Exam II

(Open Book, 50 min.)

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.*

Code Number for Posting Grades

After the exam is graded, I will post on the web a tabulation of all grades by PIN. If you would like to change your PIN, please enter the new value here.

Numerical Code: ☐☐☐☐

Enter a number only if you want to change your PIN.

1.) The major assumption in the McCabe-Thiele method is called "equimolar overflow."

5% a. What is the main consequence of this assumption upon the liquid and vapor flowrates within the enriching (rectifying) section of a distillation tower? In other words, what relationships among L_i and V_i (i = 1, 2, … N_E) are implied by equimolar overflow?

The liquid flowrate leaving each stage in the cascade is the same:

$$L_1 = L_2 = \ldots = L_{NE}$$

and the vapor flowrate leaving each stage is the same:

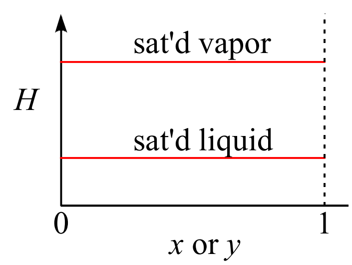
$$V_1 = V_2 = \ldots = V_{NE}$$

5% b. Does this consequence apply to mass flowrates, molar flowrates or volumetric flowrates?

The L's and V's above are **molar** flowrates.

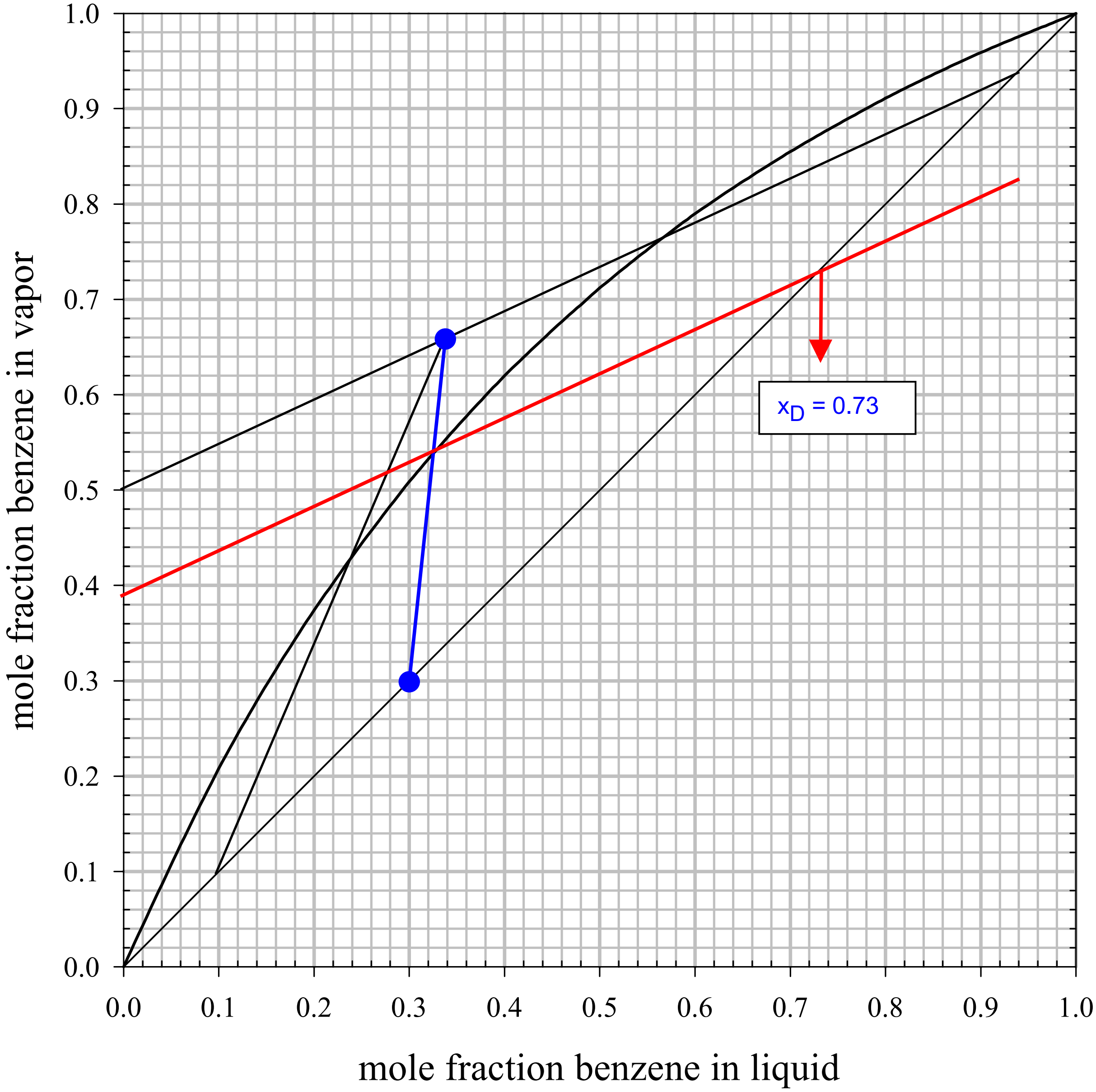
10% c. Sketch the enthalpy-concentration (i.e. Hxy) diagram for saturated vapor and saturated liquid (at constant pressure) which would exactly imply equimolar overflow.

We arrived at the equimolar overflow condition by neglecting sensible heat effects relative to latent heat effects. In other words, all that matters in the determination of enthalpy of any stream is whether it's liquid or vapor: in particular, temperature and composition are unimportant.



d. What is the main consequence of the equimolar overflow assumption upon the <u>shape</u> of the rectifying section operating line (i.e. the ROL)? In other words, just by looking at the ROL (drawn by Chemsep, say), how could you tell if equimolar overflow was assumed or not?

The ROL will be a **straight line** (not curved) under conditions of equimolar overflow.



2.) Above is an xy-diagram summarizing the vapor-liquid equilibrium of mixtures of benzene and toluene at 1 atm pressure. A feed containing 30 mol% benzene is to be fractionated to produce a distillate product of 94 mol% benzene and a bottoms product of 10 mol% benzene. As a first step in starting to solve this problem, a fellow student has drawn the operating lines shown on the graph.

10% a. What is wrong with the operating lines as drawn?

They intersect above the equilibrium curve (EC). If we started stepping off trays, starting at x_D, we could never get below the intersection between the ROL and the EC. This means that even with an infinite number of trays, we cannot achieve the separation.

5% b. What value of the reflux ratio was used?

Two points on the ROL are (x_D, x_D) and $(0, x_D/(R+1))$. We can read the y-intersept of the ROL as

$$\frac{x_D}{R+1} = 0.5$$

Substituting $x_D = 0.94$ and solving for R yields **0.88**.

10% c. What is the thermal condition of the feed (subcooled liquid, saturated liquid, two-phase mixture, saturated vapor or superheated vapor)?

The Q-line is drawn by connecting the feed point $(z_F, z_F) = (0.3, 0.3)$ with the intersection of the two operating lines (see the blue line on the xy-diagram). The thermal condition of the feed is related to the the slope of this line, which is positive:

$$\frac{q}{q-1} > 0 \text{ which implies } q>1$$

For two-phase mixtures, q is the liquid fraction. Having a liquid fraction greater than one means the **liquid is subcooled**.

5% d. Of the feed, distillate product and bottoms product, which stream has the highest temperature?

Generally the most volatile component (lowest boiling point) leaves in the distillate stream, while the least volatile component (highest boiling point) leaves in the bottoms, with the feed being in between. So the hottest stream is usually the **bottoms**.

15% e. What is the highest concentration of benzene which can be obtained in the distillate product (with a very large number of stages) for the reflux ratio used to draw the operating lines shown?

The minimum reflux ratio usually corresponds to the ROL passing through the intersection of the QL with the EC. Recall that the slope of the ROL is R/(R+1). We draw a line parallel to the original ROL (to keep R the same) which passes through the intersection of the QL with the EC. This line intersects the 45°-line at $\mathbf{x_D = 0.73}$. This represents the distillate composition which has the given R as the minimum reflux ratio for this separation.

10% 3.) In the previous problem, find the heat duty of the reboiler for a feed flowrate of 100 mol/min of saturated liquid and a reflux ratio of 3. These conditions need not correspond to those of the operating lines drawn. You may assume the column has a total condenser and a partial reboiler. The heat of vaporization is 33 kJ/mol.

The distillate flowrate is first calculated from

$$\frac{D}{F} = \frac{z_F - x_B}{x_D - x_B} = \frac{0.3 - 0.1}{0.94 - 0.1} = 0.238 \text{ so } D = 0.238(100) = 23.8 \text{ mol/min}$$

The vapor flowrate in the top section is V = (R+1)D = 4×23.8 = 95.2 mol/min. The vapor flowrate in the bottoms section is lower by the vapor fraction of the feed or (1-q)F. For a saturated liquid feed (q=1), the vapor fraction is zero so Vbar is the same. Finally, the heat duty is just the vapor flowrate times the latent heat: (95.2)(33) = **3140 kJ/min**.

10% 4.) Some of the variables which <u>must</u> be input to Chemsep are the number of stages above the feed and the number of stages below the feed. For a given composition and thermal condition specified for the feed, distillate and bottoms streams, we wish to use Chemsep to determine the minimum reflux ratio. In a sentence or two, describe a series of simulations which can be performed on Chemsep which will yield the <u>minimum reflux ratio</u>.

Hint: you might want to start by defining what is generally meant by "minimum reflux ratio."

Minimum reflux ratio corresponds to making the desired separation using a very large number of trays. If we specify the distillate and bottoms composition, the reflux ratio can be calculated from the output for a given number of stages in each section. The general idea to increase the number of stages and record the reflux ratio for each set of inputs. As $N \rightarrow \infty$ the reflux ratio should converge to the minimum value.

<u>Comment</u>: although I don't expect students to know this, the reflux ratio obtained in this fashion might depend on how the total number of trays is distributed between the two cascades. I would be inclined to try assigning different distributions (say 50%-50%, 40%-60%, 30%-70% etc) and obtain Rmin for each. The minimum value of the Rmin's would be the one satisfying the definition. However, no points should be deducted if this refinement is not included.

10% 5.) For a given composition and thermal condition specified for the feed, distillate and bottoms streams, we wish to use Chemsep to determine the <u>minimum number of stages</u>. What happens during a simulation when the number of stages is below the minimum?

If too few stages are specified, Chemsep **will not converge**.