Version NS/3

EGT3
ENGINEERING TRIPOS PART IIB

Friday 6 May 2022 9.30 to 11.10

Module 4A13

COMBUSTION AND 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.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

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

You may not remove any stationery from the Examination Room.

1 Consider the following set of reactions occurring inside a closed vessel:

$$A \xrightarrow{k_1} D \qquad \text{(R1)}$$

$$A + D \xrightarrow{k_2} \alpha\, D + \text{product} \qquad \text{(R2)}$$

$$D \xrightarrow{k_w} \text{product} \qquad \text{(R3)}$$

$$D + M \xrightarrow{k_g} M + \text{product} \qquad \text{(R4)}$$

where k_i are specific rate constants, M is a third body, A is a reactant and D is a radical.

(a) Describe what type of reactions (R1) to (R4) are, and explain the difference between (R3) and (R4). [20%]

(b) Write an equation for the rate of change of radical concentration, $[D]$, for the above set of reactions. [10%]

(c) Using your equation for part (b), show that $[D]$ is finite when

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

under the steady state condition for the radical concentration. [30%]

(d) The situation under which the radical concentration becomes very large is known as a chemical explosion. Deduce a criterion involving k_2, k_w, k_g, $[A]$, $[M]$ and α for the chemical explosion using the steady state expression for the radical concentration. [30%]

(e) Show that the criterion in part (d) becomes

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

when $k_w \ll k_g[M]$. [10%]

2 A partial oxidation reactor is used to produce hydrogen from bio-butanol having the molecular formula $C_4H_{10}O$ and atmospheric air. The reactor is operating at 1400 K with an equivalence ratio of 3.0. The products leaving the reactor are in thermodynamic equilibrium.

(a) Would you expect thermodynamic equilibrium everywhere inside the reactor? Explain your answer. [5%]

(b) Calculate the mole fractions of gases leaving the reactor, assuming that the only species present are CO_2, CO, H_2O, H_2 and N_2. [65%]

(c) Does the pressure in the reactor affect the product composition? Explain your answer. [5%]

(d) Explain how you would increase the hydrogen yield. [25%]

3 Exhaust gas is recirculated to the intake manifold of a spark-ignition engine operating at stoichiometric condition running on an ideal Otto cycle with a compression ratio of 9 and a thermal efficiency of η_{th}. In Case A, there is no exhaust gas recirculation (EGR) and the residual gas fraction is 10% by mass. The EGR is introduced in Case B and the total burned gas fraction in the charge is 30% by mass. Assume that the total mass admitted into the cylinder is unchanged, the initial temperature is 300 K, the ratio of specific heat capacities to be 1.4 for the gas mixture and the fuel mass fraction is much smaller than the mass fractions of air and burned gases in the in-cylinder charge.

(a) Show that the temperature rise after combustion can be approximated by

$$\frac{m_f}{m_a}\frac{Q(1-x_r)}{c_v}$$

where m_f and m_a are the masses of fuel and air respectively in the charge. The lower calorific value of the fuel is Q and x_r is the burned gas fraction in the charge. The specific heat capacity at constant volume of the charge, c_v, is taken to be constant and is equal to that of air. [35%]

(b) The temperature rise due to combustion in Case A is 2100 K. Estimate the maximum burned gas temperature for the two cases. [25%]

(c) Calculate the indicated fuel conversion efficiency for the engine. [10%]

(d) Calculate the percentage change in the gross indicated work per cycle between the two cases. [20%]

(e) How can one restore the indicated work per cycle in Case B to that of Case A, while keeping the EGR induction? [10%]

4 Consider an unthrottled four-stroke engine having a compression ratio of r, operating in a constant volume ideal cycle of efficiency η. The mixture density at the start of the cycle is ρ_1 with temperature T_1 and pressure p_1. The heat released per unit mass in the cylinder is q^* and it is assumed that there is negligible residual gas.

(a) Show that the indicated mean effective pressure is

$$\text{imep} = \eta q^* \rho_1 \left(\frac{r}{r-1}\right). \qquad [20\%]$$

(b) A supercharger (compressor powered by a battery) with a pressure ratio of r_c, and an isentropic efficiency of η_c is added to the system. Assume that the cycle is still the ideal constant volume cycle with unchanged q^*, the properties of the gas entering the cylinder are equal to those at the compressor exit, and that the mass fractions of fuel and residual gas are small compared to that of air.

(i) Show that the ratio of the net work rate (cycle minus compression) to the work rate without the supercharger is

$$\frac{\dot{W}'_{net}}{\dot{W}} = r_c \frac{1-bf}{1+f}$$

where $f = \left(r_c^{(\gamma-1)/\gamma} - 1\right)/\eta_c$, $b = c_p T_1/(\eta q^*)$, and the specific heat capacities at constant pressure for the mixture and air are both equal to c_p. [35%]

(ii) Sketch the above ratio, $\dot{W}'_{net}/\dot{W}$, as a function of r_c for $b = 0.1$, $\eta_c = 0.7$, and $\gamma = 1.4$. [20%]

(c) Show that the net efficiency for the supercharged cycle, defined as the net work divided by input fuel energy, is

$$\eta' = \eta - \left(\frac{c_p T_1}{q^*}\right)\left(\frac{r_c^{(\gamma-1)/\gamma} - 1}{\eta_c}\right). \qquad [20\%]$$

(d) Explain why the supercharger is used despite its reducing the overall efficiency. [5%]

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