

UNIVERSITY OF ABERDEEN

SESSION 2017–18

EX3502

Degree Examination in EX3502 Separation Processes 1

10th May 2018

2 pm – 5 pm

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.
- (iv) You **must not** take to your examination desk any electronic devices such as mobile phones or other "smart" devices. The only exception to this rule is an approved calculator.

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

- Notes:**
- (i) Candidates ARE permitted to use an approved calculator.*
 - (ii) Candidates ARE NOT permitted to use the Engineering Mathematics Handbook.*
 - (iii) Candidates ARE NOT permitted to use GREEN or RED pen in their exam booklet.*
 - (iv) Data sheets are attached to the paper.*

**Candidates must attempt ALL questions.
Each question is worth 20 marks.**

Question 1

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 bara. 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. 1 (see back of exam). **[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 (at the back of the exam). 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 bara, calculate the steam economy of the evaporator. **[3 marks]**
- f) Calculate the heat transfer area required if the overall heat transfer coefficient is $U = 1600 \text{ W m}^{-2} \text{ K}^{-1}$. **[2 marks]**

[Question total: 20marks]

Question 2

- 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 when and how these conditions are compatible with the use of Henry's law. **[4 marks]**
- c) A gas mixture of air and SO₂ comes into contact with pure water at 293 K and 4 bara in a single stage equilibrium mixer. The partial pressure of SO₂ in the inlet gas is 0.1 bara 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 the Henry's constant $\mathcal{H}_{\text{SO}_2} = 29.98$ bara at 293 K. **[8 marks]**

[Question total: 20marks]

Question 3

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 1 at the end of this question.

- 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)	C (°C)	T_{min} (°C)	T_{max} (°C)
<i>n</i> -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 bara.

[Question total: 20marks]

Question 4

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. 2 (see the back of the exam).

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

[Question total: 20marks]

Question 5

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.

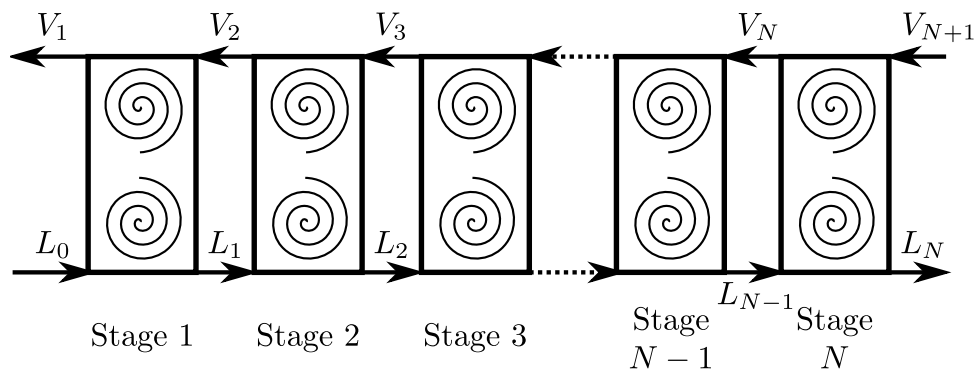


Figure: The stream numbering within a multi-stage absorber

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. 3 (see the back of the exam) 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]**

[Question total: 20marks]

END OF PAPER

DATASHEET

Conversion from Celsius to Fahrenheit:

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

Operating lines:

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

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

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

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

Relative volatility

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

Rayleigh's equation

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

If the relative volatility is constant:

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

Quadratic equation:

$$ax^2 + bx + c = 0 \quad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (8)$$

Ponchon-Savarit equations:

$$P_C = (R+1)(h_V(x=x_D) - h_L(x=x_D)) + h_L(x=x_D) \quad (9)$$

Table 2: 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

Table 3 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)
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
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 3: 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

Table 3 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)
0.28	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
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

Table 3 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)
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
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

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

Student ID:

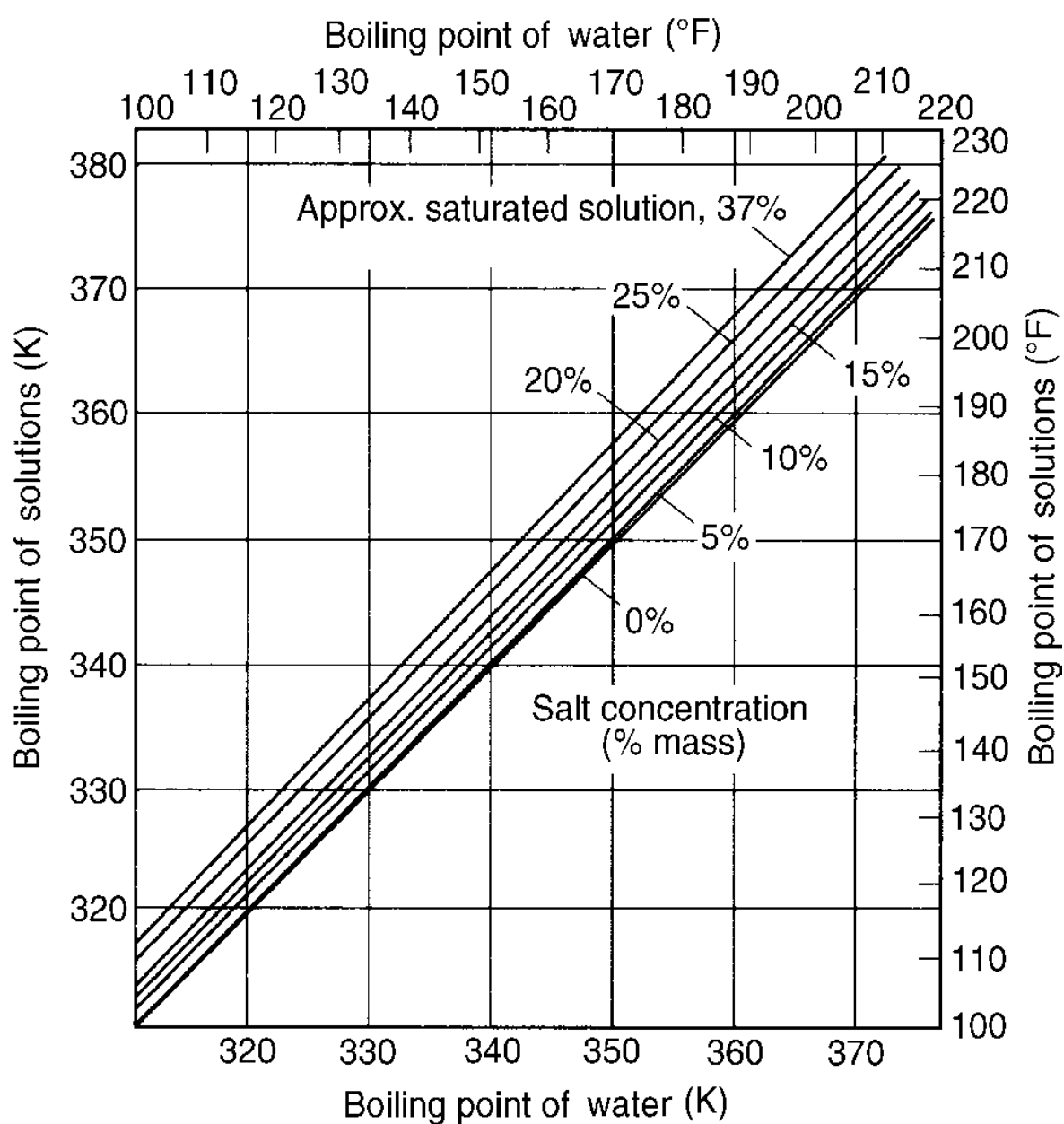


Figure 1: Boiling points for NaCl solutions, taken from Fig. 14.1, pg. 772 C&R Vol. 2. For use in Q. 1.

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

Student ID:

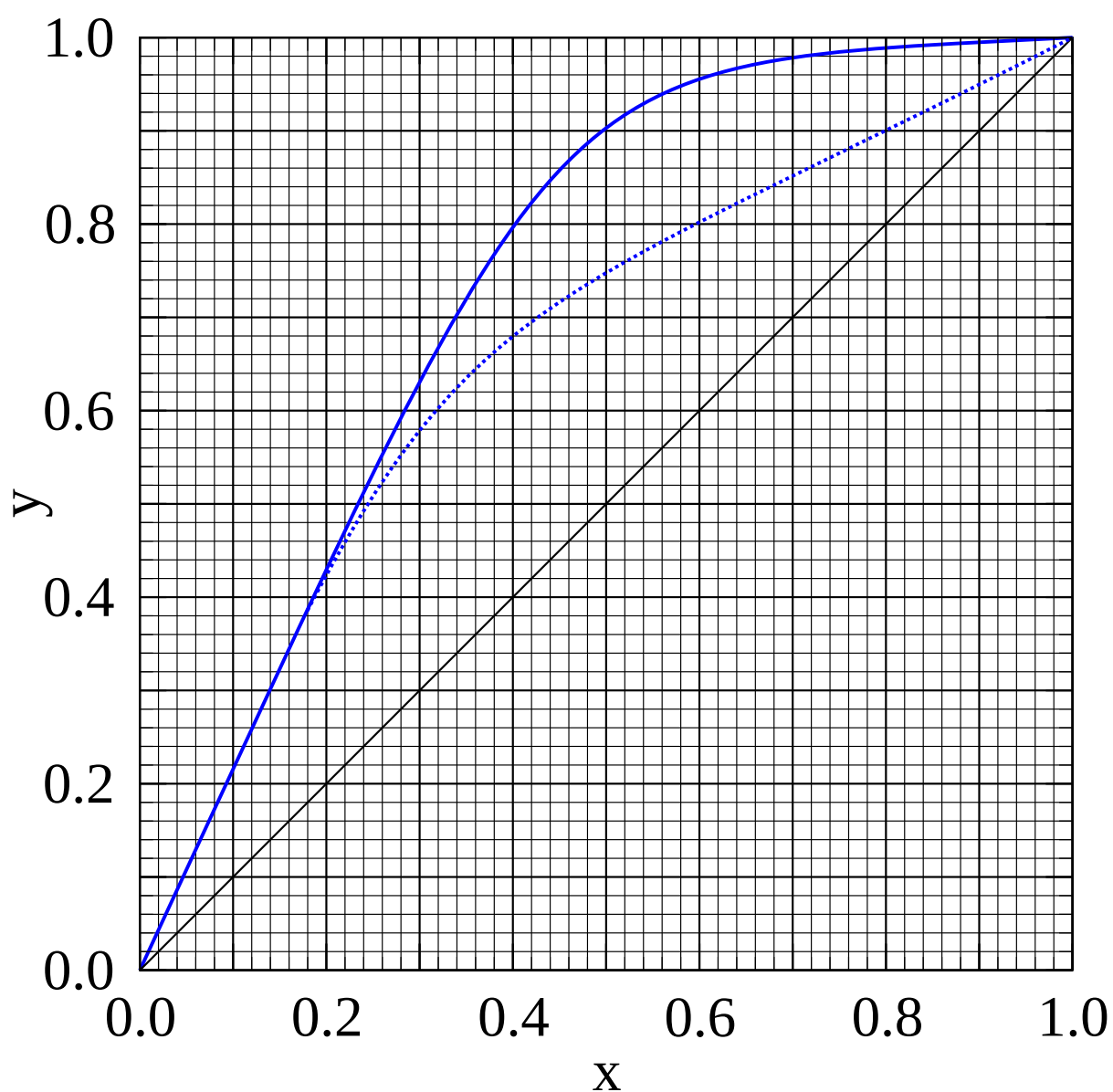


Figure 2: VLE diagram for the lipid mixture. This figure is required for Q. 4.

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

Student ID:

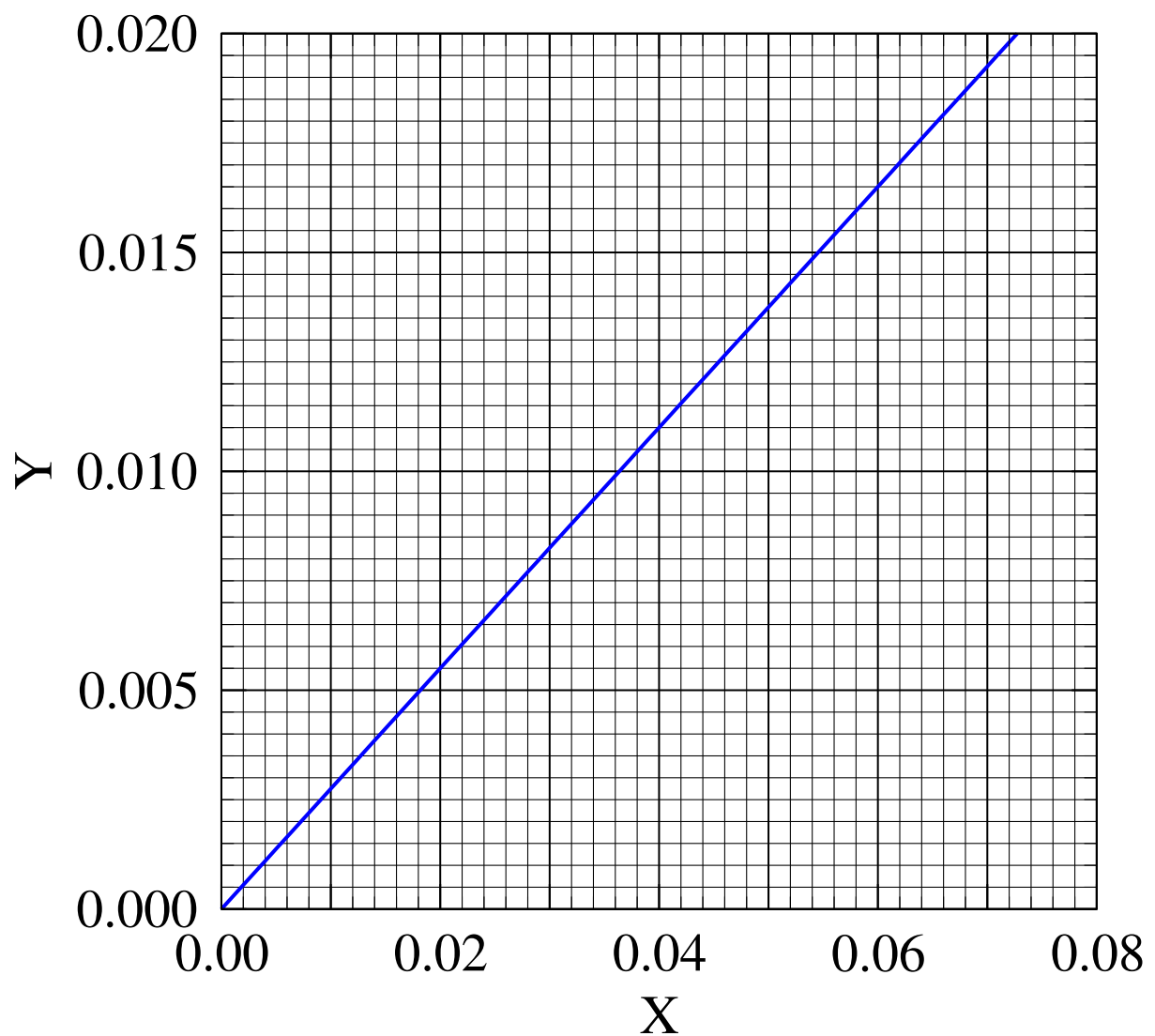


Figure 3: A X-Y graph for the coal gas scrubber in Q. 5.