UNIVERSITY OF ABERDEEN **SESSION 2023–24**

EX3502

Degree Examination in EX3502 Separation Processes 1

9th May 2024 **Time: 14:00 – 17:00**

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 ONLY permitted to use APPROVED calculators.

(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.

(v) Candidates may bring one sheet of A4 into the exam hall with notes/annotations on both sides.

Candidates must attempt *ALL* questions.

Question 1
Evaporator
An evaporator is concentrating orange juice which you can assume is a mixture of water and non-volatile "solids". It has a feed of x_F = 10.0 wt% orange juice at a temperature of 10 °C and a desired product concentration of x_L = 80.0 wt%.

You can assume all streams have the thermodynamic properties of water/steam and use the attached steam tables in the datasheet where required. The evaporator's operating pressure is 0.35 bar absolute.

a) The feed flowrate is $F = 4000\ \text{kg hr}^{-1}$, What is the vapour flowrate V in kg hr^{-1} produced by this process? **[6 marks]**

b) Calculate the duty of the evaporator in kW. You must assume the Boiling Point Rise (BPR) is given by the following equation:

$$\text{BPR}(^\circ\text{C}) = 13.2x^2 + 9.2x \tag{1}$$

where x is the weight fraction of "solids" in the stream. **[10 marks]**

c) If saturated steam is available at 50 bara to power the process, what is the steam economy? **[6 marks]**

[Question total: 22 marks]

Question 2
Absorber
An absorption process is being used to scrub a pollutant from an industrial waste gas stream before release into the environment. The pollutant is harmless below a concentration of 0.18 mol% but the incoming waste gas stream has a concentration of 2.0 mol% so it must be treated. The solvent to wash the gas stream is a dilute solution of the pollutant in water, with an inlet concentration of 0.01 mol%. The Henry's coefficient for the pollutant in water is 0.275 mol%/mol%. The waste gas flowrate is 10.2 mol/s.

a) What is the minimum flowrate of solvent capable of achieving the desired outlet concentration in mol/s? **[6 marks]**

b) If a solvent flowrate of 5.0 mol/s is used, how many stages are required? The VLE data for the pollutant in water is given in Fig. 1 (pg. 11) and you should include this in your solution booklet. **[10 marks]**

c) Packing is available for the absorber which has a height equivalent to a theoretical stage of 0.5 m/stage. Calculate the height of packing required. Discuss what additional height/space is required around the bed and how the diameter of the column is designed (i.e. what are the key considerations in selecting the diameter). **[6 marks]**

[Question total: 22 marks]

Question 3

Multi-stage distillation with Murphree efficiencies

A reactor producing toluene from benzene produces a mixture of 35 mol% benzene and 65 mol% toluene. This stream is to be distilled to recycle the benzene back for further reaction to improve conversion. To reduce wastage and improve product quality, the bottoms product must reach 10 mol% benzene while the top product must be 35 mol% toluene to improve reaction rates. The feed is preheated so that upon entry equal molar amounts of vapour and liquid are produced. Three VLE diagrams have been provided in Figs. 2, 3, and 4 (pgs. 12, 13, 14) which you should use and include in your solution booklet.

a) What is the minimum reflux ratio required for this separation? You must submit your graphical construction with your solution booklet. **[6 marks]**

b) If the reflux ratio is R = 3.0, how many theoretical stages are required to carry out the distillation? You must submit your graphical construction with your solution booklet. **[6 marks]**

c) Assuming a Murphree tray efficiency of 50% what is the real number of trays in the column? You should assume a partial reboiler is fitted. You must submit your graphical construction with your solution booklet. **[10 marks]**

[Question total: 22 marks]

Question 4

Ponchon-Savarit Distillation

A concentrated ethanol/water solution is being produced for use as an environmentally-friendly industrial solvent. A 18.0 mol% ethanol and 82.0 mol% water stream from the fermentation tanks is fed to a distillation column with an enthalpy of 10000 kJ/kmol. The ethanol in the bottoms product must be recovered down to 2.0 mol%, while a top product purity of 60.0 mol% is required for sanitisation purposes. A VLE chart has been provided in Fig. 5 (pg. 15), while a H-x-y chart is available in Fig. 6 (pg. 16) which you should use and include in your solution booklet.

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? **[3 marks]**

b) What is the minimum number of stages required to carry out this separation? You must submit your graphical construction with your solution booklet. **[4 marks]**

c) Assuming that a reflux ratio of 1.4 is used, and the feed has an enthalpy of h_F = 10000kJ kmol^{-1} use the Ponchon-Savarit method to determine how many ideal stages are required to carry out the separation. You must submit your graphical construction with your solution booklet **[12 marks]**

d) The column has an overall tray efficiency of 80%. Assuming the column has a thermosyphon (total) reboiler, what is the real number of trays in the column? If you could not solve the previous question please use an estimate of 4 ideal stages. **[3 marks]**

[Question total: 22 marks]

END OF PAPER

DATASHEET

Conversion from Celsius to Fahrenheit:

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

Operating lines:

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

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

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

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

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:

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

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 1: 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	4.22	1.888	0.0006118	2501.0	2501.0	-6.161e-08	9.155
1	0.00657	4.216	1.889	4.177	2499.0	2503.0	0.01526	9.129
2	0.00706	4.213	1.89	8.392	2496.0	2505.0	0.03061	9.103
3	0.00758	4.21	1.89	12.6	2494.0	2506.0	0.04589	9.076
4	0.00814	4.208	1.891	16.81	2491.0	2508.0	0.0611	9.051
5	0.00873	4.205	1.892	21.02	2489.0	2510.0	0.07625	9.025
6	0.00935	4.203	1.892	25.22	2487.0	2512.0	0.09134	8.999
7	0.01	4.201	1.893	29.43	2484.0	2514.0	0.1064	8.974
8	0.0107	4.199	1.894	33.63	2482.0	2516.0	0.1213	8.949
9	0.0115	4.197	1.895	37.82	2480.0	2517.0	0.1362	8.924
10	0.0123	4.196	1.896	42.02	2477.0	2519.0	0.1511	8.9
12	0.014	4.193	1.898	50.41	2472.0	2523.0	0.1806	8.851
14	0.016	4.191	1.899	58.79	2468.0	2527.0	0.2099	8.804
16	0.0182	4.188	1.901	67.17	2463.0	2530.0	0.239	8.757
18	0.0206	4.187	1.904	75.55	2458.0	2534.0	0.2678	8.711
20	0.0234	4.185	1.906	83.92	2454.0	2537.0	0.2965	8.666
25	0.0317	4.182	1.912	104.8	2442.0	2547.0	0.3673	8.557
30	0.0425	4.18	1.918	125.7	2430.0	2556.0	0.4368	8.452
35	0.0563	4.179	1.925	146.6	2418.0	2565.0	0.5052	8.352
40	0.0738	4.179	1.932	167.5	2406.0	2574.0	0.5724	8.256
45	0.0959	4.179	1.94	188.4	2394.0	2582.0	0.6386	8.163
50	0.124	4.18	1.948	209.3	2382.0	2591.0	0.7038	8.075
55	0.158	4.181	1.957	230.2	2370.0	2600.0	0.768	7.99
60	0.199	4.183	1.966	251.2	2358.0	2609.0	0.8312	7.908
65	0.25	4.185	1.976	272.1	2345.0	2618.0	0.8935	7.83
70	0.312	4.188	1.987	293.0	2333.0	2626.0	0.955	7.754
75	0.386	4.192	1.999	314.0	2321.0	2635.0	1.016	7.681
80	0.474	4.196	2.012	334.9	2308.0	2643.0	1.075	7.611
85	0.579	4.2	2.026	355.9	2295.0	2651.0	1.134	7.543
90	0.702	4.205	2.042	377.0	2283.0	2660.0	1.193	7.478
95	0.846	4.211	2.059	398.0	2270.0	2668.0	1.25	7.415
100	1.01	4.217	2.077	419.1	2256.0	2676.0	1.307	7.354
110	1.43	4.23	2.121	461.4	2230.0	2691.0	1.419	7.238
120	1.99	4.246	2.174	503.8	2202.0	2706.0	1.528	7.129
130	2.7	4.265	2.237	546.4	2174.0	2720.0	1.635	7.026
140	3.62	4.286	2.311	589.2	2144.0	2733.0	1.739	6.929

Table 2 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})
150	4.76	4.31	2.396	632.3	2114.0	2746.0	1.842	6.837
160	6.18	4.338	2.492	675.6	2082.0	2757.0	1.943	6.749
170	7.92	4.369	2.599	719.2	2049.0	2768.0	2.042	6.665
180	10.0	4.406	2.716	763.2	2014.0	2777.0	2.14	6.584
190	12.6	4.447	2.846	807.6	1978.0	2785.0	2.236	6.506
200	15.5	4.494	2.99	852.4	1940.0	2792.0	2.331	6.43
250	39.8	4.865	4.012	1086.0	1715.0	2801.0	2.793	6.072
300	85.9	5.752	6.223	1345.0	1405.0	2750.0	3.255	5.706

Table 2: 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	4.201	1.893	29.3	2484.0	2514.0	0.1059	8.975
0.015	13.0	4.192	1.898	54.69	2470.0	2525.0	0.1956	8.827
0.02	17.5	4.187	1.903	73.43	2459.0	2533.0	0.2606	8.723
0.025	21.1	4.184	1.907	88.43	2451.0	2539.0	0.3119	8.642
0.03	24.1	4.183	1.91	101.0	2444.0	2545.0	0.3543	8.577
0.035	26.7	4.181	1.914	111.8	2438.0	2550.0	0.3907	8.521
0.04	29.0	4.181	1.917	121.4	2432.0	2554.0	0.4224	8.473
0.045	31.0	4.18	1.919	130.0	2427.0	2557.0	0.4507	8.431
0.05	32.9	4.18	1.922	137.8	2423.0	2561.0	0.4763	8.394
0.055	34.6	4.179	1.924	144.9	2419.0	2564.0	0.4995	8.36
0.06	36.2	4.179	1.927	151.5	2415.0	2567.0	0.5209	8.329
0.065	37.6	4.179	1.929	157.6	2412.0	2569.0	0.5407	8.301
0.07	39.0	4.179	1.931	163.4	2408.0	2572.0	0.5591	8.275
0.075	40.3	4.179	1.933	168.8	2405.0	2574.0	0.5763	8.25
0.08	41.5	4.179	1.935	173.9	2402.0	2576.0	0.5925	8.227
0.085	42.7	4.179	1.936	178.7	2400.0	2578.0	0.6078	8.206
0.09	43.8	4.179	1.938	183.3	2397.0	2580.0	0.6223	8.186
0.095	44.8	4.179	1.94	187.6	2394.0	2582.0	0.6361	8.167
0.12	49.4	4.18	1.947	206.9	2383.0	2590.0	0.6963	8.085
0.14	52.5	4.18	1.953	220.0	2376.0	2596.0	0.7366	8.031
0.16	55.3	4.181	1.958	231.6	2369.0	2601.0	0.772	7.985
0.18	57.8	4.182	1.962	241.9	2363.0	2605.0	0.8035	7.944
0.2	60.1	4.183	1.966	251.4	2358.0	2609.0	0.832	7.907
0.22	62.1	4.184	1.971	260.1	2352.0	2613.0	0.8579	7.874

Table 2 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})
0.24	64.1	4.185	1.974	268.1	2348.0	2616.0	0.8818	7.844
0.26	65.8	4.186	1.978	275.6	2343.0	2619.0	0.904	7.817
0.28	67.5	4.187	1.982	282.6	2339.0	2622.0	0.9246	7.791
0.3	69.1	4.188	1.985	289.2	2335.0	2625.0	0.9439	7.767
0.32	70.6	4.189	1.989	295.5	2332.0	2627.0	0.9621	7.745
0.34	72.0	4.19	1.992	301.4	2328.0	2630.0	0.9793	7.725
0.36	73.3	4.19	1.995	307.0	2325.0	2632.0	0.9956	7.705
0.38	74.6	4.191	1.998	312.4	2322.0	2634.0	1.011	7.686
0.4	75.9	4.192	2.001	317.6	2318.0	2636.0	1.026	7.669
0.42	77.0	4.193	2.004	322.5	2316.0	2638.0	1.04	7.652
0.44	78.2	4.194	2.007	327.2	2313.0	2640.0	1.054	7.636
0.46	79.3	4.195	2.01	331.8	2310.0	2642.0	1.067	7.621
0.48	80.3	4.196	2.013	336.2	2307.0	2644.0	1.079	7.607
0.5	81.3	4.197	2.016	340.5	2305.0	2645.0	1.091	7.593
0.55	83.7	4.199	2.022	350.5	2299.0	2649.0	1.119	7.561
0.6	85.9	4.201	2.029	359.8	2293.0	2653.0	1.145	7.531
0.65	88.0	4.203	2.035	368.5	2288.0	2656.0	1.169	7.504
0.7	89.9	4.205	2.041	376.7	2283.0	2659.0	1.192	7.479
0.75	91.8	4.207	2.047	384.4	2278.0	2662.0	1.213	7.456
0.8	93.5	4.209	2.053	391.6	2274.0	2665.0	1.233	7.434
0.85	95.1	4.211	2.059	398.5	2269.0	2668.0	1.252	7.413
0.9	96.7	4.213	2.065	405.1	2265.0	2670.0	1.269	7.394
0.95	98.2	4.214	2.07	411.4	2261.0	2673.0	1.286	7.376
1	99.6	4.216	2.076	417.4	2258.0	2675.0	1.303	7.359
1.1	102.0	4.22	2.087	428.8	2250.0	2679.0	1.333	7.327
1.2	105.0	4.223	2.097	439.3	2244.0	2683.0	1.361	7.298
1.3	107.0	4.226	2.108	449.1	2238.0	2687.0	1.387	7.271
1.4	109.0	4.229	2.118	458.4	2232.0	2690.0	1.411	7.246
1.5	111.0	4.232	2.128	467.1	2226.0	2693.0	1.434	7.223
1.6	113.0	4.235	2.138	475.3	2221.0	2696.0	1.455	7.201
1.7	115.0	4.238	2.147	483.2	2216.0	2699.0	1.475	7.181
1.8	117.0	4.241	2.157	490.7	2211.0	2701.0	1.494	7.162
1.9	119.0	4.244	2.166	497.8	2206.0	2704.0	1.513	7.144
2	120.0	4.247	2.175	504.7	2202.0	2706.0	1.53	7.127
2.5	127.0	4.26	2.22	535.4	2181.0	2717.0	1.607	7.052
3	134.0	4.272	2.262	561.5	2163.0	2725.0	1.672	6.992
3.5	139.0	4.283	2.302	584.3	2148.0	2732.0	1.727	6.94
4	144.0	4.294	2.34	604.7	2133.0	2738.0	1.777	6.895
4.5	148.0	4.305	2.377	623.2	2120.0	2743.0	1.821	6.856
5	152.0	4.315	2.413	640.2	2108.0	2748.0	1.861	6.821

Table 2 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})
6	159.0	4.335	2.48	670.5	2086.0	2756.0	1.931	6.759
7	165.0	4.353	2.543	697.1	2066.0	2763.0	1.992	6.707
8	170.0	4.371	2.603	721.0	2047.0	2768.0	2.046	6.662
9	175.0	4.388	2.66	742.7	2030.0	2773.0	2.094	6.621
10	180.0	4.405	2.715	762.7	2014.0	2777.0	2.138	6.585
15	198.0	4.485	2.964	844.7	1946.0	2791.0	2.315	6.443
20	212.0	4.562	3.19	908.6	1890.0	2798.0	2.447	6.339
25	224.0	4.638	3.404	962.0	1840.0	2802.0	2.554	6.256
30	234.0	4.714	3.612	1008.0	1795.0	2803.0	2.646	6.186
35	243.0	4.791	3.817	1050.0	1753.0	2803.0	2.725	6.125
40	250.0	4.869	4.022	1087.0	1713.0	2801.0	2.797	6.07
45	257.0	4.949	4.228	1122.0	1676.0	2798.0	2.861	6.02
50	264.0	5.032	4.438	1155.0	1640.0	2794.0	2.921	5.974
60	276.0	5.208	4.877	1214.0	1571.0	2785.0	3.027	5.89
70	286.0	5.4	5.354	1267.0	1505.0	2773.0	3.122	5.815
80	295.0	5.614	5.883	1317.0	1442.0	2759.0	3.208	5.745
90	303.0	5.854	6.476	1364.0	1379.0	2743.0	3.287	5.679
100	311.0	6.127	7.147	1408.0	1318.0	2725.0	3.36	5.616
120	325.0	6.813	8.819	1491.0	1194.0	2686.0	3.496	5.494

Data sheet handout.
Submit this graph as part of your solution book.

Student ID:

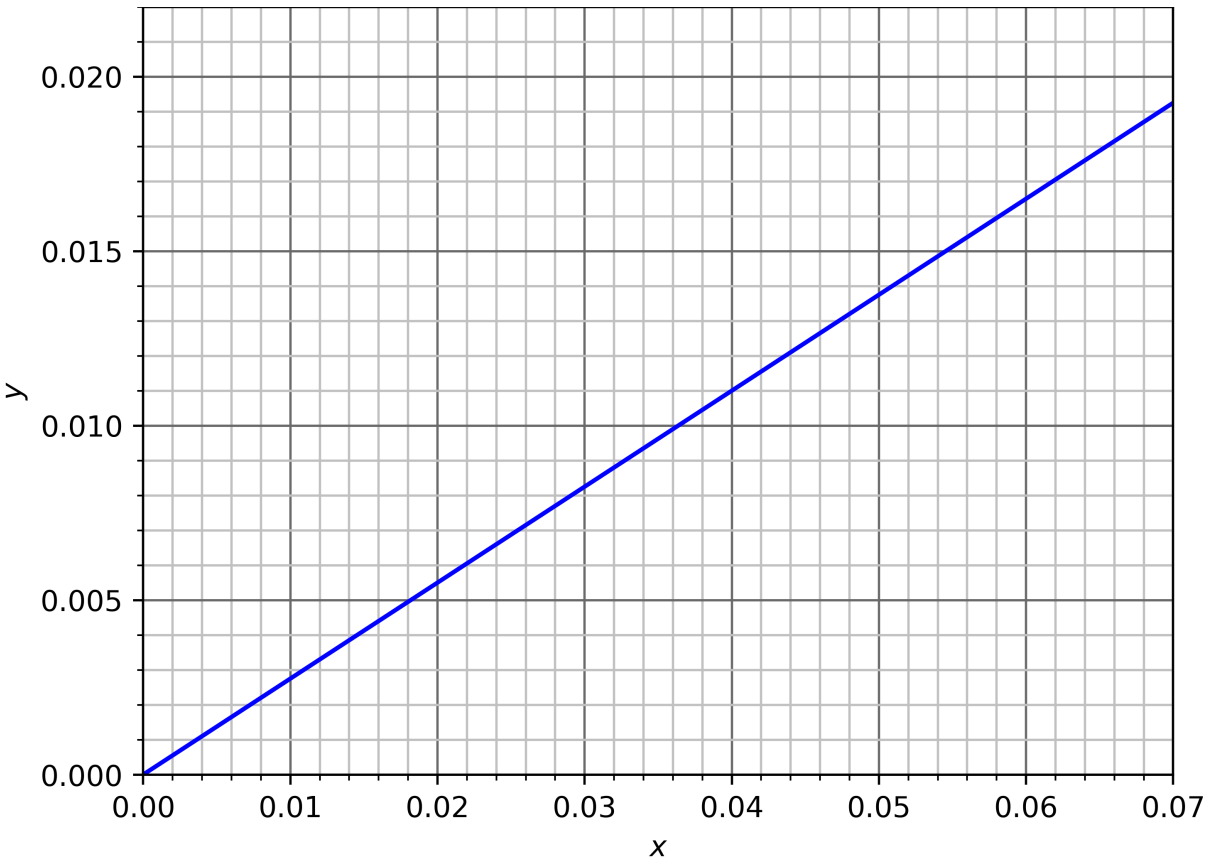

Figure 1: A blank VLE chart for use in Q. 2

Data sheet handout.
Submit this graph as part of your solution book.

Student ID:

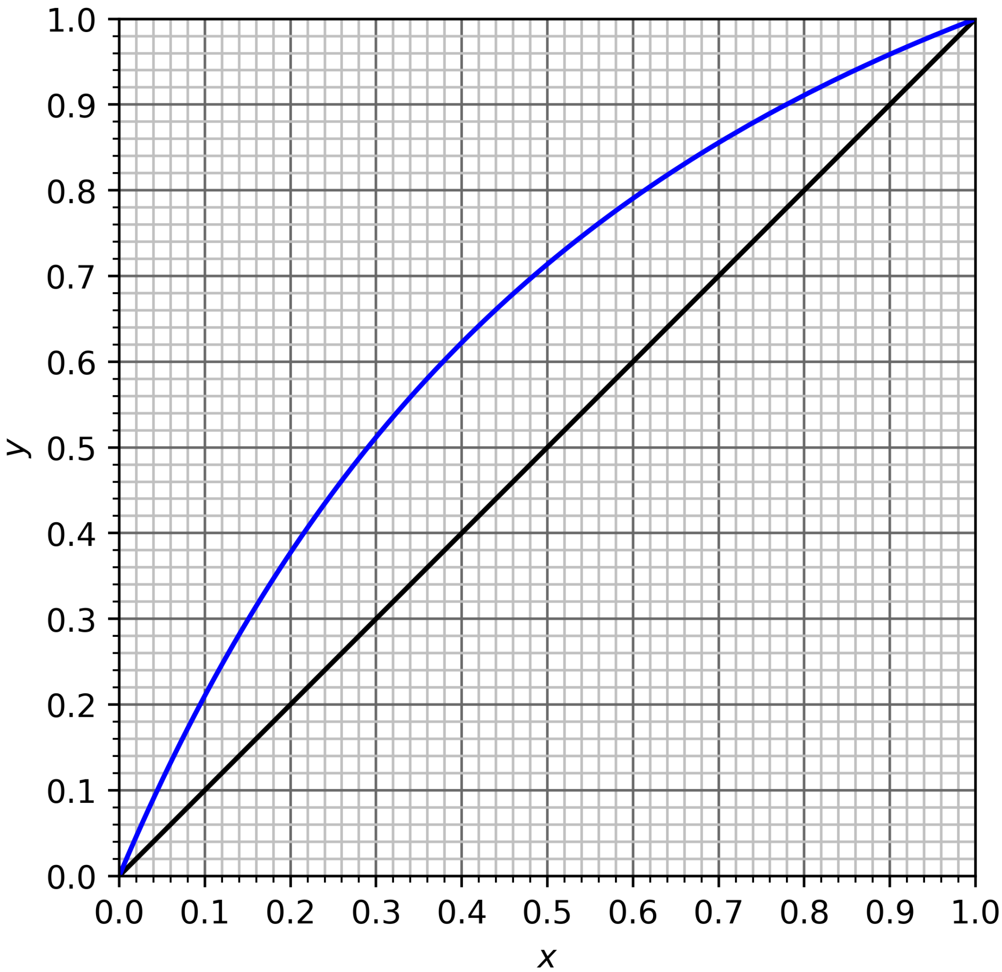

Figure 2: VLE data for the benzene-toluene system. For use in Q. 3

Data sheet handout.
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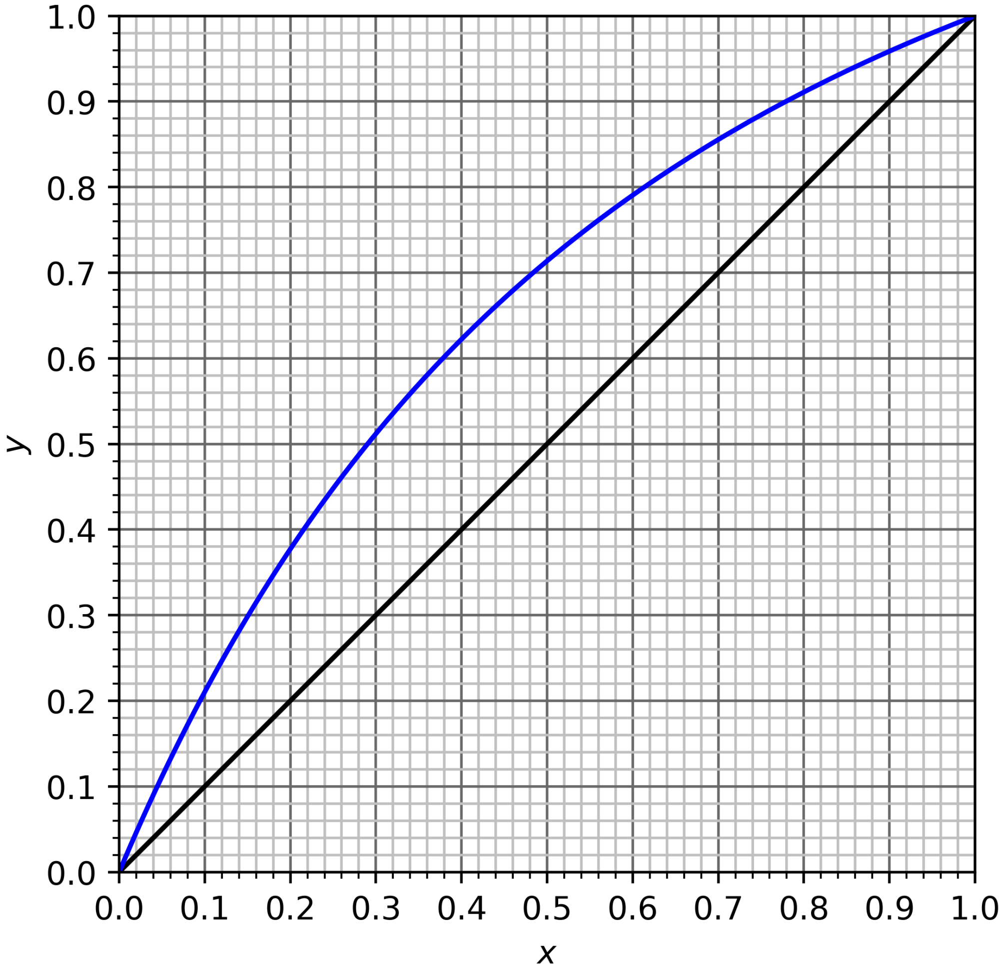

Figure 3: VLE data for the benzene-toluene system. For use in Q. 3

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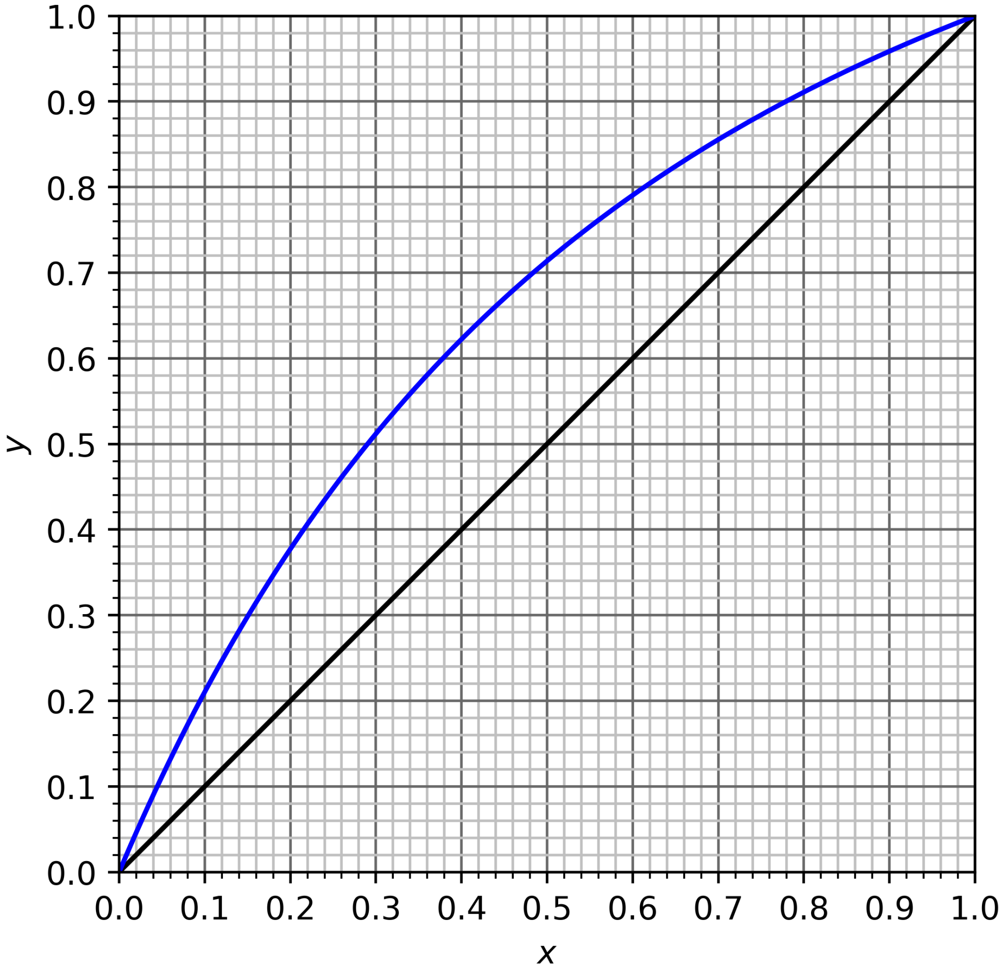

Figure 4: VLE data for the benzene-toluene system. For use in Q. 3

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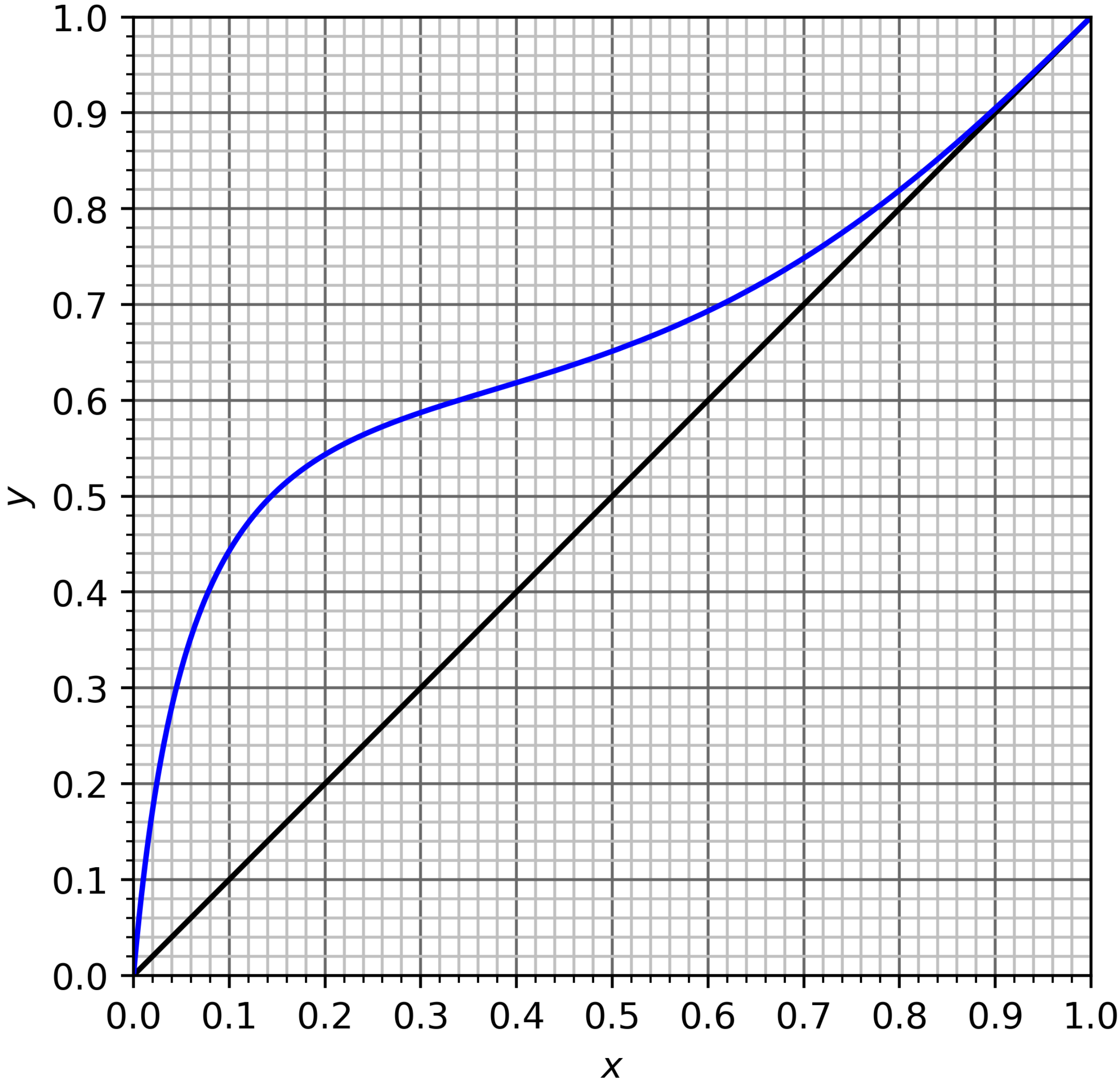

Figure 5: VLE data for the ethanol/water system. For use in Q. 4

Data sheet handout.
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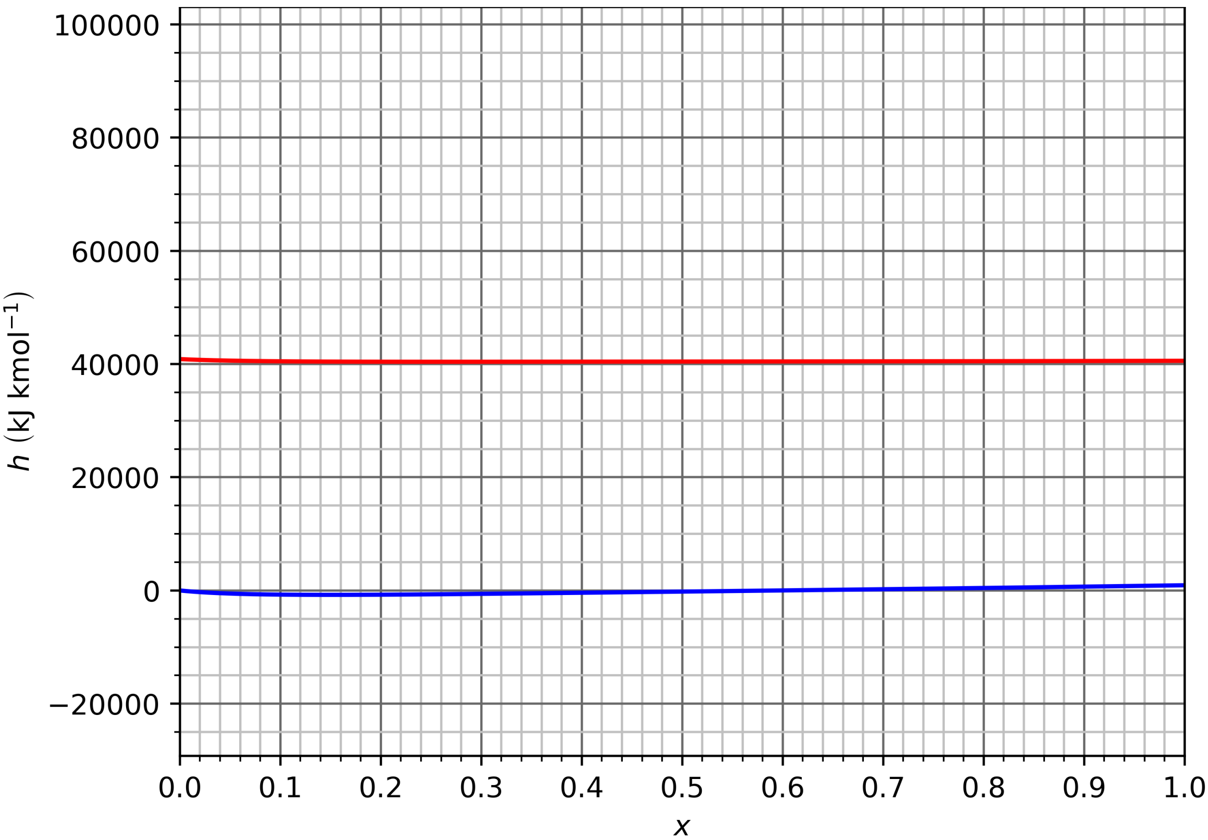

Figure 6: *H-x-y* data for the ethanol/water water system. For use in Q. 4

Data sheet handout. **Submit this graph as part of your solution book.**	**Student ID:**

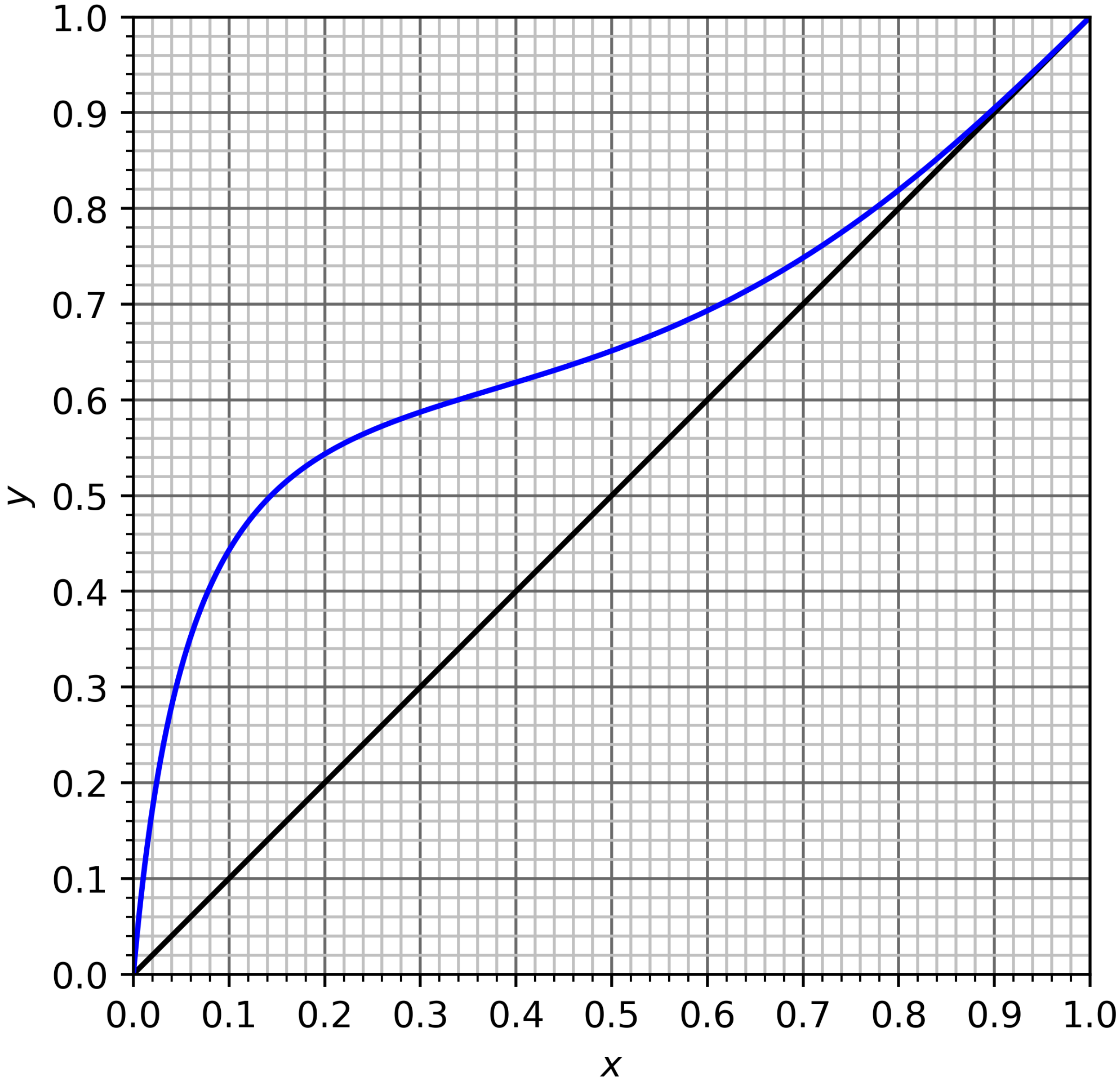

Figure 7: VLE data for the ethanol-water system. For use in Q. **??**