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Sample problems and exercises – Distillation

Sample problems

Sample 1: Calculating vapor phase composition for immiscible liquids

Calculate the equilibrium vapor phase composition of a liquid hexane–water mixture at 50 °C, assuming that hexane and water are completely immiscible. The vapor pressures of the pure components can be described by the Antoine equation:

$$\log p^0 = A - \frac{B}{T + C}.$$

The constants A, B and C are given for p^0 [torr] and T [°C]. Their values are as follows:

	Hexane	**Water**
A	6,87024	8,07131
B	1168,72	1730,63
C	224,21	233,426

Solution

When there are more than one components in a mixture, they are indexed according their volatility. The most volatile compound (owning the lowest boiling point at a given pressure) gets the index 1. Thus in this problem hexane is the compound 1, the less volatile water is the compound 2. In the case of a mixture of only two components, indexes are normally not used, but all concentrations are given for the more volatile compound, in this case hexane.

These two liquids are immiscible, thus the vapour pressure is the sum of the vapor pressures of the individual components, calculated by the Antoine equations:

$$p_1^0 = 10^{A_1 - \frac{B_1}{T + C_1}} = 10^{6{,}87024 - \frac{1168.72}{50 °\mathrm{C} + 224.21}} = 405.6\ \mathrm{torr}$$

$$p_2^0 = 10^{A_2 - \frac{B_2}{T + C_2}} = 10^{8{,}07131 - \frac{1730.630}{50 °\mathrm{C} + 233.426}} = 92.3\ \mathrm{torr}$$

The sum of the tensions gives the total pressure (if the liquid mixture is boiling):

$$P = p_1^0 + p_2^0 = 405.6\ \mathrm{torr} + 92.3\ \mathrm{torr} = 497.9\ \mathrm{torr} = 66381\,\mathrm{Pa} \approx 66\ \mathrm{kPa}.$$

If we wish to change the torr to Pa: 1 torr = 1 Hgmm = 133.322 Pa, thus 760 torr = 101325 Pa = 1 atm.

Molar fraction of hexane in the vapor phase above the liquid mixture can be calculated by the Dalton law:

$$y_1 = \frac{p_1^0}{P} = \frac{405.6\ \mathrm{torr}}{497.9\ \mathrm{torr}} = 0.815.$$

Molar fraction of the water in the vapor phase:

$$y_2 = 1 - y_1 = 1 - 0.815 = 0.185.$$

Sample 2: Calculating boiling point and vapor phase composition for immiscible liquids

Determine the boiling point and vapor phase composition of a water–toluene mixture at atmospheric pressure (P = 760 torr), assuming the complete immiscibility of the components! The Antoine constants of the pure components (given for p^0 [torr] and T [°C]) are:

	Water	**Toluene**
A	8.07131	7.5596
B	1730.63	1644.050
C	233.426	233.524

Solution

Water is the more volatile component, thus al molar compositions without indexing are given for the water content. These two liquids are immiscible, thus the vapour pressure is the sum of the tension of the individual components, calculated by the Antoine equations. The mixture starts boiling, when the sum of the vapor pressures equals to the given (atmospheric) pressure.

Let's calculate the vapor pressures of the individual components with the Antoine equations! We need to look for the temperature when the sum of the vapor pressures are exactly equal to the atmospheric pressure. It is the boiling temperature of the toluene – water mixture. It is easier to determine the exact temperature, if we calculate the values also for the (760-p^0_1) formula at each temperatures, and plot the 760-p^0_1 and p^0_2 values as functions of the temperature in a common diagram as shown in Fig. 1. Intersection of the two curves gives the temperature of boiling.

T [°C]	p^0_1 [torr]	p^0_2 [torr]	$p^0_1+p^0_2$ [torr]	760-p^0_1 [torr]
30	31.7	20.9	52.7	728.3
40	55.2	35.4	90.6	704.8
50	92.3	57.7	150.0	667.7
60	149.0	90.9	239.9	611.0
70	233.2	139.0	372.2	526.8
80	354.5	206.9	561.5	405.5
90	525.3	300.5	825.8	234.7
100	760.1	426.8	1186.9	-0.1

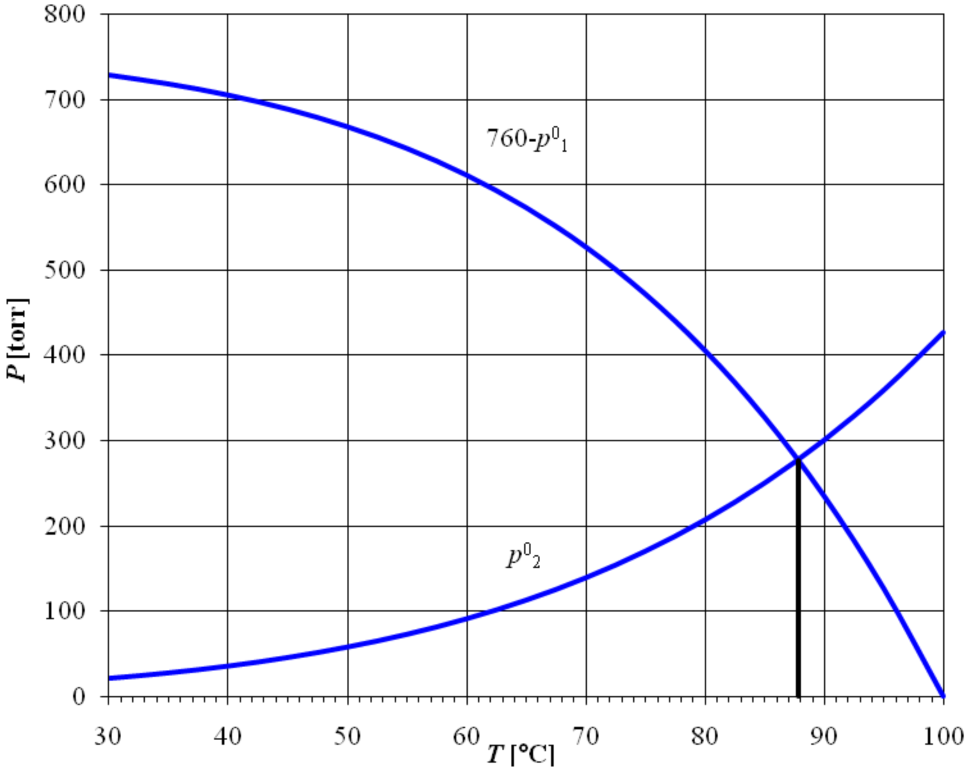

Fig. 1. Determination of the boiling temperature at the atmospheric distillation of two immiscible liquids.

The boiling point read from the diagram is 87.7 °C. At this temperature value the vapor pressures of the liquids are:

$$p_1^0 = 10^{A_1 - \frac{B_1}{T+C_1}} = 10^{8.07131 - \frac{1730.630}{87.7°\mathrm{C}+233.426}} = 480.9\ \mathrm{torr},$$

$$p_2^0 = 10^{A_2 - \frac{B_2}{T+C_2}} = 10^{7.5596 - \frac{1644.050}{87.7°\mathrm{C}+233.524}} = 276.4\,\mathrm{torr}\ .$$

Sum of the two values is almost equal to the atmospheric pressure:

$$p_1^0 + p_2^0 = 480.9\ \mathrm{torr} + 276.4\ \mathrm{torr} = 757.3\ \mathrm{torr} \approx 760\ \mathrm{torr}.$$

Molar fraction of water in the vapor phase according to Dalton’s law:

$$y_1 = \frac{p_1^0}{P} = \frac{480.9\ \mathrm{torr}}{757.3\,\mathrm{torr}} = 0.635.$$

Molar fraction of toluene in the vapor phase:

$$y_2 = 1 - y_1 = 1 - 0.635 = 0.365.$$

More exact results might be obtained by iteration or if we solve the equations numerically. Note, that the boiling point of a mixture of water and another liquid immiscible with water is always at a lower temperature than 100 °C. This makes the steam distillation viable.

Sample 3: Continuous distillation / Flash distillation

Flash distillation is used to evaporate half of a 40 mole% benzene–toluene mixture.

a) What is the composition of the resulting distillate and residue?

b) By changing the amount of evaporated mixture, what is the maximum possible benzene content of the distillate?

c) By changing the amount of evaporated mixture, what is the maximum possible toluene content of the residue?

Solution

a) What is the composition of the resulting distillate and residue?

Component balance:

$$F \cdot x_F = L \cdot x + V \cdot y \, .$$

Since 50% of the feed is evaporated: $0.5 \cdot F = L = V$.

Let's substitute it into the component balance equation:

$$F \cdot x_F = L \cdot x + V \cdot y = 0.5 \cdot F \cdot x + 0.5 \cdot Fy \, ,$$

$$x_F = 0.5x + 0.5y \, .$$

By taking into account that $x_F = 0.4$, we end up in an equation of a linear:

$$0.4 = x_F = 0.5 \cdot x + 0.5 \cdot y \, ,$$

$$0.8 = x + y \Rightarrow y = 0.8 - x \, .$$

We know, that the vapor and liquid products of a flash distillation are in equilibrium, thus the liquid composition x and vapour composition y values correspond to the coordinates of one single point of the equilibrium curve. We also derived from the balance equations that $y = 0{,}8 - x$. The intersection of this linear funcition and of the equilibrium curve gives the operation point of this flash disitillation as shown in Fig 2.

The equilibrium curve was drawn using the method described in the Appendix.

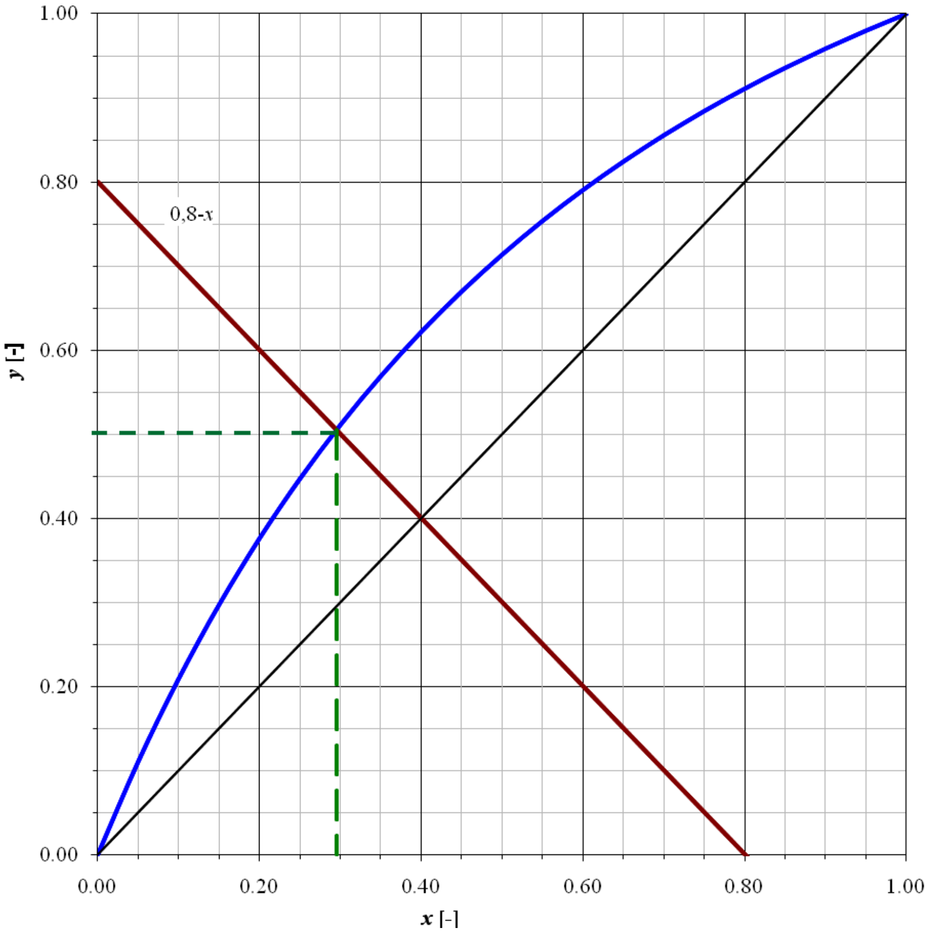

Fig. 2.Determination of the vapor and liquid composition at a flash distillation

Read from the diagram: $y = 0.51$, and $x = 0.29$.

b) By changing the amount of evaporated mixture, what is the maximum possible benzene content of the distillate?

Maximum possible benzene content of the distillate can be achived if minimum amount of vapor is evaporated. The y_{max} value can be read from Fig. 3.

$$y_{max} = 0.62.$$

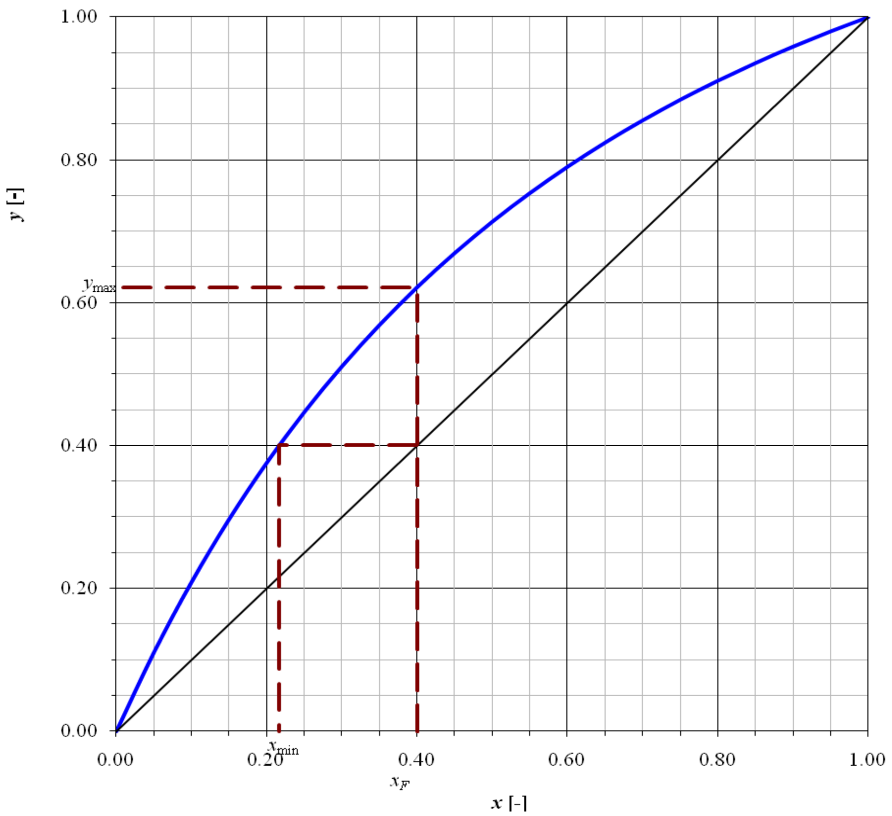

Fig. 3. Possible working intervals of a flash disitillation (sample 3. b, c)

c) By changing the amount of evaporated mixture, what is the maximum possible toluene content of the residue?

Maximum toluene content is obtained in the liquid product when almost the total feed is evaporated. . The x_{min} value can be read from Fig. 3.:

$x_{\min} = 0.22$, thus maximal toluene content is: 1-0.22 = 0.78.

Sample 4: Batch distillation

100 kmol of a 60 mole% benzene–toluene mixture is subjected to batch distillation until a 30 mole% residue is obtained. How many kg of distillate is obtained, and what is its benzene content? (Also solve the problem using relative volatility, average α)

Solution

Mass balance:

$$L_0 = L_1 + D\,.$$

Component balance:

$$L_0 \cdot x_0 = L_1 \cdot x_1 + D \cdot \overline{x_D}\,.$$

Rayleigh-equation*:*

$$\ln\frac{L_0}{L_1} = \int_{x_1}^{x_0} \frac{dx}{y-x}\,.$$

The Rayleigh-equation can be solved by numerical integration. We shall use the method of trapezoids. We read the corresponding x and y values from the equilibrium curve, calculate the values of the f(x) function and perform the numerical integration.

i	***x* [-]**	***y* [-]**	***f*(*x*)=1/(*y*-*x*) [-]**	***Δx* [-]**
1	0.60	0.79	5.263	
2	0.55	0.75	5.000	0.05
3	0.50	0.71	4.762	0.05
4	0.45	0.67	4.545	0.05
5	0.40	0.62	4.545	0.05
6	0.35	0.57	4.545	0.05
7	0.30	0.51	4.762	0.05

Based on the data of the table $f(x) = \frac{1}{y-x}$ function can be drawn (Fig 4.).

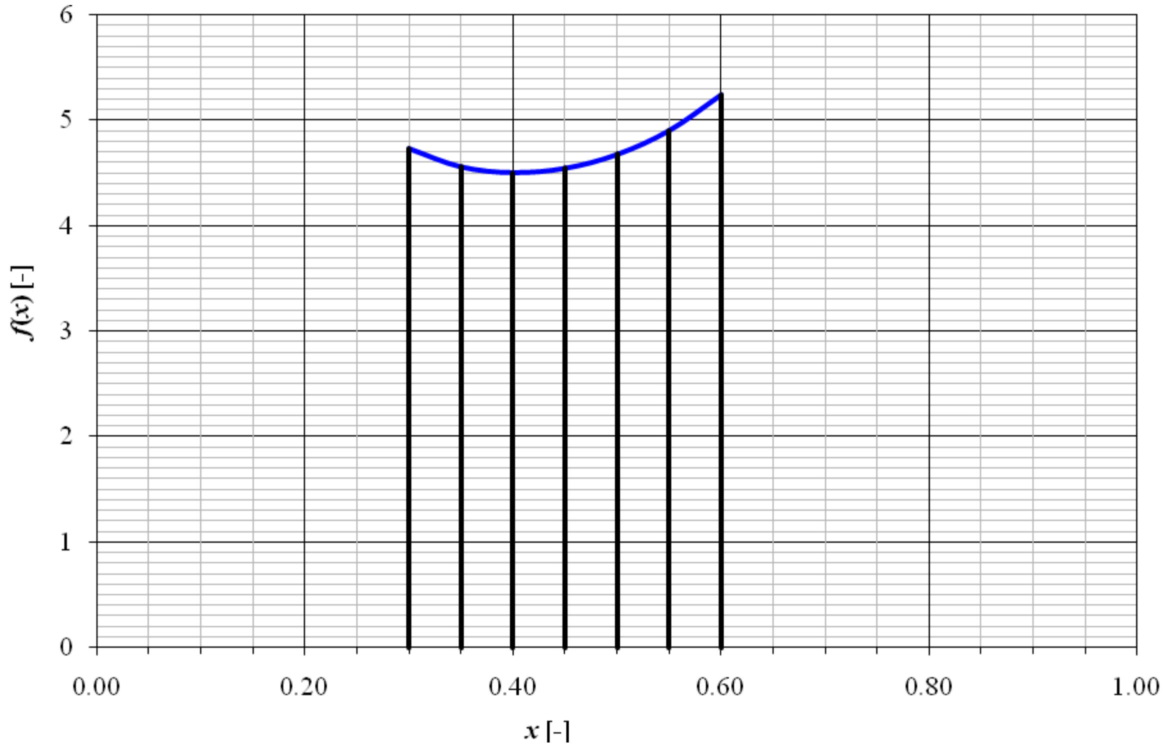

Fig 4. Graphical integration of the Rayleighequation(sample 4.)

Method of trapezoids:

$$\int_{x_1}^{x_0} \frac{dx}{y-x} \approx \sum_{i=2}^{n} \Delta x_i \frac{f(x)_{i-1} + f(x)_i}{2} = \sum_{i=2}^{n} \Delta x_i \frac{\left(\frac{1}{y-x}\right)_{i-1} + \left(\frac{1}{y-x}\right)_i}{2}$$

$$\int_{x_1}^{x_0} \frac{dx}{y-x} \approx \Delta x \left[\frac{\left(\frac{1}{y-x}\right)_1 + \left(\frac{1}{y-x}\right)_n}{2} + \sum_{i=2}^{n-1} \left(\frac{1}{y-x}\right)_i \right],$$

$$\int_{x_1}^{x_0} \frac{dx}{y-x} \approx 0{,}05 \cdot \left(\frac{5{,}263 + 4{,}762}{2} + 5 + 4{,}762 + 4{,}545 + 4{,}545 + 4{,}545 \right) = 1{,}42 .$$

$$\ln \frac{L_0}{L_1} = 1.42,$$

$$L_1 = \frac{L_0}{e^{1.42}} = \frac{100\,\text{kmol}}{e^{1.42}} = 24.17\,\text{kmol}.$$

$$D = L_0 - L_1 = 100\,\text{kmol} - 24.17\,\text{kmol} = 75.83\,\text{kmol}.$$

Average molar fraction of benzene in the distillate:

$$\overline{x_D} = \frac{L_0 x_0 - L_1 x_1}{D} = \frac{100\,\text{kmol} \cdot 0.6 - 24.17\,\text{kmol} \cdot 0.3}{75.83\,\text{kmol}} = 0.696.$$

Mass of distillate:

$$m_D = D \cdot \overline{M_D} = D\left(\overline{x_D} \cdot M_{benzene} + \left(1 - \overline{x_D}\right) \cdot M_{toluene}\right),$$

$$m_D = 75.83\,\text{kmol} \cdot \left(0.696 \cdot 78 \frac{\text{kg}}{\text{kmol}} + (1 - 0.696) \cdot 92 \frac{\text{kg}}{\text{kmol}} \right) = 6238\,\text{kg} .$$

Solution using average relative volatility

Relative volatility at the beginning of the distillation:

$$\alpha_0 = \frac{y/x}{(1-y)/(1-x)} = \frac{0.79/0.6}{(1-0.79)/(1-0.6)} = 2.52 .$$

at the end of the distillation:

$$\alpha_1 = \frac{y/x}{(1-y)/(1-x)} = \frac{0.51/0.3}{(1-0.51)/(1-0.3)} = 2.44 .$$

If we may consider the relative volatility as constant, the best estimation is to take the average of the calculated values α_0 and α_1 :

$$\alpha \cong \overline{\alpha} = \frac{\alpha_0 + \alpha_1}{2} = \frac{2.52 + 2.44}{2} = 2.48$$

a more exact estimation may be achieved if we perform the same calculations for several point:

i	**x [-]**	**y [-]**	**α [-]**
1	0.60	0.79	2.44
2	0.55	0.75	2.45
3	0.50	0.71	2.47
4	0.45	0.67	2.48
5	0.40	0.62	2.49
6	0.35	0.57	2.50

7	0.30	0.51	2.52

Rayleigh-equation using constant relative volatility:

$$\ln\frac{L_0}{L_1}=\frac{1}{\alpha-1}\left(\ln\frac{x_0}{x_1}+\alpha\cdot\ln\frac{1-x_1}{1-x_0}\right)=\frac{1}{2.48-1}\left(\ln\frac{0.6}{0.3}+2.48\cdot\ln\frac{1-0.3}{1-0.6}\right)=1.41.$$

Deviation of $\ln\frac{L_0}{L_1}$ value is less than 1 %.

$$L_1=\frac{L_0}{e^{1.41}}=\frac{100\text{kmol}}{e^{1.41}}=24.41\text{ kmol},$$

$$D=L_0-L_1=100\text{ kmol-}24.41\text{ kmol}=75.59\text{ kmol},$$

$$\overline{x_D}=\frac{L_0x_0-L_1x_1}{D}=\frac{100\text{ kmol}\cdot 0.6\text{-}24.41\text{ kmol}\cdot 0.3}{75.59\text{ kmol}}=0.697,$$

$$m_D=75.84\text{kmol}\cdot\left(0.697\cdot 78\frac{\text{kg}}{\text{kmol}}+(1-0.697)\cdot 92\frac{\text{kg}}{\text{kmol}}\right)=6216\text{kg}.$$

Sample 5: Distillation of a benzene–toluene mixture in a plate column

50 kmol/h of a 40 mole% benzene–toluene is separated on a continuous *distillation column* operating at amospheric pressure to yield a 92 mole% distillate and 8 mole% bottoms product. Feed is a liquid–vapor mixture in 1:1 ratio, introduced optimally.

a) What are the molar flows of the distillate and bottoms product?

b) What is the minimally required number of theoretical plates?

c) What is the minimal reflux ratio?

d) How many theoretical plates must the column be equivalent to, and where should the feed be introduced if the operating reflux ratio is 1.5 times the minimum? (The column is fitted with a partial reboiler.)

e) How many plates are required in a column with integrated reboiler to achieve the separation described in part d) if the average column efficiency is 0.7?

f) What is the required height of the column if plate spacing is 30 cm?

Sample 6: Distillation of a benzene–toluene mixture in a plate distillation column, with heat duty calculations

50 kmol/h of a 40 mole% benzene–toluene is separated on a continuous distillation column operating at amospheric pressure to yield a 92 mole% distillate and 8 mole% bottoms product. The operating reflux ratio is 3. The column contains 15 plates. Feed is a 1:1 ratio liquid–vapor mixture, introduced optimally. Use the ideal gas law for calculations.

a) What are the molar flows of the distillate and bottoms product?

b) What is the value of the load factor at the top and bottom of the column, assuming a column diameter of 1.1 m and a plate pressure drop of 3 torr?

c) What is the hourly requirement of heating steam (2.7 bar) and cooling water ($c_{p,water}$ = 4,18 kJ/kgK), if the cooling water temperature can rise by no more than 15 °C and assuming that the feed is

- a 1:1 ratio liquid–vapor mixture
- liquid at boiling point?

The enthalpy of vaporization for the mixture is 30336 kJ/kmol.

Sample 7: Distillation of an isopropanol–propanol mixture on a plate distillation column

2104 kg/h of a propanol–isopropanol mixture containing 45 mass% isopropanol is separated in a continuous distillation column, at atmospheric pressure to yield products containing 90 mass% isopropanol and 95 mass% propanol. The optimally introduced feed is a vapor–liquid mixture containing 5% vapor.

The propanol–isopropanol mixture can be considered to be ideal. The average enthalpy of vaporization is 40.5 kJ/mol. Both components have a molar mass of 60.1 g/mol. The Antoine constants are as follows (substitute pressure in Hgmm and temperature in °C):

	Atmospheric boiling point	A	B	C
isopropanol	82,6 °C	8,87829	2010,33	252,636
propanol	97,2 °C	7,75107	1441,63	198,85

a) What are the molar flows of the distillate and the bottoms product?

b) What is the minimal number of plates?

c) What is the minimal reflux ratio?

d) How many theoretical plates must the column be equivalent to, and where should the feed be introduced if the operating reflux ratio is 1.3 times the minimum?

e) How many plates are required in the column (fitted with a partial reboiler) if the average plate efficiency is 0.65?

f) What is the height of the column if the plates are separated by 40 cm?

g) What column diameter is required to maintain the load factor in the interval of 1,2–1,8 $\mathrm{Pa}^{1/2}$?

h) What is the hourly heat duty in the condenser and in the reboiler?

Sample 8: Distillation of a cyclohexanol–phenol mixture

38 kmol/h of a cyclohexanol–phenol mixture containing 65 mole% cyclohexanol is separated in a continuous distillation column operating at atmospheric pressure to yield a 95 mole% distillate and 20 mole% bottoms product. Feed temperature is 124 °C. The operating reflux ratio is 3. The column contains 15 plates. The ideal gas law, as well as Dalton’s and Raoult’s laws can be used for calculations. The enthalpy of vaporization for the mixture is 45700 kJ/kmol. The specific heat capacity of the liquid mixture is approximately equal to that of cyclohexanol (210 J/(mol·K)).

For the Antoine constants, see *Appendix*.

	atmospheric boiling point (°C)	M (g/mol)
cyclohexanol	161,7	94,1
phenol	181,8	100,2

a) What are the molar flows of the distillate and bottoms product?

b) What is the ratio between the operating and minimal reflux ratio (R/R_{min})?

c) Given a column diameter of 1.4 m, what is the load factor at the top of the column?

d) What is the hourly required amount of heating steam, if the heating steam temperature is 15 °C above the reboiler temperature?

Sample 9: Distillation of a benzene–toluene mixture on a plate column

10 kmol/h of a benzene–toluene mixture containing 45 mole% benzene is separated in a continuous distillation column operating at atmospheric pressure to yield a distillate containing 95 mole% benzene and a bottoms product containing 97 mole% toluene. The operating reflux ratio is 2. Feed is a 20 °C liquid, introduced optimally. The enthalpy of vaporization for the mixture is 30336 kJ/kmol, its specific heat capacity is 1.844 kJ/kgK. Use the ideal gas law for calculations.

a) What are the molar flows of the distillate and the bottoms product?

b) How many plates are required in the column fitted with an integral reboiler, given an average column efficiency of 0.75?

c) What is the required diameter of the column if the allowable load factor at the bottom of the column is 1.3 $Pa^{1/2}$ and the pressure drop across the plates is 4 torr?

Sample 10: Distillation of a benzene–toluene mixture on a packed column

10 kmol/h of a 45 mole% benzene–toluene mixture is separated in a continuous packed distillation column to yield a distillate containing 95 mole% benzene and a bottoms product containing 97 mole% toluene. The operating reflux ratio is 5. Feed is a 20 °C liquid, introduced optimally. The experimentally determined mass transfer coefficient is 0.34 mol/m^2s, the packing has a specific surface of 200 m^2/m^3. The allowable load factor at the top of the column is 1.3 $Pa^{1/2}$. The enthalpy of evaporation for the mixture is 30336 kJ/kmol, its specific heat capacity is 1.844 kJ/kgK. Use the ideal gas law for calculations.

a) What are the molar flows of the distillate and bottoms product?

b) Calculate the height of a transfer unit for the upper and lower sections!

c) Calculate the nmber of transfer units for the upper and lower sections!

d) Calculate the height of the column!

Exercises

Problem 1.

Calculate the equilibrium vapor composition of a liquid mixture containing 40 mole% benzene and 60 mole% toluene at 60 °C. Raoult's law applies to this mixture.

What is the composition of the benzene–toluene mixture that boils at 90 °C under 760 Hgmm pressure? Also determine the equilibrium vapor composition.

(Answer: $T = 60$ °C, $p^0{}_1 = 391.5$ *torr*, $p^0{}_2 = 139$ *torr*, $P = 240$ torr, $y_1 = 0.6525$, $T = 90$ °C, $p^0{}_1 = 1021$ torr, $p^0{}_2 = 406.7$ torr, $x_1 = 0.575$, $y_1 = 0.772$)

Problem 2.

Calculate the equilibrium phase compositions of a benzene–toluene mixture at 760 torr and plot the boiling point curve and the equilibrium curve based on the Raoult–Dalton law.

Based on the diagrams, determine the boiling point of a mixture containing 55 mole% benzene, and the corresponding vapor composition.

(Answer: $T_{bp} = 90.5$ *°C*, $y = 0.75$)

Problem 3.

The flash distillation of a 100 kmol/h, 0.5 mole fraction benzene–toluene mixture yields a 0.4 mole fraction residue. What is the composition of the distillate, and what are the flowrates of the distillate and residue?

(Answer: $y = 0.62$, $L = 54.55\ kmol/h$, $V = 45.45\ kmol/h$)

Problem 4.

A 70 kmol/h methanol–water mixture containing 42 mole% methanol is continuously distilled at atmospheric pressure to yield a residue of 27 mole%.

What is the composition of the distillate, and what are the flowrates of the distillate and residue?

(Answer: $x_{D,metanol} = 0.58$, $V = 33.87\ kmol/h$, $L = 36.13\ kmol/h$)

By changing the amount evaporated mixture, what is the maximum possible methanol content of the distillate?

(Answer: $y_{\mathrm{max}} = 0.735$)

Problem 5.

An 18 kmol/h phenol–metacresol mixture containing 49 mole% phenol is separated by flash distillation at atmospheric pressure and 193 °C.

a) What are the compositions and molar flow rates of the distillate and residue?

b) By changing the amount of the evaporated mixture, what is the maximal metacresol content of the residue?

(Answer: a) $x_{D,phenol} = 0.53$, $x_{W,phenol} = 0.4$, $V = 12.46\ kmol/h$, $L = 5.54\ kmol/h$. b) $x_{D,metacresol.max} = 0.375$)

Problem 6

In a flash distillation, 40% of a pentane–hexane mixture containing 35 mole% hexane is evaporated at atmospheric pressure. What is the composition of the resulting distillate and residue?

(Answer: $x_{D,pentane} = 0.79$, $x_{W,pentane} = 0.56$)

Problem 7

Using batch distillation to separate 10 kmol of a 50 mole% benzene–toluene mixture, a residue with 5 mole% benzene content is obtained. Calculate the amount of material (in moles) that must be evaporated, the masses of the distillate and residue, and the composition of the distillate.

(Answer: $ln(L_0/L_1) = 2.81$, $L_1 = 0.6\ kmol$, $D = 9.4\ kmol$, $m_1 = 54.8\ kg$, $m_D = 795\ kg$, $\bar{x}_D = 0.529$)

Problem 8

A benzene–toluene mixture containing 60 mole% toluene is batch distilled at atmospheric pressure until 903.2 kg residue having 12 mole% benzene content is obtained. What is the mass and the composition of the resulting distillate?

(Answer: $L_1 = 10\ kmol$, $L_0 = 44.8\ kmol$, $D = 34.8\ kmol$, $\bar{x}_D = 0.48$, $m_D = 2968\ kg$)

Problem 9

65 kmol of a phenol–metacresol mixture containing 55 mole% phenol is batch distilled at atmospheric pressure until a residue with 75 mole% metacresol is obtained. What is the amount and composition of the distillate?

(Answer: $L_1 = 6.52\ kmol$, $D = 58.48\ kmol$, $\bar{x}_D = 0.58$)

Problem 10

A 50 mole% methanol–water mixture is separated at atmospheric pressure in a continuous distillation column yielding a distillate containing 95 mole% methanol and a bottoms product containing 95 mole% water. Feed is liquid at boiling point.

a) Determine the minimal reflux ratio.

b) Use the McCabe–Thiele method to determine the minimal number of plates.

c) How many theoretical plates are necessary to carry out the separation with reflux ratio $R = 1$? At which theoretical plate should the feed be introduced?

(Answer: a) $x_D/(R_{min}+1) = 0.62$, $R_{min} = 0.53$, b) $N_{min} = 5$, c) $N_{theoretical} = 8$; $N_{feed} = 5$)

Problem 11

8500 kg/h of a 50 mole% benzene–toluene must be separated on a continuous distillation column into a bottoms product with 0.05 mole fraction benzene and a distillate with 0.95 mole fraction. The reflux ratio is $R = 3$. The enthalpy of vaporization for the mixture is 30336 kJ/kmol, its specific heat capacity is 1.844 kJ/kgK.

a) What are the mass flows of the distillate and the bottoms product?

b) How many theoretical plates are necessary, and where should the feed be introduced, assuming the feed is

- liquid at boiling point,
- liquid at 20 °C,
- vapor–liquid mixture containing 30% vapor?

c) How many real plates are required if the feed is a 20 °C liquid and the average plate efficiency is 75%?

d) What diameter column is required if feed is 20 °C liquid, average plate efficiency is 66%, the pressure drop across a real plate is 4 torr and the allowable load factor at the bottom of the column is 1.4 $Pa^{1/2}$?

e) What are the hourly requirements of heating steam and cooling water, assuming a heating steam pressure of 2.25 bars, cooling water entering at 20 °C and heating up by no more than 20 °C, and the feed being a 1:1 ratio liquid–vapor mixture?

(Answer: a) $F = 100\ kmol/h$, $W = 50\ kmol/h$, $D = 50\ kmol/h$, $\dot{m}_W = 4565\ kg/h$, $\dot{m}_D = 3935\ kg/h$, b) $q_{(bp)} = 1$, $N_{theo\ (bp)} = 9$, $q_{(20°C)} = 1.372$, $N_{theo(20°C)} = 9$, $q_{(30\%)} = 0.3$, $N_{theo(30\%)} = 10$, c) $N_{val} = 10.66 \approx 11$, d) $T_{reb} = 108°C$, $P_{reb} = 107191\ Pa$, $V = 200\ kmol/h$, $V' = 237.3\ kmol/h$, $\rho_{G,lower} = 3.09\ kg/m^3$, $v_{lower} = 0,8\ m/s$, $D_{column} = 1.76\ m$, e) $V = 200\ kmol/h$, $\dot{Q}_{cond} = 1685\ kW$, $\dot{m}_{water} = 72.6\ t/h$, $V' = 150\ kmol/h$, $\dot{Q}_{reboiler} = 1264\ kW$, $r_G = 2191.371\ kJ/kg$, $\dot{m}_{steam} = 2.08\ t/h$)

Problem 12

A 50 mole% benzene–toluene mixture is separated on a continuous distillation column. Requirements of the distillation: $x_D = 95$ mole% benzene, $x_M = 7$ mole% benzene. The following data about the operation of the column are available: reflux ratio $R = 3$, feed is liquid at boiling point. Reflux is the result of total condensation.

a) Assuming 100 kmol/h feed, what are the mass flows of the distillate and bottoms product?

b) How many theoretical plates are required to achieve the separation?

c) To which plate must the feed be introduced?

(Answer: $D = 48.86$ *kmol/h* $= 3530$ *kg/h*, $W = 51.14$ *kmol/h* $= 4655$ *kg/h*, $N_{theo} = 9$; $N_{feed} = 5$)

Problem 13

80 kmol/h of a 47 mole% methanol–water is separated in a continuous distillation column to yield a 90 mole% distillate and a 7 mole% bottoms product. Feed is a 60% vapor–liquid mixture. The column contains 8 plates and an integrated reboiler, column diameter is 1.5 m, operating reflux ratio is $R = 4$.

a) What are the mass flows and mass percent compositions of the products?

b) What is the ratio between the operational and minimal reflux ratio ($R/R_{\min}$)?

c) What is the average column efficiency?

d) What is the load factor F at the top and bottom of the column, if the pressure drop across the plates is negligible? Use the ideal gas law in the calculations.

(Answer: a) $D = 38.55$ *kmol/h*, $\dot{m}_D = 1180 kg/h$, $W = 41.45$ *kmol/h*, $\dot{m}_W = 787 kg/h$, $x_{D,mehtanol} = 94$ *m/m%*, $x_{W,methanol} = 12$ *m/m%*, b) $R_{min} = 0.73$, $R/R_{min} = 5.47$, c) $N_{theo} = 5$ *(reboiler is 1 theoretical plate), efficiency = 0.5*, d) $V = 192.75$ *kmol/h*, $T_{reb} = 95.5°C$, $v_{G,reb} = 0.764$ *m/s*, $\rho_{G,reb} = 0.628$ *kg/m*^{3}, $F_{reb} = 0.605$ *Pa*$^{1/2}$, $V' = 160.75$ *kmol/h*, $T_{top} = 66.6°C$, $v_{G,top} = 0.844$ *m/s*, $\rho_{G,top} = 1.098$ *kg/m*^{3}; $F_{top} = 0.885$ *Pa*$^{1/2}$)

Problem 14

A 60 kmol/h pentane–hexane mixture is to be separated. The mixture contains 40 mole% pentane. In a continuous distillation column, 90% of the pentane must be recovered in 96 mole% purity.

a) What are the molar flows of the products?

b) What is the minimal number of plates?

c) Working with 1.5 times the minimal reflux ratio, how many theoretical plates must the column be equivalent to and where should the feed (liquid at boiling point) be introduced?

(Answer: a) $D = 22.5$ *kmol/h*, $W = 37.5$ *kmol/h*, b) $N_{min} = 6$, c) $R_{min} = 1.13$, $R = 1.7$; $N_{theo} = 11$, $N_{feed} = 6$)

Problem 15

75 mol/h of a 62 mole% methanol–water mixture is separated on a continuous distillation column. A 92 mole% purity distillate and 5 mole% purity bottoms product is required. Feed is liquid at 29 °C. Reflux ratio is 2.5. The average enthalpy of vaporization of the mixture is 37132 kJ/kmol, its specific heat capacity si 3.15 kJ/kgK. Use the ideal gas law for calculations.

a) What is the required height of the column if the average plate efficiency is 0.75 and plates are spaced 10 cm apart?

b) What diameter column is required if the allowable load factor value at the top of the column is 1 $Pa^{1/2}$?

(Answer: a) $N_{theo} = 5, N_{real} = 6, H_{column} = 60\ cm$, b) $T_{bp,top} = 66°C$, $\rho_{G,top} = 1.11\ kg/m^3$, $v_{G,top} = 0.95\ m/s$, $A_{column,top} = 0.373\ m^2$, $D_{column,top} = 0.69\ m$)

Problem 16

20 kmol/h of a pentane–hexane mixture containing 52 mole% hexane is separated on a continuous distillation column. The disstillate must contain no more than 5% hexane, the bottoms product must contain no more than 6% pentane. Feed is liquid at 29 °C. Reflux ratio is 1.7. The average enthalpy of vaporization for the mixture is 37132 kJ/kmol, its specific heat capacity is 2,36 kJ/kgK. Use the ideal gas law for calculations.

a) What are the molar flows of the products?

b) What is the minimal number of plates?

c) What is the load factor at the top and bottom, if the column diameter is 0.9 m?

d) How much cooling water and atmospheric pressure heating steam is required if the cooling water can be heated up by no more than 15 C?

(Answer: a) $D = 35.39\ kmol/h$, $W = 39.61\ kmol/h$, b) $N_{min} = 6$, c) $q = 1.1$, $T_{bp,top} = 49°C$, $\rho_{G,top} = 2.86\ kg/m^3$, $V = 95.56\ kmol/h = 0.675\ m^3/s$, $v_{G,top} = 0.6\ m/s$, $F_{top} = 1\ Pa^{1/2}$, $T_{bp,bottom} = 66°C$, $\rho_{G,bottom} = 3.06\ kg/m^3$, $V' = 103.06\ kmol/h = 0.796\ m^3/s$, $v_{G,bottom} = 0.8\ m/s$, $F_{bottom} = 1.4\ Pa^{1/2}$, d) $\dot{Q}_{condenser} = 3.55 \cdot 10^6\ kJ/h$, $r_G = 2256.685\ kJ/kg$, $\dot{m}_{steam} = 1.57\ t/h$, $\dot{Q}_{reboiler} = 3.83 \cdot 10^6\ kJ/h$, $\dot{m}_{water} = 6.1\ t/h$)

Problem 17

By separating 5 kmol/h of a phenol–metacresol mixture containing 40 mole% phenol, products of 6 mole% purity must be obtained. Feed into the continuous distillation column is a 1:1 ratio liquid–vapor mixture, reflux ratio is 6.5. Use the ideal gas law for calculations.

a) What are the mass flows and mass percent phenol contents of the products?

b) How many theoretical plates are required for the separation and at which plate should the feed be introduced?

c) How many real plates are required if the average plate efficiency is 0.8?

d) What is the required height of the column, if the plates are 35 cm apart?

e) What is the required diameter of the column, if the maximum allowable load factor value at the bottom of the column is 1.1 $Pa^{1/2}$?

(Answer: a) $D = 1.93\ kmol/h = 183\ kg/h$, $W = 3.07\ kmol/h = 329\ kg/h$, $x_{D,phenol} = 93.17\ m/m\%$, $x_{W,phenol} = 5.26\ m/m\%$, $N_{theo} = 15$, $N_{feed} = 9$, $N_{real} = 18$, $H_{column} = 6.3\ m$, $T_{bp,bottom} = 201°C$, $\rho_{G,bottom} = 2.44\ kg/m^3$, $v_{G,bottom} = 0.74\ m/s$, $A_{column,bottom} = 0.184\ m^2$, $D_{column,bottom} = 0.484\ m$)

Problem 18

120 kmol/h of a 50 mole% benzene–toluene mixture is separated on a continuous distillation column. Feed is liquid at 20 °C, reflux ratio is 3.2. The distillate must contain at least 96 mole% benzene, the bottoms product must contain at least 95 mole% toluene. The average enthalpy of vaporization for the mixture is 32060 kJ/kmol, its specific heat capacity is 1,8 kJ/kgK. Use the ideal gas law for calculations.

a) What are the molar flows of the products?

b) What is the plate efficiency if the column contains 10 real plates?

c) How much cooling water and 1.7 bar (above atmospheric pressure) heating steam is required, if the cooling water can be heated up by no more than 20 °C?

(Answer: a) $D = 59.34\ kmol/h$, $W = 60.66\ kmol/h$, b) $q = 1.34$, $N_{theo} = 9$, $\eta = 0.7$, c) $V = 249.23\ kmol/h$, $\dot{Q}_{condenser} = 8 \cdot 10^6\ kJ/h$, $r_G = 2174.205\ kJ/kg$, $\dot{m}_{steam} = 3.68\ t/h$, $V' = 290.03\ kmol/h$, $\dot{Q}_{reboiler} = 9.3 \cdot 10^6\ kJ/h$, $\dot{m}_{water} = 111\ t/h$)

Problem 19

90 kmol/h of a methanol–water mixture containing 60 mole% water is to be separated. Using a continuous distillation column, 95% of the methanol must be recovered in 90 mole% purity. Feed is a liquid–vapor mixture containing 60% liquid. Reflux ratio is 3. The average enthalpy of vaporization of the mixture is 36440 kJ/kmol. Use the ideal gas law for calculations.

a) What is the minimal number of plates?

b) How much cooling water and 120 °C heating steam is required if the cooling water can be heated up by no more than 15 °C?

c) What is the required column diameter, if the maximum allowable load factor at the top of the column is 1.2 $Pa^{1/2}$?

(Answer: a) $N_{min} = 4$, b) $D = 38\ kmol/h$, $W = 52\ kmol/h$, $x_{w,methanol} = 3.46\ mol\%$, $V = 219.56\ kmol/h$, $\dot{Q}_{condenser} = 8 \cdot 10^6\ kJ/h$, $r_G = 2202.675\ kJ/kg$, $\dot{m}_{steam} = 3.63\ t/h$, $V' = 167.56\ kmol/h$, $\dot{Q}_{reboiler} = 6.1 \cdot 10^6\ kJ/h$, $\dot{m}_{water} = 97.4\ t/h$, c) $T_{bp,top} = 67°C$, $\rho_{G,top} = 1.1\ kg/m^3$, $v_{G,top} = 1.14\ m/s$, $A_{column,top} = 1.03\ m^2$, $D_{column,top} = 1.145\ m$)

Problem 20

In a packed column, 1 kmol/h of a phenol–metacresol mixture containing 40 mole% phenol must be separated into 90 mole% phenol and 92 mole% cresol. Reflux ratio is 7. Feed is an 80% liquid–vapor mixture, introduced optimally. The experimentally determined mass transfer coefficient is 0.59 mol/m^2s. Column diameter is 23.4 cm, specific surface area of the packing is 200 m^2/m^3. The allowable load factor at the top of the column is 1.2 $Pa^{1/2}$. Calculate the number and height of transfer units in the upper and lower sections! What is the required height of the column?

(Answer: $D = 0.39\ kmol/h$, $V = 0.87\ mol/s$, $T_{top} = 183.5°C$, $\rho_{G,upper} = 2.55\ kg/m^3$, $v_{upper} = 0.75\ m/s$, $A_{column} = 0.043\ m^2$, $HTU_{y,upper} = 0.17\ m$, $V' = 0.81\ mol/s$, $HTU_{y,lower} = 0.16\ m$, $NTU_{y,upper} = 6.928$, $NTU_{y,lower} = 5.661$, $H_{upper} = 1.1\ m$, $H_{lower} = 0.79\ m$, $H = 1.89\ m$)

Problem 21

5 kmol/h of a methanol–water mixture containing 45 mol% water is separated in a packed column. Both the distillate and the bottoms product must have 95 mole% purity. Reflux ratio is 6, feed is at boiling point. Column diameter is 0.4 m, specific surface area of the packing is 200 m^2/m^3. Mass transfer coefficient is experimentally determined to be 0.43 mol/m^2s.

a) Calculate the number and height of transfer units in the lower and upper sections!

b) Calculate the height of the column!

(Answer: a) $NTU_{upper} = 4.36$, $NTU_{lower} = 1.86$, $D = 2.22\ kmol/h$, $V = 15.56\ kmol/h$, $HTU_{upper} = 0.4\ m$, $V' = 15.56\ kmol/h$, $HTU_{lower} = 0.4\ m$, b) $H_{column,upper} = 1.74\ m$, $H_{column,lower} = 0.74\ m$, $H_{column} = 2.48\ m$)

Problem 22

2 kmol/h of a pentane–hexane mixture containing 40 mole% hexane is to be separated by continuous distillation on a packed column. Distillate hexane content is 5 mole%, bottoms product hexane content

is 90 mole%. Reflux ratio is 5.8, feed is a 1:1 ratio vapor–liquid mixture. Column diameter is 0.3 m, specific surface area of the packing is 200 m^2/m^3. The experimentally determined mass transfer coefficient is 0.4 mol/m^2s.

a) Calculate the number and height of transfer units in the lower and upper sections!

b) Calculate the height of the column!

(Answer: a) $NTU_{upper} = 3.59$, $NTU_{lower} = 2.32$, $D = 1.18$ *kmol/h*, $V = 8$ *kmol/h*, $HTU_{upper} = 0.4$ *m*, $V' = 7$ *kmol/h*, $HTU_{lower} = 0.34$ *m*, b) $H_{column,upper} = 1.41$ *m*, $H_{column,lower} = 0.94$ *m*, $H_{column} = 2.32$ *m*)

Problem 23

By continuous distillation in a packed column, 400 mol/h of a50 mole% phenol–metacresol mixture is separated. Phenol content in the distillate is 90 mole%, phenol content in the bottoms product is 5 mole%. Reflux ratio is 5, feed is liquid at boiling point. Column diameter is 15 cm, specific surface area of the packing is 200 m^2/m^3. Column height is 1.7 m, feed is introduced 1 m from the bottom. Calculate the height of transfer units in the upper and lower sections!

(Answer: $NTU_{upper} = 6.78$, $NTU_{lower} = 8.71$, $D = 2.22$ *kmol/h*, $HTU_{upper} = 0.1$ *m*, $HTU_{lower} = 0.11$ *m*)

Appendix

Antoine constants

The constants in the Antoine equation are determined by phase equilibrium measurements. When creating equilibrium diagrams using the Antoine equation and applying Raoult's and Dalton's laws, always consider the following:

Raoult's and Dalton's laws can only be applied to ideal mixtures. While during distillation, the gas phase can usually be considered ideal (Dalton's law is applicable), the liquid phase is often non-ideal (Raoult's law is not necessarily applicable). Thus, the method of calculation cannot be used to construct the equilibrium diagram of non-ideal mixtures. Mixtures with an azeotropic point are examples of highly non-ideal mixtures. The calculation method detailed below can be used for nearly ideal solutions:

Using the Antoine equation, calculate the vapor pressures of the pure components at different temperatures, distributed evenly in the interval between the boiling points of the pure components. The boiling point of a pure component at a given pressure can also be calculated from the Antoine equation: $p^0 = 10^{A - \frac{B}{T+C}}$.

Assuming that the vapor space contains only the vapors of the two components, the given total pressure can be expressed as the sum of the partial pressures: $P = p_1 + p_2$.

If Raoult's law is applicable, then there is an explicit relationship between partial pressure and the liquid phase mole fraction (index 1 refers to the more volatile component): $p_1 = x \cdot p_1^0$ and $p_2 = (1 - x) \cdot p_2^0$.

From these equations, for a given total pressure, the mole fraction of the more volatile compound can be expressed at each chosen temperature: $x = \frac{P - p_2^0}{p_1^0 - p_2^0}$.

Dalton's law also applies, thus the vapor phase mole fraction of the more volatile compound can be expressed: $y = \frac{p_1}{P} = \frac{x \cdot p_1^0}{P}$.

- The Antoine constants of pure components, found in databases and in literature *describe the relationship between vapor pressure and temperature only in a certain pressure and temperature interval*. Outside this interval, they cannot be used, or yield unreliable results.
- The Antoine constants have no dimensions themselves, but the units in which temperature must be substituted (K, °C , °F) and the units in which the calculated pressure is obtained (torr, Pa, bar stb.) is always specified. Antoine constants specified for different units can be converted among each other, based on the conversion factors of different units of pressure:

	pascal (Pa or N/m^2)	bar (bar)	technical atmosphere (at or kp/cm^2)	physical atmosphere (atm)	(torr) and (Hgmm)	pounds per square inch (psi)
1 Pa		10^{-5}	$10.197\cdot10^{-6}$	$9.8692\cdot10^{-6}$	$7.5006\cdot10^{-3}$	$145.04\cdot10^{-6}$
1 bar	100 000		1.0197	0.98692	750.06	14.504
1 at	98 066.5	0.980665		0.96784	735.56	14.223
1 atm	101 325	1.01325	1.0332		760	14.696
1 torr	133.322	$1.3332\cdot10^{-3}$	$1.3595\cdot10^{-3}$	$1.3158\cdot10^{-3}$		19.337·10−3
1 psi	6.89476	$68.948\cdot10^{-3}$	$70.307\cdot10^{-3}$	$68.046\cdot10^{-3}$	51.715	≡ 1 lbf/in²

The following example demonstrates converting Antoine constants specified in Hgmm and °C into Antoine constants specified in Pa and K:

$$p^0[\mathrm{Hgmm}]=10^{A_{\mathrm{Hgmm,°C}}-\frac{B_{\mathrm{Hgmm,°C}}}{T[°\mathrm{C}]+C_{\mathrm{Hgmm,°C}}}}=p^0[\mathrm{Pa}]/133{,}322\frac{\mathrm{Pa}}{\mathrm{Hgmm}}$$

$$A_{\mathrm{Hgmm,°C}}-\frac{B_{\mathrm{Hgmm,°C}}}{T[°\mathrm{C}]+C_{\mathrm{Hgmm,°C}}}=\log_{10}\left(p^0[\mathrm{Pa}]/133{,}322\right)=\log_{10}\left(p^0[\mathrm{Pa}]\right)-\log_{10}(133{,}322)$$

$$\left(A_{\mathrm{Hgmm,°C}}+\log_{10}(133{,}322)\right)-\frac{B_{\mathrm{Hgmm,°C}}}{\left(T[K]-273{,}15K\right)+C_{\mathrm{Hgmm,°C}}}=\log_{10}\left(p^0[\mathrm{Pa}]/133{,}322\right)=\log_{10}\left(p^0[\mathrm{Pa}]\right)$$

$$\left(A_{\mathrm{Hgmm,°C}}+\log_{10}(133{,}322)\right)-\frac{B_{\mathrm{Hgmm,°C}}}{\left(T[K]-273{,}15K\right)+C_{\mathrm{Hgmm,°C}}}=A_{\mathrm{Pa,K}}-\frac{B_{\mathrm{Pa,K}}}{\left(T[K]\right)+C_{\mathrm{Pa,K}}}$$

thus: $A_{\mathrm{Pa,K}}=A_{\mathrm{Hgmm,°C}}+\log_{10}(133{,}322)$, $B_{\mathrm{Pa,K}}=B_{\mathrm{Hgmm,°C}}$ és $C_{\mathrm{Pa,K}}=C_{\mathrm{Hgmm,°C}}-273{,}15\,\mathrm{K}$.

The following table lists the Antoine constants of some pure components near atmospheric pressure, as well as their atmospheric boiling points and molar masses. Pressure is specified in Hgmm. temperature is specified in °C.

	$A_{\mathrm{Hgmm,°C}}$	$B_{\mathrm{Hgmm,°C}}$	$C_{\mathrm{Hgmm,°C}}$	M (g/mol)	T_{bp} (°C)
benzene	6.90565	1211.03	220.79	78.0	80.1
cyclohexane	6.95333	1343.94	219.38	92.1	110.6
cyclohexanol	5.95583	777.36	91.11	94.1	161.7
ethanol	7.68117	1332.04	199.20	46.0	78.3
ethylbenzene	6.94994	1420.32	212.61	106.2	136.4
phenol	7.12194	1509.68	174.20	100.2	181.8
heptane	6.90338	1268.64	216.95	100.2	98.4
hexane	6.87772	1171.53	224.37	86.2	68.7

i-butane	7.20316	1132.11	-274.07	58.1	-12.1
i-propanol	8.87829	2010.33	252.64	60.1	82.6
i-octane	6.81185	1257.84	220.74	114.3	99.2
methanol	8.08097	1582.27	239.73	32.0	64.5
m-cresol (3-methyl-phenol)	6.76147	1355.92	146.73	108	202.7
n-butane	6.72508	909.65	237.00	58.1	-0.4
octane	6.92373	1355.13	209.52	114.3	125.7
pentane	6.87632	1075.78	233.205	72.0	36
propanol	7.75107	1441.63	198.85	60.1	97.2
toluene	6.95464	1344.80	219.48	92.0	110.6
water	8.07131	1730.63	233.43	18.0	100.0

Important properties of unordered packings

Packing	Material	Specific weight (kg/m^3)	Size (mm×mm)	Specific surface area (m^2/m^3)	Void volume (m^3/m^3)	F_t factor (-)
Raschig-ring	Ceramic	795	12×12×1,8	360	0,67	580
		605	25×25×3	195	0,73	155
		570	35×35×4	140	0,76	95
		535	50×50×5	98	0,77	65
		575	70×70×7	72	0,77	37
Raschig-ring	Metal		12,5×12,5			410
			25×25			137
			51×51			57
			75×75			32
Berl-saddle	Ceramic	780	12,5×12,5	545	0,65	240
		640	25×25	260	0,68	110
Pall-ring	Polypropylene	80	25×25	220	0,91	52
		65	35×35	160	0,93	40
		65	50×50	110	0,93	25
		53	90×90	86	0,94	16
Pall-ring	Metal	460	25×25	215	0,94	48
		390	38×38	135	0,95	28
		380	50×50	105	0,95	20
		360		78	0,96	16
HY-PAK-ring	Metal	304	25×25		0,96	42
		224	50×50		0,97	18
		208	75×75		0,97	15
Intalox-saddle	Ceramic	740	12,5×12,5	625	0,71	200
		672	25×25	255	0,73	98
		625	38×38	195	0,76	52
		610	51×51	118	0,76	40
		580	76×76	92	0,79	22
Super-Intalox	Polypropylene	80	25×12,5×1,2	288	0,85	33
		56,4	51×25×1,5	250	0,96	21
		59,2	76×38×2,6	200	0,97	16
Super-Intalox	Ceramic	625	25×12,5		0,79	60
		595	51×25		0,81	30

Tellerett	Poliprolilén	128	25×9×1,5×2	269	0,82	488
		11	47×19×3×3	285	0,88	271
		103	51×19×3×3	280	0,89	255
		102	59×19×3×3	250	0,92	213
		102	73×28×3×4	127	0,89	180
		88	95×37×3×6	94	0,9	129
		47	145×48×3×6	65	0,95	76