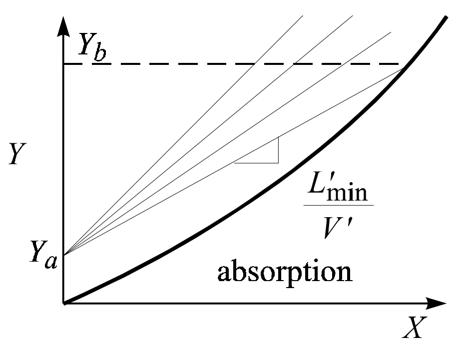
Review of Lectures 25-36

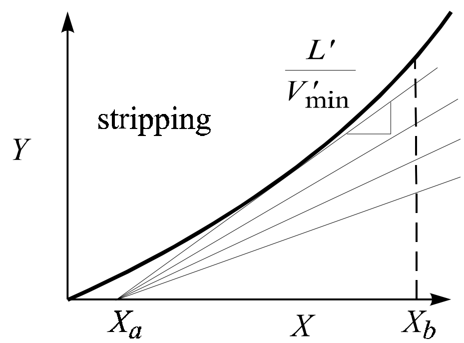
Chapters 14-16 of Notes

Gas Absorption/Stripping in Packed Towers

Minimum Flowrates

For absorption of gas into liquid. there is usually some minimum flowrate of liquid required to process a given quantity of gas; likewise, for stripping of a liquid by a gas, there is some minimum flowrate of gas required to process a given quantity of liquid



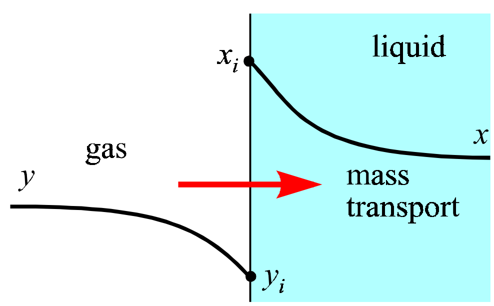


If only one component is transferred between phases, then the operating lines will be linear when plotted on mole ratio coordinates:

$$X = \frac{x}{1-x} \quad \text{and} \quad Y = \frac{y}{1-y}$$

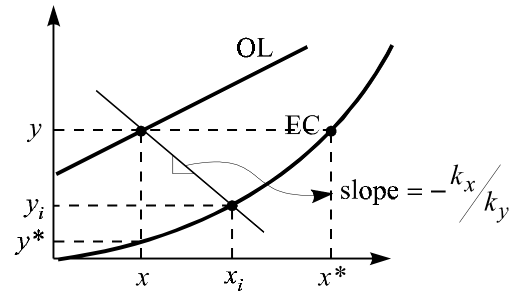
Interfacial Mass Transfer

Rates of interfacial mass transfer can be characterized using either single-phase driving forces or "overall" driving forces. Each has its own mass transfer coefficient:



$$\frac{\text{molar rate of transfer}}{\text{interfacial area}} = k_x(x_i - x) = k_y(y - y_i)$$
$$= K_x(x^* - x) = K_y(y - y^*)$$

where x^* and y^* are defined as shown on the figure at right. The single-phase coefficients k_x and k_y are the ones we can usually find correlations for. If they are both known, we could find the interfacial concentrations (x_i, y_i) corresponding to the bulk concentration (x,y) using the graphical procedure suggested at right. But it is usually much easier to work with the overall coefficients, which can be calculated from



$$\frac{1}{K_y a} = \frac{1}{k_y a} + \frac{m}{k_x a} \quad \text{or} \quad \frac{1}{K_x a} = \frac{1}{m k_y a} + \frac{1}{k_x a}$$

where $m = dy^*/dx$ is the local slope of the equilibrium curve. These formulas take the form of two "resistances in series."

Equimolar Counter-Diffusion

$$\underbrace{N_{Az}}_{\substack{\text{flux relative to} \\ \text{stationary reference frame}}} = \underbrace{J^*_{Az}}_{\substack{\text{flux relative to} \\ \text{mass-average velocity}}} = k'_y\left(y_{A1} - y_{A2}\right)$$

Diffusion of A through Stagnant B

For the same driving force across the film, diffusion through a stagnant film (relative to stationary reference frame) is faster than equimolar counter diffusion:

$$N_{Az} = \frac{k'_y}{\left(1 - y_A\right)_M}\left(y_{A1} - y_{A2}\right) = k_y\left(y_{A1} - y_{A2}\right)$$

where

$$\left(1 - y_A\right)_M = \frac{\left(1 - y_A\right)_1 - \left(1 - y_A\right)_2}{\ln \dfrac{\left(1 - y_A\right)_1}{\left(1 - y_A\right)_2}}$$

Depth of Packing Required

Once the mass transfer coefficients are known, the depth of packing required can be calculated from the design equation, one form of which (corresponding to the overall gas-phase driving force) is

$$Z_T = \underbrace{\left(\frac{V/S}{K_y a}\right)_{\text{avg}}}_{H_{Oy}} \underbrace{\int_{y_a}^{y_b} \frac{dy}{y - y^*}}_{N_{Oy}}$$

when both operating and equilibrium curves are straight, this integral can be performed analytically:

straight OL and EC: $$N_{Oy} = \frac{y_b - y_a}{\overline{(y - y^*)}_L}$$

where $\overline{(y - y^*)}_L$ is the log-mean of y_b-y_b* and y_a-y_a* which represent the driving force at the bottom and top of the tower, respectively.

The mass transfer coefficients can also be expressed as a height of a "transfer unit". The same relationships we had between the single-phase and overall coefficients lead to similar relationships between the heights of single-phase transfer units and overall-transfer units:

$$H_{Oy} = H_y + m\frac{V}{L}H_x \quad \text{and} \quad H_{Ox} = H_x + \frac{L}{mV}H_y$$

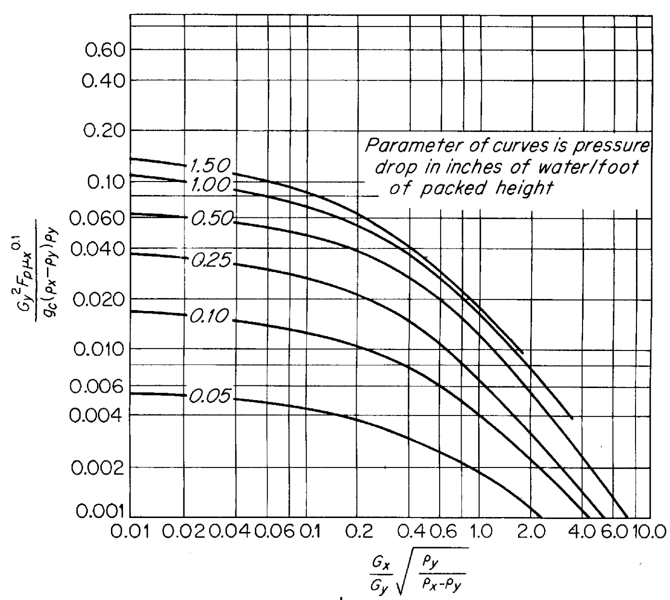
Pressure Drop and Column Diameter

The diameter of the column is usually chosen so that the flowrates of liquid and vapor required for the desired separation will generate a particular pressure drop (0.25 - 0.5 inch of water/foot of packing). For fixed molar flowrates of liquid and gas, the pressure drop generally drops as the diameter of the column increases, since the pressure drop depends on the mass flux, which generally decreases with column diameter:

$$G_x = \frac{\overline{M}_L}{S} L$$

and $$G_y = \frac{\overline{M}_V}{S} V$$

where $$S = \tfrac{1}{4}\pi D_T^2$$



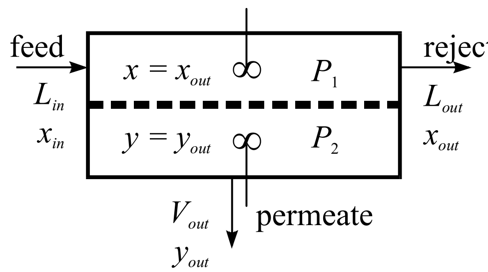
Symbol	Units
G_x, G_y	lb/ft^2-s
μ_x	cP
ρ_x, ρ_y	lb/ft^3
g_c	32.2 lb$_f$-ft/lb-s^2

Membrane Separation

The steady state flux of gas A through a nonporous membrane is given by Fick's law as

$$J_A = Q_A\left(P_{A1} - P_{A2}\right) \quad \text{where} \quad Q_A = \frac{D_A S_A}{\ell}$$

where P_A is the partial pressure of component A and Q_A is the membrane permeability to component A. Assuming gases on both sides of the membrane are "well-stirred" and denoting the low-pressure side by "2" and the high-pressure side by "1", then the mole fraction of the gas on the low-pressure side is the same as the ratio of molar flowrates of the two gases:



$$y = \frac{J_A}{J_A + J_B}$$

which equals the nonextraneous root of

$$\left(\alpha - 1\right) y^2 + \left\{1 - \alpha - \frac{1}{R} - \frac{x_{out}\left(\alpha - 1\right)}{R}\right\} y + \frac{\alpha x_{out}}{R} = 0$$

where
$$\alpha \equiv \frac{Q_A}{Q_B} \quad \text{and} \quad R \equiv \frac{P_2}{P_1}$$

For very low pressures on the downstream side, this quadratic reduces to

$R \to 0$:
$$y = \frac{\alpha x_{out}}{\left(\alpha - 1\right) x_{out} + 1}$$

For a significant value of stage cut θ, x_{in} and x_{out} are not equal, but are related by a mass balance:

$$x_{out} = \frac{x_{in} - \theta y_{out}}{1 - \theta} \quad \text{or} \quad y_{out} = \frac{x_{in} - \left(1 - \theta\right) x_{out}}{\theta}$$

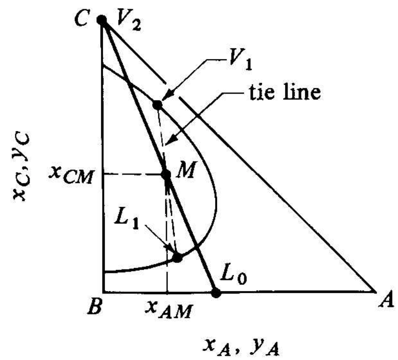
where stage cut is defined as

$$\theta \equiv \frac{\text{total molar permeate rate}}{\text{total molar feed rate}} = \frac{V_{out}}{L_{in}}$$

In terms of x_{in}, y is the nonextraneous root of

$$\left(\alpha - 1\right)\left[\theta + R\left(1 - \theta\right)\right] y^2 - \left\{\alpha\theta + \left(\alpha - 1\right)\left[x_{in} + R\left(1 - \theta\right)\right] + \left(1 - \theta\right)\right\} y + \alpha x_{in} = 0$$

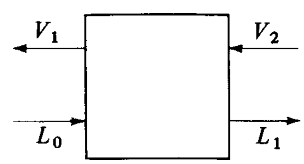
Liquid-Liquid Extraction



(Rectangular) Phase Diagram

Each point inside right triangle represents a particular mixture of the three components (A, B & C). The curve separates points in the 2-phase region from points in the 1-phase region. ***Tie lines*** across the 2-phase region connect points giving the composition of the two phases which are in equilibrium.

Single-Stage Extractor



Given the flowrates and compositions of the two feeds streams (denoted L_0 and V_2), find the flowrates and composition of the two product streams (L_1 and V_1).

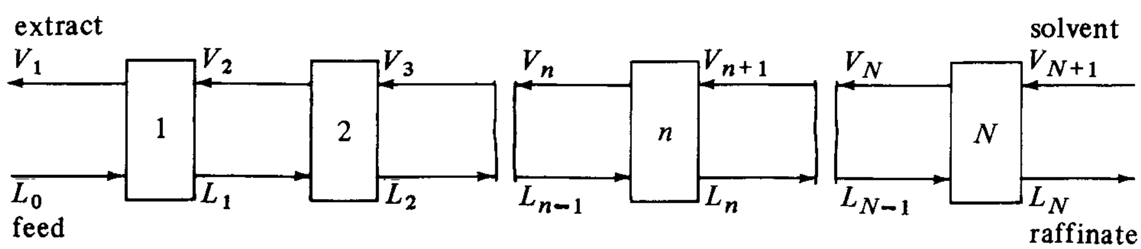
1. Using the compositions of the two feed streams to locate the points L_0 and V_2 on the phase diagram.

2. Use the ***lever arm rule*** to locate the mixing point M: $\overline{VM}/\overline{LM} = \frac{L_0}{V_2}$

3. Find the tie line passing through M.

4. Read the compositions of L_1 and V_1 at the end points of this tie line.

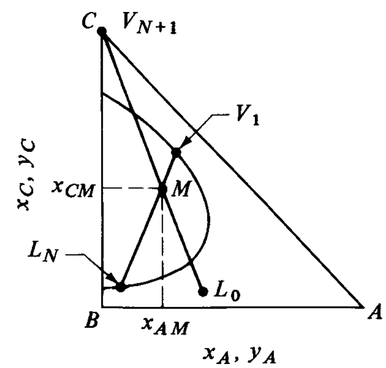
Output of CC-Cascade of Stages



Given: L_0, V_{N+1}, x_{A0}, $x_{C0} = 0$, $y_{AN+1} = 0$, $y_{CN+1} = 1$ and x_{AN}

Find: L_N, V_1, x_{CN}, y_{A1} and y_{C1}

Solution:



Step 1: Locate points L_0 and V_{N+1}

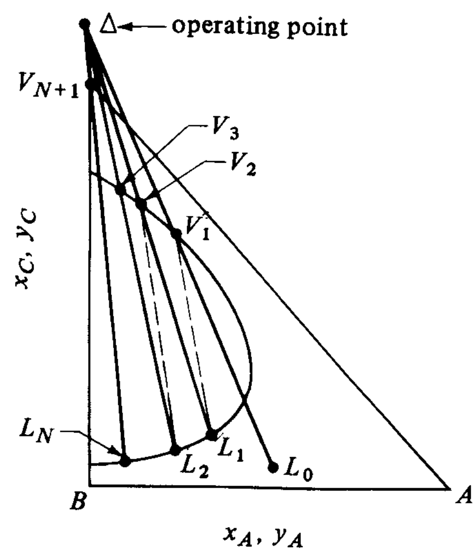
Step 2: Locate their mixing point M.

Step 3: Using the known value of x_{AN}, locate the point L_N on the lower portion of the equilibrium curve.

Step 4: Draw a straight line connecting L_N and M; then extend this line until it crosses the equilibrium curve again.

Step 5: The intersection of this line with the equilibrium curve is point V_1.

Number of Stages



Given: L_0, V_{N+1}, x_{A0}, $x_{C0} = 0$, $y_{AN+1} = 0$, $y_{CN+1} = 1$ and x_{AN}

Find: number of stages required

Solution:

Step 1: Locate points L_0 and Δ. The coordinates of Δ are:

$$x_{A\Delta} = \frac{L_0 x_{A0} - V_1 y_{A1}}{L_0 - V_1}$$

$$x_{C\Delta} = \frac{L_0 x_{C0} - V_1 y_{C1}}{L_0 - V_1}$$

Step 2: Connect L_0 and Δ with a straight line.

Step 3: Locate V_1 as the point where this line crosses the (upper part of) the equilibrium curve

Step 4: Determine the tie line passing through V_1. Locate L_1 as the other end of this tie line.

Step 5: Connect L_1 and Δ with a straight line.

Step 6: Locate V_2 as the point where this line crosses the (upper part of) the equilibrium curve

Step 7: Determine the tie line passing through V_2. Locate L_2 as the other end of this tie line.

Step 8: Repeat steps 5-7 until the desired composition is obtained for L_N.