UNIVERSITY OF ABERDEEN   **SESSION 2016–17**

EX3502

Degree Examination in EX3502 Separation Processes 1

8th May 2017   **9 am – 12 am**

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

Answer all parts of this question.

a) 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.

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

  i) Determine the compositions of the liquid and vapour given that the relative volatility of the system $\alpha \approx 2.5$. **[8 marks]**

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

Question 2

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, with a mole fraction of CO_2 of 0.20. The liquid flow rate entering is 300 kg mol water/h. 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 3

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 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).
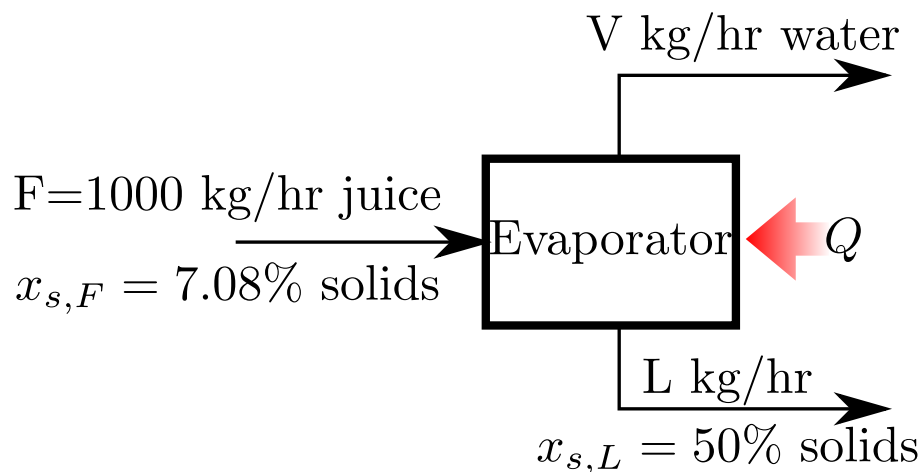

Figure 1: Orange juice concentrator.

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. **[3 marks]**

e) How much steam is required to operate this evaporator? **[2 marks]**

Question 4

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. 3 and VLE data is available in Table 1. 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]**

Table 1: 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

Note: A blank x-y diagram is available in Fig. 3.

Question 5

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). In your workings, use the stream numbering scheme outlined in Fig. 2.
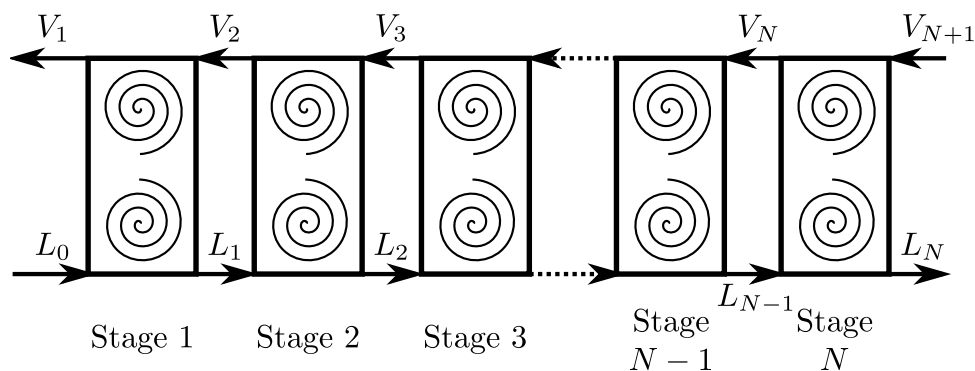
Figure 2: The stream numbering within a multi-stage absorber

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 2, determine the number of equilibrium stages required to perform the absorption. Plot your graph in x-y coordinates on Fig. 4 and ensure that you adequately capture the curvature of the operating line. **[12 marks]**

Table 2: 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

END OF PAPER

DATASHEET

Conversion from Celsius to Fahrenheit:

$$°F = °C \times 1.8 + 32$$

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:

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

Ponchon-Savarit equations:

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

Table 3: 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 4 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 4: 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 4 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 4 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.
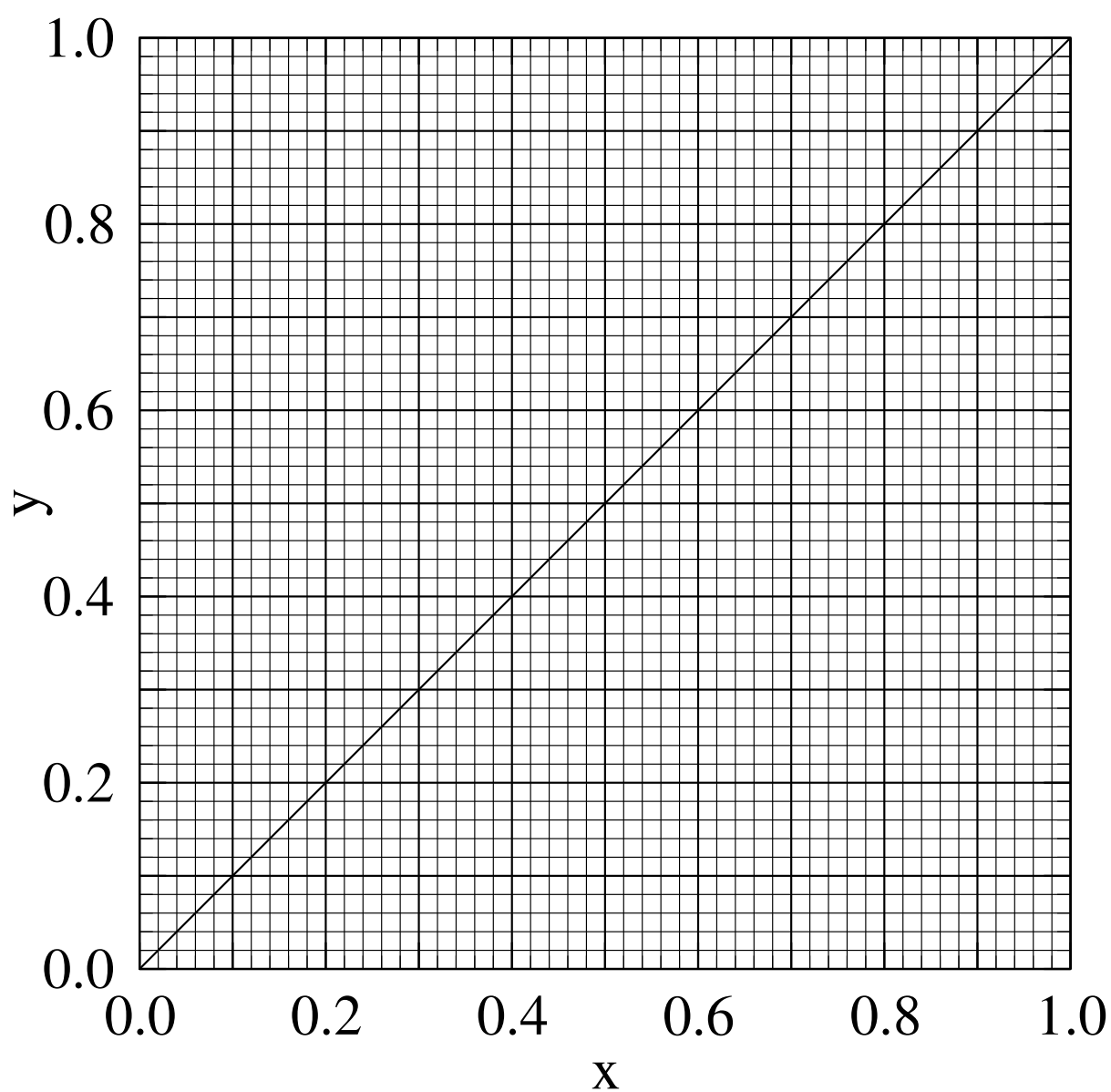
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Figure 3: A blank chart for plotting VLE/operating-line data on. For use in Q. 4.

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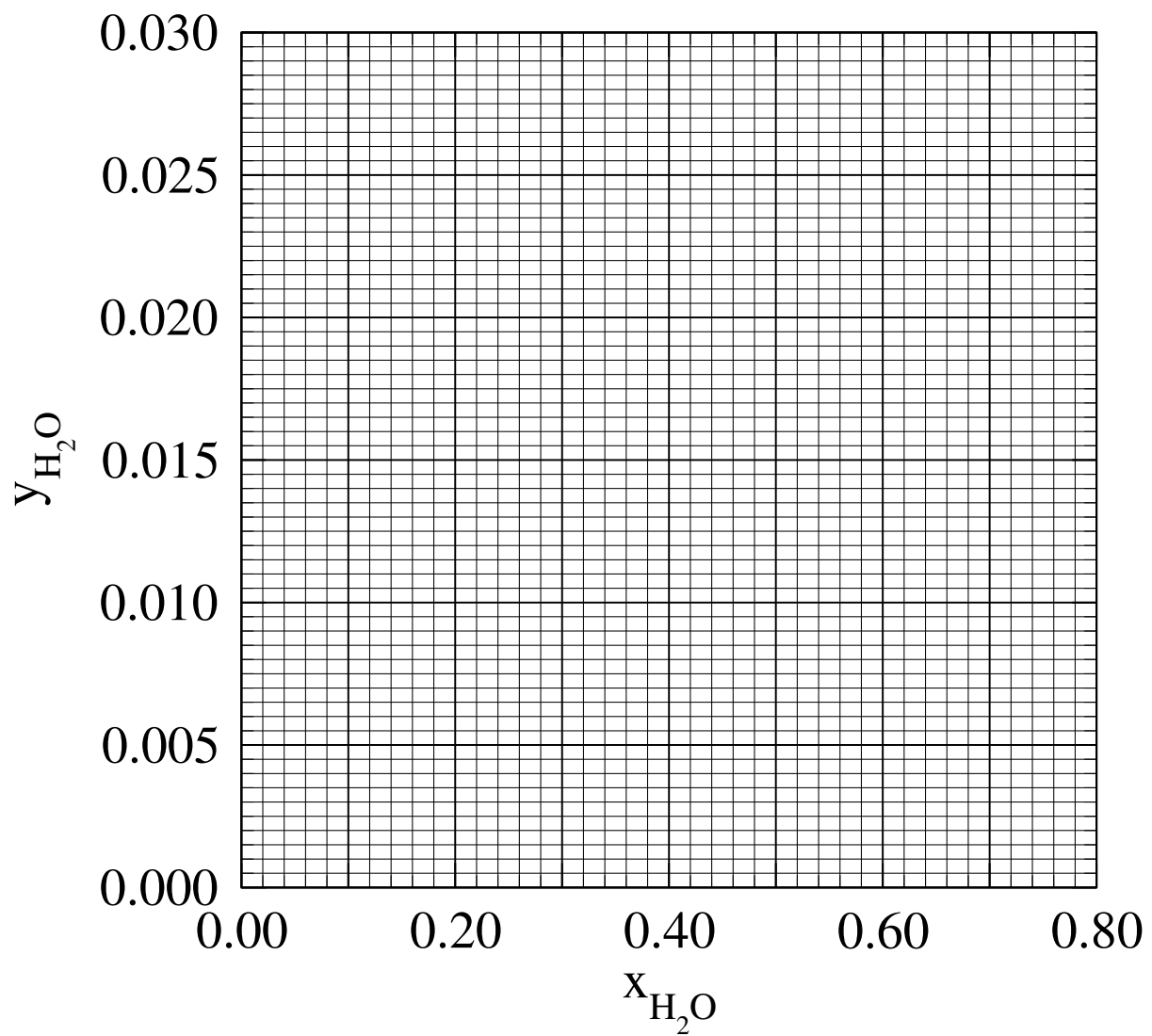
Student ID:

Figure 4: Blank graph for the air dryer in Q. 5.