EGT3
ENGINEERING TRIPOS PART IIB

Thursday 4 May 2017 9.30 to 11

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.*

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
Attachment: None

10 minutes reading time is allowed for this paper.

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

1 (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 (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

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

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 (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%]

2 A droplet of n-dodecane ($C_{12}H_{26}$) with density ρ_ℓ and diameter d is evaporating in a stagnant environment of N_2 at 1 bar and temperature $T_a = 700$ K. The fuel vapour mass fraction at the droplet surface is $Y_{f,0}$ and its value in the far-field is $Y_{f,\infty}$. The droplet initial diameter is d_0.

(a) Taking the fuel mass flux due to evaporation to be $\dot{m}'' = \rho_\ell \beta/(4d)$, where β is a constant, derive an expression for the variation of d with time. [20%]

(b) Using your result for (a) and

$$\beta = \frac{8\rho\mathscr{D}}{\rho_\ell} \ln\left(\frac{1-Y_{f,\infty}}{1-Y_{f,0}}\right)$$

where ρ is the gas mixture density and $\mathscr{D}$ is the mass diffusivity, deduce an expression for the time, t_v, taken to completely evaporate the droplet. [15%]

(c) Considering the energy balance at the evaporating surface and taking the surface heat flux to be $\dot{q}'' = 2\lambda\,(T_a - T_s)/d$, where T_s is the saturation temperature for the fuel at 1 bar, show that the fuel mass fraction at the surface is

$$Y_{f,0} = 1 - \exp\left[-c_p\,(T_a - T_s)/h_{fg}\right]$$

for the binary mixture of unity Lewis number. The mixture specific heat capacity at constant pressure is c_p and the enthalpy of evaporation is h_{fg}. [35%]

(d) Calculate t_v for $\rho_\ell = 750$ kg m^{-3}, $c_p = 1.075$ kJ kg^{-1}K^{-1}, $T_s = 490$ K, $\mathscr{D} = 1.78 \times 10^{-5}$ m^2 s^{-1}, $h_{fg} = 256$ kJ kg^{-1} and $d_0 = 20$ μm. Using carefully drawn diagrams, explain how does t_v change with T_a, d_o and pressure? [20%]

(e) Briefly explain how you would modify the above analysis if the droplet is evaporating in a convective flow field? [10%]

3 Exhaust gas is recirculated to the intake manifold of a spark-ignition engine that follows an ideal Otto cycle. The residual gas fraction, x_r, without exhaust gas recirculation (EGR), is 10% by mass (case A). After introducing EGR, the total residual gas fraction in the charge is 30% by mass (case B). Assume that the total mass admitted into the cylinder is unchanged and the engine operates at stoichiometric condition for both cases.

(a) Show that the temperature rise after combustion is given by

$$\Delta T = \frac{Q(1-x_r)}{c_v(AFR+1)}$$

where c_v is the mean specific heat capacity at constant volume, and AFR is the mass air-to-fuel ratio. [30%]

(b) The initial mixture temperature is 300 K, the compression ratio is 9, the ratio of specific heats is 1.4, and the specific heat capacity at constant volume over the temperature for the gas mixture is $1.5\ \mathrm{kJ\,kg^{-1}K^{-1}}$. The fuel is iso-octane (C_8H_{18}), with a lower heating value of $Q = 51\ \mathrm{MJ\,kg^{-1}}$. Estimate the temperature rise and the final temperature due to combustion in case A, and state your assumptions with justification. [25%]

(c) Estimate the fractional change in temperature rise and indicated mean effective pressure between cases A and B. State any further assumptions made. [25%]

(d) Suggest a method by which the indicated work of the cycle in case B might be restored to that of case A, while keeping EGR induction. [10%]

(e) Explain why EGR is used in spark ignition engines, its advantages and disadvantages. [10%]

4 An intercooled turbocharged compression-ignition engine operates with a compression ratio of r. The cycle can be represented by an ideal limited-pressure cycle, in which a fraction β of the fuel energy is released during the constant volume part of the heat addition, with a volumetric expansion ratio αr during the constant pressure heat addition. The overall non-dimensional energy release is $q = Q/(mc_v T_1)$, where Q/m is the total energy release per unit mass, c_v is the specific heat capacity at constant volume, and T_1 is the pre-compression charge temperature.

(a) Draw a p-V diagram for the turbocharged cycle, indicating the relevant parameters. Overlay a real cycle on the ideal cycle, indicating the key differences. [20%]

(b) Show that

$$\alpha = \frac{1}{r}\left[\frac{(1-\beta)q}{\gamma\left(\beta q + r^{\gamma-1}\right)} + 1\right]$$

[20%]

(c) Show that the mean specific gross work, w_g, for the cycle is

$$\frac{w_g}{c_v T_1} = q - r\alpha^{\gamma}\left(\beta q + r^{\gamma-1}\right) + 1$$

[20%]

(d) Explain the differences in combustion characteristics, and the limits to compression ratio and load in the real and ideal compression-ignition cycles. [20%]

(e) Explain the advantages and disadvantages of turbocharging and intercooling for compression-ignition engines. Give reasons for the greater prevalence of such techniques in compression-ignition rather than spark-ignition engines. [20%]

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Numerical Answers - 2017

2. (d) t_v = 5 ms

3. (b) Temperature rise is 1900 K; the final temperature is 2622 K

   (c) $(\Delta T_B/\Delta T_A) = 0.77$; & $(IMEP_B/IMEP_A) = 0.77$