ENGINEERING TRIPOS PART IIB

Wednesday 11 May 2005 9 to 10.30

Module 4A5

INTERNAL COMBUSTION ENGINES

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** number of marks allocated to each part of a question is indicated in the right margin.*

Special Attachments: Special datasheet for 4A5 (4 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

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1 (a) Name the three major pollutants from gasoline and from diesel engines. Briefly explain the origin of these pollutants in the exhaust of gasoline engines. [30%]

(b) Briefly explain the construction of a three-way monolith catalyst including a simple sketch. Discuss the purpose of each major components used in the construction. Draw a carefully proportioned sketch to show the variation of the conversion efficiency of this catalyst with AFR for the three major pollutants, with notes making appropriate justifications. [50%]

(c) Can a three-way catalyst be used in diesel engines? Explain your answer. [20%]

2 (a) Prove that the variation in Y_i, the bulk gas mass fraction of species i, along a catalyst cell is given by

$$\varepsilon u \frac{dY_{i,b}}{dx} + h_{D,i} S (Y_{i,b} - Y_{i,s}) = 0 .$$

The symbols have their usual meaning. Under what conditions is the above equation equivalent to equation 4 given in the attached data sheet. Is this condition valid in practice? Briefly explain your answer. [40%]

(b) Prove that the reaction rate of species i at the wall of a catalyst is related to the bulk and surface values of its mass fraction by

$$a\hat{R}_i = \frac{\rho h_{D,i}}{M_i} S (Y_{i,b} - Y_{i,s}) .$$

The symbols have their usual meaning. [20%]

(c) Consider an isothermal monolith catalyst operating with a stoichiometric mixture of carbon monoxide and oxygen at very low concentrations. Show that the surface and bulk gas mass fractions of carbon monoxide are related by

$$\frac{Y_{CO,s}}{\theta} = \left(1 + 2\frac{Y_{CO,b}}{\theta}\right)^{1/2} - 1$$

where θ is given by

$$\theta = \frac{p\, h_{D,CO}\, S\, M_{CO}}{R\, a\, k_1\, M^2} .$$

The symbols have their usual meaning. [40%]

3 (a) What is particulate matter (PM)? Is the PM emission of major concern in present day gasoline engines? Explain your answer. What is the current control strategy for this pollutant emission from diesel engines? [20%]

(b) Show that the mass flow rate per unit area and the pressure in the inlet channel of a diesel particulate filter (DPF) vary as

$$\frac{d(\rho u_i)}{dx} = -\left(\frac{P}{A_c}\right)\rho u_w$$

and

$$-\frac{dp_i}{dx} = \frac{d\left(\rho u_i^2\right)}{dx} + 2C\left(\frac{\mu u_i}{d^2}\right).$$

The symbols have their usual meaning. [70%]

(c) What are the two major modes of DPF operation? How does the pressure drop vary across the DPF during these modes of operation? [10%]

4 (a) Sketch the typical variation of volumetric efficiency with mean piston speed for a naturally aspirated gasoline and a diesel engine, both at full load. Justify the curves that you have drawn, using additional sketches as required. [35%]

(b) For gasoline and diesel engines, describe the components that comprise the pumping mean effective pressure, taking into account load and speed, and give typical quantitative data, if desired in graphical form, and justify the trends you have identified. [35%]

(c) For gasoline engines, discuss the causes of cyclic variability in combustion, and describe, with reference to a sketch of spark timing versus equivalence ratio, the limits of combustion, and MBT timing. [30%]

END OF PAPER

DATA SHEET - Catalysts

For steady laminar flow in a constant area tube

$$\frac{dp}{dx} = -\frac{CP^2 \mu RT\dot{m}}{A^3 p} \qquad 1$$

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 = 14.25, 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.

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

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

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

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

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

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

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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 K*

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) = $(\alpha / \rho\, c_p)/D$

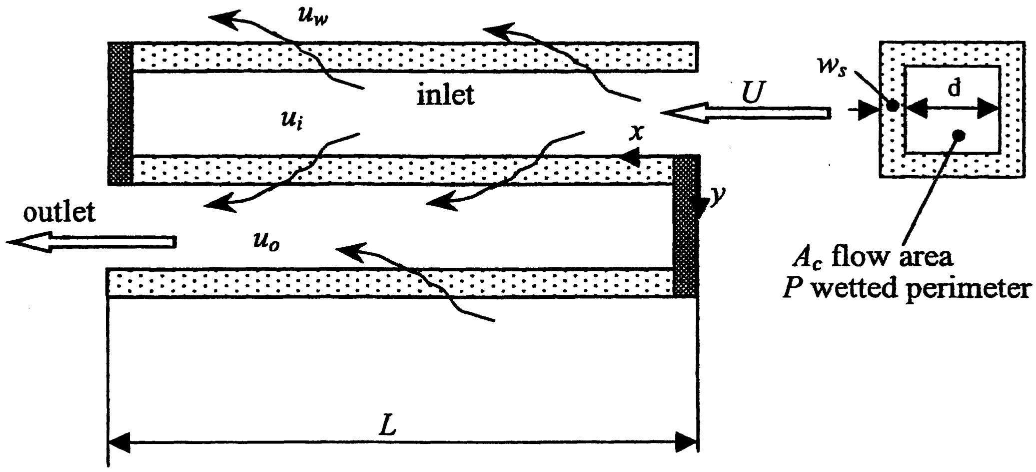
The coefficient of mass diffusion, $h_{D,i}$ *(m/s)*, is defined via the following relationship for the mass flux of a species i across an area A (m^2), where the concentrations (*kg* of the species per cubic meter) through which diffusion occurs are denoted $C_{i,1}$ and $C_{i,2}$ respectively.

$$\dot{m}_i = h_{D,i} A\left(C_{i,1} - C_{i,2}\right) \qquad 8$$

Data Sheet for Diesel Particulate Filter Elementary Analysis

There are two dominant modes of DPF operation, viz., (i) loading or filtration – during which the particulate matters are filtered and (ii) regeneration – burning of the deposited particulate matter. The sequence of these operations depends on the DPF design, for example one can have a continuously regenerative trap. Normally the operation of DPF is a transient process, but for the purpose of presenting an elementary modelling analysis and to make initial DPF sizing, let us assume that the loading process is steady and ignore the regeneration.

Typical inlet and outlet channel may be sketched as below.



Mass conservation

Inlet channel: $\dfrac{d\rho u_i}{dx} = -\left(\dfrac{P}{A_c}\right)\rho u_w$ 9

Outlet channel: $\dfrac{d\rho u_o}{dx} = \left(\dfrac{P}{A_c}\right)\rho u_w$ 10

Momentum conservation

Inlet channel: $\rho\dfrac{du_i^2}{dx} = -\dfrac{dp_i}{dx} - 2C\left(\dfrac{\mu u_i}{d^2}\right)$ 11

Outlet channel: $\rho\dfrac{du_o^2}{dx} = -\dfrac{dp_o}{dx} - 2C\left(\dfrac{\mu u_o}{d^2}\right)$ 12

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Pressure jump across the porous wall (Darcy law) is: $p_i - p_o = \frac{\mu}{\kappa} u_w w_s$ where κ is the permeability of the porous wall (unit - m^2).

The total pressure drop across the DPF is given by

$$(\Delta p)_{total} = \frac{\mu \dot{Q}}{4V_{DPF}} (d + w_s)^2 \left\{ \frac{w_s}{\kappa d} + \frac{16CL^2}{3d^4} \right\} \qquad 13$$

where V_{DPF} is the volume of the DPF trap. C is a constant related to the skin friction coefficient and is 14.25 for square cross section. Experimental studies show that $L/D \approx 1$ gives the smallest pressure drop when other parameters are held constant.

Mass conservation of particle of size d_p across the porous wall is

$$\frac{dC_{d_p}}{dy} = -\frac{3}{2} \frac{(1-\varepsilon)}{\varepsilon d_c} \overline{\eta} C_{d_p} \qquad 14$$

where d_c is the collector diameter $d_c = \frac{3}{2} \frac{(1-\varepsilon)}{\varepsilon} d_{pore}$. The average collection efficiency is the composite efficiency of Brownian diffusion and interception processes and is given by $\overline{\eta} = 64\overline{Pe}^{-1/3} d_p / (d_c + d_p)$. The average Peclet number is $\overline{Pe} = \frac{d_c}{\varepsilon D} \frac{dU}{4L}$. The diffusion coefficient for Brownian motion is given by Stokes-Einstein relationship $D = kT / (3\pi \mu d_p)$, where k = 1.38E-23 J/molecule-K is the Boltzmann constant.

DPF trap efficiency is defined as $E(d_p) = 1 - C_{d_p}^{out} / C_{d_p}^{in}$ and is given by

$$E(d_p) = 1 - \exp\left(-\frac{3}{2} \frac{(1-\varepsilon)}{\varepsilon d_c} \overline{\eta} W_s \right) \qquad 15$$

<u>Data for typical DPF</u>:

Porosity, ε	=	0.5
Permeability κ	=	6.0E-13 m^2
Pore diameter d_{pore}	=	2 μm
Channel size d	=	2.5mm