

CH3030 APPLICATIONS OF MASS TRANSFER

Assignment 4

CH13B009-R Arun

CH13B059-Shyam Shankar

Problem 1: M. B. Azzie is a plant operator in Dizzy Breweries Ltd. He is in-charge of a flash vaporization unit where 100 mole/h of an equimolar mixture of ethanol-water system at 30°C and 1 atm. is fed to a flash vaporization unit. The vapor and liquid product stream compositions are measured using composition sensors with provisions for alarm if product compositions change from usual steady state values. The flash vaporization unit is operated at 75°C and 0.8 atm. pressure. Azzie, puts a splitter block in the feed stream and diverts 20% of the feed to a tank kept in his truck. Due to this, will the alarm bells ring in the company or Azzie can get away? The Company management suspects something is amiss. (What may have aroused their suspicions?) What will you suggest to them to avoid such further incidents?

You are preparing a report for Dizzy Breweries Ltd. In this report you wish to compare the following before and after the theft.

- a. Bubble point of the original feed mixture = 74.2 Celsius (from the Txy diagram)
- b. Dew point of the vapor product = 78.8 Celsius
- c. Vapor fraction=0.46(approx.)
- d. Product compositions
- e. Rate of energy required to be provided to the heater =158.173 Cal/s
- f. T-x-y diagram for ethanol-water system at 0.8 atm. Use UNIQUAC model.

[20]

Solution:

Flow rate doesn't affect the composition of outlets and hence the **bells won't ring**. They should monitor the heat duty which will vary with flow rate feed to avoid such further incidents.

The bubble point, dew point, Vapor fraction and the Product compositions remain the same. Only the rate of energy required changes, which comes out to be **158.173 Cal/s**.

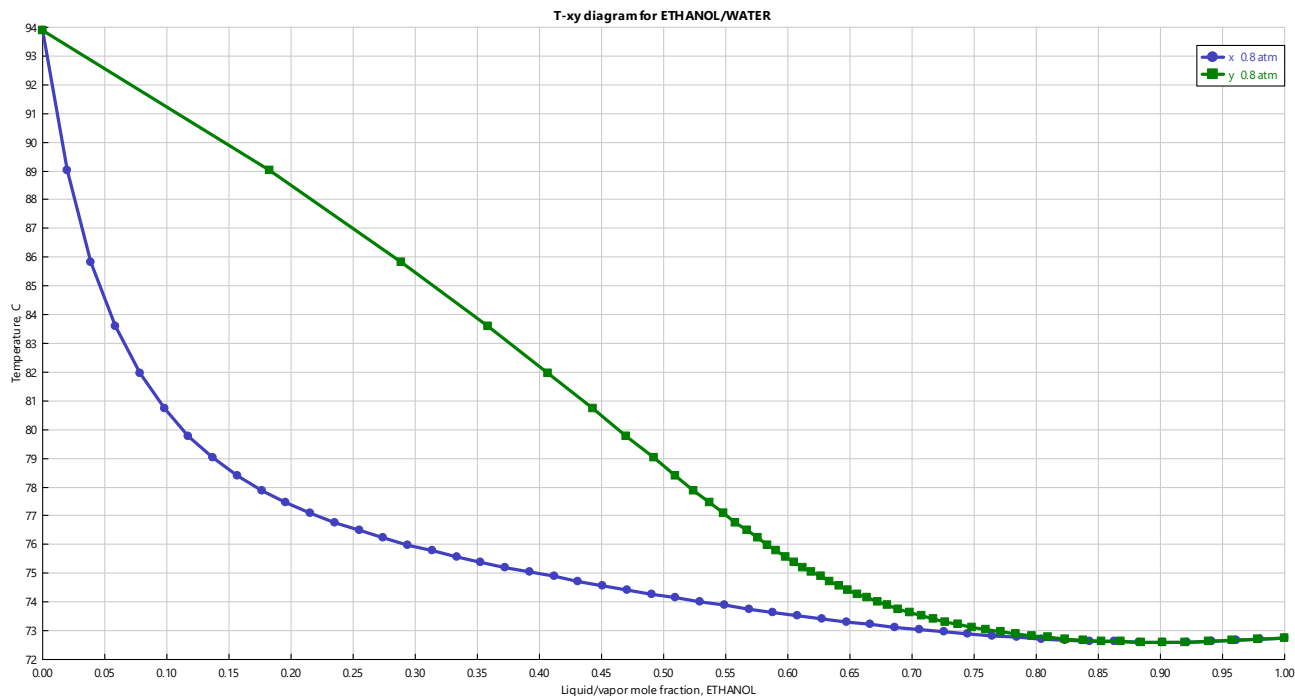
Before theft:

Heat and Material Balance Table				
Stream ID		S2	S5	S6
From		B1	B1	
To				B1
Phase		VAPOR	LIQUID	LIQUID
Substream: MIXED				
Mole Flow	kmol/hr			
ETHANOL		.0284924	.0215075	.0500000
WATER		.0173726	.0326273	.0500000
Mole Frac				
ETHANOL		.6212230	.3972954	.5000000
WATER		.3787770	.6027046	.5000000
Total Flow	kmol/hr	.0458650	.0541349	.1000000
Total Flow	kg/hr	1.625593	1.578623	3.204216
Total Flow	l/min	27.29719	.0326571	.0634086
Temperature	C	75.00000	75.00000	30.00000
Pressure	bar	.8106000	.8106000	1.013250
Vapor Frac		1.000000	0.0	0.0
Liquid Frac		0.0	1.000000	1.000000
Solid Frac		0.0	0.0	0.0
Enthalpy	cal/mol	-56072.27	-66256.78	-67279.87
Enthalpy	cal/gm	-1582.044	-2272.109	-2099.730
Enthalpy	cal/sec	-714.3777	-996.3347	-1868.885
Entropy	cal/mol-K	-33.58914	-51.92739	-60.11532
Entropy	cal/gm-K	-.9476968	-1.780719	-1.876132
Density	mol/cc	2.80035E-5	.0276278	.0262845
Density	gm/cc	9.92527E-4	.8056545	.8422131
Average MW		35.44292	29.16091	32.04216
Liq Vol 60F	l/min	.0328509	.0306679	.0635189

After theft:

Heat and Material Balance Table						
Stream ID		S1	S2	S3	S5	S7
From			B1	B2	B1	B2
To		B2		B1		
Phase		LIQUID	VAPOR	LIQUID	LIQUID	LIQUID
Substream: MIXED						
Mole Flow	kmol/hr					
ETHANOL		.0500000	.0227939	.0400000	.0172060	.0100000
WATER		.0500000	.0138981	.0400000	.0261018	.0100000
Mole Frac						
ETHANOL		.5000000	.6212230	.5000000	.3972954	.5000000
WATER		.5000000	.3787770	.5000000	.6027046	.5000000
Total Flow	kmol/hr	.1000000	.0366920	.0800000	.0433079	.0200000
Total Flow	kg/hr	3.204216	1.300474	2.563373	1.262899	.6408432
Total Flow	l/min	.0634086	21.83776	.0507269	.0261257	.0126817
Temperature	C	30.00000	75.00000	30.00000	75.00000	30.00000
Pressure	bar	1.013250	.8106000	1.013250	.8106000	1.013250
Vapor Frac		0.0	1.000000	0.0	0.0	0.0
Liquid Frac		1.000000	0.0	1.000000	1.000000	1.000000
Solid Frac		0.0	0.0	0.0	0.0	0.0
Enthalpy	cal/mol	-67279.87	-56072.27	-67279.87	-66256.78	-67279.87
Enthalpy	cal/gm	-2099.730	-1582.044	-2099.730	-2272.109	-2099.730
Enthalpy	cal/sec	-1868.885	-571.5022	-1495.108	-797.0678	-373.7771
Entropy	cal/mol-K	-60.11532	-33.58914	-60.11532	-51.92739	-60.11532
Entropy	cal/gm-K	-1.876132	-.9476968	-1.876132	-1.780719	-1.876132
Density	mol/cc	.0262845	2.80035E-5	.0262845	.0276278	.0262845
Density	gm/cc	.8422131	9.92527E-4	.8422131	.8056545	.8422131
Average MW		32.04216	35.44292	32.04216	29.16091	32.04216
Liq Vol 60F	l/min	.0635189	.0262807	.0508151	.0245343	.0127037

Temperature Profile:



Problem 2: 100 kmol/h of an equimolar mixture of benzene and toluene at 70°C and 1 atm. Pressure is to be separated by a 20 stage distillation column. The feed is introduced at the centre of the column and a reflux ratio of 3 is used. A total condenser is used and a residue flow rate of 50 kmol/h is specified. Ignore pressure drop in column for now

- Find the product compositions and flow rates.
- Take a representative stage and check whether material and energy balances are satisfied.
- Plot the stage to stage variation of molar enthalpies and flow rates of the vapor and liquid streams. What do you infer?
- Plot the temperature profile inside the column.
- What is the role played by reflux ratio in distillation?
- Explore the effect of increasing reflux ratio on product purities.
- Vary the feed stage location to see the effect on product purities.

H. Compare the results from this simulation to the famous McCabe Thiele method for binary distillation. [20]

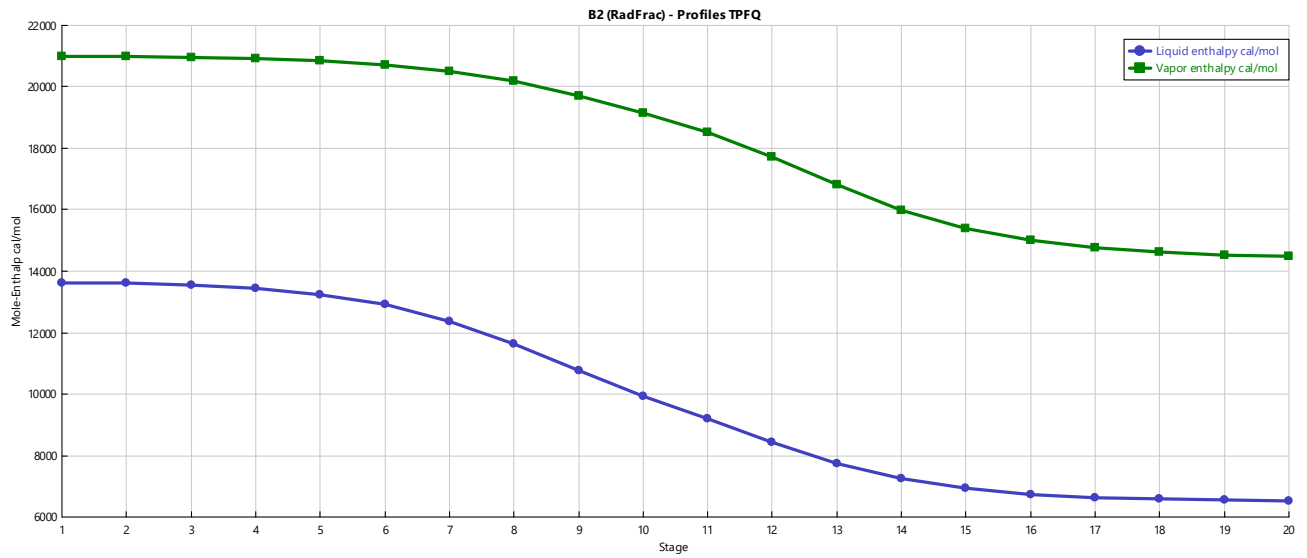
Solution:

a) Product Composition and Flow Rate

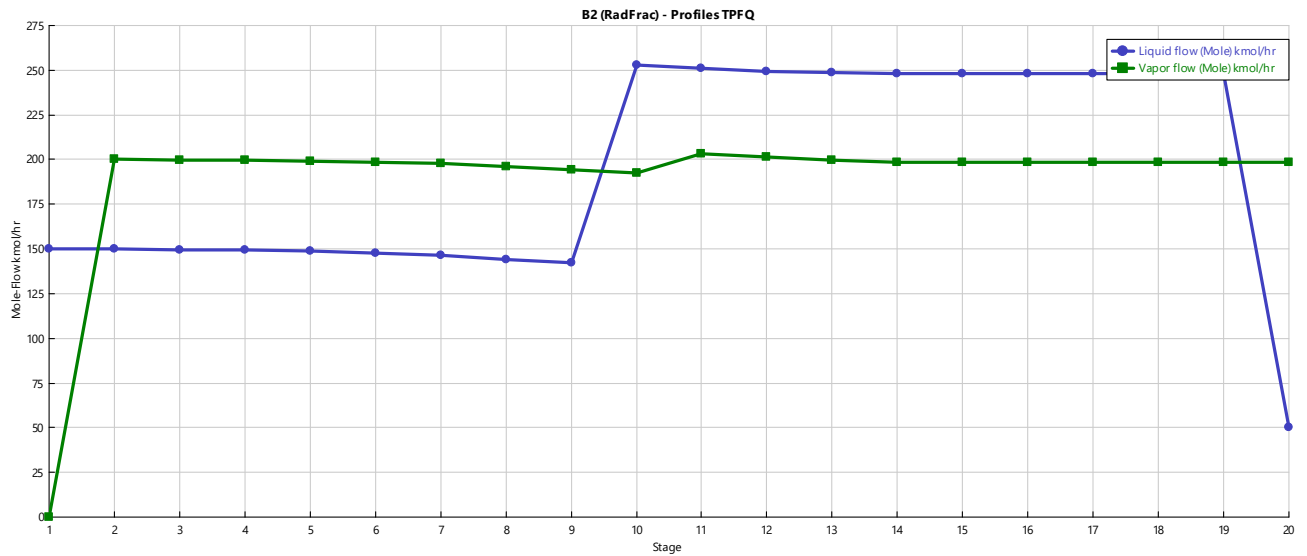
Heat and Material Balance Table				
Stream ID		FEED	HEAVY	LIGHT
From			B2	B2
To		B2		
Phase		LIQ UID	LIQ UID	LIQ UID
Substream: MIXED				
Mole Flow	kmol/hr			
BENZENE		50.00000	.1351015	49.86490
TO WENE		50.00000	49.86490	.1351015
Mole Frac				
BENZENE		.5000000	2.70203E-3	.9972980
TO WENE		.5000000	.9972980	2.70203E-3
Total Flow	kmol/hr	100.0000	50.00000	50.00000
Total Flow	kg/hr	8512.708	4605.131	3907.577
Total Flow	l/min	172.5844	98.30149	79.97312
Temperature	C	70.00000	110.5549	80.18169
Pressure	bar	1.013250	1.013250	1.013250
Vapor Frac		0.0	0.0	0.0
Liquid Frac		1.000000	1.000000	1.000000
Solid Frac		0.0	0.0	0.0
Enthalpy	cal/mol	9010.399	6521.629	13631.31
Enthalpy	cal/gm	105.8464	70.80829	174.4215
Enthalpy	cal/sec	2.50289E+5	90578.18	1.89324E+5
Entropy	cal/mol-K	-64.39450	-71.09208	-54.54265
Entropy	cal/gm-K	-.7564514	-.7718791	-.6979088
Density	mol/cc	9.65711E-3	8.47732E-3	.0104201
Density	gm/cc	.8220814	.7807835	.8143522
Average MW		85.12708	92.10262	78.15154
Liq Vol 60F	l/min	162.0226	88.22580	73.79678

c)

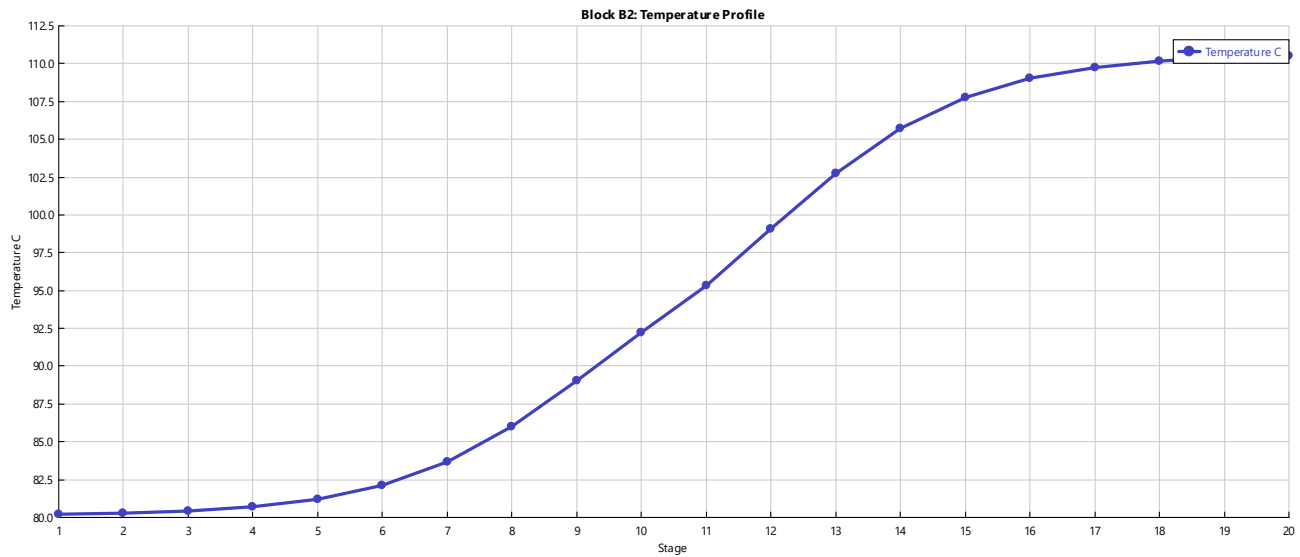
Variation of molar enthalpies of liquid and vapor with stage



Variation of flow rates of liquid and vapor with stage



d) Temperature Profile inside the column



e) Reflux ratio plays determining the purity of the product, concentration profiles within the distillation column, condenser and re-boiler duties. It also helps us in determining an optimum feed stage location.

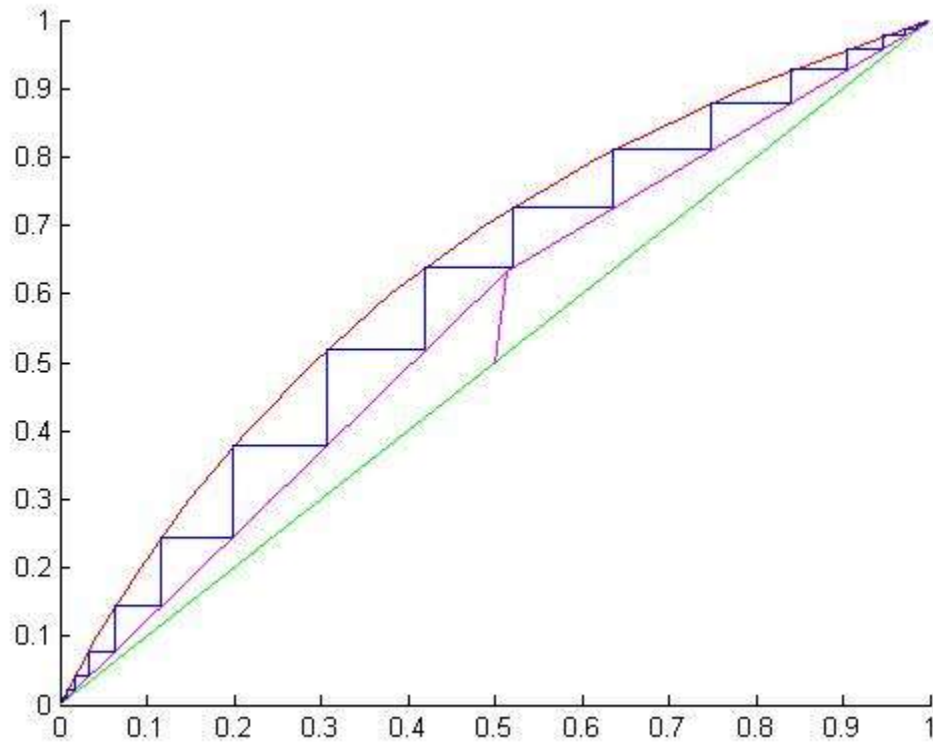
f) As the reflux ratio increases, purity of lighter component in product stream increases and at reflux ratio of infinity, minimum number of plates are required.

g)

Input Stage	Benzene mole fraction In distillate	Toluene mole fraction in distillate
1	0.667822732	0.332177268
2	0.873206447	0.126793553
3	0.928991978	0.0710080215
4	0.96018241	0.0398175904
5	0.977842567	0.0221574327
6	0.987728482	0.0122715179
7	0.993070993	0.006929007
8	0.995745755	0.00425424528
9	0.996913705	0.00308629496
10	0.997297208	0.00270279187
11	0.997206529	0.00279347066
12	0.996612643	0.00338735664
13	0.995169637	0.0048303633
14	0.992182814	0.00781718564
15	0.986557907	0.0134420934
16	0.976615248	0.0233847517
17	0.959792572	0.0402074281
18	0.932252045	0.0677479554
19	0.888227336	0.111772664
20	0.81855810	0.18144181

Optimum stage for feed input is stage 10.

h) From McCabe Thiele Method:



Total Number of stages obtained is **19** using this method which is closer to the actual value.

Problem 3: As an entrepreneur you buy a second hand plant from North America, dismantle it and install it in your locality. You distill a saturated liquid mixture of methanol-water mixture (100 kmol/hr, equimolar mixture, 30°C, 1 atm.) in the distillation column supposedly equipped with 10 ideal stages and feed tray located as the 5th tray from the bottom. Use a total condenser. The recommended reflux ratio is 2.5. Distillate flow rate is 45 kmol/hr. Use UNIFAC as the thermodynamic property model.

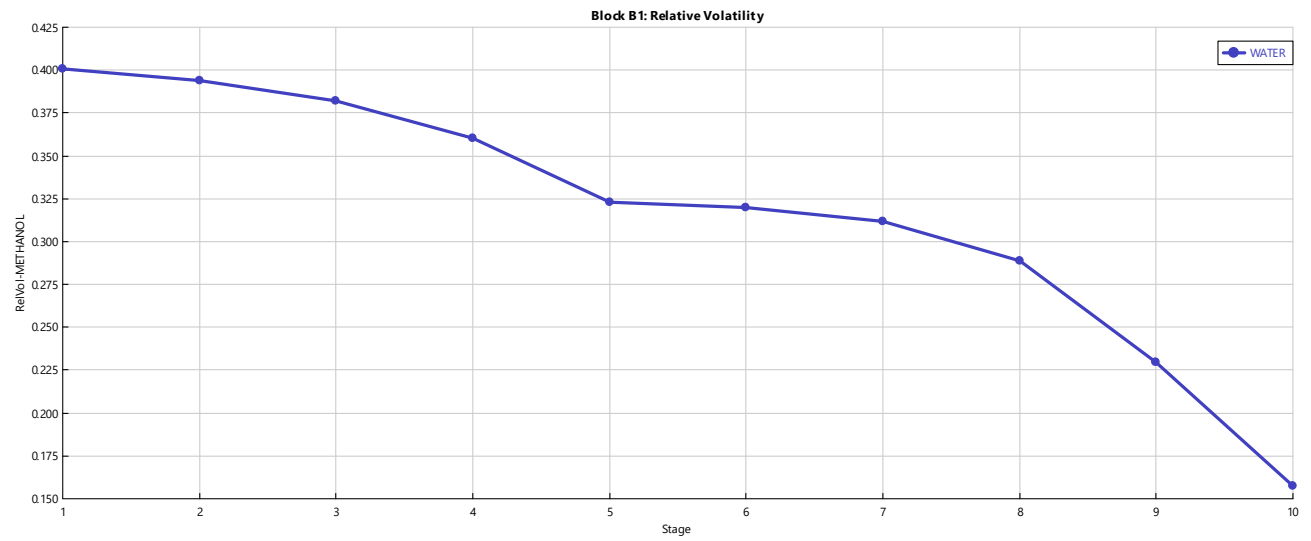
- What are the expected purities of the products?
- Calculate the relative volatilities of the mixture along the column.

[5]

a) Expected purities of products:

Heat and Material Balance Table				
Stream ID		FEED	HEAVY	LIGHT
From			B1	B1
To		B1		
Phase		LIQ UID	LIQ UID	LIQ UID
Substream: MIXED				
Mole Flow	kmol/hr			
METHANOL		50.00000	5.889649	44.11035
WATER		50.00000	49.11035	.8896493
Mole Frac				
METHANOL		.5000000	.1070845	.9802300
WATER		.5000000	.8929155	.0197699
Total Flow	kmol/hr	100.0000	55.00000	45.00000
Total Flow	kg/hr	2502.872	1073.454	1429.418
Total Flow	l/min	49.47615	20.25841	31.97097
Temperature	C	30.00000	87.35241	64.83937
Pressure	bar	1.013250	1.013250	1.013250
Vapor Frac		0.0	0.0	0.0
Liquid Frac		1.000000	1.000000	1.000000
Solid Frac		0.0	0.0	0.0
Enthalpy	cal/mol	-62556.53	-65877.07	-56238.43
Enthalpy	cal/gm	-2499.390	-3375.309	-1770.461
Enthalpy	cal/sec	-1.7377E+6	1.0065E+6	7.0298E+5
Entropy	cal/mol-K	-46.94563	-36.87178	-54.04625
Entropy	cal/gm-K	-1.875671	-1.889180	-1.701448
Density	mol/cc	.0336862	.0452486	.0234587
Density	gm/cc	.8431240	.8831341	.7451647
Average MW		25.02872	19.51734	31.76485
Liq Vol 60F	l/min	48.65383	18.73331	29.92053

b) Variation of Relative volatility along the column



Problem 4: However, the distillation column procured as per problem 3 produces only a methanol overhead mole fraction of 0.974 instead of 0.98. You open the column and find that the last four trays have corroded and there are only gaping holes instead of trays. You have to quickly meet the product specification of the customer failing which the product will be returned and you will lose the market share.

a. What will you do to overcome the crisis quickly?

b. You also have a long term plan to buy new trays. What are the different distillation trays available in the market? Compare their advantages and disadvantages using referenced diagrams.

[15]

a) In order to overcome the crisis, we have to change the reflux ratio. Changing pressure in the distillation column and changing feed location also works, but the best feasible solution is changing reflux ratio.

b) **Different Types of Trays:**

Bubble Cap Tray:

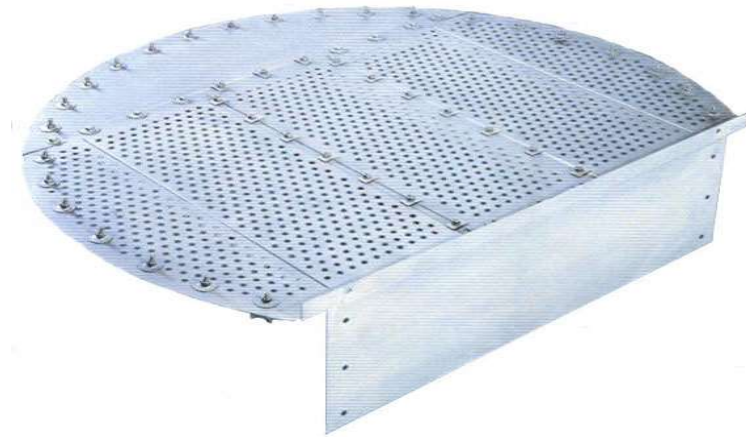


It consists of a slotted cap on a central riser. The gas flows up through the riser, reverse flow under the cap, passes downward through the annulus between riser and cap, and finally passes into the liquid through a series of openings or "slots" in the lower side of the cap.

This device has a built-in liquid seal (i.e. the riser) which prevents liquid drainage at low gas rates. This design does not rely on the velocity of the upcoming vapor to hold the liquid on the tray.

It provides intimate contact between liquid and vapor and offers excellent performances and good efficiencies. But, because of its high cost and complexity, most modern column designs favor the use of sieve or valve trays over bubble-cap trays. Bubble-caps should only be used where very low vapor rates have to be handled, or adequate residence time is necessary for separation and/or chemical reaction, or in applications where a positive liquid seal is essential at all flow rates.

Sieve Tray



The sieve tray has the simplest design among the various tray types. There are no mechanical moving parts. There is no liquid seal and it is the passage of vapor that effectively prevents the loss of liquid through the sieves. A phenomenon known as weeping can occur at low vapor flow and/or high liquid rates when the liquid height on the tray exceeds the tray pressure drop.

Typical sieve sizes used industrially range from as small as 1/16-inch to 1-inch. Small sieves are not suitable for fouling or corrosive services as they may be susceptible to blockage, leading to excessive pressure drop and premature flooding.

Small holes have better turndown characteristics because they reduce tray weeping and therefore increase tray capacity. In terms of cost, larger holes are cheaper as the holes can be punched, and there are fewer holes to be punched. Smaller holes are more expensive as drilling may be required.

They are cheap and easy to maintain. If vapor velocity is very low, it may lead to dumping of liquid through the holes.

Valve Tray

A valve tray is a flat perforated plate, with each perforation fitted with a movable disk (the "valve"). See the Figure below.



The perforations and disks may be circular or rectangular. The disks (valves) are the movable component of the tray. The valves will move up or down in response to changing vapor flow rates. At normal flow rate, the valve is roughly in the middle position. At low vapor rates, the

disk settles over the perforation and covers it to avoid liquid weeping. The valves should be heavy enough to prevent excessive opening at low vapor flowrates. As the vapor rate is increased, the disk rises vertically. The upward movement of the disk is restricted either by retaining legs or a cage. Weeping may result if excessive valve opening occurs prematurely. This will reduce the tray turndown.

In dirty or fouling services, the valves may get stuck due to the build-up of sludge or corrosion products around the valve. "Sticking" valves reduce the tray open area and can lead to premature flooding. Valve trays offer larger operating range and greater capacity compared to sieve trays. In terms of cost, valve trays are more expensive than sieve trays.

One of the major advantages is it prevents dumping of liquid at low vapor flow rates through valves. This gives intimate contact between liquid and vapour. But the efficiency is lower as compared to bubble cap trays.

Dual flow tray:



Dual flow tray is a sieve tray without a down comer. Vapors move up to the tray above through the hole, while the liquid travels down in the same hole that can result in mal-distribution and low efficiency. Dual flow trays are designed with enough open area on the tray deck to eliminate stagnation and promote back mixing that makes it suited to handle highly fouling services, slurries, and corrosive services. Dual flow trays are well suited also for the fractionation of polymerizable compounds and give more bubbling area; therefore have a greater capacity than other tray types.

Dual flow tray is also the least expensive to make and easiest to install and maintain. Dual flow tray performs best in the operating region of 60 to 85 % of flood and increases the efficiency with vapor rate. The challenge of dual flow tray is mal-distribution in larger diameter towers.

References:

http://www.separationprocesses.com/Operations/POT_Ch02d.htm

http://www.separationprocesses.com/Operations/POT_Ch02b.htm

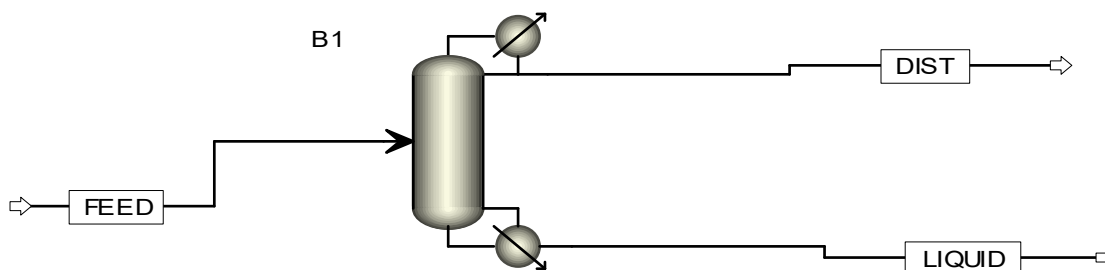
http://www.separationprocesses.com/Operations/POT_Ch02c.htm

<https://www.google.co.in/> (for images)

Problem 5: A saturated liquid feed stream contains benzene (0.1 mole fraction), toluene (0.4 mole fraction), xylene (0.4 mole fraction) and rest cumene. The feed rate is 100 kmol/h. The column contains 20 stages and the feed is at stage 9 from the top. The column is atmospheric and a distillate to feed ratio of 0.51 toluene from the feed to the column is required. Use molar reflux ratio of 3.

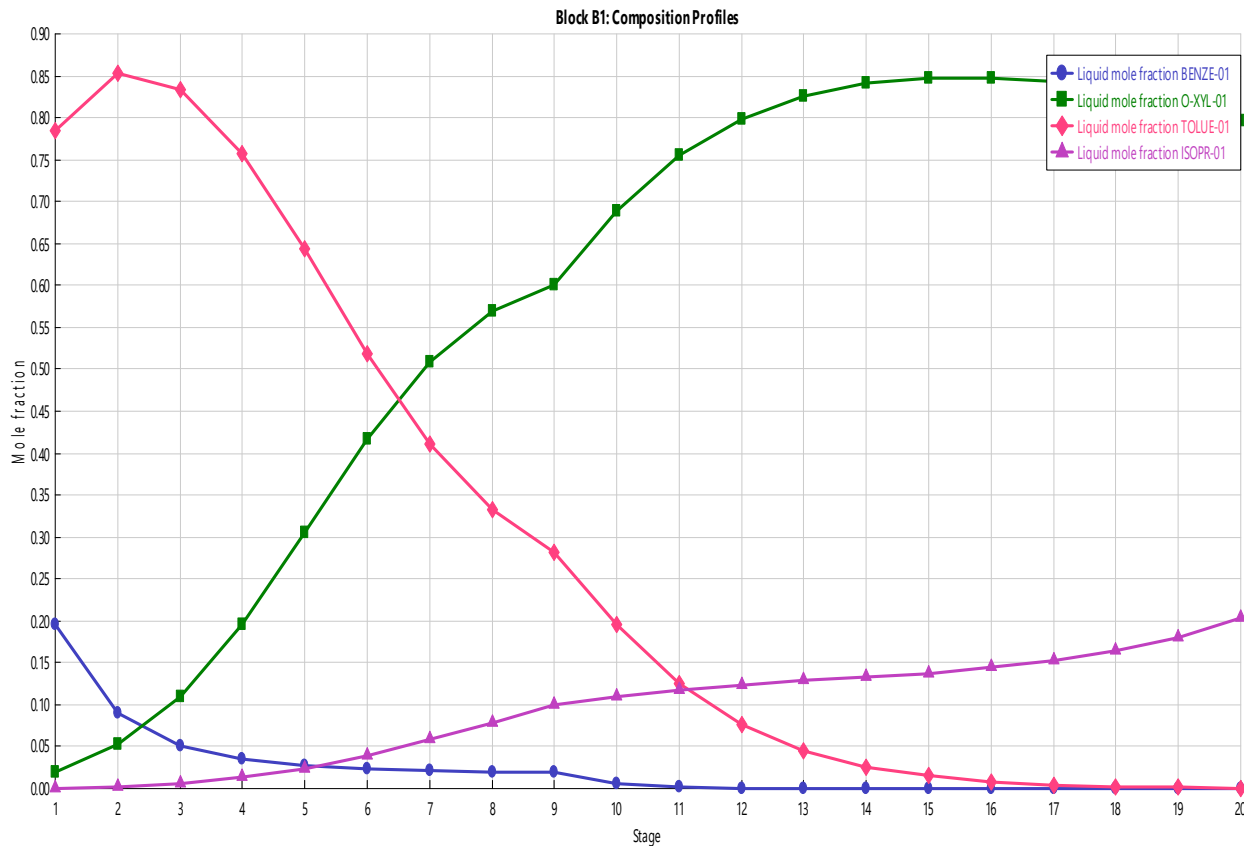
- Obtain the composition profiles for both vapor and liquid phases inside the column.
- Identify the light and heavy key components for this system.
- Identify the light and heavy non key components.
- Show that the presence of the non-key component may produce a maximum in the key component composition profile. Explain why (See Wankat's book "Separation Processes Engineering – Including Mass Transfer Analysis", 3rd ed.).
- Rank the four components in the decreasing order of relative volatilities. Use Peng Robinson EOS.

[20]



Heat and Material Balance Table				
Stream ID		DIST	FEED	LIQUID
Temperature	C	103.7	119.2	145.7
Pressure	bar	1.013	1.013	1.013
Vapor Frac		0.000	0.000	0.000
Mole Flow	kmol/hr	51.000	100.000	49.000
Mass Flow	kg/hr	4573.897	9915.396	5341.499
Volume Flow	cum/hr	5.808	12.710	7.001
Enthalpy	Gcal/hr	0.387	0.331	-0.019
Mole Flow	kmol/hr			
BENZE-01		10.000	10.000	trace
O-XYL-01		0.995	40.000	39.005
TOLUE-01		39.968	40.000	0.032
ISOPR-01		0.037	10.000	9.963

a) Composition Profile



b) Based on vapor and liquid composition profiles, we conclude that the **Light Key** Component is **Toluene** and **Heavy Key** Component is **Xylene**.

c) Based on vapor and liquid composition profiles, we conclude that the **Light Non-Key** Component is **Benzene** and the **Heavy Non-Key** Component is **Cumene**.

d) From the graph in part A, we observe that the concentration profile of **toluene** (light key component) attains a **maximum**. This happens because the light non-key component, benzene, is more volatile than toluene and condenses some amount of toluene in the higher stages leading to lower concentration.

e)

Order of Relative volatilities:

Benzene > Toluene > Xylene > Cumene

Problem 6: The mixture containing acetone (n.b.p = 56.2 °C) and methanol (n.b.p. = 64.7 °C) form a minimum-boiling azeotrope of 78 mole percentage acetone at a temperature of 55.7 °C at 1 atm. pressure. Hence acetone-methanol mixture cannot be separated by ordinary distillation to get products of very high purities. Since water does not form binary or ternary azeotrope with acetone and / or methanol at 1 atm. pressure it is a possible solvent for extractive distillation of acetone-methanol mixture. Methanol is selectively attracted towards water which has a significantly higher boiling point (n.b.p = 100°C) than acetone and methanol. Thus the more volatile acetone is removed in the distillate and methanol is removed along with water in the bottom product. Water alters the VLE of the feed mixture. More specifically, large amounts of water increases the activity coefficient of acetone in the liquid phase, changes that of methanol moderately (usually the activity coefficient of methanol reduces towards unity) and improves their relative volatility. Water does not escape to the distillate appreciably while methanol is easily separated from water in the subsequent distillation unit. The extractive distillation scheme is sketched in the figure below. Use UNIQUAC model to simulate this process and explore the effects of

- Increasing Reflux ratio (explain the anomalous results)
- Feed stage location of water w.r.t. to acetone-methanol feed
- Water flow rate.

[20]

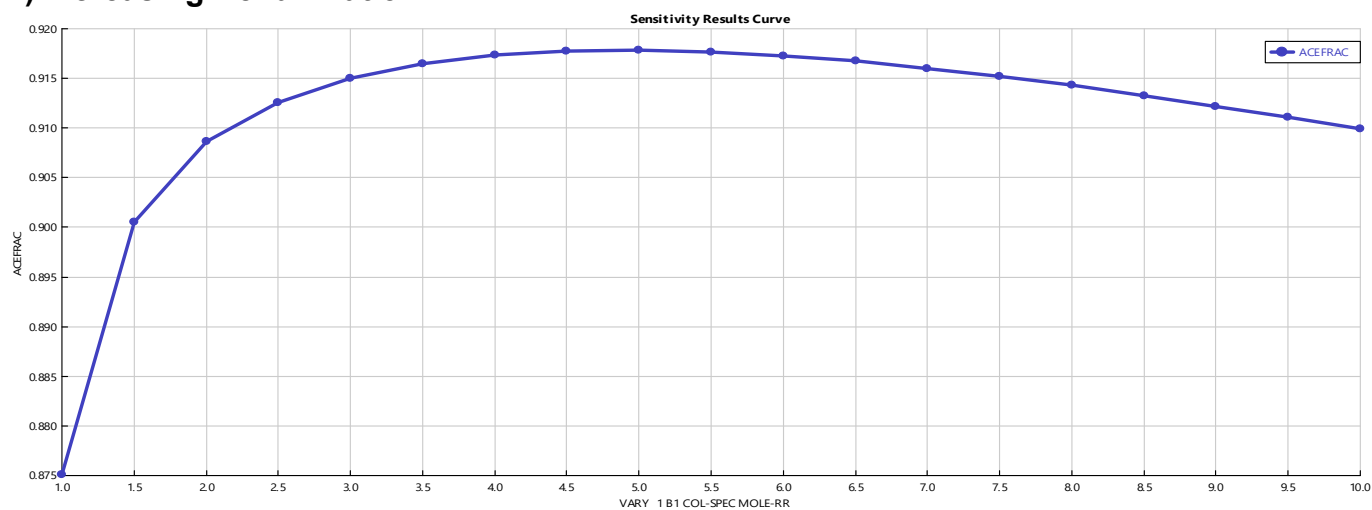
Table 4.1 Extractive Distillation Simulation

Specifications		Typical Case Study
Number of stages(including condenser and reboiler)		20
Condenser		Partial (equilibrium stage)
Reboiler		Partial (equilibrium stage)
Bottom rate		68.774 mol/s
Pressure		Intermediate stages : linear pressure profile between top and bottom stage pressure
Feed 1 (Solvent : Water)	Location	stage 3
	State, T&P	liquid at 323 K, 103.33 kPa

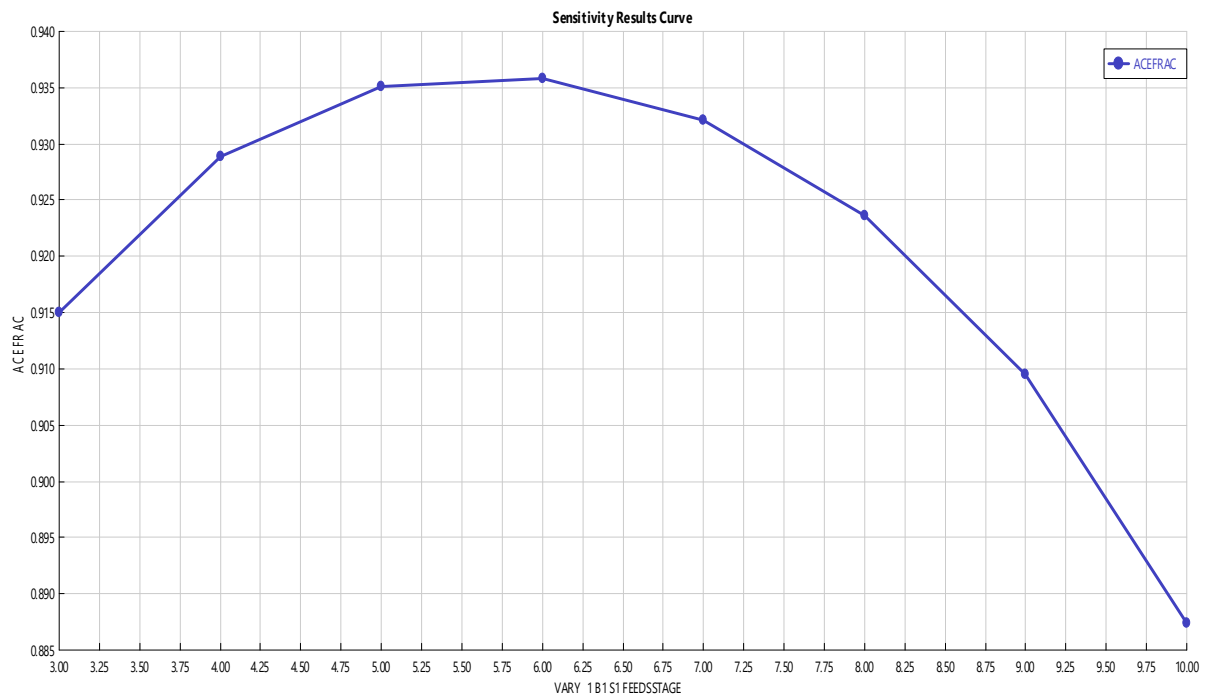
	Flow rates	Acetone 0.0 mol/s, Methanol 0.0 mol/s, Water 60 mol/s
Feed 2 Acetone-Methanol Mixture	Location	stage 10
	State, T&P	bubble point liquid (330.48 K), 108.39 kPa.
	Flow rates	Acetone 30 mol/s, Methanol 10 mol/s Water 0 mol/s

SENSITIVITY ANALYSIS

A) Increasing Reflux Ratio:



B) Varying Feed stage location of water



C) Varying water flow rate

