Final Exam

(Open Book, 3 hours)

Name ________________ Key

INSTRUCTIONS: Please read the following before beginning the exam.

- *Please show all work for each problem in the space provided. If there is insufficient space provided, use the back of the page. Be sure to indicate in the space provided that additional work is on the back.*
- *Circle your answers. Be sure to include units!*
- *A teaching assistant or the instructor will be in the room at all times. Feel free to ask questions.*
- *First answer those questions which require no calculation. Trial-and-error should not be necessary.*
- *If a subsequent question requires a numerical answer from a previous question (which you are unable to answer), take any reasonable value for the previous question or assign a variable name to the previous answer; then proceed with the subsequent question. You will not be penalized twice for missing the previous question.*

Code Number for Posting Grades

After the exam is graded, I will post a tabulation of all grades using your current 4-digit indentification number (PIN). If you wish to change your number, please write it below.

Numerical Code: | | | | |

Enter a number only if you want to change it.

1.) A dilute aqueous solution containing 1 mole% ammonia is being stripping of the ammonia by contact with fresh air (no ammonia) in a tower packed with one-inch Raschig rings. At the operating temperature and pressure (1 atm, 25°C) of the stripper, the equilibrium curve for dilute ammonia mixtures in air or water is given by

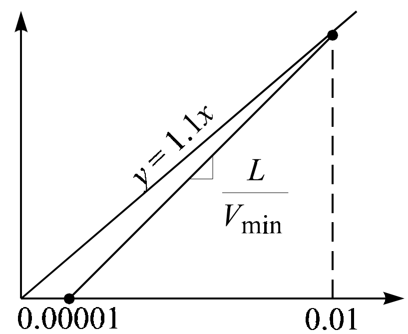
$$y^* = 1.1x$$

You may assume both operating line and equilibrium curve are straight on mole fraction coordinates.

10% a. Find the minimum air flowrate (in moles of air per mole of water) required to remove 99.9% of the ammonia from the water.

$$\frac{L}{V_{min}} = \frac{1.1 \times 0.01 - 0}{0.01 - 0.00001} = 1.10$$

So V_{min}/L = **0.908** moles of air per mole of water.



15% b. Using an air flowrate of 1 mole of air per mole of water, how many overall gas-phase transfer units are required to accomplish the desired separation.

The outlet gas concentration becomes

$$y_a = y_b + \frac{L}{V}(x_a - x_b) = 0 + 1(0.01 - 0.00001) = 0.0100$$

$$y_a^* = 1.1x_a = 0.0110$$

$$y_a^* - y_a = 0.0110 - 0.0100 = 0.0010$$

$$y_b = 0$$

$$y_b^* = 1.1x_b = 1.1(0.00001) = 0.0000110$$

$$y_b^* - y_b = 0.0000110 - 0 = 0.0000110$$

For a straight OL and EC, we can use

$$N_{Oy} = \frac{y_b - y_a}{\overline{(y - y^*)}_L} = \frac{y_a - y_b}{\overline{(y^* - y)}_L}$$

$$\overline{(y^* - y)}_L = \frac{(y^* - y)_a - (y^* - y)_b}{\ln \frac{(y^* - y)_a}{(y^* - y)_b}} = \frac{0.001 - 0.00001}{\ln \frac{0.001}{0.00001}} = 2.15 \times 10^{-4}$$

Finally $$N_{Oy} = \frac{y_a - y_b}{\overline{(y^* - y)}_L} = \frac{0.01 - 0}{2.15 \times 10^{-4}} = \mathbf{46.5}$$

5% c. Suppose the answer to part b) is greater than the number of transfer units available in the existing stripper. How would you change the gas flowrate (increase or decrease?) to reduce the number of transfer units required for the separation?

To reduce the number of transfer units, we need to increase the driving force for mass transfer (y*-y). This can be accomplished by lowering the slope of the operating line so it is further from the equilibrium curve. Since the slope is L/V, we need to **increase V.**

20% 2.) Suppose the stripping operation of Problem 1 were performed in a tray tower instead of a packed tower. How many ideal trays would be required? The air flowrate is that given in part 1b.

The "tower" consists of one countercurrent cascade of stages with the aqueous ammonia solution fed to the top stage and the fresh (ammonia-free) air fed to the bottom stage.

Hint: this problem can be solved without the use of graphs, but a sheet of graph paper is included below for your use.

The operating line and equilibrium curve are the same as in Problem 1. Since both lines are straight, we can calculate the number of ideal trays required using the Kremser equation:

$$N = \frac{\log\left[\left(y_a^* - y_a\right) / \left(y_b^* - y_b\right)\right]}{\log\left[\left(y_a^* - y_b^*\right) / \left(y_a - y_b\right)\right]} = \mathbf{47.4\ ideal\ stages}$$

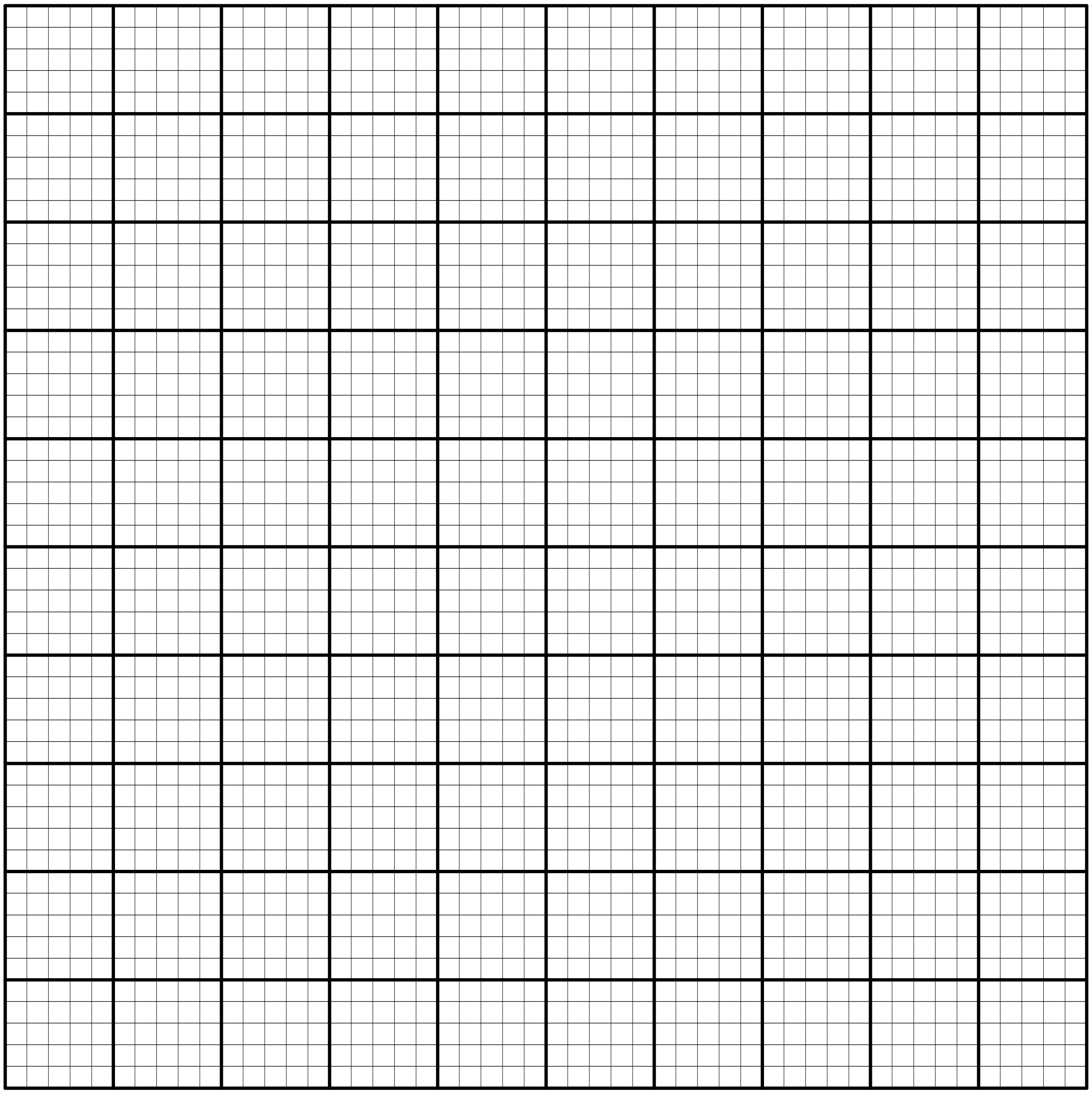
The numbers can be found in our solution to Problem 1:

$$y_a^* - y_a = 0.0010 \quad \text{and} \quad y_b^* - y_b = 0.0000110$$

$$y_a^* - y_b^* = 0.0110 - 0.0000110 = 0.0110$$

$$y_a - y_b = 0.0100 - 0 = 0.0100$$

Because of the large number of steps required, this would not be easily solved graphically: several "blow-ups" would be required.



20% 3.) A hollow-fiber membrane cartridge is being considered to produce a gas containing at least 95 mole% nitrogen using air (79 mole% nitrogen, 21 mole% oxygen) as the feed. Previous experiments have shown that the available membrane is ten times more permeable to oxygen than nitrogen. Is it possible to produce the desired nitrogen-rich gas using the available membrane in a single cartridge and air as the feed? Multiple stages are not permitted (for economic reasons).

Although a simple "yes" or "no" answer is finally required, you must include some calculations and an explanation to support your answer.

Since the membrane is more permeable to oxygen, the permeate will always have a higher oxygen concentration than the feed and a lower nitrogen concentration; thus we are interested in the reject stream, which will be depleted in oxygen and enriched in nitrogen. The greatest depletion of oxygen (highest nitrogen concentration) will occur for a stage cut approaching unity. The lowest oxygen concentration in the reject stream can be calculated from Geankoplis eq. (13.4-12):

$$\lim_{\theta \to 1} x_{out} = \frac{x_{in}\left[1 + R(\alpha - 1)(1 - x_{in})\right]}{\alpha - (\alpha - 1)x_{in}} = 0.026$$

The smallest value of x_{out} is obtained using R=0. Substituting $\alpha=10$ and R=0, we obtain the value above. Subtracting from 1, we obtain 97.4 mole% nitrogen as the largest concentration which can be obtained. **Yes**, the cartridge can produce the desired stream.

Unfortunately, the revised Notes contain this equation with a sign error. Using that equation results in a negative value for x_{out}.

Alternate Solution. For R=0 and any stage cut, the permeate concentration is related to the reject concentration by

$$y_{out} = \frac{\alpha x_{out}}{(\alpha - 1)x_{out} + 1} = 0.345$$

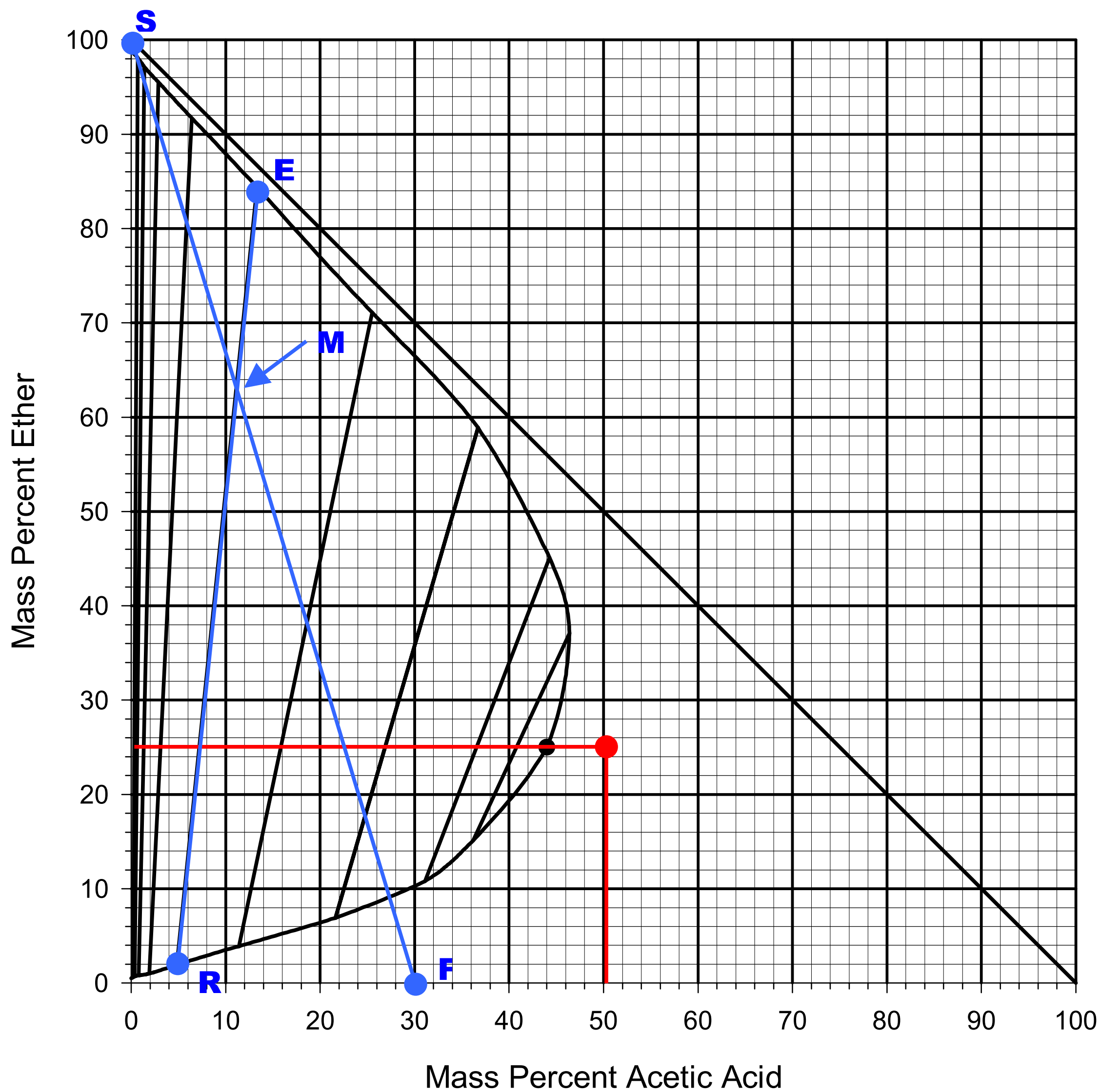
Substituting $\alpha=10$ and the desired $x_{out} = 0.05$, we obtain the value above. To find the stage cut (if any) for which this x_{out} and y_{out} is obtained, we use the component mass balance and definition of stage cut:

$$x_{in} = (1-\theta)x_{out} + \theta y_{out}$$

Solving for θ:

$$\theta = \frac{x_{in} - x_{out}}{y_{out} - x_{out}} = 0.542$$

Substituting $x_{in} = 0.21$ along with x_{out} and y_{out}, we obtain the stage cut value above. Since this value is in the interval of nonextraneous values $0 < \theta < 1$, the desired separation is possible.



5% 4.) One kilogram of acetic acid is mixed with 0.5 kilogram each of isopropyl ether and water and allowed to equilibrate at 25°C. Use the rectangular diagram above to determine how many liquid phases are formed at equilibrium.

This mixture has 50% acetic acid and 25% ether. Locating this point on the rectangular diagram above (red point), we see that it is in the **one phase** region.

5.) One hundred kilograms per hour of a 30wt% acetic acid solution (no ether) is contacted with pure isoproply ether in a single mixer-settler. Use the phase diagram on the previous page.

20% a. What flowrate of ether is needed to reduce the acetic acid concentration to 5wt% in the raffinate (water-rich) stream using a single stage?

The mixing point **M** for the two feeds streams must lie somewhere along a straight line connecting the feed point **F** and the solvent point **S**. This is also the mixing point for the two product streams which lie at opposite ends of the same tie line. The tie lie passing through the desired raffinate stream **R** (having 5% acetic acid) is shown. The ratio of the solvent flowrate to the feed flowrate is (from the inverse lever-arm rule) equal to the ratio of the length of line

$$\frac{S}{F} = \frac{63 - 0}{100 - 63} = 1.703$$

where 63wt% is the concentration of ether of the mixing point. Given that F = 100 kg/hr, we obtain S = **170 kg/hr**.

5% b. What is the corresponding concentration of acetic acid in the extract (solvent rich) stream?

This the x-coordinate of the opposite end of the tie line (labelled **E**) which is **13wt%** acetic acid.