UNIVERSITY OF ABERDEEN SESSION 2013–2014

Degree Examination in EG3502 Separation Processes 1

24th May 2014 9 am – 12 pm

Notes: *(i) Candidates ARE permitted to use an approved calculator.*

(ii) Candidates ARE permitted to use the Engineering Mathematics Handbook.

(iii) Candidates ARE permitted to use steam tables, which will be provided.

(iv) Data sheets are attached to the paper.

PLEASE NOTE THE FOLLOWING

(i) You **must not** have in your possession any material other than that expressly permitted in the rules appropriate to this examination. Where this is permitted, such material **must not** be amended, annotated or modified in any way.

(ii) You **must not** have in your possession any material that could be determined as giving you an advantage in the examination.

(iii) You **must not** attempt to communicate with any candidate during the exam, either orally or by passing written material, or by showing material to another candidate, nor must you attempt to view another candidate's work.

Failure to comply with the above will be regarded as cheating and may lead to disciplinary action as indicated in the Academic Quality Handbook

(`www.abdn.ac.uk/registry/quality/appendix7x1.pdf`) **Section 4.14 and 5.**

Candidates must attempt *all* questions from PART A AND *two* questions from *three* in PART B.

PART A: Answer ALL Questions

Question 1

A liquid mixture of 80 mole% n-Hexane and 20 mole% Benzene enters a long and narrow pipeline at 3 bara and 100 mol/s and quickly reaches the ambient conditions of 50°C. Antoine data are available for both components in Table 1.

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

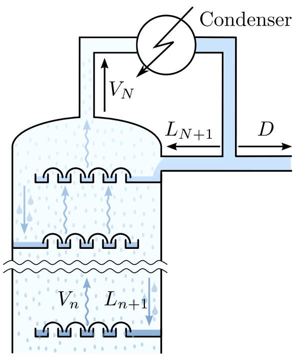
Question 2

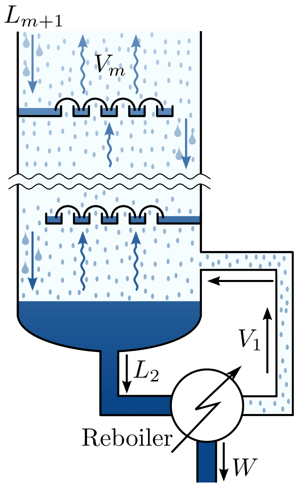
a) Describe the q parameter in distillation and identify the state of the feed for the following q-values, $q =< 0$, 0, 0.5, 1, and > 1. [7 marks]

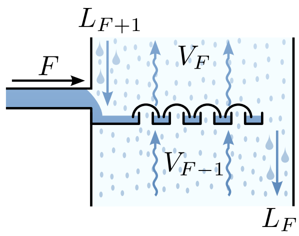
b) Derive the following equation describing the q-line.

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

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

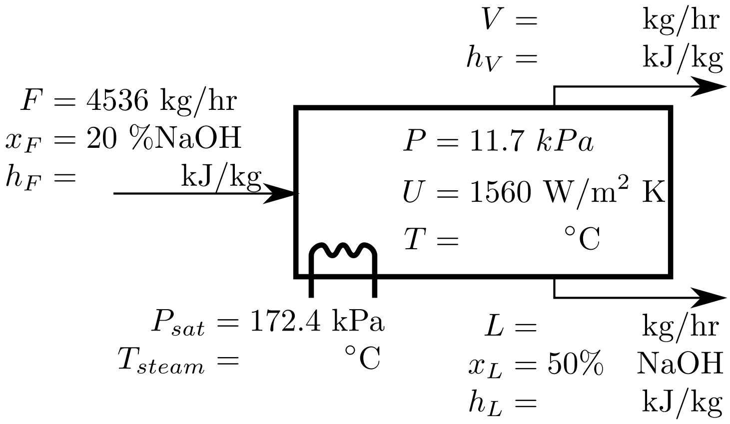






Question 3

An evaporator is used to concentrate 4536 kg/hr 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.



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. 1. [4 marks]

d) Determine the duty of the evaporator. You may neglect the sensible-heat change of the feed stream but you must clearly state any other approximations you make. An enthalpy-concentration diagram for aqueous NaOH mixtures is available in Fig. 2. [8 marks]

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

PART B: Answer TWO Questions From THREE

Question 4

An undergraduate is investigating the distillation of a 40 mole% isopropanol and 60 mole% 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. 3, calculate the final concentration in the batch still and average vapour concentration if 50 mole% of the mixture is evaporated. [8 marks]

c) Consider the integrated VLE data in Fig. 3, 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]

Question 5

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]

c) 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. Using the enthalpy-composition chart (see Fig. 4), determine:

   i) the minimum number of theoretical stages required to achieve the desired separation. [5 marks]

   ii) the actual number of theoretical stages required if the reflux ratio to the top plate is 1.25 and the feed, having a composition of 0.25 mole fraction n-hexane, is supplied as liquid at its boiling point. [5 marks]

Note: If you draw on the H-x-y graph provided (Fig. 4), remember to include it in your exam booklet for marking.

Question 6

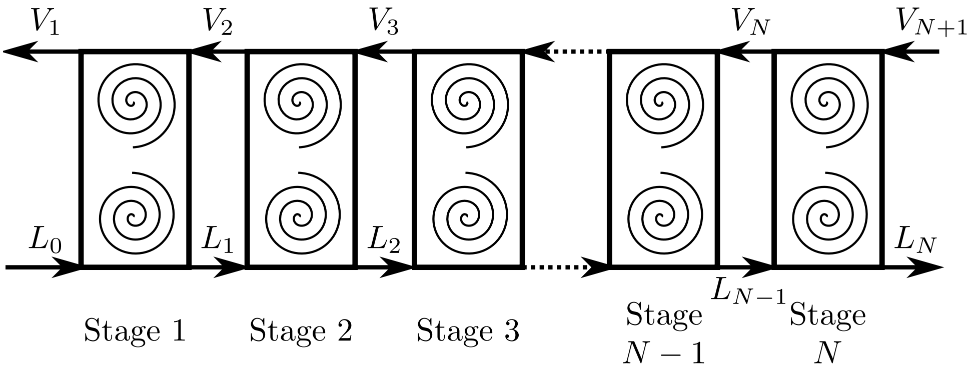


Figure: The stream numbering within a multi-stage absorber

A 30 kmol/hr gas stream produced from coal contains a light oil vapour (2 mole%) 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/hr non-volatile heavy oil absorbent.

The heavy oil absorbent initially contains 0.005 mole% 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. 5 and the HETP is 1.4 m/stage. Determine the height of packing required to carry out the specified absorption in a counter-current column. [20 marks]

Note: If you draw on the VLE graph provided (Fig. 5), remember to include it in your exam booklet for marking.

END OF PAPER

DATASHEET

Conversion from Celsius to Fahrenheit:

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

Operating lines:

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

$$y_m = x_{m+1}\frac{L_m}{V_m} - x_W\frac{W}{V_m} \qquad \text{Stripping line} \qquad (2)$$

$$y = x\frac{q}{q-1} - \frac{x_F}{q-1} \qquad q\text{-line} \qquad (3)$$

$$\frac{y_{A,n+1}}{1-y_{A,n+1}} = \frac{L'}{V'}\frac{x_{A,n}}{1-x_{A,n}} + \frac{y_{A,1}}{1-y_{A,1}} - \frac{L'}{V'}\frac{x_{A,0}}{1-x_{A,0}} \qquad \text{Absorption} \qquad (4)$$

Relative volatility

$$y_A = \frac{\alpha\, x_A}{1+(\alpha-1)x_A} \qquad (5)$$

Rayleigh's equation

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = \int_{x_{initial}}^{x_{final}} \frac{\mathrm{d}x}{y-x} \qquad (6)$$

If the relative volatility is constant:

$$\ln\left(\frac{L_{final}}{L_{initial}}\right) = (\alpha-1)^{-1}\ln\left(\frac{x_{final}(1-x_{initial})}{x_{initial}(1-x_{final})}\right) + \ln\left(\frac{1-x_{initial}}{1-x_{final}}\right) \qquad (7)$$

Quadratic equation:

$$a\,x^2 + b\,x + c = 0 \qquad x = \frac{-b \pm \sqrt{b^2 - 4\,a\,c}}{2\,a} \qquad (8)$$

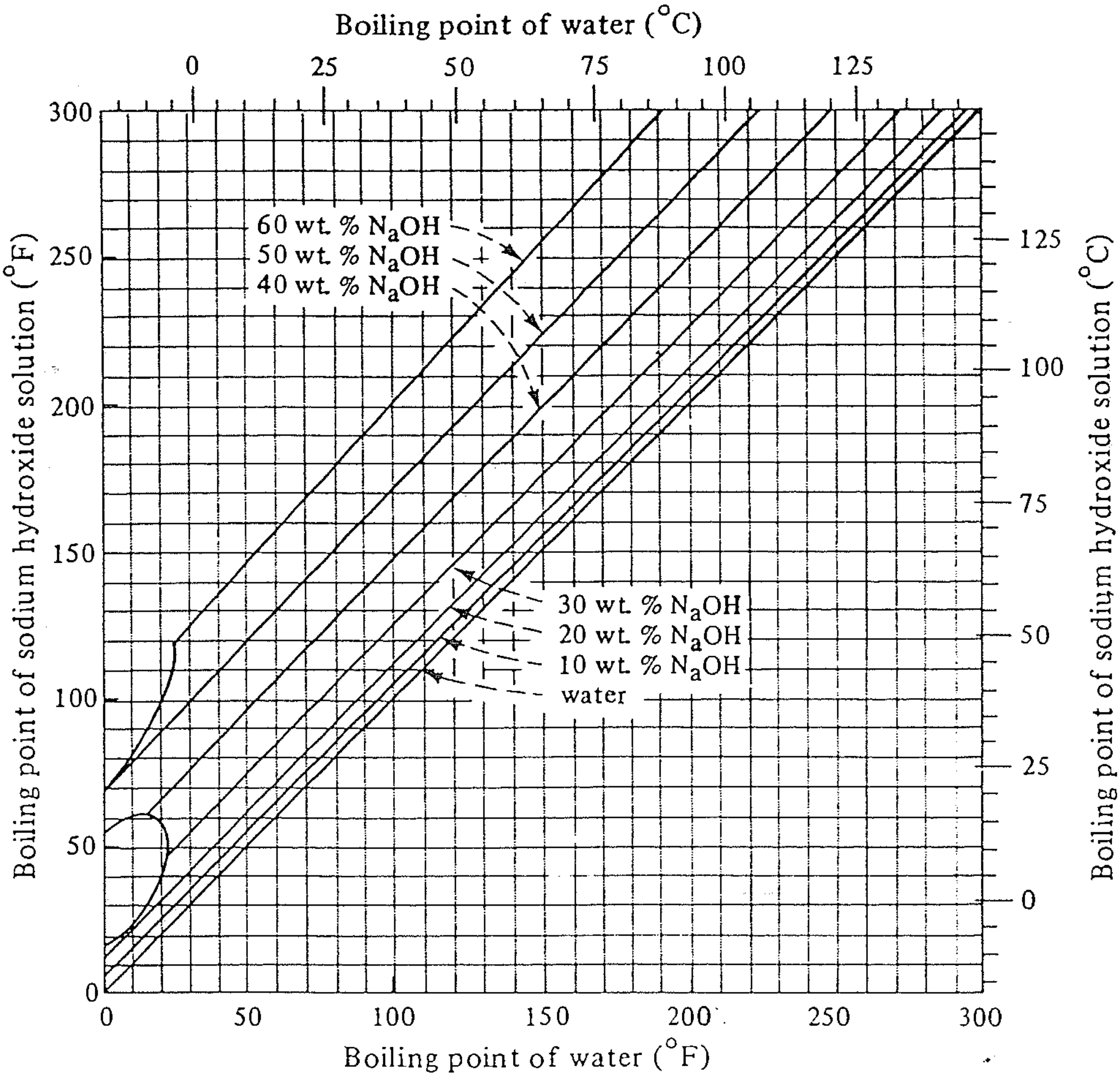


Figure 1: Dühring chart for NaOH-water solutions. This figure is needed for Q. 3.

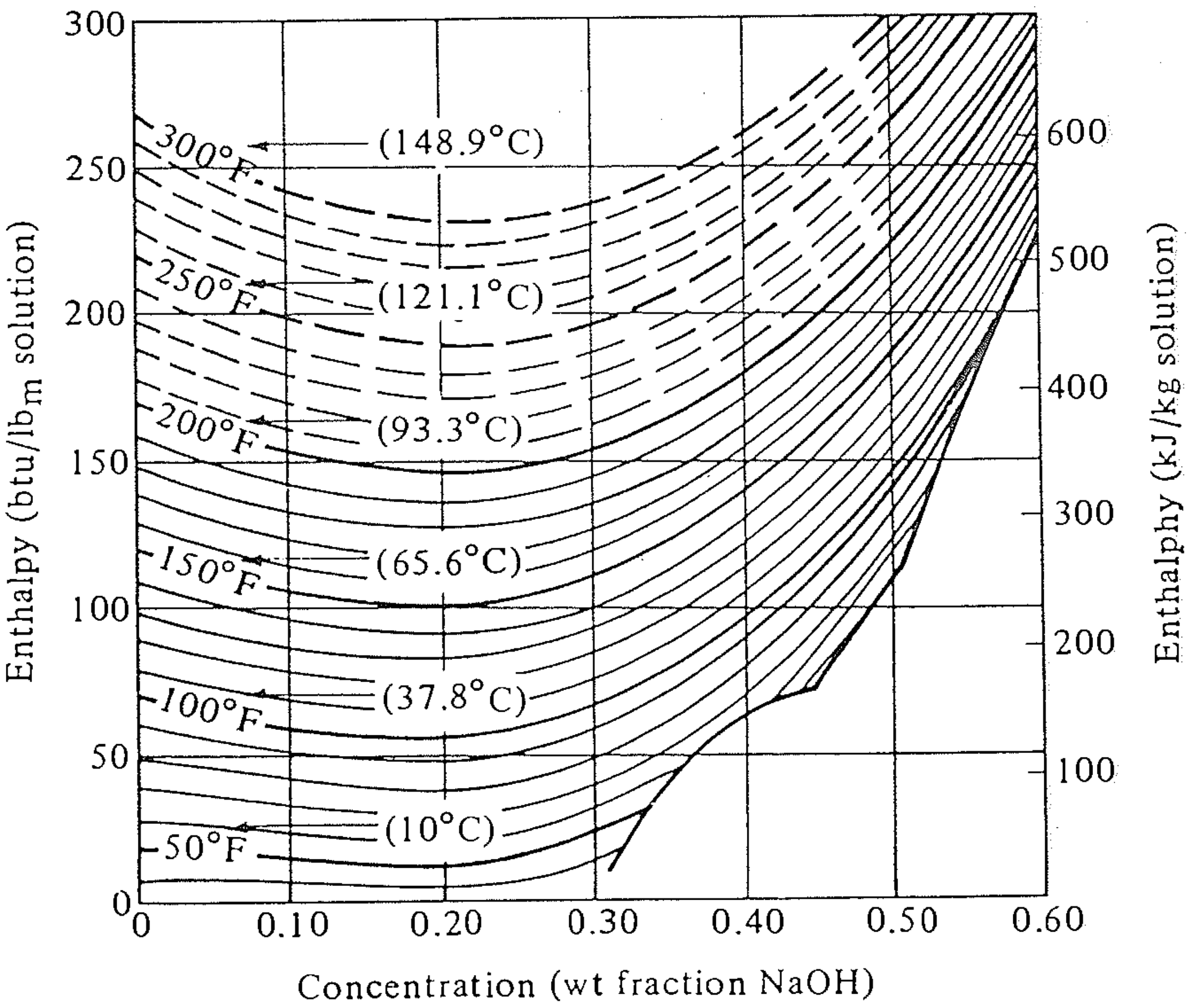


Figure 2: Enthalpy chart for NaOH-water solutions. The zero-enthalpy reference is liquid water at 0°C. This figure is needed for Q. 3.

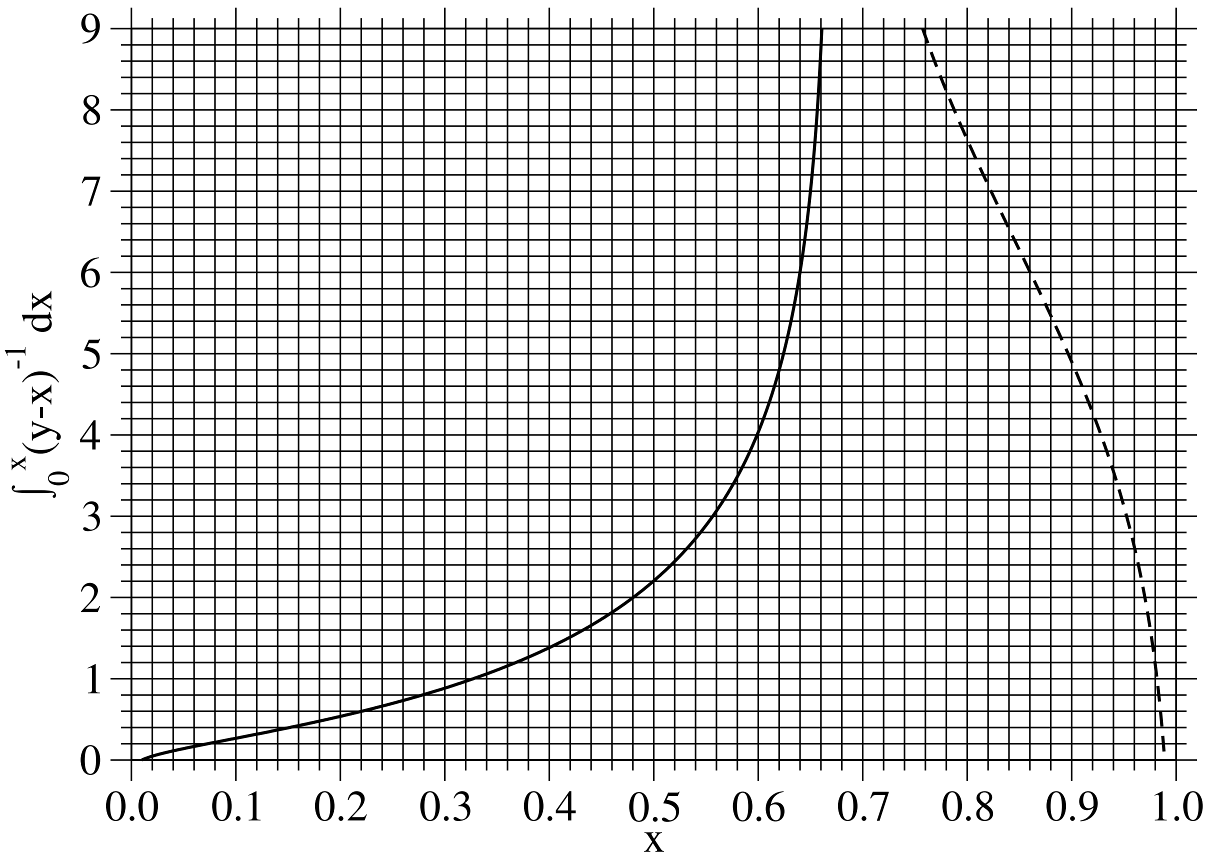


Figure 3: Integrated VLE data for the Isopropanol-water system in Q. 4. **Note:** The solid and dashed curves are distinct and no single-stage equilibrium process connects them.

If you use this graph, you must attach it to your exam booklet using the provided tag.
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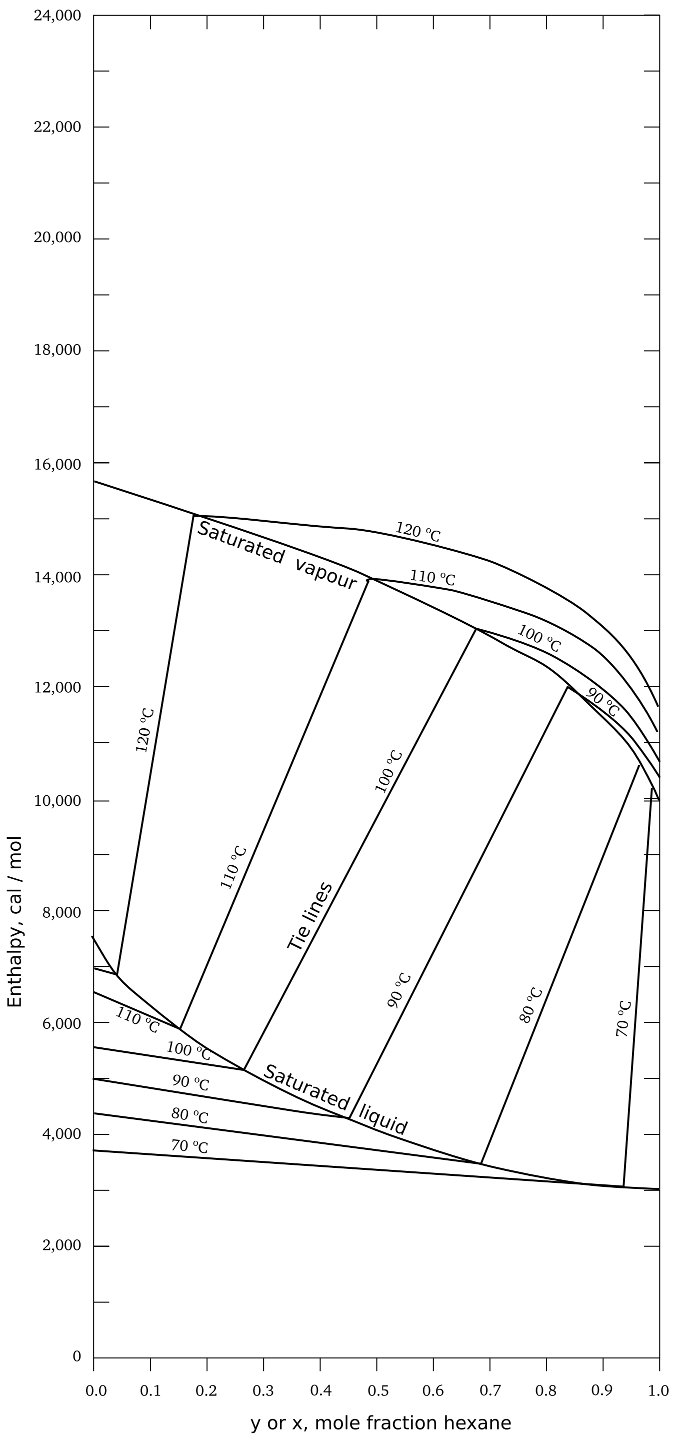

Figure 4: A H-xy graph for n-Hexane/n-Octane mixtures, including VLE tie-lines, used for Q. 5.

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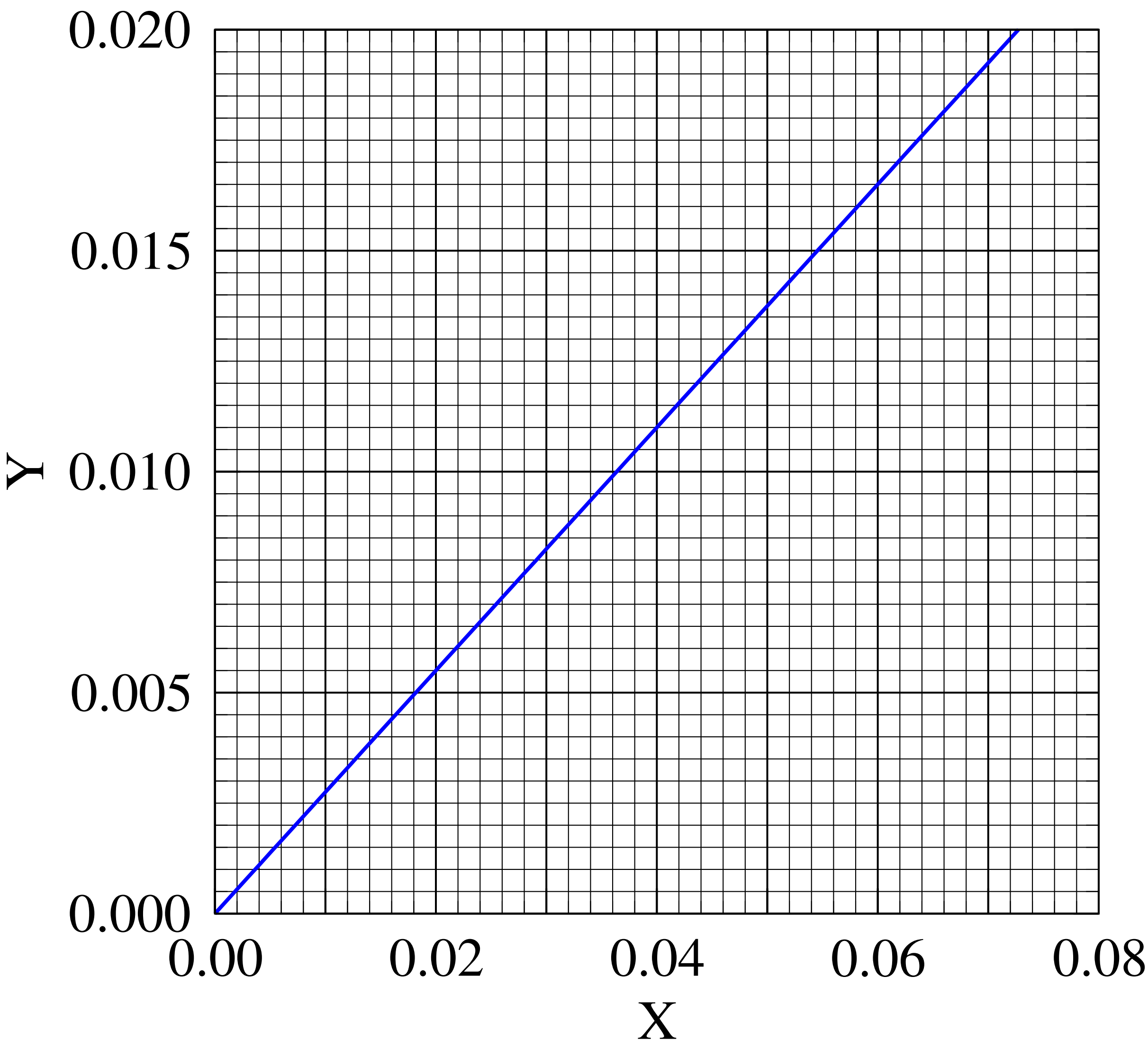

Figure 5: A X-Y graph for the coal gas scrubber in Q. 6.