Chemical Engineering: 4M3
Separation Processes
McMaster University: *Final examination*

Duration of exam: 3 hours **Instructor: Kevin Dunn**
07 December 2013 **kevin.dunn@mcmaster.ca**

This exam paper has 6 pages (which includes 2 pages of graphs) and 7 questions. You are responsible for ensuring that your copy of the paper is complete. Bring any discrepancy to the attention of the invigilator.

Note:

- You may bring in any printed materials to the exam; any textbooks, any papers, *etc*.
- You may use **any calculator** during the exam.
- You may answer the questions in any order on all pages of the answer booklet.
- *Time saving tip*: please use bullet points to answer, where appropriate, and **never repeat the question** back in your answer.
- Please use a problem solving strategy on longer questions that is proven to work; *define, explore, plan, do, and importantly, always check*.
- Total marks: 108 marks.
- Total time: 3 hours.

Question 1 [5 = 1 + 1 + 1 + 1 + 1]

Quick short answers:

1. Microfiltration, ultrafiltration, nanofiltration are terms associated with _____ (type of separator). **[1]**
2. State the letter for all options which are *true*: for a Sorbex adsorber column **[1]**
   (a) the solid phase moves from stage to stage
   (b) the liquid is pumped in a way that appears counter-current to the solids direction
   (c) the rotary valve stays in a certain position, then rotates to the next position after some time
   (d) the column operates on a continuous basis
3. We used Stokes' law many times to derive equations for solid-fluid separators. Under which condition(s) is it applicable? **[1]**
4. In a single liquid-liquid extraction mixer-settler stage, what are the typical names given to the two streams leaving? **[1]**
5. The "Tyler sequence" is associated with _____ (type of equipment). **[1]**

Question 2 [13 = 1 + 2 + 3 + 3 + 2 + 2]

Slightly longer answers are required here. Use bullets as far as possible.

1. Give a single sentence to describe the purpose of the Σ number for a centrifuge. **[1]**
2. Give 2 reasons why liquid-liquid extraction could be used to separate, as opposed to distillation. **[2]**
3. Name 3 reasons why drying is used at the end of a flowsheet. **[3]**
4. List 3 criteria used to select a solvent in a liquid-liquid extraction system. **[3]**
5. Adsorption in a packed bed leads to depletion of the bed's capacity after some time. Name two main mechanisms by which the adsorbent may be regenerated. **[2]**
6. Membrane fouling and concentration polarization can deteriorate a membrane's performance. List 4 measures that can be implemented to counteract these problems. **[2]**

Question 3 [16 = 3 + 2 + 4 + 5 + 2]

Questions that require more explanation, diagrams and/or some calculation:

1. Draw a plot that shows the difference between a diffuse and sharp cut-off on a membrane, in terms of the rejection coefficient. Under which conditions would you prefer a sharp cut-off? **[3]**
2. After starting up a packed-bed adsorber, describe the characteristics of the packed bed's **adsorbent** in the region at the start of the bed, prior to the MTZ. **[2]**
3. What is the MTZ? Why does an MTZ exist? Is it desirable? If not, why not? **[4]**
4. You measure a wet bulb temperature of 42.5°C and a dry bulb temperature of 80°C for a gas entering a dryer. What are: **[5]**
   (a) the humidity amount [mass/mass basis],
   (b) percentage humidity,
   (c) dew point temperature of this gas,
   (d) the humid heat of the gas, and
   (e) the approximate humid volume (no calculation required)?
5. For constant pressure filtration in a batch filtration unit, draw an expected plot shape of the volume of filtrate collected against time (x-axis). **[2]**

Question 4 [18 = 1 + 14 + 3]

The isotherm for benzene, at 25°C, on an activated carbon adsorbent is given as:

$$C_{\mathrm{A,S}} = 32 C_{\mathrm{A}}^{0.428}$$

where $C_{\mathrm{A,S}}$ is in units of mg benzene per gram of carbon, and C_{A} is in units of mg benzene per litre of water-based solution.

You want to create your own adsorber packed bed from a piece of piping that has diameter of 24.5 cm.

The activated carbon supplier has given you the following specification sheet (and the isotherm information above):

- activated carbon mean diameter = 2 mm
- activated carbon size distribution range 0.4 mm to 3.8 mm
- activated carbon bulk density = 410 g/L
- activated carbon particle density = 520 g/L
- cost of activated carbon is $5.50 per kilogram.

You would like a breakthrough time of 4 hours when treating a feed stream containing 2.8 g of benzene per litre. You have to treat 30 L per minute of waste water.

1. What type of adsorption isotherm is this? **[1]**
2. How long should your packed bed be? Be clear with any simplifying assumptions you make. **[14]**

   Use the rule of thumb that if you cannot perform a lab experiment to calculate the MTZ, that your MTZ is 4ft, and assuming a symmetric wavefront, that the LUB $= 2 \times$ MTZ.
3. What will be the cost of the adsorbent you need to purchase? **[3]**

Question 5 [15 = 12 + 2 + 1]

A filter cake from a plate-and-frame press is to be dried by circulating warm, dry air over the solids. Trays of solids are 3 cm high, with an area of 2.0 m^2. Each tray contains 80 kg of wet filter cake, and the press leaves the solids with approximately 30 wt% moisture on a dry basis.

Air at 1 atmosphere, 70°C, and a relative humidity of 10% is used, at an approximate velocity of $4.2 \mathrm{m.s}^{-1}$, in a direction that flows parallel to the solids.

1. Estimate the mass of water that would be evaporated from the cake after 4 hours. Be clear on all assumptions you make as you proceed. **[12]**
2. What is the moisture content of the cake after 4 hours, expressed on a dry basis? **[2]**
3. Name one method we can implement to reduce the drying time. **[1]**

Question 6 [13 = 2 + 8 + 3]

$140\,\text{kg.hr}^{-1}$ of a 40% acetone-in-water mixture are to be separated in a **cross-current** extraction system, using trichloroethane as solvent.

1. Draw a simple flow diagram that illustrates the cross-current streams; use labelling that you will transfer onto the next part of this question. **[2]**
2. If $80\,\text{kg.hr}^{-1}$ of pure solvent is fed into the first stage and $60\,\text{kg.hr}^{-1}$ into the second stage, what will be the acetone purity leaving in the raffinate from each stage? **[8]**

   Show all constructions and calculations on the ternary diagram (or in your exam booklet if you prefer, or need more space). **Rather use pencil to construct the diagram, as spare exam copies are not available**. But make sure all lines are clearly visible.
3. What is the overall acetone recovery from such a 2-stage system? **[3]**

Question 7 [28 = 5 + 2 + 12 + 2 + 3 + 2 + 2]

A reverse osmosis plant treats $120,000\,\text{m}^3$ of seawater per 8 hours, at 20°C and 3.5 wt% solids (assume it to be NaCl). The molar mass of NaCl is 58.4 g/mol and is 18.02 g/mol for water). The aim is to obtain $35,000\,\text{m}^3$ of drinking water within an 8 hour period, with only 500 ppm (0.05 wt%) dissolved solids in it.

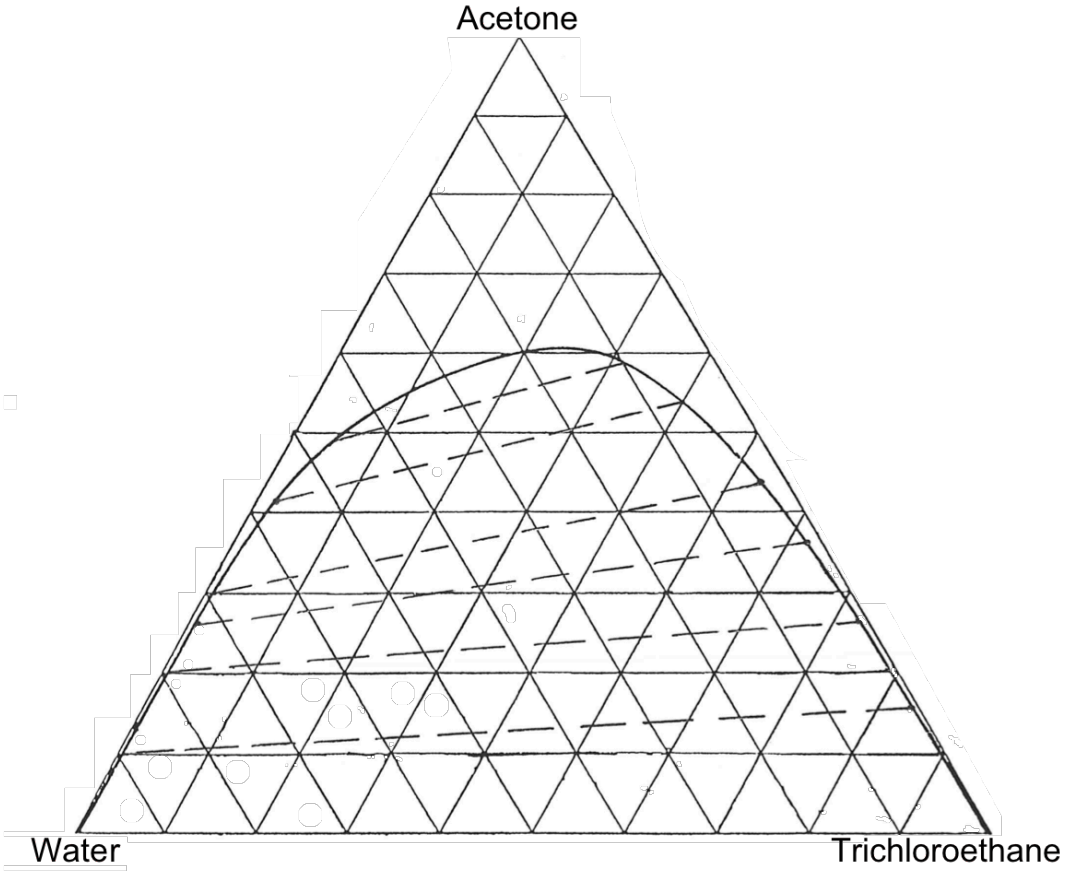
The feed pressure is 140 atm entering and leaving at 4 atm in the permeate. The total area of the spiral wound membranes is $180,000\,\text{m}^2$. The plant only operates 8 hours per day, in the evenings, when electricity is cheapest. Storage tanks are used to hold the water produced during the 8 hours, so that it is available 24 hours per day to the town.

From lab experiments at the supplier, the permeance of water through a single membrane module was found to be $5.5 \times 10^{-5}\,\text{kg.s}^{-1}\text{.m}^{-2}\text{.atm}^{-1}$. The permeance of salt through the membrane was $21 \times 10^{-8}\,\text{m.s}^{-1}$.

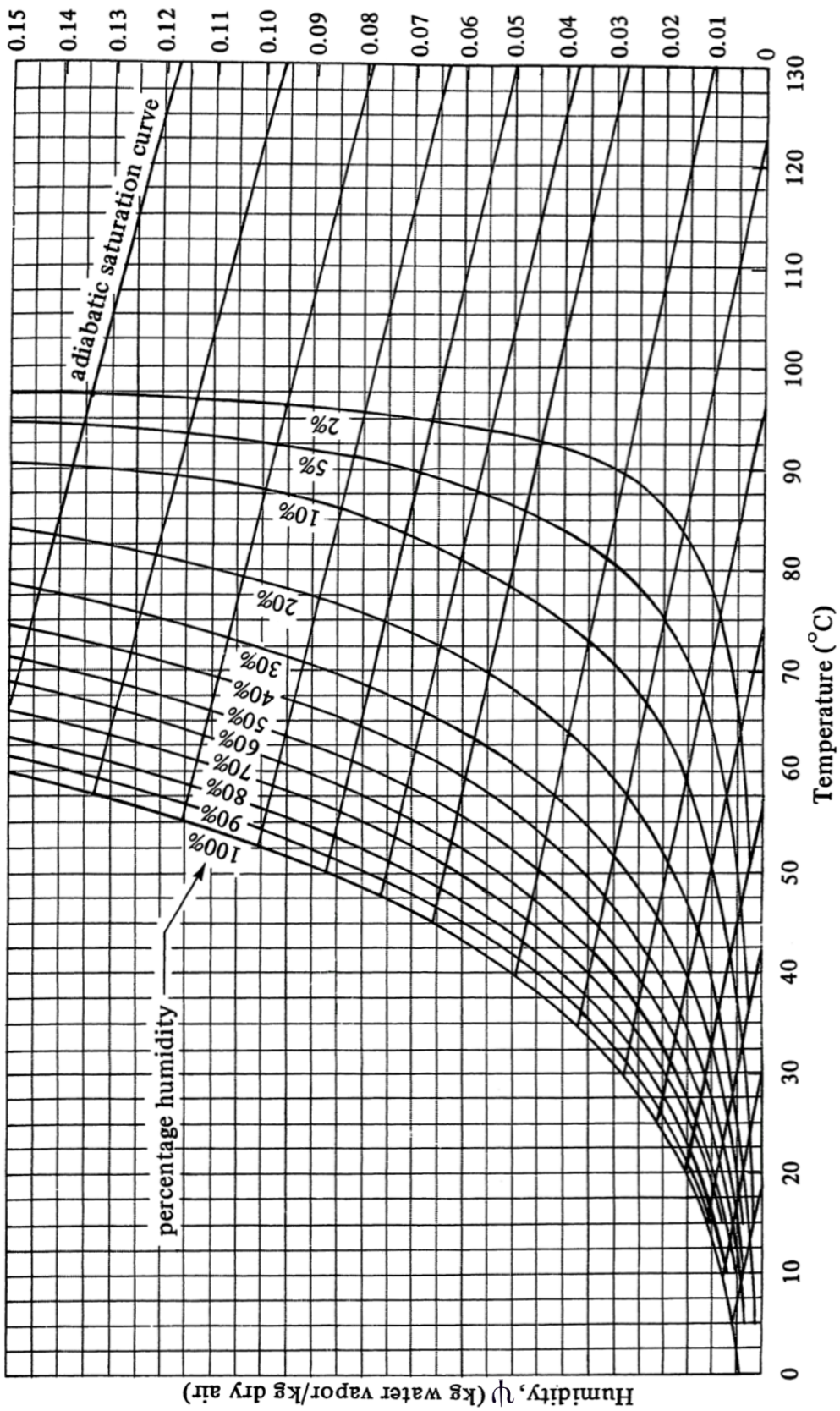
1. Give a few bullet points that describe how the membrane's permeance with respect to water is calculated. Your description must take the given units into account. **[5]**
2. Is that water permeance value applicable to all $180,000\,\text{m}^2$ of membrane area? Explain. **[2]**
3. Calculate the actual flow rate of drinking water leaving the plant. **[12]**
4. Will the drinking water flow meet the demand required? If the demand cannot be met, name one thing that can be improved or changed to meet demand. **[2]**
5. Is this flux close to typical LMH values experienced on reverse osmosis applications? Explain why. **[3]**
6. What is the rejection coefficient for this system? **[2]**
7. What is the cut value? **[2]**

Student number: _____

*Question number:*_____



Feel free to use this page for calculations as well


Humidity, ψ (kg water vapor/kg dry air)
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
adiabatic saturation curve
2%
5%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percentage humidity
Temperature (°C)
0
10
20
30
40
50
60
70
80
90
100
110
120
130

The end.