24CGC051

Transfer Processes

Semester 1 2024/25 | In-Person Exam paper

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 **2 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).

Answer **ALL** questions. Each question carries 25 marks.

Candidates should show full working for calculations and derivations.

Please detach the Mollier diagram on the final page of the paper and submit with your answer booklet. Please remember to include your ID number.

1. A flow rate of 10 kg s^{-1} of moist air at 22°C and 1 bar is humidified without any heat supply from 60 to 100% relative humidity. Determine the absolute humidity and temperature of the exit air stream if the air becomes saturated by adding:

   (a) Dry saturated steam at 2 bar and 200°C. [11 marks]

   (b) Hot water at 100°C. [9 marks]

   (c) For each of the conditions in Q1(a) and Q1(b), draw a corresponding line in the Mollier diagram that represents the change of air state. See the diagram on the final page. [5 marks]

   Relevant Data

   Specific enthalpy of dry saturated steam at 2 bar and 200°C is 2870 kJ kg^{-1}.

   Specific enthalpy of water at 100°C is 419 kJ kg^{-1}.

   Partial pressure of water vapour in the saturated humid air at 22°C is p_{ws} = 2.64 kPa.

   Mollier diagram (Figure Q1) for humid air at 1 bar is supplied at the end of the paper.

2. Carbon dioxide is absorbed as it bubbles through a pool of water at 20°C. The bubbles contain pure CO_2 and have a mean diameter of 8.3 mm. Assume that the bubbles are spherical and uniform in size, and their rise velocity is given approximately by $V_b = 0.42\sqrt{gd}$, where g is the gravitational acceleration and d is the bubble diameter. At the experimental conditions, the equilibrium is represented by Henry's law, $y^* = 1070x$, where x and y are *mol*e fractions in the liquid and gas phases, respectively.

(a) Calculate the liquid side mass transfer coefficient from Higbie's penetration theory.

[5 marks]

(b) Assuming that the water contains negligible dissolved CO_2, calculate the mass transfer rate (kg s^{-1}) from each bubble. [5 marks]

(c) Derive an expression for the interfacial area per unit volume of the two-phase mixture.

[5 marks]

(d) For a gas volume fraction of 25%, estimate the mass transfer rate per unit volume (kg m^{-3} s^{-1}) of the gas-liquid mixture. [5 marks]

(e) If the bubble size (diameter) is halved and the gas volume fraction remains at 25%, calculate the factor by which the mass transfer rate per unit volume change compared to the value calculated in part (d) above. [5 marks]

<u>Relevant Data</u>

Gravitational acceleration = 9.8 m s^{-2}

Density of water at 20°C = 1000 kg m^{-3}

RMM of water = 18

RMM of CO_2 = 44

Diffusion coefficient of CO_2 in water (20°C) = 1.9×10^{-9} m^2 s^{-1}

3. (a) Air at 1 bar flows through a cylindrical pipe with an inner radius of 5 mm at an average velocity of 1.5 m s^{-1}. The temperature profile in the upstream section 1 and the downstream section 2 of the pipe is shown in Figure Q3(a).

Confirm that the flow in the pipe is laminar and find the heat transfer coefficient.

Physical properties of air are: density = 1.0078 kg m^{-3}, dynamic viscosity = 20.705×10^{-6} Pas, and heat conductivity = 0.02948 W m^{-1} K^{-1}.

[3 + 3 marks]

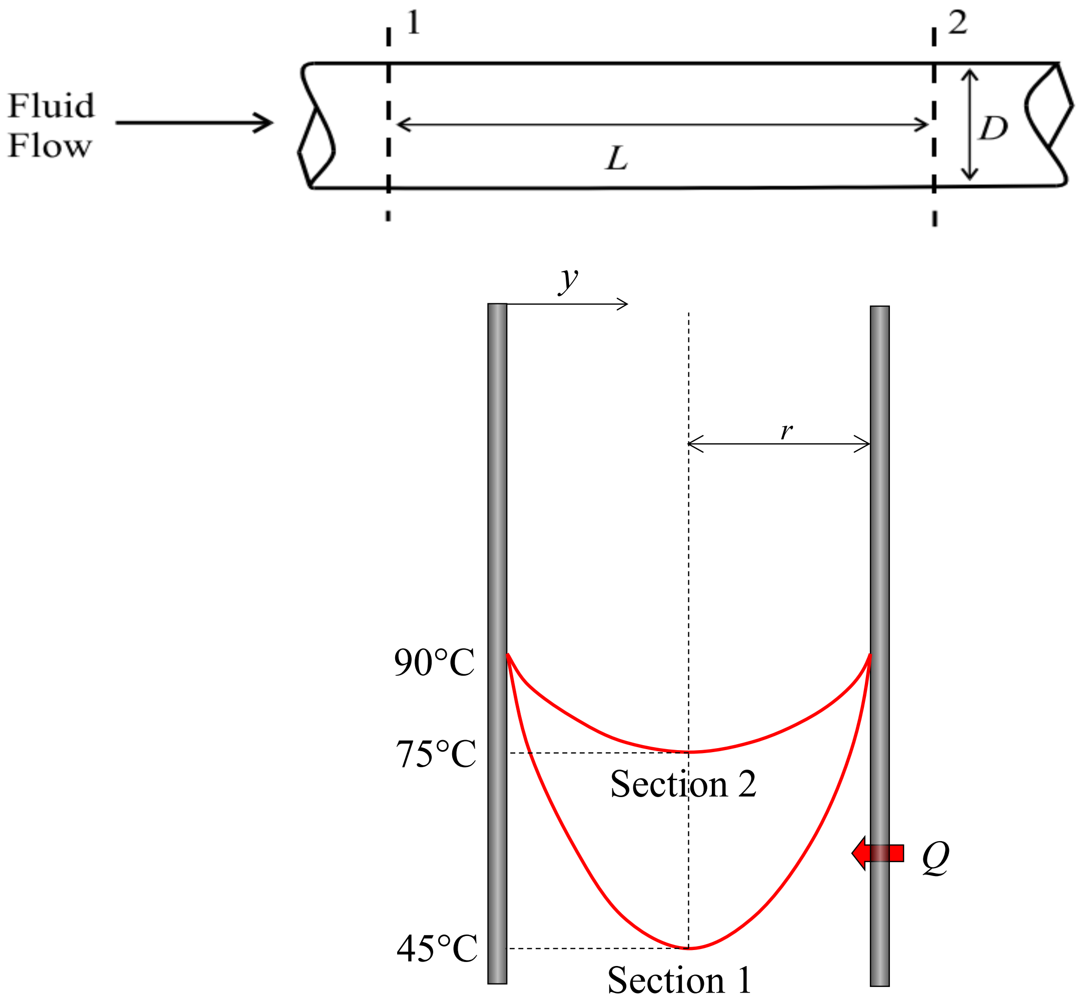

Figure Q3(a): Distribution of temperature in the two sections of a cylindrical tube

(b) What is the distance L and the heat rate of flow Q between the two sections? The specific heat of air is 1009.8 J kg^{-1} K^{-1}.

[4 + 3 marks]

Continued/…

Q3 Continued/…

(c) Consider the case where gas A diffuses from the bulk gas phase to a catalyst surface, where it reacts irreversibly in a heterogeneous reaction as follows:

$$A \rightarrow 2B$$

Gas B diffuses back, as shown in Figure Q3(b). Show that the molar flux of A is given by

$$N_A = \frac{CD_{AB}}{\delta} ln \frac{1 + y_{A1}}{1 + y_{A2}}$$

where symbols have their usual meanings. [6 marks]

(d) Pure gas A diffuses from point 1 at a partial pressure of 101.32 kPa to point 2, a distance 2 mm away. At point 2 it undergoes a chemical reaction at the catalyst surface and $A \rightarrow 2B$. Component B diffuses back at steady state. See Figure Q3(b). The total pressure is 101.32 kPa. The temperature is 300 K and D_{AB}= 0.15 × 10^{-4} m^2 s^{-1}. Calculate the molar flux of A for an instantaneous rate of reaction. [6 marks]

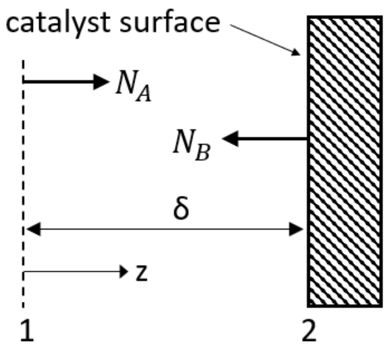

Figure Q3(b): Diffusion of A and heterogeneous chemical reaction at a catalyst surface

Relevant Data for parts (c) and (d)

Universal gas constant, R = 8314 J $kmol^{-1}$ K^{-1}

END OF PAPER

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List of equations (symbols have their usual meaning)

- Fick's rate equation for a binary system

$$N_A = y_A(N_A + N_B) - D_{AB} C \frac{dy_A}{dz}$$

- Mass transfer fluxes

$N_A = k_g(c_g - c_{gi})$ $= k_y(y - y_i)$ $= k_G(p - p_i)$	For gas film mass transfer coefficient
$N_A = k_l(c_{li} - c_l)$ $= k_x(x_i - x)$	For liquid film mass transfer coefficient
$N_A = K_g(c_g - c_g^*)$ $= K_y(y - y^*)$ $= K_G(p - p^*)$	Overall mass transfer coefficient
$N_A = K_l(c_l^* - c_l)$ $= K_x(x^* - x)$	Overall mass transfer coefficient

- Two-film theory

$\frac{1}{K_G} = \frac{1}{k_G} + \frac{H}{k_L}$	$\frac{1}{K_L} = \frac{1}{H\,k_G} + \frac{1}{k_L}$	$\frac{1}{K_g} = \frac{1}{k_g} + \frac{H_c}{k_L}$	$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{H_c\,k_g}$

- Higbie's Penetration Theory

$$\overline{k_l^0} = 2\sqrt{\frac{D}{\pi\tau}}$$

- Danckwert's Surface renewal model

$$\overline{k_l^0} = \sqrt{Ds}$$

- Mass transfer coefficients for Stirred Tank Reactors (STR)

Coalescing systems

$k_l a = 0.01\,(P/V)^{0.475}\,(j_g)^{0.4}$

Non-coalescing systems

$k_l a = 0.02\,(P/V)^{0.475}\,(j_g)^{0.4}$

- Specific enthalpy of humid air of absolute humidity *x* (kg kg^{-1}) at temperature θ (°C):

$$h = \theta + x(1.86\theta + 2500) \qquad \frac{kJ}{kg\ dry\ air}$$

- Absolute humidity of humid air:

$$x = 0.622\frac{\varphi p_{ws}}{P - \varphi p_{ws}} \qquad \frac{kg}{kg\ dry\ air}$$

- Combined heat and mass balance for the injection of steam or water into air stream:

$$\frac{h_2 - h_1}{x_2 - x_1} = h_w$$

where h_w is the enthalpy of steam (water). The subscripts 1 and 2 denote the air conditions before and after the injection of water or steam, respectively.

- Temperature distribution for laminar flow in a cylindrical pipe

$$\ln\frac{(\theta_0 - \theta_{B1})}{(\theta_0 - \theta_{B2})} = \frac{2hL}{\rho u r C_p}$$

$$\theta_s - \theta_0 = \frac{\theta_{\mathrm{B}} - \theta_0}{0.583}$$

$$Nu = 4.1$$

where θ_0 is the wall temperature, θ_B is the bulk fluid temperature (subscripts 1 and 2 are related to sections 1 and 2), θ_s is the temperature at the pipe axis, h is the heat transfer coefficient, L is the distance between the two sections, and Nu is the Nusselt number.

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TRANSFER PROCESSES
(24CGC051)

This sheet must be attached to your Answer Book.
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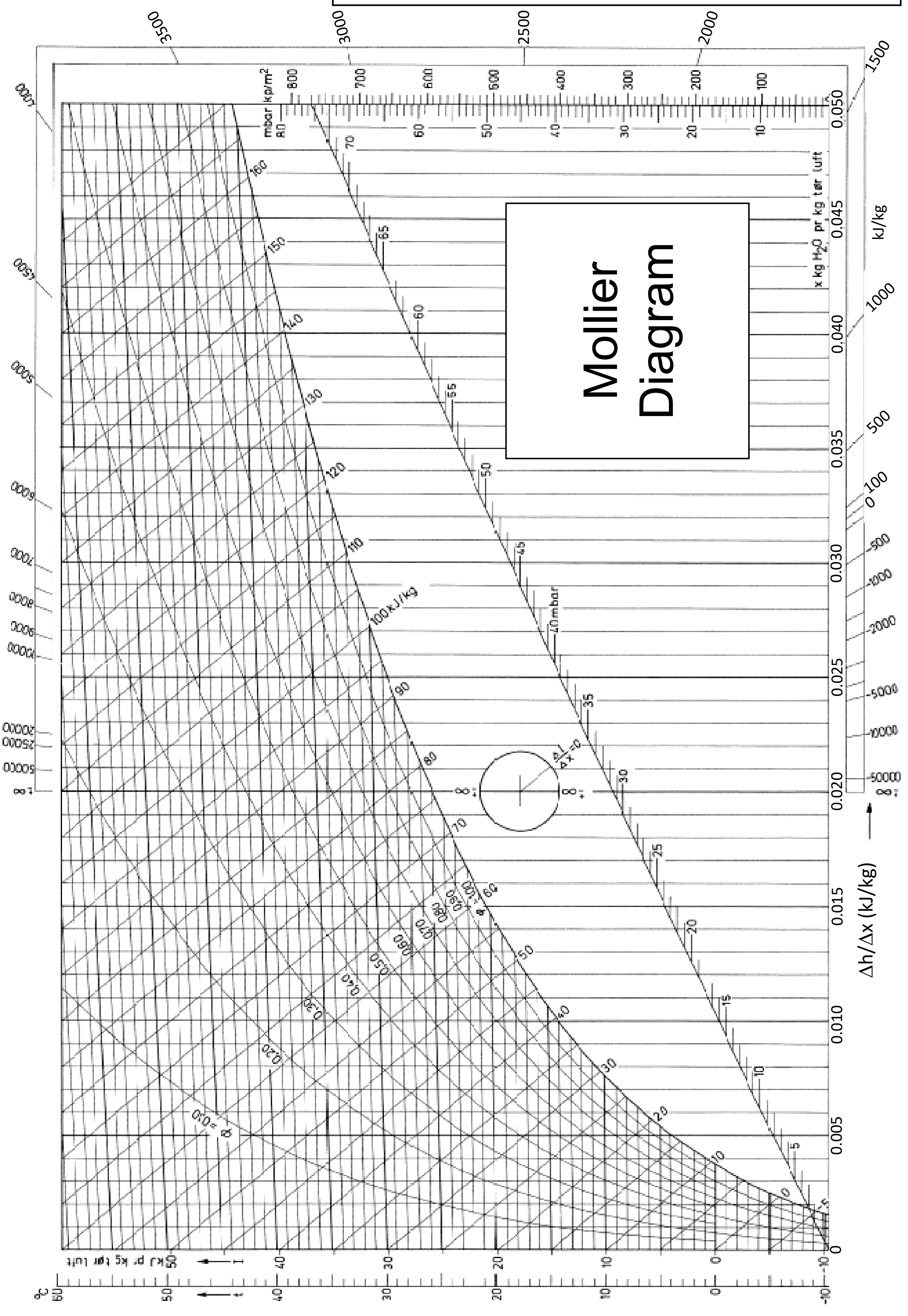

Figure Q1. Mollier diagram for humid air at 1 bar
(Datum 0°C and liquid water)