# 22CGC051

## Transfer Processes

Semester 1 2022/23 In-Person Exam paper

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This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **3 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Attempt **THREE** questions in total.

Each question carries 25 marks.

Candidates should show full working for all calculations and derivations.

1. In semi-conductor manufacture, thin layers of gallium arsenide (GaAs) are deposited onto a substrate using chemical vapour deposition (CVD), in which hydrogen gas containing small amounts of trimethylgallium (TMG) and arsine ($AsH_3$) is passed over a flat plate (the substrate) that is heated to 600 K, as shown in Figure Q1. A very fast reaction occurs on the substrate, by thermal decomposition of TMG and arsine, leading to deposition of GaAs:

$$(CH_3)_3Ga + AsH_3 \rightarrow GaAs + 3CH_4$$

The rate of deposition is sufficiently slow that the concentration of TMG in the free stream may be taken as constant. The gas velocity at the reactor entry is 0.08 m $s^{-1}$ and the substrate is 0.2 m long and 0.2 m wide. The mole fraction of TMG in the free stream is equal to $80\times10^{-6}$. If the minimum permissible thickness of the GaAs layer on the substrate is 100 nm, calculate:

(a) The time required to deposit the minimum required thickness at the trailing edge of the plate. [14 marks]

(b) The minimum mass of GaAs that should be deposited. [7 marks]

(c) Explain why the thickness of GaAs layer is minimal at the trailing edge of the substrate. [4 marks]

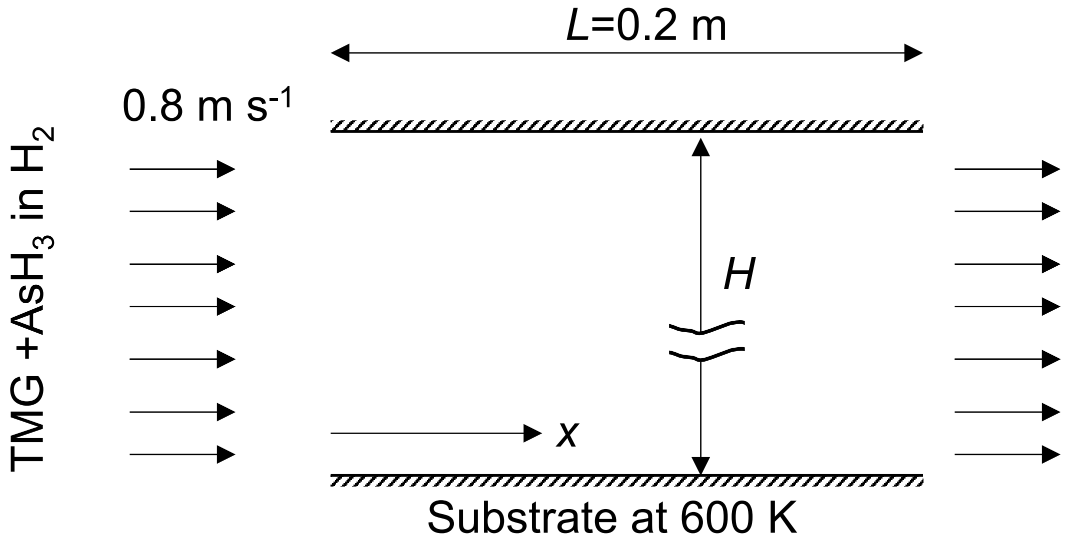

**Figure Q1**

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Q1 Continued/…

Data

Density of hydrogen = 0.040 kg m$^{-3}$

Viscosity of hydrogen = 1.4×10$^{-5}$ Pa s

Diffusion coefficient of TMG in hydrogen = 0.8×10$^{-4}$ m$^2$ s$^{-1}$

Density of the solid GaAs is 5300 kg m$^{-3}$ (RMM = 144.6)

The laminar-turbulent transition occurs at $Re_x$ = 3×10$^5$

**Table Q1: Mass transfer correlations** (symbols have their usual meaning)

| **Laminar flow over a flat plate** | |
|---|---|
| Local Sherwood number at distance $x$ from leading edge | $Sh_x = \frac{h_D x}{D} = 0.323\left(\frac{\mu}{\rho D}\right)^{1/3}\left(\frac{u_s \rho x}{\mu}\right)^{1/2}$ |
| Mean Sherwood number over a length $L$ | $Sh_m = \frac{h_{Dm} L}{D} = 0.65\left(\frac{\mu}{\rho D}\right)^{1/3}\left(\frac{u_s \rho L}{\mu}\right)^{1/2}$ |
| **Turbulent flow over a flat plate** | |
| Local Sherwood number at distance $x$ from leading edge | $Sh_x = \frac{h_D x}{D} = 0.0292\left(\frac{\mu}{\rho D}\right)\left(\frac{u_s \rho x}{\mu}\right)^{4/5}$ |
| Mean Sherwood number over a length $L$ | $Sh_m = \frac{h_{Dm} L}{D} = 0.0365\left(\frac{\mu}{\rho D}\right)\left(\frac{u_s \rho L}{\mu}\right)^{4/5}$ |

2. (a) The gas ammonia (A) is diffusing at a steady state through stagnant nitrogen (B) in a conduit of length $L$ at temperature $T$ and a total pressure of $P$. The partial pressure of A at the left end is $p_{A1}$ and at the other end $p_{A2}$. The cross-section of the conduit is in the shape of an equilateral triangle, the length of each side of the triangle being $l_1$ at the left end and tapering uniformly to $l_2$ at the right end. The diffusivity of A in B is $D_{AB}$.

   (i) By stating the assumptions, show that molar flux of A at a distance $z$ from left end is given by:

$$N_A = -\frac{D_{AB}}{RT}\frac{dp_A}{\left(1 - {}^{p_A}/_{P}\right)dz}$$

[5 marks]

   (ii) Starting with the equation obtained in part (i), derive an equation for molar flux of ammonia ($Q_A$) through the conduit. [10 marks]

(b) Carbon dioxide is absorbed as it bubbles through a pool of water at 293 K. The bubbles contain pure $CO_2$ and have a mean diameter of 2.5 mm and a rise velocity of 0.15 m $s^{-1}$. The diffusion coefficient of $CO_2$ in water is $1.85 \times 10^{-9}$ $m^2$ $s^{-1}$. At the experimental conditions, the equilibrium is represented by Henry's law, $y^* = 1060\ x$, where $x$ and $y$ are *mol*e fractions in the liquid and gas phases, respectively.

   (i) Calculate the liquid side mass transfer coefficient from Higbie's penetration theory. [2 marks]

   (ii) Assuming that the water contains negligible dissolved $CO_2$, calculate the mass transfer rate (kg $s^{-1}$) from each bubble. [4 marks]

   (iii) For a gas volume fraction of 15%, estimate the mass transfer rate per unit volume (kg $m^{-3}$ $s^{-1}$) of the gas-liquid mixture. [4 marks]

Relevant Data

Density of water is 1000 kg $m^{-3}$

Molar mass of water is 18 kg $kmol^{-1}$

Molar mass of carbon dioxide is 44 kg $kmol^{-1}$

3. (a) Explain the fractional crystallisation method using a solubility diagram. Explain how one pure crystalline substance can be obtained using this method. [7 marks]

   (b) Explain the main differences between crystals, amorphous solids, and liquid crystals. What are polymorphous substances and what is polymorphism? [5 marks]

   (c) Provide definitions of allotropes and allotropy. [3 marks]

   (d) Describe, with the aid of a schematic, the design and operation of *any* type of industrial crystalliser and discuss its advantages and possible limitations.

   [3 marks scheme + 4 marks description + 3 marks advantages/limitations]

4. (a) Consider a catalyst surrounded by a stagnant gas film through which gas A has to diffuse to reach the catalyst surface, as shown in Figure Q4(a). At the catalyst surface, the reaction A (g) → 2B (g) occurs, and the product B then diffuses back out through the gas film to the main turbulent gas stream composed of A and B. The reaction at the catalyst-coated surface is first order with respect to A in the fluid at the interface, and the rate constant is $k_1$. The effective gas film thickness is $\delta$ and the bulk concentration of A away from the catalyst surface is $y_{A,\infty}$. Starting from Fick's rate equation, show that the local rate of reaction per unit area of the catalytic surface ($R_A$) is given by the transcendental equation:

$$R_A = \frac{D_{AB}C}{\delta} \, ln \, \frac{(1 + N_A/k_1C)}{\left(1 + y_{A,\infty}\right)}$$

where symbols have their usual meaning.

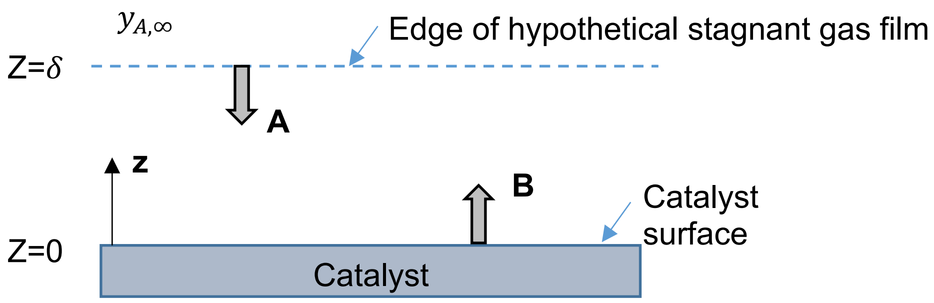

Figure Q4(a): Model of the diffusion problem near the surface of a catalyst

[12 marks]

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Q4 Continued/…

(b) An ethanol (A) – water (B) solution in the form of a stagnant film 2.5 mm thick at 293 K is in contact at one surface with an organic solvent in which ethanol is soluble and water is insoluble (see Figure Q4(b)). At point 1 the concentration of ethanol is 14.0 wt % and the solution density is $\rho_1 = 970.8\ kg\ m^{-3}$. At point 2 the concentration of ethanol is 5 wt% and $\rho_2 = 987.2\ kg\ m^{-3}$. The diffusivity of ethanol is $0.740\ \times 10^{-9}\ m^2 s^{-1}$. Molecular weights of ethanol and water are 46.05 kg kmol$^{-1}$ and 18.02 kg kmol$^{-1}$, respectively.

(i) Derive an equation for the steady-state flux of ethanol ($N_A$). [5 marks]

(ii) Calculate $N_A$. [8 marks]

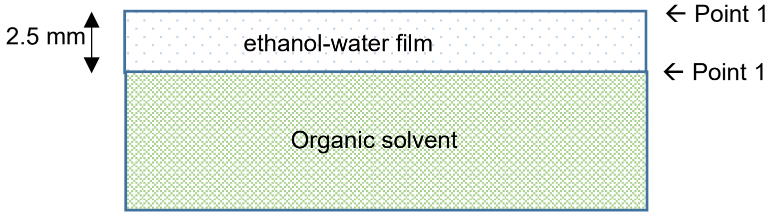

Figure Q4(b): Diffusion of ethanol through a water layer into organic solvent

END OF PAPER

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