Version NS/2

EGT3
ENGINEERING TRIPOS PART IIB

Monday 12 May 2025 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 (a) Consider the following set of reactions occurring inside a closed vessel:

$$A + A \underset{k_2}{\overset{k_1}{\rightleftharpoons}} A + A^* \qquad \text{(R1)}$$

$$A^* \xrightarrow{k_3} P \qquad \text{(R2)}$$

where k_i are specific rate constants, A is a reactant and A^* is activated A which decays to a product P.

(i) Deduce an expression for the rate of formation of P if A^* is taken to be in steady state. [25%]

(ii) Show that the rate of formation of P is first order in the high pressure limit and is second order in the low pressure limit. [25%]

(b) The products of methane-air combustion at an equivalence ratio of 2.0 are in chemical equilibrium at 5 bar and 1200 K. Calculate their volumetric composition, assuming that the only species present are CO_2, CO, H_2O, H_2 and N_2. Would a change in pressure affect this composition? [50%]

2 (a) What are the types of elementary reactions? Explain them briefly with an example for each type. [5%]

(b) Describe the classification of chain reactions with examples. [10%]

(c) Carefully draw typical variations of temperature, fuel, oxygen, product and intermediate concentrations across a freely propagating laminar premixed flame. Indicate regions of interest for various classes of chain reactions and give brief explanations. [20%]

(d) Take the overall thickness of the flame structure that you have drawn for part (c) to be δ_f, which is propagating at a speed of s_l into stationary reactant mixture with temperature T_r and the fuel consumption rate per unit volume in this flame is $\dot{\omega}$. By applying appropriate conservation laws, deduce that

$$\delta_f \simeq \sqrt{\lambda/(c_p\dot{\omega})} \qquad \text{and} \qquad s_l \simeq \sqrt{\lambda\,\dot{\omega}/\left(c_p\,\rho_r^2\right)}$$

where the reactant density, thermal conductivity and specific heat capacity at constant pressure are ρ_r, λ and c_p respectively. [25%]

(e) Assume that $\dot{\omega} \approx p^n\, Y_r\, A_f\, \exp(-T_a/T_f)$, where p is the pressure, n is the overall order of combustion reaction, Y_r is the fuel mass fraction in the reactant mixture, A_f is the pre-exponential factor for the reaction kinetics with activation temperature T_a and T_f is the product temperature. Substituting for $\dot{\omega}$ in s_l given in part (d), discuss the variation of s_l with p, T_r and the equivalence ratio, ϕ, of the reactant mixture using carefully drawn diagrams. [40%]

 (TURN OVER

3 (a) A model gas turbine combustor for zero-carbon fuels shown schematically in Fig. 1a has a thermal power of 15 kW. The combustion chamber is cylindrical of length L. Air is supplied from a plenum through 5 nozzles each with a diameter of $7.5d$ as shown in Figs. 1b and 1c. Fuel is injected at 90° into the air stream in each nozzle through two opposed holes of diameter $d = 1$ mm. The centre of these holes are at $7.5d$ upstream of the combustion chamber entry. The air and fuel mass flow rates are the same in each nozzle and these flow rates are denoted as $\dot{m}_{cf}$ and $\dot{m}_j$ respectively. The streamwise evolution of the fuel jet centreline is given by

$$\frac{y}{d\sqrt{J}} = 1.6\left(\frac{x}{d\sqrt{J}}\right)^{1/3} \quad \text{with} \quad J = \frac{\rho_j U_j^2}{\rho_{cf} U_{cf}^2}$$

where ρ is the density and U is the bulk-mean velocity. The subscripts j and cf denote the fuel and air streams respectively. The spatial coordinates x and y are marked in Fig. 1c. The air has a density of $1.17\,\text{kg/m}^3$.

(i) Hydrogen with a density of $0.082\ \text{kg/m}^3$ and a lower calorific value of $120\ \text{MJ/kg}$ is used as a fuel. The total air to fuel mass flow rates ratio is $\dot{m}_a/\dot{m}_f = 100$. Calculate the hydrogen jet centreline location at the combustor entry. [25%]

(ii) When ammonia with a density of $0.69\,\text{kg/m}^3$ and a lower calorific value of $18.6\,\text{MJ/kg}$ is used the ratio of the mass flow rates is adjusted to $\dot{m}_a/\dot{m}_f = 7.5$. Calculate the ammonia jet centreline location at the combustor entry. [25%]

(iii) Comment on the differences in the jet trajectories between hydrogen and ammonia, and their implications for safe operation. Suggest any modifications to fuel injection and their implications for fuel flexibilty. [20%]

(b) Discuss the effect on the Damköhler number in the terms of flame stability for the two fuels. Derive an expression for the ratio of the chemical time scales of ammonia to hydrogen. [30%]

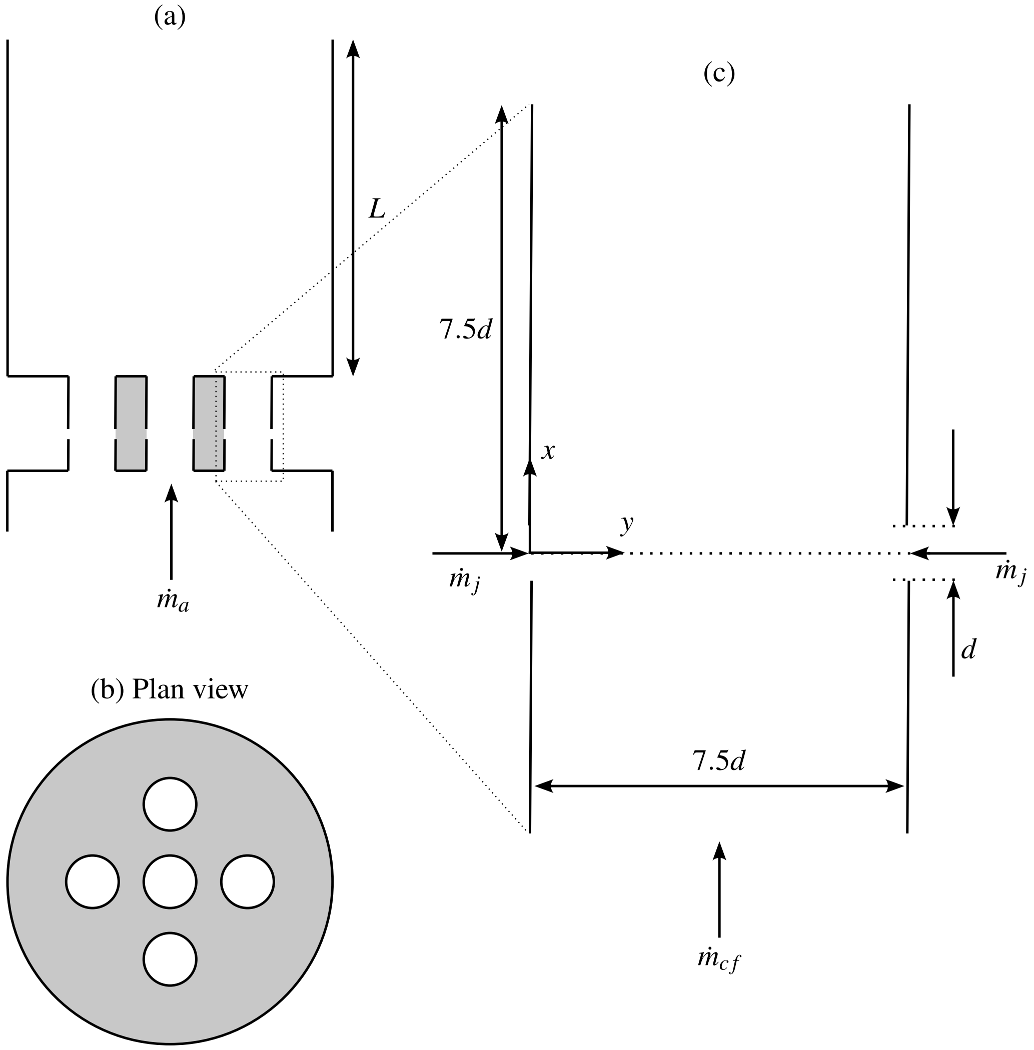

Fig. 1

4 (a) Explain why compression ignition (CI) engines are more efficient than spark ignition (SI) engines. Discuss the differences in the requirements of fuels for SI and CI engines. [25%]

(b) Discuss formation of nitrogen oxides and soot when burning hydrocarbon fuels in the context of a $\phi - T_f$ diagram, where ϕ is the equivalence ratio and T_f is the flame temperature. Mark the operating regions of SI and CI engines in that diagram. [25%]

(c) (i) Discuss the role of fluid mechanics during each phase of the 4-stroke engine cycle. [40%]

(ii) Briefly comment on the differences in the fluid mechanics between a small diesel engine and a large diesel marine engine. [10%]

END OF PAPER

Numerical Answers - 2025

1. (b) $x_{CO2} = 0.0426, x_{CO} = 0.1053,\ x_{H2O} = 0.1053, x_{H2} = 0.1905, x_{N2} = 0.5563$

3. (a)(i) y = 3.26 mm, (ii) y = 9.01 mm