CHAPTER 6:

ABSORPTION AND STRIPPING OF DILUTE MIXTURES

WHAT IS ABSORPTION?

interface

liquid solvent

\[\text{ABSORBENT}\]

\[\text{mass transfer}\]

inert gas + soluble vapor

\[\text{mixture}\]

\[\text{SOLUTE}\]

\[\text{Liquid}\]

\[\text{vapor}\]

HOW DO WE GET THE SEPARATION?

\[\Rightarrow \text{ADDED A MASS SEPARATING AGENT (Liquid solvent)}\]

\[\Rightarrow \text{MASS TRANSFER by Concentration Gradient Driving Force}\]

\[\text{(Gas phase} \Rightarrow \text{Liquid phase)}\]
Key examples:

1) CO$_2$ and H$_2$S Removal from natural gas
   (liquid solvent = solution of amines or alkaline salts)

2) NH$_3$ Removal from air
   (liquid solvent = water)

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WHAT IS DESORPTION (STRIPPING)?

Liquid
+ Volatile component

interface

Mass transfer
gas

How do we get the separation?
SAME AS ABSORPTION, JUST OPPOSITE DIRECTION
(liquid phase → gas phase)
Key examples:

1) VOC Removal from water
   \( \text{(gas} = \text{air}) \)

2) Solvent deoxygenation
   \( \text{(gas} = N_2 \) \)

3) Absorbent regeneration
   \( \text{(gas} = \text{varied}) \)

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**Absorption and Stripping Factors:**

\[ \text{Equilibrium operation (between 2 phases)} \]

- **GAS**
  - Ideal
  - Non-Ideal

- **LIQUID**
  - Ideal
  - Non-Ideal

How do we relate compositions in EACH PHASE?
Recall, **Modified Raoult's Law**

\[ y_i \cdot P = x_i \cdot \gamma_i \cdot P_i^{\text{sat}} \]

\[ \frac{y_i}{x_i} = K_i = \frac{\gamma_i \cdot P_i^{\text{sat}}}{P} \]

from solution thermodynamics...

\( P_i^{\text{sat}} \) from Antoine Equation

\( \gamma_i \) from activity coefficient model

\( P \) given or measured

if we know composition \((x_i, y_i)\), then know \( K_i \)

\[ K_i = f(x, y) \] and different at each stage ⇒

Absorption Factor will be stage specific.

\[ A_N = \frac{L}{V \cdot K} \]

\( L \) Absorption factor for stage \( N \).
Note: We have made an assumption

\[ L + V \text{ are constant.} \]

Reasonable?

Remember, we are absorbing solute from dilute solution. Since only the solute is transferred, then \( L + V \) (molar flow rates) are approximately constant.

\[ S_N = \frac{V K}{L} = \frac{1}{A_N} \]

\( L \) stripping factor for stage \( N \).

Now, \( K \) set by composition ... what happens to \( A_N + S_N \) when \( V + L \) change.
Case 1: \( V \) increases \( \quad L \) constant

\[ \Rightarrow A_N \downarrow \]

Why? Less contact time

Case 2: \( V \) decreases \( \quad L \) constant

\[ \Rightarrow A_N \uparrow \]

Why? Higher residence time

Case 3: \( V \) constant \( \quad L \) increases

\[ \Rightarrow A_N \uparrow \]

Why? More liquid \( \Rightarrow \) higher driving force

(Does not get as concentrated in soluble component)

Case 4: \( V \) constant \( \quad L \) decreases

\[ \Rightarrow A_N \downarrow \]

Why? Less liquid \( \Rightarrow \) lower driving force

(Liquid gets concentrated faster w/ soluble vapor component and concentration gradient decreases)
Notice that all of this was very logical. Can make similar analysis for desorption/stripping.

Different types of absorption:

Physical: movement of molecules from phase A to phase B. Still exist as the molecule in new phase.

Reactive: movement into new phase includes reaction in the new phase to a different type of molecule.
(can be irreversible or reversible)

Well, what do the columns look like?
Liquid Feed

May contain:
1. plates/trays (like distillation)
2. Structured packing
3. Dumped (random) packing

Gas Feed

Grid to hold in packing + distribute flow

Baffles to prevent channeling (Bypass)

Notice: NO condensers
NO reboilers

Biggest concern is pressure drop
Figure 6.2 Industrial equipment for absorption and stripping: (a) trayed tower; (b) packed column; (c) spray tower; (d) bubble column; (e) centrifugal contactor.
Figure 6.3 Details of a contacting tray in a trayed tower. [Adapted from B.F. Smith, Design of Equilibrium Stage Processes, McGraw-Hill, New York (1963).]
Figure 6.5 Three types of tray openings for passage of vapor up into liquid: (a) perforation; (b) valve cap; (c) bubble cap; (d) Tray with valve caps.
Figure 6.7 Typical materials used in a packed column: (a) random packing materials; (continued)
Figure 6.7 (Continued) (b) structured packing materials.
DESIGNING ABSORPTION TOWERS:

BASED ON TWO CONCEPTS:

1. MATERIAL BALANCE MODEL
2. FLOODING CALCULATION

OBJECTIVE:

FIND TOWER HEIGHT + DIAMETER

MATERIAL BALANCE:
(around top of column)

\[ \text{IN} = \text{OUT} \]
\[ yV + L_a x_a = y_a V_a + L_x \]

Solve for \( y \):
\[ y = \left( \frac{L}{V} \right) x + \left[ \frac{V y_a - L a x_a}{V} \right] \]

OPERATING LINE

Slope Op Line = \( \frac{L}{V} \) molar basis
NOTES:

1) BOTTOM LOCATION
   INLET GAS HIGHER CONC. IN SOLUTE

2) TOP LOCATION
   OUTLET GAS HAS LESS SOLUTE

3) OP. LINE ABOVE EQ. LINE
   SOLUTE CONC. IN GAS PHASE GREATER THAN EQ
   ⇒ MASS TRANSFER FROM GAS → LIQUID.
FLOODING CALCULATION:

\[
\psi = \sqrt{\frac{G_x}{G_y}} \sqrt{\frac{F_p}{e_x - e_y}}
\]

Pressure Drop in \( \text{in. H}_2\text{O} \) per ft packing

\[
\psi = f(G\text{as FLUX, PACKING, GAS/LIQ. PROPERTIES})
\]

For air/\( \text{H}_2\text{O} \)

\[
\psi \approx 0.007 \frac{G_x^2 F_p}{G_y e_x (e_x - e_y) e_y} \quad \text{for air/\( \text{H}_2\text{O} \)}
\]

\[
\psi \approx 0.034 \left( \frac{G_x}{G_y} \right) \quad \text{for air/\( \text{H}_2\text{O} \)}
\]

\[
\psi \approx 0.021 \left( \frac{L}{V} \right) \quad \text{for air/\( \text{H}_2\text{O} \)}
\]

\([=] \quad \text{lbs} \quad \text{ft}^2 \cdot \text{s}^{-1}
\]

packing factor

\((f(\text{type/size of packing}))\)
MATERIAL BALANCE ⇒ HEIGHT

FLOODING CALCULATION ⇒ DIAMETER

GETTING STARTED . . .

Typical Knowns:

(1) GAS FLOW IN (V or Gy)

(2) GAS COMPOSITION IN (Yb)

(3) FRACTION SOLUTE REMOVED
   (Allows calculation of ya)

(4) LIQ. COMPOSITION IN (Xa)

(5) EQ. DATA

(6) MASS TRANSFER COEFFICIENT DATA.
   (kj, kx, ky, kxa, kya, kxa)

use these when area unknown
Typical Unknowns:

1. Liquid Flow Rate \( (L \text{ or } G_x) \)
2. Composition of Liquid Out \( (x_b) \)
3. \( \Delta P \) in Column (Flooding)
4. Kind of Packing
5. Column Cross-Sectional Area
6. Column Height

Example: Column Diameter + \( \Delta P \)

\[ G_x = \frac{1 \text{ lb lig}}{16 \text{ lb gas}} \]\n
\[ T = 20^\circ C \quad \text{P = 1 atm} \]

\[ 1'' \text{ Intalox SADDLES.} \]

\[ 25,000 \text{ ft}^3 \text{ inlet gas} \]

\[ 29 \text{ NH}_3 \text{ lb volume} \]
(a) if \( G_y = \frac{1}{2} (G_y)_{\text{flood}} \)

\[ D_{\text{Tower}} = ? \]

As with most of these things, use correlated data:

![Graph showing flooding velocities in ceramic Intalox saddles, air-water system.](image)

**FIGURE 18.5**
Flooding velocities in ceramic Intalox saddles, air-water system. (1,000 lb/ft²·h = 1.356 kg/m²·s)

Remember, \( \frac{G_x}{(G_y)_{\text{flood}}} = 1 \) \( \Rightarrow \) so, for 1" saddles

\[ G_x = (G_y) \approx 1700 \frac{1b}{ft^2/hr} \]
\[
\text{Our } G_y = \frac{1}{2} (G_y)_{\text{flood}} = \frac{850 \text{ lb}}{\text{ft}^2 \cdot \text{hr}}
\]

Total Gas flow = \(25,000 \text{ ft}^3/\text{hr}\)

Convert to lbs. \(\Rightarrow G_y\)

Avg. \(\text{mole of gas} = \frac{(29)(0.98) + (17)(0.02)}{2} = 28.76\)

\[
P = \frac{(28.76) \text{ lbs}}{\text{volumes}} = \frac{(28.76) \text{ lbs}}{1 \text{ lb mole}} \left( \frac{1 \text{ atm}}{0.7302 \text{ ft}^3 \cdot \text{atm}} \right)
\]

\[
\mu \text{w} = \frac{1}{(68+460) \text{R}} = 0.0746 \text{ lb/ft}^3
\]

\[
\Rightarrow 25,000 \frac{\text{ft}^3}{\text{hr}} \left| 0.0746 \frac{\text{lb}}{\text{ft}^3} \right| = 1864.9 \frac{\text{lb}}{\text{hr}}
\]

Cross-sectional area = \(1864.9 \frac{\text{lb}}{\text{hr}} \left| \frac{\text{ft}^2 \cdot \text{hr}}{850 \text{ lb}} \right| = 2.19 \text{ ft}^2\)

\(\Rightarrow\) Here, get for empty column.
\[ 2.19 ft^2 = \frac{\pi D_{\text{Tower}}^2}{4} \]

\[ \Rightarrow D_{\text{Tower}} = 1.67 \text{ ft} \]

Note: We used 1" Intalox Saddles.

For Column design

\[ \frac{D_{\text{Packing}}}{D_{\text{Tower}}} \leq 0.1 \]

Here = \[ \frac{1 \text{ in}}{20.04 \text{ in}} = 0.05 \] \( \leq 0.1 \)


b) Pressure Drop?
FIGURE 18.4
Pressure drop in a packed tower for air-water system with 1-in. Intalox saddles. (1,000 lb/ft²·h = 1.356 kg/m²·s; 1 in. H₂O/ft = 817 Pa/m)

\[ G_x = G_y = \frac{850 \text{ lb}}{\text{ft}^2 \cdot \text{hr}} \Rightarrow \Delta P = 0.35 \text{ in. H}_2\text{O/ft} \]

in our comfort zone

if column is 20 ft high, \( \Rightarrow \Delta P = 7 \text{ in. H}_2\text{O} \)

\( \Rightarrow 0.23 \text{ atm} \)

\( \not= \text{INSIGNIFICANT} \)

\( \Rightarrow \text{CHOOSE YOUR PACKING WISELY} \)
**Column Height:** \( Z_T \)

\( Z_T = H_{0y} N_{0y} = H_{0x} N_{0x} \)

**Overall Gas:**
\[
H_{0y} = \frac{V/s}{K_y a}
\]
\[
N_{0y} = \int \frac{dy}{y-y^*}
\]

**Height of transfer unit based on overall gas mass transfer coefficient**

**Complimentary \# of stages**

**Overall Liquid:**
\[
H_{0x} = \frac{L/s}{K_x a}
\]
\[
N_{0x} = \int \frac{dx}{x^*-x}
\]

**Height of transfer unit based on overall Liq. mass transfer coefficient**

**Complimentary \# of stages**
\[ V = \text{molar gas flow rate} \quad \text{[} \text{mol} \text{ per time}] \]

\[ S = \text{cross-sectional area} \quad \text{[} \text{length}^2 \text{]} \]

\[ L = \text{molar liq. flow rate} \quad \text{[} \text{mol} \text{ per time}] \]

\[ K_{ya} = \text{Overall gas phase mass transfer coefficient} \quad \text{[} \text{time}^{-1} \text{]} \]

\[ K_{xa} = \text{Overall liq. phase mass transfer coefficient} \quad \text{[} \text{time}^{-1} \text{]} \]

\[ Z_T = \text{Tower height} \quad \text{[} \text{length} \text{]} \]

**Note:** CAN GET \( K_{ya} \) AND \( K_{xa} \) FROM individual mass transfer coefficients. *(see mass transfer notes)*
EXAMPLE: TOWER HEIGHT

![Diagram of tower height with fluid flow and conditions]

99% removal of A

25°C

1 atm

3.0% A

gas stream

Gas Flux = \frac{20 \text{ mol}}{\text{hr. ft}^2}

Liq. Flux = \frac{100 \text{ mol}}{\text{hr. ft}^2}

EQ. DATA: \quad y^* = 3.1x \quad @ 25°C

k_{\text{xa}} = 60 \text{ mol/ hr. ft}^2. \text{ unit mol fraction}

k_{\text{ya}} = 15 \text{ mol/ hr. ft}^2. \text{ unit mol fraction}
(a) FIND \( N_{O_y}, H_{O_y} + Z_T \)

**Assumptions:**
- Isothermal
- No change in gas/liquid flow rates
- \( \alpha \) line has constant slope
  \( \Rightarrow \) a straight line

\[ X_a = ? \quad \text{Assume clean water} \Rightarrow X_a = 0 \]

\[ X_b = \frac{\text{moles } A \text{ added}}{\text{moles total}} = \frac{\text{fraction } A \text{ removed}}{100} = \frac{(20)(0.03)(0.99)}{100} \]

\[ X_b = 0.00594 \]

**EQ. Line:**

\[ y_b^* = (3.1)(0.00594) = 0.01841 \]

**Driving Force:**

\( \text{Not linear} \Rightarrow \log \text{mean} \)

(Similar to heat transfer)

\( @ \text{ Top: } y_a - y_a^* = \frac{(20)(0.03)(0.01)}{20} - 0 = 0.0003 \)
\[ \Delta y_L = \frac{(y_b - y_b^*) - (y_a - y_a^*)}{\ln \left( \frac{y_b - y_b^*}{y_a - y_a^*} \right)} = 0.00309 \]

\[ N_{0y} = \int \frac{dy}{y - y^*} \]

Let us substitute a constant for \( y - y^* \)

\[ N_{0y} = \int \frac{dy}{\Delta y_L} = \frac{1}{\Delta y_L} \int dy = \frac{\Delta y}{\Delta y_L} \]

\[ N_{0y} = \frac{0.03 - 0.0003}{0.00309} = \frac{0.00307}{0.00309} = 9.61 \]

\[ \uparrow \text{fractional stage} \]

\[ N_{0y} \text{ ok for packed column.} \]
Next, we need to calculate $K_y$.

\[
\frac{1}{K_y} = \frac{1}{k_y} + \frac{M}{k_x} \quad \text{Slope EQ Line}
\]

\[
\frac{1}{K_y} = \frac{1}{15} + \frac{3.1}{60} = 0.11833
\]

\[
\Rightarrow K_y = 8.45
\]

\[
H_{oy} = \left( \frac{20 \text{ mol}}{\text{ft}^2 \cdot \text{hr}} \right) \left( \frac{1 \text{ ft}^3 \cdot \text{hr}}{8.45 \text{ mol}} \right) = \frac{2.37 \text{ ft.}^2}{H_{oy}}
\]

\[
Z_f = (9.61)(2.37) = 22.7 \text{ ft}
\]

Similar analysis for liq. phase.

Note: $H_{oy}$ is not equal to $H_{ox}$, but $H_{ow} = H_{ox}$.