



SCHOOL OF ENGINEERING

MAIN EXAMINATIONS: JUNE 2025

COURSE AND CODE: ADVANCED MASS TRANSFER

ENCH4MT

DURATION: 2 HOURS

TOTAL MARKS: 60

INTERNAL EXAMINER:

PROF. W.M. NELSON

INTERNAL MODERATOR:

PROF. A.H. MOHAMMADI

EXTERNAL MODERATOR:

PROF. T. LOUW

INSTRUCTIONS:

1. **ALL** questions should be attempted. **Answer in ink.**
2. Any programmable or non-programmable calculator may be used, provided it has been cleared of any information that would subvert the purpose of the examination.
3. Calculations must be detailed to illustrate your understanding of the procedure.
4. Formulae are provided on Pages 6 & 7.
5. All flows and compositions are on a **molar basis**.
6. This examination question paper, together with all associated diagrams, **MUST BE HANDED IN TOGETHER WITH YOUR SCRIPT.**

Student Number:

QUESTION 1 [30]

A conventional distillation sequence separates a four-component aromatic hydrocarbon mixture containing butylbenzene, cumene, toluene, and benzene into four high-purity products. The first column in the sequence will perform the initial separation under atmospheric pressure. For this column, operating specifications are to be determined. The feed is introduced as a saturated liquid, and the column is designed to recover the light key in the distillate and the heavy key in the bottoms with 99.5% recovery for each. Data for the separation is given below in Table 1.

Table 1: Feed and product information for the distillation sequence.

Component	Feed flow rate (kmol/hr)	Heat of Vaporisation (kJ/mol)	Equilibrium ratio, K_i	Mole purity (%)
butylbenzene	50	36.2	0.01	99.7
cumene	30	35.0	0.05	99.4
toluene	20	33.2	0.18	99.5
benzene	10	30.8	0.53	99.7

1.1. Using the information in Table 1, propose the light and heavy key components for the first column in this distillation sequence. Explain the reason for the first column in the separation sequence. [4]

1.2. Assuming the Fenske equation is applicable, calculate the minimum number of theoretical trays required for the first conventional distillation column in the sequence. [7]

1.3. Given the above calculation, check the distribution of the most important non-key component. [4]

1.4. Determine the minimum internal reflux ratio of this column. [11]

1.5. Is a single divided-wall column (DWC) a suitable configuration for separating this quaternary mixture into four pure products? Justify your answer by discussing any economic and practical implications. [4]

TOTAL /30/

QUESTION 2 [10]

An azeotrope divides the phase envelope into two distillation regions separated by a single distillation boundary for a binary mixture. This constraint can be overcome using enhanced distillation techniques. The binary system of methanol (1) + methyl acetate (2) exhibits an azeotrope. Pressure-swing distillation can be used to obtain pure products without adding a third component. Table 2 gives the boiling points for the pure components and azeotropic mixtures at 1 and 10 atm, respectively, for the binary system.

Table 2: Azeotropic and boiling point information for the binary mixture of methanol (1) + methyl acetate (2).

Component	Temperature (°C)	Pressure (atm)	Composition
Methanol	64.2	1	$x_1 = 1.000$
Methyl acetate	56.7	1	$x_1 = 0.000$
Azeotrope	53.3	1	$x_1 = 0.331$
Methanol	136.8	10	$x_1 = 1.000$
Methyl acetate	142.9	10	$x_1 = 0.000$
Azeotrope	130.6	10	$x_1 = 0.551$

Sketch a schematic indicating the column sequence and how pressure-swing distillation can purify a binary feed of 30% methanol into two pure products (99%). Include all necessary information in the sketch, such as component purities, temperatures, stream names and column pressures.

TOTAL /10/

QUESTION 3 [12]

A binary mixture of two close-boiling components, cyclohexane (1) + benzene (2), exhibits positive deviation from Raoult's law. N-methylpyrrolidine (NMP) can be used as a solvent in an extractive distillation process to produce both a cyclohexane and benzene product. Phase equilibrium diagrams for the relevant mixtures are shown below.

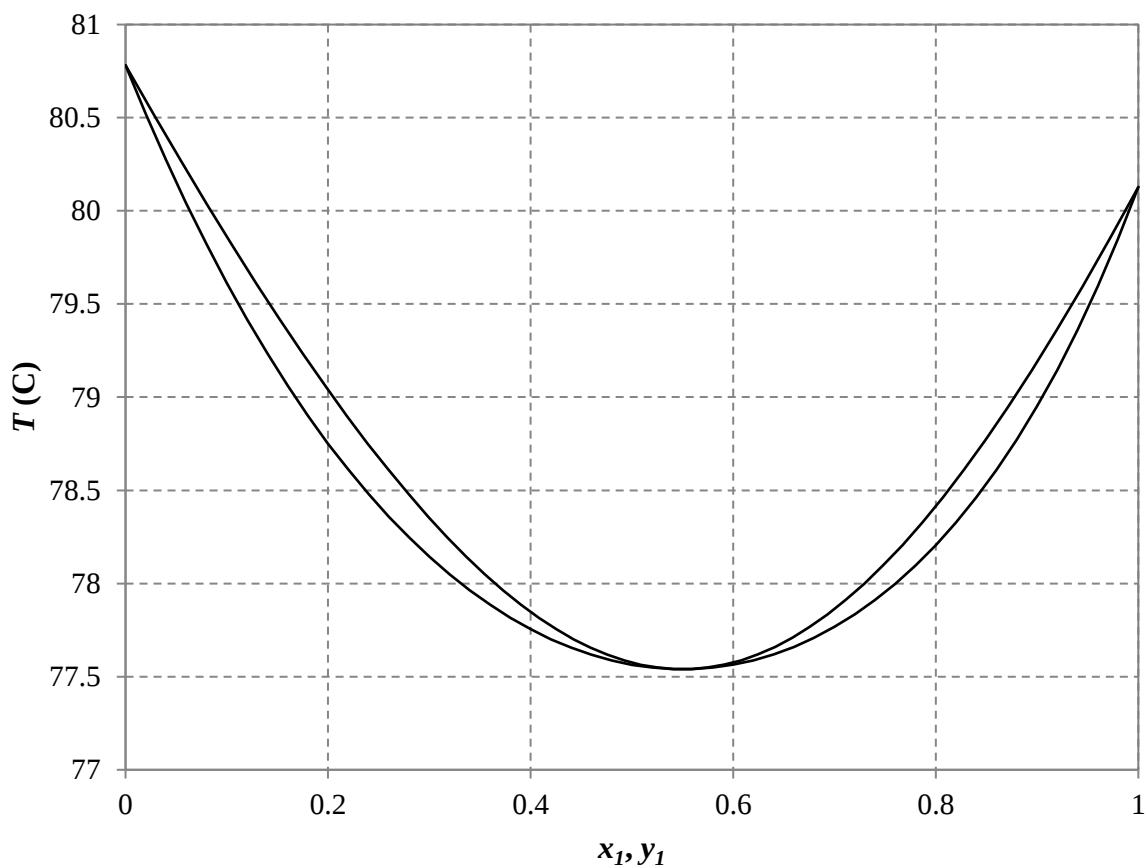


Figure 1. Phase equilibrium (T - x - y) data for the binary mixture of benzene (1) + cyclohexane (2) at atmospheric pressure.

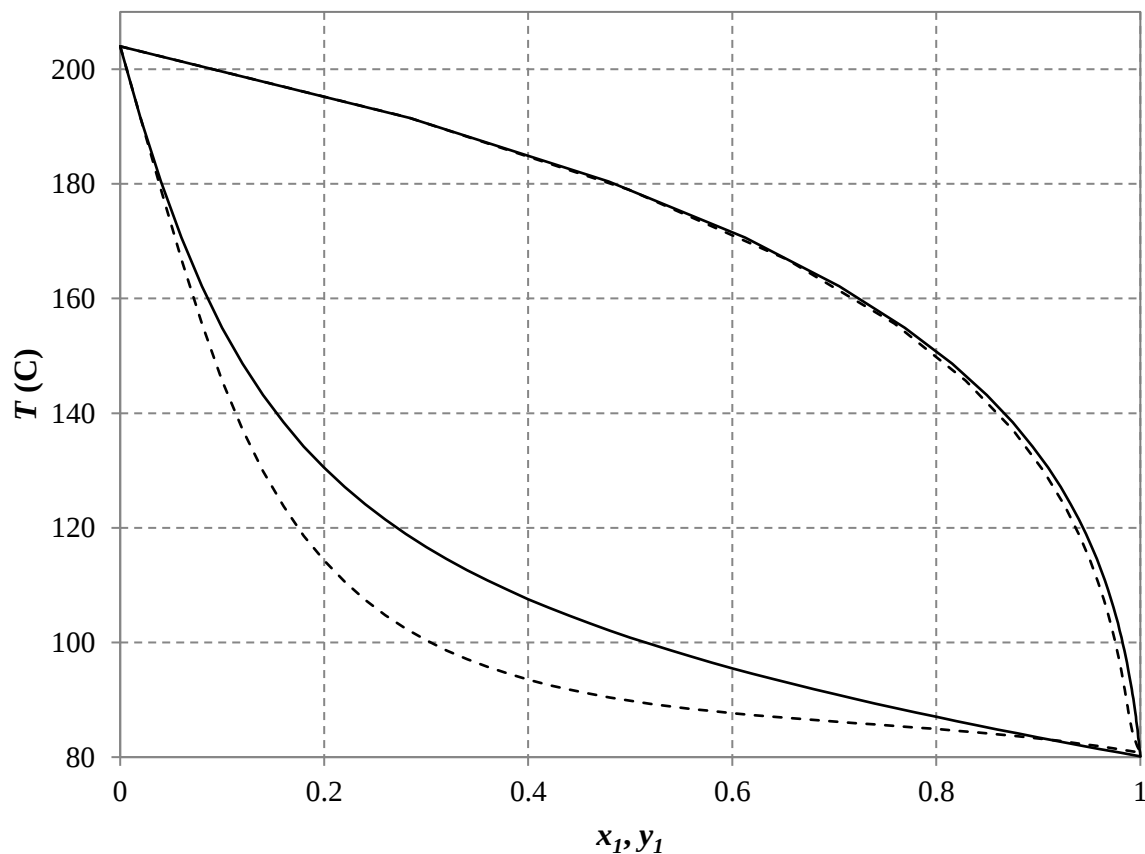


Figure 2. Phase equilibrium (T - x - y) data for the binary systems for benzene (1) + NMP (2) are displayed by the solid line, and cyclohexane (1) + NMP (2) are shown by the dashed line.

3.1. Provide a schematic for the extractive distillation process to purify a feed consisting of an equimolar mixture of benzene and cyclohexane. Ensure that all products, columns, and streams are labelled and clearly defined. [5]

3.2. To illustrate your answer above, please draw all necessary material balance lines on the residue curve map (Figure 3 – Page 8 of 8). [3]

3.3. With the use of a process simulator, the total heating load can generally be used as a proxy for cost in the optimisation of the operating specifications (feed stages, reflux ratio) of an extractive distillation column. Explain two cases where this may not be applicable. [4]

QUESTION 4 [8]

A chemical manufacturing facility producing methylamine is seeking to reduce volatile organic compound (VOC) emissions from its vent gas stream, which contains low concentrations of methylamine and trace amounts of methanol. The company is considering the use of a fixed-bed adsorption system to capture and recover these VOCs before atmospheric release.

4.1. Identify the type of adsorption system that would be appropriate for the removal of the VOCs from a dilute gas stream. List a suitable adsorbent for the process. Discuss two disadvantages of the appropriate process. [5]

4.2. What adsorption isotherm models would be suitable to describe the equilibrium uptake of methylamine on the sorbent at low partial pressures? List two models and briefly describe when these models would be suitable. [3]

TOTAL /8/

FORMULAE SHEET

Summation equation

$$\sum_{i=1}^c x_i = 1; \quad \sum_{i=1}^c y_i = 1;$$

Isothermal Flash calculation

$$f(\Psi) = \sum_{i=1}^c \frac{z_i(1 - K_i)}{1 + \Psi(K_i - 1)} = 0$$

Bubble point equation

$$\sum_{i=1}^c z_i K_i = 1$$

Dew point equation

$$\sum_{i=1}^c z_i / K_i = 1$$

Fenske Equation

$$N_{\min} = \frac{\log \left\{ \left(x_{i,N+1} / x_{i,1} \right) \left(x_{j,1} / x_{j,N+1} \right) \right\}}{\log \alpha_m}$$

$$N_{\min} = \frac{\log \left[(d_i / d_j) (b_j / b_i) \right]}{\log \alpha_m}$$

Distribution of non-key components

$$f_i = d_i + b_i$$

$$b_i = \frac{f_i}{1 + (d_r / b_r) (\alpha_{i,r})_m^{N_{\min}}}$$

$$d_i = \frac{f_i (d_r / b_r) (\alpha_{i,r})_m^{N_{\min}}}{1 + (d_r / b_r) (\alpha_{i,r})_m^{N_{\min}}}$$

Underwood Equations (Class 1)

$$\frac{(L_{\infty})_{\min}}{F} = \frac{\left(\frac{L_F}{F} \right) \left[\frac{D x_{LK,D}}{L_F x_{LK,F}} - (\alpha_{LK,HK})_F \frac{D x_{HK,D}}{L_F x_{HK,F}} \right]}{(\alpha_{LK,HK})_F - 1}$$

Underwood Equations (Class 2)

$$1 - q = \sum_{i=1}^c \frac{\alpha_{i,r} Z_i}{\alpha_{i,r} - \phi}$$
$$\sum_{i=1}^c \frac{\alpha_{i,r} X_{i,D}}{\alpha_{i,r} - \phi} = 1 + R_{\min}$$

Gilliland Correlation (Molokanov Equation)

$$Y = \frac{N - N_{\min}}{N + 1} = 1 - \exp \left[\left(\frac{1 + 54.4X}{11 + 117.2X} \right) \left(\frac{X - 1}{X^{0.5}} \right) \right]$$

$$X = \frac{R - R_{\min}}{R + 1}$$

Kirkbride Equation

$$\frac{N_R}{N_S} = \left[\frac{z_{HK}}{z_{LK}} \left(\frac{x_{LK,B}}{x_{HK,D}} \right)^2 \frac{B}{D} \right]^{0.206}$$

Column Sequencing

$$N = \frac{[2(P - 1)]!}{P! (P - 1)!}$$

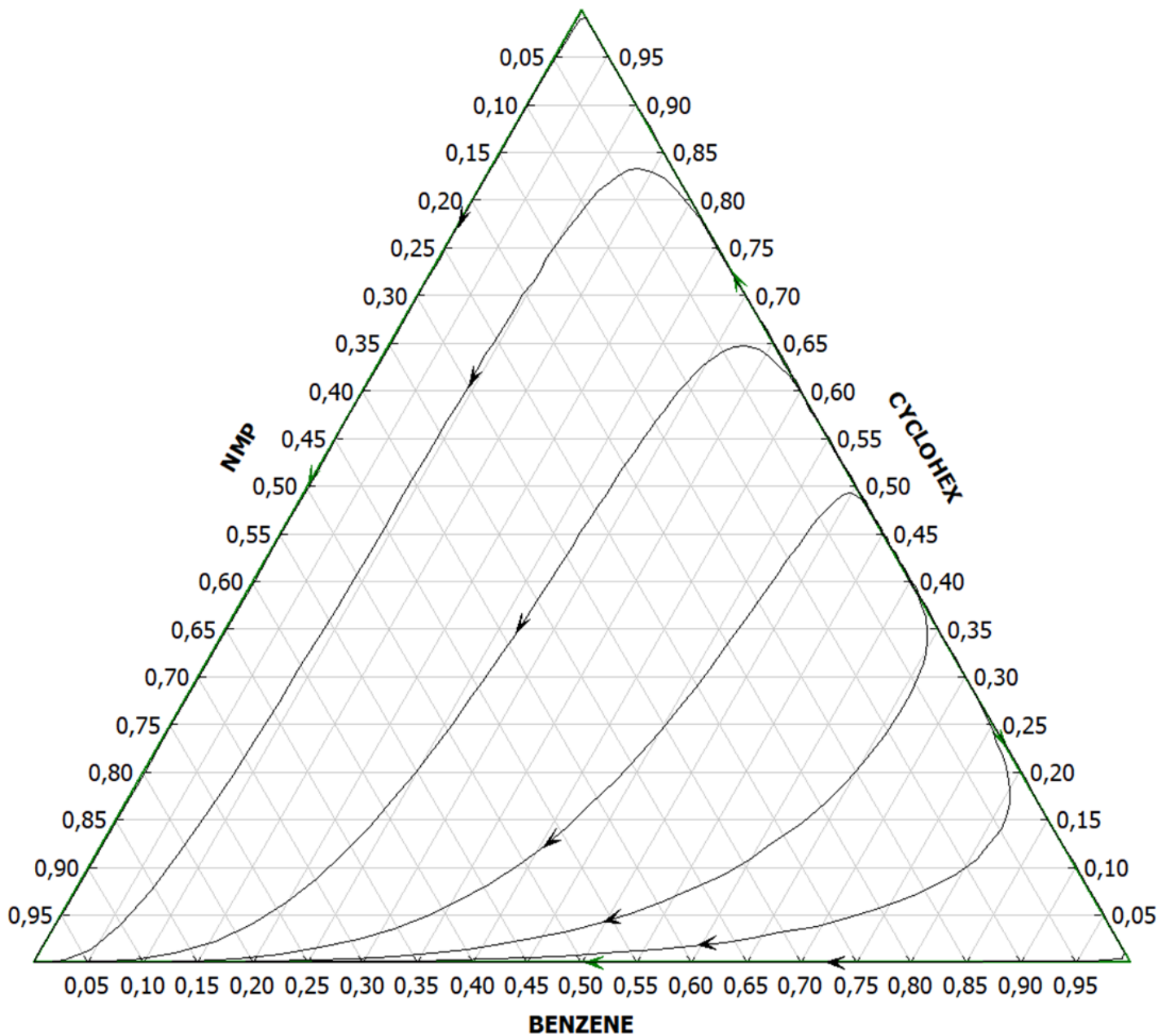
Adsorption

$$q_e = \frac{q_{\max} K C_e}{1 + K C_e}$$

$$q_e = K C_e^{1/n}$$

NAME: _____ STUDENT NUMBER: _____

DO NOT DETACH.

**Figure 3:** Triangular diagram for QUESTION 3