CE407 Exam 01 06/18/2020

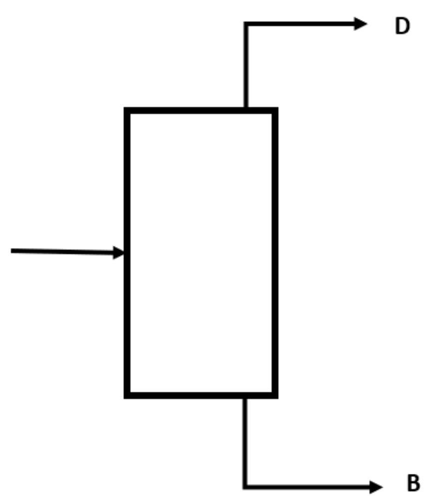
1. (50 points) A 100 mol/minute feed of saturated liquid with a composition of 0.6 mole fraction toluene and 0.4 mole fraction ethylbenzene is fed to a fractionating column. There is a 95% recovery of toluene in the distillate and a 93% recovery of the ethylbenzene in the bottom product. The column is equipped with a total condenser. The column is to operate with a reflux ratio R = 2.5.
   a. What are x_D and x_B?
   b. How many stages are required for this separation?
   c. What is optimal feed stage?
   d. What is the required rate of cooling at the condenser (q_c) and the required rate of heating (q_r) to the reboiler? **Give answers in kJ/hr**
   e. What are the required rates of cooling water and steam? **Give answers in kg/hr**

- Equilibrium data provided via the attached T_{xy} diagram and Vapor Liquid Equilibrium Chart
- Define reference states such that the liquid enthalpy is zero for each pure component at 383.9 K.
- Heat capacity of Water 4.186 kJ/kg C. Allow for a 10 C temperature rise in the cooling water.
- Steam: use 159 psig steam, which has a latent heat of evaporation of 1986 kJ/kg
- **$H_x(T, x)$ = 10,750 x + 185 T – 28 xT – 71,022 J/mol**
- **$H_y(T, y)$ = 27,060 y + 169 T - 65.3 yT - 28870 J/mol**
  - **T is in K for these enthalpy formulas**

Solution:

100 mole basis

Exam 1 Problem 1



D:

1:	0.95 * 60	57.0 mol
2:	40 – 37.2	2.8 mol
Total		59.8 mol

F:

1:	60 mol
2:	40 mol

B:

1:	60 - 57	3.0 mol
2:	0.93 * 40	37.2 mol
Total		40.2 mol

1 = Toluene
2 = Ethylbenzene

a) Calculate mole fraction in the distillate and bottom streams:

$$x_D = \frac{\boldsymbol{mol\ Toluene\ in\ Distillate}}{\boldsymbol{total\ mol\ Distillate}} = \frac{\mathbf{57.0}}{\mathbf{59.8}} = \mathbf{0.953}$$

$$x_B = \frac{\boldsymbol{mol\ Toluene\ in\ Bottoms}}{\boldsymbol{total\ mol\ Bottoms}} = \frac{\mathbf{3.0}}{\mathbf{40.2}} = \mathbf{0.075}$$

b) R operating line is given by the following formula:

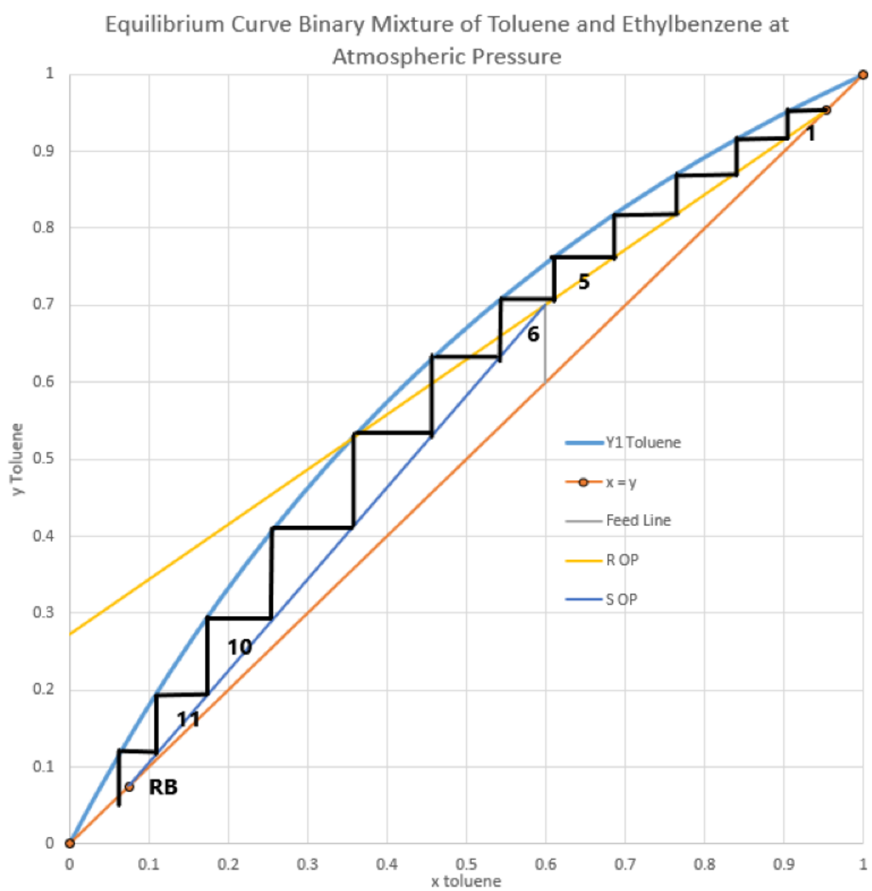
$$y_{n+1} = \frac{x_D}{R+1} + x_n \frac{R}{R+1}$$

This can be easily plotted by placing a point at $(x_D, x_D) = (0.953. 0.953)$

And drawing a line to the intercept $\left(\mathbf{0}, \frac{x_D}{R+1}\right) = (\mathbf{0}, \mathbf{0.273})$

The S operating line can be drawn in easily by placing a point at $(x_B, x_B) = (0.075. 0.075)$ and connecting to the intersection of the feed line (vertical line at x = x_F = 0.6) and the R operating line.

Draw in the steps and determine that there are 11 stages + Reboiler



c) The feed stage is the one that crosses the feed line and is stage 6

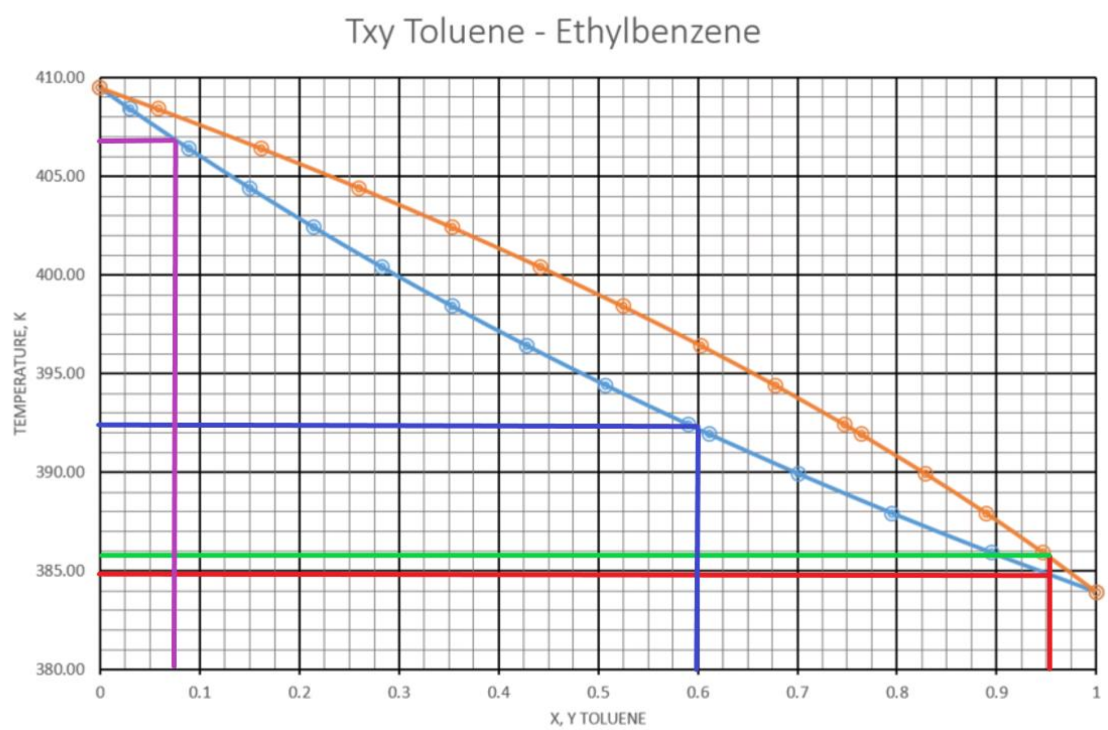
d) Required cooling and heating calculation:

$$-q_c = D(1+R)(H_{x,0} - H_{y,1})$$
$$q_r - q_c = DH_D + BH_B - FH_F$$

From preliminary calculations we know that:
F = 100 mol/min
D = 59.8 mol/min
B = 40.2 mol/min

We need to determine the temperature of the Feed, Distillate, and Bottoms streams in order to evaluate the enthalpies of these streams. This information can be obtained from the T_{xy} diagram:

Temperature of Distillate (D & x_0) is that of saturated liquid at x = 0.953 and is 385 K
Temperature of Vapor entering condenser (y_1) is that of saturated vapor at y = 0.953 and is 386 K
Temperature of Feed (F) is that of saturated liquid at x = 0.6 and is 392.5 K
Temperature of Bottoms (B) is that of saturated liquid at x = 0.075 and is 407 K



From problem statement:

$$H_x(T, x) = 10{,}750\, x + 185\, T - 28\, xT - 71{,}022 \text{ J/mol}$$
$$H_y(T, y) = 27{,}060\, y + 169\, T - 65.3\, yT - 28870 \text{ J/mol}$$

Evaluate Enthalpies:

$H_{x,0}(T, x) = H_D(T, x) = H_x(385 \text{ K}, 0.953) = 10{,}750 * 0.953 + 185 * 385 - 28 * 0.953 * 385 - 71{,}022 \text{ J/mol} = 174.4 \text{ J/mol}$

$H_{y,1}(T, y) = H_{y,1}(386 \text{ K}, 0.953) = 27{,}060 * 0.953 + 169 * 386 - 65.3 * 0.953 * 386 - 28870 \text{ J/mol} = 38{,}131.1 \text{ J/mol}$

$H_B(T, x) = H_x(407, 0.075) = 10{,}750 * 0.075 + 185 * 407 - 28 * 0.075 * 407 - 71{,}022 \text{ J/mol} = 4224.6 \text{ J/mol}$

$H_F(T, x) = H_x(392.5, 0.6) = 10{,}750 * 0.6 + 185 * 392.5 - 28 * 0.6 * 392.5 - 71{,}022 \text{ J/mol} = 1446.5 \text{ J/mol}$

$$-q_c = D(1+R)\left(H_{x,0} - H_{y,1}\right)$$

$$-q_c = 59.8\,\frac{mol}{min} * \frac{60\ min}{hr} * (1+2.5) * (174.4 - 38{,}131.1)\frac{J}{mol}$$

$$q_c = 4.767 * 10^8\,\frac{J}{hr} = 4.767 * 10^5\,\frac{kJ}{hr}$$

$$q_r - q_c = DH_D + BH_B - FH_F$$

$$q_r - 4.766 * 10^8\,\frac{kJ}{hr} = \left(59.8 * \frac{mol}{min} * 174.4 + 40.2\,\frac{mol}{min} * 4224.6\,\frac{J}{mol} - 100\,\frac{mol}{min} * 1446.5\,\frac{J}{mol}\right) * \frac{60\ min}{hr}$$

$$q_r = 4.788 * 10^8\,\frac{J}{hr} = 4.788 * 10^5\,\frac{kJ}{hr}$$

e) **<u>Cooling water requirement</u>**

$C_{p,\,water}$ = 4186.8 J/(kg C)

q_c = (mass flow cooling water) * $C_{p,\,water}$ * ($T_{out} - T_{in}$)

$4.767 * 10^8$ J/hr = **m** * 4186.8 J/(kg C) * 10 C

$m_{cooling\ water}$ = 11,386 kg/hr

<u>Steam Requirement</u>

ΔH^{vap}_{steam} = 1986 kJ/kg

q_r = (mass flow steam) * ΔH^{vap}_{steam}

$4.788 * 10^5$ kJ/hr = **m** * 1986 kJ/kg

m_{steam} = 241.1 kg/hr

2. (35 points) A 200 mol/hr stream of contaminated air (composition 96 mole percent air, 4 mole percent toxin) must be cleaned up by countercurrent contact with water in an absorption tower operating isothermally at 25 C and atmospheric pressure. The exiting air should have toxin mole fraction no greater than 0.003. Entering water is pure.

   a. What is the minimum flow rate of water required to achieve the desired cleanup, corresponding to an infinite number of stages? *Hint: Curvature of equilibrium line will lead to first contact occurring at the "b" (or "dirty") end of the tower.*
   b. If the entering water flow rate is 20.0 mole/hr, how many ideal stages are required? *Calculate at least three points on the operating curve in order to capture its shape.*

As usual, you may neglect evaporation of water as well as dissolution of air in the liquid. The equilibrium curve is provided.

Solution:

At **a** end of tower we are given that:

$$y_a = 0.003 = \frac{V_a \, mol \, toxin}{V_a \, mol \, toxin + V_c \, mol \, air}$$

The moles of air exiting will be the same as the moles entering:

$$mol \, air = 0.96 * 200 \, mol \, total = 192 \, mol \, air$$

Therefore:

$$y_a = 0.003 = \frac{V_a \, mol \, toxin}{V_a \, mol \, toxin + 192}$$

$$V_a \, mol \, toxin = 0.578 \, mol$$

Mole balance on toxin:

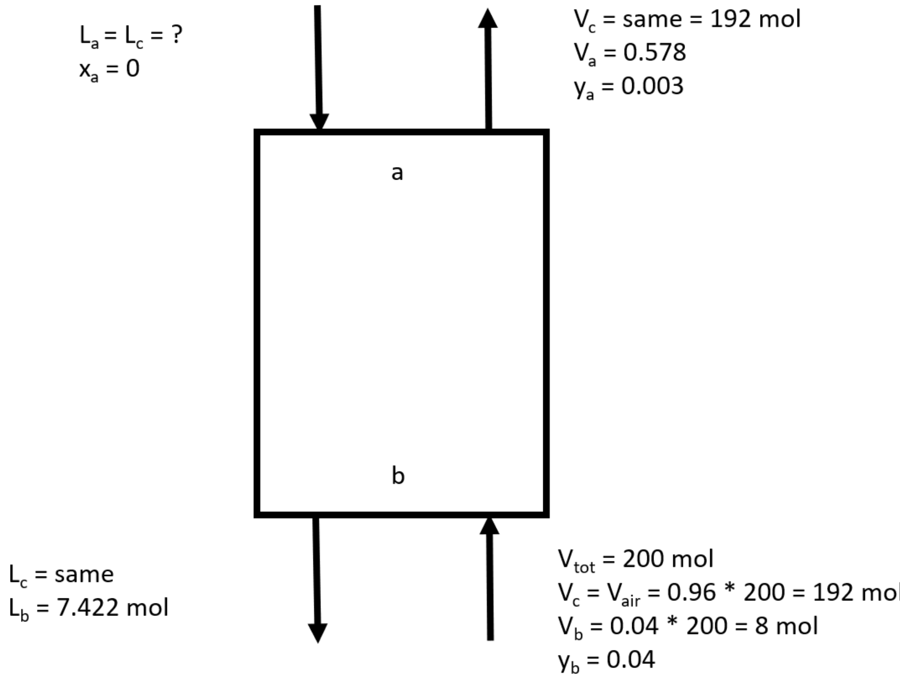
$$Entering = Exiting$$

$$200 * 0.04 + 0 = 0.578 + \ L_b$$

$$L_b = 7.422 \, mol$$

Exam 01 Problem 02

1 hour basis



Calculate Minimum Water Flow:

Problem states that we can look for first contact at the "b" end, therefore at minimum water flow the exiting liquid will be in equilibrium with the entering gas:

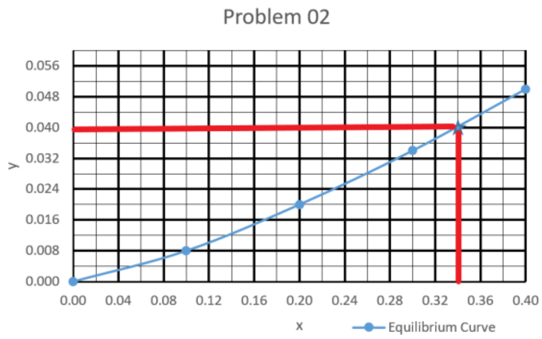
$$y_b = y^*(x_{b,min})$$

or

$$x_{b,min} = x^*(y_b)$$

From the equilibrium data on the graph:

$$y_b = 0.04 \rightarrow x_{b,min} = 0.34$$



$$x_{b,min} = 0.34 = \frac{L_b\ mol\ toxin}{L_b\ mol\ toxin + L_{c,min}} = \frac{7.422\ mol/hr}{7.422\ mol/hr + L_{c,min}}$$

a) Minimum Liquid Flow

$$\boldsymbol{L_{c,min} = 14.41\ mol/hr}$$

b) For a liquid flow of

$$\boldsymbol{L_c = 20\ mol}$$

$$\boldsymbol{x_b = \frac{L_b\ mol\ toxin}{L_b\ mol\ toxin + L_{c,min}} = \frac{7.422\ mol/hr}{7.422\ \frac{mol}{hr} + 20\ \frac{mol}{hr}} = 0.27}$$

Calculate points on the operating line:

$$y_{n+1} = 1 - \left[\frac{L_c}{V_c}\left(\frac{1}{1-x_n} - \frac{1}{1-x_a}\right) + \frac{1}{1-y_a}\right]^{-1}$$

$L_c = 20$

$V_c = 192$

$x_a = 0$

$y_a = 0.003$

$$y_{n+1} = 1 - \left[\frac{20}{192}\left(\frac{1}{1-x_n} - \frac{1}{1-0}\right) + \frac{1}{1-0.003}\right]^{-1}$$

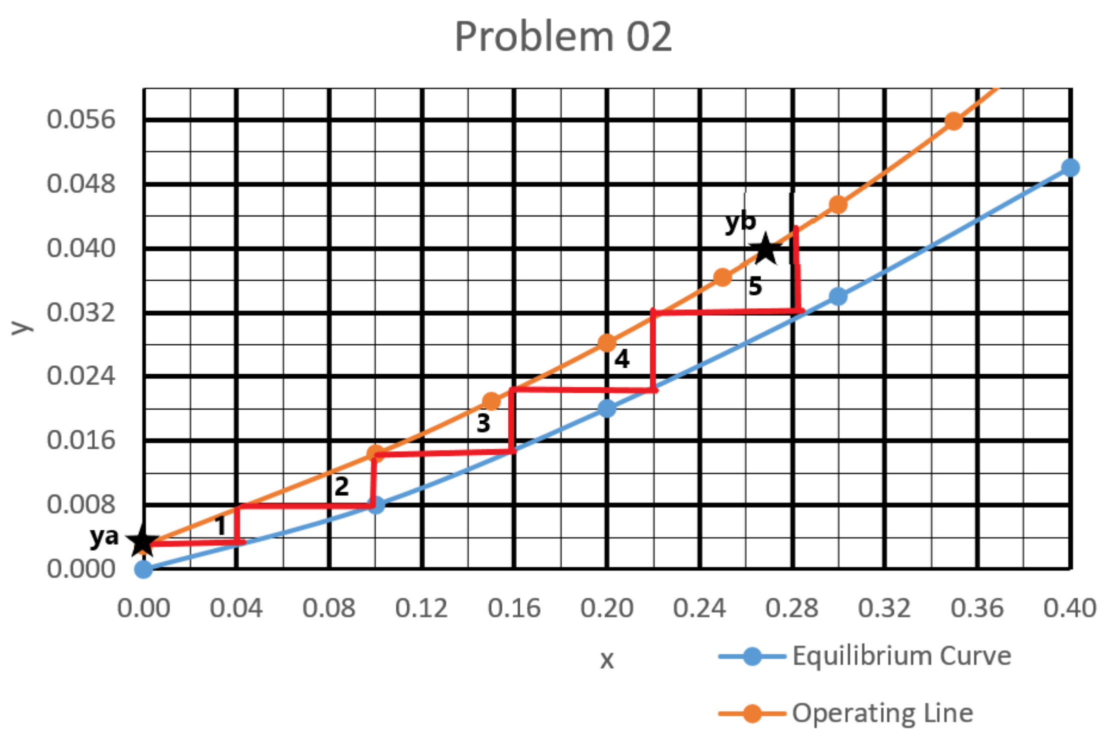
$$y_{n+1} = 1 - \left[0.1042\left(\frac{1}{1-x_n} - 1\right) + 1.003\right]^{-1}$$

Operating Line	
xn	yn+1
0	0.003
0.1	0.014373
0.15	0.020943
0.2	0.028231
0.25	0.036359
0.3	0.045484
0.35	0.055801
0.4	0.067559

We will now step off the stages starting on the operating line at the "a" end:

$(x_a, y_a) = (\mathbf{0}, \mathbf{0.003})$ and step off to the point $(x_b, y_b) = (\mathbf{0.27}, \mathbf{0.04})$

We see that it will require about 4.75 stages – round to 5 stages



3. (15 points) A ternary mixture with the following composition is to be split into separate streams of (relatively) pure components. If each column is capable of 98% recovery of the light key in the distillate and 98% recovery of the heavy key in the bottoms, design a column sequence and calculate the final purity of each component.

Component	Mole Fraction
C3	0.25
C4	0.30
C8	0.45

100 mole basis

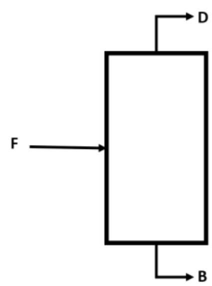
Problem 3 Column 1

Feed:

C_3: 25 mol

C_4: 30 mol

C_8: 45 mol



LK = C_3
HK = C_4

Distillate sent to Product 1
Bottoms sent to Column 2

Distillate (D):

C_3:	0.98 * 25	24.5 mol	x = 24.5/25.10 =	0.976
C_4:	30-29.40	0.60 mol	x = 0.60/25.10 =	0.024
C_8:		0 mol	x =	0
Total		25.10 mol		

Bottoms (B):

C_3:	25 – 24.5	0.50 mol
C_4:	0.98 * 30	29.40 mol
C_8:		45.00 mol
Total		74.90 mol

100 mole basis

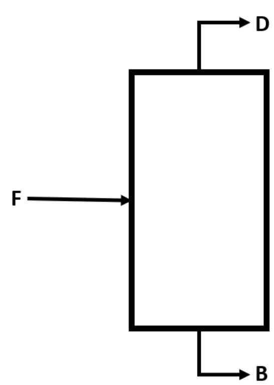
Problem 3 Column 2

Feed:

C_3: 0.50 mol

C_4: 29.40 mol

C_8 45.00 mol



LK = C_4
HK = C_8

Distillate sent to Product 2
Bottoms sent to Product 3

Distillate (D):

C_3:		0.50 mol	x = 0.50/30.21 =	0.016
C_4:	0.98 * 29.40	28.81 mol	x = 28.81/30.21 =	0.954
C_8:	45 – 44.10	0.90 mol	x = 0.90/30.21 =	0.030
Total		30.21 mol		

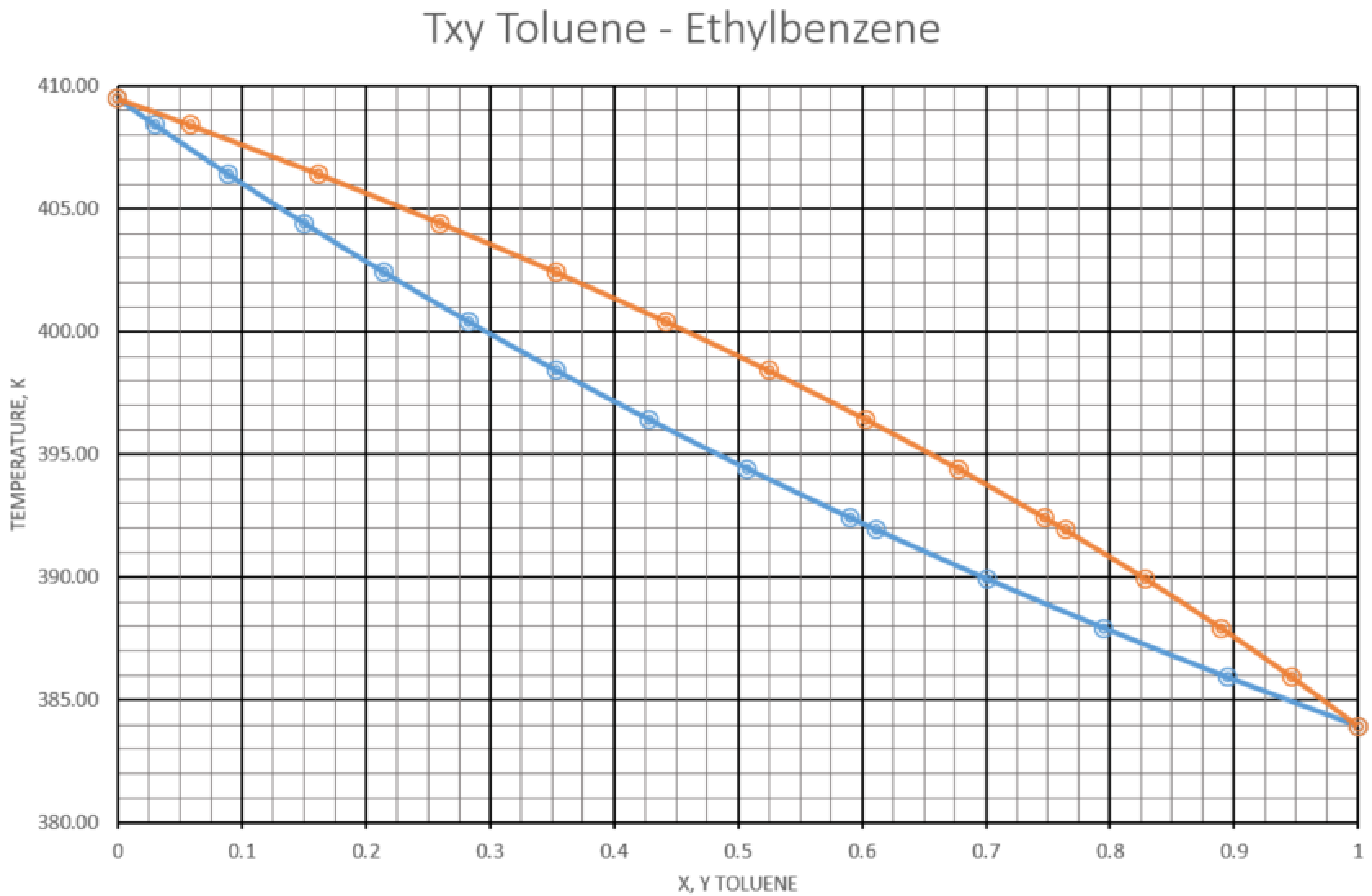
Bottoms (B):

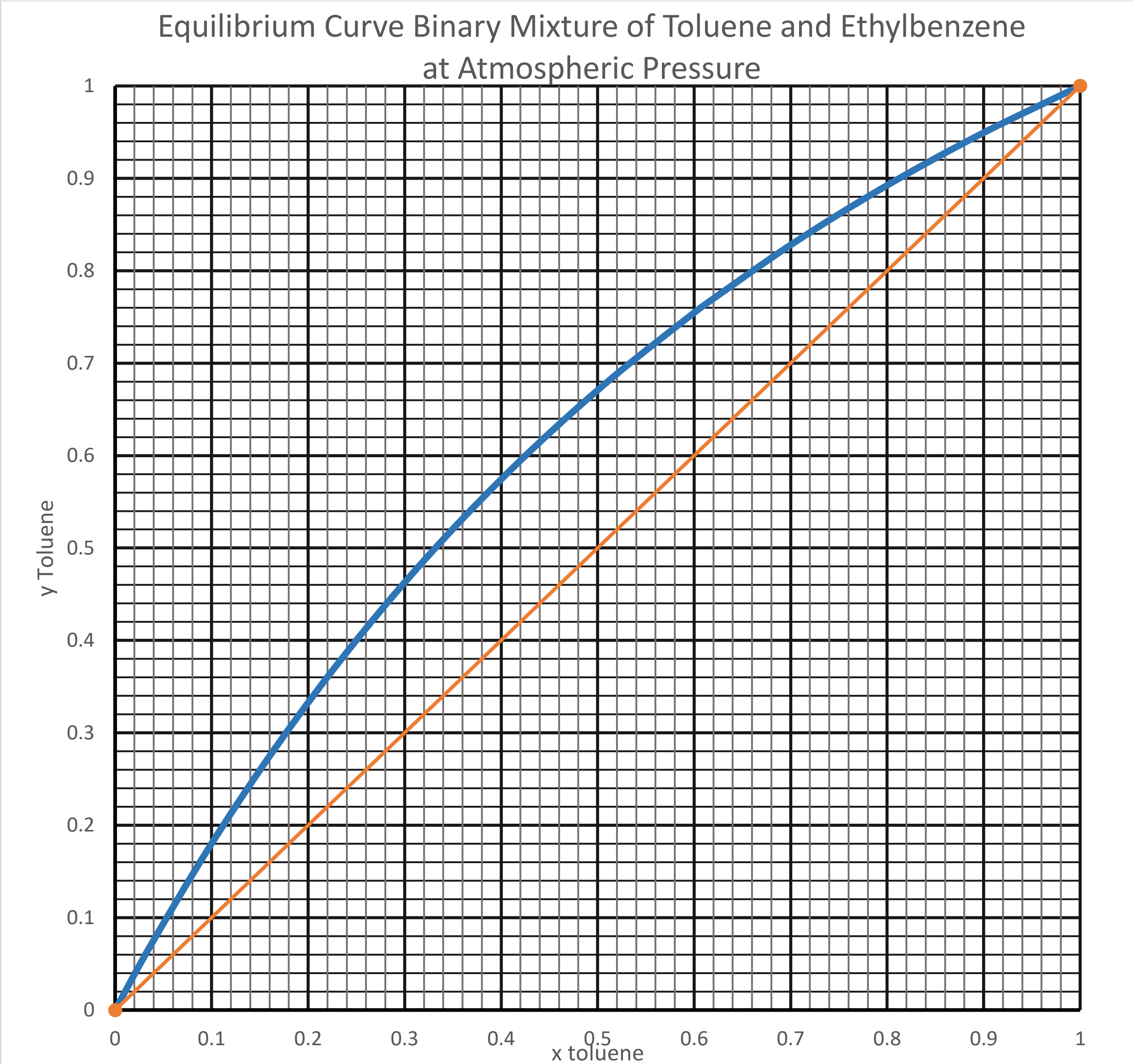
C_3:		0 mol	x = 0/44.69 =	0.00
C_4:	29.40 – 28.81	0.59 mol	x = 0.59/44.69 =	0.013
C_8:	0.98 * 45	44.10 mol	x = 44.10/44.69 =	0.987
Total		44.69 mol		

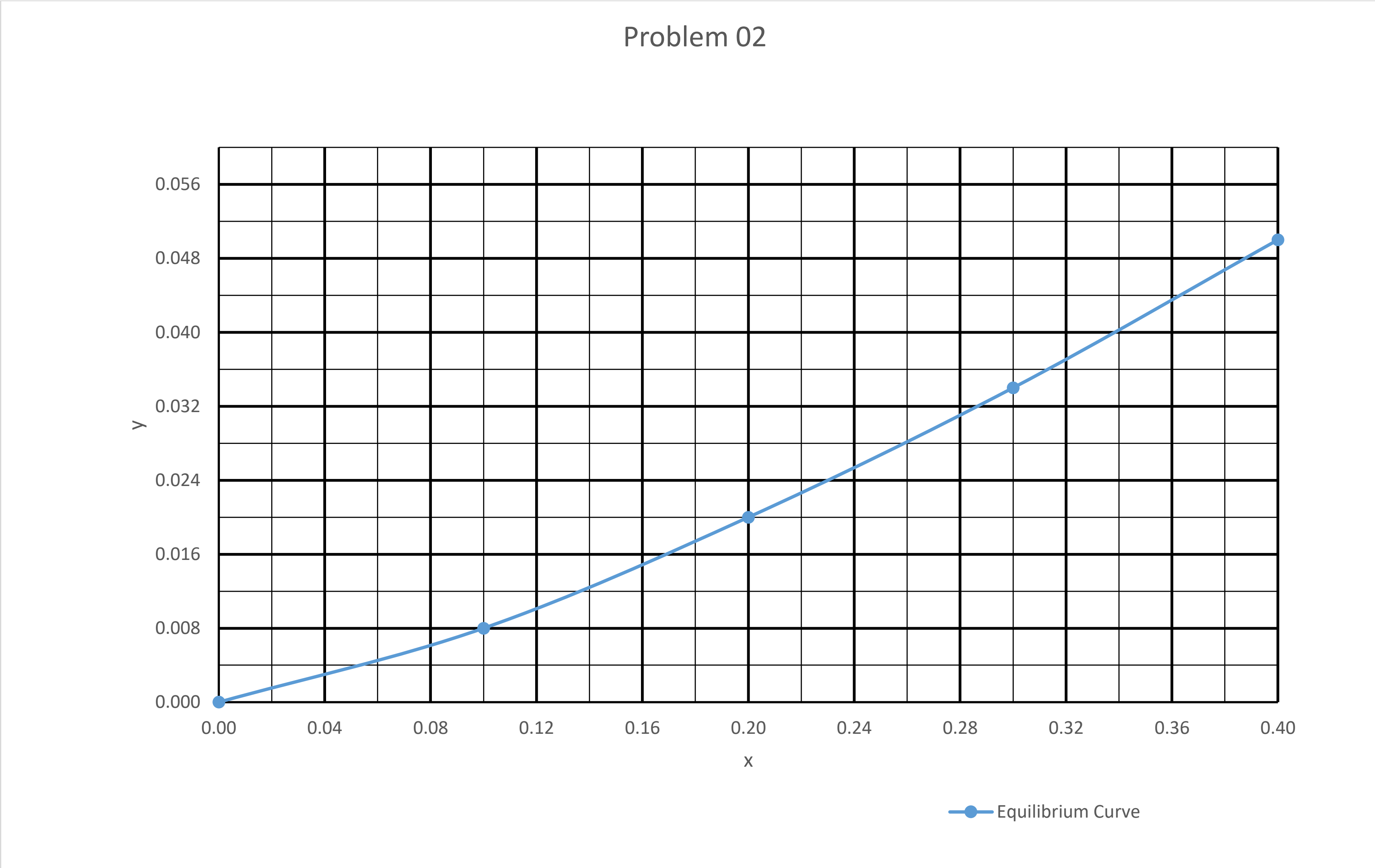
C_3 product has mole fraction x = 0.976

C_4 product has mole fraction x = 0.954

C_8 product has mole fraction x = 0.987


Txy Toluene - Ethylbenzene
410.00
405.00
400.00
395.00
390.00
385.00
380.00
TEMPERATURE, K
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
X, Y TOLUENE


Equilibrium Curve Binary Mixture of Toluene and Ethylbenzene
at Atmospheric Pressure
y Toluene
x toluene
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Problem 02
y
0.056
0.048
0.040
0.032
0.024
0.016
0.008
0.000
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
0.40
x
Equilibrium Curve