

Chapter 5

Absorption and Stripping

5.1 Introduction

In *absorption* (also called *gas absorption*, *gas scrubbing*, or *gas washing*), there is a transfer of one or more species from the gas phase to a liquid solvent. The species transferred to the liquid phase are referred to as *solutes* or *absorbate*. Absorption involves no change in the chemical species present in the system. Absorption is used to separate gas mixtures, remove impurities, or recover valuable chemicals. The operation of removing the absorbed solute from the solvent is called *stripping*. Absorbers are normally used with strippers to permit regeneration (or recovery) and recycling of the absorbent. Since stripping is not perfect, absorbent recycled to the absorber contains species present in the vapor entering the absorber. When water is used as the absorbent, it is normally separated from the solute by distillation rather than stripping.

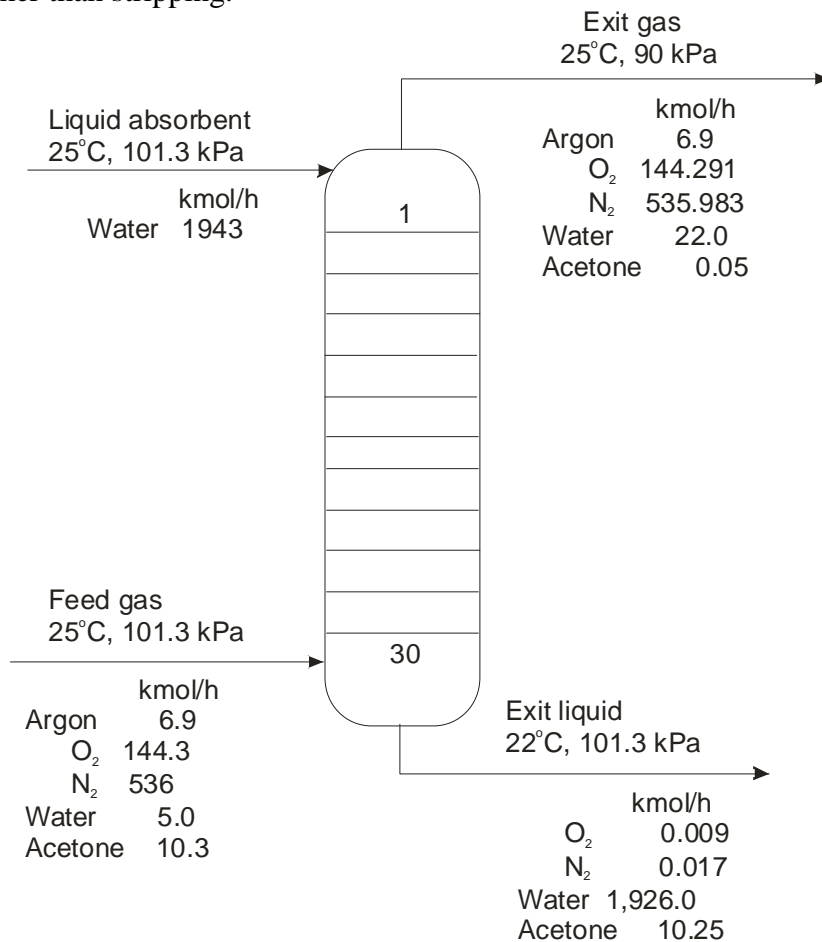


Figure 5.1-1 Typical absorption process.

A typical industrial operation for an absorption process is shown in Figure 5.1-1¹. The feed, which contains air (21% O₂, 78% N₂, and 1% Ar), water vapor, and acetone vapor, is the gas

¹ J. D. Seader and E. J. Henley, *Separation Process Principles*, Wiley, 2006, pg. 194

leaving a dryer where solid cellulose acetate fibers, wet with water and acetone, are dried. Acetone is removed by a 30-tray absorber using water as the absorbent. The percentage of acetone removed from the air stream is

$$\frac{10.25}{10.3} \times 100 = 99.5\%$$

Although the major component absorbed by water is acetone, there are also small amounts of oxygen and nitrogen absorbed by the water. Water is also stripped since more water appears in the exit gas than in the feed gas. The temperature of the exit liquid decreases by 3°C to supply the energy of vaporization needed to strip the water. This energy is greater than the energy of condensation liberated from the absorption of acetone.

Three approaches have generally been employed to develop equations used to predict the performance of absorbers and absorption equipment: mass transfer coefficients, graphical solution, and absorption factor. The use of mass transfer coefficient is covered in Chapter 2.2. The graphical solution is simple to use for one or two components and provides explicit graphical presentation of the interrelationships of the variables and parameters in an absorption process. However the graphical technique becomes very tedious when several solutes are present and must be considered. The absorption factor approach can be utilized either for hand or computer calculation. Absorption and stripping are conducted mainly in packed columns and plate columns (trayed tower) as shown in Figure 5.1-2.

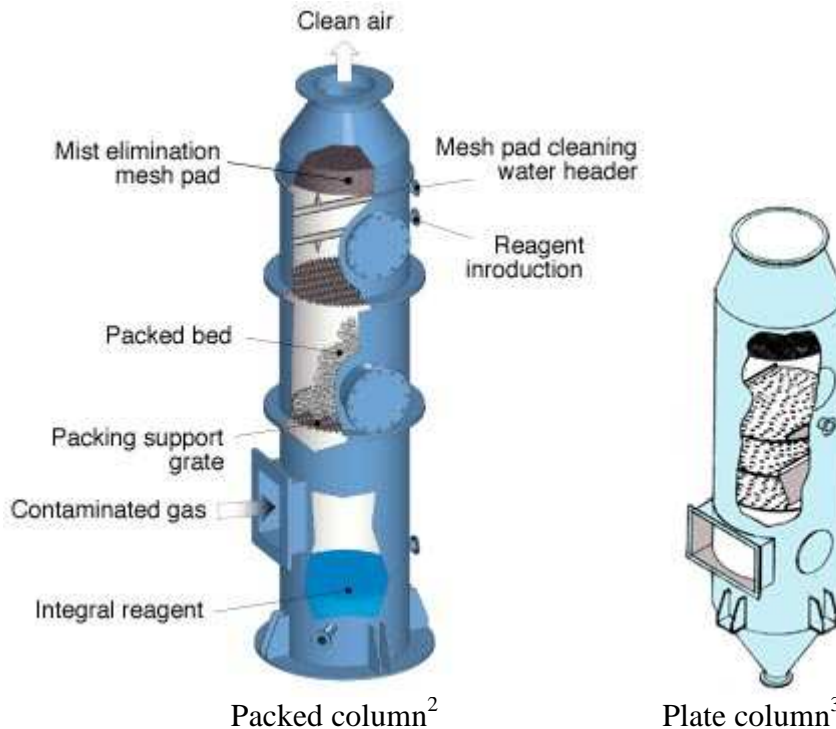


Figure 5.1-2 Equipment for absorption and stripping.

² www.mikropul.com/products/wscrubber/packed.htm (Aug. 25 2009)

³ http://www.cgscgs.com/ga_tt.htm (Aug. 25 2009)

5.2 Single-Component Absorption

Most absorption or stripping operations are carried out in counter current flow processes, in which the gas flow is introduced in the bottom of the column and the liquid solvent is introduced in the top of the column. The mathematical analysis for both the packed and plated columns is very similar.

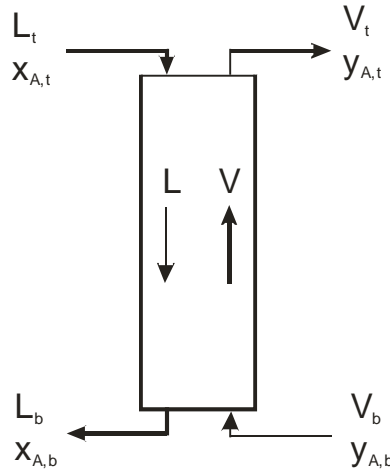


Figure 5.2-1 Countercurrent absorption process.

The overall material balance for a countercurrent absorption process is

$$L_b + V_t = L_t + V_b \quad (5.2-1)$$

where V = vapor flow rate
 L = liquid flow rate
 t, b = top and bottom of tower, respectively

The component material balance for species A is

$$L_b x_{A,b} + V_t y_{A,t} = L_t x_{A,t} + V_b y_{A,b} \quad (5.2-2)$$

where y_A = mole fraction of A in the vapor phase
 x_A = mole fraction of A in the liquid phase

For some problems, the use of *solute-free* basis can simplify the expressions. The solute-free concentrations are defined as:

$$\bar{X}_A = \frac{x_A}{1 - x_A} = \frac{\text{mole fraction of A in the liquid}}{\text{mole fraction of non-A components in the liquid}} \quad (5.2-3a)$$

$$\bar{Y}_A = \frac{y_A}{1 - y_A} = \frac{\text{mole fraction of A in the vapor}}{\text{mole fraction of non-A components in the vapor}} \quad (5.2-3b)$$

If the carrier gas is completely insoluble in the solvent and the solvent is completely nonvolatile, the carrier gas and solvent rates remain constant throughout the absorber. Using

\bar{L} to denote the flow rate of the nonvolatile and \bar{V} to denote the carrier gas flow rate, the material balance for solute A becomes

$$\bar{L} \bar{X}_{A,b} + \bar{V} \bar{Y}_{A,t} = \bar{L} \bar{X}_{A,t} + \bar{V} \bar{Y}_{A,b} \quad (5.2-4)$$

or

$$\bar{Y}_{A,t} = \frac{\bar{L}}{\bar{V}} \bar{X}_{A,t} + \left(\bar{Y}_{A,b} - \frac{\bar{L} \bar{X}_{A,b}}{\bar{V}} \right) \quad (5.2-5)$$

The material balance for solute A can be applied to any part of the column. For example, the material balance for the top part of the column is

$$\bar{Y}_{A,t} = \frac{\bar{L}}{\bar{V}} \bar{X}_{A,t} + \left(\bar{Y}_A - \frac{\bar{L} \bar{X}_A}{\bar{V}} \right) \quad (5.2-6)$$

In this equation, \bar{X}_A and \bar{Y}_A are the mole ratios of A in the liquid and vapor phase, respectively, at any location in the column including at the two terminals. Equation (5.2-6) is called the operation line and is a straight line with slope $\frac{\bar{L}}{\bar{V}}$ when plotted on $\bar{X}_A - \bar{Y}_A$ coordinates.

The equilibrium relation is frequently given in terms of the Henry's law constant which can be expressed in many different ways:

$$P_A = \mathcal{H} C_A = m x_A = K x_A \quad (5.2-7)$$

In this equation, P_A is the partial pressure of species A over the solution and C_A is the molar concentration with units of mole/volume. The Henry's law constant \mathcal{H} and m have units of pressure/molar concentration and pressure/mole fraction, respectively. K is the equilibrium constant or vapor-liquid equilibrium ratio. Table 5.2-1 list Henry's law constant m for various gases in water.

Table 5.2-1 Henry's Law constant for Gases in water⁴ ($m \times 10^{-4}$ atm/mole fraction)

$T(^{\circ}\text{C})$	CO ₂	CO	C ₂ H ₆	C ₂ H ₄	He	H ₂	H ₂ S	CH ₄	N ₂	O ₂
0	0.0728	3.52	1.26	0.552	12.9	5.79	0.0268	2.24	5.29	2.55
10	0.104	4.42	1.89	0.768	12.6	6.36	0.0367	2.97	6.68	3.27
20	0.142	5.36	2.63	1.02	12.5	6.83	0.0483	3.76	8.04	4.01
30	0.186	6.20	3.42	1.27	12.4	7.29	0.0609	4.49	9.24	4.75
40	0.233	6.96	4.23		12.1	7.51	0.0745	5.20	10.4	5.35

Example 5.2-1. ⁵-----

A solute A is to be recovered from an inert carrier gas B by absorption into a solvent. The gas entering into the absorber flows at a rate of 500 kmol/h with $y_A = 0.3$ and leaving the absorber with $y_A = 0.01$. Solvent enters the absorber at the rate of of 1500 kmol/h with $x_A =$

⁴ Geankoplis, C.J., Transport Processes and Separation Process Principles, 4th edition, Prentice Hall, 2003, pg. 988

⁵ Hines, A. L. and Maddox R. N., Mass Transfer: Fundamentals and Applications, Prentice Hall, 1985, pg. 255

0.001. The equilibrium relationship is $y_A = 2.8 x_A$. The carrier gas may be considered insoluble in the solvent and the solvent may be considered nonvolatile. Construct the x - y plots for the equilibrium and operating lines using both mole fraction and solute-free coordinates.

Solution -----

The flow rates of the solvent and carrier gas are given by

$$\bar{L} = L_t(1 - x_{A,t}) = 1500(1 - 0.001) = 1498.5 \text{ kmol/h}$$

$$\bar{V} = V_b(1 - y_{A,b}) = 500(1 - 0.3) = 350 \text{ kmol/h}$$

The concentration of A in the solvent stream leaving the absorber can be determined from the following expressions:

$$x_{A,b} = \frac{\text{Moles A in } L_b}{\text{Moles A in } L_b + \bar{L}}$$

$$\text{Moles of A in } L_b = \text{Moles of A in } L_t + \text{Moles of A in } V_b - \text{Moles of A in } V_t$$

$$\text{Moles of A in } L_b = 1500 \times 0.001 + 500 \times 0.3 - \text{Moles of A in } V_t$$

$$y_{A,t} = \frac{\text{Moles A in } V_t}{\text{Moles A in } V_t + \bar{V}} \Rightarrow 0.01 = \frac{\text{Moles A in } V_t}{\text{Moles A in } V_t + 350}$$

$$\text{Moles of A in } V_t = 350 \times 0.01 / (1 - 0.01) = 3.5354 \text{ kmol/h}$$

$$\text{Moles of A in } L_b = 1.500 + 150 - 3.5354 = 147.965 \text{ kmol/h}$$

$$x_{A,b} = \frac{\text{Moles A in } L_b}{\text{Moles A in } L_b + \bar{L}} = \frac{147.965}{147.965 + 1498.5} = 0.0898$$

For the solute free basis:

$$\bar{X}_A = \frac{x_A}{1 - x_A}, \bar{Y}_A = \frac{y_A}{1 - y_A}$$

$$\bar{X}_{A,t} = \frac{x_{A,t}}{1 - x_{A,t}} = \frac{0.0010}{1 - 0.0010} = 0.0010$$

$$\bar{X}_{A,b} = \frac{x_{A,b}}{1 - x_{A,b}} = \frac{0.0898}{1 - 0.0898} = 0.0987$$

$$\bar{Y}_{A,t} = \frac{y_{A,t}}{1 - y_{A,t}} = \frac{0.010}{1 - 0.010} = 0.0101$$

$$\bar{Y}_{A,b} = \frac{y_{A,b}}{1 - y_{A,b}} = \frac{0.30}{1 - 0.30} = 0.4286$$

The equilibrium curves in both mole fraction and solute-free coordinates are calculated from the following procedures:

- 1) Choose a value of x_A between 0.001 and 0.10
- 2) Evaluate the corresponding $\bar{X}_A = \frac{x_A}{1 - x_A}$
- 3) Evaluate $y_A = 2.8 x_A$
- 4) Evaluate the corresponding $\bar{Y}_A = \frac{y_A}{1 - y_A}$

The operating lines in both mole fraction and solute-free coordinates are calculated from the following procedures:

- 1) Choose a value of x_A between 0.001 and 0.0898
- 2) Evaluate the corresponding $\bar{X}_A = \frac{x_A}{1 - x_A}$
- 3) Evaluate $\bar{Y}_A = \frac{\bar{L}}{\bar{V}} \bar{X}_A + \left(\bar{Y}_{A,b} - \frac{\bar{L}\bar{X}_{A,b}}{\bar{V}} \right)$
- 4) Evaluate the corresponding $y_A = \frac{\bar{Y}_A}{1 + \bar{Y}_A}$

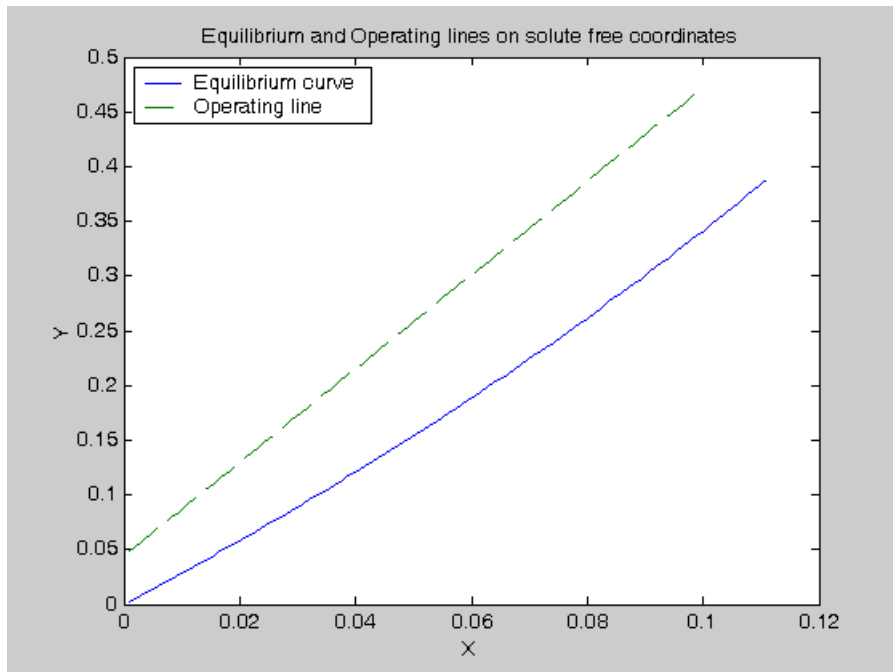
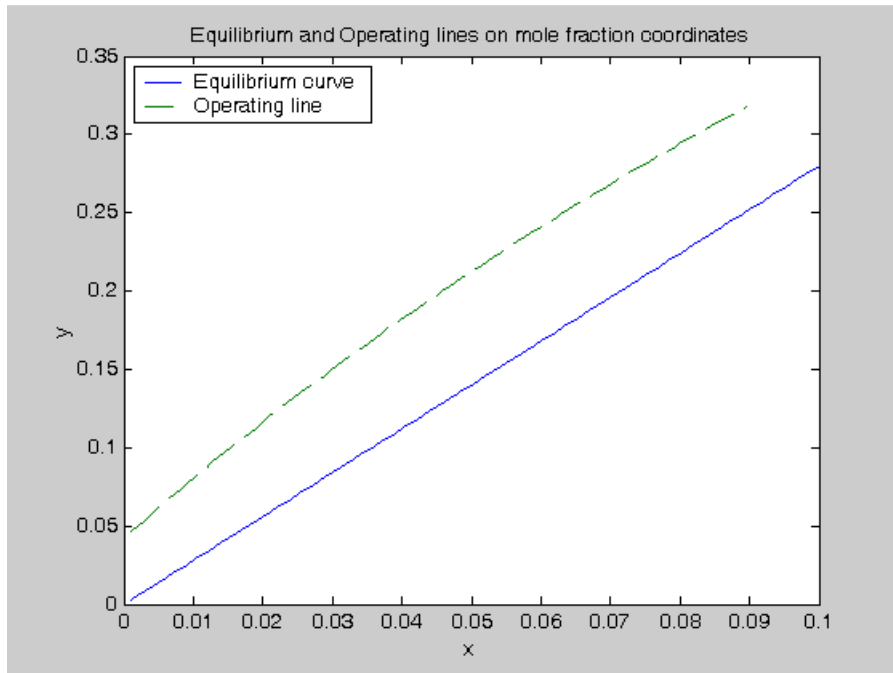
The following Matlab codes plot the equilibrium and operating lines in both mole fraction and solute-free coordinates.

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% Example 5.2-1
xe=linspace(0.001,0.1);
ye=2.8*xe;
Xe=xe./(1-xe);Ye=ye./(1-ye);
x=linspace(0.001,0.0898);
Lbar=1498.5;Vbar=350;
X=x./(1-x);Xb=.0898;Yb=0.4286;
LoV=Lbar/Vbar;
Y=LoV*X+Yb-LoV*Xb;
y=Y./(1+Y);
plot(xe,ye,x,y,'--')
legend('Equilibrium curve','Operating line',2)
xlabel('x');ylabel('y')
Title('Equilibrium and Operating lines on mole fraction coordinates')
figure(2)
plot(Xe,Ye,X,Y,'--')
legend('Equilibrium curve','Operating line',2)

```

xlabel('X');ylabel('Y')
Title('Equilibrium and Operating lines on solute free coordinates')



The equilibrium relation in the mole fraction coordinates is a straight line while the operating line in the solute-free coordinates is a straight line. Normally the equilibrium relation is not a straight line in the mole fraction coordinates. Therefore it is advantage to use solute-free coordinates because the operating line will always be straight.

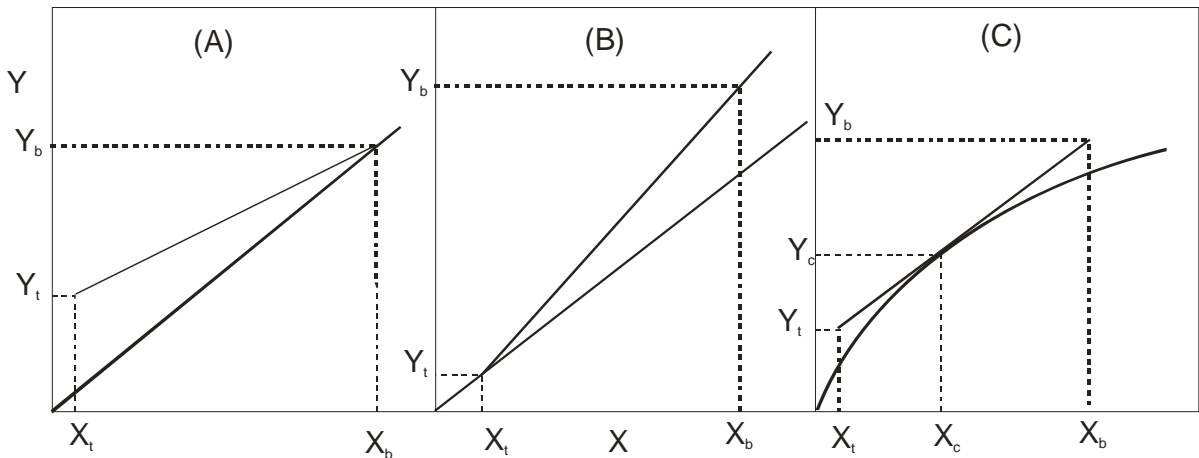


Figure 5.2-2 Limiting conditions for absorption process.

The driving force for mass transfer becomes zero whenever the operating line intersects or touches the equilibrium curve. This limiting condition represents the minimum solvent rate to recover a specified quantity of solute or the solvent rate required to remove the maximum amount of solute. In Figure 5.2-2A, the intersection of the equilibrium and operating lines occurs at the bottom of the absorber. This condition defines the minimum solvent rate to recover a specified quantity of solute. This minimum solvent rate can be calculated from the following expression:

$$\left(\frac{\bar{L}}{\bar{V}}\right)_{\min} = \frac{\bar{Y}_b - \bar{Y}_t}{\bar{X}_b - \bar{X}_t} \quad (5.2-8a)$$

In Figure 5.2-2B, the intersection of the equilibrium and operating lines occurs at the top of the absorber. This condition represents the solvent rate required to remove the maximum amount of solute. This solvent rate can be calculated from the following expression:

$$\left(\frac{\bar{L}}{\bar{V}}\right)_{\max} = \frac{\bar{Y}_b - \bar{Y}_t}{\bar{X}_b - \bar{X}_t} \quad (5.2-8b)$$

Equation (5.2-8b) is exactly the same as Eq. (5.2-8a) except in this case the bottom compositions are fixed so that the maximum slope of the operating line occurs when the operating line intersects the equilibrium curve at the top of the column.

Figure 5.2-2C shows the case when the operating line becomes tangent to the equilibrium curve. The minimum liquid-to-vapor ratio for this case can be determined from

$$\left(\frac{\bar{L}}{\bar{V}}\right)_{\min} = \frac{\bar{Y}_c - \bar{Y}_t}{\bar{X}_c - \bar{X}_t} \quad (5.2-9)$$

In this equation, \bar{Y}_c and \bar{X}_c are the coordinates of the tangent point.