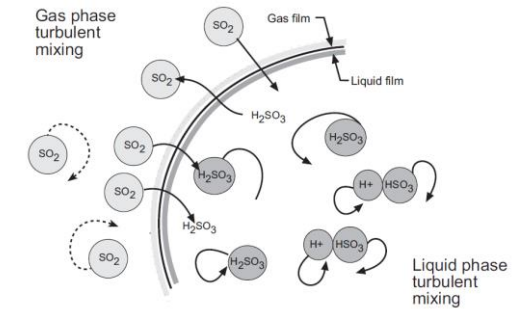


# **13 Gas Absorption**

## 13.1 Introduction

In air pollution control work, absorption refers to the **selective transfer** of material from a **gas** to a contacting **liquid**. The separation principle involved is the preferential **solubility** of a gaseous component in the **liquid**. In a majority of pollution control applications, the contacting liquid is water, and the process is sometimes referred to as scrubbing or washing. Frequently encountered examples of the application of gas absorption in pollution control include

1. Removal and recovery of  $\text{NH}_3$  in fertilizer manufacture
2. Removal of HF from glass furnace exhaust
3. Control of  $\text{SO}_2$  from combustion sources
4. Recovery of water-soluble solvents such as acetone and methyl alcohol
5. Control of odorous gases from rendering plants
6.  $\text{CO}_2$  capture



Gas absorption involves the diffusion of material **from a gas** through a **gas-liquid interface** and ultimate **dispersion** in the **liquid**. Both **molecular** and **turbulent** (eddy) mass transfer **are present** in the absorption process. **Eddy diffusion** is **many times** faster than the **molecular mechanism**, and is maximized by designing absorption equipment to operate at high levels of turbulence. Even so, the **major resistance** to mass transfer between the liquid and the gas is due to the **laminar layers** at the **phase boundary**.

### Gas Absorption Equipment

Gas absorption is usually carried out in packed **towers** such as shown in Figure 13.1. The **gas** stream **enters** the **bottom** of the column and passes upward through a wetted packed bed. The **liquid** **enters** the **top** of the column and is uniformly distributed over the column packing. Countercurrent contact of liquid and gas is employed to maximize the driving forces. To provide **a large liquid surface area** for mass transfer, a means of breaking the liquid stream into **small droplets** or **thin films** is provided in the gas absorber. The most commonly used devices are columns containing **packing** or regularly **spaced plates**.

The requirements of a satisfactory packing are

1. High wetted area per unit volume
2. Minimal weight
3. Sufficient chemical resistance
4. Low liquid holdup
5. Low pressure drop
6. Low cost

Several types of packings are shown in Figure 13.1. Packings are available in a number of materials, including ceramics, glass, metal, and various plastics.

Gases of more **limited solubility**, such as  $\text{SO}_2$ ,  $\text{Cl}_2$ , and  $\text{H}_2\text{S}$ , can be absorbed readily in an **alkaline solution** such as dilute  $\text{NaOH}$ . Thus, when water is used as the solvent, it may **contain added species**, such as acids, alkalines, oxidants, or reducing agents to react with the gas being absorbed and **enhance its solubility**. Nonaqueous, organic liquids of low volatility can be used for absorption of gases with low water solubility, such as hydrocarbons. Examples of such solvents are dimethylaniline and amines. Organic solvents are often limited to treating particle-free gases to avoid sludge formation.

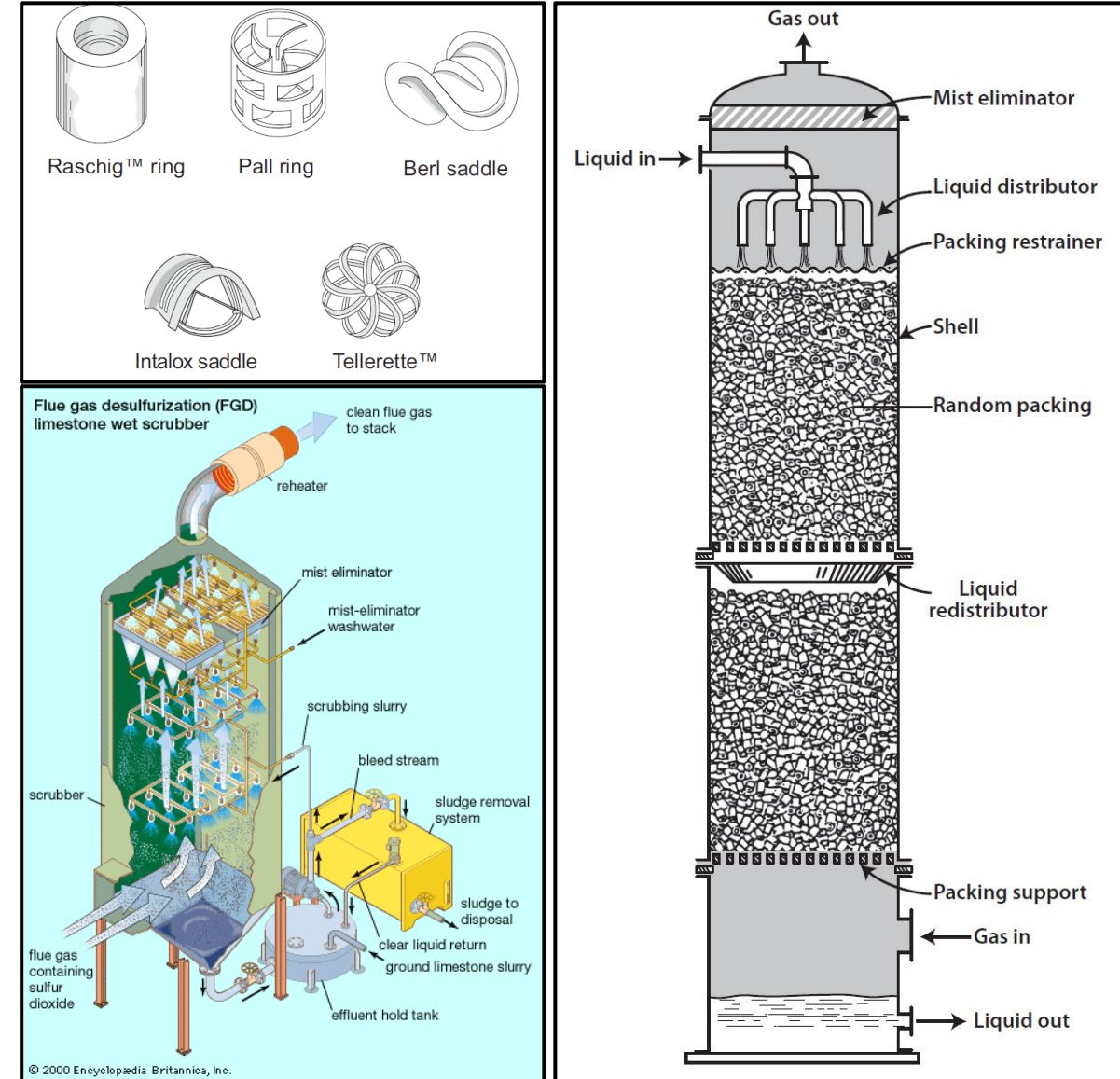


Figure 13.1 Schematic diagram of a packed gas absorption tower

## 13.2 Theory

### Henry's Law

Henry's law describes how the concentration of a gas dissolved in a liquid is directly proportional to the partial pressure of the gas in the gas phase above the solution. In other words, at a constant temperature, the **concentration of a gas in a solution increases linearly with the pressure of the gas**. This relationship is expressed by the equation:

$$C = H \times P \quad (13.1)$$

where: C is the concentration of the gas in the solution which is usually expressed in **molarity**, so the common unit is molar (mol/m<sup>3</sup>); P is the **partial pressure** of the gas **in the gas phase** above the solution expressed in atmospheres (Pa); H is **Henry's constant**, which depends on the nature of the gas, the solvent and the temperature. Henry's constant will have units of mol/m<sup>3</sup>·Pa. The concentration of a gas in a solution has to be **sufficiently low**.

### FICK'S First Law

Fick's first law relates the diffusive flux to the gradient of the concentration. It postulates that the **flux goes** from regions of **high concentration** to regions of **low concentration**, with a **magnitude** that is **proportional** to the **concentration gradient** (spatial derivative), or in simplistic terms the concept that a solute will move from a region of high concentration to a region of low concentration across a concentration gradient. In one (spatial) dimension, the law can be written in various forms, where the most common form is in a molar basis:

$$J = -D \frac{\partial c}{\partial x} \quad (13.2)$$

where  $J$  is the diffusion flux,  $\text{mol}/(\text{m}^2 \cdot \text{s})$ ;  $D$  is the diffusion coefficient,  $\text{m}^2/\text{s}$ ;  $\frac{\partial c}{\partial x}$  is the concentration gradient,  $\text{mol}/(\text{m}^3 \cdot \text{m})$ ;  $c$  is the concentration,  $(\text{mol}/\text{m}^3)$ ;  $x$  is position in the direction of diffusion,  $\text{m}$ .

## Two-film theory(Interfacial mass transfer)

The two-film theory is a useful model for **mass transfer between phases**. Mass transfer of solute **from one phase to the interface**, then movement **from the interface into the bulk of the second phase**. The two-film theory visualizes **all resistance** to transfer across the interface as resulting **from a laminar film on each side of the interface**. One is a **gas film**, another is a **liquid film**. The model assume that the gas and the liquid are in **equilibrium at the interface**.

$$N_A = \frac{D_G}{Z_G}(p - p_i) = k_G(p - p_i) = \frac{D_L}{Z_L}(c_i - c) = k_L(c_i - c) \quad (13.3)$$

$$N_A = k_y(y - y_i) = k_x(x_i - x) \quad (13.4)$$

When the **concentration** of component **A** in the liquid **is extremely low, conform to Henry's law**.

$$c_i = H p_i \quad y_i = m x_i \quad (13.5)$$

$$k_G = D_G/Z_G \quad k_L = D_L/Z_L \quad (13.6)$$

Substitution of Eq.(13.5)~Eq.(13.7) into Eq.(13.3) eliminates  $p_i$  and  $c_i$ , Eq.(13.3) and (13.4) can be rewritten as

$$N_A = K_G(p - p^*) = K_y(y - y^*) = K_L(c^* - c) = K_x(x^* - x) \quad (13.7)$$

$$\left. \begin{aligned} \frac{1}{K_G} &= \frac{1}{k_G} + \frac{1}{H k_L} & \frac{1}{K_y} &= \frac{1}{k_y} + \frac{m}{k_x} \\ \frac{1}{K_L} &= \frac{H}{k_G} + \frac{1}{k_L} & \frac{1}{K_x} &= \frac{1}{m k_y} + \frac{1}{k_x} \end{aligned} \right\} \quad (13.8)$$

$$p^* = c/H \quad y^* = m x \quad (13.9)$$

$$c^* = H p \quad x^* = y/m \quad (13.10)$$

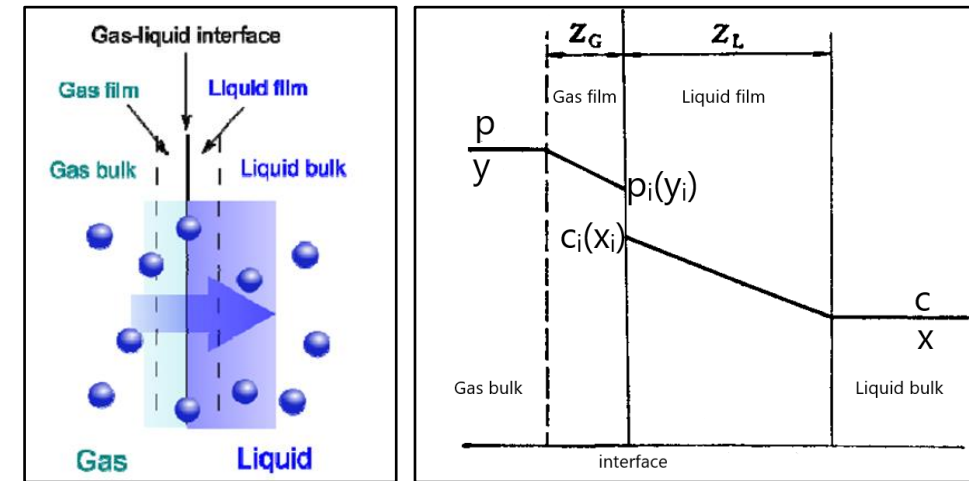


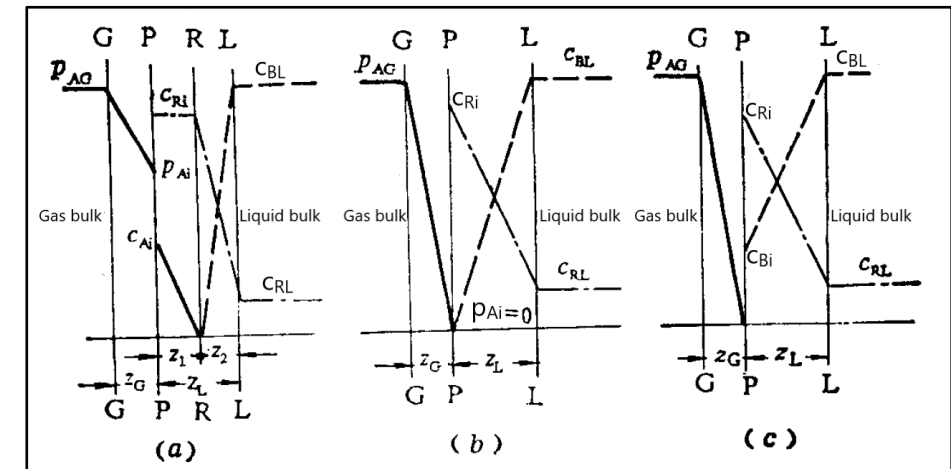
Figure 13.2 Schematic diagram of the two-film theory

where:  $N_A$  = transfer rate of component A, kmol/(m<sup>2</sup>·s);  $D_G, D_L$  = the diffusion coefficient of component A in the gas and in the liquid, mol/(m·s·Pa), m<sup>2</sup>/s, respectively;  $Z_G, Z_L$  = thickness of the gas film and the liquid film, m, respectively;  $p, p_i$  = partial pressure of component A in the gas bulk and at the gas-liquid interface, Pa, respectively;  $k_G, k_L$  = single-phase mass-transfer coefficient of component A in the gas film and in the liquid, kmol/(m<sup>2</sup>·s·Pa), m/s, respectively;  $c, c_i$  = concentration of component A in the liquid bulk and at the gas-liquid interface, mol/m<sup>3</sup>, respectively;  $H$  = Henry's constant of component A, mol/m<sup>3</sup>·Pa;  $K_G, K_L$  = overall mass-transfer coefficients (two-phase) of component A in the gas and the liquid, mol/(m<sup>2</sup>·s·Pa), m/s, respectively;  $p^*$  = partial pressure of component A in the gas that would be in equilibrium with the concentration of component A in the liquid bulk, Pa;  $c^*$  = concentration of component A in the liquid bulk that would be in equilibrium with the partial pressure of component A in the gas bulk, mol/m<sup>3</sup>;  $k_y, k_x$  = single-phase mass-transfer coefficient of component A in the gas film and in the liquid film, kmol/(m·h·mol fraction), respectively;  $y, y_i$  = mole fraction of component A in the gas bulk and at the gas-liquid interface;  $x, x_i$  = mole fraction of component A in the liquid bulk and at the gas-liquid interface;  $K_y, K_x$  = overall mass-transfer coefficients (two-phase) of component A in the gas and in the liquid, kmol/(m<sup>2</sup>·s·mol fraction), respectively;  $m$  = Henry's constant of component A.

## Mass transport with chemical reaction

For a typical gas-liquid phase reaction  **$A(\text{gas}) + bB(\text{liquid}) \rightarrow mM$** , according to the two-film theory, the entire reaction can be considered to go through the following processes: (1) The reaction **component A** in the gas phase diffuses **from the gas phase through the gas film** to the **gas-liquid interface** and **dissolves** at the interface (assuming that the interface reaches gas-liquid equilibrium); (2) The reaction **component B** in the liquid phase diffuses **from the liquid phase through the liquid film** to **the interface**;

(3) **Component A** diffuses from the interface to the liquid and **reacts** chemically with **component B**; (4) The generated reaction **product M**, if the reaction product remains in the liquid phase, diffuses to the liquid bulk; if the reaction product is a gas, diffuses to the interface and diffuses to the gas bulk through the gas film.





It can be seen that the excessive gas-liquid phase reaction is a process in which **mass transfer** and **chemical reaction** are **connected** in series. The **chemical reaction rate** and the **physical mass transfer rate must be considered at the same time**. Therefore, the **macroscopic reaction rate** (or total reaction rate) of the gas-liquid phase reaction is a comprehensive reaction rate that **includes the mass transfer and chemical reaction rates**.

The **reaction surface is inside the liquid film**. Assume that the distance between the reaction surface and the phase interface is  $z_1$ , the thickness of the liquid film on the right side of the reaction surface is  $z_2$ .

The mass transfer rate of the component A through the gas film is:

$$N_A = k_{AG}(p_{AG} - p_{Ai}) \quad (13.11)$$

The mass transfer rate of component A through the liquid film with a thickness of  $z_1$  is:

$$N_A = \frac{D_{AL}}{z_1}(c_{Ai} - 0) \quad (13.12)$$

When the absorption process reaches stability, the two mass transfer rates are equal.

The mass transfer rate of component B in the liquid phase through the liquid film is:

$$N_B = \frac{D_{BL}}{z_2}(c_{BL} - 0) \quad (13.13)$$

From the chemical reaction formula:

$$N_B = bN_A \quad (13.14)$$

Liquid film thickness:

$$Z_L = Z_2 + Z_1 \quad (13.15)$$

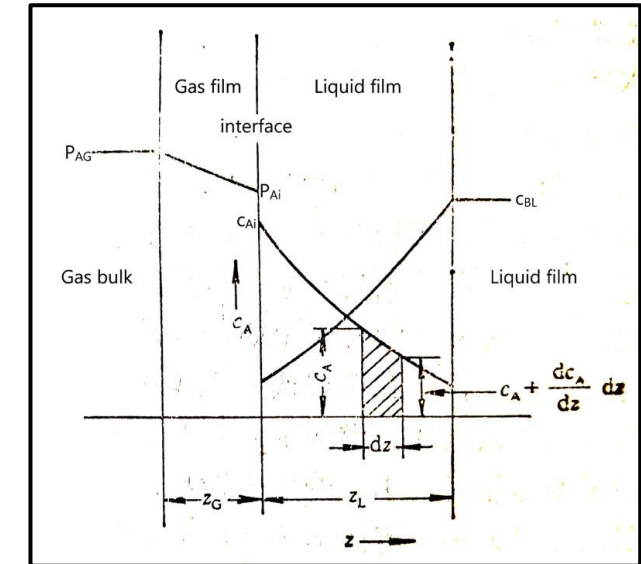
Substitution of Eq.(13.15) and Eq.(13.14) into Eq.(13.12) and Eq.(13.13), Then, we obtain

$$N_A = \frac{D_{AL}}{Z_L} \left( 1 + \frac{D_{BL}c_{BL}}{bD_{AL}c_{Ai}} \right) c_{Ai} \quad (13.16)$$

$$N_A = k_{AL} \left( 1 + \frac{D_{BL}c_{BL}}{bD_{AL}c_{Ai}} \right) c_{Ai} = \beta_{\infty} k_{AL} c_{Ai} \quad (13.17)$$

$$\beta_{\infty} = 1 + \frac{D_{BL}c_{BL}}{bD_{AL}c_{Ai}} \quad (13.18)$$

where  $\beta_{\infty}$  is the enhancement coefficient of mass transfer associated with chemical reaction. That is to say, compared with physical absorption, the **chemical absorption rate increases by  $\beta_{\infty}$  times**.



Substitution of Eq.(13.5) into Eq.(13.18) eliminates  $c_{Ai}$ , Eq.(13.18) can be rewritten as

$$N_A = \frac{p_{AG} + \frac{1}{bH_A} \frac{D_{BL}}{D_{AL}} C_B}{\frac{1}{k_{AG}} + \frac{1}{H_A k_{AL}}} = K_{AG} (p_{AG} + \frac{1}{bH_A} \frac{D_{BL}}{D_{AL}} C_{BL}) \quad (13.19)$$

The partial pressure of component A in the gas-liquid interface

$$p_{Ai} = \frac{k_{AG} p_{AG} - \frac{1}{b} \frac{D_{BL}}{D_{AL}} k_{AL} C_{BL}}{H_A k_{AL} + k_{AG}} \quad (13.20)$$

When  $k_{AG} p_A = \frac{1}{b} \frac{D_{BL}}{D_{AL}} k_{AL} C_{BL}$ . Henry's law shows that  $c_{Ai} = 0$ , that is, when there is no component A on the interface, the concentration of component B in the liquid phase is called the **critical concentration**, expressed by  $c_{kp}$ , then

$$C_{kp} = \frac{bk_{AG}}{k_{AL}} \frac{D_{AL}}{D_{BL}} p_A \quad (13.21)$$

It can be seen that the conditions for the application of equations (13.19) and (13.20) are  $c_{BL} < c_{kp}$ , At this time, the reaction surface is located inside the liquid film.

When  $c_{BL} \geq c_{kp}$ , The **reaction surface** is **located** at the **phase interface**, that is, the reaction surface coincides with the phase interface. The mass transfer rate is

$$N_A = k_{AG} p_{AG} \quad (13.22)$$



## 13.3 Absorption Tower Design

### Packing layer height

#### Gas absorption without chemical reaction

The basic gas absorption design problem is the following. Given:

- A gas stream entering at a rate  $G$  ( $\text{mol} \cdot \text{h}^{-1} \cdot \text{m}^{-2}$  of empty tower) containing a known mole fraction of component,  $A, y_2$
- A desired exit gas mole fraction  $y_1$
- A specified mole fraction of  $A$  in the inlet liquid,  $x_1$
- The equilibrium curve of  $y$  versus  $x$  for the system

Let us consider a differential height of the column  $dz$ . If the interfacial area per unit volume is  $a$ , a balance on component  $A$  in the gas phase over the height  $dz$ :

$$N_A a S dz = d(GSy) \quad (13.23)$$

where  $N_A$  = transfer rate of component  $A$ ,  $\text{kmol}/(\text{m}^2 \cdot \text{s})$ ;  $a$  = available area for mass transfer,  $\text{m}^2/\text{m}^3$  of packing;  $S$  = cross-sectional area of the tower,  $\text{m}^2$ ;  $G$  = molar flux of gas and liquid through tower respectively,  $\text{kmol}/(\text{m}^2 \cdot \text{s})$ ;  $y$  = molar fraction of gas phase  $A$  component (dimensionless).

Packing layer height

$$H = \int_0^H dz = \int_{y_1}^{y_2} \frac{dGy}{aN_A} \quad (13.24)$$

On account of  $G$  continually decreasing, The gas flow  $G$  consists of  $A$  + inert gas, We denote inert gas flow rates by  $G'$ ,  $G'$  always remain constant down the tower

$$G' = G(1 - y) \Rightarrow d(Gy) = G' \left( \frac{dy}{1 - y} \right) \quad (13.25)$$

Substitution of Eq.(13.4) into Eq.(13.24),we obtain

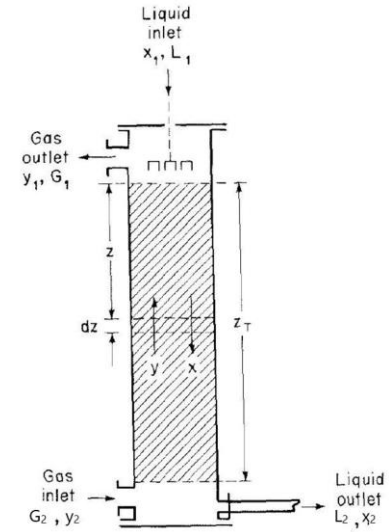


Figure 13.4A Schematic diagram of a packed tower showing the design variables

$$H = \int_{y_1}^{y_2} \frac{d(Gy)}{aN_A} = \int_{y_1}^{y_2} \frac{G}{1-y} \frac{dy}{ak_y(y-y_i)} = \int_{y_1}^{y_2} \frac{G}{ak_y(1-y)(y-y_i)} dy = \overline{\left(\frac{G}{k_y a}\right)} \int_{y_1}^{y_2} \frac{dy}{(1-y)(y-y_i)} \quad (13.24A)$$

To determine the total height  $z_T$ , we must evaluate the integral in (13.24A). The method of integration depends on the shape of the equilibrium line, the variation in  $G$ , and the relative importance of the two mass transfer coefficients  $k_x a$  and  $k_y a$ .

$$N_y = \int_{y_1}^{y_2} \frac{dy}{(1-y)(y-y_i)} \quad H_y = \frac{\bar{G}}{k_y a} \quad H = N_y H_y \quad (13.24B)$$

where  $N_y$  is **the number of transfer units** and  $H$  is **the height of a transfer unit**.

From Eq.(13.4), we note that

$$\frac{y-y_i}{x_i-x} = \frac{k_x}{k_y} \quad (13.26)$$

Thus, at any point, (13.26) describes a straight line with slope  $k_x a / k_y a$ , passing through  $(x, y)$  and  $(x_i, y_i)$ . From a knowledge of  $k_x a / k_y a$  we can determine  $x_i$  and  $y_i$  corresponding to any  $(x, y)$  on the [operating line](#).

When the dissolution of component A in the liquid satisfies **Henry's law** conditions (the concentration of A at the phase interface  $y_i$  can be eliminated)

$$H = \int_{y_1}^{y_2} \frac{G}{aK_y(1-y)(y-y^*)} dy = \overline{\left(\frac{G}{k_y a}\right)} \int_{y_1}^{y_2} \frac{dy}{(1-y)(y-y^*)} = H_{0y} N_{0y} \quad (13.24C)$$

When  $y_A \leq 5\%$ ,  $G' \approx G$ ,

$$H = \int_0^H dz = G \int_{y_1}^{y_2} \frac{1}{aK_y(1-y)(y-y^*)} dy \quad (13.24D)$$

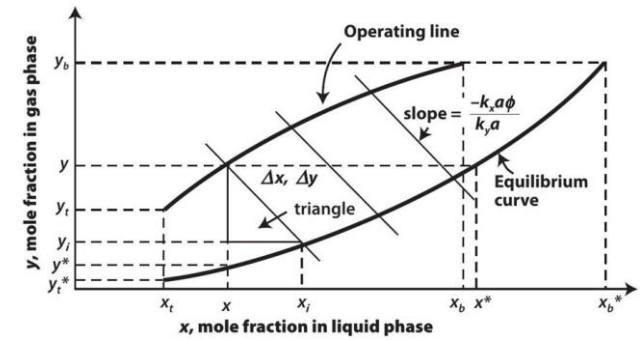
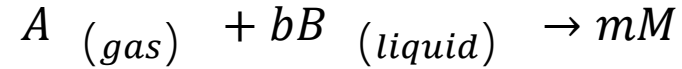


Figure 13.5 Graphical construction of the  $(\Delta x, \Delta y)$  triangle, and representation of the overall gas-phase driving force.

## Gas absorption with chemical reaction

The following reaction is taking place in the packed tower shown in Figure 13.4



A is the gas phase component, B is the liquid phase component, and b mol of B component is consumed for every 1 mol of A component absorbed. Therefore, the number of moles of A component reduced in the gas phase is equal to 1/b times the number of moles of B component reduced in the liquid phase.

Setting  $G_A, L_B$  = molar flux of gas and liquid through tower respectively, kmol/(m<sup>2</sup>·s);  $G'_A, L'_B$  = molar flux of inert component in the gas and liquid through tower respectively, kmol/(m<sup>2</sup>·s);  $p_A$  = the partial pressure of gas phase A component (Pa);  $y_A$  = the molar fraction of gas phase A component (dimensionless);  $c_B$  = the concentration of liquid phase B component (kmol/m<sup>3</sup>);  $x_B$  = the molar fraction of liquid phase B component (dimensionless).

$$N_A a S dZ = -\frac{1}{b} d(LSx_B) \quad (13.27)$$

The height of the packing layer is still calculated using the Eq.(13.24), but the  $N_A$  should use the Eq. (13.19)

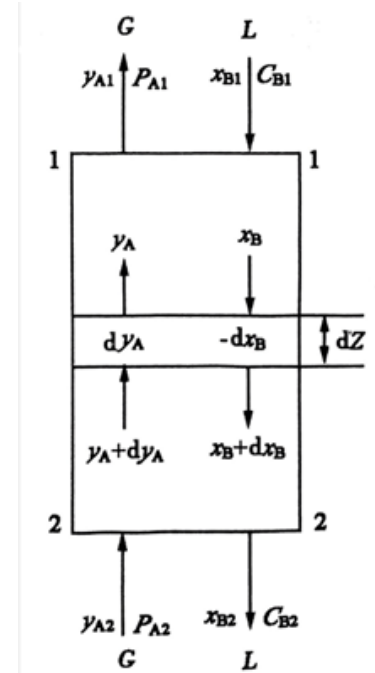


Figure 13.4B Schematic diagram of a packed tower showing the design variables

## Diameter of the Packing Tower

$$D_T = \sqrt{\frac{4Q}{\pi v_0}} \quad (13.28)$$

where  $D_T$  =Diameter of the Packing Tower, m;  $Q$  =the gas flow rate,  $\text{m}^3/\text{s}$ ;  
 $v_0$  =superficial gas velocity,  $v_0 = (0.6 \sim 0.75)v_f$ , m/s.

The flooding velocity  $v_f$  is estimated using Figure 13.6, which is a logarithmic plot of

$$\frac{G_y^2 F_p (\mu_x)^{0.2}}{g_c (\rho_x - \rho_y) \rho_y} \text{ versus } \frac{G_x}{G_y} \sqrt{\frac{\rho_y}{\rho_x - \rho_y}} \quad (13.29)$$

where  $F_p$  =packing factor from Table 13.1,  $\text{ft}^{-1}$ ;  $\rho_x$ =liquid density,  $\text{lb}_m/\text{ft}^3$ ;  $\rho_y$ =gas density,  $\text{lb}_m/\text{ft}^3$ ;  $\mu_x$  =liquid viscosity, cp;  $g_c$ =units conversion factor,  $32.17 \text{ft} \cdot \text{lb}_m/\text{s}^2 \cdot \text{lb}_f$ ;  $G_x$  =liquid mass flux through tower,  $\text{lb}_m/\text{s} \cdot \text{ft}^2$ ;  $G_y$  =gas mass flux through tower,  $\text{lb}_m/\text{s} \cdot \text{ft}^2$ .

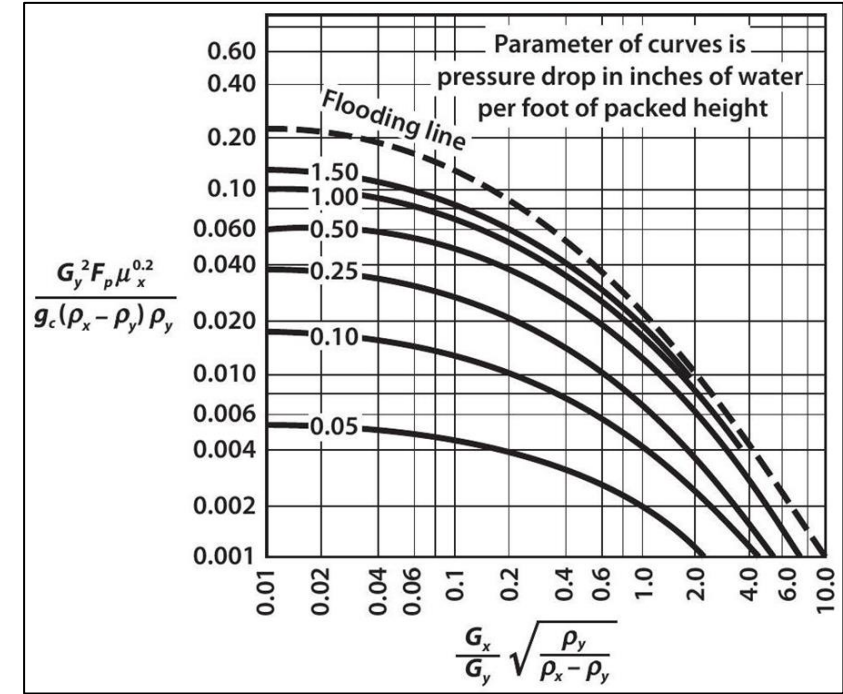


Figure 13.6 Generalized correlation for flooding and pressure drop in packed towers.

## Pressure Drop

To use Figure 13.5, we calculate the abscissa value from previously determined values of  $L_m$  and  $V_m$  (converted to mass flows). Note that  $G_x/G_y$  can be obtained from  $L_m/V_m$  because the (as yet unknown) cross-sectional area  $S$  divides out. In most pollution control applications,  $\rho_y$  is calculated assuming ideal gas behavior and  $\rho_x$  is taken as that for water (or the absorbing solution) at the average tower operating temperature. We determine a value of the ordinate at the intersection of the abscissa value with the flooding curve. From the ordinate value we obtain  $G_y$  at flooding, and the tower diameter is then based on  $G_{y(\text{flooding})}/2$ . We then use this new value of  $G_y$  to calculate a new ordinate value, which is then used to find the pressure drop per foot of packing.

Table 13.1 Tower Packing Characteristics

Type	Material	Nominal Size, in.	Bulk Density, lb <sub>m</sub> /ft <sup>3</sup>	Total Area, ft <sup>2</sup> /ft <sup>3</sup>	Porosity $\varepsilon$	Packing Factors	
						$F_p$	$f_p$
Berl saddles	Ceramic	1/2	54	142	0.62	240	§1.58
		1	45	76	0.68	110	§1.36
		1 <sup>1/2</sup>	40	46	0.71	65	§1.07
Intalox saddles	Ceramic	1/2	46	190	0.71	200	2.27
		1	42	78	0.73	92	1.54
		1 <sup>1/2</sup>	39	59	0.76	52	1.18
		2	38	36	0.76	40	1.0
		3	36	28	0.79	22	0.64
Raschig rings	Ceramic	1/2	55	112	0.64	580	§1.52
		1	42	58	0.74	155	§1.36
		1 <sup>1/2</sup>	43	37	0.73	95	1.0
		2	41	28	0.74	65	§0.92
Pall rings	Steel	1	30	63	0.94	48	1.54
		1 <sup>1/2</sup>	24	39	0.95	28	1.36

\* Bulk density and total area are given per unit volume of column.

# Factor  $F_p$  is a pressure-drop factor and  $f_p$  a relative mass-transfer coefficient.

§ Based on NH<sub>3</sub> – H<sub>2</sub>O data; other factors based on CO<sub>2</sub> – NaOH data.

### Example 13.1

A 10,000acfm exhaust from a heat treating process contains 25 mole percent ammonia, and the average exhaust conditions are 115°F and 1.0 atm . Estimate the height of packing, the tower diameter, and the tower pressure drop for an absorption tower that will provide 95% ammonia removal based on the following design parameters:

Average tower temperature is 86°F

Tower pressure is 1.0 atm

Pure water is used as absorbing liquid

Water rate is 1.5 times minimum

Packing is 1.0 -in. ceramic Raschig rings

$$k_y a \text{ is } 15 \frac{\text{lbmol}}{\text{hr}\cdot\text{ft}^3-\Delta y} \quad k_x a \text{ is } 60 \frac{\text{lbmol}}{\text{hr}\cdot\text{ft}^3-\Delta x}$$

### Solution

The total molar flow rate of gas is  $G_{mb} = \frac{10,000\text{ft}^3}{\text{min}} \times 60\text{min} \times \frac{1\text{lbmol}}{359\text{scf}} \times \frac{492}{575} = 1430 \text{ lbmol/hr}$

moles of NH<sub>3</sub> entering in the gas =  $1430 \text{ lbmol/hr} \times 0.25 = 357.5 \text{ lbmol/hr}$

Moles of air entering in the gas  $G'_{mb} = 1430 \text{ lbmol/hr} \times 0.75 = 1072.5 \text{ lbmol/hr}$

moles of NH<sub>3</sub> leaving in the gas =  $357.5 \text{ lbmol/hr} \times (1 - 0.95) = 17.875 \text{ lbmol/hr}$

$$\text{So, } y_b = 0.25, y_t = \frac{17.875}{1072.5 + 17.875} = 0.0164$$

Since fresh (not recirculated) water is used,  $x_t = 0$ .

Next plot the equilibrium curve for ammonia-water system at 1.0 atm and 86°F. Use the ammonia solubility data given in Appendix Table B.4. This table gives the concentration of NH<sub>3</sub> as lbNH<sub>3</sub>/100 lb<sub>m</sub>H<sub>2</sub>O versus the partial pressure of NH<sub>3</sub> in mm Hg . To convert to mole fractions, use the following equations:

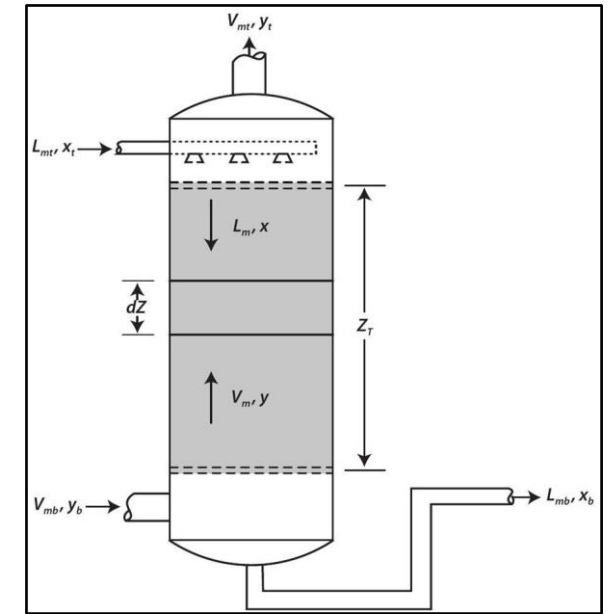


Figure 13.7 Schematic diagram of a packed tower showing the design variables.



$$y_e \text{ or } y_i = \bar{P}_A/760$$

$$x_e \text{ or } x_i = \frac{C_A/17}{C_A/17+100/18}$$

where

$\bar{P}_A$  = partial pressure of  $\text{NH}_3$ , mmHg

$C_A$  = concentration of  $\text{NH}_3$ , in the water,  $\text{gNH}_3/100 \text{ gH}_2\text{O}$

$C_A, \frac{\text{g NH}_3}{100\text{g H}_2\text{O}}$	$x_e$	$\bar{P}_A, \text{mm Hg}$	$y_e$
2	0.0207	19.3	0.0254
3	0.0308	29.6	0.0389
4	0.0406	40.1	0.0528
5	0.0503	51.0	0.0671
7.5	0.0736	79.7	0.105
10	0.0957	110	0.145
15	0.1371	179	0.236

These  $x - y$  data are plotted in Figure 13.8 (bottom curve).

Next, find the minimum water rate.

From the plot where  $y_b = y_e = 0.25$ , then  $x = x_b^* = 0.14$ (0.15).

Now, make material balance for the entire tower,  $x_t = 0, y_t = 0.0164$ ,  $y_b = 0.25$ , and  $x = x_b^* = 0.14$ , we get:

$$L'_{m_{\min}} \left( \frac{0}{1-0} - \frac{0.140}{1-0.140} \right) = 1072.5 \left( \frac{0.0164}{1-0.0164} - \frac{0.25}{1-0.25} \right)$$

$$L'_{m_{\min}} (-0.163) = 1072.5 \times (0.01667 - 0.3333) = -339.5857$$

$$L'_{m_{\min}} = 2083.358 \text{ molH}_2\text{O}$$

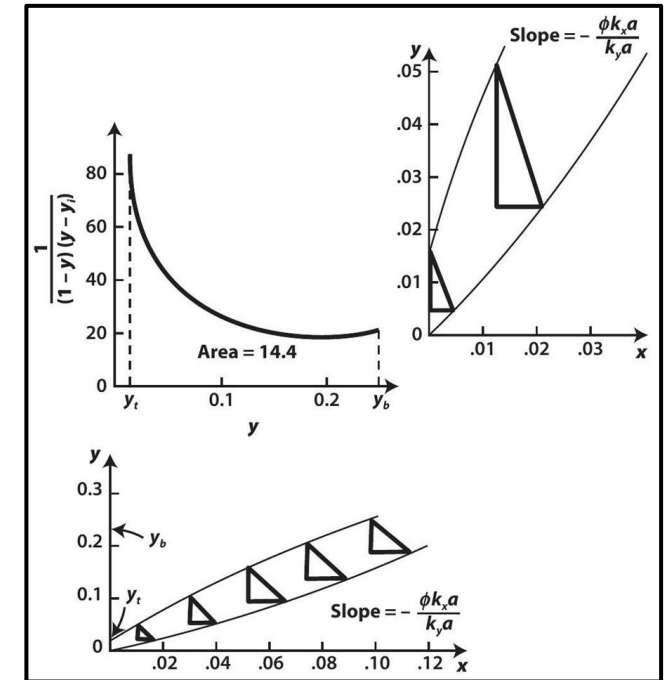
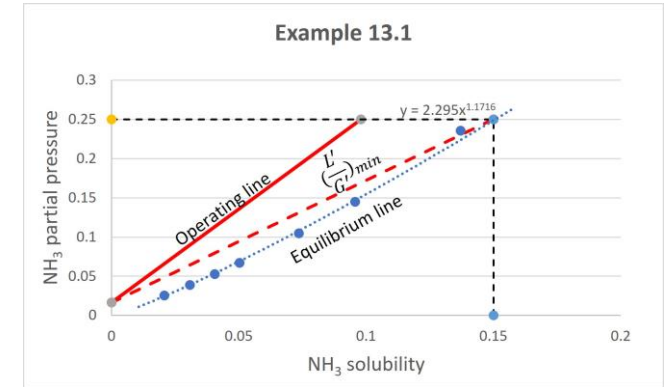


Figure 13.8 Graphs used in solution of Example 13.1.

The actual water rate is  $L'_m = 1.5 \times 2083.358 = 3125.037 \text{ molH}_2\text{O}$ .

Next, we find the tower diameter, using Figure 13.6. First we calculate the loading parameter,  $(G_x/G_y) \times \sqrt{\rho_y/(\rho_x - \rho_y)}$ , as follows:

molecular weight of entering gas =  $0.75 \times 29.0 + 0.25 \times 17.0 = 26.0 \text{ lb}_m/\text{mol}$

$$\rho_y = \frac{PMW}{RT} = \frac{14.7 \times 26.0}{10.73 \times 546} = 0.0652 \frac{\text{lb}_m}{\text{ft}^3}, \quad \rho_x = 62.15$$

$$\frac{G_x}{G_y} \sqrt{\frac{\rho_y}{\rho_x - \rho_y}} = \frac{3125.037 \times 18}{1430 \times 26} \sqrt{\frac{0.0652}{62.15 - 0.0652}} = 0.049$$

From Figure 13.6, at the intersection of the abscissa value (which equals 0.0490) with the flooding curve, we see that

$$\frac{G_y^2 F_p \mu_x^{0.2}}{g_c (\rho_x - \rho_y) \rho_y} = 0.195$$

Thus, at flooding,  $G_y = \left( \frac{0.195 \times 32.174 \times 0.0652 \times (62.15 - 0.0652)}{155 \times 0.80^{0.2}} \right)^{1/2} = 0.413 \text{ lb}_m/\text{ft}^2 - \text{sec}$

Operate at 50% of flooding, then  $G_y(\text{actual}) = \frac{0.413}{2} = 0.206 \text{ lb}_m/(\text{sec} \cdot \text{ft}^2) = 741.6 \text{ lb}_m/(\text{hr} \cdot \text{ft}^2)$

The total gas flow entering the column, then, is  $\frac{1430 \text{ mol}}{\text{hr}} \times \frac{26.0 \text{ lb}_m}{\text{mol}} = 37180 \text{ lb}_m/\text{hr}$

Thus, the tower cross-section is  $\frac{37180}{741.6} = 50.1 \text{ ft}^2$

The diameter of the tower is  $\left( \frac{50.1 \times 4}{\pi} \right)^{1/2} = 7.99 \text{ ft} \approx 8.0 \text{ ft}$

Now solve for (x, y) points to plot the actual operating line

$$3125.037 \left( \frac{x}{1-x} - \frac{0}{1-0} \right) = 1072.5 \left( \frac{y}{1-y} - \frac{0.0164}{1-0.0164} \right)$$

$$\frac{x}{1-x} = 0.343 \left( \frac{y}{1-y} - 0.0167 \right)$$

$y$	$1 - y$	$y/(1 - y)$	$y/(1 - y) - 0.0167$	$x/(1 - x)$	$x$
0.025	0.975	0.0256	0.0089	0.0031	0.0031
0.05	0.95	0.0526	0.0359	0.0123	0.0122
0.10	0.90	0.111	0.094	0.0322	0.0312
0.15	0.85	0.177	0.160	0.0549	0.0520
0.20	0.80	0.250	0.233	0.0799	0.0740
0.25	0.75	0.333	0.316	0.108	0.0975

Use values of  $x$  and  $y$  calculated to plot the operating line. Now calculate  $-(k_x a/k_y a)$  and draw  $\Delta x \Delta y$  triangles.  $-(k_x a/k_y a) = -4$ . To graphically integrate  $dy/[(1 - y)(y - y_i)]$ , we prepare the following table, using  $\Delta x \Delta y$  triangles:

$y$	$y_i$	$1 - y$	$y - y_i$	$\frac{1}{(1 - y)(y - y_i)}$
0.0164	0.0042	0.984	0.0122	83.30
0.052	0.023	0.950	0.0270	38.99
0.10	0.056	0.900	0.0440	25.25
0.15	0.097	0.850	0.0530	22.19
0.20	0.138	0.800	0.0620	20.16
0.25	0.186	0.750	0.0640	20.83

To evaluate  $\int dy/[(1 - y)(y - y_i)]$ ,  $y$  is plotted as the abscissa and  $1/(1 - y)(y - y_i)$  as the ordinate. The area under the resulting curve between  $y = 0.0164$  and  $y = 0.25$  is the value of the integral. See Figure 13.8 (top left). This area under the curve is 7.0 .

Now we calculate  $(G_{my})_{\text{avg}}$ , as follows:

$$(G_{my})_b = \frac{1430 \text{ lbmol}}{\text{hr}} \times \frac{1}{50.10 \text{ ft}^2} = \frac{28.54 \text{ lbmol}}{\text{hr-ft}^2}, (G_{my})_t = \frac{1072.5 + 17.875}{50.10} = \frac{21.76 \text{ lbmol}}{\text{hr-ft}^2}, \Rightarrow (G_{my})_{\text{avg}} = 25.15$$

$$H = \int_{y_{A1}}^{y_{A2}} \frac{G_A}{ak_{Ay} (1-y_A)(y_{AG}-y_{Ai})} dy_A = \frac{(G_{my})_{\text{avg}}}{ak_{Ay}} \int_{y_{A1}}^{y_{A2}} \frac{dy_A}{(1-y_A)(y_{AG}-y_{Ai})} = \frac{25.15}{15} \times 7.0 = 11.7 \text{ ft}$$

Now, we calculate the  $\Delta P$  for the tower. The abscissa remains the same at 0.049 ; the ordinate is now

$$\frac{(0.206)^2 (155) (0.80)^{0.2}}{32.2 (62.2 - 0.065) (0.065)} = 0.048$$

From Figure 13.6, we estimate  $\Delta P/Z$  as 0.45 in. H<sub>2</sub>O/ft, and the tower  $\Delta P$  is

$$0.45 \frac{\text{in. H}_2\text{O}}{\text{ft}} \times 11.7 \text{ ft} = 5.3 \text{ in. H}_2\text{O}$$

## 采用化学吸收时

例13.2 采用填料塔吸收净化废气，要求废气中气态污染物A的浓度从0.1%降低到0.02%。已知 $k_{AG}a = 3.158 \times 10^{-4} \text{ kmol} / (\text{m}^3 \cdot \text{h} \cdot \text{Pa})$ ， $k_{AL}a = 0.1 \text{ h}^{-1}$ ；亨利系数 $H_A = 7.895 \times 10^{-5} \text{ kmol} / (\text{Pa} \cdot \text{m}^3)$ ；废气流量 $G = 100 \text{ kmol} / (\text{h} \cdot \text{m}^2)$ ；液体流量 $L = 700 \text{ kmol} / (\text{h} \cdot \text{m}^2)$ ；总压 $p = 1.0133 \times 10^5 \text{ Pa}$ ；液体总摩尔浓度 $c_T = 56 \text{ kmol} / \text{m}^3$ ，并假设不变。试计算以下两种情况吸收塔的填料层高度：

(1) 用纯水吸收；(2) 水中加入活性组分B，与A发生极快化学反应，B的浓度为 $c_{BL} = 0.8 \text{ kmol} / \text{m}^3$ ，反应式为 $A + B \rightarrow M$ ，设 $k_{AL} \approx k_{BL} \approx k_L$ 。

解 根据 $p_A = y_A p$ ，则进出塔A组分的分压分别为

进塔： $p_{AG2} = 1.0133 \times 10^5 \text{ Pa} \times 0.1\% = 101.33 \text{ Pa}$ ， 出塔： $p_{AG1} = 20.27 \text{ Pa}$

(1) 用纯水吸收 此情况为物理吸收过程。填料塔进出口气液相浓度如右图所示。

1) 由物料平衡确定操作线方程：填料塔处理的是稀溶液，作填料塔物料衡算得：

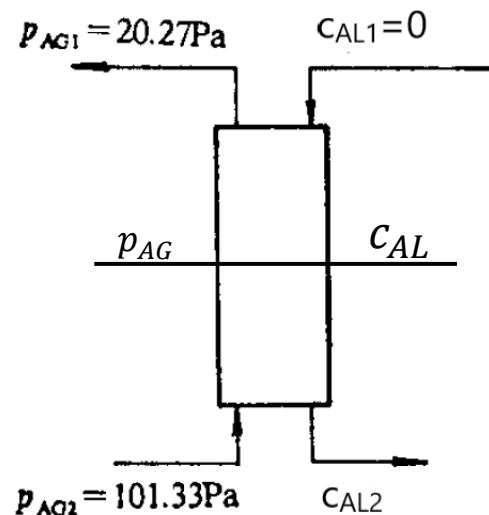
$$\frac{G}{p} (p_{AG} - p_{AG1}) = \frac{L}{c_T} (c_{AL} - c_{AL1})$$

代入已知条件

$$p_{AG} - 20.27 = \frac{700 \times 1.0133 \times 10^5}{100 \times 56} c_{AL}$$

可得操作线方程

$$c_{AL} = 7.895 \times 10^{-5} p_{AG} - 160 \times 10^{-5}$$



2) 计算吸收推动力总传质系数, 气相总传质系数 $K_{AG}a$ 用下式计算

$$\begin{aligned} 1/(K_{AG}a) &= 1/(k_{AG}a) + 1/(H_A k_{AL}a) \\ &= 1/3.158 \times 10^{-4} + 1/(7.895 \times 10^{-5} \times 0.1) \\ &= 129829 \end{aligned}$$

3) 计算填料层高度:

$$H = \frac{G}{p} \int_{p_{AG1}}^{p_{AG2}} \frac{dp_{AG}}{N_A a} = \frac{G}{p} \int_{p_{AG1}}^{p_{AG2}} \frac{dp_{AG}}{K_{AG}(p_{AG} - p_A^*)a} = \frac{G}{p} \times \frac{1}{K_{AG}a} \int_{p_{AG1}}^{p_{AG2}} \frac{dp_{AG}}{p_{AG} - p_A^*}$$

$$\text{而 } p_{AG} - p_A^* = p_{AG} - \frac{c_{AL}}{H_A} = p_{AG} - \frac{7.895 \times 10^{-5} p_{AG} - 160 \times 10^{-5}}{7.895 \times 10^{-5}} = 20.266$$

$$H = \frac{100}{1.0133 \times 10^5} \times 129829 \times \int_{20.27}^{101.33} \frac{dp_{AG}}{20.266} = 512.47 \approx 512 \text{ m}$$

由此可见, 采用纯水吸收, 需要的塔高约512米, 这显然是不可能的。



(2) 用  $c_{BL}=0.8\text{kmol} / \text{m}^3$  的吸收剂来净化废气，此情况活性组分B的浓度很高，发生极快反应。

1) 物料平衡确定操作线方程：从塔任一截面到塔顶作物料衡算

$$G \frac{p_{AG} - p_{AG1}}{p} = L \frac{c_{BL1} - c_{BL}}{c_T}$$

$$p_{AG} - p_{AG1} = \frac{Lp}{Gc_T} (c_{BL1} - c_{BL})$$

$$p_{AG} - 20.27 = \frac{700 \times 1.0133 \times 10^5}{100 \times 56} (0.8 - c_{BL})$$

得操作线方程：  $c_{BL} = 80159 \times 10^{-5} - 7.895 \times 10^{-5} p_{AG}$

液体出塔处B组分的浓度为：  $c_{BL2} = 80159 \times 10^{-5} - 7.895 \times 10^{-5} \times 101.33 = 0.794 \text{ kmol/m}^3$

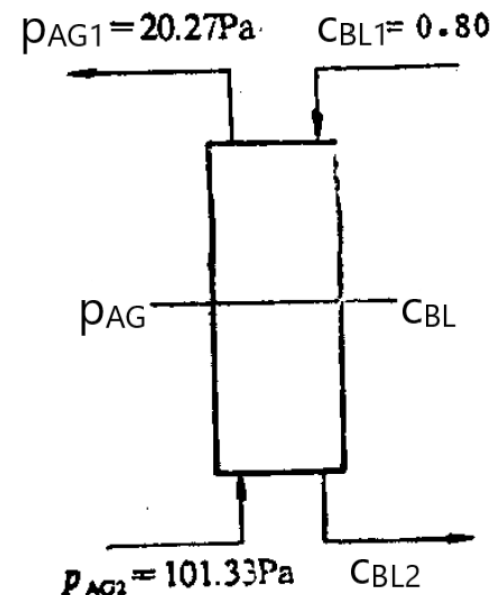
2) 判断宏观动力学形式：采用  $c_{BL}$  与临界浓度  $c_{kp}$  的相对大小来判断采用宏观动力学形式。

$$\text{临界浓度 } c_{kp} = b \frac{k_{AG} \cdot a}{k_{AL} \cdot a} \times \frac{D_{AL}}{D_{BL}} p_{AG} = \frac{3.158 \times 10^{-4}}{0.1} p_{AG} = 3.158 \times 10^{-3} p_{AG}$$

在塔顶处：  $c_{kp} = 3.158 \times 10^{-3} \times 20.27 = 0.064$ ,  $0.064\text{kmol/m}^3 = c_{kp} < c_{BL1} = 0.8\text{kmol/m}^3$

在塔底处：  $c_{kp} = 3.158 \times 10^{-3} \times 101.33 = 0.32$ ,  $0.32\text{kmol/m}^3 = c_{kp} < c_{BL2} = 0.794\text{kmol/m}^3$

可见无论在塔顶还是在塔顶还是在塔底处，都是  $c_{BL} > c_{kp}$ ，可认为整个塔内均为气膜传质控制。反应在相界面处进行，取  $p_{Ai} = 0$ ，所以宏观反应速率方程采用式（7-43），即  $N_A = k_{AG} p_{AG}$ 。



3) 计算填料层高度:

$$H = \frac{G}{p} \int_{P_{AG1}}^{P_{AG2}} \frac{dp_{AG}}{N_A a} = \frac{G}{p} \int_{P_{AG1}}^{P_{AG2}} \frac{dp_{AG}}{k_{AG} a p_{AG}} = \frac{100}{1.0133 \times 10^5 \times 3.158 \times 10^{-4}} \ln \frac{101.33}{20.27} = 5.03$$

填料层高度由512m下降到6m, 说明化学吸收可大幅度降低吸收塔高度。