UNIVERSITY OF ABERDEEN   SESSION 2014–2015

Degree Examination in EG3502 Separation Processes 1

11$^{\text{th}}$ May 2015   9 am – 12 am

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 are attached in the datasheet.

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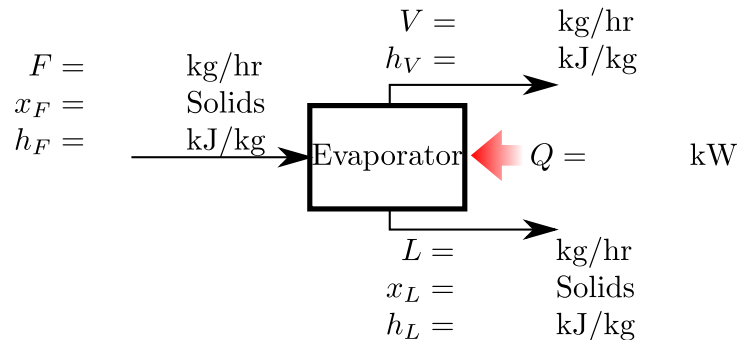
$$y = x\frac{q}{q-1} - \frac{x_F}{q-1}$$

The following diagrams are provided to aid you in labelling your streams. [9 marks]
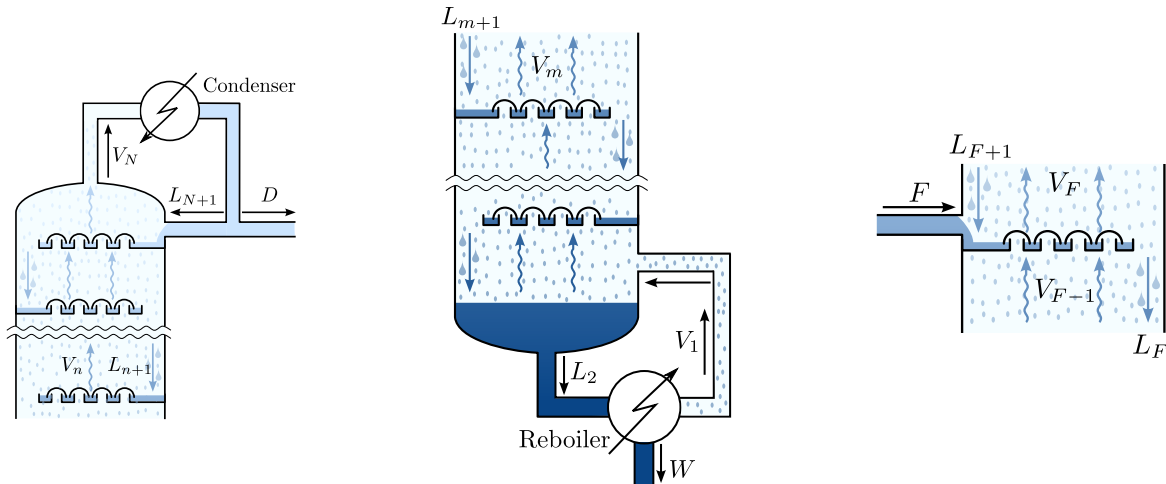
c) The molar enthalpies of saturated liquid and saturated vapour are 20 MJ kmol^{-1} and 50 MJ kmol^{-1} respectively. Determine the values of "q" and the gradient of the "q-line" given that the molar enthalpy of the feed is:

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

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

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

Question 2

An evaporator is used to concentrate 4536 kg/hr of a 20 mole% solution of NaOH in water entering at 60 °C (140 °F) to a product of 50 mole% 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/m² K.

$$
\begin{array}{lll}
 & V = & \text{kg/hr} \\
 & h_V = & \text{kJ/kg} \\
F = & \text{kg/hr} & \\
x_F = & \text{Solids} & \\
h_F = & \text{kJ/kg} & \\
 & \text{Evaporator} \quad Q = & \text{kW} \\
 & L = & \text{kg/hr} \\
 & x_L = & \text{Solids} \\
 & h_L = & \text{kJ/kg}
\end{array}
$$

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]

Question 3

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/hr of fresh cream and the VLE curve for the taint in cream is presented in Fig. 3.
Note: If you draw on the VLE graph provided (Fig. 3), remember to include it in your exam booklet for marking.

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]

PART B: Answer TWO Questions From THREE

Question 4

When 10 000 kg of a mixture of heptane (100 g/mol) and n-octane (114 g/mol) 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 contains 85 mol% n-hexane.VLE data is provided in Fig. 4.
Note: If you draw on the VLE graph provided (Fig. 4), remember to include it in your exam booklet for marking.

a) Determine the initial composition of the liquid in the still.   [5 marks]

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 amount and average composition of the distillate collected.   [10 marks]

c) If the boil-up rate in the still is constant and equal to 10 kmol/hr, how long will the process take?   [3 marks]

d) Why could the above separation not be achieved using a simple Rayleigh distillation?   [2 marks]

Question 5

Note: If you draw on the VLE graph provided (Fig. 5), remember to include it in your exam booklet for marking.
An equimolar mixture of carbon tetrachloride and toluene is to be fractionated at atmospheric pressure to produce a top product containing 6 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 1 & 2 and a blank chart is provided in Fig. 5. 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)	h_{fg} (kJ/kmol)
CCl_4	76.4	5904 at 76.4 °C	15940
toluene	110.4	21250 at 110.4 °C	34430

Table 1: Enthalpic data for carbon tetrachloride (CCl_4) and toluene. This is required for Q. 5.

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 2: Vapour-liquid equilibrium for carbon tetrachloride and toluene. This is required for Q. 5.

Question 6

Note: If you draw on the VLE graph provided (Fig. 6), remember to include it in your exam booklet for marking.
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. 6.   [10 marks]

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

END OF PAPER

DATASHEET

Conversion from Celsius to Fahrenheit:

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

Operating lines:

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

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

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

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

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 K)	$C_{p,v}$ (kJ/kg)	h_l (kJ/kg)	h_{lv} (kJ/kg)	h_v (kJ/kg)	s_l (kJ/kg K)	s_v (kJ/kg K)
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

Table 4 continued: Thermodynamic properties of saturated steam by temperature.

T	P	$C_{p,l}$	$C_{p,v}$	h_l	h_{lv}	h_v	s_l	s_v
(°C)	(bar)	(kJ/kg K)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg K)	(kJ/kg K)
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	T	$C_{p,l}$	$C_{p,v}$	h_l	h_{lv}	h_v	s_l	s_v
(bar)	(°C)	(kJ/kg K)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg K)	(kJ/kg K)
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

Table 4 continued: Thermodynamic properties of saturated steam by pressure.

P (bar)	T (°C)	$C_{p,l}$ (kJ/kg K)	$C_{p,v}$ (kJ/kg)	h_l (kJ/kg)	h_{lv} (kJ/kg)	h_v (kJ/kg)	s_l (kJ/kg K)	s_v (kJ/kg K)
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
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

Table 4 continued: Thermodynamic properties of saturated steam by pressure.

| P | T | $C_{p,l}$ | $C_{p,v}$ | h_l | h_{lv} | h_v | s_l | s_v |
(bar)	(°C)	(kJ/kg K)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg K)	(kJ/kg K)
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

If you draw on this graph, you must attach it to your exam booklet using the provided tag AND fill in your student ID.
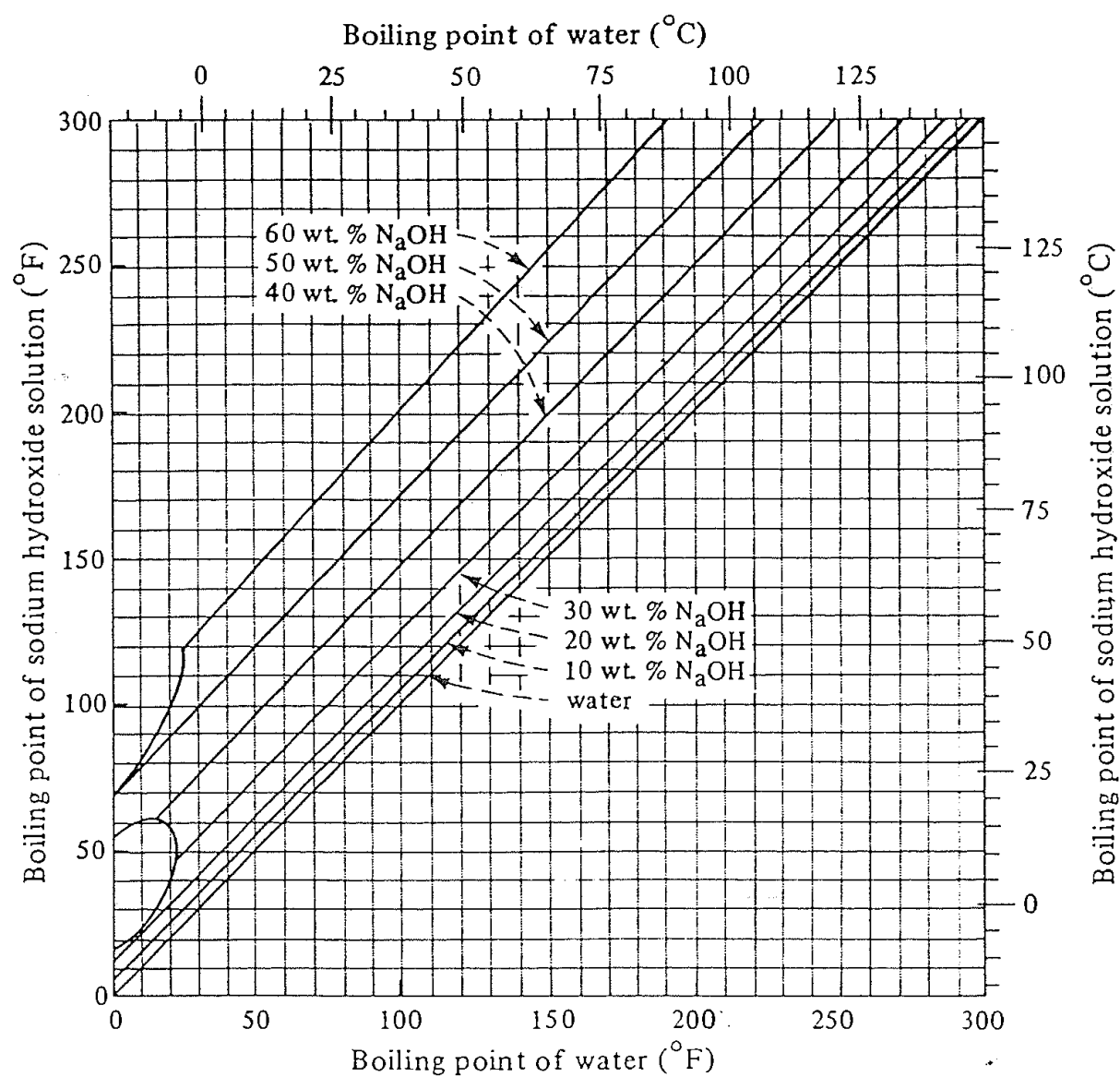
Student ID:

Figure 1: Boiling points for NaOH solutions for use in Q. 2.

If you draw on this graph, you must attach it to your exam booklet using the provided tag AND fill in your student ID.
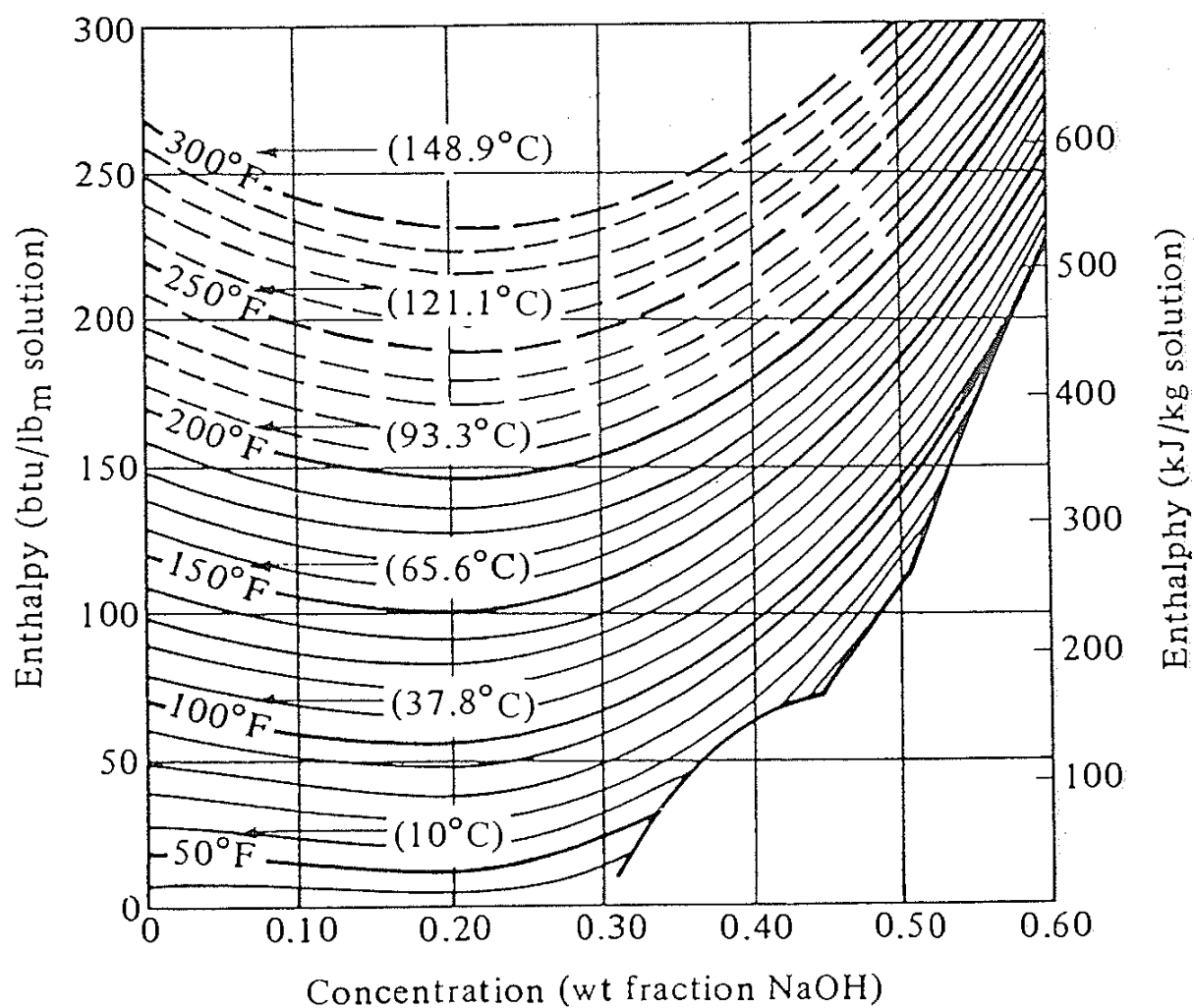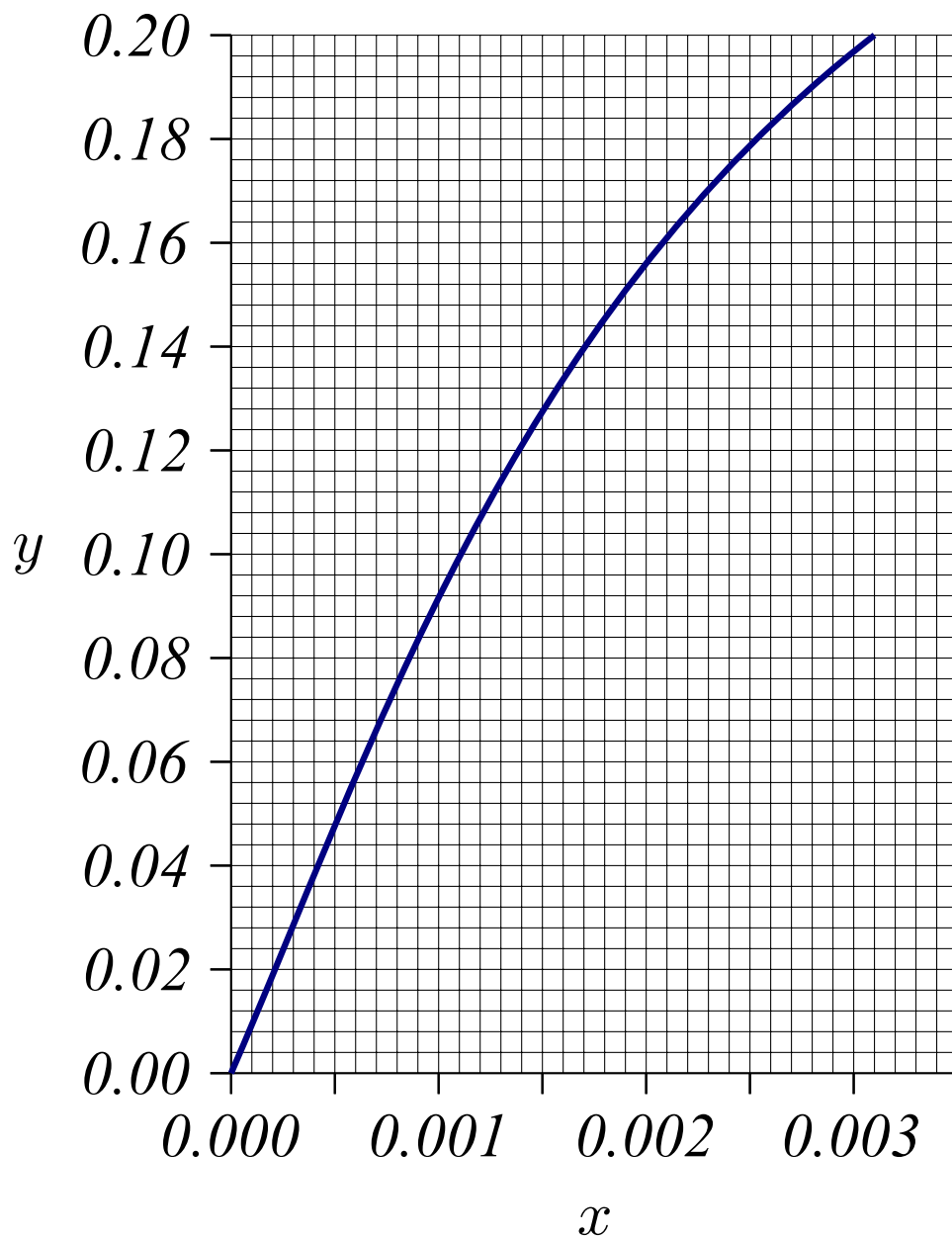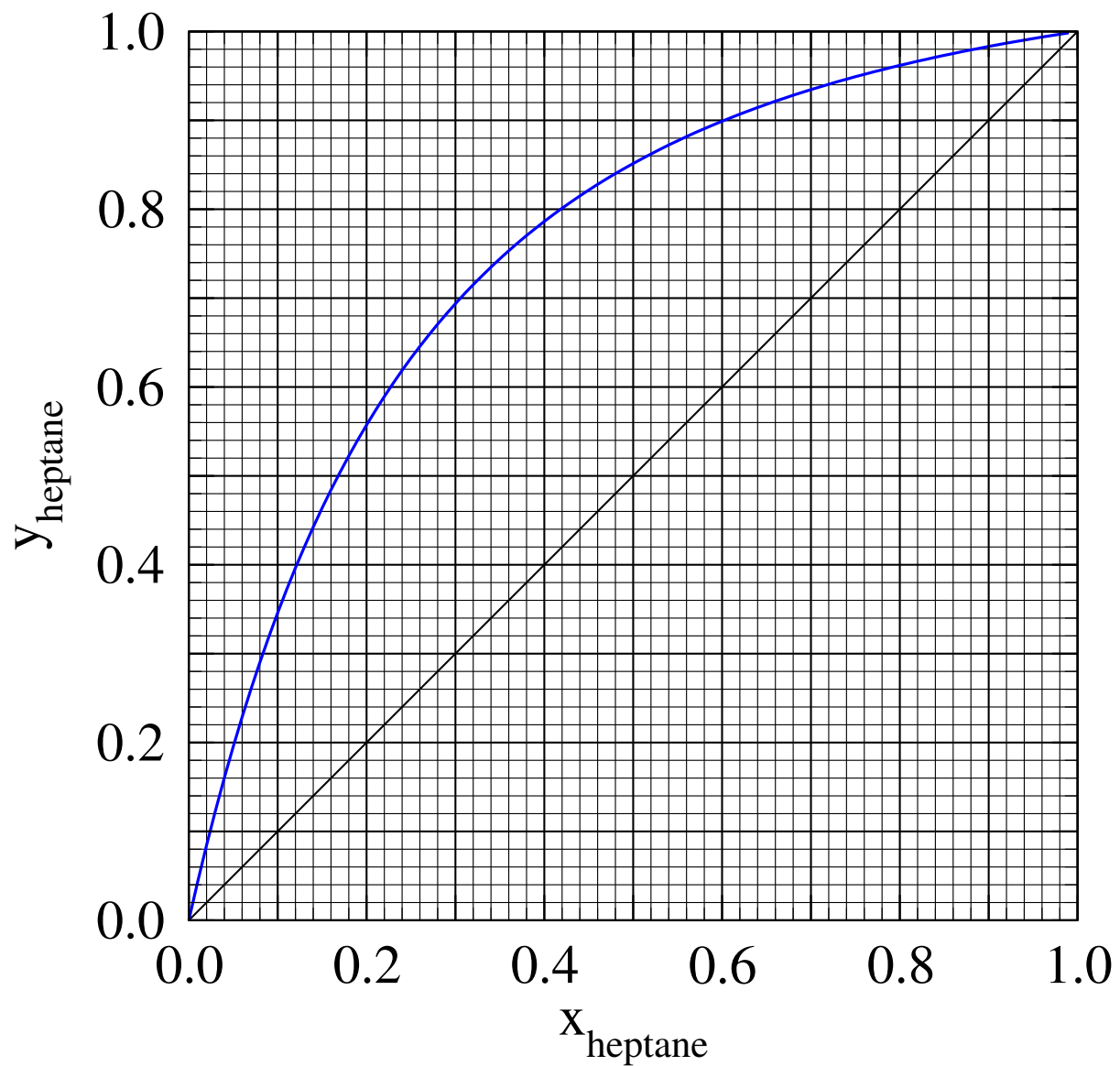
Student ID:

Figure 2: Enthalpies of NaOH solutions for use in Q. 2.

If you draw on this graph, you must attach it to your exam booklet using the provided tag AND fill in your student ID.

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Figure 3: VLE data (mole fraction in vapour y versus mole fraction in liquid x) for an odorous taint in cream. For use in Q. 3

If you draw on this graph, you must attach it to your exam booklet using the provided tag AND fill in your student ID.
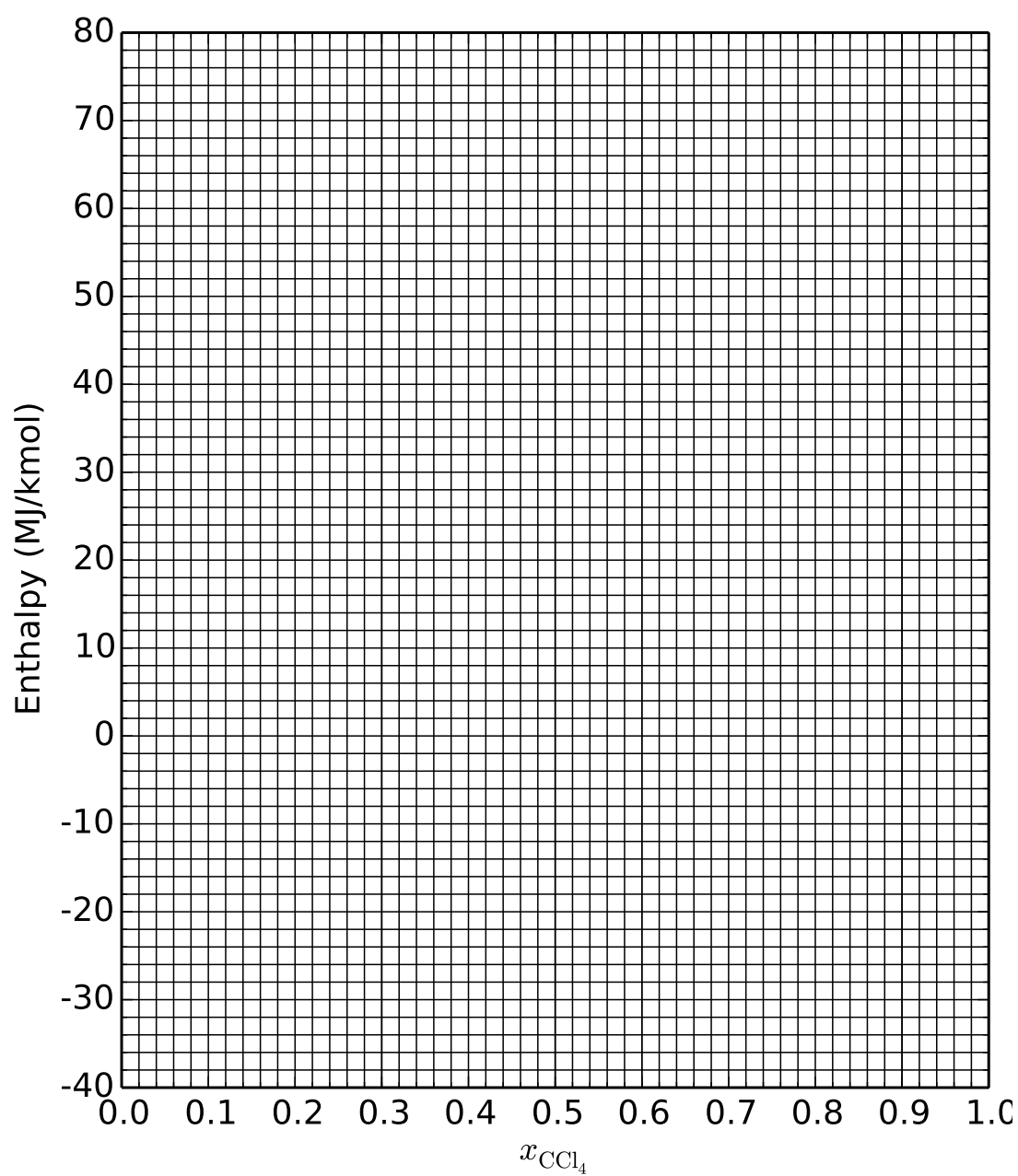
Student ID:

Figure 4: VLE data for the heptane-octane system at 1 atm. For use in Q. 4

If you draw on this graph, you must attach it to your exam booklet using the provided tag AND fill in your student ID.

Student ID:

Figure 5: A blank H-x-y diagram for Q. 5

If you draw on this graph, you must attach it to your exam booklet using the provided tag AND fill in your student ID.
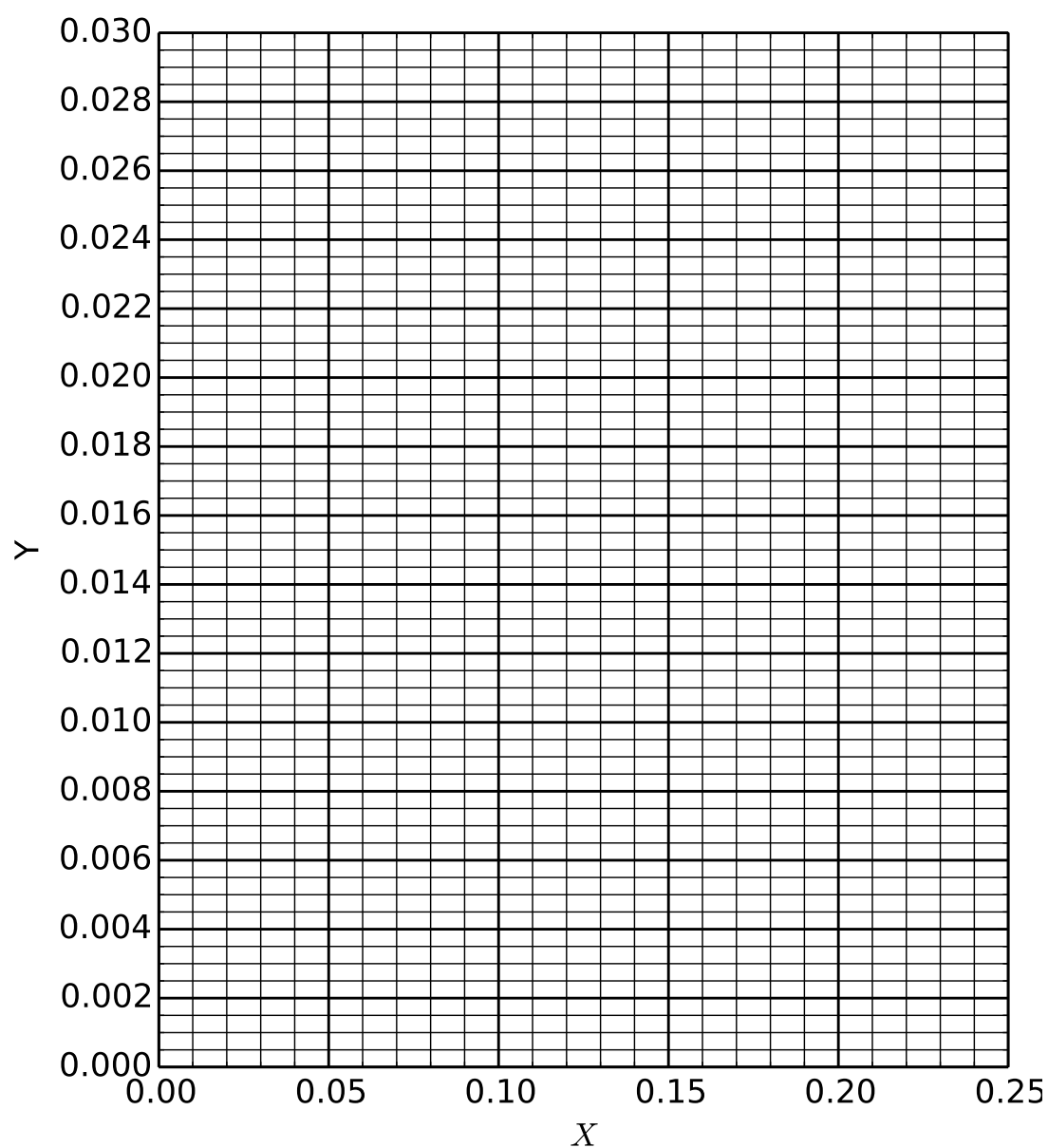
Student ID:

Figure 6: A blank *X-Y* graph for use in Q. 6.