This document contains the tutorial questions for the 15-credit EX3502 Separation Processes 1 course delivered at the University of Aberdeen.

The recommended questions you should solve for each week are:

- Tutorial 1: Q. 3.

- Tutorial 2: Q. 5.

- Tutorial 3: Q. 7.

- Tutorial 4: Q. 9.

- Tutorial 5: Q. 18 and Q. 19.

- Tutorial 6: Q. 23.

- Tutorial 7: Q. 24 and Q. 31.

- Tutorial 8: Q. 34, Q. 14, and Q. 35.

- Tutorial 9: Q. 36.

All other questions are provided for additional practice and should help you to explore all aspects of the course.
Fully worked solutions are given but you should attempt the problems without the solutions, it is the only way to find out what you don't know.
Where marks are given, these are indicative of the relative weighting each part of a question might have if it was set in an exam, but variations in exams regarding balancing of difficult/easy question parts along with revision of questions means these are not exact.
All past exam questions are collected in this document.

Question 1
A company is investigating the concentration of orange using the process outlined in Fig. 1. The evaporator must be able to process 1000 kg h^{-1} of raw orange juice which has a solids concentration of 7.08% w/w into a 50% w/w solids stream. For this rough design, you may assume that all streams have the same thermodynamic properties as pure water. The raw orange juice is supplied to the evaporator at 20 °C and the evaporator operates at 1 atm(a).

a) Determine the flow-rate of all streams.   [3 marks]

b) Determine the duty of the evaporator.   [6 marks]

c) The evaporator may be operated at 0.725 bar(g). Update your calculations for this operating condition. Comment if this is a more favourable operating point.   [6 marks]

d) Size the evaporator assuming that the process is operated at 1 atm(a). You may assume that 1.5 bar(a) steam is available for heating the evaporator and the overall heat transfer coefficient is 1.4 kW m^{-2} K^{-1}.   [3 marks]

e) How much steam is required to operate this evaporator?   [2 marks]
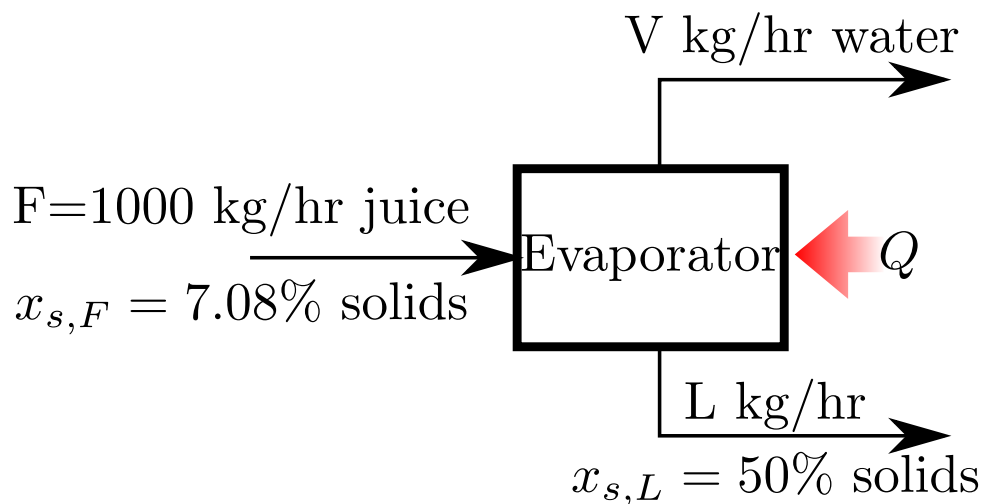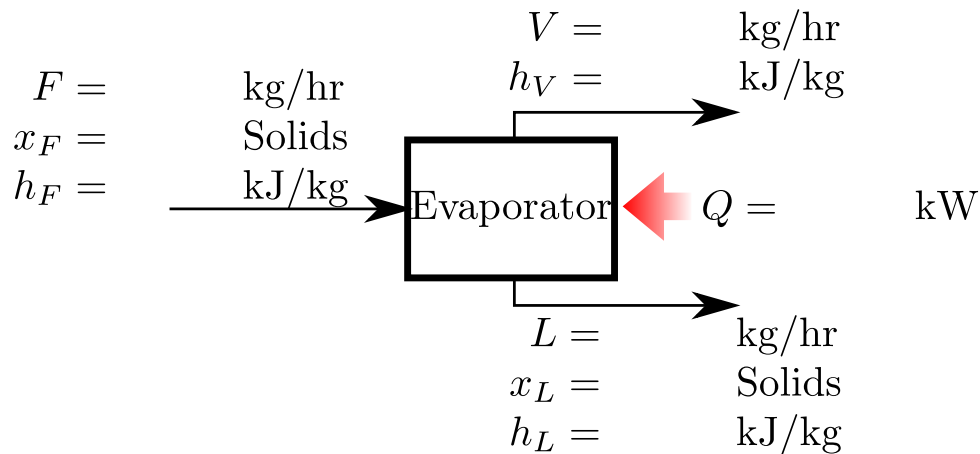
Figure 1: Orange juice concentrator.

Question 2

In the production of sea salt, seawater is first evaporated to form a concentrated brine before then being passed to a crystallizer. The seawater feed to the evaporator can be modelled as a 4% w/w NaCl-water mixture and is available at a temperature of 9 °C. The brine must reach a concentration of 37% w/w NaCl before leaving the evaporator, otherwise the crystallizer will be unable to function.

a) An evaporator is needed to process 100 kg of sea salt per hour. Perform mass balances over the evaporator to determine the required flow rates of seawater, brine, and water vapour.   [5 marks]

b) For maximum efficiency, the evaporator is operated at an absolute pressure of 0.48 bar. Calculate the operating temperature of the evaporator, stating any assumptions you make, and estimate the boiling point rise of the solution. You may need the Dühring data provided in Fig. 2.   [4 marks]

c) Why is it convenient to talk in terms of a boiling point rise for mixtures at a certain concentration?   [2 marks]

d) Calculate the duty of the evaporator using your steam tables. You may neglect the effect of NaCl concentration on the specific enthalpy. Comment on the superheat of the vapour.   [4 marks]

e) Saturated steam is available at 1.5 bar, calculate the steam economy of the evaporator.   [3 marks]

f) Calculate the heat transfer area required if the overall heat transfer coefficient is $U = 1600$ W m^{-2} K^{-1}.   [2 marks]

Question 3

An evaporator is required to produce 1000 kg h^{-1} of fresh water from seawater. The seawater can be approximated as a 4% w/w solution of NaCl and is available at 7°C. Due to scale concerns, the sea water is to be released at 20% w/w concentration. The change in enthalpy due to the addition of NaCl to water is assumed to be constant ($h_{sol} = 65$ kJ kg^{-1} dissolved NaCl) at 0°C). The heat capacity of the solution can be assumed to be the same as for pure water and Dühring data is given in Fig. 2.

$$V = \quad \text{kg/hr}$$
$$h_V = \quad \text{kJ/kg}$$

$$F = \quad \text{kg/hr}$$
$$x_F = \quad \text{Solids}$$
$$h_F = \quad \text{kJ/kg}$$

Evaporator $\quad Q = \quad \text{kW}$

$$L = \quad \text{kg/hr}$$
$$x_L = \quad \text{Solids}$$
$$h_L = \quad \text{kJ/kg}$$

a) Explain why evaporators are generally operated at a reduced pressure.

b) Calculate the missing flow rates F and L in the process diagram. Remember to state any assumptions that you make.

c) It is decided to operate the evaporator at a pressure of 0.42 bar. Calculate the operating temperature of the evaporator at this pressure and the boiling point rise.

d) Determine the specific enthalpies of every stream. You may ignore the small superheat of the vapour stream (assume it is at it's saturation pressure).
   Note: Use reference enthalpies of $h_{\text{water}} = 0$ and $h_{\text{NaCl}} = 0$ at $0°C$.

e) Calculate the duty, Q, of the evaporator.

f) Saturated steam is available at 1.6 bar for heating the evaporator. Determine the amount of steam required and the steam economy.

g) Determine the heat transfer area required for a heat transfer coefficient of $U = 1600\ \text{W}\,\text{m}^{-2}\,\text{K}^{-1}$.
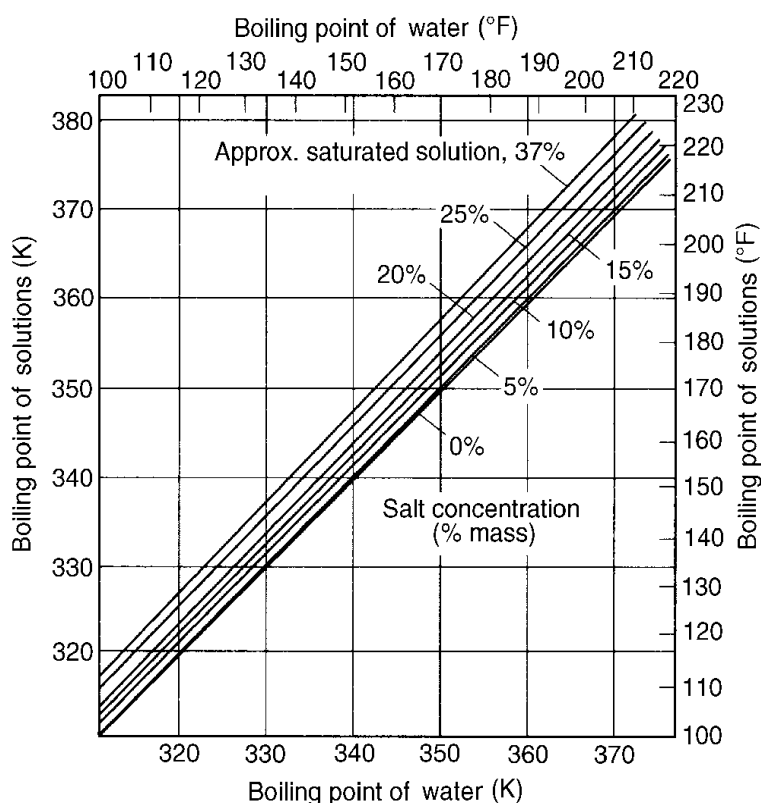
Figure 2: Boiling points for NaCl solutions, taken from Fig. 14.1, pg. 772 C&R Vol. 2.

Question 4

An evaporator is used to concentrate 4536 kg h^{-1} of a 20 % w/w solution of NaOH in water entering at 60 °C (140 °F) to a product of 50% w/w solids. The pressure of the saturated steam used is 172.4 kPa and the pressure in the vapour space of the evaporator is 11.7 kPa. The overall heat-transfer coefficient is 1560 W m^{-2} K^{-1}.
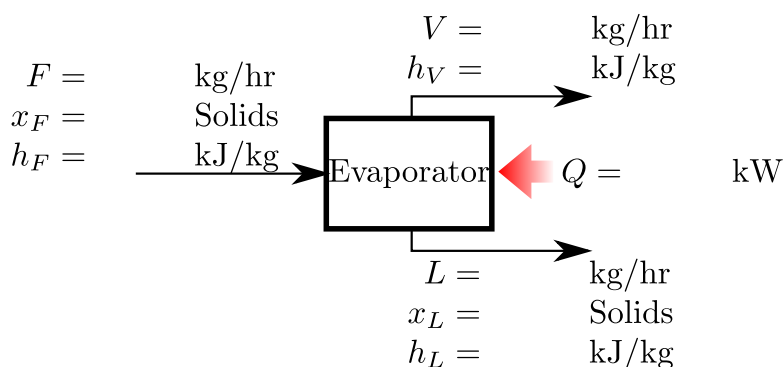
a) Explain why the evaporator is operated at a reduced pressure.   [2 marks]

b) Determine the stream flow-rates remembering to clearly state any assumptions you make.   [3 marks]

c) Calculate the boiling point rise and operating temperature of the evaporator. Why is it convenient to discuss a boiling point rise rather than an absolute temperature? A Dühring chart for NaOH-water mixtures is available in Fig. 4.   [4 marks]

d) Determine the duty of the evaporator. You must clearly state any other approximations you make. An enthalpy-concentration diagram for aqueous NaOH mixtures is available in Fig. 5.   [8 marks]

e) Determine the evaporator area, mass flow-rate of steam required, and the steam economy.   [3 marks]

Question 5

A triple effect evaporator in a forward feed configuration is to be used to concentrate a 10% w/w NaOH solution entering the evaporator at $37.8°$C, up to a concentration of 50% w/w. Steam is available at 58.6 kPa (gauge). The operating pressure of the final stage is 6.76 kPa. The feed rate is 13608 kg h^{-1}. The heat transfer coefficients are $U_1 = 6246$ W m^{-2} K^{-1}, $U_2 = 3407$ W m^{-2} K^{-1}, and $U_3 = 2271$ W m^{-2} K^{-1}. The constraint on the design is that all effects must have the same area. Calculate the surface area per effect, steam consumption and steam efficiency.
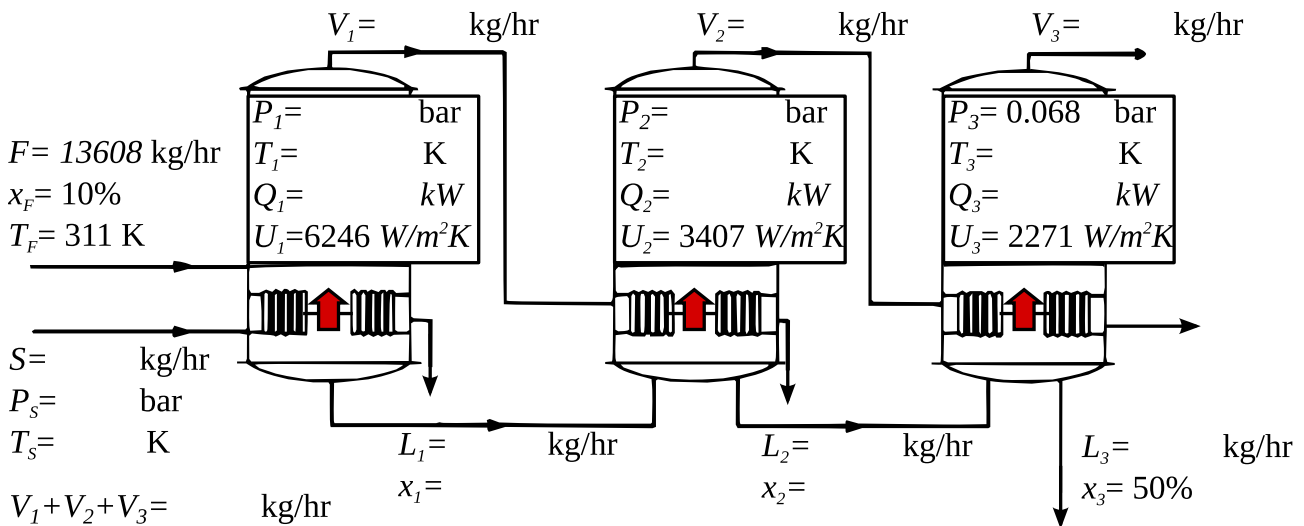
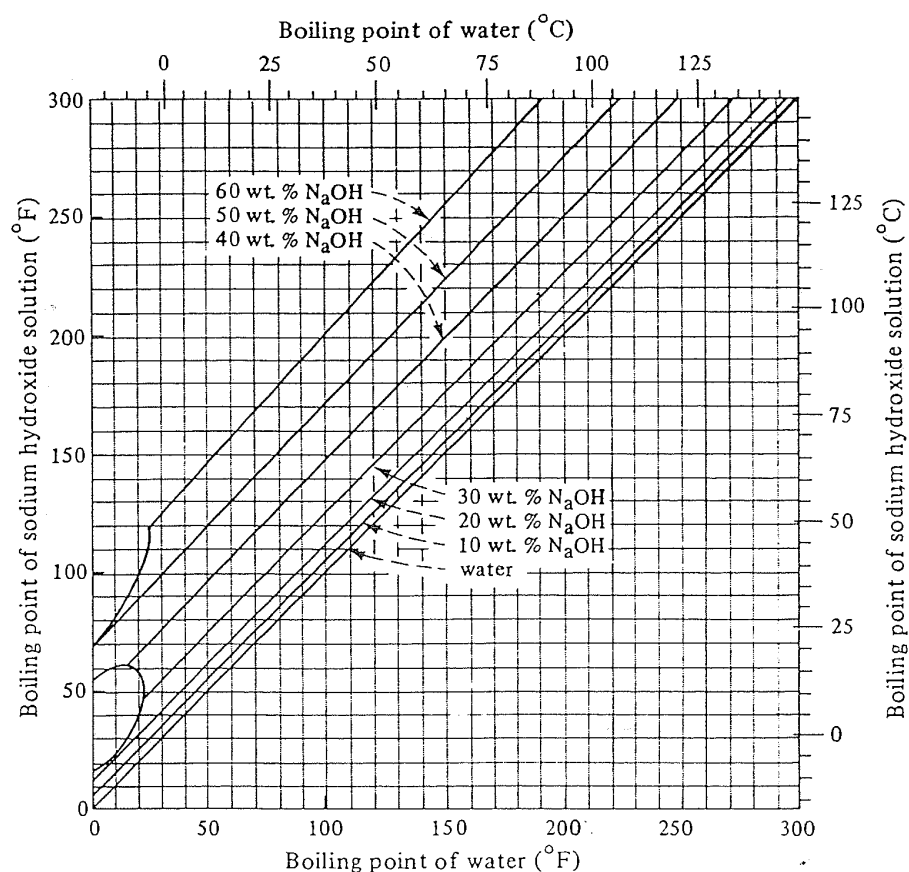Figure 3: The starting flowsheet for the triple-effect evaporator in Q. 5.

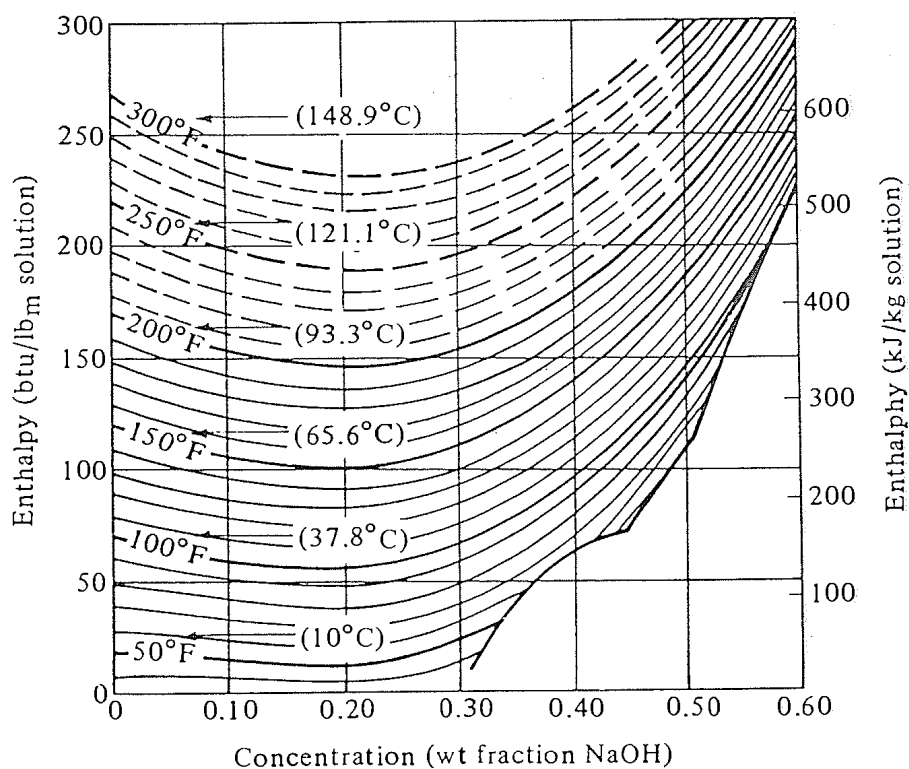Figure 4: Boiling points for NaOH solutions for use in Q. 5.

Figure 5: Enthalpies of NaOH solutions for use in Q. 5.

Question 6
What is the concentration of O_2 in $25°C$ water under atmospheric conditions?
Note: Henry's constant for O_2 in water at $25°C$ is 4.259×10^4 atm.

Question 7
A gas mixture at 2.026×10^5 Pa total pressure containing air and SO_2 is contacted in a single-stage equilibrium mixer with pure water at 293 K. The partial pressure of SO_2 in the original gas is 1.52×10^4 Pa. The inlet gas is flowing at a total of 5.70 kmol s^{-1} and the inlet water is flowing at a total of 2.20 kmol s^{-1}. The exit gas and liquid leaving are in equilibrium.

a) Derive the following balance equation from a mass balance over a single stage contactor. Remember to state your assumptions and show your workings. A small diagram with labelled streams would also be appreciated.

$$L'\frac{x_{SO_2,0}}{1-x_{SO_2,0}} + V'\frac{y_{SO_2,2}}{1-y_{SO_2,2}} = L'\frac{x_{SO_2,1}}{1-x_{SO_2,1}} + V'\frac{y_{SO_2,1}}{1-y_{SO_2,1}}$$

b) Calculate the flow-rates and compositions of the outlet phases using the data in Fig. 6.
Answer: $x_{SO_2,1} = 0.00495$, $y_{SO_2,1} = 0.0733$, $L_1 = 2.21$ kmol s^{-1}, $V_1 = 5.69$ kmol s^{-1}
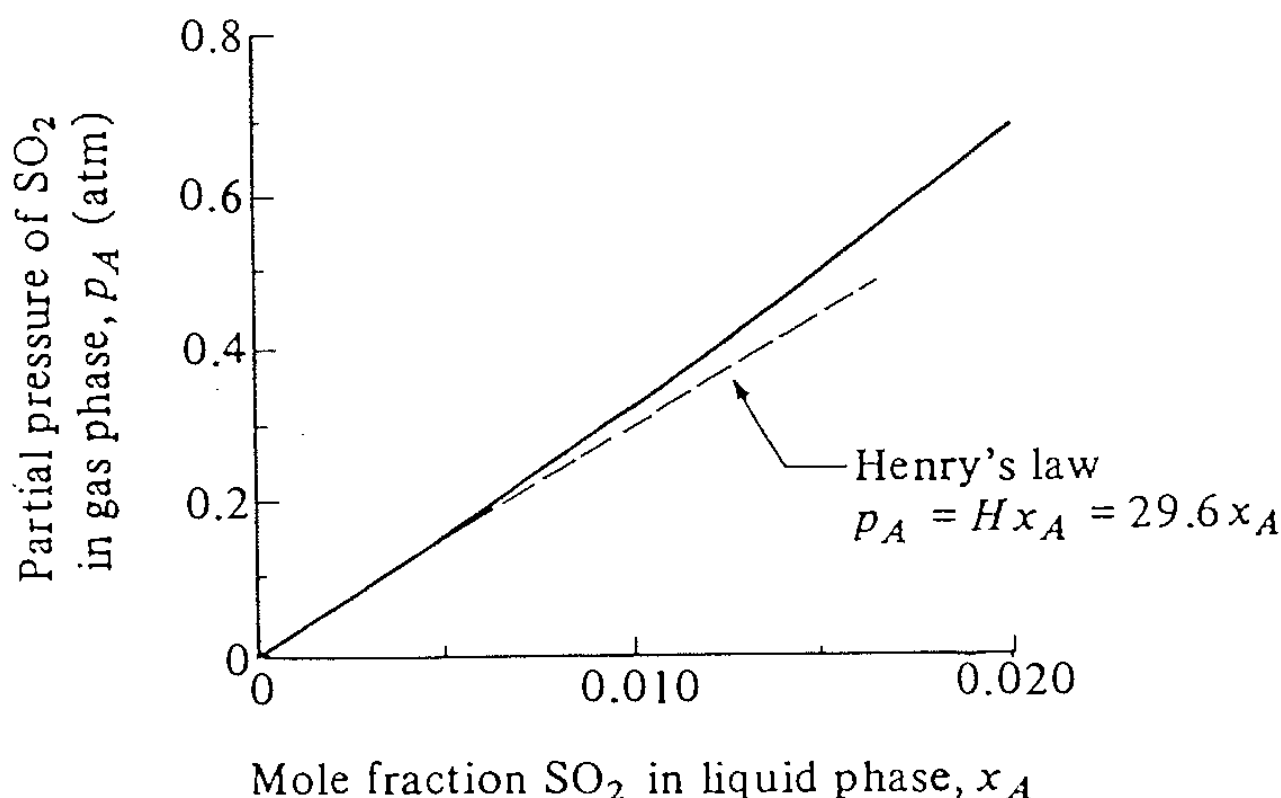

Figure 6: Equilibrium plot for water-SO2 system at $20°C$.

Question 8
A gas mixture at 1.0 atm(a) pressure containing air and CO_2 is contacted in a single-stage mixer continuously with pure water at 293 K. The two exit gas and liquid streams reach equilibrium as they are discharged. The inlet gas flow rate is 100 kg mol h^{-1}, with a mole

fraction of CO_2 of 0.20. The liquid flow rate entering is 300 kg mol water h^{-1}. Calculate the amounts and compositions of the two outlet phases. You may assume that water does not vaporize (i.e., no water in the gas phase) and use the Henry's law constant for CO_2 at 293 K in water as $H = 1.438 \times 10^8$ Pa. [20 marks]

Question 9
It is decided to deodorise fresh cream by stripping the cream with pure steam. The cream enters the stripper carrying 0.0015 mole fraction of a odorous taint, and it is desired to reduce this to 0.0003 mole fraction to prevent the consumer detecting it. The absorber will need to process 100 kmol h^{-1} of fresh cream and the VLE curve for the taint in cream is presented in Fig. 7.
Note: Real taints in cream are usually in the ppm.

a) Determine the theoretical minimum steam flow rate required to strip the taint from the stream. [9 marks]

b) From experience, it is known that the optimal steam rate is approximately twice the minimum flow rate. Determine the number of theoretical trays required to carry out the stripping. [9 marks]

c) A tray tower is to be used to carry out the stripping. Plates are available with an overall column efficiency of 28%. Determine the number of real plates required to perform the stripping. [2 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.
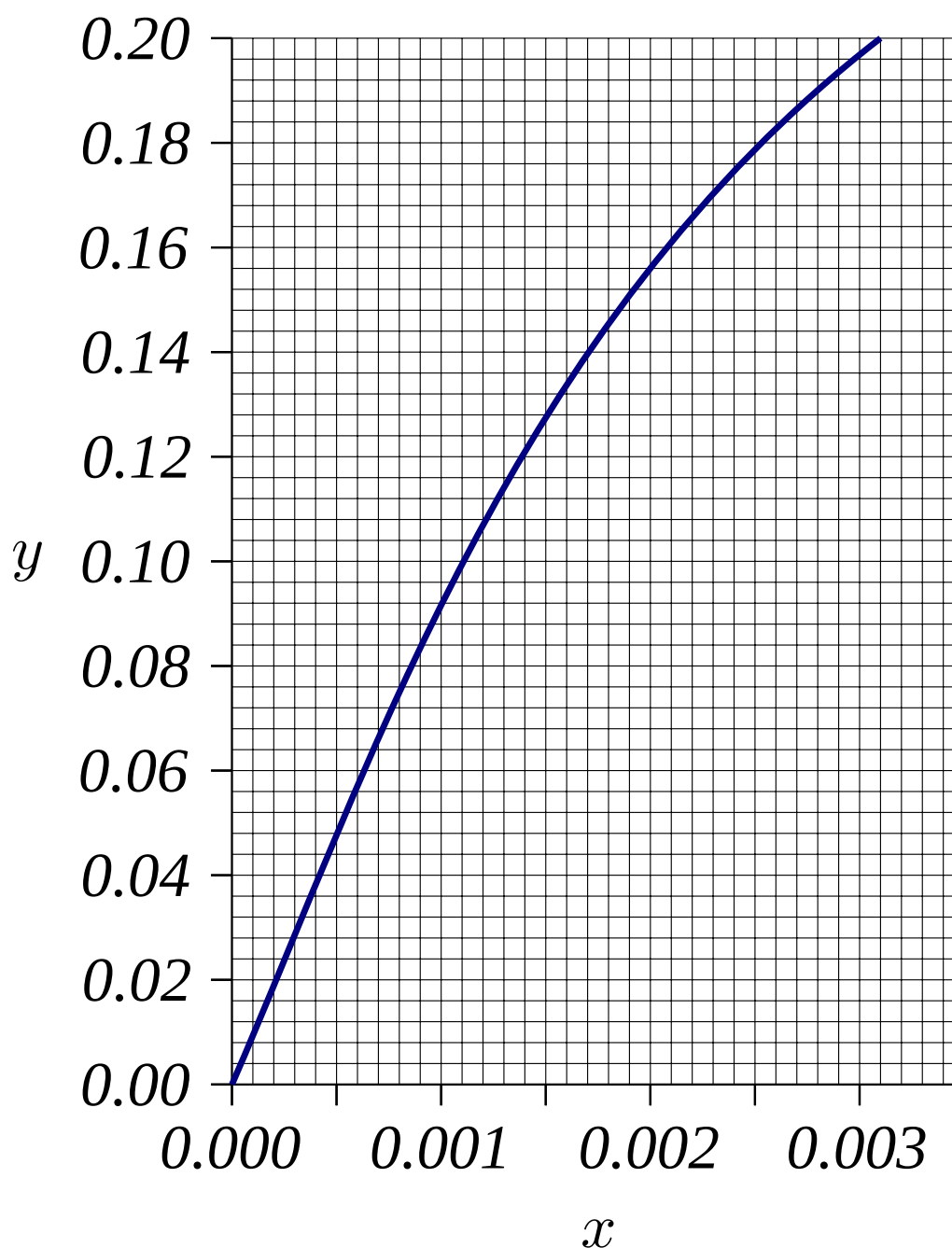
Student ID:

Figure 7: VLE data (mole fraction in vapour y versus mole fraction in liquid x) for an odorous taint in cream. For use in Q. 9

Question 10

a) Derive the operating line equation for an absorber, given below. Clearly state any assumptions that you make.   [8 marks]

$$\frac{y_{A,n+1}}{1 - y_{A,n+1}} = \frac{L'}{V'}\frac{x_{A,n}}{1 - x_{A,n}} + \frac{y_{A,1}}{1 - y_{A,1}} - \frac{L'}{V'}\frac{x_{A,0}}{1 - x_{A,0}}$$

b) Simplify the operating line equation to a linear form using the assumption of low absorbent concentrations. Discuss how these conditions are compatible with the use of Henry's law.   [4 marks]

c) A gas mixture of air and SO_2 comes into contact with pure water at 293 K and 4 bar in a single stage equilibrium mixer. The partial pressure of SO_2 in the inlet gas is 0.1 bar and the total inlet gas flow-rate is 5.13 kmol s^{-1}. The inlet flow rate of water is 2 kmol s^{-1} and the outlets are in equilibrium. Using the Henry's law expression below, calculate the compositions and flow rates of all streams.

$$P_A = \mathcal{H}_A\, x_A$$

where $\mathcal{H}_{SO_2} = 29.98$ bar at 293 K.   [8 marks]

Question 11
A 30 kmol h^{-1} gas stream produced from coal contains a light oil vapour (2 mol%) which is scrubbed out using an absorption column. The light oil vapour is washed out of the gas by contacting the gas with a 13 kmol h^{-1} non-volatile heavy oil absorbent.
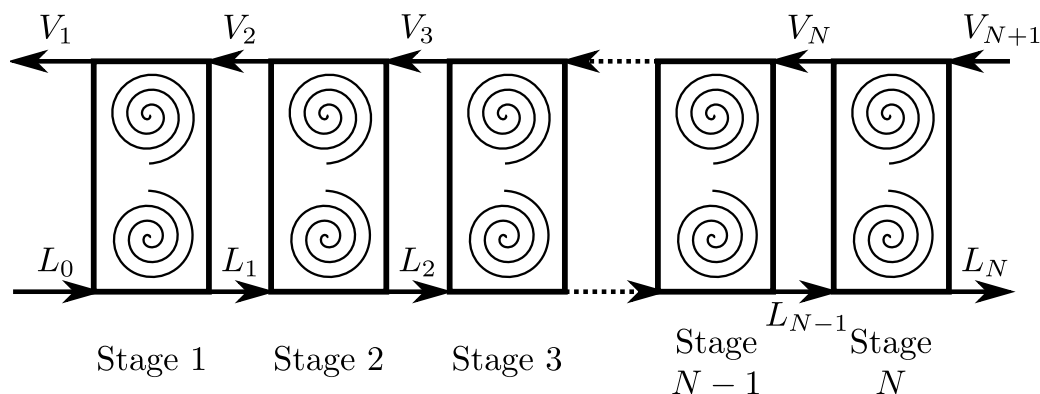
Figure 8: *
Figure: The stream numbering within a multi-stage absorber

The heavy oil absorbent initially contains 0.005 mol% of absorbed light oil and it absorbs 90% of the light oil in the inlet gas. The equilibrium between the light oil vapour and the absorbed light oil is given by $y = 0.275\,x$. An X-Y diagram is provided in Fig. 9 and the HETP is 1.4 m stage^{-1}. Determine the height of packing required to carry out the specified absorption in a counter-current column.   [20 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:

Figure 9: A X-Y graph for Q. 11.

Question 12

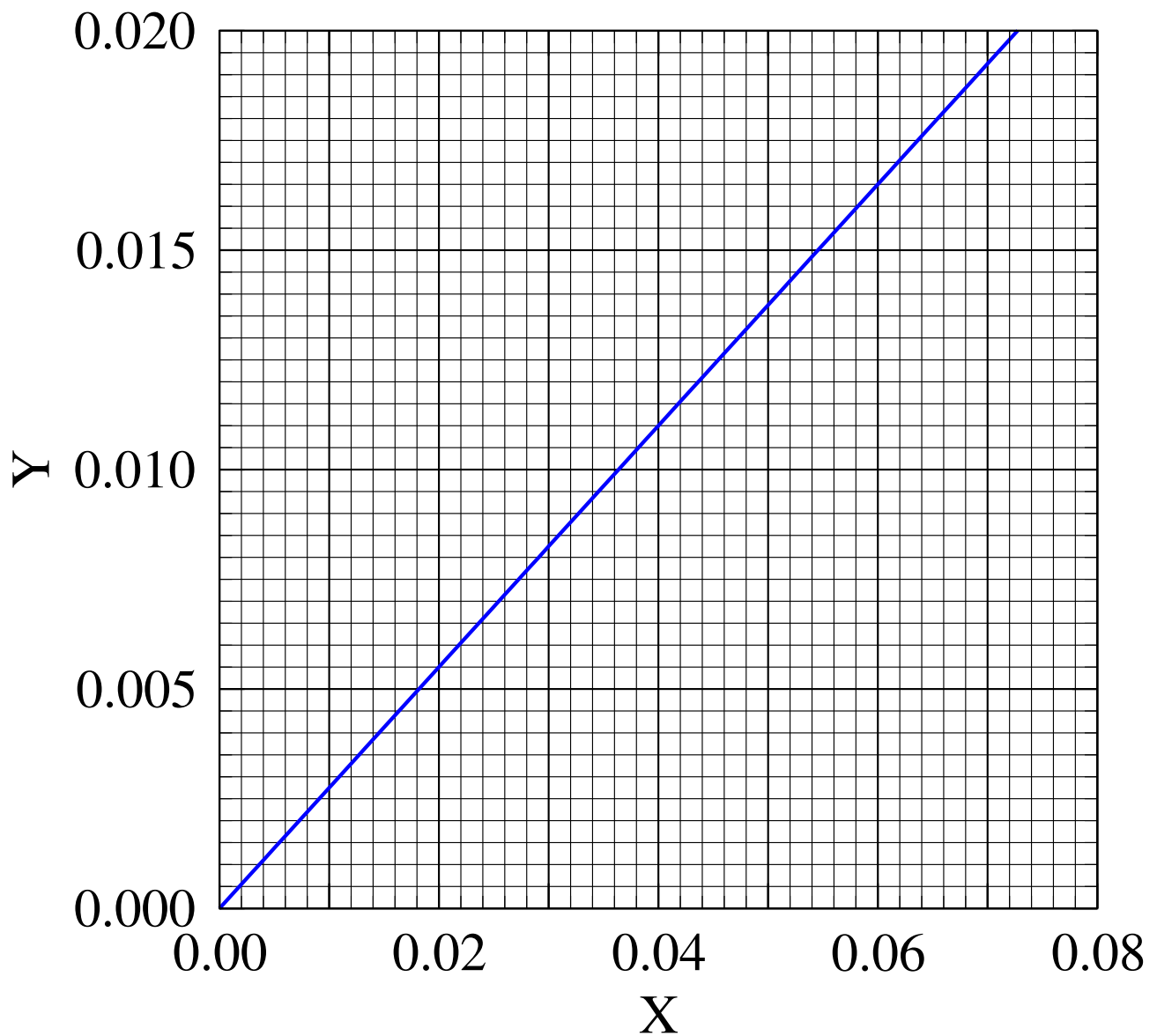Air is dried by contacting it with a solution of sulphuric acid in a counter-current absorber column. The air enters the absorber with 2.7 mol% of water and leaves with 0.8 mol% of water. Absorbent is supplied to the column at a concentration of 67 mol% H_2SO_4 and 33 mol% water, and exits the column at a concentration of 40 mol% H_2SO_4. The column is operating at atmospheric pressure (760 mmHg) and at a temperature of $25°C$. You may assume that water is the only component transferred between the phases (H_2SO_4 remains in the liquid phase and no air dissolves).
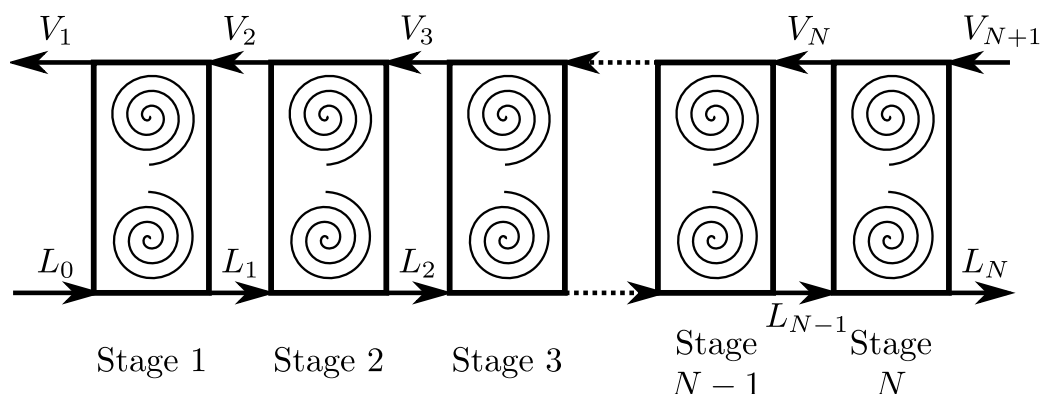
Figure 10: The stream numbering within a multi-stage absorber

a) Determine the ratio of the flow rate of dry air to the flow rate of H_2SO_4. [8 marks]

b) Using the equilibrium data provided in Table 1, determine the number of equilibrium stages required to perform the absorption. Plot your graph in x-y coordinates on Fig. 11 and ensure that you adequately capture the curvature of the operating line (or use X-Y coordinates). [12 marks]

Table 1: Partial pressure data for water over aqueous solutions of sulphuric acid at $25°C$.

Liquid Water conc. (mol%)	Partial Pressure of Water (mmHg)
80	20.8
70	17.8
60	13.5
50	8.45
40	3.97
30	1.03
20	0.124
10	0.00765

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:

Figure 11: Blank graph for the air dryer in Q. 12.

Question 13

A straw oil used to absorb benzene (C_6H_6) from coke-oven gas is to be stripped with pure steam in a sieve plate column at atmospheric pressure to recover the dissolved benzene. Equilibr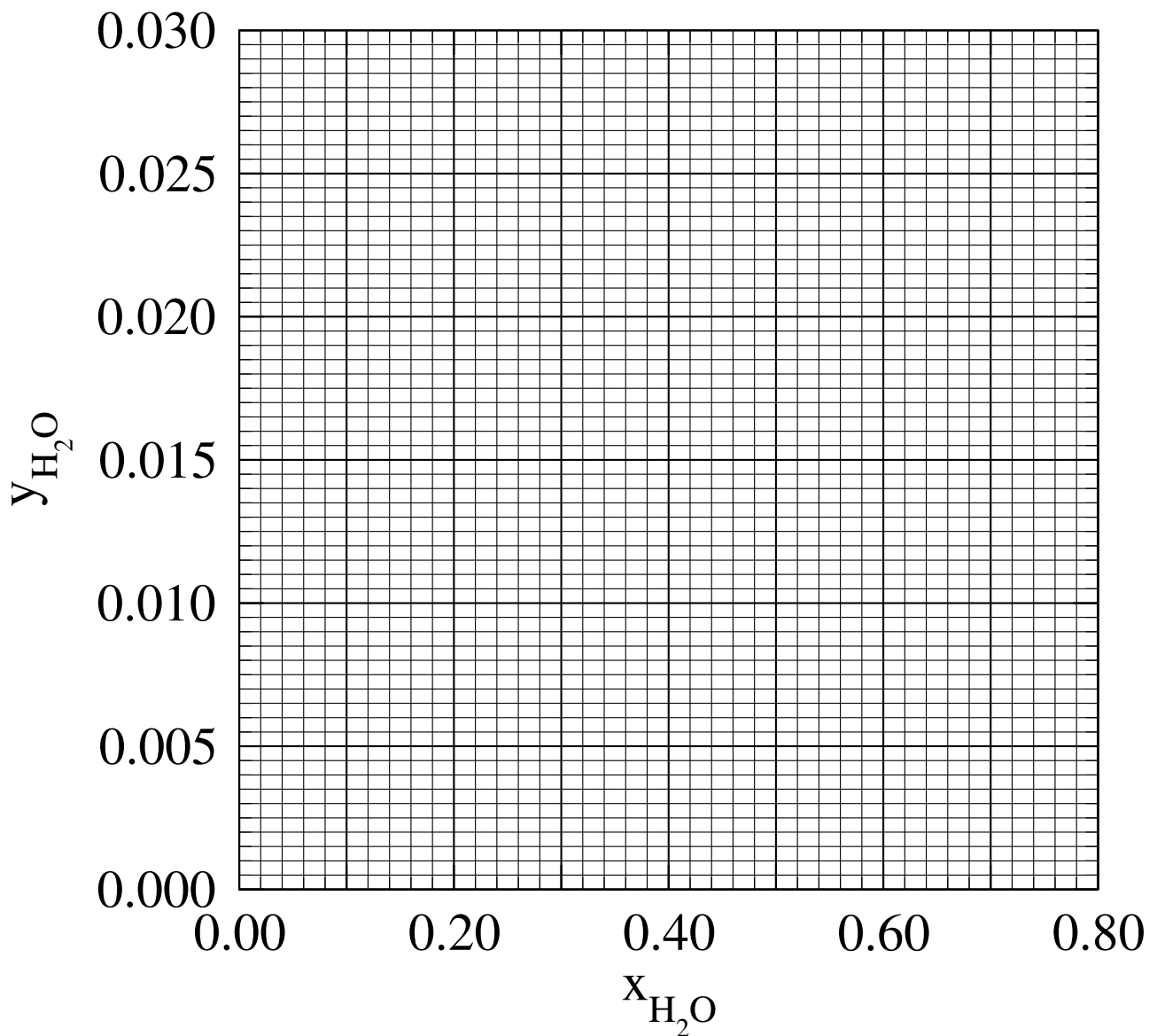ium conditions at the operating temperature are approximated by Henry's law such that, when the oil phase contains 10 mol% C_6H_6, the C_6H_6 pressure above the oil is 5.07 kPa. The oil may be considered non-volatile. The oil enters containing 8 mol% benzene, 75% of which is to be recovered. The steam leaves containing 3 mol% C_6H_6.

Note: If you perform a graphical design you will need to submit your graph paper.

a) Determine the flowrates of the non-volatile components (steam and straw oil) using a basis of 100 mol for the liquid feed.   [4 marks]

b) How many theoretical stages are required?   [14 marks]

c) A plate column with an overall efficiency of 62% is available, determine the number of plates required.   [2 marks]

Question 14

Show that for a binary mixture having a constant relative volatility, α, the mole fraction of the Most Volatile Vomponent (MVC) in the vapour phase, y_A, is related to the mole fraction of the MVC in the liquid phase, x_A, by the following equation: [10 marks]

$$y_A = \frac{\alpha\, x_A}{1 + (\alpha - 1)x_A}$$

State clearly any assumptions made.

Question 15

A 20 mol% benzene and 80 mol% toluene mixture is heated then passes through a controlled pressure-reducing valve, causing the stream to flash such that 20% of the feed is vapourised.

a) Determine the composition of the liquid and vapour given that the relative volatility of the system is $\alpha \approx 2.5$.   [8 marks]

b) How might a higher degree of separation be achieved?   [2 marks]

Question 16

Practice using Raoult's law and Dalton's law by setting up a calculation for VLE data (a spreadsheet or MATLAB program will do). Plot "smooth curve" data for benzene-toluene binary mixtures (including a x-y line using

a) Data you find in the literature.

b) Data calculated using a constant relative volatility of 2.4.

c) Data from the following temperature and vapour pressure values (1 atm).

T (°C)	$P^0_{benzene}$	$P^0_{toluene}$
80.1	101.32	-
85	116.9	46.0
90	135.5	54.0
95	155.7	63.3
100	179.2	74.3
105	204.2	86.0
110.6	240.0	101.32

d) Calculate values of y for $x \in [0.195, 0.372, 0.647, 0.800, 0.910, 0.019]$.

e) Explore the effect of relative volatility on the x-y plot. What is the significance of:

   i) Decreasing relative volatility.

   ii) A relative volitility of one.

   iii) A relative volatility less than one.

   iv) Relative volatilities of zero and infinity.

Question 17

A liquid mixture of 80 mol% n-hexane and 20 mol% benzene enters a long and narrow pipeline at 3 bara and 100 mol s^{-1} and quickly reaches the ambient conditions of $50°$C. Antoine data are available for both components in Table 2.

a) Describe the assumptions required to use Raoult's law and justify its use for the hexane-benzene mixture.   [3 marks]

b) Using Raoult's law, calculate the allowable pressure drop before the mixture separates into two phases.   [5 marks]

c) Calculate the relative volatility of n-hexane at $50°$C and describe the three categories of relative volatility.   [4 marks]

d) At the end of the pipeline, the pressure suddenly drops to 0.45 bara, causing the temperature to drop and 15 mol% of the stream to vapourise. Assuming the exit vapour and liquid phases are in equilibrium, calculate the composition and flow rate of the two phases. You should perform mass balances over the pipeline and assume that the relative volatility is constant.   [8 marks]

Component	A	B	C	T_{min} (°C)	T_{max} (°C)
n-hexane	6.91058	1189.640	226.280	-30	170
benzene	6.87987	1196.760	219.161	8	80

Table 2: $\log_{10} P_{sat}(T) = A - B/(T + C)$ where T is in Celsius and P_{sat} is in torr. Please note that 760 torr=1 atm=1.013 bar.

Question 18

VLE data is needed for a proposed separation of isopropanol (AKA propan-2-ol or 2-propanol) and water at 1 atm. Experimental data is available in Table 3, but a smooth x-y relationship is required for the design calculations.

   i) Use Raoult's law to calculate the T-x-y VLE curve for the system and compare it to the experimental data. Expressions for the pure component vapour pressures are given in Table 4. Explain any deviations you observe in terms of the chemical structure of the components.

   General Hint:
   You need to solve the following equation for the temperature T which corresponds to the operating pressure:

$$P(T, x_A, x_B, \ldots) = \sum_i P_i^{sat}(T) x_i \tag{1}$$

Once this is done, you can then work out the corresponding vapour concentration using the following expression:

$$y_A(T, x_A, x_B, \ldots) = \frac{P_A^{sat}(T)\, x_A}{\sum_i P_i^{sat}(T)\, x_i}$$

You will need to do this repeatedly for a range of liquid concentrations to plot a smooth curve. Double check the units of all parameters and please note that the $\log$ function in the Antoine expression is base 10.

Excel Hint:
To solve the equation above using excel, set the liquid concentrations, then use goal seek to vary the temperature to match the calculated pressure to the operating pressure. Ensure your temperature is initially set to a reasonable value (non-zero, positive) before running goal seek, otherwise it might not converge.

Matlab Hint:
Use the *fsolve* function to numerically solve the equation $P(T, x) - P_{target} = 0$ by varying the boiling temperature T. Ensure your initial guess for the temperature is reasonable (non-zero, positive).

ii) Use modified Raoult's law to calculate the T-x-y curve and compare to the experimental data. Comment on the agreement and its suitability for design calculations.

The Margules equations for the activity coefficients are:

$$\ln \gamma_A = x_B^2 \left(\mathcal{A}_{AB} + 2\, x_A \left[\mathcal{A}_{BA} - \mathcal{A}_{AB} \right] \right)$$
$$\ln \gamma_B = x_A^2 \left(\mathcal{A}_{BA} + 2\, x_B \left[\mathcal{A}_{AB} - \mathcal{A}_{BA} \right] \right)$$

where the coefficients for isopropanol(A)-water(B) are $A_{AB} = 2.3319$ and $A_{BA} = 0.8976$, taken from Table 13-2 of Perry's 7th Ed.

Table 3: Experimental VLE data for Isopropanol-water mixtures at 1 atm.

T °C	82.2	81.48	80.70	80.37	80.23	80.11	80.16	80.15	80.31	80.38	80.67
x	100.00	95.35	87.25	80.90	76.50	69.55	66.05	64.60	55.90	51.45	44.60
y	100.00	93.25	83.40	77.45	73.70	69.15	67.15	66.45	62.55	60.75	59.20

T °C	80.90	81.28	81.29	81.23	81.62	81.75	81.58	81.99	82.32	82.70	84.57
x	38.35	29.80	29.75	28.35	24.50	19.35	18.95	16.65	12.15	10.00	5.70
y	57.00	55.10	55.40	55.30	53.90	53.20	53.75	52.15	51.20	50.15	45.65

T °C	88.05	93.40	95.17	100.0
x	3.65	1.60	1.15	0.00
y	36.55	21.15	16.30	0.00

Table 4: Antoine coefficients for isopropanol and water (taken from Table 13-4 in Perry's 7th ed.).

Species	A	B	C	Range
2-Propanol	8.87829	2010.320	252.636	$-26 \rightarrow +83\ °C$
Water	8.07131	1730.630	233.426	$+1 \rightarrow +100\ °C$

$\log_{10} P^{sat} = A - B/(T + C)$ where P^{sat} is in units of torr and T is in units of Celcius.

Question 19

You are in the business development (BD) unit of Nirvana Compounds Ltd, a company that specialises in producing volatile organic compounds (VOCs). They have asked you, as their top process engineer, to perform a study into the efficiency of batch and flash distillation when used to separate a benzene-toluene mixture. This product will then be sold under the TeenSpirit volatile compounds brand.

An equimolar mixture of toluene and benzene is produced from an existing process and is available for separation.

a) What is the outlet concentration of the vapour and liquid streams from a flash drum? The flash drum is operated so that only 20% of the feed stream is vapourised. x-y VLE data is available in Fig. 12.   [7 marks]

b) What is the average vapour concentration and the final liquid concentration if the same feed is supplied to a single-stage batch still instead? You should assume the same proportion of vapour is produced as in the flash drum. Integrated VLE data is available in Fig. 13 for this calculation.   [8 marks]
Note: You may find the following expression useful

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = \int_0^{x_{final}} (y - x)^{-1}\, \mathrm{d}x - \int_0^{x_{initial}} (y - x)^{-1}\, \mathrm{d}x$$

c) A young maverick process engineer laughs at your use of graphical methods, and says you should just have used a relative volatility of $\alpha \approx 2.45$ and the formula given in the lecture notes. Does this give reasonable results when compared to the graphical solution?   [5 marks]

d) You decide to teach the maverick a lesson, literally, and tell them when is it acceptable to use a constant relative volatility and how this constant volatility is calculated?

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.
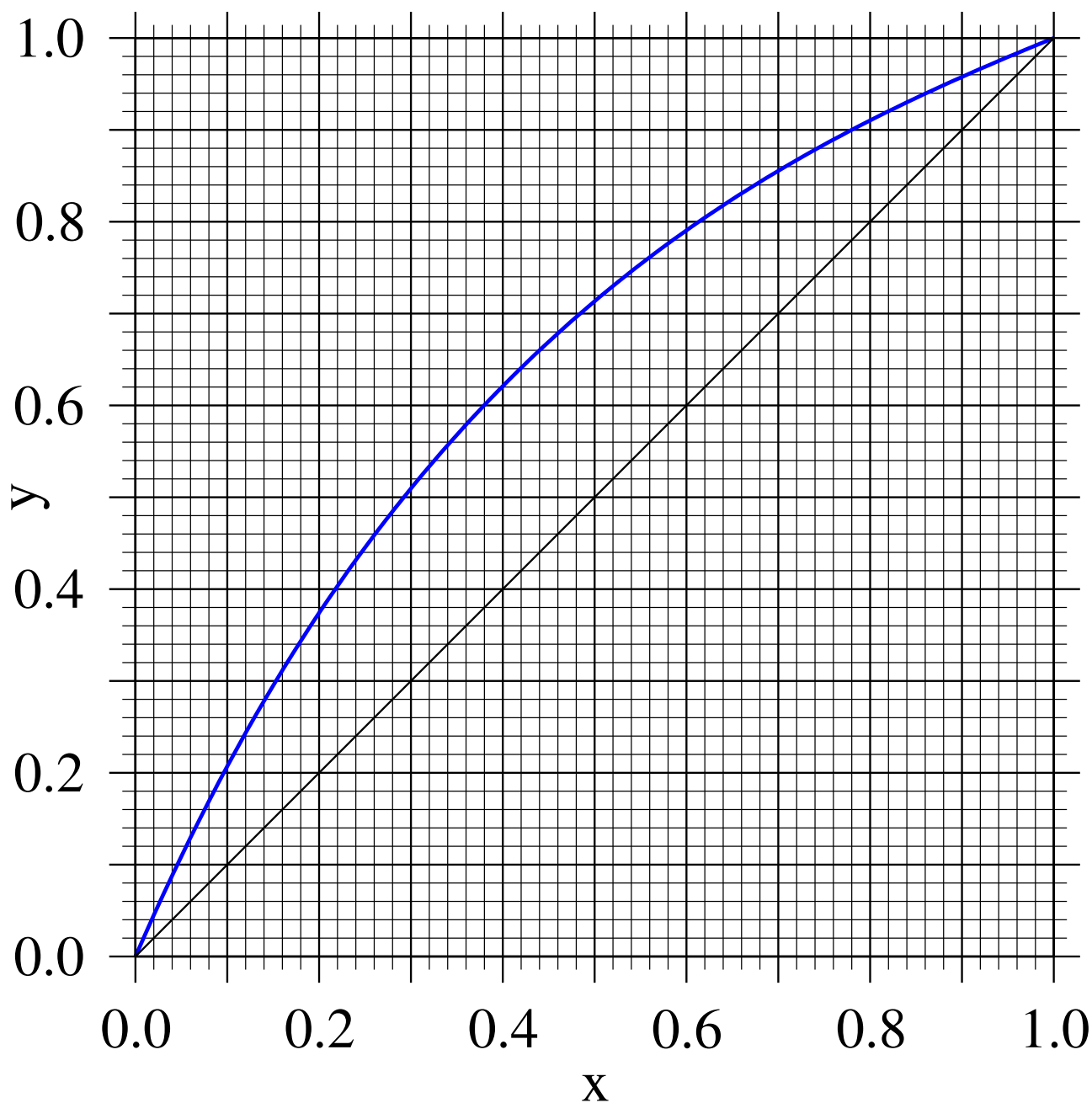
Student ID:

Figure 12: VLE data for benzene(x/y)-toluene mixtures. For use in Q. 19, 20, and 30.

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.
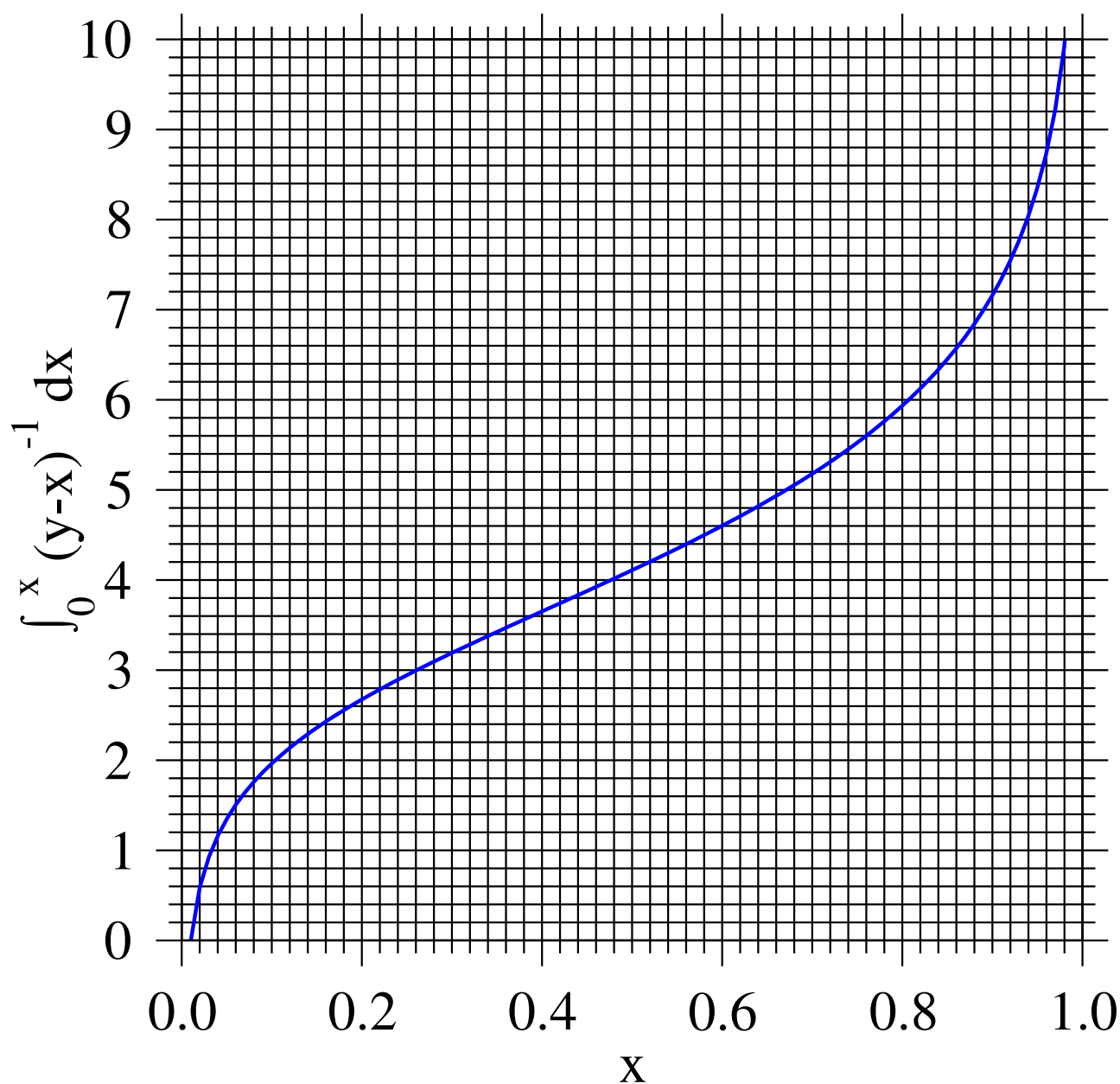
Student ID:

Figure 13: Integrated VLE data for benzene(x/y)-toluene mixtures. For use in Q. 19 and 20.

Question 20

A 10,000 kmol benzene-toluene mixture is sent for batch distillation at atmospheric pressure. Integrated VLE data is available in Fig. 13 and standard VLE data is available in Fig. 12.

a) Derive the following equation, known as Rayleigh's equation, for the concentration in the evaporator. [10 marks]

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = \int_{x_{initial}}^{x_{final}} \frac{\mathrm{d}x}{y - x}$$

where $L_{initial}$ and L_{final} are the initial and final molar amounts of liquid within the still, x is the concentration of the liquid, and y is the concentration of the produced vapour.

b) The distillation is begun and the initial vapour concentration is 60 mol% benzene. Determine the initial liquid concentration in the still. [2 marks]

c) Distillation is continued until the produced vapour concentration drops to 40 mol% benzene. Determine the amount of liquid remaining in the still. [6 marks]

d) Calculate the average concentration of the collected distillate. [2 marks]

Question 21

An undergraduate is investigating the distillation of a 40 mol% isopropanol and 60 mol% water mixture in the Chemical Engineering laboratory. The distillation unit has had its column removed and is being operated as a single-stage unit.

a) Derive the following equation, known as Rayleigh's equation, for the concentration in the evaporator. [10 marks]

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = \int_{x_{initial}}^{x_{final}} \frac{\mathrm{d}x}{y - x}$$

where $L_{initial}$ and L_{final} are the initial and final molar amounts of liquid within the still, x is the concentration of the liquid, and y is the concentration of the produced vapour.

b) Using the integrated VLE data in Fig. 14, calculate the final concentration in the batch still and average vapour concentration if 50 mol% of the mixture is evaporated. [8 marks]

c) Consider the integrated VLE data in Fig. 14, why does the graph diverge in the middle of the plot? Why can you not use batch distillation to distill from low concentrations to high concentrations?
Hint: The VLE behaviour of isopropanol-water mixtures is similar to ethanol-water systems. [2 marks]
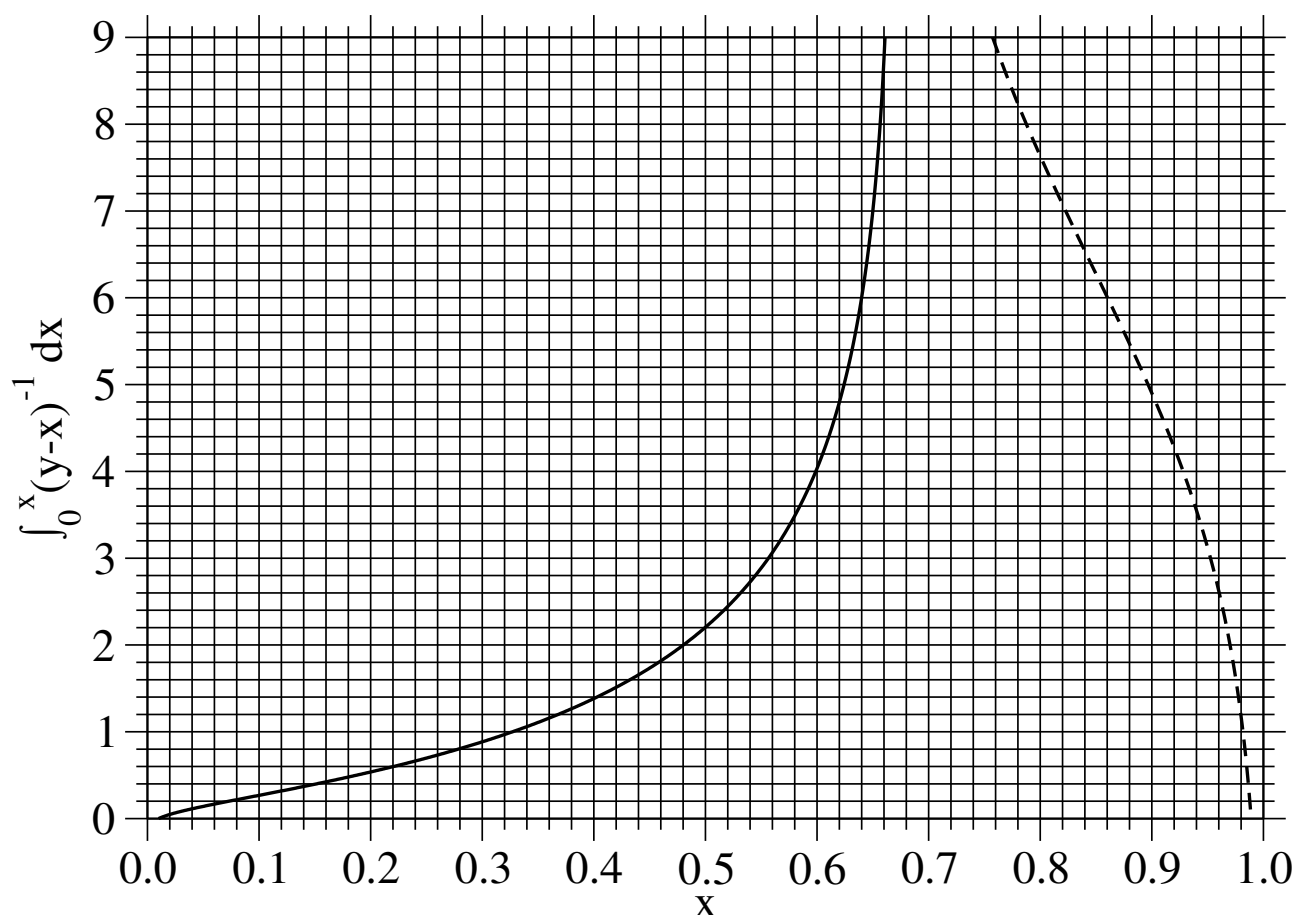
Figure 14: Integrated VLE data for the Isopropanol-water system in Q. 21. **Note:** The solid and dashed curves are distinct and no single-stage equilibrium process connects them.

Question 22

For mixtures with an almost constant relative volatility, Rayleigh's equation may be solved to give

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = (\alpha - 1)^{-1} \ln\left(\frac{x_{final}(1 - x_{initial})}{x_{initial}(1 - x_{final})}\right) + \ln\left(\frac{1 - x_{initial}}{1 - x_{final}}\right)$$

a) Define the relative volatility and describe the three cases, $\alpha > 1$, $\alpha = 1$, and $\alpha < 1$.
[3 marks]

b) A poteen producer wants to distill a 2.4 kmol mixture of ethanol (3.5 mol%) and water using Rayleigh distillation to produce a liqueur. Assuming an effective relative volatility of $\alpha \approx 7$, determine the concentration of the liqueur if 0.6 kmol of distillate is produced.
[7 marks]

Question 23

A saturated liquid feed of 200 kmol h^{-1} of a heptane-Ethyl Benzene mixture containing 42% heptane and 58% ethyl benzene is to be fractionated at 101.32 kPa to give a distillate containing 97% heptane and a bottoms containing 1.1% heptane. The reflux ratio used is $R = 2.5$ and vapour-liquid equilibrium data for the mixture is given in Table 5 below.

a) Calculate the number of theoretical trays required to perform this distillation **and** the feed tray number. A blank VLE graph is given in Fig. 15.
   Answer: 10.5 stages (but may be around 12 depending on your accuracy).

b) Calculate the flow-rates of the top and bottom product.

Temperature (K)	x	y	Temperature (K)	x	y
409.3	0.000	0.000	383.8	0.485	0.730
402.6	0.080	0.230	376.0	0.790	0.904
392.6	0.250	0.514	371.5	1.000	1.000

Table 5: Boiling temperature and VLE data for a heptane-ethyl benzene mixture at 101.32 kPa. Concentrations are reported in the mole fraction of the most volatile component (heptane).

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.
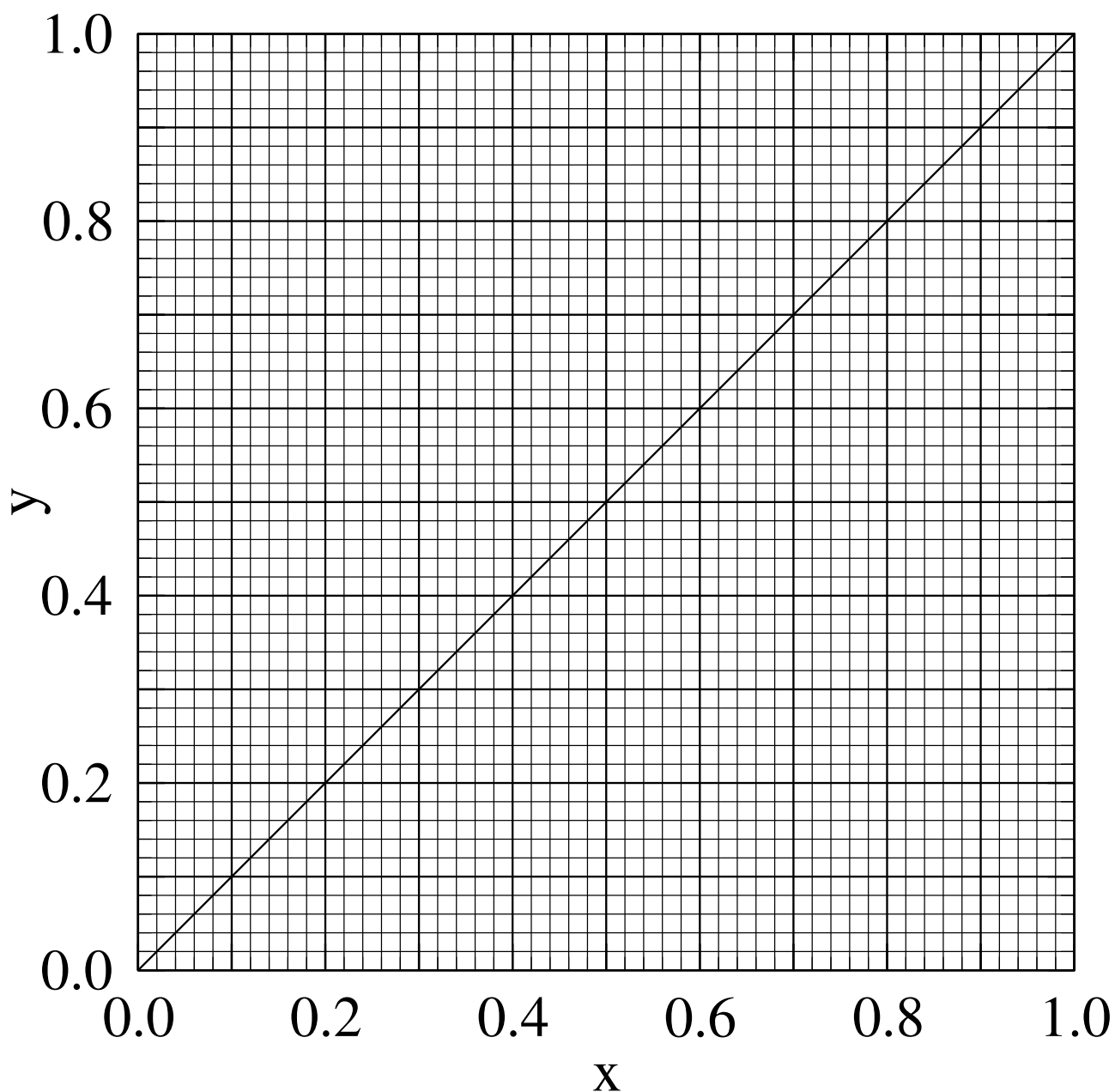
Student ID:

Figure 15: A blank chart for plotting VLE/operating-line data on. For use in Q. 23.

Question 24

Derive the following operating line equation for the enriching section of a column using a mass balance.

$$y_n = \frac{R}{R+1}x_{n+1} + \frac{x_D}{R+1}$$

State any assumptions you make and discuss their range of validity.   [10 marks]
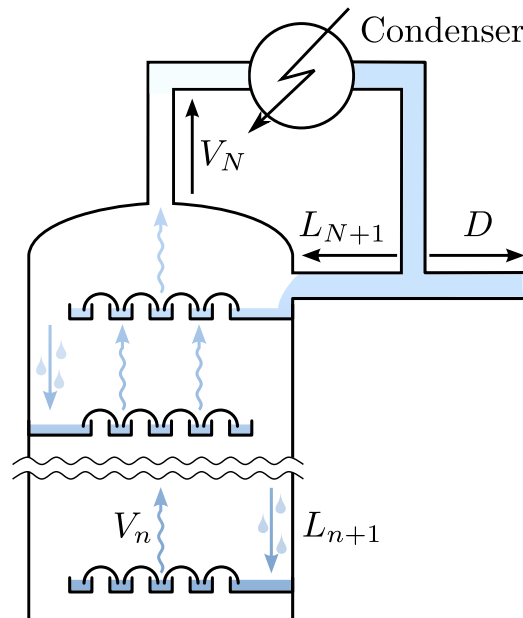
Figure 16: A diagram of the streams in the enrichment section of a distillation column.

Question 25

Calculate the *minimum* number of ideal stages required in a distillation column to separate ethanol-water mixtures to a purity of 5 mol% bottoms and 60 mol% distillate. Why is the feed concentration unimportant in this limit? VLE data for ethanol-water mixtures is available in Fig. 17.   [8 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:

Figure 17: VLE diagram for ethanol-water mixtures at a pressure of 1 atm. This figure is required for Q. 25.

Question 26

a) Derive the following operating line equation for the stripping section of a column using a mass balance.

$$y_m = x_{m+1}\frac{L_m}{V_m} - x_W\frac{W}{V_m}$$

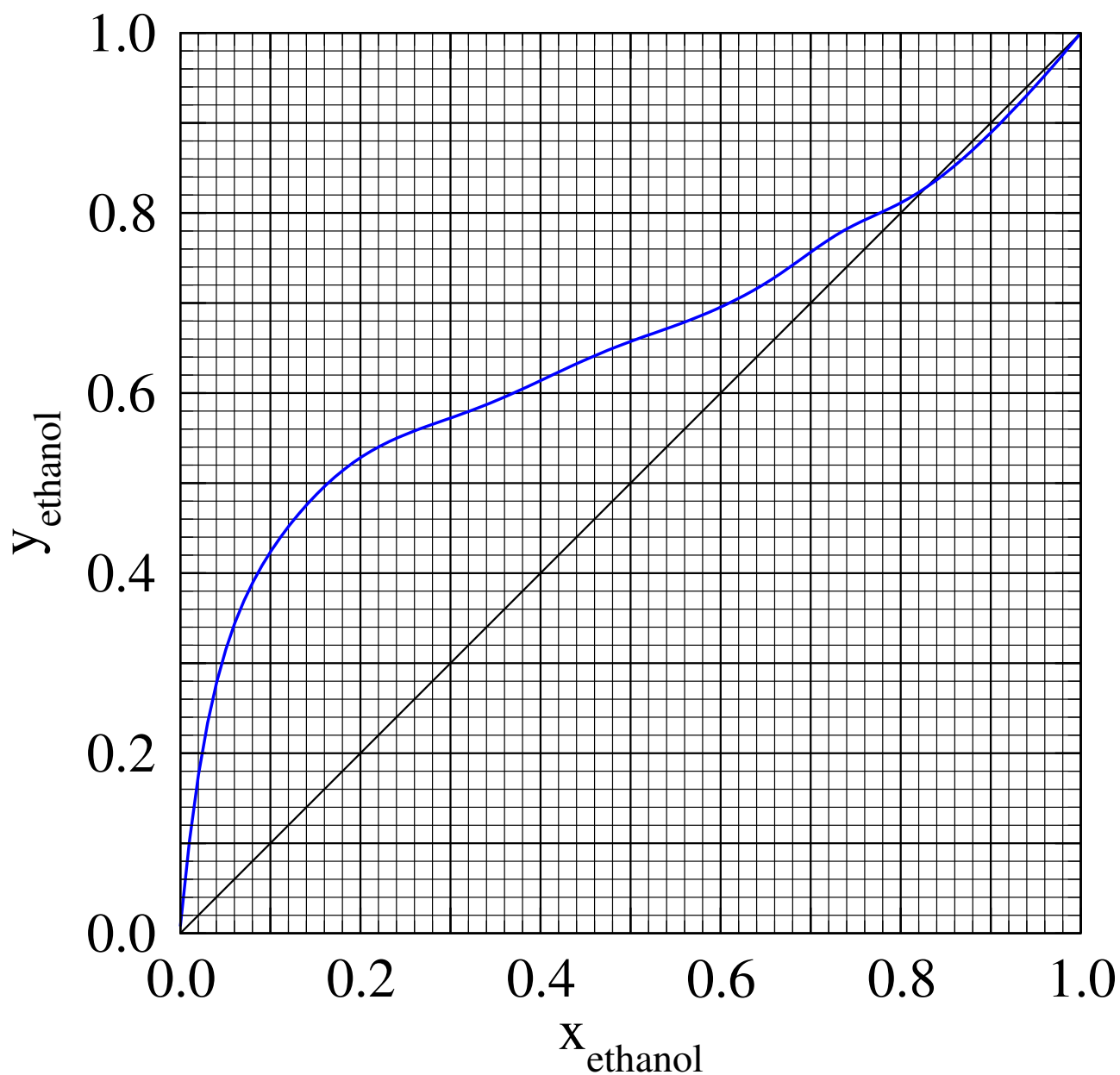State any assumptions you make and discuss their range of validity. A diagram including a suggested labelling of streams is available in Fig. 18. [5 marks]
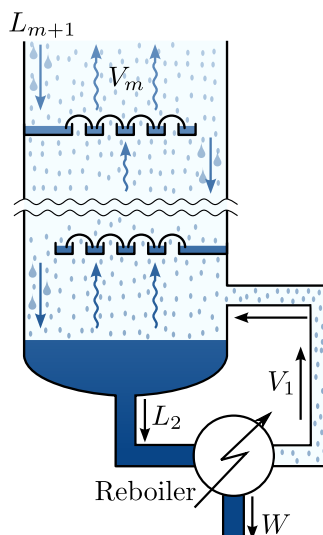
Figure 18: A diagram of the streams in the stripping section of a distillation column.

b) Explain why the stripping section operating line equation is inconvenient to use when compared to the enrichment operating line if the reflux ratio and the q value are selected as the design variables. [3 marks]

c) Determine the location of one point on the stripping operating line. [2 marks]

d) Define the relative volatility and describe the three cases, $\alpha > 1$, $\alpha = 1$, and $\alpha < 1$. [3 marks]

e) A knockout drum is used to remove condensate from a 8 kmol s^{-1} methanol vapour stream. The vapour stream enters the knockout drum at a temperature of $72°$C and contains 5 mol% water. Determine the exit concentration of the vapour and liquid streams if 0.5 kmol s^{-1} of condensate is collected in the drum.

You may assume methanol has a constant relative volatility of $\alpha = 3.9$ when compared with water. [7 marks]

Question 27

a) Consider the VLE data for ethanol-water mixtures which are presented in Fig. 19.

   i) What VLE "feature" is present at high mole fractions of ethanol ($x_{ethanol} \approx 0.9$) and what difficulties will it present when trying to distill high purity ethanol from dilute feedstock? [3 marks]

ii) Describe one method for how such a feature might be broken/overcome?

[3 marks]

b) Using a mass balance, derive the following operating line equation for a flash drum.

$$y = (x_F - x\,q)/(1 - q)$$

where $q = L/F$ is the fraction of un-vapourised feed, x_F is the feed concentration, x is the outlet liquid concentration, and y is the outlet vapour concentration.   [6 marks]

c) A flash drum, operating at 1 atm, is used to distill a 60 mol% ethanol and 40 mol% water mixture at a flow rate of 150 kmol h^{-1}. The heat exchanger before the flash drum is set so that 80 mol% of the feed will vapourise in the drum. Graphically determine the outlet concentrations of the vapour and liquid streams using the VLE data for ethanol-water mixtures available in Fig. 19.   [8 marks]
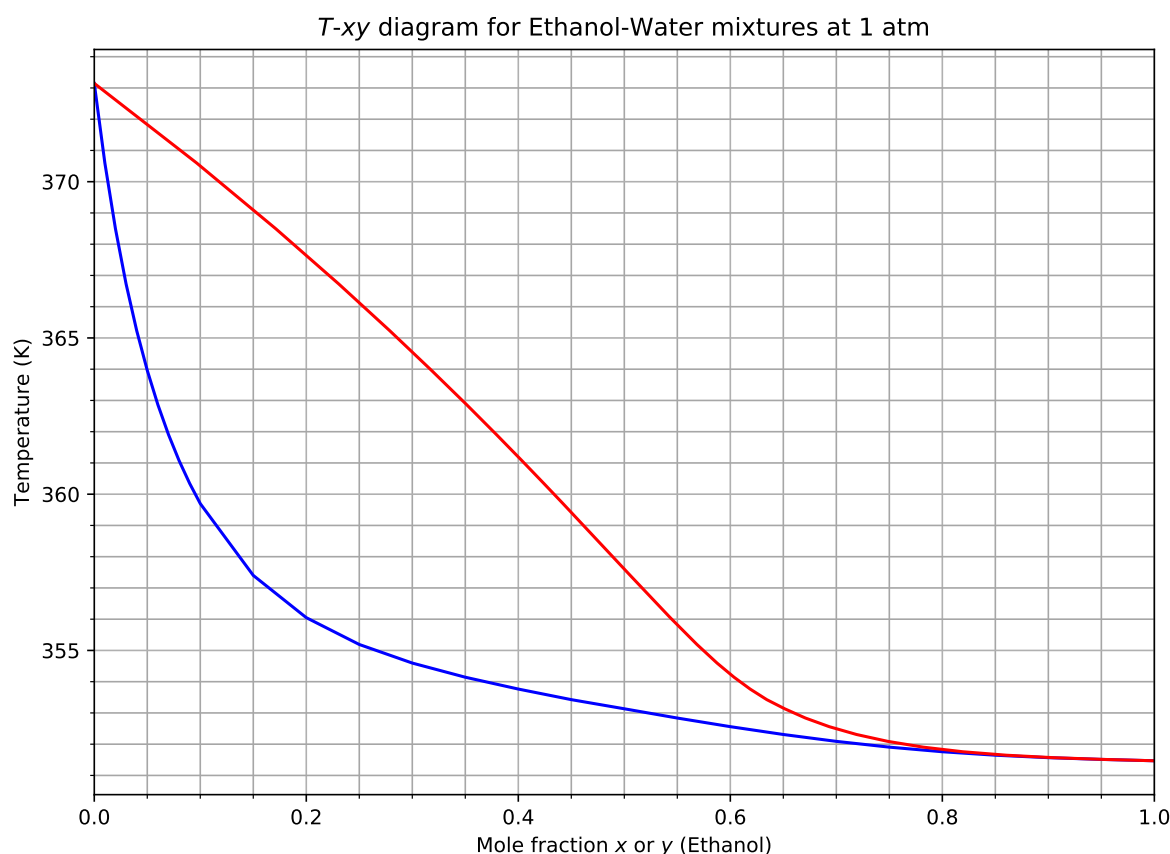
Figure 19: The T-xy diagram for a ethanol-water mixture at atmospheric pressure. Data was calcuated using the Margules activity coefficients (taken from Perry's) and Antoine coefficients from the Dortmund database. For use in Q. 27.

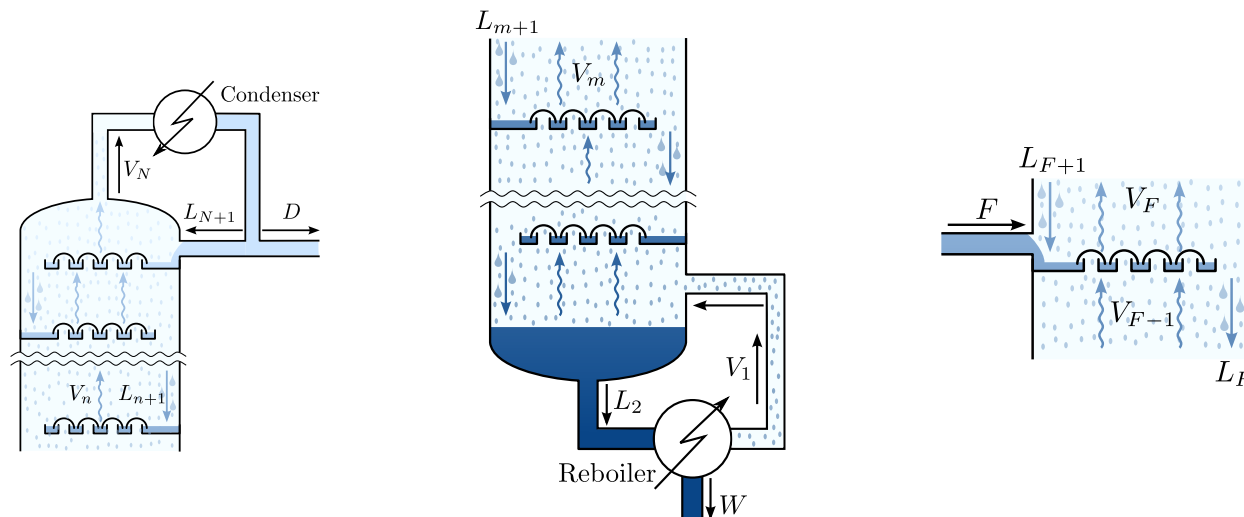**Question 28**

a) Give the definition of the q parameter in multi-stage distillation and identify the state of the feed for the following q-values, $q < 0$, $q = 0$, $q = 0.5$, $q = 1$, and $q > 1$.   [5 marks]

b) Derive the following equation describing the q-line.

$$y = x\frac{q}{q-1} - \frac{x_F}{q-1}$$

The following diagrams are provided to aid you in labelling your streams.   [13 marks]

c) The molar enthalpies of saturated liquid and saturated vapour are 20 MJ kmol^{-1} and 50 MJ kmol^{-1} respectively. Determine the values of "q" and the gradient of the "q-line" given that the molar enthalpy of the feed is:

   i) 18 MJ kmol^{-1}.   [2 marks]

   ii) 20 MJ kmol^{-1}.   [2 marks]

   iii) 52 MJ kmol^{-1}.   [2 marks]

Question 29
A mixture of 40 mol% benzene and 60 mol% toluene is fed to a distillation column for purification. The bottoms product is specified at 10 mol% benzene and a minimum of 95 mol% benzene is required in the top product. 50 mol% of the feed flashes to vapour upon entering the column. VLE data is provided in Fig. 20.

a) Determine the minimum reflux ratio for this separation.   [3 marks]

b) Calculate the number of theoretical stages required to perform the distillation at twice the minimum reflux ratio ($R = 2\,R_{min}$).   [5 marks]

c) Calculate the number of real stages, using a Murphree tray efficiency of 0.5 below the feed and 0.75 above the feed.   [10 marks]

d) Calculate and comment on the overall tray efficiency of the column.   [2 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.
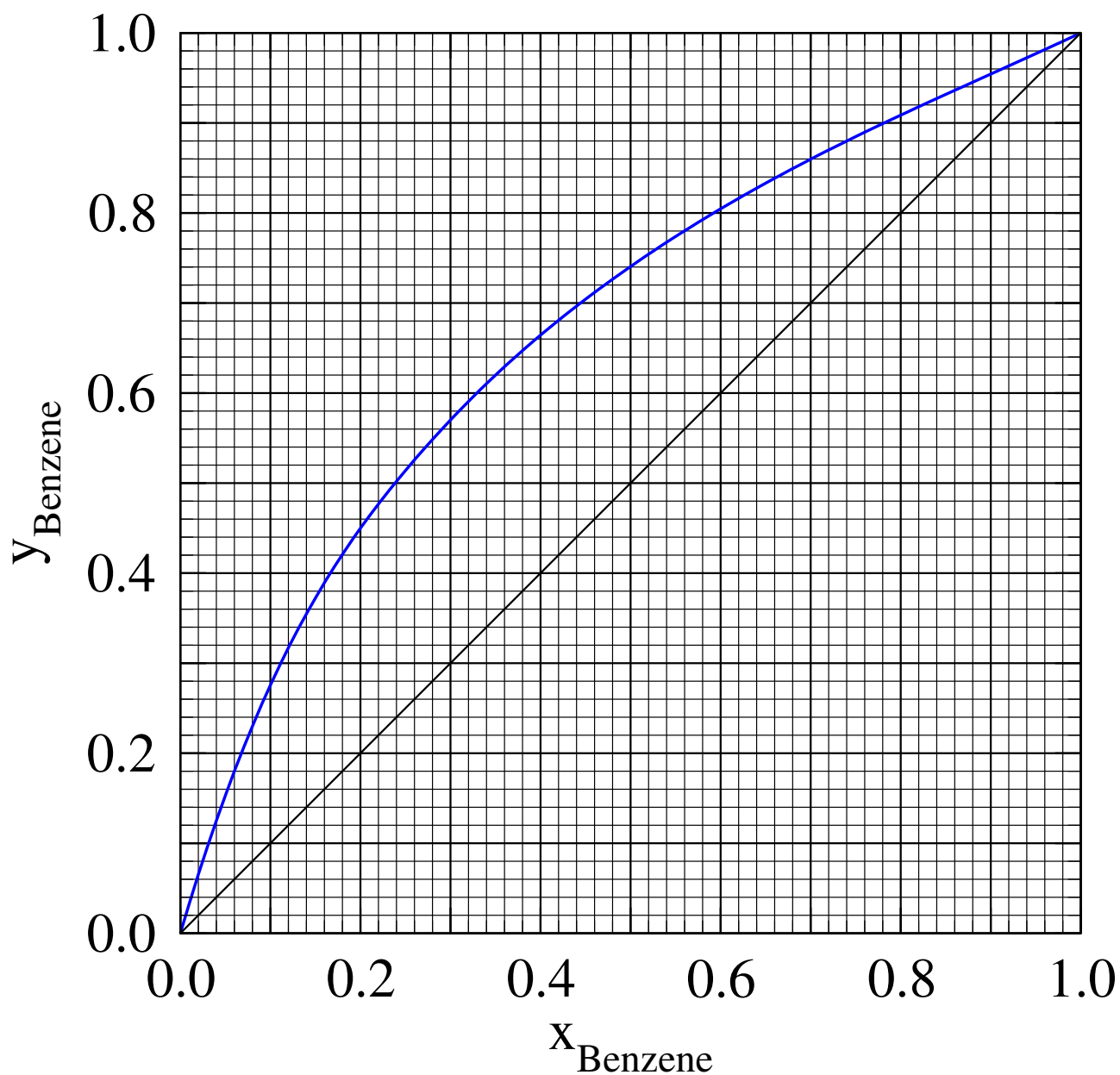
Student ID:

Figure 20: VLE diagram for benzene-toluene mixtures at 1 atm. This figure is required for Q. 29.

Question 30

A continuous distillation column is being used to separate benzene from toluene. There are six plates above the feed plate and the column is operated with a reflux ratio of 3. When the feed composition is 40 mol% benzene, the top product has a composition of 97 mol% benzene. VLE data for the system is provided in Fig. 12.

a) What range of q-values will yield the top-product specification?   [10 marks]

b) Discuss what the optimum q-value for the column is and how it affects the costs of construction and operation.   [5 marks]

c) Using the optimum q-value, calculate how many plates/trays are required below the feed tray. You may assume that a partial reboiler is used and the bottoms product is 8 mol% benzene.   [3 marks]

d) Why would it be impractical to operate the column with a fully vapourised feed ($q = 0$)?   [2 marks]

Question 31

 Note: This question is a lighthearted problem on a *ficitional* compound and was written around the time of the Avatar film's release (although the compound has featured in a number of other popular science fiction works). It is used to demonstrate that pinch points on operating lines may appear in a number of places and you cannot immediately tell which operating line will pinch first.

The mining company RDA wants to perform a separation of the volatile component unobtainium from water (VLE curve provided in Fig. 21, print at least three copies as you will need them!). A 44% unobtainium-water feed is available which will need to be concentrated to 90% unobtainium before shipment. To meet the lax environmental regulations, the water in the bottoms product must reach a concentration of 96% water before being discarded. The column will be operated at atmospheric pressure, and the feed stream will flash to equal moles of vapour and liquid at these conditions. A thermosyphon (total) reboiler is used and therefore it does not function as a stage of distillation.

a) Determine the minimum reflux ratio, R_{min}, needed for this separation. Clearly mark your pinch point.
   Hint: Pinches can occur on either operating line!

b) The economic reflux ratio is around $R = 1.5 \times R_{min}$. Determine the required number of theoretical stages to perform the separation at this value of R.

c) The bubble-cap trays selected for carrying out the distillation have a Murphree tray efficiency of 50%. Calculate the real number of trays required to perform the distillation.

d) What is the overall column tray efficiency? Compare this to the Murphree tray efficiency.

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:
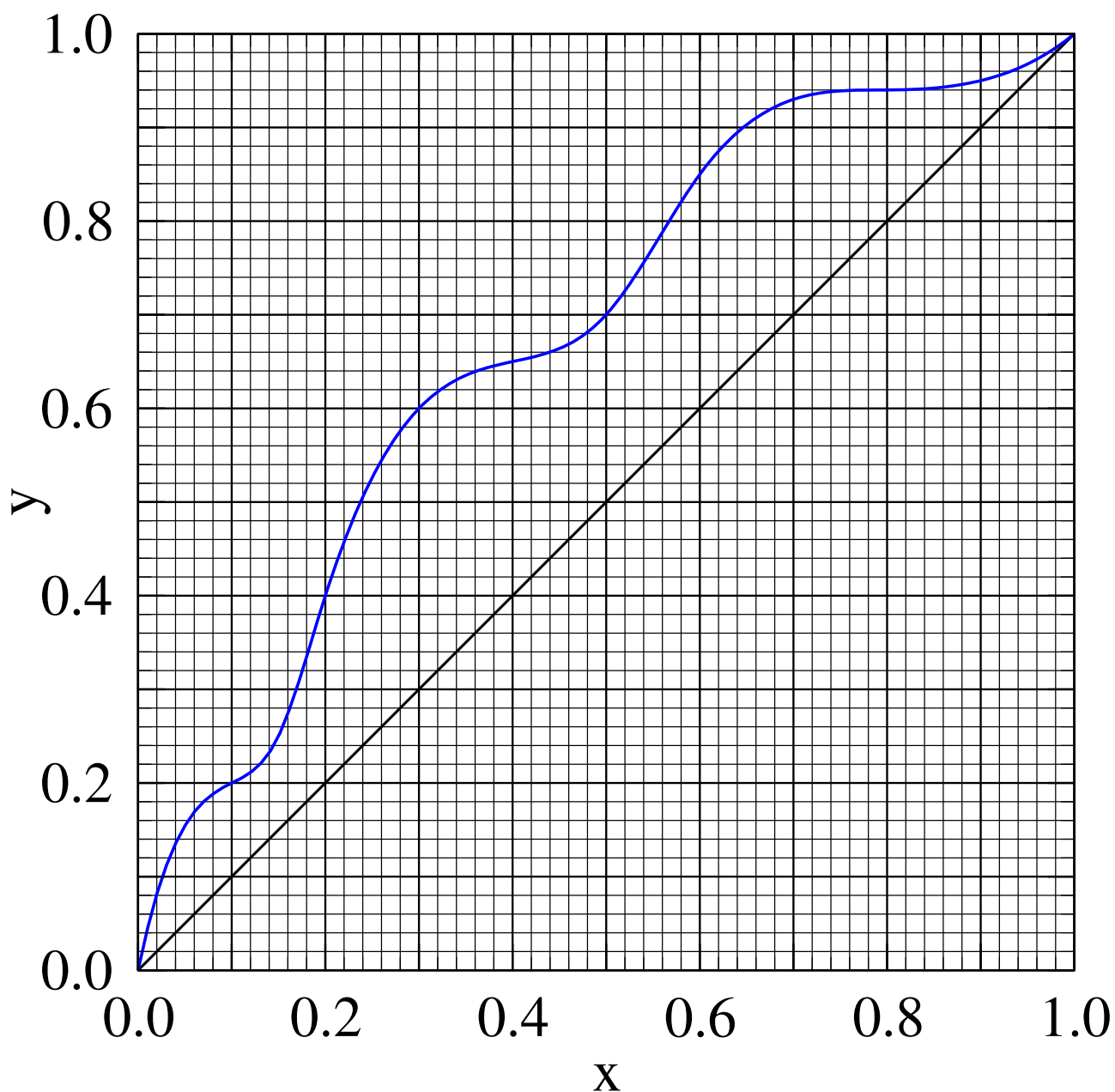
Figure 21: The VLE data for a unobtainium-water mixture at atmospheric pressure. Unobtainium is more volatile than water. For use in Q. 31.

Question 32

A hot product stream, containing 40 mol% of a volatile lipid, from a reactor producing soap is to be continuously distilled in a plate tower until it reaches a purity of 90 mol% of lipid and a waste stream containing less than 10 mol% of lipid. As the lipid mixture increases in concentration it begins to foam and the column plate efficiencies begin to drop. The theoretical and the effective "Murphree" VLE lines for the column are plotted in Fig. 22.

a) The column is operating at a reflux ratio of $R = 1.5 \times R_{min}$. Using the effective VLE line, determine the operating reflux ratio of the column if the feed mixture is supplied to the column as a saturated liquid. [5 marks]

b) Determine the number of stages in the column required to perform the distillation. Assume that the column is fitted with a partial reboiler and a total condenser. [8 marks]

c) Define the Murphree plate efficiency, and calculate its values for the two stages above the feed plate. [7 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:
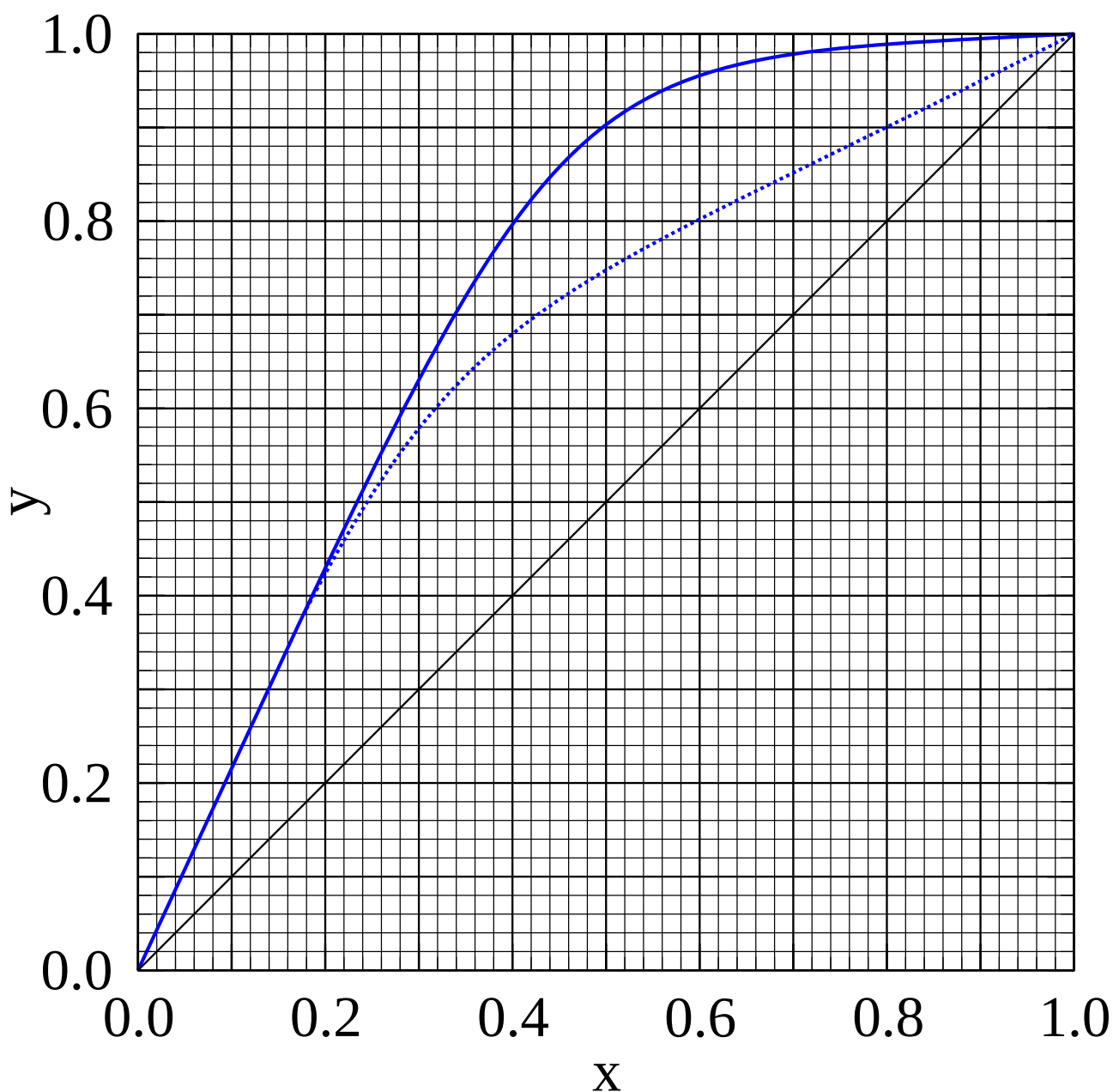
Figure 22: VLE diagram for the lipid mixture. This figure is required for Q. 32.

Question 33

A solvent vapour is to be scrubbed from an air stream before the treated air can be released to the atmosphere. Absorption using clean water in a plate column is recommended. The solvent vapour-air mixture enters the column at a concentration of 2 kmol solvent vapour per 100 kmol solvent-free air. The maximum allowable loss to the atmosphere is 0.1 kmol solvent vapour per 100 kmol solvent-free air. A liquid rate of 1.3 times the minimum is employed, and the Murphree plate efficiency is known to be 50% based on the gas phase. Equilibrium data are represented by $Y = 0.5\,X^2$, where Y and X are the molar ratios of the solvent in the gas and liquid phases respectively.

a) Show graphically the meaning of the Murphree plate efficiency. [5 marks]

b) Determine the number of real plates required. A blank X-Y graph is provided in Fig. 23. [10 marks]

c) Determine the overall column efficiency. [5 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:
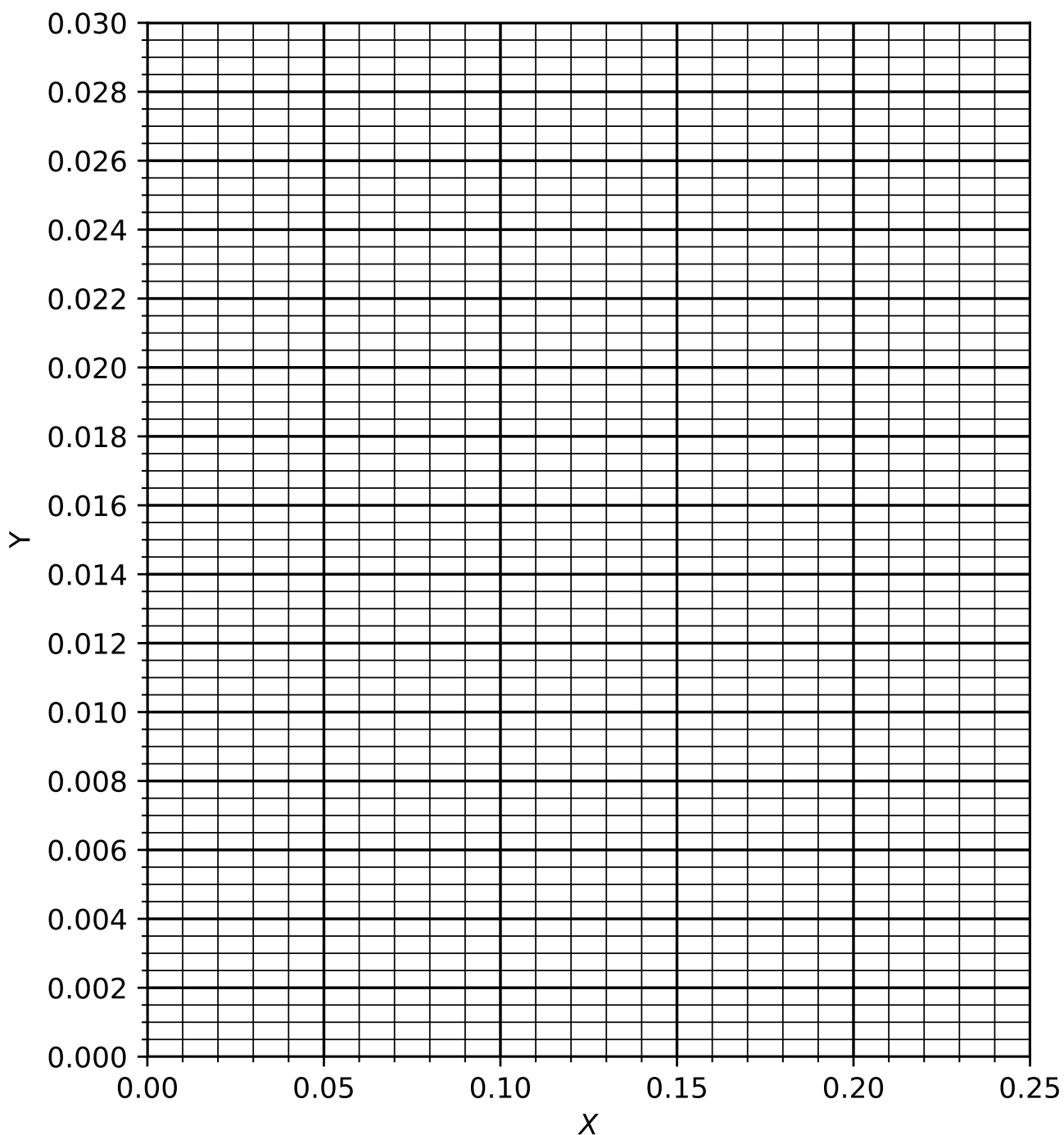
Figure 23: A blank X-Y graph for use in Q. 33.

Question 34

It is desired to absorb 90% of the acetone in a gas containing 1.0 mol% acetone in air in a counter-current stage tower. The total inlet gas flow to the tower is 30.0 kg mol h^{-1}, and the total inlet pure water flow to be used to absorb the acetone is 90 kg mol H_2O h^{-1}. The process is to operate isothermally at 300 K and a total pressure of 101.3 kPa. The equilibrium relation for the acetone (A) in the gas-liquid is $y_A = 2.53\,x_A$. Determine the number of theoretical stages required for this separation using a XY-plot (do not assume the change in flow-rates are negligible). [20 marks]

Question 35

When 10 000 kg of a mixture of heptane (mol. mass 100 g) and n-octane (mol. mass 114 g) is boiled and undergoes batch rectification in a column comprising three theoretical stages (including the still) with a reflux ratio of 1.2, the initial distillate containes 85 mol% n-heptane. **Note:** VLE data is provided in Fig. 24.

a) Determine the initial composition of the liquid in the still.

b) If the process is continued at the same reflux ratio until the still composition has been reduced to half its initial value, calculate the fraction of the initial charge vapourised and the average composition of the distillate collected.

c) If the boil-up rate in the still is constant and equal to 10 kmol h^{-1}, how long will the process take?

d) Why could the above separation not be achieved using a simple Rayleigh distillation?

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:
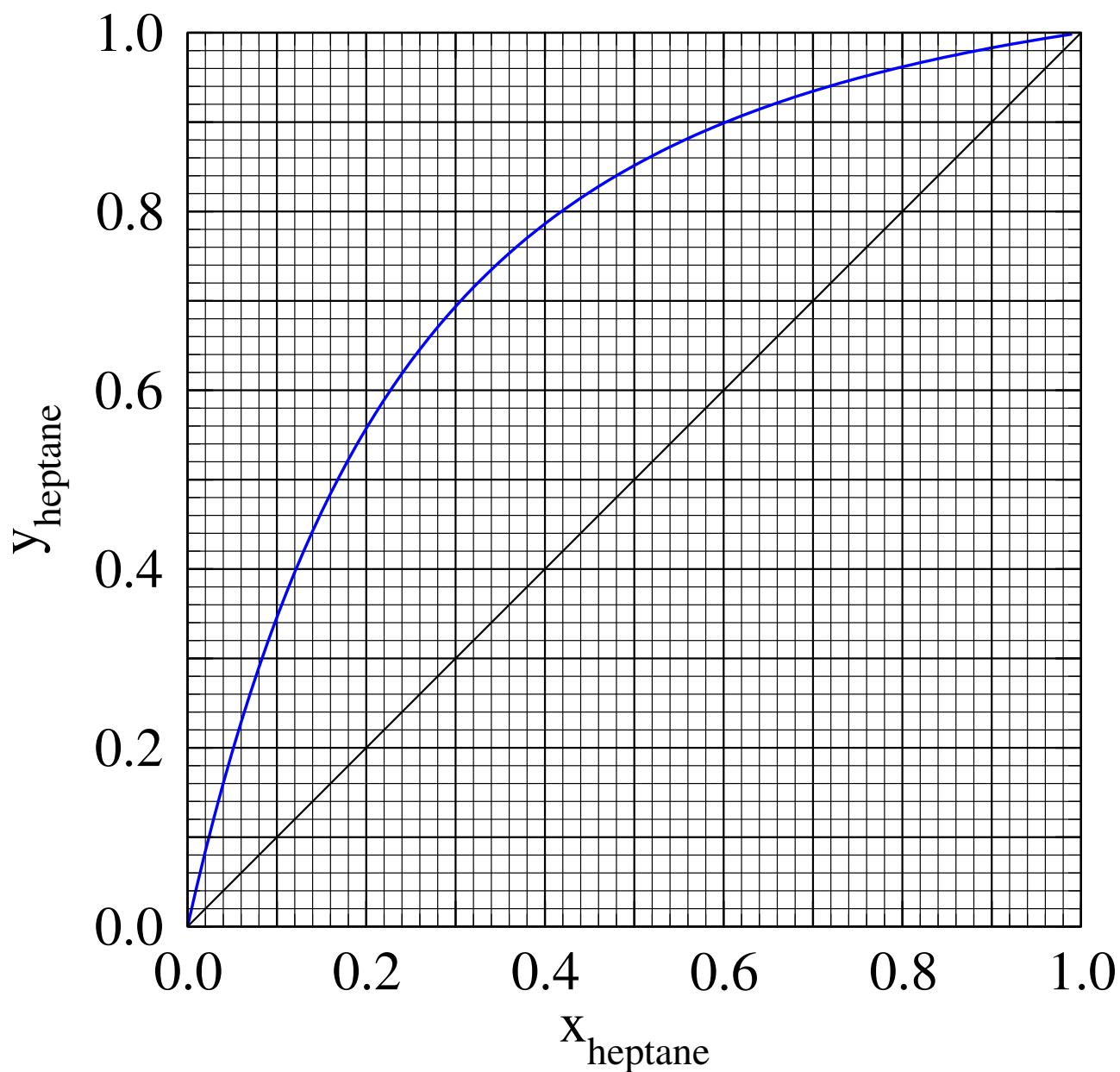
Figure 24: VLE data for the heptane-octane system at 1 atm. For use in Q. 35.

Question 36
In the production of high-purity ethanol, grape alcohol is distilled from a feedstock concentration of 3.3 mol% to 74 mol%. Do not assume constant molar overflow in this case. VLE data are provided in Fig. 19 and enthalpy data are available in Fig. 25. Assuming a multi-stage batch *rectification* column is used, calculate:

a) Demonstrate the mole fractions of 3.3 mol% and 74 mol% ethanol are equivalent to 10% ABV (alcohol by volume) and 90% ABV (you may assume that water and ethanol have constant densities of 998 kg/m^3 and 789 kg m^{-3}).

b) What is the *initial* minimum number of trays required at the feedstock concentration to achieve the required product concentration?   [5 marks]

c) What is the *initial* minimum reflux ratio required to perform this separation?   [5 marks]

d) Assuming an *initial* reflux ratio of $R = 4$, determine the theoretical number of stages required to perform the *initial* separation.   [5 marks]

e) Assuming the reflux ratio is varied to keep the top product concentration constant over the batch distillation, what is the minimum liquid concentration which can be reached in the still?   [5 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:
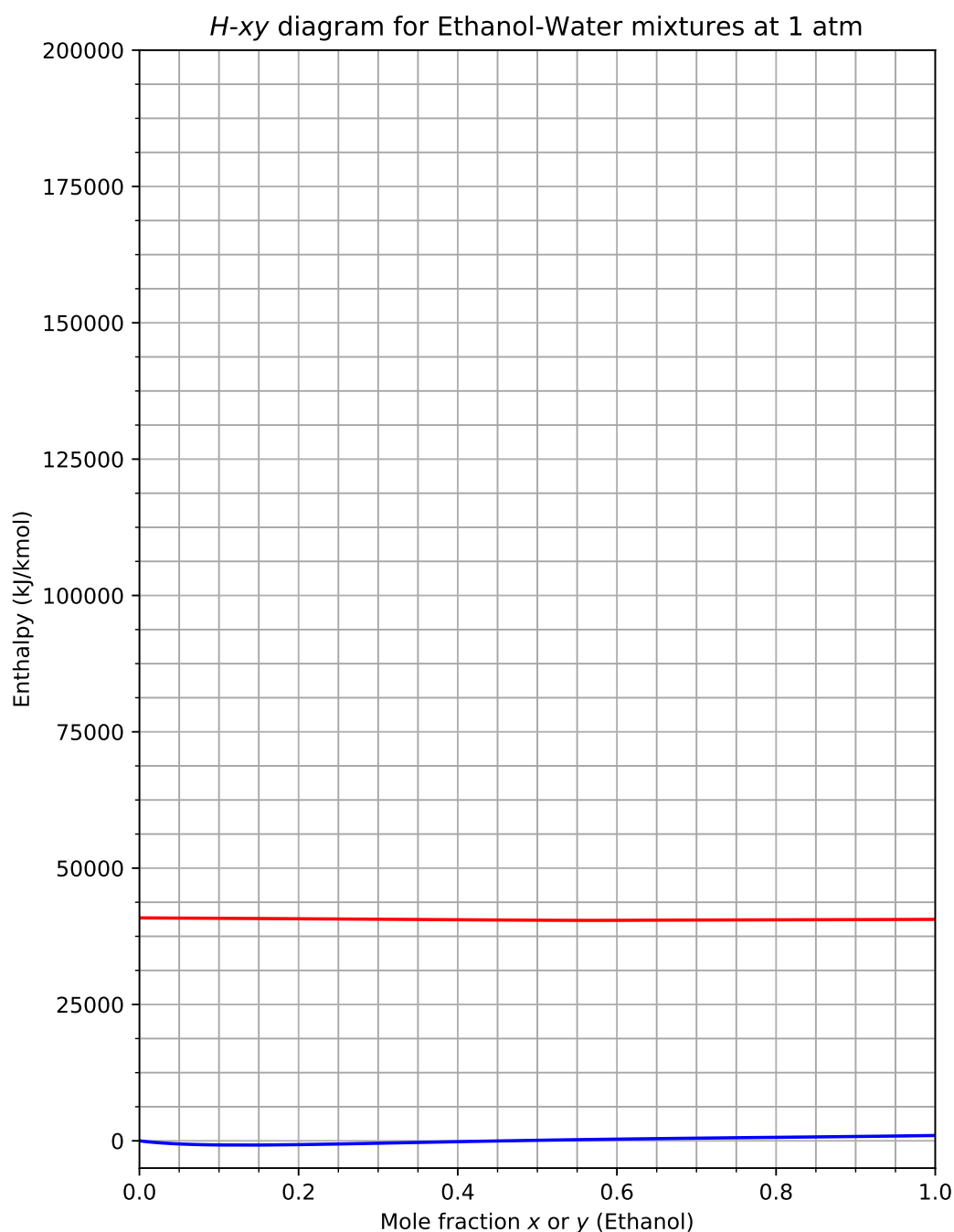
Figure 25: The enthalpy-concentration diagram for a ethanol-water mixture at atmospheric pressure. Data was calculated using the NASA Glenn thermodynamic database, and latent heats of mixing estimated using the equation given in doi:10.1016/0021-9614(75)90261-X (it should be noted that the latent heats of mixing have an almost negligble effect for this system). For use in Q. 36.

Question 37

a) Under what circumstances does the Ponchon-Savarit method provide a better estimate of the number of theoretical stages required for a given distillation application, when compared to the McCabe-Thiele method?   [4 marks]

b) Using overall balances, component balances, and heat balances demonstrate that the condenser pole point (P_c), the reboiler pole point (P_R) and the feed point (P_F) must all lie on the same straight line on the enthalpy-composition diagram.   [6 marks]

Question 38

a) A mixture of n-hexane and n-octane is to be separated by distillation to produce a bottom product containing no more than 3 mol% n-hexane and a top product of at least 95% purity of n-hexane. An enthalpy-composition chart is given in Fig. 26 which you should use and include in your solution booklet.

   a) Determine the minimum number of theoretical stages required to achieve the desired separation.   [6 marks]

   b) Calculate the actual number of theoretical stages required if the reflux ratio is 1.25 and the feed, having a composition of 0.25 mole fraction n-hexane, is supplied as liquid at its boiling point.   [11 marks]

   c) Determine the number of trays in the column if the overall efficiency is 70% and a partial reboiler is used. If you do not have an answer, use an estimate of 9 ideal stages for the previous question.   [3 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:

Figure 26: Enthalpy concentration diagram for hexane-octane mixtures at 760 mmHg. For use in Q. 38.

Question 39

It is required to separate 1 kg s^{-1} of a solution of ammonia in water, containing 30% by mass of ammonia, to give a top product of 99.5% purity and a weak solution containing 10% by mass of ammonia. You may assume that the feed and output streams are liquids at their boiling points. Constant molar overflow does not apply in this system.

T-xy data is available in Fig. 27 and enthalpy-concentration data in Fig. 28.

a) Determine the number of theoretical stages required to perform the separation assuming reflux is 20% in excess of the minimum.   [13 marks]

b) Calculate the heat to be rejected in the condenser.   [4 marks]

c) A partial reboiler and a tray column with a overall overall ideal efficiency of 60% is proposed to be used. Calculate the number of trays needed.   [3 marks]

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.
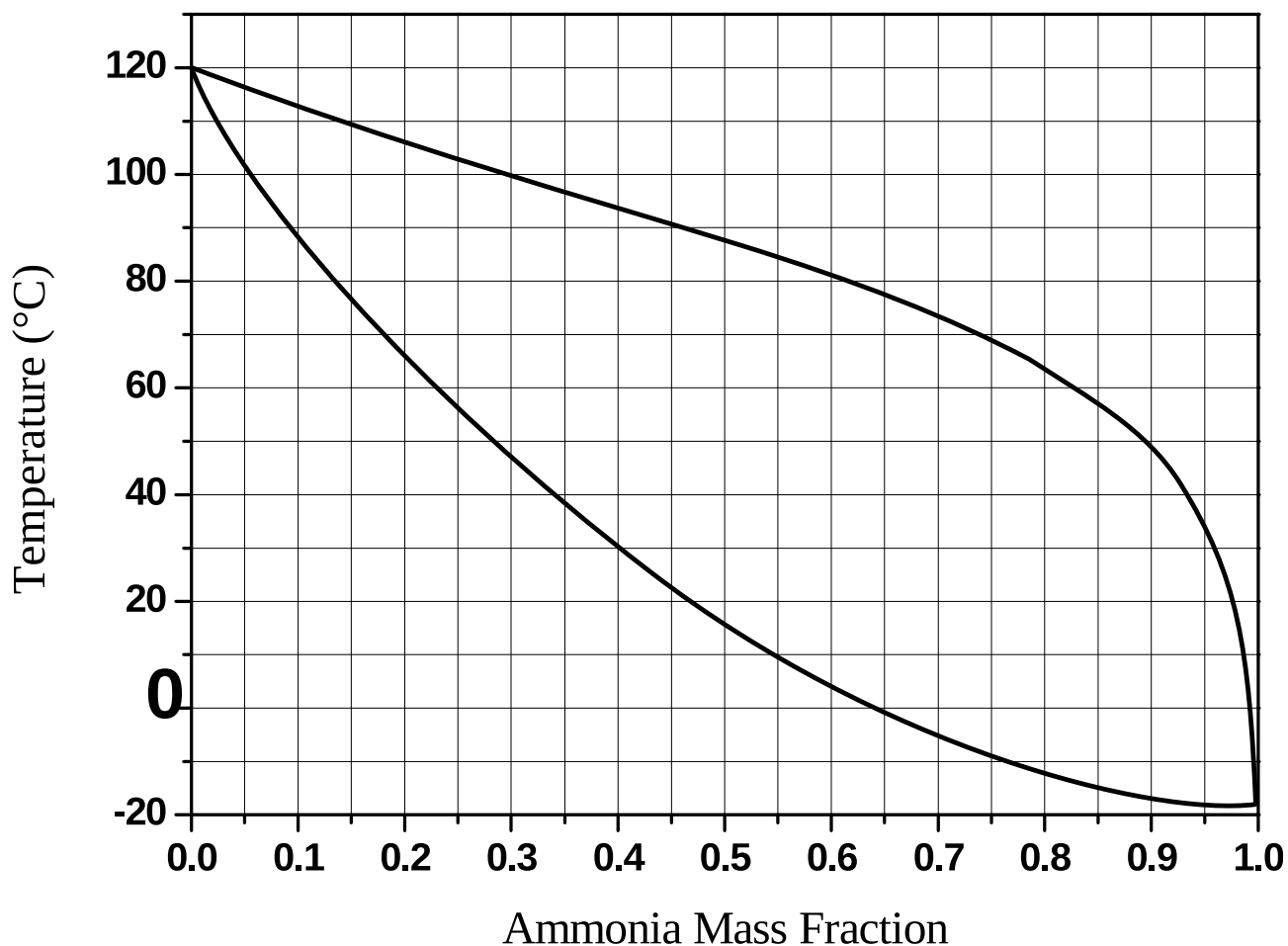
Student ID:

Figure 27: The T-xy diagram for a ammonia-water mixture at atmospheric pressure. For use in Q. 39.

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:

Figure 28: The enthalpy-concentration diagram for a ammonia-water mixture at atmospheric pressure. For use in Q. 39.

Question 40
Using the enthalpy-composition diagram for hexane-octane in Fig. 29, construct a temperature-composition (T-x-y) diagram and a x-y diagram at the same pressure of 760 mmHg. The boiling temperatures of the pure components are 68.5 and 125.8°C.

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:

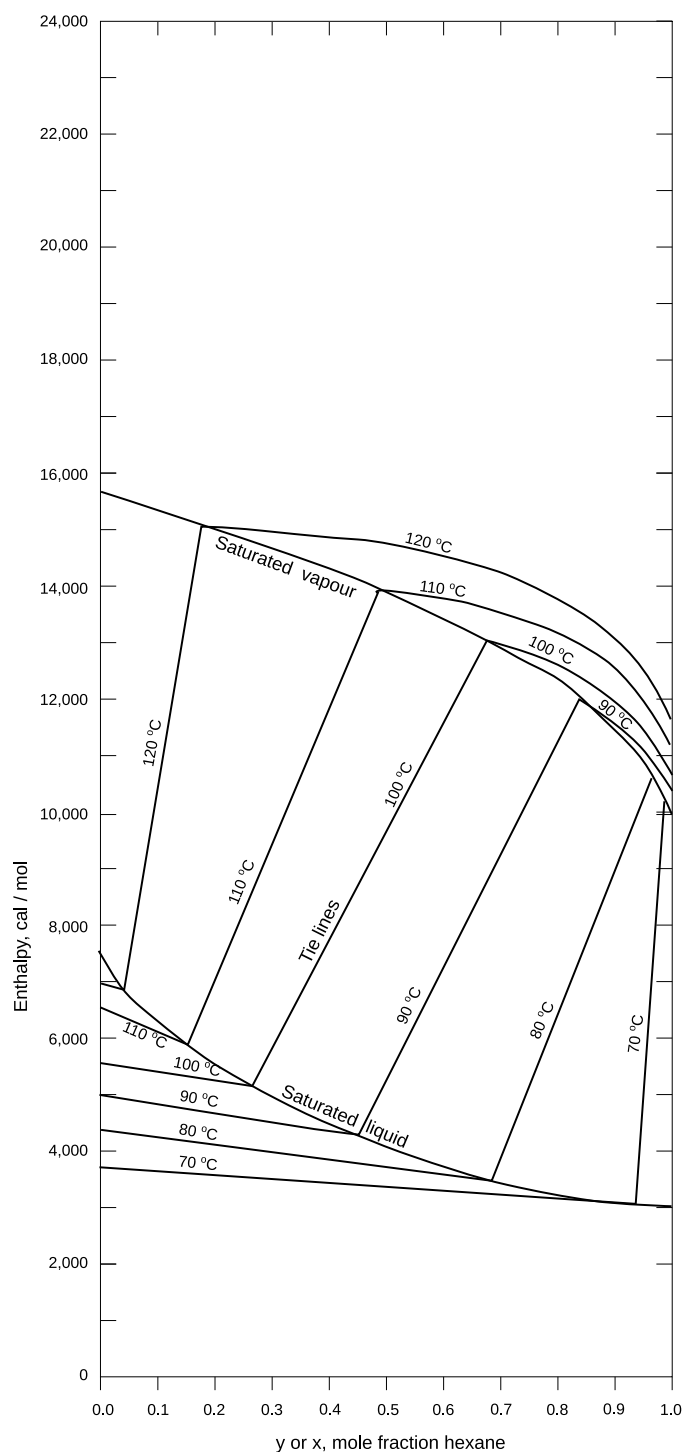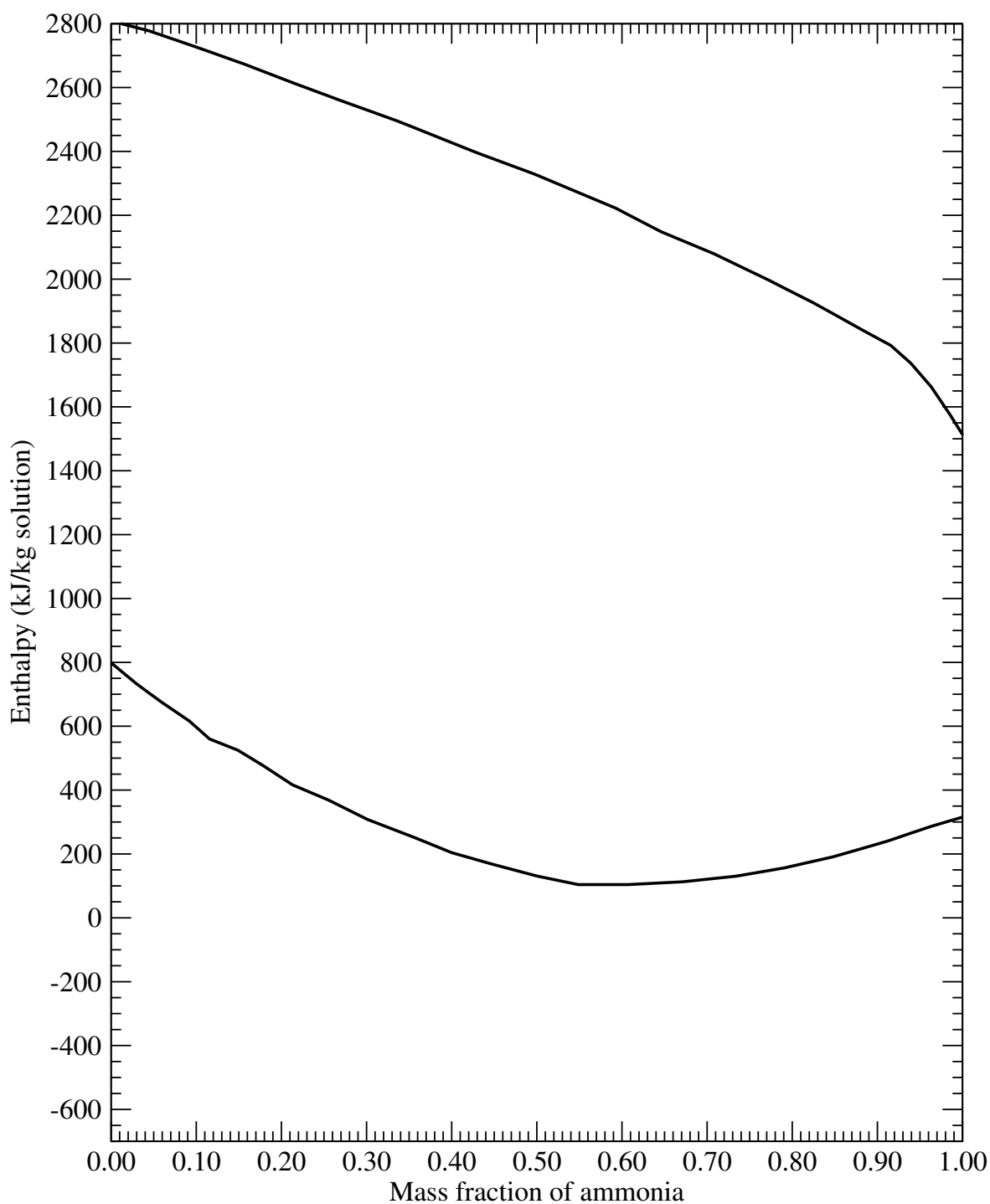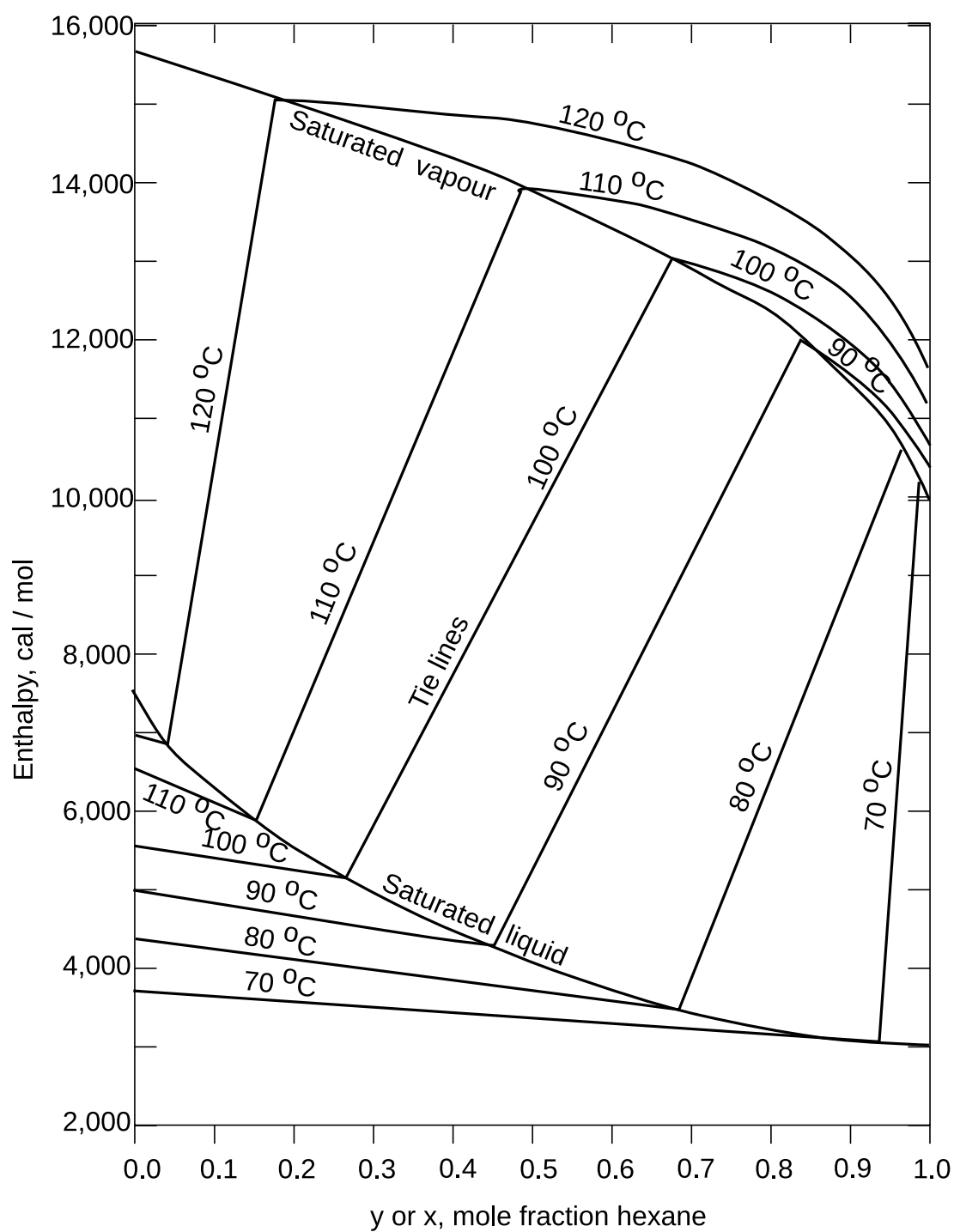Figure 29: Enthalpy concentration diagram for hexane-octane mixtures at 760 mmHg. For use in Q. 40, and 41.

Question 41

An equimolar mixture of hexane and octane is throttled from a moderately high pressure into a flash vessel maintained at a pressure of 760 mmHg. Determine the temperature at which the vessel must be maintained for each of the following degrees of vaporisation (V/F): 0.00, 0.25, 0.50, 0.75, 1.00. You will need the enthalpy-composition diagram for hexane-octane in Fig. **??**.

Question 42

An aqueous solution of acetic acid is to be enriched by simple (differential) distillation. The flask is initially charged with 0.025 kmol of solution of composition 0.600 mol fraction water.

x	0.300	0.350	0.400	0.450	0.500	0.550	0.600
y	0.420	0.483	0.537	0.592	0.638	0.685	0.728

a) Distillation is continued until the composition of the liquid in the flask has fallen to 0.300 mol fraction water. Assuming that the vapour is completely condensed and collected in a cooled reciever, calculate the quantity and composition of the distillate.

b) Repeat the calculation for the case in which distillation is stopped when the composition of the liquid in the still has reached 0.500 mol fraction water.

c) Explain why the separation is so poor, particularly in the case studied in Q. a.

Question 43

Two miscible liquids, A and B, having equal molar heats of vaporisation, are being separated by batch rectification. At a particular point of the distillation, the composition of the vapour leaving the still is 44% A and that of the overhead product being produced at that time is 95% A.

a) If the reflux ratio is set at 3:1, estimate:

   i) The number of equilibrium stages in the column.
   ii) The temperature of the liquid leaving each stage.
   iii) The temperature and composition of the liquir in the still.

T (°C)	138.0	131.5	126.2	121.5	117.2	113.5	110.0	107.0	104.0
x_A	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900
y_A	0.330	0.530	0.660	0.750	0.820	0.875	0.920	0.955	0.980

The boiling temperatures of the pure components are 102.0°C and 145.0°C.

b) Using the equilibrium data and the equation of the operating line, make a stage to stage calculation (non-graphical) of the stream compositions.

Question 44

A mixture of the same two liquids, A & B, as in Q. 43, is to be distilled in a batch rectification column, containing 3 equilibrium stages, to produce a distillate rich in A. When the column is operated with a reflux ratio of 2.5 the initial product composition is 89% A. Distillation continues at a constant reflux ratio until the composition of the liquor in the still has fallen to 10.5% A.

Compare the above with operation at a constant product composition (to produce the same amount of distillate of the same composition). Which is the more economical mode of operation for this separation?

Question 45
Determine the values of "q" and the gradient of the "q-line" for a feed having each of the following states:

a) The molar enthalpies of saturated liquid and saturated vapour are 20 MJ kmol^{-1} and 50 MJ kmol^{-1} respectively; the molar enthalpy of the feed is:

    i) 18 MJ kmol^{-1}.

    ii) 19 MJ kmol^{-1}.

    iii) 20 MJ kmol^{-1}.

    iv) 21 MJ kmol^{-1}.

    v) 30 MJ kmol^{-1}.

    vi) 52 MJ kmol^{-1}.

b) The molar enthalpies of saturated liquid and saturated vapour are 9.0 MJ kmol^{-1} and 48.6 MJ kmol^{-1} respectively. The bubble point and dew point temperatures are 93 °C and 99.3 °C, and the molar heat capacities of the liquid and vapour are 75 KJ kmol^{-1} K^{-1} and 36 KJ kmol^{-1} K^{-1} respectively. The feed has each of the following temperatures:

    i) 80.0 °C.

    ii) 90.0 °C.

    iii) 99.5 °C.

    iv) 120.0 °C.

Question 46
A binary mixture containing 40 mol percent of the more volatile component (mvc) is fed to a continuous distillation column to produce a top product containing 90 mol percent and a bottom product containing 10 mol percent of the mvc. If the operating reflux ratio is 1.5 times the minimum, estimate the number of theoretical stages required when the feed is a saturated vapour. The relative volatility of the mvc is 8.5.

Question 47
A methanol/isopropanol (i.e., propan-2-ol) feed is continuously fractionated in a plate column to produce a top product containing 95 mol% methanol and a bottom product containing 10 mol% methanol. The feed, which has a composition 40 mol% methanol, is introduced as liquid at its bubble point temperature and the column operates with a reflux ratio of 4. A blank xy diagram is available in Fig. 15 and VLE data is available in Table 6. The proposed column design utilises a thermosyphon reboiler, which is a total reboiler (i.e., not an equilibrium stage). What is the overall column efficiency if the Murphree stage efficiencies are 80% in the rectifying section and 60% in the stripping section?   [20 marks]
Note: A blank x-y diagram is available in Fig. 15.

Table 6: VLE data for methanol-isopropanol mixtures. The most volatile compound is methanol.

x_A	0	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
y_A	0	0.085	0.167	0.317	0.45	0.57	0.67	0.75	0.83	0.895	0.955	1.00

Question 48

An equimolar mixture of carbon tetrachloride and toluene is to be fractionated at atmospheric pressure to produce a top product containing 4 mol% toluene and a bottom product containing 4 mol% carbon tetrachloride. The feed is liquid at its bubble point and it may be assumed that the molar enthalpies of the liquid and of the vapour are linear funtions of composition. Enthalpic and VLE data is available in Table 7 & 8 and a blank chart is provided in Fig. 30. Using the Ponchon-Savarit method, calculate:

a) The minimum reflux ratio.   [5 marks]

b) The minimum number of equilibrium stages.   [7 marks]

c) The number of equilibrium stages when the reflux ratio from the condenser is 2.5. [8 marks]

	Boiling Point (°C)	h_l (kJ kmol^{-1})	h_{fg} (kJ kmol^{-1})
CCl$_4$	76.4	5904 at 76.4 °C	15940
toluene	110.4	21250 at 110.4 °C	34430

Table 7: Enthalpic data for carbon tetrachloride (CCl$_4$) and toluene. This is required for Q. 48.

y_{CCl_4}	0.0	0.37	0.62	0.79	0.92	1.0
x_{CCl_4}	0.0	0.20	0.40	0.60	0.80	1.0

Table 8: Vapour-liquid equilibrium for carbon tetrachloride and toluene. This is required for Q. 48.

Data sheet handout. If submitting answers to the question, ensure you submit this graph as part of your solution.

Student ID:
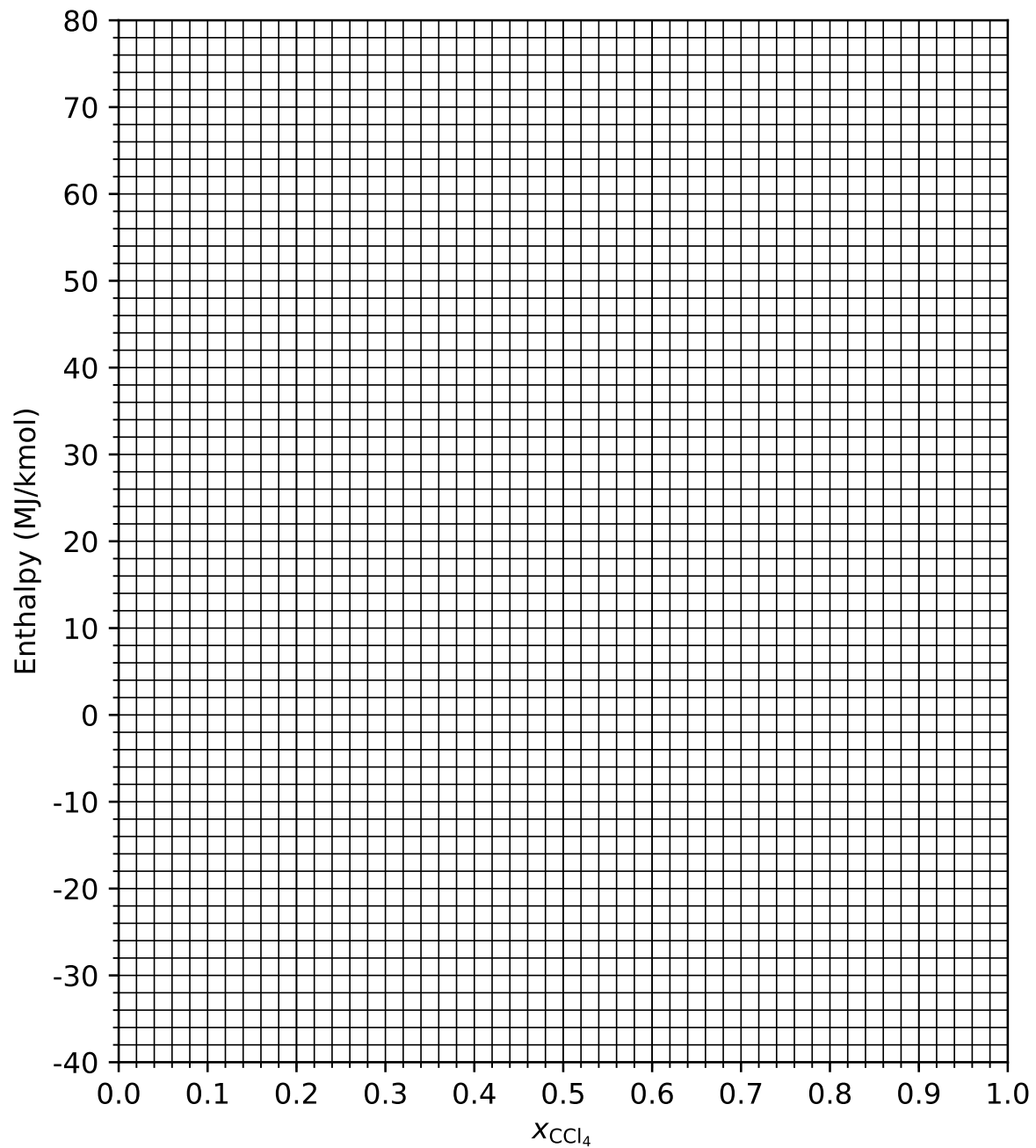
Figure 30: A blank H-x-y diagram for Q. 48

DATASHEET

Conversion from Celsius to Fahrenheit:

$$^\circ F = {}^\circ C \times 1.8 + 32$$

Operating lines:

$$y_n = x_{n+1}\frac{R}{R+1} + \frac{x_D}{R+1} \qquad\qquad \text{Enrichment line} \qquad (2)$$

$$y_m = x_{m+1}\frac{L_m}{V_m} - x_W\frac{W}{V_m} \qquad\qquad \text{Stripping line} \qquad (3)$$

$$y = x\frac{q}{q-1} - \frac{x_F}{q-1} \qquad\qquad q\text{-line} \qquad (4)$$

$$\frac{y_{A,n+1}}{1-y_{A,n+1}} = \frac{L'}{V'}\frac{x_{A,n}}{1-x_{A,n}} + \frac{y_{A,1}}{1-y_{A,1}} - \frac{L'}{V'}\frac{x_{A,0}}{1-x_{A,0}} \qquad \text{Absorption} \qquad (5)$$

Relative volatility

$$y_A = \frac{\alpha\, x_A}{1+(\alpha-1)x_A} \qquad (6)$$

Rayleigh's equation

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = \int_{x_{initial}}^{x_{final}} \frac{\mathrm{d}x}{y-x} \qquad (7)$$

If the relative volatility is constant:

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = (\alpha-1)^{-1}\ln\left(\frac{x_{final}(1-x_{initial})}{x_{initial}(1-x_{final})}\right) + \ln\left(\frac{1-x_{initial}}{1-x_{final}}\right) \qquad (8)$$

Quadratic equation:

$$a\,x^2 + b\,x + c = 0 \qquad\qquad x = \frac{-b \pm \sqrt{b^2 - 4\,a\,c}}{2\,a} \qquad (9)$$

Ponchon-Savarit equations:

$$P_C = (R+1)(h_V(x = x_D) - h_L(x = x_D)) + h_L(x = x_D) \qquad (10)$$

Table 9: Thermodynamic properties of saturated steam by temperature, calculated using the NASA CEA database and the vapour pressure data of Wexler or Wagner and Pruss (1990). The reference state is the triple point of saturated liquid water.

T (°C)	P (bar)	$C_{p,l}$ (kJ kg^{-1} K^{-1})	$C_{p,v}$ (kJ kg^{-1} K^{-1})	h_l (kJ kg^{-1})	h_{lv} (kJ kg^{-1})	h_v (kJ kg^{-1})	s_l (kJ kg^{-1} K^{-1})	s_v (kJ kg^{-1} K^{-1})
0.01	0.00612	4.228	1.859	0.000	2501	2501	0.000	9.155
1	0.00657	4.220	1.859	4.182	2499	2503	0.01528	9.129
2	0.00706	4.213	1.860	8.398	2496	2505	0.03063	9.103
3	0.00758	4.207	1.860	12.61	2494	2506	0.04591	9.077
4	0.00813	4.202	1.860	16.81	2491	2508	0.06111	9.051
5	0.00872	4.198	1.860	21.01	2489	2510	0.07623	9.025
6	0.00935	4.194	1.860	25.21	2487	2512	0.09129	9.000
7	0.0100	4.191	1.860	29.40	2484	2514	0.1063	8.975
8	0.0107	4.189	1.861	33.59	2482	2516	0.1212	8.950
9	0.0115	4.187	1.861	37.78	2480	2518	0.1361	8.925
10	0.0123	4.185	1.861	41.97	2477	2519	0.1509	8.900
12	0.0140	4.183	1.861	50.33	2473	2523	0.1803	8.852
14	0.0160	4.182	1.862	58.70	2468	2527	0.2096	8.805
16	0.0182	4.181	1.862	67.06	2464	2531	0.2386	8.758
18	0.0206	4.181	1.863	75.43	2459	2534	0.2674	8.713
20	0.0234	4.182	1.863	83.79	2454	2538	0.2960	8.668
25	0.0317	4.183	1.864	104.7	2443	2547	0.3668	8.559
30	0.0425	4.183	1.866	125.6	2431	2557	0.4363	8.455
35	0.0563	4.183	1.867	146.5	2420	2566	0.5048	8.356
40	0.0738	4.182	1.868	167.4	2408	2575	0.5721	8.260
45	0.0959	4.181	1.870	188.4	2396	2585	0.6383	8.169
50	0.123	4.181	1.871	209.3	2385	2594	0.7035	8.082
55	0.158	4.181	1.873	230.2	2373	2603	0.7677	7.998
60	0.199	4.183	1.875	251.1	2362	2613	0.8309	7.918
65	0.250	4.185	1.876	272.0	2350	2622	0.8933	7.841
70	0.312	4.188	1.878	292.9	2339	2632	0.9547	7.767
75	0.386	4.191	1.880	313.9	2327	2641	1.015	7.696
80	0.474	4.195	1.882	334.9	2316	2650	1.075	7.628
85	0.578	4.199	1.884	355.9	2304	2660	1.134	7.562
90	0.701	4.203	1.886	376.9	2292	2669	1.192	7.499
95	0.845	4.209	1.888	397.9	2281	2679	1.250	7.439
100	1.01	4.217	1.890	419.0	2269	2688	1.307	7.381
110	1.43	4.224	1.894	461.2	2246	2707	1.418	7.271
120	1.99	4.246	1.899	503.6	2222	2726	1.527	7.169
130	2.70	4.271	1.904	546.3	2199	2745	1.634	7.075
140	3.62	4.294	1.908	589.2	2175	2764	1.739	6.987
150	4.76	4.316	1.913	632.4	2151	2783	1.842	6.906
160	6.18	4.339	1.918	675.8	2127	2802	1.943	6.830
170	7.92	4.366	1.924	719.5	2102	2822	2.043	6.759
180	10.0	4.398	1.929	763.5	2077	2841	2.140	6.693
190	12.6	4.437	1.934	807.9	2052	2860	2.237	6.632
200	15.5	4.485	1.940	852.9	2027	2879	2.332	6.575

Table 10 continued: Thermodynamic properties of saturated steam by temperature.

T (°C)	P (bar)	$C_{p,l}$ (kJ kg^{-1} K^{-1})	$C_{p,v}$ (kJ kg^{-1} K^{-1})	h_l (kJ kg^{-1})	h_{lv} (kJ kg^{-1})	h_v (kJ kg^{-1})	s_l (kJ kg^{-1} K^{-1})	s_v (kJ kg^{-1} K^{-1})
250	39.8	4.861	1.969	1088.	1889	2977	2.799	6.338
300	85.9	5.746	1.999	1354.	1723	3076	3.275	6.163

Table 10: Thermodynamic properties of saturated steam by pressure, calculated using the NASA CEA database and the vapour pressure data of Wexler or Wagner and Pruss (1990). The reference state is the triple point of saturated liquid water.

P (bar)	T (°C)	$C_{p,l}$ (kJ kg^{-1} K^{-1})	$C_{p,v}$ (kJ kg^{-1} K^{-1})	h_l (kJ kg^{-1})	h_{lv} (kJ kg^{-1})	h_v (kJ kg^{-1})	s_l (kJ kg^{-1} K^{-1})	s_v (kJ kg^{-1} K^{-1})
0.01	6.97	4.191	1.860	29.28	2485	2514	0.1059	8.975
0.015	13.0	4.182	1.862	54.61	2470	2525	0.1953	8.828
0.02	17.5	4.181	1.863	73.33	2460	2533	0.2602	8.724
0.025	21.1	4.182	1.863	88.32	2452	2540	0.3115	8.644
0.03	24.1	4.182	1.864	100.9	2445	2546	0.3539	8.579
0.035	26.7	4.183	1.865	111.7	2439	2551	0.3903	8.524
0.04	29.0	4.183	1.865	121.3	2433	2555	0.4221	8.476
0.045	31.0	4.183	1.866	129.9	2429	2559	0.4504	8.435
0.05	32.9	4.183	1.866	137.7	2424	2562	0.4759	8.397
0.055	34.6	4.183	1.867	144.8	2420	2565	0.4992	8.364
0.06	36.2	4.182	1.867	151.4	2417	2568	0.5206	8.333
0.065	37.6	4.182	1.868	157.6	2413	2571	0.5404	8.305
0.07	39.0	4.182	1.868	163.3	2410	2574	0.5588	8.279
0.075	40.3	4.182	1.868	168.7	2407	2576	0.5761	8.255
0.08	41.5	4.181	1.869	173.8	2404	2578	0.5923	8.232
0.085	42.7	4.181	1.869	178.6	2402	2580	0.6076	8.211
0.09	43.8	4.181	1.869	183.2	2399	2582	0.6221	8.191
0.095	44.8	4.181	1.870	187.6	2397	2584	0.6359	8.173
0.12	49.4	4.181	1.871	206.9	2386	2593	0.6961	8.092
0.14	52.6	4.181	1.872	220.0	2379	2599	0.7365	8.039
0.16	55.3	4.181	1.873	231.5	2373	2604	0.7719	7.993
0.18	57.8	4.182	1.874	241.9	2367	2609	0.8034	7.953
0.2	60.1	4.183	1.875	251.4	2362	2613	0.8318	7.917
0.22	62.1	4.184	1.875	260.1	2357	2617	0.8578	7.884
0.24	64.1	4.185	1.876	268.1	2352	2620	0.8817	7.855
0.26	65.9	4.186	1.877	275.6	2348	2624	0.9039	7.828
0.28	67.5	4.187	1.877	282.6	2344	2627	0.9245	7.803
0.3	69.1	4.187	1.878	289.2	2341	2630	0.9439	7.780
0.32	70.6	4.188	1.878	295.5	2337	2633	0.9621	7.758
0.34	72.0	4.189	1.879	301.4	2334	2635	0.9793	7.738
0.36	73.4	4.190	1.879	307.0	2331	2638	0.9956	7.719
0.38	74.6	4.191	1.880	312.4	2328	2640	1.011	7.701
0.4	75.9	4.192	1.880	317.6	2325	2643	1.026	7.684

Table 10 continued: Thermodynamic properties of saturated steam by pressure.

P (bar)	T (°C)	$C_{p,l}$ (kJ kg^{-1} K^{-1})	$C_{p,v}$ (kJ kg^{-1} K^{-1})	h_l (kJ kg^{-1})	h_{lv} (kJ kg^{-1})	h_v (kJ kg^{-1})	s_l (kJ kg^{-1} K^{-1})	s_v (kJ kg^{-1} K^{-1})
0.42	77.1	4.193	1.881	322.5	2322	2645	1.040	7.668
0.44	78.2	4.194	1.881	327.3	2320	2647	1.054	7.652
0.46	79.3	4.195	1.882	331.8	2317	2649	1.066	7.637
0.48	80.3	4.195	1.882	336.2	2315	2651	1.079	7.623
0.5	81.3	4.196	1.882	340.5	2312	2653	1.091	7.610
0.55	83.7	4.198	1.883	350.5	2307	2657	1.119	7.579
0.6	85.9	4.199	1.884	359.9	2302	2662	1.145	7.550
0.65	88.0	4.201	1.885	368.5	2297	2665	1.169	7.524
0.7	90.0	4.203	1.886	376.7	2292	2669	1.192	7.500
0.75	91.8	4.205	1.887	384.4	2288	2673	1.213	7.478
0.8	93.5	4.207	1.887	391.7	2284	2676	1.233	7.457
0.85	95.2	4.209	1.888	398.6	2280	2679	1.252	7.437
0.9	96.7	4.211	1.889	405.1	2277	2682	1.269	7.419
0.95	98.2	4.214	1.889	411.4	2273	2685	1.286	7.401
1	99.6	4.216	1.890	417.5	2270	2687	1.303	7.385
1.1	102.	4.217	1.891	428.8	2264	2692	1.333	7.355
1.2	105.	4.218	1.892	439.3	2258	2697	1.361	7.327
1.3	107.	4.220	1.893	449.0	2253	2702	1.386	7.301
1.4	109.	4.223	1.894	458.3	2247	2706	1.410	7.278
1.5	111.	4.227	1.895	467.0	2243	2710	1.433	7.256
1.6	113.	4.231	1.896	475.2	2238	2713	1.454	7.236
1.7	115.	4.235	1.897	483.0	2234	2717	1.475	7.217
1.8	117.	4.239	1.897	490.5	2230	2720	1.494	7.200
1.9	119.	4.243	1.898	497.7	2226	2723	1.512	7.183
2	120.	4.247	1.899	504.5	2222	2726	1.530	7.167
2.5	127.	4.264	1.902	535.2	2205	2740	1.607	7.098
3	134.	4.279	1.905	561.4	2190	2752	1.672	7.043
3.5	139.	4.292	1.908	584.3	2178	2762	1.727	6.997
4	144.	4.302	1.910	604.8	2166	2771	1.777	6.957
4.5	148.	4.312	1.912	623.3	2156	2779	1.821	6.922
5	152.	4.320	1.914	640.3	2146	2787	1.861	6.891
6	159.	4.337	1.918	670.7	2129	2800	1.932	6.839
7	165.	4.352	1.921	697.4	2114	2812	1.993	6.794
8	170.	4.367	1.924	721.3	2101	2822	2.047	6.757
9	175.	4.382	1.926	743.0	2089	2832	2.095	6.724
10	180.	4.397	1.929	763.0	2078	2841	2.139	6.694
15	198.	4.477	1.939	845.1	2031	2876	2.316	6.584
20	212.	4.557	1.947	909.2	1994	2904	2.449	6.509
25	224.	4.636	1.954	962.9	1963	2926	2.557	6.452
30	234.	4.713	1.959	1010.	1936	2945	2.649	6.406
35	243.	4.789	1.964	1052.	1911	2963	2.730	6.368
40	250.	4.865	1.969	1090.	1888	2978	2.803	6.336
45	257.	4.942	1.973	1125.	1867	2992	2.868	6.308
50	264.	5.022	1.977	1158.	1847	3005	2.929	6.284

Table 10 continued: Thermodynamic properties of saturated steam by pressure.

P (bar)	T (°C)	$C_{p,l}$ (kJ kg^{-1} K^{-1})	$C_{p,v}$ (kJ kg^{-1} K^{-1})	h_l (kJ kg^{-1})	h_{lv} (kJ kg^{-1})	h_v (kJ kg^{-1})	s_l (kJ kg^{-1} K^{-1})	s_v (kJ kg^{-1} K^{-1})
60	276.	5.192	1.984	1218.	1810	3028	3.039	6.242
70	286.	5.384	1.991	1273.	1775	3048	3.136	6.208
80	295.	5.603	1.996	1325.	1742	3066	3.226	6.179
90	303.	5.854	2.001	1373.	1710	3083	3.309	6.153
100	311.	6.140	2.006	1420.	1678	3098	3.388	6.131
120	325.	6.827	2.015	1511.	1615	3126	3.538	6.093