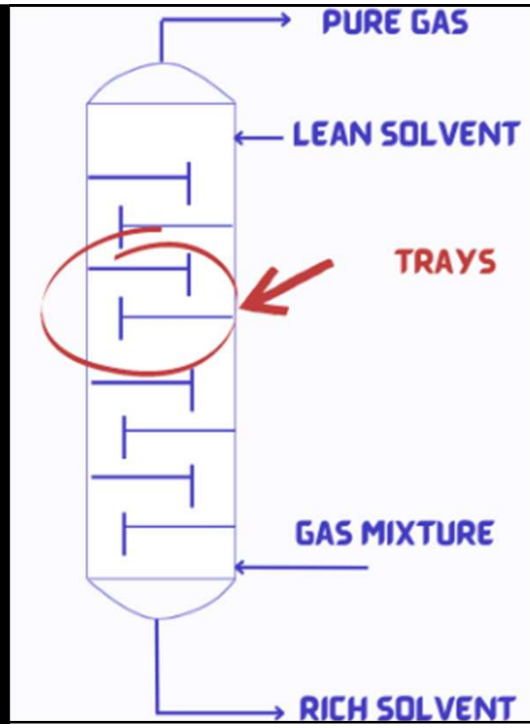
Unit Operation I

Spring 2025

Lecture #1

Dr. Haydar Aljaafari



Background:

PhD Chemical & Biochemical Engineering, University of Iowa, IA, United States, 2022

MSc Chemical Engineering, University of Technology, Iraq, 2012

BSc Chemical Engineering, University of Technology, Iraq, 2006

Contact Information:

Email: haydar.alaa.salih@uomus.edu.iq

Academic Profile:

DR. ALJAAFARI

Course Objectives

1- Understand the basics of gas absorption, stripping and distillation.

2- Design absorbers, strippers and distillation columns.

3- Find Operating lines, feed line and No. of trays or amounts of packing required.

4- Calculate columns efficiency.

Resources

- Coulson, J. M & Richardson J. F. (2006). “Chemical engineering, Volume 1”, 3P rdP Edition, Robert Maxwell. M. C.
- Dutta Binary K. (2007), “Principles of Mass Transfer & Separation Process”, Bvt. Ltd. Prentice Hall, ISPN 8-1203-2990-2.
- Treybal Robert E. (1975), “Mass transfer Operation” 2ed Edition, Mc-Graw-Hill Book.
- McCabe, W., Smith, J., Harriott, P. (2004), “Unit Operations of Chemical Engineering”, M Graw-Hill Co., 7P thP Edition, ISBN0072848235.

Topics

- Introduction to separation processes
- Absorption in tray towers
- Absorption in packed bed column
- Introduction to stripper towers
- Introduction to distillation process
- Multi-component Distillation
- Number of theoretical plates

Absorption Process

Absorption

Absorption is a mass transfer operation where a solute from a gas phase is transferred to a liquid phase.

Examples:

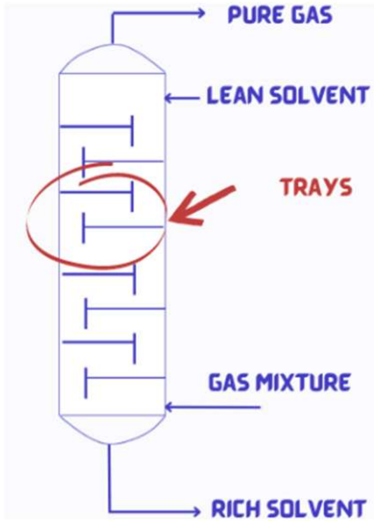
- Absorption of CO_2 in water.
- Ammonia absorption in sulfuric acid.

Industrial Applications: Gas treatment, pollution control, chemical reaction

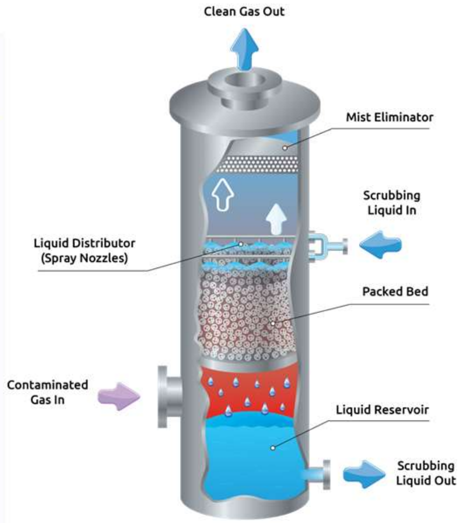
Absorption Process

Equipment

- **Tray Tower**
- **Packed Tower**
- **Spray Tower**
- **Bubble Column**



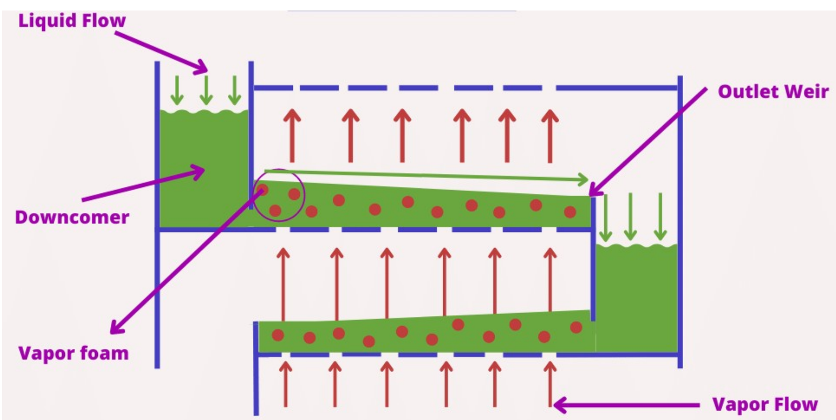
Tray Tower



Pack Tower

Tray Tower

A tray tower is a vertical cylindrical vessel in which the liquid flows down by gravity across trays over the outlet weir and into a downcomer to the tray below, and the gas flows up through the opening in each tray, bubbling through the liquid.



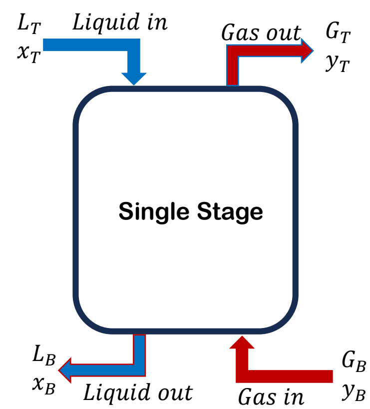
Tray Tower

The absorption process can be carried out in a **single-stage** or **multistage** unit.

A- Single Stage :

Consider the following:

- The unit is running under isobaric, isothermal and steady-state flow conditions.
- The liquid phase enters from the top while gas enters from the bottom, and both are with known amounts and compositions.
- The two exit streams (Liquid & Gas) are **leaving at the equilibrium.**



Where

L: molar flow rate of the liquid phase (moles/time)
G: molar flow rate of gas phase (moles/time)
*x: is the mole fraction of solute A in the **liquid** phase*
*y: is the mole fraction of solute A in the **gas** phase*
*T: for the streams in the **top***
*B: for the streams in the **bottom***

Tray Tower

A- Single Stage Unit:

Overall Material Balance

$$L_T + G_B = L_B + G_T \qquad \text{..........(1)}$$

Component (A) is transferring from gas to liquid

Component (A) Material Balance

$$L_T . x_T + G_B . y_B = L_B . x_B + G_T . y_T \qquad \text{............(2)}$$

Since only component (A) is transferring between the two phases then

$\bar{G} = G_T\ (1 - y_T)$; $\quad G_T = \frac{\bar{G}}{(1 - y_T)}$

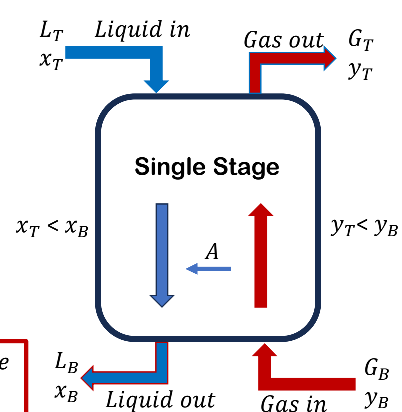
$\bar{G} = G_B\ (1 - y_B)$; $\quad G_B = \frac{\bar{G}}{(1 - y_B)}$

$\bar{L} = L_T\ (1 - x_T)$; $\quad L_T = \frac{\bar{L}}{(1 - X_T)}$

$\bar{L} = L_B\ (1 - x_B)$; $\quad L_B = \frac{\bar{L}}{(1 - x_B)}$

$\bar{G}$ *is the inert rate (everthing in the gas other than A)*, (moles/time)

$\bar{L}$ *is the solvent rate (everthing in the liquid other than A)*, (moles/time)



Tray Tower

A- Single Stage Unit:

$$L_T . x_T + G_B . y_B = L_B . x_B + G_T . y_T \qquad ....(2)$$

$$\frac{\bar{L}}{(1-X_T)} . x_T + \frac{\bar{G}}{(1-y_B)} . y_B = \frac{\bar{L}}{(1-x_B)} . x_B + \frac{\bar{G}}{(1-y_T)} . y_T \qquad ....(3)$$ **(Operating Eq.)**

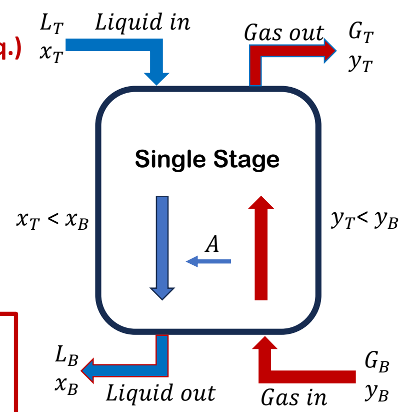
Assume $\frac{y_i}{(1-y_i)} = Y_i$; $\frac{x_i}{(1-x_i)} = X_i$

$$\bar{L} . X_T + \bar{G} . Y_B = \bar{L} . X_B + \bar{G} . Y_T \qquad ....(4)$$

Since only component (A) is transferring between the two phases then

The inert rate $\bar{G}$ and the solvent rate $\bar{L}$ **are constants**.

Notes:
If $(y_B \text{ or } x_T) \geqslant 0.1$ then the solution is considered concentrated
If $(y_B \text{ or } x_T) < 0.1$ then the solution is considered diluted
Equilibrium eq. for dilute solutions $P_A = H * x$ or $\frac{P_A}{P_{total}} = \frac{H}{P_{total}} * x \rightarrow y = \bar{H} * x$



Tray Tower

Example 1: In a single-stage absorption process, a gas mixture at 1 atm pressure containing air and H_2S is contacted with pure water at 30 °C. The exit gas and liquid streams reach equilibrium. The inlet gas flow rate is 200 kmol/hr, with a 0.2 mole fraction of H_2S, while the liquid flow rate entering is 600 kmol/hr. Calculate the amount and composition of the two outlet phases. Assume water does not vaporize into the gas phase.
Given: Henry's constant H = 0.0609*10^4 atm/mole fraction.

Solution

Since the inlet liquid is pure water, thus, $x_T = 0$ And, $\bar{L} = L_T = 600$ kmole/hr (pure water)

$\bar{G} = G_B (1 - y_B) = 200 * (1 - 0.2) = 160$ kmole/hr

Applying the operating equation of the single-stage absorption

$$\frac{\bar{L}}{(1-X_T)} . x_T + \frac{\bar{G}}{(1-y_B)} . y_B = \frac{\bar{L}}{(1-x_B)} . x_B + \frac{\bar{G}}{(1-y_T)} . y_T$$

$$\frac{600}{(1-0)} . 0 + \frac{160}{(1-0.2)} . 0.2 = \frac{600}{(1-x_B)} . x_B + \frac{160}{(1-y_T)} . y_T$$

$$40 = \frac{600}{(1-x_B)} . x_B + \frac{160}{(1-y_T)} . y_T \qquad ....(*)$$

Since x_B is in equilibrium with y_T and Henry's constant is given then

Tray Tower

Example 1: H = 0.0609*10[4] atm/mole fraction.

Solution

$$40 = \frac{600}{(1-x_B)} \cdot x_B + \frac{160}{(1-y_T)} \cdot y_T \quad \text{...........(*)}$$

Since x_B is in equilibrium with y_T and Henry's constant is given then

$$y = \frac{H}{P_{total}} * x \quad \rightarrow \quad y = \frac{0.0609*104}{1} * x \rightarrow \quad y_T = 609 * x_B \quad \textit{sub in } (*)$$

$$40 = \frac{600}{(1-x_B)} \cdot x_B + \frac{160}{(1-609x_B)} * 609x_B$$

Solve for x_B

x_B = 0.000327 then y_T from the equilibrium equation $y_T = 609 * 0.000327 = 0.199$

Then the flow rates are:

$$G_T = \frac{\bar{G}}{(1-y_T)} = \frac{160}{(1-0.199)} = 199.8 \frac{Kmole}{hr} \quad ; \quad L_B = \frac{\bar{L}}{(1-x_B)} = \frac{600}{(1-0.000327)} = 600.196 \frac{Kmole}{hr}$$

Tray Tower

B- Multiple Stages:

Consider the following:

- The tower is running under isobaric, isothermal and steady-state flow.
- Phase equilibrium is assumed to be achieved at each tray between the vapor and liquid streams leaving the tray. (each tray is treated as equilibrium stage)
- Assume that the only component transferred from one phase to the other is solute A

Overall Material Balance

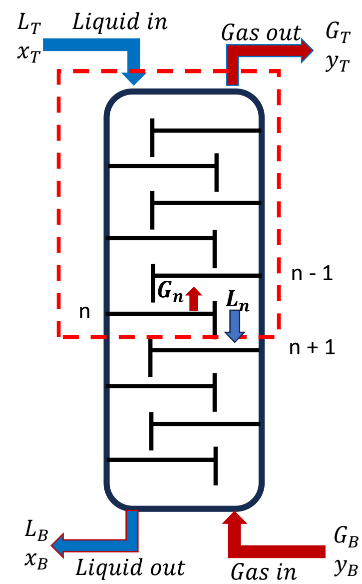
$$L_T + G_{n+1} = L_n + G_T$$

Component (A) Material Balance

$$L_T \cdot x_T + G_{n+1} \cdot y_{n+1} = L_n \cdot x_n + G_T \cdot y_T$$

Since only component (A) is transferring between the two phases then

$$\frac{\bar{L}}{(1-X_T)} \cdot x_T + \frac{\bar{G}}{(1-y_{n+1})} \cdot y_{n+1} = \frac{\bar{L}}{(1-x_n)} \cdot x_n + \frac{\bar{G}}{(1-y_T)} \cdot y_T$$



Tray Tower

B- Multiple Stages:

Overall Material Balance

$L_T + G_{n+1} = L_n + G_T$

Component (A) Material Balance

$L_T . x_T + G_{n+1} . y_{n+1} = L_n . x_n + G_T . y_T$

Since only component (A) is transferring between the two phases then

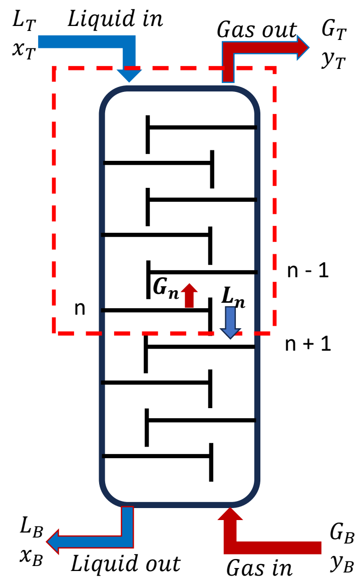
$\frac{\bar{L}}{(1-X_T)} . x_T + \frac{\bar{G}}{(1-y_{n+1})} . y_{n+1} = \frac{\bar{L}}{(1-x_n)} . x_n + \frac{\bar{G}}{(1-y_T)} . y_T$

Assume $\frac{y_i}{(1-y_i)} = Y_i$; $\frac{x_i}{(1-x_i)} = X_i$

$\bar{L} . X_T + \bar{G} . Y_{n+1} = \bar{L} . X_n + \bar{G} . Y_T$ Divide by $\bar{G}$

$\frac{\bar{L}}{\bar{G}} . X_T + Y_{n+1} = \frac{\bar{L}}{\bar{G}} . X_n + Y_T \rightarrow$ $Y_{n+1} = \frac{\bar{L}}{\bar{G}} . X_n + (Y_T - \frac{\bar{L}}{\bar{G}} . X_T)$ **Operating Equation**

This is the equation of straight line, with a slop of $\frac{\bar{L}}{\bar{G}}$ and intercept of $(Y_T - \frac{\bar{L}}{\bar{G}} . X_T)$



Tray Tower

B- Multiple Stages:

$Y_{n+1} = \frac{\bar{L}}{\bar{G}} . X_n + (Y_T - \frac{\bar{L}}{\bar{G}} . X_T)$ **Operating Equation**

This is the equation of straight line, with a slop of $\frac{\bar{L}}{\bar{G}}$ and intercept of $(Y_T - \frac{\bar{L}}{\bar{G}} . X_T)$

When using the normal axis (y, x) the operating line equation will appear as a curve and not as a straight line unless we are **dealing with dilute solutions**, otherwise we have to convert the equilibrium data to (Y, X) and use the axis as (Y, X) axis to draw the operating line and the equilibrium data.

When dealing with **dilute** solutions, we can use the ordinary axis (y, x) and the operating line equation will appear as a straight line also the equilibrium data as

$\frac{y_i}{(1-y_i)} = y_i$; $\frac{x_i}{(1-x_i)} = x_i$