EGT3
ENGINEERING TRIPOS PART IIB

Friday 5 May 2023   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 simple model of a one-dimensional planar laminar premixed flame is shown in Fig. 1. The unburnt mixture with density ρ_u at temperature T_u is flowing into the flame at a constant velocity s_l. This mixture has thermal conductivity of λ and specific heat capacity at constant pressure of c_p. The flame zone thickness is δ_f which consumes fuel at a rate of $\dot{\omega}$ per unit volume. The adiabatic burnt gas temperature is T_b and it flows at a velocity of u_b.

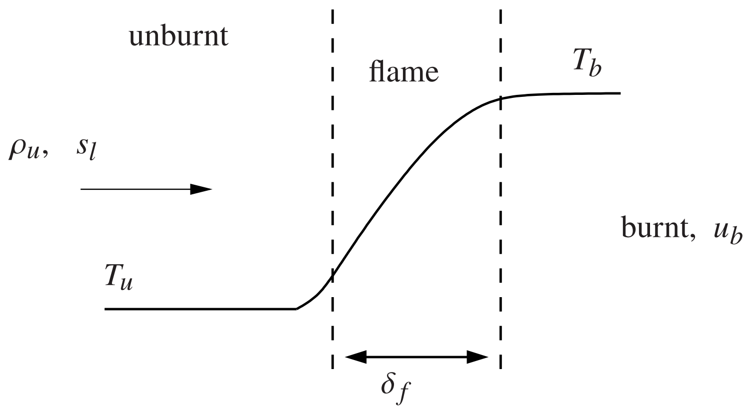

Fig. 1

(a) Deduce that $\delta_f^2 \approx \lambda \left(c_p\, \dot{\omega}\right)^{-1}$ and $s_l \approx \left(\lambda\, \dot{\omega}/c_p\right)^{1/2} \rho_u^{-1}$. [20%]

(b) Consider $\dot{\omega} \approx p^n Y_f \mathcal{A} \exp\left(-T_a/T_b\right)$, where p is the pressure, n is the overall order of combustion reaction, Y_f is the fuel mass fraction in the reactant mixture, $\mathcal{A}$ is the pre-exponential factor for the reaction kinetics with activation temperature T_a. Using this in the expression for s_l, discuss the variation of s_l with p, T_u and the equivalence ratio of the reactant mixture using carefully drawn diagrams. [35%]

(c) Using the overall mass balance across the flame, show that the velocity of the burnt mixture can be written as $u_b = (1 + \tau)\, s_l$, where $\tau = (T_b - T_u)/T_u$. Clearly state any assumptions you may need. [20%]

(d) Consider that this flame is propagating through a tube of diameter d. Deduce a relationship between d and δ_f for the flame to be quenched. [25%]

2 In a gas turbine engine, hot air from the compressor at $T_1 = 1000$ K and 10 bar flows at a rate of $0.21\ \text{kg}\,\text{s}^{-1}$ through a straight circular combustor duct of diameter $D = 0.055$ m and length L_c. This engine runs on a liquid fossil fuel which is injected parallel to the air stream uniformly across the duct. The fuel droplets evaporate as they flow, this evaporation may be assumed to be isothermal at T_1 and complete evaporation occurs over a length of $L_v < L_c$. The fuel has an activation temperature of $T_a = 15000$ K. The autoignition of the fuel vapour occurs roughly half-way through the combustor. The engine operator decides to use a liquid biofuel $C_{20}H_{38}O_4$, which is injected at a rate of $0.01\ \text{kg}\,\text{s}^{-1}$ with an initial droplet diameter of 30 microns. The activation temperature for the biofuel is 5% higher than that for the fossil fuel.

(a) If no combustion occurs in the initial part of the duct, what is the equivalence ratio of the mixture after complete evaporation of the biofuel? [20%]

(b) Derive an expression for the variation of droplet diameter with time and hence calculate L_v for the biofuel. Take the mass flux of fuel to be $\dot{m}'' = \rho_f B/(4d)$ at the surface of an evaporating droplet of diameter d. Take the mass transfer number as $B = 1.5 \times 10^{-7}\ \text{m}^2\,\text{s}^{-1}$. [40%]

(c) Estimate the autoignition length for the biofuel. Would there be any practical implications? Explain your answer. [30%]

(d) What would you do to keep this autoignition length to be the same for the fossil fuel? Justify your answer clearly. [10%]

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3 (a) Discuss the advantages and disadvantages of ammonia as potential fuel for future gas turbines from a combustion perspective. [40%]

(b) A gas turbine combustor of a length L, burning a mixture with laminar burning velocity of $S_{L,0}$ at pressure P_0 and unburnt mixture temperature of T_0, is to operate at $2P_0$. The residence time inside the combustor is to be kept the same. Derive an expression for the new inlet temperature to maintain flame stability. State your assumptions clearly. [30%]

(c) To achieve decarbonisation, a combustor is switched from methane to hydrogen. The fuel is injected through N small holes of diameter d at 90° to the air stream. The designer maintains this injection strategy for the new fuel. The overall combustor power, the air mass flow rate, momentum flow rate, and the momentum flow rate ratio between the air and fuel streams are to remain the same. Discuss how should N and d change for hydrogen operation relative to the original methane operation. [30%]

4 (a) Compare a diesel engine and a gas turbine for power generation applications considering typical efficiencies, fuel flexibility, emissions, potential for waste heat utilisation, and any other pertinent factors. [50%]

(b) Discuss the expected emissions of NO_x, unburnt hydrocarbons, CO, and particulate matter from diesel engines burning a hydrocarbon fuel in the context of the ϕ–T_f diagram, where ϕ is the equivalence ratio and T_f is the flame temperature. Discuss in-cylinder emission reduction methods. [50%]

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Numerical Answers - 2023

1. (d) $d = 2\sqrt{2}\delta_f$

2. (a) $\phi = 0.526$, (b) $L_v = 15.35$, (c) $L_{\text{ign,bio}} = 2.117 L_{\text{ign,foss}}$.