = \frac{p_3 V_c}{\gamma - 1}\left(1 - \left(\frac{V_c}{V_m}\right)^{\gamma-1}\right)$

(c) p_3 = 32.7 bar, gimep = 4.0 bar

(d) $W_{pump} = 0.44 V_m$, net imep = 3.5 bar

(e) –