Loughborough University

23CGB012

Mass Transfer and Separations

Semester 2 2023/24 — 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 **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.

<u>Help during the exam</u>

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 FOUR questions in total — TWO from EACH SECTION.

Each question carries 25 marks.

Candidates should show full working for all calculations and derivations.

Formulae and Nomenclature provided separately.

Section A

Attempt **TWO** questions

1. Ammonia is selectively removed from an air-NH_3 mixture by absorption into water. In this steady-state process, ammonia diffuses through a stagnant gas layer 1 cm thick and then through a stagnant water layer 1 mm thick. The mole fraction of ammonia at the outer boundary of the gas layer is 0.045 and the concentration at the outer edge of the water layer is essentially zero. The temperature of the system is 21°C and the pressure 1 atm. The concentration at the interface between gas and liquid phases is given by the following data:

x (NH_3)	0.01	0.02	0.03	0.04	0.05	0.06
P (NH_3) (mmHg)	9.9	15.0	27.4	35	42.6	50.2

Draw the x-y diagram with equilibrium line and then determine the rate of diffusion of ammonia, N_A, making clear any assumptions relating to dilute solutions.

[25 Marks]

Data:

Diffusivity in liquid phase = 1.72×10^{-9} m^2 s^{-1}

Diffusivity in gas phase = 2.05×10^{-5} m^2 s^{-1}

R = 8314 Pa m^3 kmol^{-1} K^{-1};

1 atm = 760 mmHg = 1.013×10^5 Pa

2. (a) Obtain the equation for calculating the flux N_A during diffusion of A through stagnant non-diffusing B, starting from

$$N_A = -cD_{AB}\frac{dy_A}{dz} + \frac{c_A}{c}(N_A + N_B)$$

where: N_A & N_B are the total fluxes of A & B, respectively, relative to a stationary point; c is the total molar concentration of the A & B mixture; c_A is the molar concentration of A; D_{AB} is the diffusivity of A in B; y_A is the mole fraction of A; and z is the diffusion path length.

[6 marks]

(b) Through the accidental opening of a valve, water has been spilt onto the floor of an industrial plant. Estimate the time required to evaporate the water into the surrounding air through a film which is 5.5 mm thick. The water layer is 1.2 mm thick, the temperature of both air and water may be assumed to be 24 ºC and the air is at atmospheric pressure (1.013×10^2 kN m^{-2}).

[7 marks]

<u>Data:</u>

Diffusion coefficient for water vapour in air = 2.59×10^{-5} m^2 s^{-1}

mole fraction of water vapour in saturated air, y_{A1} = 0.0301;

mole fraction of water vapour in main air stream, y_{A2} = 0.0041;

R = 8314.5 N m $kmol^{-1}$ K^{-1}.

(c) A Stephan diffusion tube is used to measure the diffusivity of liquid A in air at 25°C and 1 atm (1.013×10^5 N m^{-2}) pressure. The liquid density of A at 25 °C is 1500 kg m^{-3}, M_A of the liquid is 120 kg $kmol^{-1}$ and its vapour pressure is 0.3 atm. At the beginning of the test (t = 0) the liquid A surface was at z_0 = 68 mm from the top of the tube and after t_F = 10 h it had dropped by 5 mm. What is the gas diffusion coefficient of A in air, if it is assumed that pure air flows across the top of the tube? [12 marks]

3. A packed column is used to remove SO_2 from an air stream using pure water operating at 17°C and 1.013 x 10^5 N m^{-2}. The gas entering the column contains 0.03 mol fraction SO_2 and 95% of the SO_2 is removed by the water stream. The water stream leaving the bottom of the column contains 0.00067 mol fraction SO_2. The total gas inlet rate is 100 kmol m^{-2} h^{-1}. For this system, the mass transfer film coefficients, k_x and k_y, can be assumed constant throughout the column at 19.5 and 1.45 kmol m^{-2} h^{-1} respectively.

(a) Draw the *x*-*y* diagram: the operating line and the equilibrium line. [4 marks]

(b) What is the liquid to gas ratio? [2 marks]

(c) Determine the interface compositions at the top and at the bottom of the column. [9 marks]

(d) Calculate the total height of the packing required. [10 marks]

<u>Data:</u>

equilibrium curve $y^* = 21.93\,x$

specific surface area of packing = 460 m^{-1}

Section B

Attempt **TWO** questions

4. An engineer is required to design a tank to contain mixtures of waste ethanol and hexane. The tank should be designed assuming a maximum operating temperature of 60°C. An estimate of the corresponding maximum operating pressure is necessary as part of this design. The composition of the mixture can vary and so the engineer must assume that the ethanol/hexane ratio could potentially take any value.

   (a) Using the data below, or otherwise, calculate the total pressures (in bara) of liquid mixtures of ethanol/hexane at mole fractions of ethanol of 0%, 20%, 40%, 60%, 80% and 100%. [12 marks]

   (b) Plot a graph of total pressure (in bara) versus composition. Hence, estimate the maximum possible pressure at this temperature to the nearest 0.01 bar. Calculate the total pressure for at least two further compositions to further increase the degree of confidence in the result. [9 marks]

   (c) Comment on the relative sensitivity of the tank pressure to variations in temperature and composition. [4 marks]

   Data

   The van Laar equations are:

$$\ln \gamma_1 = \frac{A}{\left[1 + \frac{A x_1}{B x_2}\right]^2} \quad ; \qquad \ln \gamma_2 = \frac{B}{\left[1 + \frac{B x_2}{A x_1}\right]^2}$$

   For ethanol (1) and hexane (2), $A = 2.708$, $B = 1.746$

Continued/…

Q4 Continued/…

The vapour pressures (P^{sat}, mmHg) of pure ethanol and hexane are given as functions of temperature, T (°C) by the following equations:

Ethanol: $$\log_{10} P^{sat} = 8.1 - \frac{1593}{T + 226}$$

Hexane: $$\log_{10} P^{sat} = 6.9 - \frac{1176}{T + 225}$$

N.B. 1 bar = 760 mmHg

5. Methanol and water are to be separated using a continuous distillation column. The column has two feed streams that enter the column at their optimal trays. One feed enters the column at 120 kmol h^{-1}, with a composition of 72 mol% methanol and is at its dew point. The second feed also enters the column at 120 kmol h^{-1} but has a composition of 42 mol% methanol and is 60% vapour.

   The product streams have a composition of (i) 90 mol% methanol and (ii) 98 mol% water. Assume constant molal overflow, that the column has a total condenser, that the reflux ratio is 1.6, and that each stage is an equilibrium stage.

   (a) Calculate the molar flowrates of the two product streams. [6 marks]

   (b) Calculate the recovery of methanol in the distillate stream. [2 marks]

   (c) Calculate the molar flows of liquid and vapour in each section of the column (upper, middle and lower). [6 marks]

   (d) Using a graphical technique determine:

   (i) The number of ideal trays required for the separation. [9 marks]

   (ii) The trays on which the two feeds enter the column. [2 marks]

Data

Methanol-water equilibrium data are provided in Figure Q5 (attach to your answer book when complete and ensure you fill in your student ID number at the top).

6. Part of a process to manufacture polyethylene terephthalate (PET) involves separating toluene from a mixture of xylenes. A bubble-point feed is supplied to a distillation column at a total flow rate of 100 kmol h^{-1}, and with a molar composition of 49% toluene, 17% *p*-xylene, 17% *m*-xylene and 17% *o*-xylene (in order of decreasing volatility). The column has a total condenser and is to be designed to recover 85% of the toluene in the distillate product, and 90% of the *p*-xylene in the bottom product.

(a) Using the short-cut design method, estimate the mole fractions and flow rates of all components in the distillate and bottoms products. State any approximations or assumptions you have used. [7 marks]

(b) Using Raoult's law and assuming an average temperature of 150 °C, show that the relative volatility of toluene relative to *p*-xylene is 2.01. Hence, estimate the minimum number of equilibrium stages for the separation. [4 marks]

(c) Provide an improved calculation for the mole fraction of *m*-xylene in the distillate. Hence, comment on the accuracy of the mass balance in part (a) and propose a method to improve its accuracy. [5 marks]

Use the approximate mass balance from part (a), for the following two parts.

(d) Calculate the pressure at the top of the column, if the <u>top plate</u> operates at 139 °C. [4 marks]

(e) Assuming constant molar overflow, no heat losses, equilibrium stages and a reflux ratio of 1.7, find the mole fraction of toluene in the vapour leaving the <u>second top</u> plate. [5 marks]

Relevant equations and data:

Fenske's equation: $N_m = \dfrac{\ln\left[\dfrac{(x_{i,D}/x_{j,D})}{(x_{i,B}/x_{j,B})}\right]}{\ln(\alpha_{ij})}$

Antoine equation: $\ln p^* = A - \frac{B}{C+T}$, where p^* (bar) is the vapour pressure, T (°C) is the temperature and the constants A, B and C are given in the below.

Component		***A***	***B***	***C***
1	toluene	9.393	3096.5	219.5
2	*p*-xylene	9.476	3346.6	215.3
3	*m*-xylene	9.519	3367.0	215.1
4	*o*-xylene	9.495	3395.6	213.7

Student ID:

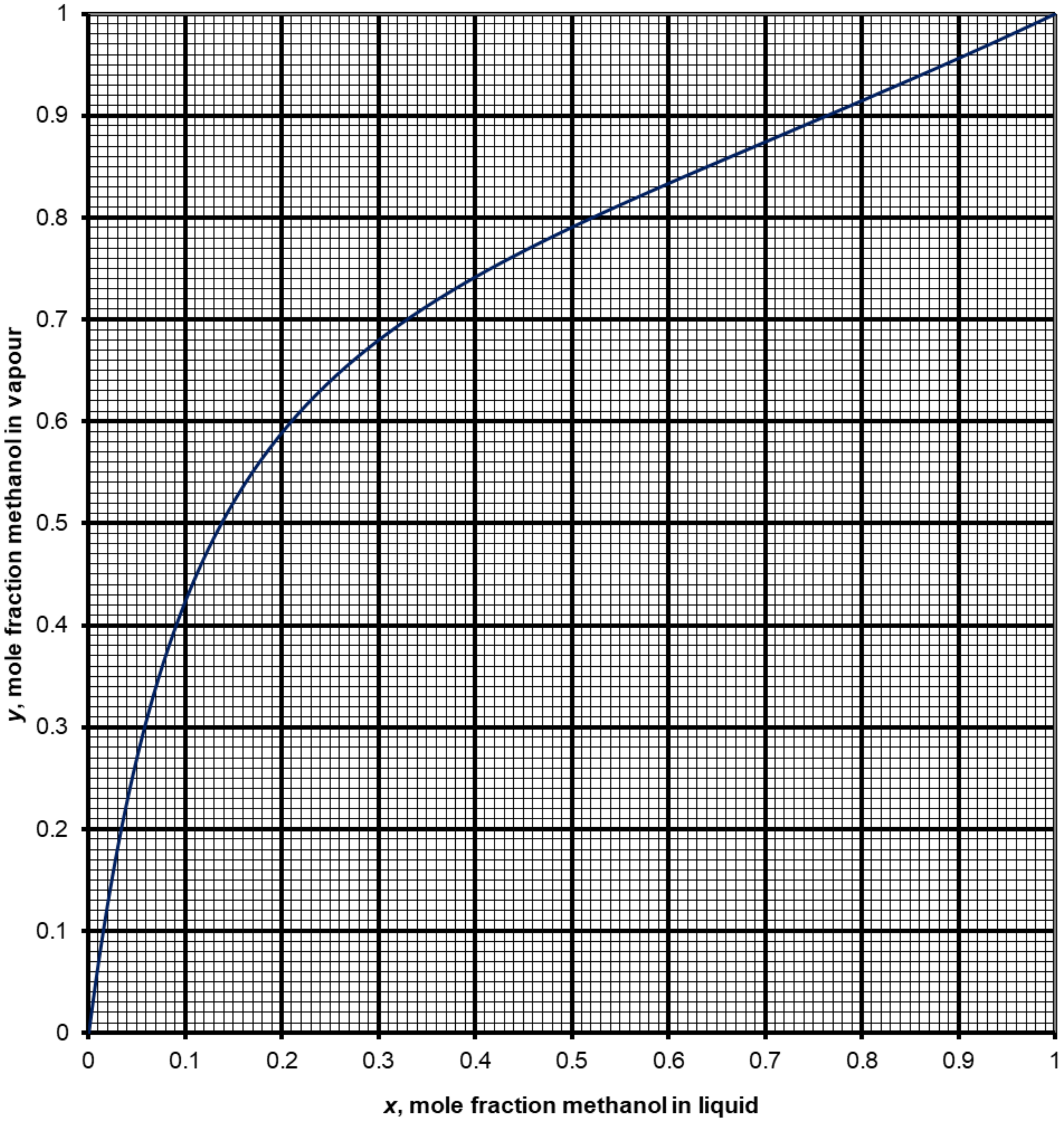

Fig. Q5 Equilibrium data for methanol and water

Please attach this figure to your answer book

END OF PAPER

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