

Stage and continuous gas-liquid separation processes

- Chemical process materials are often mixtures of different components. To remove or separate one or more of the components from the original mixture, it must be contacted with another phase.
- Solute/s can diffuse/s from one phase to another. The two phases are usually only somewhat miscible in each other. The two phases can be gas-liquid, gas-solid, liquid-liquid, or liquid-solid.

Types of separation processes

- Absorption: When the two contacting phases are gas and liquid, where the solute or several solutes are absorbed from the gas phase into the liquid phase. (Ex: Absorption of ammonia from air by liquid water).
- Distillation: Where a volatile vapor phase, and a liquid phase that vaporizes are involved. (Ex: Distillation of an ethanol-water solution, ammonia-water solution).
- Liquid-liquid extraction: When the two phases are liquids a solute or solutes are removed from one liquid to another liquid phase. (Ex. Extraction of acetic acid from water solution by isopropyl ether).
- Leaching: If a fluid is being used to extract a solute from a solid we call it leaching. (Ex. Leaching vegetable oils from solid soybeans by organic solvents such as hexane).
- There are other types of separation processes such as membrane separation, crystallization, adsorption and ion exchange. (are not covered in this course)

Equilibrium relations between phases

Equilibrium relation between partial pressure of component (A) in the gas phase and the mole fraction of (A) in the liquid phase can be expressed by Henry's law at low concentrations:

$$P_A = Hx_A$$

P_A : Partial pressure of (A) in the gas phase.

H : Henry's law constant (atm/mole).

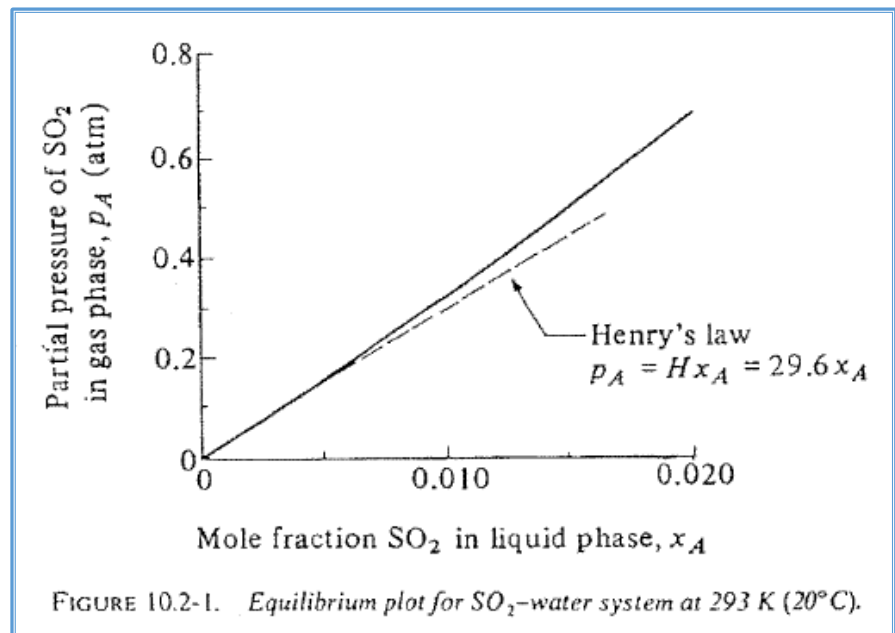
x_A : Mole fraction of (A) in the liquid phase.

Rewriting

$$\frac{P_A}{P} = \frac{H}{P} x_A$$

$$y_A = H' x_A$$

H' : Henry's law constant (mole frac gas/mole frac liquid)



EXAMPLE 10.1-1. Dissolved Oxygen Concentration in Water

What will be the concentration of oxygen dissolved in water at 298 K when the solution is in equilibrium with air at 1 atm total pressure? The Henry's law constant is 4.38×10^4 atm/mol fraction.

Single equilibrium contact stage

If two different phases brought into intimate contact for enough time where various components diffuse and redistribute themselves between the two phases, the **components are essentially at equilibrium** in the two phases after separation.



This process is considered as a single equilibrium stage.

If the system contains three components (A, B and C), the balance equation on A and C is:

$$L_0 x_{A0} + V_2 y_{A2} = L_1 x_{A1} + V_1 y_{A1} = M x_{AM}$$

$$L_0 x_{C0} + V_2 y_{C2} = L_1 x_{C1} + V_1 y_{C1} = M x_{CM}$$

$$x_A + x_B + x_C = 1$$

Exchange of solute(A) is in the gas phase (A+B) and liquid phase (A+C).

Assuming the gas phase is insoluble in the liquid phase and the liquid phase is not vaporize to the gas phase we will get a binary system in both phases.

Since component (A) is the only component that redistribute between the two phases, a balance on (A) is as follows:

$$L' \frac{x_{A0}}{(1 - x_{A0})} + V' \frac{y_{A2}}{(1 - y_{A2})} = L' \frac{x_{A1}}{(1 - x_{A1})} + V' \frac{y_{A1}}{(1 - y_{A1})}$$

$$y_{A1} = H' x_{A1}$$

- $L' = L(1 - x_A)$: Moles of inert solvent/water
- $V' = V(1 - y_A)$: Moles of inert gas/air

EXAMPLE 103-1. Equilibrium Stage Contact for CO₂–Air–Water

A gas mixture at 1.0 atm pressure abs containing air and CO₂ is contacted in a single-stage mixer continuously with pure water at 293 K. The two exit gas and liquid streams reach equilibrium. The inlet gas flow rate is 100 kg mol/h, with a mole fraction of CO₂ of $y_{A2} = 0.20$. The liquid flow rate entering is 300 kg mol water/h. Calculate the amounts and compositions of the two outlet phases. Assume that water does not vaporize to the gas phase.

Solution: The flow diagram is the same as given in Fig. 10.3-1. The inert water flow is $L = L_0 = 300$ kg mol/h. The inert air flow V' is obtained from Eq. (10.3-6).

$$V' = V(1 - y_A) \quad (10.3-6)$$

Hence, the inert air flow is $V' = V_2(1 - y_{A2}) = 100(1 - 0.20) = 80$ kg mol/h. Substituting into Eq. (10.3-4) to make a balance on CO₂ (A),

$$300\left(\frac{0}{1 - 0}\right) + 80\left(\frac{0.20}{1 - 0.20}\right) = 300\left(\frac{x_{A1}}{1 - x_{A1}}\right) + 80\left(\frac{y_{A1}}{1 - y_{A1}}\right) \quad (10.3-7)$$

At 293 K, the Henry's law constant from Appendix A.3 is $H = 0.142 \times 10^4$ atm/mol frac. Then $H' = H/P = 0.142 \times 10^4/1.0 = 0.142 \times 10^4$ mol frac gas/mol frac liquid. Substituting into Eq. (10.3-5),

$$y_{A1} = 0.142 \times 10^4 x_{A1} \quad (10.3-8)$$

Substituting Eq. (10.3-8) into (10.3-7) and solving, $x_{A1} = 1.41 \times 10^{-4}$ and $y_{A1} = 0.20$. To calculate the total flow rates leaving,

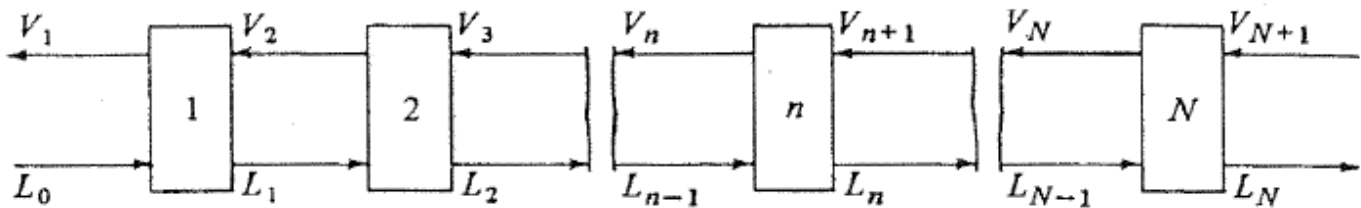
$$L_1 = \frac{L}{1 - x_{A1}} = \frac{300}{1 - 1.41 \times 10^{-4}} = 300 \text{ kg mol/h}$$

$$V_1 = \frac{V'}{1 - y_{A1}} = \frac{80}{1 - 0.20} = 100 \text{ kg mol/h}$$

In this case, since the liquid solution is so dilute, $L_0 \cong L_1$.

Countercurrent Multiple-contact stages

In order to transfer more solute from the V phase and conserve the use of the L phase (L), a countercurrent multiple stage contacting is generally used. It is shown below.



The V stream contains mainly B while the L stream mainly contains C. Only the solute (A) is exchanged between two streams. Both V and L streams are immiscible in each other.

$$L_0 + V_{N+1} = L_N + V_1 = M$$

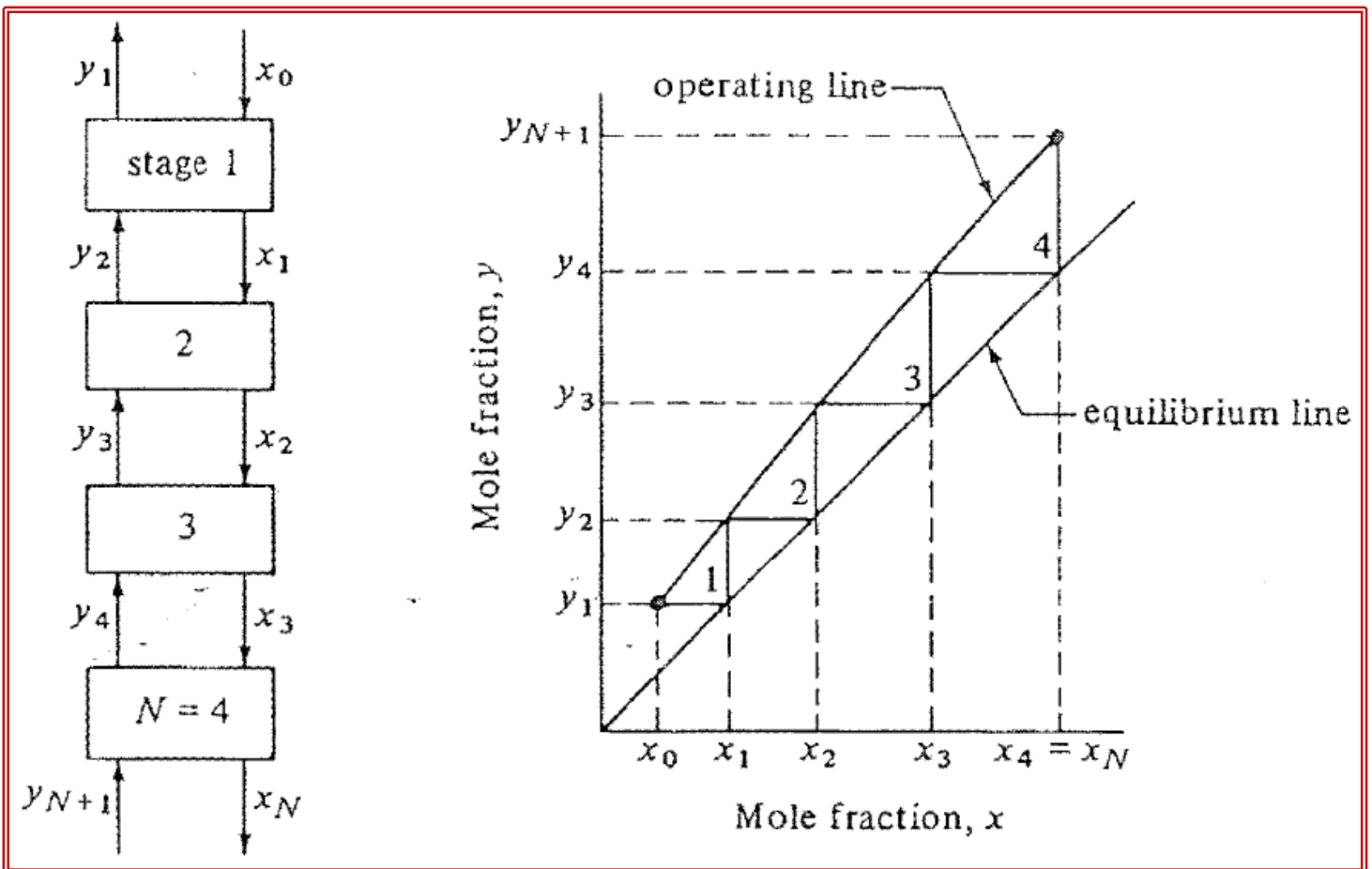
$$L_0x_0 + V_{N+1}y_{N+1} = L_Nx_N + V_1y_1 = Mx_M$$

$$L_0 + V_{n+1} = L_n + V_1$$

$$L_0x_0 + V_{n+1}y_{n+1} = L_nx_n + V_1y_1$$

$$y_{n+1} = \frac{L_n}{V_{n+1}}x_n + \frac{V_1y_1 - L_0x_0}{V_{n+1}}$$

- This is the operating line equation. This line determines the L phase composition coming out from nth stage with one of V phase entering nth stage.
- Equilibrium line determine the compositions of streams leaving the stage.
- If the streams L and V are dilute in A, the streams are approximately constant and the slope (L_n/V_{n+1}) of the operating line is nearly constant. Hence, the operating line is essentially a straight line on an x-y plot.



Solution Porcedure for Ideal stages

Required: Thermodynamic data for equilibrium line at given T and P

Usually, fraction of A in the inlet L stream and the outlet V stream (y_1, x_0) and their flowrates (L, V) are known. Also known is inlet composition of V, i.e y_{N+1}

Step 1: Draw equilibrium line

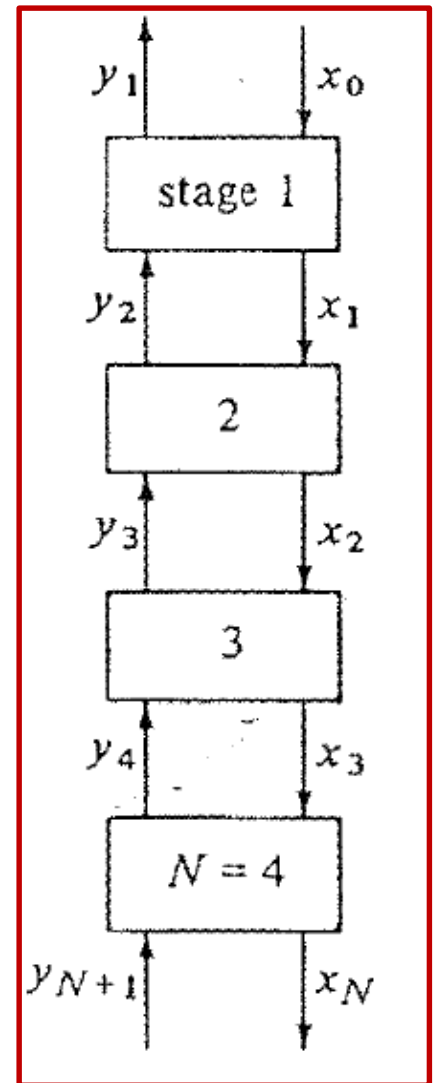
Step 2: Locate (x_0, y_1)

Step 3: Draw operating line with slope (L, V) strating from (x_0, y_1)

Step 4: From (x_0, y_1) , move horizontally to Equilibrium line to locate (x_1, y_1) . Next move vertically to locate (x_1, y_2) on the operating line. This complete Stage 1 of multi-stage contacting. This procedure is repeated till y_{N+1} is reached.

EXAMPLE 10.3-2. Absorption of Acetone in a Countercurrent Stage Tower

It is desired to absorb 90% of the acetone in a gas containing 1.0 mol % acetone in air in a countercurrent stage tower. The total inlet gas flow to the tower is 30.0 kg mol/h, and the total inlet pure water flow to be used to absorb the acetone is 90 kg mol H₂O/h. The process is to operate isothermally at 300 K and a total pressure of 101.3 kPa. The equilibrium relation for the acetone (A) in the gas-liquid is $y_A = 2.53x_A$. Determine the number of theoretical stages required for this separation.



SOLUTION:

$$P = 101.3 \text{ kPa}; \quad T = 300\text{K};$$

$$L = \text{Water}; \quad V = \text{Air}; \quad \text{Solute (A)} = \text{Acetone}$$

$$x_0 = 0.0; \quad y_{N+1} = 0.01$$

$$L_0 = 90.0; \quad V_{N+1} = 30.0$$

Required: 90% removal of acetone from air

$$\text{Acetone in} = V_{N+1}y_{N+1} = 30.0 \times 0.01 = 0.30$$

$$\text{Air in} = V_{N+1}(1 - y_{N+1}) = 30.0 \times (1 - 0.01) = 29.7$$

$$\text{For 90\% removal of acetone from air, Acetone out in } L_N = 0.30 \times 0.9 = 0.27$$

$$\text{For 90\% removal of acetone from air, Acetone out in } V_1 = 0.30 \times 0.1 = 0.030$$

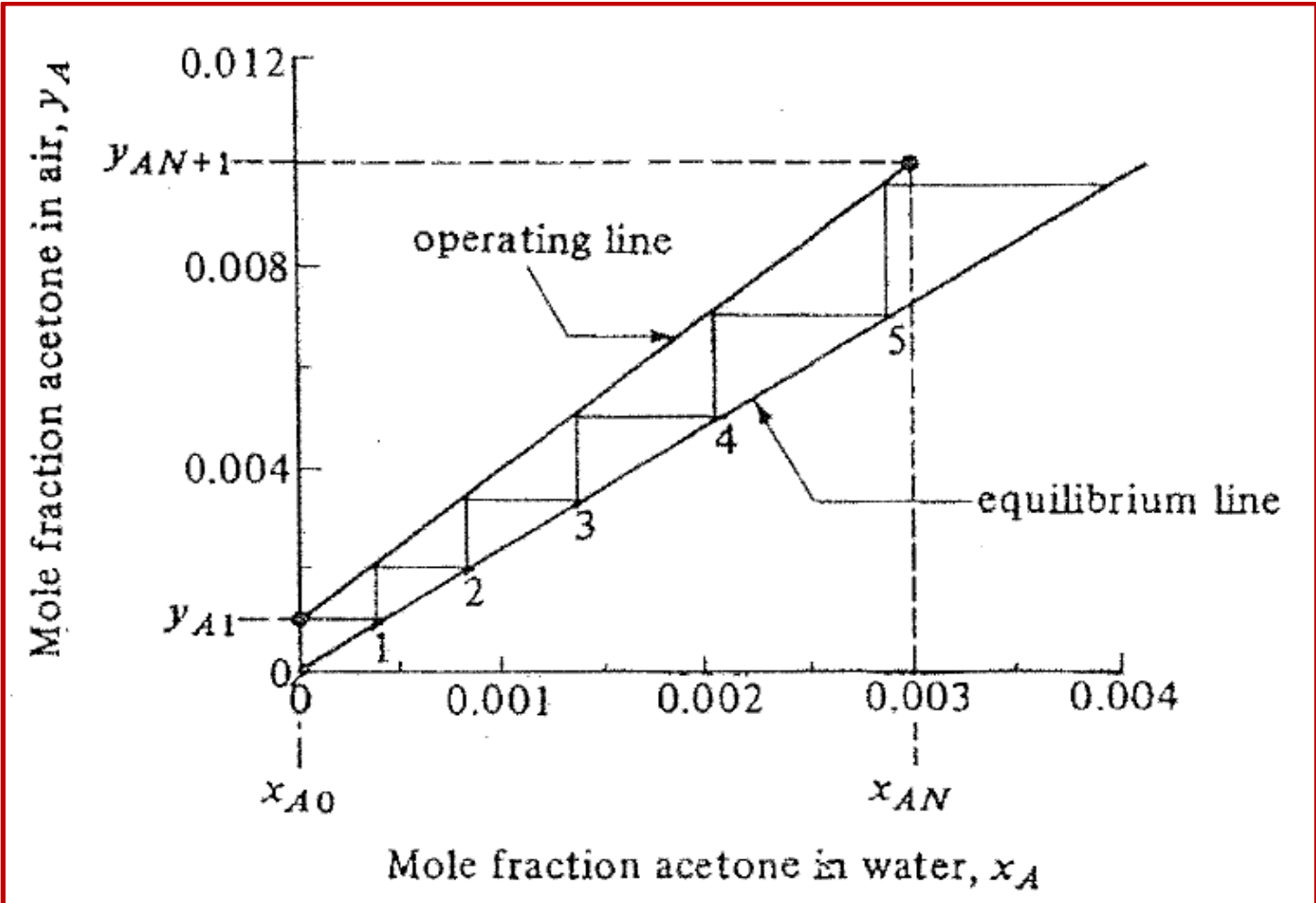
$$V_1 = 29.7 + 0.030 = 29.73; \quad y_1 = \frac{0.03}{29.73} = 0.0010$$

$$L_N = 90.0 + 0.27 = 90.27; \quad x_{AN} = \frac{0.27}{90.27} = 0.0030$$

$$\frac{L}{V} = \frac{L_0}{V_1} = \frac{90.00}{29.73} = 3.03$$

$$\frac{L}{V} = \frac{L_N}{V_{N+1}} = \frac{90.27}{30.00} = 3.01$$

Therefore, the operating line is a straight line of slope 3.02



Analytical/Kremser equation for countercurrent multiple stages

For **ABSORPTION** (transfer of solute A from V to L)

$$\frac{y_{N+1} - y_1}{y_{N+1} - mx_0} = \frac{A^{N+1} - A}{A^{N+1} - 1}$$

$$N = \log \left[\frac{y_{N+1} - mx_0}{y_1 - mx_0} \left(1 - \frac{1}{A} \right) + \frac{1}{A} \right] / \log A$$

$$A = 1; \Rightarrow N = \frac{y_{N+1} - y_1}{y_1 - mx_0}$$

$$A_1 = \frac{L_o}{mV_1}; A_N = \frac{L_N}{mV_{N+1}}; \quad A_1 \neq A_N \quad A = \sqrt{A_1 A_N}$$

For **STRIPPING** (transfer of solute A from L to V)

$$\frac{x_0 - x_N}{x_0 - (y_{N+1}/m)} = \frac{S^{N+1} - S}{A^{N+1} - 1}$$

$$N = \log \left[\frac{x_0 - (y_{N+1}/m)}{x_N - (y_{N+1}/m)} \left(1 - \frac{1}{S} \right) + \frac{1}{S} \right] / \log S$$

$$S = 1; \Rightarrow N = \frac{x_0 - x_N}{x_N - (y_{N+1}/m)}$$

$$A = \frac{1}{S} = \frac{L}{mV}; y = mx$$

EXAMPLE 10.3-2. Absorption of Acetone in a Countercurrent Stage Tower

Given:

$$x_0 = 0.0000; x_N = 0.0030$$

$$y_1 = 0.0010; y_{N+1} = 0.010$$

$$L_0 = 90.00; V_1 = 29.73$$

$$L_N = 90.27; V_{N+1} = 30.0$$

$$A_1 = \frac{L_0}{mV_1} = 1.2; \quad A_N = \frac{L_N}{mV_{N+1}} = 1.19 \quad A = \sqrt{A_1 A_N} = 1.195$$

$$N = \log \left[\frac{y_{N+1} - mx_0}{y_1 - mx_0} \left(1 - \frac{1}{A} \right) + \frac{1}{A} \right] / \log A$$

$$N = \log \left[\frac{0.01 - 2.53 \times 0}{0.00101 - 2.53 \times 0} \left(1 - \frac{1}{1.195} \right) + \frac{1}{1.195} \right] / \log(1.195) = 5.04$$

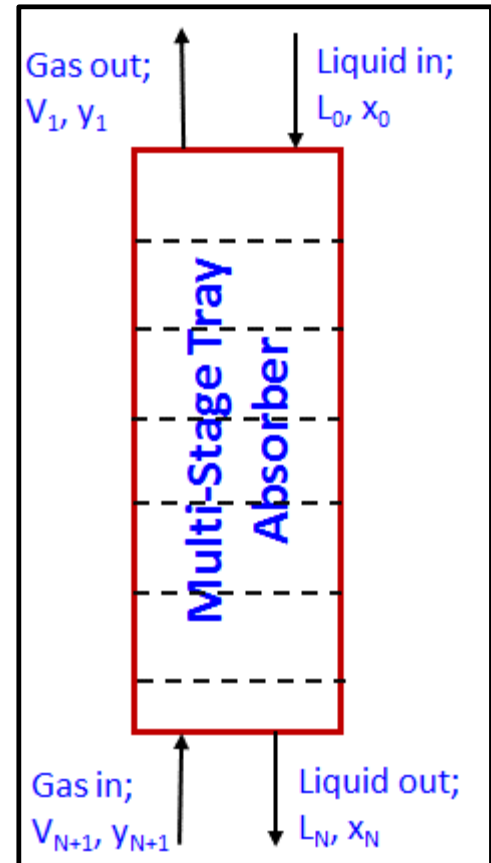
Summary:

- Graphical solution = 5.2 Stages
- Analytical solution = 5.04 Stages

Practice Session Question -1:

An inlet air stream entering a counter-current absorption tower contains 2 mol% acetone vapor. It is required to remove the 90% acetone using liquid water as solvent. The total inlet air flow is 50 kg mol/h, and the total inlet pure water flow is 150 kg mol/h. The process is to operate isothermally at 293 K and a total pressure of 101.32 kPa. The equilibrium relation for the acetone (A) can be assumed to be $y_A = mx_A = 2x_A$

- Determine the flow rate and composition of the solvent leaving the absorber
- Determine the flow rate and composition of the gases leaving the absorber
- Determine the required number of ideal stages. Show the clear sketch on the graph paper using a pencil
- Compare your graphical results with the analytical Kremeser equation
- Composition of stream leaving stage 2
- Composition of streams entering stage 2
- Determine minimum solvent requirement for given separation using single equilibrium stage.



$$P = 101.3 \text{ kPa}; \quad T = 300\text{K};$$

$$L = \text{Water}; \quad V = \text{Air}; \quad \text{Solute (A)} = \text{Acetone}$$

$$x_0 = 0.0; \quad y_{N+1} = 0.01$$

$$L_0 = 150.0; \quad V_{N+1} = 50.0$$

Required: 90% removal of acetone from air

$$\text{Acetone in feed} = V_{N+1}y_{N+1} = 50.0 \times 0.02 = 1.0$$

$$\text{Inert air in feed} = V_{N+1}(1 - y_{N+1}) = 50.0 \times (1 - 0.02) = 49.0$$

$$\text{For 90\% removal of acetone from feed, the Acetone out in } L_N = 1.0 \times 0.9 = 0.90$$

$$L_N = 150 + 0.9 = 150.9; x_{AN} = \frac{0.90}{150.9} = 0.006$$

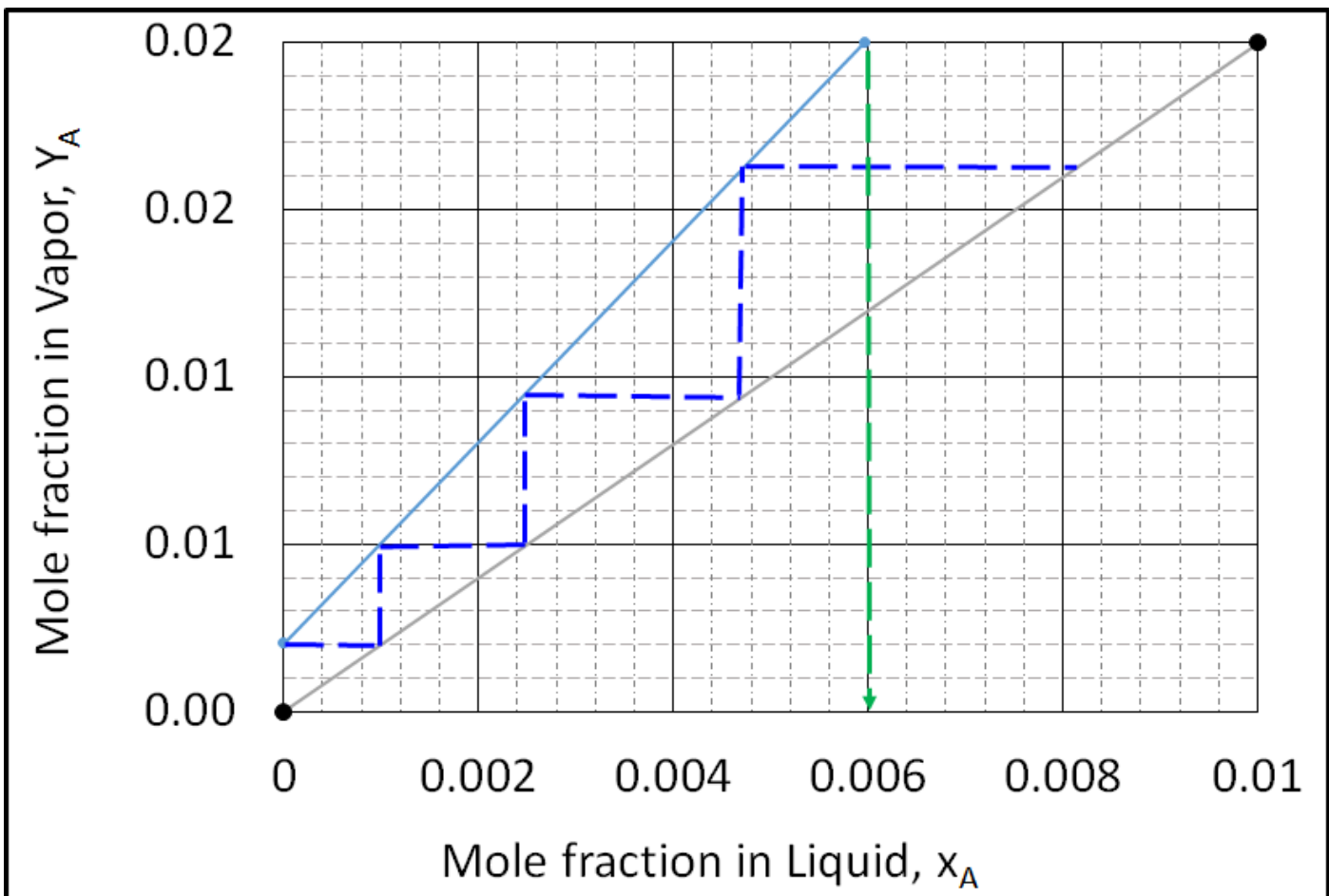
For 90% removal of acetone from feed, the Acetone out in $V_1 = 1.0 \times 0.1 = 0.10$

$$V_1 = 49 + 0.1 = 49.10; y_1 = \frac{0.10}{49.1} = 0.002$$

Since the solution is dilute,

$$\frac{L}{V} \cong \frac{L_0}{V_1} \cong \frac{L_N}{V_{N+1}}$$

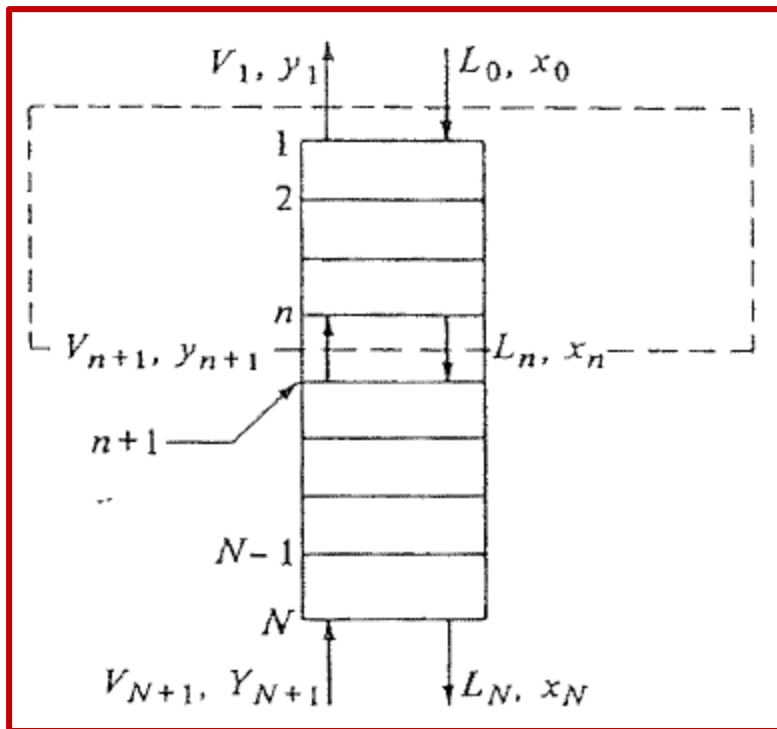
The operating line can be assumed straight as shown in the following figure.



Discussion:

- What will be the effect of decreasing the temperature
- What will be the effect of increasing/decreasing the equilibrium constant, *i.e.* m
- What will be the effect of increasing/decreasing the solvent flowrate

Design Equations for Plate Absorption Towers Derived from Material Balance



For Solute (A):

$$L' = L_0(1 - x_0) = L_N(1 - x_N): \quad \text{Moles of inert solvent/water}$$

$$V' = V_1(1 - y_1) = V_{N+1}(1 - y_{N+1}): \quad \text{Moles of inert gas/air}$$

Over-all	$L' \frac{x_0}{(1 - x_0)} + V' \frac{y_{N+1}}{(1 - y_{N+1})} = L' \frac{x_N}{(1 - x_N)} + V' \frac{y_1}{(1 - y_1)}$
\$n^{\text{th}}\$ tray	$L' \frac{x_0}{(1 - x_0)} + V' \frac{y_{n+1}}{(1 - y_{n+1})} = L' \frac{x_n}{(1 - x_n)} + V' \frac{y_1}{(1 - y_1)}$

EXAMPLE 10.6-1. Absorption of SO₂ in a Tray Tower

A tray tower is to be designed to absorb SO₂ from an air stream by using pure water at 293 K. The entering gas contains 20 mol % SO₂ and that leaving 2 mol % at a total pressure of 101.3 kPa. The inert air flow rate is 150 kg air/h.m², and the entering water flow rate is 6000 kg water/h.m². Assuming an overall tray efficiency of 25%, how many theoretical trays and actual trays are needed? Assume that the tower operates at 293 K.

SOLUTION:

$$P = 101.3 \text{ kPa}; \quad T = 293\text{K};$$

$$L = \text{Water}; \quad V = \text{Air}; \quad \text{Solure (A)} = \text{SO}_2$$

$$x_0 = 0.0; \quad y_{N+1} = 0.20; \quad y_1 = 0.020;$$

$$V' = \frac{150}{29} = 5.18 \frac{\text{kg mol inert air}}{\text{h} \cdot \text{m}^2}; \quad L' = \frac{6000}{18} = 333 \frac{\text{kg mol inert water}}{\text{h} \cdot \text{m}^2}$$

Over-all

$$L' \frac{x_0}{(1-x_0)} + V' \frac{y_{N+1}}{(1-y_{N+1})} = L' \frac{x_N}{(1-x_N)} + V' \frac{y_1}{(1-y_1)}$$

$$333 \frac{0}{(1-0)} + 5.18 \frac{0.20}{(1-0.20)} = 333 \frac{x_N}{(1-x_N)} + 5.18 \frac{0.02}{(1-0.02)}$$

$$x_N = 0.00355$$

nth tray

$$L' \frac{x_0}{(1-x_0)} + V' \frac{y_{n+1}}{(1-y_{n+1})} = L' \frac{x_n}{(1-x_n)} + V' \frac{y_1}{(1-y_1)}$$

$$333 \frac{0}{(1-0)} + 5.18 \frac{y_{n+1}}{(1-y_{n+1})} = 333 \frac{x_n}{(1-x_n)} + 5.18 \frac{0.02}{(1-0.02)}$$

$$y_{n+1} = 0.07 \Rightarrow x_N = 0.000855$$

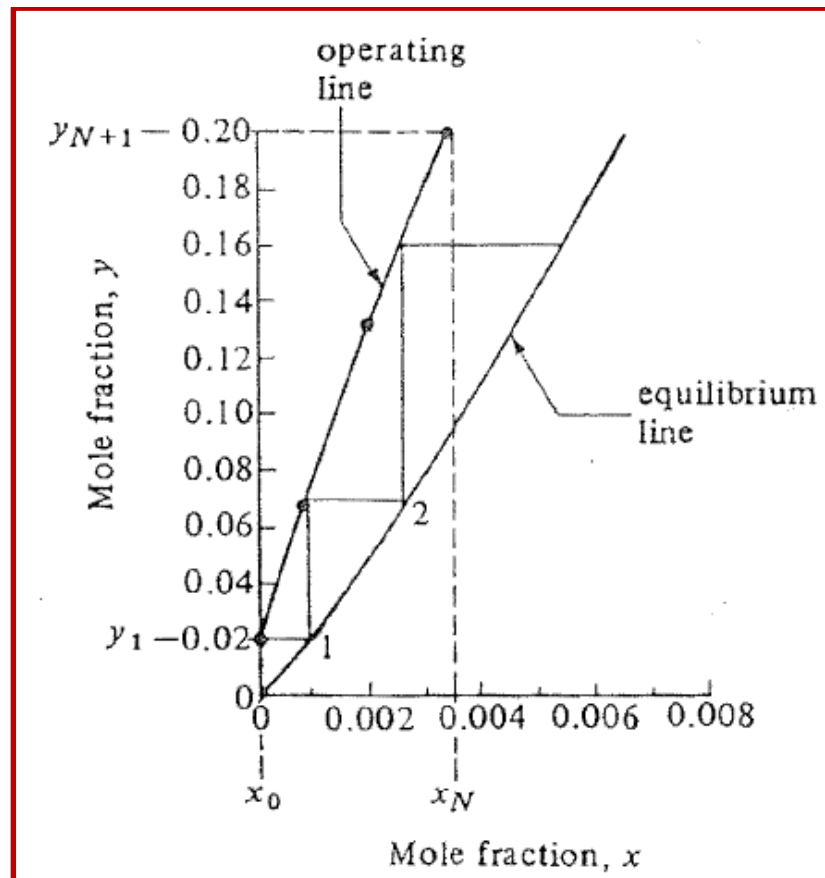
$$y_{n+1} = 0.13 \Rightarrow x_N = 0.00201$$

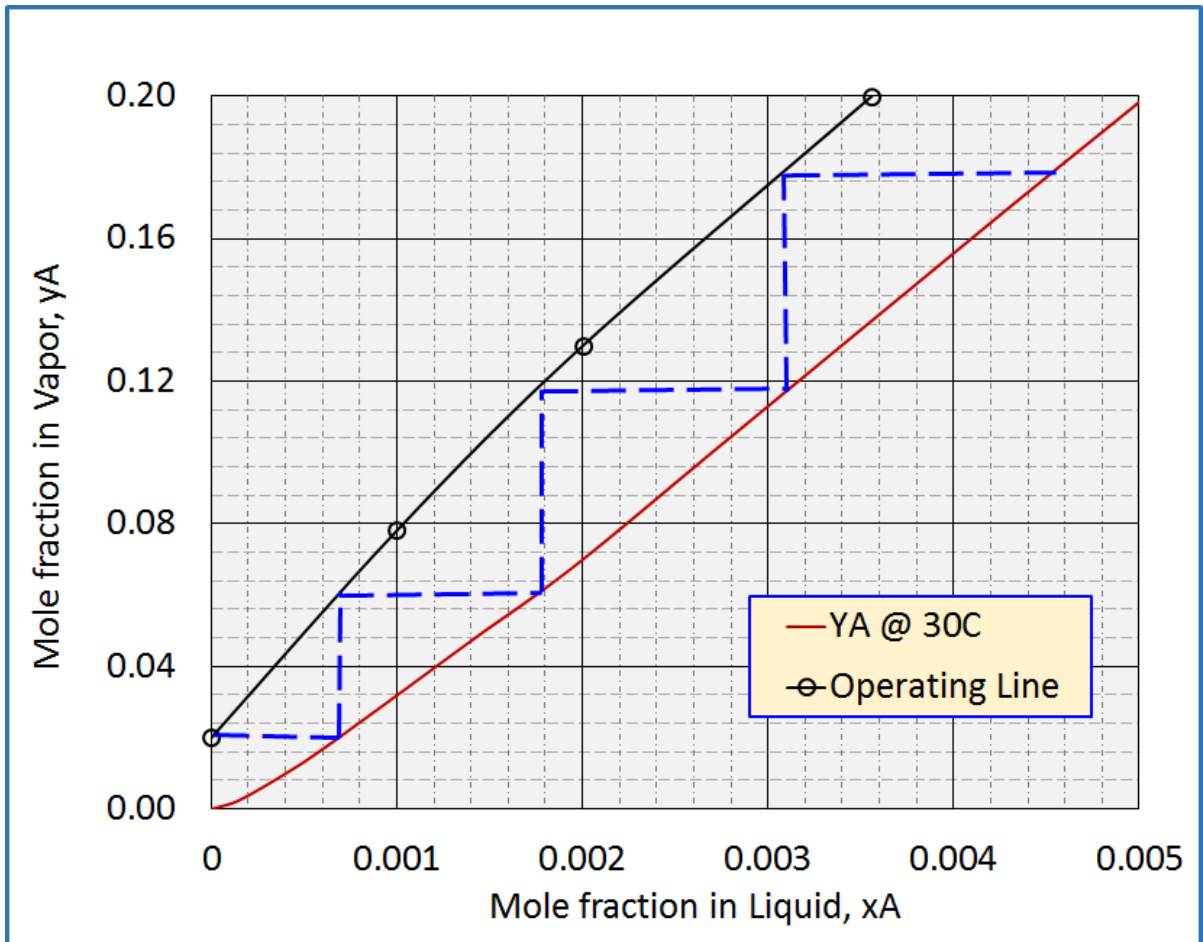
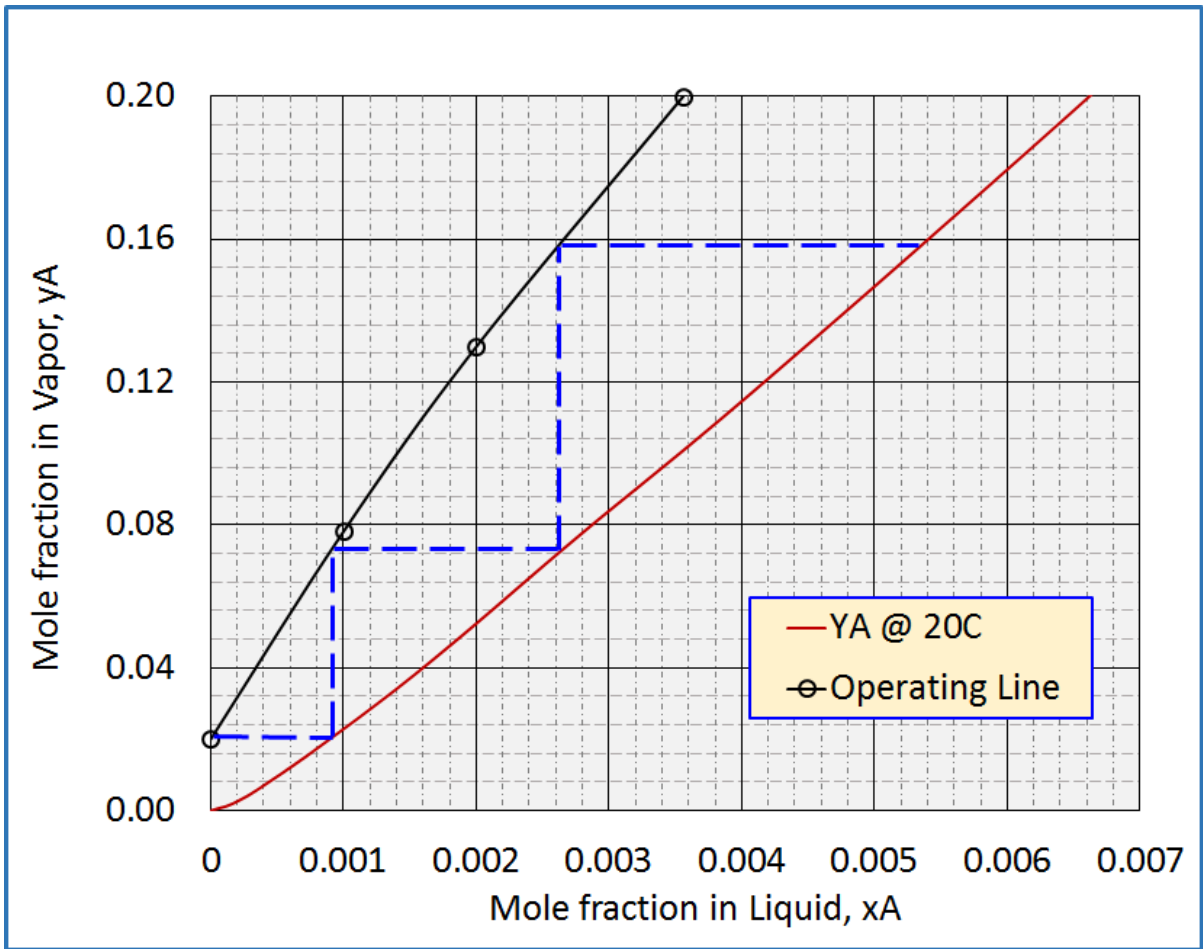
Operating line	X	0.000	0.000855	0.00201	0.00355
	y	0.020	0.07	0.13	0.20

A.3-19 Equilibrium Data for SO₂-Water System

Mole Fraction SO ₂ in Liquid, x_A	Partial Pressure of SO ₂ in Vapor, p_A (mm Hg)		Mole Fraction SO ₂ in Vapor, y_A ; $P = 1$ Atm	
	20°C (293 K)	30°C (303 K)	20°C	30°C
0	0	0	0	0
0.0000562	0.5	0.6	0.000658	0.000790
0.0001403	1.2	1.7	0.00158	0.00223
0.000280	3.2	4.7	0.00421	0.00619
0.000422	5.8	8.1	0.00763	0.01065
0.000564	8.5	11.8	0.01120	0.0155
0.000842	14.1	19.7	0.01855	0.0259
0.001403	26.0	36	0.0342	0.0473
0.001965	39.0	52	0.0513	0.0685
0.00279	59	79	0.0775	0.1040
0.00420	92	125	0.121	0.1645
0.00698	161	216	0.212	0.284
0.01385	336	452	0.443	0.594
0.0206	517	688	0.682	0.905
0.0273	698		0.917	

Source : T. K. Sherwood, *Ind. Eng. Chem.*, 17, 745 (1925).





A tray tower is to be designed to absorb ethyl alcohol from an inert gas stream using pure water at 303 K and 101.3 kPa. The inlet gas stream flow rate is 100 kg mol/h and contains 2.2 mol % alcohol. It is desired to recover 90% of the alcohol. The equilibrium relationship is:

$$y_A = mx_A = 0.68x_A$$

Using 1.5 times the minimum liquid flow rate, determine the number of trays needed using both graphical as well as analytical method.

P = 101.3 kPa;

T = 303 K;

L = Water/Solvent;

V = Air/Gas;

Solute (A) = Ethyl alcohol

$$x_0 = 0.0; y_{N+1} = 0.0220;$$

Required: 90% removal of solute from gas

Solute in inlet gas = $V_{N+1}y_{N+1} = 100.0 \times 0.022 = 2.2$

Inert gas in inlet gas = $V_{N+1}(1 - y_{N+1}) = 100.0 - 2.2 = 97.8$

For 90% removal of solute,

Amount of solute in $L_N = 2.2 \times 0.9 = 1.98$

Amount of solute in $V_1 = 2.2 \times 0.1 = 0.22$

$$V_1 = 97.8 + 0.22 = 98.02; y_1 = \frac{0.22}{98.02} = 0.00224$$

Solvent composition at L_{min} requires equilibrium relationship, $y_A = mx_A = 0.68x_A$. Therefore,

$$(x_N)_{max} = y_{N+1}/m = 0.022/0.68 = 0.03235$$

From overall-material balance applied to L'_{min}

$$L' \frac{x_0}{(1-x_0)} + V' \frac{y_{N+1}}{(1-y_{N+1})} = L' \frac{x_N}{(1-x_N)} + V' \frac{y_1}{(1-y_1)}$$

$$L'_{min} \frac{x_0}{(1-x_0)} + V' \frac{y_{N+1}}{(1-y_{N+1})} = L'_{min} \frac{(x_N)_{max}}{(1-(x_N)_{max})} + V' \frac{y_1}{(1-y_1)}$$

$$L'_{min} \frac{0}{(1-0)} + 97.8 \frac{0.022}{(1-0.022)} = L'_{min} \frac{0.03235}{(1-0.03235)} + 97.8 \frac{0.00224}{(1-0.00224)}$$

$$L'_{min} = 59.24 \text{ kg mol/h}$$

$$L' = 1.5L'_{min} = 1.5 \times 59.24 = 88.86 \text{ kg mol/h}$$

Therefore, require solvent composition,

$$L' \frac{x_0}{(1-x_0)} + V' \frac{y_{N+1}}{(1-y_{N+1})} = L' \frac{x_N}{(1-x_N)} + V' \frac{y_1}{(1-y_1)}$$
$$88.86 \frac{0}{(1-0)} + 97.8 \frac{0.022}{(1-0.022)} = 88.86 \frac{x_N}{(1-x_N)} + 97.8 \frac{0.00224}{(1-0.00224)}$$
$$x_N = 0.0218$$

$$L_0 = L'/(1-x_0) = 88.86 \text{ kg mol/h};$$

$$L_N = L'/(1-x_N) = 88.86/(1-0.0218) = 90.84 \text{ kg mol/h}$$

$$A_1 = \frac{L_0}{mV_1} = \frac{88.86}{0.68 \times 98.02} = 1.333$$

$$A_N = \frac{L_N}{mV_{N+1}} = \frac{90.84}{0.68 \times 100.00} = 1.336$$

$$A = \sqrt{A_1 A_N} = \sqrt{1.333 \times 1.336} = 1.335$$

$$N = \log \left[\frac{y_{N+1} - mx_0}{y_1 - mx_0} \left(1 - \frac{1}{A} \right) + \frac{1}{A} \right] / \log A$$
$$= \frac{1}{\log 1.335} \log \left[\frac{0.022 - m \times 0}{0.00224 - m \times 0} \left(1 - \frac{1}{1.335} \right) + \frac{1}{1.335} \right] = 4.04$$