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

Duration of exam: 3 hours **Instructor: Kevin Dunn**
February 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.
- Time management on this exam is important.
- Total marks: 103 marks.
- Total time: 3 hours.

Some equations, where r is the radius in all cases:

- Perimeter of a circle = $2\pi r$ and area of a circle = πr^2
- Area of a sphere = $4\pi r^2$ and volume of a sphere = $\dfrac{4}{3}\pi r^3$

Question 1 [15 = 2 + 2 + 2 + 4 + 2 + 1 + 2]

Reverse osmosis of a $50\,\text{g.L}^{-1}$ sucrose-water solution is being experimentally investigated. The osmotic pressure in a sucrose-water system is approximated by $\pi = 0.054m$, where m is the sucrose concentration in g.L^{-1}, and π has units of atmospheres. The membrane is operated so the cut is 40%, with a feed rate of $0.25\,\text{m}^3.\text{hr}^{-1}$. Using a pressure difference of 30 atm, the permeance of the membrane with respect to the solvent is $5.4 \times 10^{-4}\text{kg.s}^{-1}.\text{m}^{-2}.\text{atm}^{-1}$. For reference, the molar mass of water is $18\,\text{g.mol}^{-1}$, and for sucrose it is $342\,\text{g.mol}^{-1}$.

If the retentate concentration leaving the system is measured as $81.8\,\text{g.L}^{-1}$ of sucrose, calculate the following other quantities:

1. The retentate flow rate leaving the membrane. **[2]**
2. The permeate concentration in g.L^{-1}. **[2]**
3. The osmotic pressure difference across the membrane. **[2]**
4. The solvent (water) flux expressed in LMH. **[4]**
5. The solute (sucrose) **mass** flux expressed on an hourly basis. **[2]**
6. The rejection coefficient. **[1]**
7. The separation factor. **[2]**

Question 2 [9]

In the course presentations we saw several applications of centrifuges. List 3 applications of centrifuges where for each example you must state:

- the two materials being separated,
- the type of centrifuge used,
- why that centrifuge is suitable for the application.

Question 3 [9]

$100\,\text{kg.hr}^{-1}$ of a 50% acetone-water mixture are to be separated in a **counter-current** extraction system. If only $25\,\text{kg.hr}^{-1}$ of trichloroethane solvent is fed, show a construction on the ternary diagram for the number of stages required to obtain a 15% acetone mixture leaving at equilibrium. Make sure to draw a flow sheet/diagram illustrating where the streams are that appear on your ternary diagram.

Show all constructions and calculations on the ternary diagram (or in the exam booklet if more space is required). **Rather use pencil to construct the diagram, as spare exam copies are not available**. Make sure all lines are clearly visible.

Question 4 [11 = 2 + 1.5 + 1.5 + 1 + 1 + 3 + 1]

Provide single word, or short sentence answers to the following (no explanation required, no equations).

1. Describe what the MWCO is in the context of membrane systems. **[2]**
2. List 3 adsorbents. **[1.5]**
3. Cyclones are widely used as a separator in solid-liquid, solid-gas, and liquid-liquid operations. Name 3 general advantages of using cyclones as a separator that explains their widespread use. **[1.5]**
4. Name a chemical flocculant that is commonly used as an MSA for wastewater treatment. **[1]**
5. The operating costs for various separators were shown in the course presentations, which typically were for the ESA and/or MSA. Which other cost showed up consistently as being one of the highest operating costs? **[1]**
6. What is the wet-bulb temperature, dew point temperature, and percentage humidity of an air stream at 90°C and containing 100 grams of water per kilogram of dry air? **[3]**
7. What occurs in the MTZ in an adsorber? **[1]**

Question 5 [25 = 3 + 2 + 2 + 2 + 2 + 4 + 5 + 2 + 3]

Slightly longer answers requiring a sentence or two, or a couple of bullet points, but definitely no more than 25% of a page per sub-question.

1. Carbon dioxide gas when heated above 32°C and a pressure exceeding 7.4 MPa behaves as a supercritical fluid, and is used, for example, to decaffeinate coffee beans. Describe two characteristics of supercritical fluids and why they are advantageous in the context of this example. **[3]**

2. A cyclone at your mining facility is rated with a cut-size of $32\,\mu m$. Write down concisely what this means to your engineering colleague. **[2]**
3. Describe the characteristics of a number 30 Tyler mesh screen. **[2]**
4. Adsorption in a packed bed leads to depletion of the bed's capacity after some time. However, for waste water treatment we learnt in the course presentations that sometimes it is advantageous not to regenerate the bed. Give a single sentence explanation why this is the case. **[2]**
5. Describe how a packed bed is regenerated in pressure swing adsorption. **[2]**
6. A centrifuge is operated to clarify a fruit juice from pulp and other particles (e.g. crushed seeds). The electrical motor on the device is operating at its maximum speed, but the required clarity is still not being achieved, i.e. you are not removing the required small particles. What can you do (given very specific bullet-point instructions to your colleague to implement) to achieve the desired cut diameter without spending capital or modifying the centrifuge? Be sure to describe why this approach will work and what the magnitude of the effect will be (e.g. your answer should be something like: "if you double this variable, then the cut diameter will halve") **[4]**
7. A low concentration liquid impurity is completely miscible in another liquid stream. A colleague has suggested using a distillation column to reduce the impurity's concentration. Name 2 alternative separation units that could be considered: **[5]**
    - name the alternative unit,
    - which physical properties of the impurity and the base liquid are exploited in your suggested alternative to cause the separation,
    - explain one advantage over distillation,
    - explain a disadvantage of the proposed unit.
8. 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]**
9. Describe two important, and interesting, things you learned about separation processes while working on your term project. **[3]**

Question 6 [10 = 6 + 4]

An undesirable solute is to be removed from $20\,\text{m}^3$ of liquid by contacting it with a batch of adsorbent. The adsorption of the solute on the adsorbent follows a Langmuir type adsorption isotherm:

$$C_{\text{A,S}} = \frac{1.5C_{\text{A}}}{0.5 + C_{\text{A}}}$$

where C_{A} is measured in kg.m^{-3} and $C_{\text{A,S}}$ is in kg.kg^{-1}. The concentration of the solute in the feed liquid is 0.1 kg.m^{-3} when it is first charged to the batch reactor.

1. How much adsorbent will be needed to reduce the solute concentration in the liquid to 0.01 kg.m^{-3}? And what mass of solute is loaded onto the adsorbent?
2. Describe an experimental procedure (use bullet points) that will provide the data necessary to fit the two coefficients in the Langmuir isotherm. Note, do not provide details how to numerically calculate the coefficients, only describe the exact procedure to obtain a data table of C_{A} and $C_{\text{A,S}}$ values.

Question 7 [24 = 2 + 2 + 4 + 10 + 4 + 2]

A cylindrically-shaped food product (e.g. snack food, or pet food) that is 0.5cm in diameter and 2cm in length according to the product requirements, is extruded with a moisture content of 35% on a dry basis. These extruded pellets are to be dried to 8% dry basis to obtain the correct level of consistency for flowability and long-term storage, another product requirement. Drying air is available from an facility at your site, and is rated at 30% humidity and 70°C; this is provided at a velocity of $3\,\text{m.s}^{-1}$ in the batch drier. The mass of moist material is 150 kg, and corresponds to about 50,000 pellets per tray.

Heat transfer coefficients for drying are estimated from correlations. For a packed bed, a correlation by Gamson, Thodos and Hougen in *AIChE Journal*, **39**, p $1 - 35$, 1943 where:

- h is the heat transfer coefficient, in $[\text{W.m}^{-2}.\text{K}^{-1}]$
- G is the mass flux of air, in $[\text{kg.hr}^{-1}.\text{m}^{-2}]$
- d_p is the particle size diameter [m], for spherical particles, are then used in the following equation:

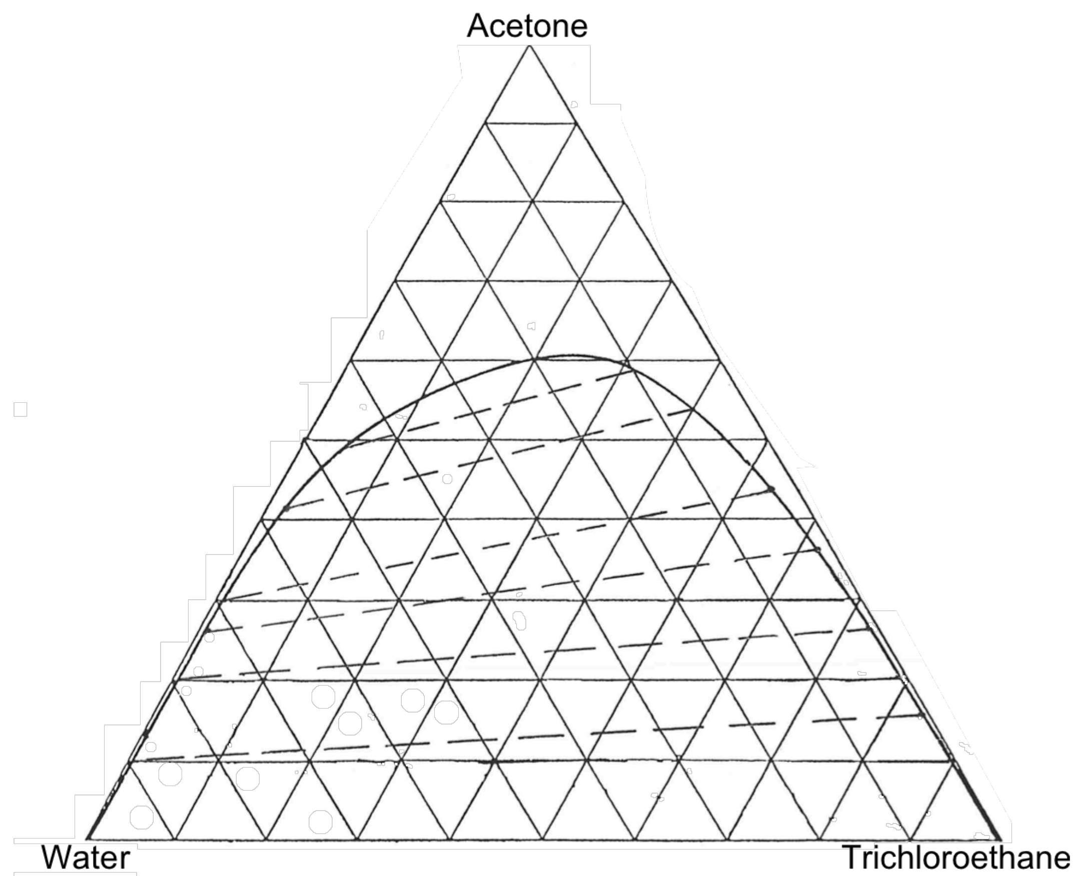
$$h = 0.151\frac{G^{0.59}}{d_p^{0.41}}$$

1. Explain why food products often require a specific level of dryness. **[2]**
2. Since these particles are not spherical, *justify* a suitable equivalent-particle diameter to use as d_p in the above heat transfer correlation. **[2]**
3. Now *calculate* this equivalent-particle diameter. **[4]**
4. Calculate the drying time required *in minutes*. State any assumptions made. **[10]**

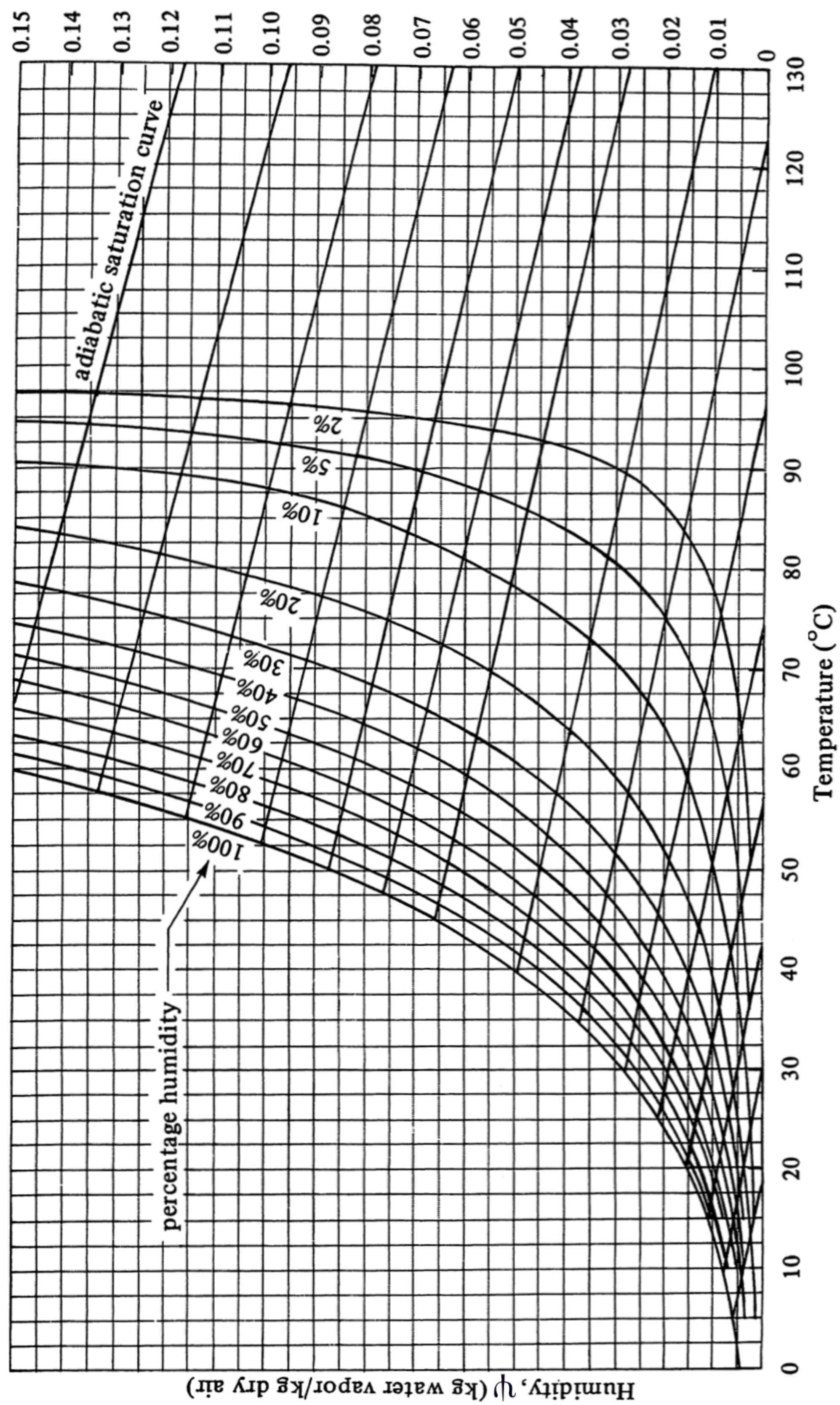
   Note: for packed beds, it is common practice to use only 50% of the external air stream velocity as the effective velocity within the packed bed.
5. This correlation requires the packed bed Reynolds number, $N_{\text{Re}} = \dfrac{d_p G}{\mu} > 350$, where the air's viscosity is approximately $2 \times 10^{-5}\,\text{kg.m}^{-1}.\text{s}^{-1}$. Is this condition met? Note that G must be expressed in SI units for calculating the Reynolds number. **[4]**
6. Describe a parameter you could adjust on the drier to decrease the drying time, and why your change would work. You can consider minor capital expenditure to implement this change. **[2]**

Student number: ______________

Question number: ______________



Feel free to use this page for calculations as well


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

The end.