UNIVERSITY OF CAMBRIDGE

ENGINEERING TRIPOS PART IIB

Wednesday 5 May 2004 9 - 10.30

Module 4A5

INTERNAL COMBUSTION 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 the question is indicated in the right margin.*

You may use the results given on the data sheet without proof, except where indicated otherwise.

Attachments: special datasheet for 4A5 (2 pages)

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

(TURN OVER

1 (a) Prove that the variation in concentration of a species i along a catalyst cell is given by

$$\varepsilon u \frac{d\, y_{i,g}}{dx} + h_{D,i} S(y_{i,g} - y_{i,s}) = 0$$

where the symbols have their usual meaning. [30%]

(b) An isothermal monolith operates under conditions of a single, very low concentration reactant, high oxidant concentration, and constant pressure. Show that the change of reactant concentration with distance is given by

$$\frac{y^{x}{}_{i,g}}{y^{x=0}{}_{i,g}} = \exp\left(\frac{-h_{D,i} S}{\varepsilon u (1+\beta)} x\right)$$

where

$$\beta = \frac{p h_{D,i}\, S}{RMk_i y_{O_2} a}$$

where the symbols have the usual meaning. [35%]

(c) Assuming that this analysis applies, determine the minimum temperature at which 50% conversion of carbon monoxide will take place for a mass flow of 0.015 kgs^{-1}, through a catalyst of 0.012 m^2 frontal area and length 0.15 m. The carbon monoxide is in air, and the pressure is 1 bar. Assume a catalyst with void fraction 0.7 and square cells of dimension 1 mm. [35%]

2 (a) Describe the operation of a "three-way" catalyst in terms of its characteristics of conversion efficiency against lambda, for common exhaust gaseous pollutants. What damage mechanisms may occur in practice? [20%]

(b) It is proposed to treat the feed gas emissions from a 1.4 litre, I4 4-stroke gasoline engine by means of an oxidation catalyst with square cells. At fully warmed up conditions, the objective is to achieve, for carbon monoxide and uHC's, a minimum conversion efficiency of 99%, at a mass flow corresponding to 50% of maximum. At maximum power, the combined pressure drop should not exceed 0.3 bar. Assume that the pressure drop through the system can be ignored at the 50% load condition. Use data for typical automotive catalysts from the data sheet attached, and make sensible estimates for other data you may require.

(Cont.

(i) Determine a relationship between the number of monolith cells required and their length. [30%]

(ii) Determine a relationship between the number of cells, the cell size and length of the catalyst using the maximum permissible pressure drop criterion at full power. [30%]

(iii) If the cell size, is 0.6 mm, determine the length and number of cells. [20%]

3 (a) For a conventional port injected gasoline engine draw a carefully proportioned graph, showing how the maximum torque varies with engine speed. Also sketch on this graph contours of constant specific fuel consumption, indicating appropriate trends. Make notes to justify all the characteristics of the sketch you have produced. [70%]

(b) Add to the graph constructed in (a) a top gear road load characteristic, justifying its form. Add three constant power contours, and discuss, in relation to the figure, the opportunities presented by continuously variable transmissions. [30%]

4 (a) For gasoline engines, describe the origin of unburnt hydrocarbon, carbon monoxide and NOx emissions in the exhaust. How does the concentration of each pollutant vary with the following engine operating variables: speed, lambda, spark advance, manifold pressure and EGR rate? [50%]

(b) For Diesel engines, describe the origin of NOx and particulate emissions in the exhaust. How does the concentration of each pollutant vary with the following engine operating variables: speed, lambda, start of injection and EGR rate? [50%]

For both parts, use carefully proportioned qualitative graphs as necessary.

END OF PAPER

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DATASHEET FOR 4A5

For steady laminar flow in a constant area tube

$$\frac{dp}{dx} = -\frac{C P^2 \mu R T \dot{m}}{8 A^3 p} \qquad 1$$

where P is the tube perimeter, A is the cross-sectional area, m is the mass flow and μ, R, T, and p the mixture dynamic viscosity, gas constant, absolute temperature and absolute pressure respectively. C is a constant which depends on the cell shape. For a cylinder, C = 16, for a square, C = 14.227, for a triangle C = 13.333, for an infinitely wide slot, C = 24.

For steady flow in the cells of a catalyst monolith, neglecting radial temperature gradients, the following relationships hold for mass and heat balances in the bulk gas (subscript g) and at the surface (subscript s). u is the mean velocity in *each channel.* The other symbols have their usual meaning.

$$\varepsilon u \rho c_p \frac{d T_g}{dx} + hS(T_g - T_s) = 0 \qquad 2$$

$$a \hat{R}_i = \frac{\rho h_{D,i}}{M} S(y_{i,g} - y_{i,s}) \qquad 3$$

For steady laminar flow in a constant area tube

$$\varepsilon u \frac{d y_{i,g}}{dx} + h_{D,i} S(y_{i,g} - y_{i,s}) = 0 \qquad 4$$

$$\lambda(1 - \varepsilon) \frac{d^2 T_s}{d x^2} + a \Sigma_1^n [(-\Delta H_i) \hat{R}_i] + hS(T_g - T_s) = 0 \qquad 5$$

The kinetics for oxidation of CO and C_3H_6 on a noble metal surface may be assumed to be given by

$$\hat{R}_i = \frac{k_i y_{i,s} y_{O_2,s}}{G} \qquad 6$$

where k is the rate constant, $y_{i,s}$ is the surface mol fraction of species i, and G is given by

$$G = T(1 + K_1 y_{CO} + K_2 y_{C_3H_6})^2 (1 + K_3 y_{CO}^2 y_{C_3H_6}^2)(1 + K_4 y_{NO}^{0.7}) \qquad 7$$

(Cont.

Rate constants *(k_i), (kmol.K/ m^2 s)*

k_1	*CO and* H_2	*6.7E10.exp(-12556/T)*
k_2	C_3H_6	*1.39E12.exp(-14556/T)*
k_3	C_3H_8 *and* CH_4	*7.326E7.exp(-19000/T)*

Frequency Factors (K_i)

$K_1 = 65.5.exp(961/T)$

$K_2 = 2.08E3.exp(361/T)$

$K_3 = 3.98.exp(11611/T)$

$K_4 = 4.79E5.exp(-3733/T)$

Typical catalyst monolith data.

Void fraction (ε)	*0.7*
Cell dimension (d)	*0.001 m*
Substrate density	*2500 kg/m*^{3}
Catalytic surface area (a)	10 times geometric surface area (S)
Substrate thermal conductivity (λ)	*1.675 W/m K*
Substrate specific heat (c_p)	*1100 J/kg*

Gas molecular diffusivities (D) at typical catalyst temperatures (m^2/s)

CO	*1.332E-4*
C_3H_6	*0.8095E-4* (take as typical for uHC's)
H_2	*5.2E-4*
O_2	*1.35E-4*

For laminar gas flow in catalysts with combined heat and mass transfer, $Sh \cong Nu \cong 4$, and $Le \cong 1$. The Sherwood number is defined by $Sh = h_D\, d/D$, and the Lewis number is defined by Le = (thermal diffusivity)/(molecular diffusivity) = $(\alpha/\rho c_p)/D$

The coefficient of mass diffusion, $h_{D,i}$ *(m/s)*, is defined via the following relationship for the mass flux of a species i across an area A *(m^2)*, where the concentrations (*kg* of the species per cubic meter) through which diffusion occurs are denoted $C_{i,1}$ and $C_{i,2}$ respectively.

$$\dot{m}_i = h_{D,i} A(C_{i,1} - C_{i,2})$$

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