Version NS/5

EGT3
ENGINEERING TRIPOS PART IIB

Friday 7 May 2021 9 to 10.40

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 and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
You are allowed access to the electronic version of the Engineering Data Books.

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

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 (a) Describe briefly flame *blow-off*, using a carefully drawn graph for the physics of a well-stirred reactor. [10%]

(b) An approximate theory suggests that flame blow-off occurs in a combustor when

$$\tau_{\mathrm{chem}} > C\,\tau_{\mathrm{res}}$$

where C is a constant. The chemical time scale of a flammable mixture at an initial temperature of T_0 is τ_{chem}. The residence time is $\tau_{\mathrm{res}} = L/U$ with U as the bulk-mean velocity of the mixture entering the combustor of length L. Assume that the reactant mixture is an ideal gas and τ_{chem} varies as $T_0^{-5/2}$. Find the percentage change in the mass flow rate of the mixture at blow-off when

(i) T_0 is doubled with all other parameters kept constant; [40%]

(ii) L is doubled with all other parameters kept constant. [30%]

(c) Briefly describe the various mechanisms of nitric oxide generation from combustion. Discuss strategies used to mitigate nitric oxide emissions from combustion applications. [20%]

2 (a) A simple model of a one-dimensional planar laminar premixed flame is shown in Fig. 1. The reactant mixture of density ρ_u at a temperature T_u is flowing into the flame at a constant velocity s_l. The thermal conductivity of the mixture is λ and its specific heat capacity at constant pressure is c_p. The flame zone has a thickness of δ_f and consumes fuel at a rate of $\dot{\omega}$ per unit volume. The adiabatic burnt gas temperature is T_b. Deduce that the flame thickness is $\delta_f^2 \approx \lambda \left(c_p\, \dot{\omega}\right)^{-1}$ and $s_l \approx \left(\lambda\, \dot{\omega}/c_p\right)^{1/2} \rho_u^{-1}$. Also, show that the thermal diffusivity is $\alpha = \delta_f s_l$. [30%]

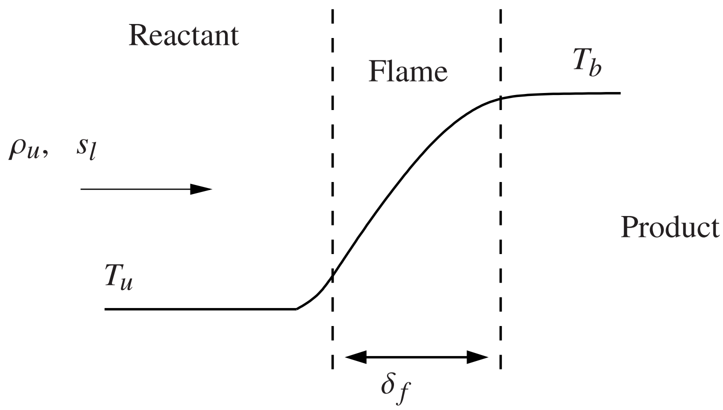

Fig. 1

(b) A metal plate with small circular holes of diameter d is to be installed at the entry of a combustion chamber burning methane-air mixture at temperature $T_u = 298$ K and 1 bar to prevent the potential of flame flashback. This mixture behaves as an ideal gas. The flame is quenched as a result of heat loss to the plate.

(i) Deduce a relationship between d and δ_f, the laminar flame thickness given in part (a), for the flame to be quenched. [30%]

(ii) If the operating pressure is increased by five times, estimate the percentage change in the hole diameter for flame quenching to occur. [20%]

(iii) Estimate the percentage change in the hole diameter for the flame quenching, if the mixture temperature is increased to 400 K. Assume that the thermal conductivity, λ, varies as $\sqrt{T_u}$ and the temperature dependence of c_p can be ignored. [20%]

3 A series hybrid powertrain has only an electrical connection between the gasoline IC engine and the transmission. With a battery, such a system allows for the possibility of improving fuel economy by running the IC engine in “start/stop” mode. To attempt an initial estimate of the possible fuel economy improvement, we wish to compare two vehicles, A and B, operated in an urban environment. Vehicle A has a conventional powertrain, and the average inlet manifold pressure is estimated to be 0.35 bar absolute. Vehicle B uses the same engine but runs in start/stop mode, and while running, is unthrottled.

The engine is assumed to run on the ideal Otto cycle with air as the working fluid with properties as at ambient conditions. The compression ratio is 9:1. The ambient conditions are 1 bar absolute and 300 K. The engine speed and AFR are fixed, and the temperature rise due to combustion at all engine running conditions is 1800 K.

(a) Assuming that there are no losses in either powertrain, determine the percentage of the time that the start/stop engine is running, and the fuel economy benefit. [60%]

(b) Discuss the practical issues that will affect the viability of such a start/stop vehicle. [40%]

You may assume without proof that the work done during the isentropic compression of a perfect gas between states 1 and 2 is given by

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

in the usual notation.

4 Consider the combustion process starting near top dead centre of the compression stroke in a spark-ignited engine using premixed gases. The charge mass burnt fraction in the cylinder is x and the unburnt fraction is $(1 - x)$. Assume that the combustion takes place at top dead centre under constant volume, adiabatic conditions, and that both the burnt and unburnt gases behave as perfect gases with constant and identical properties. The lower heating value of the fuel per unit mass of the mixture is q, the specific heat capacity at constant volume is c_v, and the ratio of specific heats is γ.

(a) Starting from the energy conservation equation, show that the differential pressure rise $\mathrm{d}p$ is related to the differential mass fraction burnt, $\mathrm{d}x$, by the following equation

$$\frac{\mathrm{d}p}{\rho R} = \mathrm{d}T_u + x\,\mathrm{d}(T_b - T_u) + (T_b - T_u)\,\mathrm{d}x$$

where T_b and T_u are the absolute temperatures of the burnt and unburnt gases respectively, ρ is the charge density with a gas constant R. [30%]

(b) Assuming that $\Delta T = (T_b - T_u)$ is constant during the heat release process and that the gases are compressed isentropically, obtain an expression for x as a function of p. The pressure and temperature of the compressed unburnt gas prior to the sparking are p_0 and T_{u0} respectively. [30%]

(c) Sketch the temperatures of a mass element burning at $x = 0.01$, 0.50 and 0.99. Annotate salient features. [30%]

(d) Deduce an expression for p_f/p_0 using the overall energy balance, where p_f is the pressure at the end of the combustion process. State your observations by comparing this expression with that obtained in part (b). [10%]

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Numerical Answers - 2021

1. (b)(i) 183% increase, (b)(ii) 100% increase.

2. (b)(ii) hole diameter decreases by nearly 55%, (b)(iii) hole diameter decreases by about 13.7%

3. (a) the start/stop engine runs 18.5% of the time, the fuel saving is 47%