

14 Air Stripping and Aeration

14-1 Introduction to Air Stripping and Aeration

Bringing about Air-Water Contact
Air Stripping
Aeration

14-2 Gas-Liquid Equilibrium

Vapor Pressure and Raoult's Law
Henry's Law
Other Units for Henry's Law Constants
Sources of Henry's Law Constants
Estimation of Henry's Constant Using Molecular Techniques or Using Vapor Pressure and Solubility
Factors Influencing Henry's Constant

14-3 Classification of Air-Stripping and Aeration Systems

Droplet or Thin-Film Air-Water Contactors
Diffusion and Dispersion Aerators
Aspirators
Mechanical Aerators
Advantages and Disadvantages of Various Air-Stripping and Aeration Systems
Selection of Appropriate Equipment

14-4 Fundamentals of Packed-Tower Air Stripping

Mass Balance Analysis for a Countercurrent Packed Tower
Mass Balance for Multistage Stripping Tower
Design Equation for Determining Packed-Tower Height

14-5 Analysis and Design of Packed-Tower Air Stripping

Properties Needed to Determine Packed-Tower Height
Power Requirements
Design versus Rating Analysis of Packed Towers
Design Variables
Design Approach
Factors Influencing Packed-Tower Performance

14-6 Analysis of Low-Profile Air Strippers

Description
Design Approach

14-7 Analysis of Spray Aerators

Description

Design Approach

14-8 Other Air-Stripping and Aeration Processes

Spray Towers

Diffused Aeration

Mechanical Aerators

Problems and Discussion Topics**References****Terminology for Air Stripping and Aeration**

Term	Definition
Absorption	Transfer of volatile substances from air to water.
Air Stripping	Process of removing or desorbing volatile and gaseous constituents from water into air by contacting fresh air with the contaminated water.
Aeration	Process of adding or absorbing gases (e.g., oxygen, ozone) from air into water by contacting the gaseous-laden air with the water.
Aspirator contactors	Devices that force pressurized water through a constriction, changing the pressure head of the water to velocity head, creating a low-pressure zone for atmospheric air or gas to be drawn into the water (e.g., Venturi tube).
Countercurrent packed tower	Tower in which water enters at the top and flows downward over a packing material while air is blown up from the bottom of the column and flows up through the voids of the column.
Desorption	Process for transfer of volatile substances from water to air.
Diffusion contactors	Devices that force compressed air into the water, forming bubbles and creating the surface area available for transfer of a constituent from one phase to another.
Droplet air–water contactors	Devices creating small water drops that are dispersed into fresh air for a given contact time to allow transfer of a constituent from one phase to the other depending on objective (e.g., absorption or desorption).

Term	Definition
Height of a transfer unit (HTU)	Parameter that is a measure of the effectiveness of a particular air–water contact device.
Mechanical contactors	Devices that agitate the water, creating renewed air–water surface for transfer of a constituent from one phase to the other.
Number of transfer units (NTUs)	Dimensionless number that is a measure of the effectiveness of stripping a constituent from water to air. As NTU increases, the maximum possible removal efficiency increases.
Packing factor	Parameter for a random packing material that is used in conjunction with the Eckert pressure drop correlation to estimate the gas pressure drop through the packing.
Random packing	Small geometrically designed irregularly-shaped pieces (typically plastic), randomly packed to a specified height in the tower to provide a high surface area and efficient air–water contact within the tower.
Stripping factor (S)	Dimensionless number defined as the slope of the equilibrium line to the slope of the operating line for countercurrent packed towers and that can be used to assess the ability of a constituent to be removed from water.
Thin-film contactors	Devices that allow water to flow over surfaces, creating a thin water film that is exposed to flowing air and allowing the constituent to be transferred from one phase to the other.

Air stripping and aeration are two water treatment unit processes that utilize the principles of mass transfer to accomplish specific water treatment objectives. Both of these water treatment unit processes bring air and water into intimate contact to transfer volatile substances from the water (e.g., hydrogen sulfide, carbon dioxide, volatile organic compounds) into the air or from the air (e.g., carbon dioxide, oxygen) into the water. The mass transfer process involving the removal of volatile substances from water into the air is known as *desorption*. Air stripping is one of the most common desorption processes used in water treatment. The addition of gases from air into water is the mass transfer process known as *absorption*. Aeration involving the addition of oxygen to water is a commonly used absorption process.

An understanding of the principles of the underlying mass transfer processes, including how to calculate diffusion coefficients and the basis for mass transfer correlations (discussed previously in Chap. 7), is necessary to design air strippers and aerators effectively. In this chapter, the focus is on the application of the aforementioned mass transfer principles to water treatment unit processes. Specific topics considered in this chapter include (1) an introduction to air stripping and aeration, (2) gas–liquid equilibria (Henry's law), (3) the classification of air stripping and aeration systems, (4) the fundamentals of packed tower air stripping, (5) analysis and design for packed tower air stripping, (6) an analysis of low-profile air strippers, (7) an analysis of spray aerators, and (8) other air stripping and aeration processes. Other gas–liquid contacting systems are presented in other chapters, such as Chap. 13, where ozone contactors are discussed.

14-1 Introduction to Air Stripping and Aeration

Water treatment objectives that can be achieved through the gas–liquid mass transfer process are summarized in Table 14-1. In both air stripping and aeration, air–water contactors are used to increase the contact opportunities between the gas and liquid phases. By increasing the air–water contact opportunities, the desorption or absorption mass transfer process is accelerated above the rate that would occur naturally, meaning volatile

Table 14-1
Applications of air–water mass transfer in water treatment

Examples	Water Treatment Objectives
Adsorption	
O ₂	Oxidation of Fe ²⁺ , Mn ²⁺ , S ²⁻ ; lake destratification
O ₃	Disinfection, color removal, oxidation of selected organic compounds
Cl ₂	Disinfection; oxidation of Fe ²⁺ , Mn ²⁺ , H ₂ S
ClO ₂	Disinfection
CO ₂	pH control
SO ₂	Dechlorination
NH ₃	Chloramine formation for disinfection
Desorption	
CO ₂	Corrosion control
O ₂	Corrosion control
H ₂ S	Odor control
NH ₃	Nutrient removal
Volatile organics (e.g., CHCl ₃)	Taste and odor control, removal of potential carcinogens

substances move more rapidly from the water into the air or gases that are not as soluble move more rapidly from the air into the water. The increase in contact opportunities between the two phases occurs through increasing the air–water interface in the air–water contactor by increasing the air–water ratio.

Over the years, a number of methods have been developed to bring about effective air–water contact. Packed towers or slat countercurrent flow towers, known as gas-phase contactors, have a continuous gas phase and a discontinuous water phase and are typically used to remove (or strip) gases or volatile chemicals from water. Air–water contactors such as basins with diffused aeration, also called bubble columns, are known as flooded contactors. In flooded contactors the water phase is continuous and the gas phase is discontinuous because the air is present as discontinuous bubbles. Flooded contactors are typically used to add gases (e.g., O₂, CO₂, O₃) into water.

One confusing concept with air stripping and aeration is that aerators can be used to accomplish air–water contact in both air-stripping and aeration processes. In general, aerators are a relatively simple method for increasing the air–water ratio by (1) spraying water into the air or (2) introducing air into the water through surface turbines or submerged nozzles and diffusors (bubble columns). Thus, aerators allow both of the mass transfer processes, desorption and absorption, to occur in a relatively cost-effective manner. However, because backmixing can occur in aeration systems, a high degree of removal may be difficult to achieve.

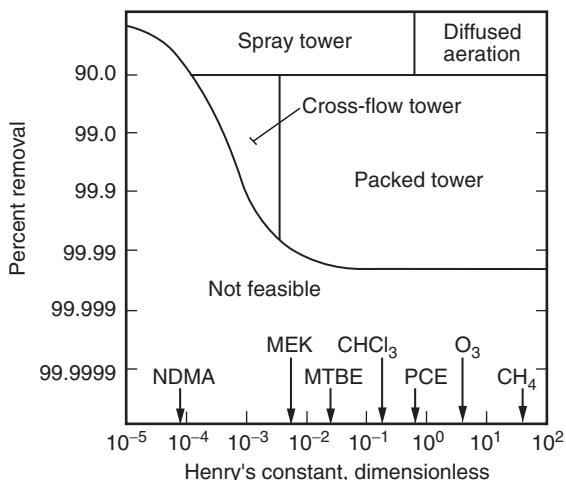
Two major types of air–water contactors are used for air stripping: (1) towers and (2) aerators. The two principal factors that control the selection of the type of air–water contactor for stripping are (1) the desired degree of removal of the compound and (2) the Henry's law constant of the compound. Towers are used when either a high degree of removal is desired or the compound has a high affinity for water (is not very volatile so it has a low Henry's law constant), as shown on Fig. 14-1. Aerators are used when either the desired degree of removal is not very high or the gas has a low affinity for water (is very volatile so it has a high Henry's law constant). When removals less than 90 percent are required, both spray and diffused aeration systems, including mechanical aeration, may be economically attractive. More information on the various types of air-stripping and aeration systems used in water treatment is presented in Sec. 14-3.

Aeration is used to increase the oxygen content in the water by adding air into water through (1) diffusors in a pipe, channel, or process basin; (2) cascading water over stacked trays; or (3) surface turbines and wheels that mix air into water at the top of basins. Oxygenation can also be

Bringing about Air–Water Contact

Air Stripping

Aeration

**Figure 14-1**

Schematic diagram for selection of feasible aeration process for control of volatile compounds (Adapted from Kavanaugh and Trussell, 1981.)

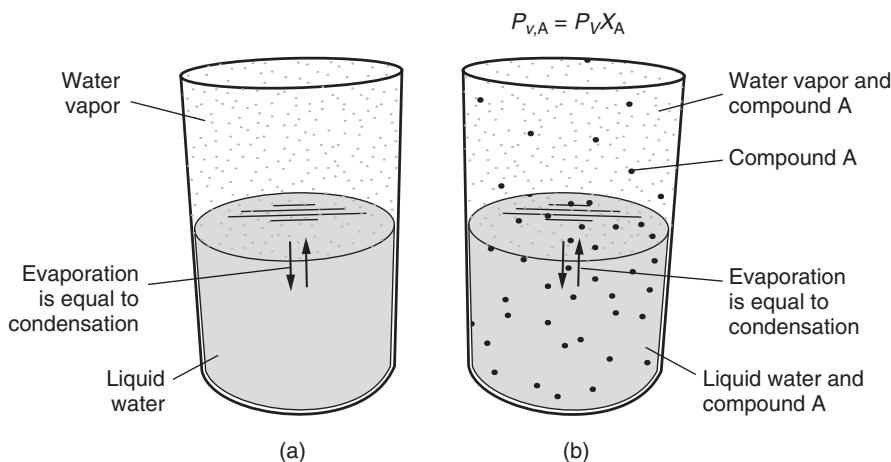
accomplished using pure oxygen. The various types of aeration systems are presented in Sec. 14-3 and the specific details of spray aerators are covered in Sec. 14-7.

14-2 Gas–Liquid Equilibrium

When gas-free water is exposed to air, compounds such as oxygen and nitrogen will diffuse from the air into the water until the concentration of these gases in the water reaches equilibrium with the gases in the air. Conversely, if water in deep wells is brought to the ground surface, dissolved gases such as methane or carbon dioxide will be released to the air because their concentrations in groundwater typically exceed equilibrium conditions with air. The eruption of a carbonated beverage after it is opened is a more familiar example of carbon dioxide release after a pressure change. In each case, the driving force for mass transfer is the difference between the existing and equilibrium concentrations in the two phases, as discussed in Chap. 7.

Vapor Pressure and Raoult's Law

Consider water poured into a closed container that contains some headspace as shown on Fig. 14-2a. Some water molecules will have enough energy to overcome the attractive forces among the liquid water molecules and escape into the headspace above the liquid water, which is called evaporation. At the same time, some water molecules that have escaped into the gas phase above the liquid water may lose energy and move back into the liquid water, which is called condensation. When the rates of evaporation and condensation are equal, the system is at equilibrium. The partial pressure exerted by the water vapor above the liquid water in the

**Figure 14-2**

Schematic diagram for solution equilibrium description of vapor pressure with (a) vapor pressure of water and (b) partial pressure of compound A in the presence of water.

container at equilibrium is called the vapor pressure. Vapor pressure is dependent on temperature and increases with increasing temperature. For example, the vapor pressure of water is 1.23 kPa at 10°C and 3.17 kPa at 25°C. Other volatile liquids (e.g., acetone, benzene) behave the same way and also have a vapor pressure.

If a volatile compound (A) is placed in the same closed container containing water as shown on Fig. 14-2b, it too would come to equilibrium between the liquid and gas phases and exert a partial pressure above the liquid water. If the solution is assumed to behave ideally in which the molecular forces between the solute (A) and the solvent (water) are identical to the solvent-solvent forces, and the solute (or solvent) molecule behaves identically regardless of whether it is surrounded by solute or solvent molecules, then the partial pressure of the solute would be a function of its vapor pressure and the mole fraction of the solute. The partial pressure of solute A can be calculated from the following expression, known as Raoult's law:

$$P_A = P_{v,A} X_A \quad (14-1)$$

where P_A = partial pressure of solute A, Pa

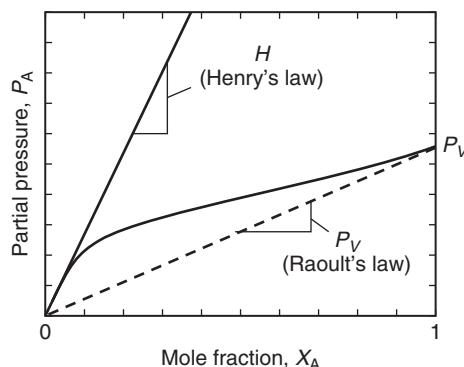
$P_{v,A}$ = vapor pressure of pure liquid A, Pa

X_A = mole fraction of solute A in water, dimensionless

The mole fraction of A is defined as

$$X_A = \frac{n_A}{\sum_i n_i} = \frac{n_A}{n_A + n_{H_2O}} \quad (14-2)$$

where n = amount of A (solute) and water (solvent), mol

**Figure 14-3**

Relationship between partial pressure of a volatile compound and the mole fraction of the volatile compound in solution.

The relationship between partial pressure and mole fraction for solute A is illustrated on Fig. 14-3, and ideal solutions follow Raoult's law and the slope is $P_{v,A}$. For nonideal solutions the molecular forces between the solute and solvent are not identical to the solvent–solute forces because the molecular forces between water molecules are very strong, so the solute–solvent attractions are smaller than the solvent–solvent attractions. Since there are smaller attractive forces holding the solute in solution, it is pushed out of solution and into the gas phase. Consequently, as shown, the partial pressure of the solute is higher than predicted by Raoult's law (a positive deviation from Raoult's law).

Henry's Law

For very dilute solutions most often found in environmental applications, the molecular interactions do not change significantly as additional solute is added, so partial pressure is proportional to mole fraction as shown in Figure 14-3, and this relationship is known as Henry's law. The equilibrium partitioning of a chemical solute between a liquid and gas phase is governed by Henry's law when the solute is very dilute in the mixture. Henry's law in equation form is

$$P_A = H_{PX,A} X_A \quad (14-3)$$

where $H_{PX,A}$ = Henry's law constant for solute A in solvent (water), atm

Henry's law is valid and constant up to mole fractions of 0.01 and has been shown to be valid for concentrations up to 0.1 mol/L (Rogers, 1994). Solvent–solvent forces are unaffected by small amounts of solute and the solvent follows Raoult's law for dilute solutions. Henry's law constants are valid for binary systems (e.g., component A in water). For systems where there are several solutes in a solvent (water) and the solution is still considered dilute, Henry's law will be valid for each solute. The presence of air does not affect the Henry's law constant for volatile organic chemicals (VOCs) or gases because the constituents of interest have low concentrations in air.

The units of Henry's law constant, H_{PX} , in Eq. 14-3 are in atm because the standard conditions for pressure in the gas phase and concentration in the liquid phase were given in atmospheres and mole fractions, respectively. Henry's law constants can also be expressed in terms of concentration or partial pressure of A for the gas phase and mole fraction or concentration for the liquid or water phase. The gas-phase concentration expressed as either partial pressure (atm) or concentration in mol/L is related through the ideal gas law as shown below:

$$P_A V = n_A R T \quad \text{or} \quad Y_A = \frac{n_A}{V} = \frac{P_A}{R T} \quad (14-4)$$

where R = universal gas constant, 0.082057 atm · L/mol · K

$Y_A = n_A/V$ = gas-phase concentration (mol/L)

V = volume of the gas phase, m³

The liquid-phase concentration can be expressed as either mole fraction (mol/mol) or concentration (mol/L) as

$$X_A = \frac{n_A}{n_A + n_W} \approx \frac{n_A}{n_W} = \frac{C_A}{C_W} \quad (14-5)$$

where n_W = amount of water in solution, mol

$$C_W = \frac{\text{density of water}}{\text{molecular weight of water}} = \frac{1000 \text{ g/L}}{18 \text{ g/mol}} = 55.56 \text{ mol/L}$$

$$C_A = X_A C_W = X_A (55.56 \text{ mol/L})$$

Applying these relationships results in three common forms of expressing Henry's law, which are summarized in Table 14-2. A particularly useful set of units is when the solute is expressed as concentration (either mass or molar) in both the gas and liquid phases. These units are known as

Table 14-2

Unit conversions for Henry's law constants

$$\begin{aligned} H_{YC} \left(\frac{L_{H_2O}}{L_{Air}} \right) &= \frac{H_{PC} [\text{atm}/(\text{mol/L})]}{RT} \\ &= \frac{H_{PX} (\text{atm})}{RT \times (55.6 \text{ mol H}_2\text{O/L H}_2\text{O})} \\ H_{PC} [\text{atm}/(\text{mol/L})] &= \frac{H_{PX} (\text{atm})}{55.6 \text{ mol H}_2\text{O/L H}_2\text{O}} \\ H_{PX} (\text{atm}) &= H_{YC} \left(\frac{L_{H_2O}}{L_{Air}} \right) \times RT \times (55.6 \text{ mol H}_2\text{O/L H}_2\text{O}) \end{aligned}$$

Note: subscripts on H correspond to units as follows:

Y = gas phase concentration, C = liquid-phase concentration, P = partial pressure,

X = mole fraction

Other Units for Henry's Law Constants

“dimensionless” forms of Henry’s law and are widely used in environmental engineering. Use of the relationships displayed in Table 14-2 is illustrated in Example 14-1.

Example 14-1 Henry’s law constants

What is the dimensionless Henry’s law constant for a compound that has a value of 250 atm? What is the Henry’s law constant in atmospheres and atm/(mol/L) for a compound that has a dimensionless Henry’s law constant of 0.0545? Assume the temperature is 25°C.

Solution

- Determine the dimensionless Henry’s law constant. Inserting Henry’s law constant of 250 atm into the relationship shown in Table 14-2 for converting H_{PC} to H_{YC} results in the expression

$$\begin{aligned} H_{YC} &= \frac{H_{PX}}{RT(55.6)} \\ &= \frac{250 \text{ atm}}{[0.082057 \text{ atm} \cdot \text{L/mol} \cdot \text{K}][(273 + 25) \text{ K}](55.6 \text{ mol/L})} \\ &= 0.183 \end{aligned}$$

- Determine Henry’s law constant in atmospheres. Rearranging the expression for H_{PX} in terms of H_{YC} and solving for H_{PX} for an H_{YC} of 0.0545, the following result is obtained:

$$\begin{aligned} H_{PX} &= RT \times 55.6 H_{YC} \\ &= [0.082057 \text{ atm} \cdot \text{L/mol} \cdot \text{K}][(273 + 25)\text{K}](55.6 \text{ mol/L})(0.0545) \\ &= 74.1 \text{ atm} \end{aligned}$$

- Determine Henry’s law constant in atm/(mol/L) for an H_{YC} equal to 0.0545. Inserting Henry’s law constant of 0.0545 dimensionless into the relationship shown in Table 14-2 for converting H_{PC} to H_{YC} and solving for H_{PC} results in the expression

$$\begin{aligned} H_{PC} &= RTH_{YC} = [0.082057 \text{ atm} \cdot \text{L/mol} \cdot \text{K}](273 + 25)\text{K}(0.0545) \\ &= 1.33 \text{ atm/(mol/L)} \end{aligned}$$

Sources of Henry’s Law Constants

Methods have been developed to determine Henry’s law constants for volatile compounds. In the early 1980s methods that included measuring the compound’s vapor pressure and solubility, direct measurement of a compound’s vapor pressure and aqueous concentrations in an equilibrium

system, and using batch air stripping techniques to determine Henry's law constants were evaluated and compared (Mackay and Shiu, 1981). However, these techniques can be unreliable, and a more suitable method was developed called the equilibrium partitioning in closed systems (EPICS) technique (Lincoff and Gossett, 1984). This method consists of the addition of equal masses of a volatile solute to two sealed serum bottles that are identical in all respects except they possess different water volumes. The gas-phase concentrations are measured, and the following equation is used to determine Henry's law constant (Gossett, 1987):

$$H_{YC} = \frac{V_{W2} - [(C_{g1}/M_1) / (C_{g2}/M_2)] V_{W1}}{[(C_{g1}/M_1) / (C_{g2}/M_2)] V_{g1} - V_{g2}} \quad (14-6)$$

where V_{W1} = volume of water in bottle 1, L

V_{W2} = volume of water in bottle 2, L

V_{g1} = volume of headspace in bottle 1, L

V_{g2} = volume of headspace in bottle 2, L

M_1 = total mass of solute added to bottle 1, mol

M_2 = total mass of solute added to bottle 2, mol

C_{g1} = concentration of solute in the gas in bottle 1, mol/L

C_{g2} = concentration of solute in the gas in bottle 2, mol/L

In the evaluation of H_{YC} using Eq. 14-6 the actual masses M_1 and M_2 do not need to be known but only their ratio. This means that if the same stock solution of a solute is used and injected into the two serum bottles, the actual concentration of the stock required need not be known because a gravimetric measure of the relative quantity of the stock added to the bottles is all that is needed (Gossett, 1987). The reported precision or coefficient of variation of this method is within 2 to 5 percent. This technique has become widely used to experimentally determine Henry's constants for VOCs (Gossett, 1987; Ashworth et al., 1988; Robbins et al., 1993; Dewulf et al., 1995; Heron et al., 1998; Ayuttya et al., 2001).

Henry's law constants are readily available in the published literature (Yaws et al., 1976; Mckay et al., 1979; Nicholson et al., 1984; U.S. EPA, 1986; Ashworth et al., 1988; Sander, 1999). Values can also be found in Internet databases, including at sites maintained by NIST (2011) and SRC (2011). Table 14-3 displays Henry's constants for several VOCs encountered in water supplies. Note their values change with temperature, and a discussion of the impact of temperature on Henry's constants is presented below. Most Henry's constants reported in the literature are performed using organic-free laboratory water. Natural waters used for drinking supply may contain concentrations of dissolved solids (50 to 600 mg/L TDS) and natural organic matter (0.5 to 15 mg/L as DOC). The value of Henry's constants is not impacted by the range of these dissolved constituents in

Table 14-3

Dimensionless Henry's law constants for selected volatile organic chemicals

Component	Henry's Law Constants, H				
	10°C	15°C	20°C	25°C	30°C
Benzene	0.142	0.164	0.188	0.216	0.290
Carbon tetrachloride	0.637	0.808	0.96	1.210	1.520
Chloroform	0.0741	0.0968	0.1380	0.1720	0.2230
cis-1,2-Dichloroethylene	0.116	0.138	0.150	0.186	0.231
Dibromochloromethane	0.0164	0.0190	0.0428	0.0483	0.0611
1,2-Dichlorobenzene	0.0702	0.0605	0.0699	0.0642	0.0953
1,3-Dichlorobenzene	0.0952	0.0978	0.1220	0.1170	0.1700
1,2-Dichloropropane	0.0525	0.0533	0.0790	0.1460	0.1150
Ethylbenzene	0.140	0.191	0.250	0.322	0.422
Methyl ethyl ketone	0.01210	0.01650	0.00790	0.00532	0.00443
Methyl t-butyl ether (MTBE)	0.0117	0.0177	0.0224	0.0292	0.0387
m-Xylene	0.177	0.210	0.249	0.304	0.357
n-Hexane	10.3	17.5	36.7	31.4	62.7
o-Xylene	0.123	0.153	0.197	0.199	0.252
1,1,2,2-Tetrachloroethane	0.01420	0.00846	0.03040	0.01020	0.02820
Tetrachloroethylene	0.364	0.467	0.587	0.699	0.985
Toluene	0.164	0.210	0.231	0.263	0.325
Trichloroethylene	0.237	0.282	0.350	0.417	0.515

Source: Adapted from Ashworth et al. (1988).

natural waters (Nicholson et al., 1984). The impact of high dissolved constituent concentrations on Henry's constants is discussed below. For water supplies that contain multiple VOCs in low concentrations, their Henry's constant values are not impacted by the other VOCs present in the water.

When experimental values of Henry's constant are not available, they can be estimated using software that incorporates molecular group or bond contribution calculations or from solubility and vapor pressure data as discussed in the following section.

Estimation of Henry's Constant Using Molecular Techniques or Using Vapor Pressure and Solubility

ESTIMATION OF HENRY'S CONSTANTS USING MOLECULAR TECHNIQUES

Molecular methods have been developed to estimate Henry's constants for solutes that lack reliable experimental data. Methods involving group contributions are widely used to estimate Henry's constants for solutes in water. Group contribution methods separate a molecular structure of a molecule into smaller parts, known as functional groups or fragments such that the molecule property is obtained from summing its functional groups. The small functional groups or segments are determined by fitting to a set of experimental data containing many solutes, while assuming the interaction parameter values for a functional group or fragment are

independent of the molecules in which they make up and can be used to estimate Henry's constants of more complex solutes (Lin and Sandler, 2002). Group and bond contribution methods to predict Henry's constants of solutes in water have been developed and presented in the literature (Hine and Mookerjee, 1975; Nirmalakhandan and Speece, 1988; Meylan and Howard, 1991; Suzuki et al., 1992; Meylan, 1999; Lin and Sandler, 2000, 2002). Many of these methods are incorporated into user-friendly programs that can be used to estimate Henry's constants for solutes in water. The most widely known software program is HENRYWIN, which is a part of EPI (Estimation Programs Interface) Suite. EPI Suite is a Windows-based suite of physical/chemical property and environmental fate estimation programs developed by the EPA's Office of Pollution Prevention Toxics and Syracuse Research Corporation (Meylan, 1999). EPI Suite is available for free download on the EPA's website. Another commonly used software package is the System to Estimate Physical Properties (StEPP). StEPP contains a database of over 600 compounds and their physical properties including experimentally determined values of Henry constants as well as estimation methods using a group contribution method (Hokanson, 1996).

ESTIMATION OF HENRY'S CONSTANTS FROM VAPOR PRESSURE AND SOLUBILITY DATA

Compounds with strong repulsive interactions with water molecules have low aqueous solubilities. These compounds usually have large deviations between Henry's constant and vapor pressure. The ratio of vapor pressure to Henry's constant is approximately equal to the aqueous solubility of the compound as shown in the expression

$$C_{S,A} \approx \frac{P_{V,A}}{H_{PCA}} \quad (14-7)$$

where $C_{S,A}$ = aqueous solubility of compound A, mol/L

$P_{V,A}$ = vapor pressure of compound A, atm

Consequently, Henry's constant for a slightly soluble compound A can be estimated from vapor pressure and aqueous solubility as

$$H_{PCA} \approx \frac{P_{V,A}}{C_{S,A}} \quad (14-8)$$

For completely miscible compounds, the Henry law constant approaches the value of the vapor pressure:

$$H_{PX,A} \approx P_{V,A} \quad (14-9)$$

Using this approach, the estimated values are typically within ± 50 to 100 percent of the experimentally reported values and should, therefore, only be used when measured values of the constants are not available. This approach is valid for compounds that are liquid at standard conditions.

Factors Influencing Henry's Constant

Temperature, pressure, ionic strength, surfactants, and solution pH (for ionizable species such as NH₃ and CO₂) can influence the equilibrium partitioning between air and water. The impact of total system pressure on H_{YC} is negligible because other components in air have limited solubility in water.

EFFECT OF TEMPERATURE

Henry's constants for several compounds (at different temperatures) and gases (at 20°C) are listed in Table 14-4. Assuming that the standard enthalpy change (ΔH_{dis}°) for the dissolution of a component in water is constant over the temperature range of interest, the change in H_{YC} with temperature can be estimated using the van't Hoff equation (see Chap. 5):

$$H_{YC,T_2} = H_{YC,T_1} \exp \left[\frac{-\Delta H_{dis}^\circ}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \right] \quad (14-10)$$

where H_{YC,T_2} = dimensionless Henry's law constant at temperature T_2

H_{YC,T_1} = dimensionless Henry's law constant at temperature T_1

ΔH_{dis}° = standard enthalpy change of dissolution in water, J/mol

R = universal gas constant, 8.314 J/mol · K

T_1, T_2 = absolute temperature, K (273 + °C)

Equation 14-10 can be simplified to the following expression, and K_C and ΔH_{dis}° values for selected compounds are reported in Table 14-4:

$$H_{YC} = K_C \exp \left(-\frac{\Delta H_{dis}^\circ}{RT} \right) \quad (14-11)$$

Table 14-4

Dimensionless Henry's law constants at 20°C and temperature dependence for gases in water

Compound	ΔH_{dis}° ^a	K_C	H_{YC}
Air	10.28	3,368	49.58
Ammonia	36.12	1,526	0.0006
Carbon dioxide	19.97	4,013	1.1
Chlorine	16.80	420	0.43
Chlorine dioxide	28.26	4,300	0.04
Hydrogen sulfide	17.84	567	0.38
Methane	14.86	12,402	28.41
Nitrogen	7.94	1,563	60.01
Oxygen	13.40	7,537	30.75
Ozone	24.28	83,848	3.92
Sulfur dioxide	23.15	358	0.03

^a ΔH_{dis}° in units of kJ/mol.

The application of Eq. 14-11 to calculate H_{YC} as a function of temperature is illustrated in Example 14-2. Another common method of expressing the temperature dependence of H_{YC} is to define K_C and $\Delta H_{dis}^\circ/R$ as fitting parameters K_A and K_B , respectively, using the equation

$$H_{YC} = \exp\left(K_A - \frac{K_B}{T}\right) \quad (14-12)$$

Values of K_A and K_B for several compounds valid for temperatures ranging from 283 to 303 K are presented in Ashworth et al. (1988).

The relationship between H_{YC} and temperature over a wide temperature range is displayed in Fig. 14-4 for benzene and hexane. For most

Example 14-2 Henry's law constant and temperature effect

Calculate Henry's law constant at 5 and 20°C for ozone using Eq. 14-11 and Table 14-4.

Solution

- At 5°C: Using Eq. 14-11 and the constants provided in Table 14-4, Henry's law constant for ozone at 20°C can be estimated as follows:

$$K_C = 83,848$$

$$\Delta H_{dis}^\circ = 24.28 \times 10^3 \text{ J/mol}$$

$$H_{YC} = K_C \exp\left(-\frac{\Delta H_{dis}^\circ}{RT}\right)$$

$$= 83,848 \exp\left\{-\frac{24.28 \times 10^3 \text{ J/mol}}{(8.314 \text{ J/mol} \cdot \text{K})[(273 + 5) \text{ K}]}\right\}$$

$$= 2.3$$

- At 20°C:

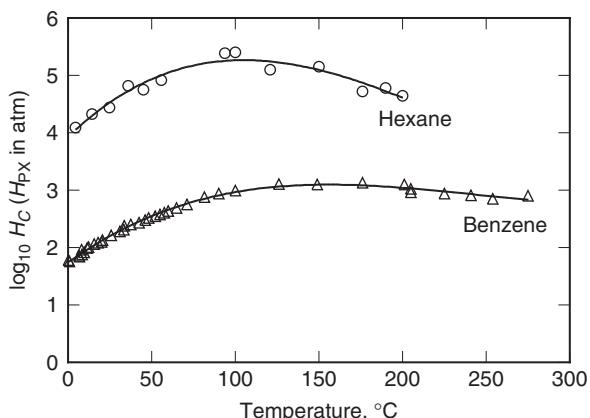
$$H_{YC} = K_C \exp\left(-\frac{\Delta H_{dis}^\circ}{RT}\right)$$

$$= 83,848 \exp\left\{-\frac{24.28 \times 10^3 \text{ J/mol}}{(8.314 \text{ J/mol} \cdot \text{K})[(273 + 20) \text{ K}]}\right\}$$

$$= 3.93$$

Comment

From the above computations, it is clear that temperature has an effect on the dimensionless form of Henry's law.

**Figure 14-4**

Relationship between Henry's law constant and temperature for benzene and heptane. (Adapted from Lan, 2009).

environmental applications where the temperature is less than 30°C, the relationship is nearly linear and can be approximated by the van't Hoff and related equations (Eqs. 14-11 and 14-12). Depending on the volatility of the compound, for temperatures greater than 30°C, H_{YC} increases nonlinearly with temperature reaching a maximum and then decreasing as temperature continues to increase (Miller and Hawthorne, 2000; Lau 2009). For benzene, H_{YC} reaches a maximum at 100°C followed by a decrease as temperature continues to increase. While this may not be important for air stripping at ambient temperatures, it may be important for other applications such as steam stripping of VOCs from industrial wastes.

IONIC STRENGTH

Gases or synthetic organic chemicals (SOCs) have a higher apparent Henry's law constant ($H_{YC,app}$) when the dissolved solids are high because equilibrium depends on activity, not concentration. Thus, the apparent Henry's law constant takes activity into account:

$$Y_A = H_{YC} \{A\} = H_{YC} \gamma_A C_A = H_{YC,app} C_A \quad (14-13)$$

where $H_{YC,app} = H_{YC} \gamma_A$ = apparent Henry's law constant, dimensionless

Y_A = gas-phase concentration, mol/L

γ_A = activity coefficient of A

C_A = concentration of A, mol/L

H_{YC} = dimensionless Henry's constant

The activity coefficient γ_A is a function of ionic strength and can be calculated using the following empirical equation for neutral species:

$$\log \gamma_A = K_s \times I \quad (14-14)$$

where K_s = Setschenow, or “salting-out,” constant, L/mol

I = ionic strength of water, mol/L

Values of K_s need to be determined experimentally because there is no general theory for predicting them. Salting-out coefficients for several compounds in seawater are available in the literature (Gossett, 1987; Schwarzenbach et al., 1993). Significant increases in volatility and the apparent Henry constant are observed only for high-ionic-strength waters such as seawater.

EFFECT OF SURFACTANTS

Surfactants can impact the volatility of compounds. In most natural waters, surfactant concentrations are relatively low; consequently, surfactants do not affect the design of most aeration devices. However, when surfactants are present in relatively high concentrations, the volatility of other compounds may decrease by several mechanisms. The dominant mechanism is collection of surfactants at the air–water interface, decreasing the mole fraction of the volatile compound at the interfacial area, thereby lowering the apparent Henry law constant. For example, the solubility of oxygen in water can decrease by 30 to 50 percent due to the presence of surfactants.

Another surfactant effect for hydrophobic organic compounds is the incorporation of dissolved organic compounds into micelles in solution. Above the critical micelle concentration, the formation of additional micelles will decrease the concentration of the organic compound at the air–water interface and decrease the compound’s volatility.

IMPACT OF pH

The pH does not affect the Henry’s constant directly, but it does affect the distribution of species between ionized and un-ionized forms, which influences the overall gas–liquid distribution of the compound because only the un-ionized species are volatile.

Uncharged weak acids such as H_2CO_3 , HCN, or H_2S cannot be stripped at pH values significantly above their pK_a value. For example, if hydrogen sulfide is a weak acid with the following equilibrium (note, the second ionization constant can be neglected because $pK_{a2} > 14$):



Ionization constants for weak acids were described in Chap. 5. The equilibrium constant (K_a) for the reaction in Eq. 14-15 is 7.94×10^{-8} ($pK_a = 7.1$). Since only the un-ionized species is volatile, Henry’s law can be written as

$$Y_A = H_{YC} [\text{H}_2\text{S}] = H_{YC}\alpha_0 C_{T,S} = H_{YC,\text{app}} C_{T,S} \quad (14-16)$$

$$\alpha_0 = \frac{[\text{H}^+]}{[\text{H}^+] + K_a} \quad (14-17)$$

where $[H_2S]$ = hydrogen sulfide concentration, mol/L

$C_{T,S}$ = total sulfide concentration, mol/L

α_0 = fraction of total sulfide present as hydrogen sulfide

$H_{YC,app}$ = apparent Henry's law constant, dimensionless

K_a = acid dissociation constant

If the pH is equal to 5.1, two pH units lower than the pK_a , then sulfide is only 1 percent ionized and the apparent Henry's constant is essentially the same as the H value. If the pH is two units higher than the pK_a value, then sulfide is 99 percent ionized and the apparent Henry's constant is 1 percent of the H value.

14-3 Classification of Air-Stripping and Aeration Systems

Gas–liquid contactors are classified as either gas phase contactors or flooded contactors and then further classified into four subgroups based on the method that is used to either remove gas from water or add gas to water. The four basic types of air–water contact systems that are discussed in this section are (1) droplet or thin-film air–water contactors, (2) diffusion or bubble aerators, (3) aspirator-type aerators, and (4) mechanical aerators. Characteristics and typical applications of air–water contact systems that fall into one of these four groups are summarized in Table 14-5. Some of these systems may be used to contact water with gases other than air, and while these uses are listed in Table 14-5, they are discussed in other chapters such as Chap. 13.

Droplet or Thin-Film Air–Water Contactors

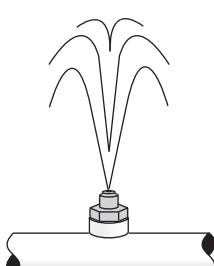


Figure 14-5
Schematic of fountain spray aerator.

Droplet or thin-film air–water contactors are gas-phase contactors designed to produce small droplets of water or thin films, which promote rapid mass transfer.

DROPLET AIR–WATER CONTACTORS

Contactors that use droplets are spray devices, such as towers and the fountain spray aerator shown on Fig. 14-5. Spray devices are designed to provide the desired droplet size for the desired contact time with the gas phase, which is typically air. Spray aerators are an efficient method of gas transfer; however, for efficient operation spray aerators should be placed in large basins or reservoirs in favorable climatic conditions.

THIN-FILM AIR–WATER CONTACTORS

Thin films of water are created in cascade and multiple-tray aerators and packed columns and towers. Air–water contact occurs when water flows by gravity over the surfaces of packing materials that are placed in

Table 14-5

Characteristics of gas–liquid contacting systems

Type of Contacting Device	Process Description	Method of Gas Introduction	Typical Applications	Oxygen Transfer Rate, kg O ₂ /kW · h	Number of Transfer Units (NTU)	Hydraulic Head Required, m (ft)	Loading Factor
Spray aerator	Water to be treated is sprayed through nozzles to form disperse droplets; typically, a fountain configuration. Nozzle diameters usually range from 2.5 to 4 cm (1–1.6 in.) to minimize clogging.	Natural aeration through convection	H ₂ S, CO ₂ , and marginal VOC removal; taste and odor control, oxygenation	—	0.5–0.7	1.5–7.6 (5–25)	Surface area of 0.10–0.30 m ² · s/L
Spray tower	Water to be treated is sprayed downward through nozzles to form disperse droplets in a tower configuration; air–water ratio is controlled; typically countercurrent flow.	Forced-draft aeration	H ₂ S, CO ₂ , and VOC removal; taste and odor control	—	1–1.5	1.5–7.6 (5–25)	Surface area of 0.10–0.30 m ² · s/L
Packed tower	Water to be treated is sprayed onto high-surface-area packing to produce a thin-film flow; process configuration typically countercurrent.	Forced-draft aeration	H ₂ S, CO ₂ , and VOC removal; taste and odor control	—	1–4	3–12 (10–40)	

(continued)

Table 14-5 (Continued)

Type of Contacting Device	Process Description	Method of Gas Introduction	Typical Applications	Oxygen Transfer Rate, kg O ₂ /kW · h	Number of Transfer Units (NTU)	Hydraulic Head Required, m (ft)	Loading Factor
Cascade	Water to be treated flows over the side of sequential pans, creating a waterfall effect to promote droplet-type aeration.	Aeration primarily by natural convection	CO ₂ removal, taste and odor control, aesthetic value, oxygenation	—	0.5–0.7	0.9–3 (3–10)	
Multiple tray	Water to be treated trickles by gravity through trays containing media [layers 0.1–0.15 m (4–6 in.) deep] to produce thin-film flow. Typical media used include coarse stone or coke [50–150 mm (2–6 in.) in diameter] or wood slats.	Natural or forced-draft aeration	H ₂ S, CO ₂ removal, taste and odor control	—	<1	1.5–3 (5–10)	0.007–0.014 m/s (10 – 20 gpm/ft ²)
Low profile (sieve tray)	Water flows from entry at the top of the tower horizontally across series of perforated trays. Large air flow rates are used, causing frothing upon air–water contact, which provides large surface area for mass transfer. Units are typically less than 3 m (10 ft) high.	Air introduced at bottom of tower	VOC removal	—	—	—	Water flow rates less than 0.065 m ³ /s (1000 gpm)

Diffuser	Fine bubbles are supplied through porous diffusers submerged in the water to be treated; tank depth is typically restricted to 4.5 m (15 ft).	Compressed air or ozone	Fe and Mn removal, CO ₂ removal, taste and odor control, oxygenation, ozonation	0.5	0.5–1.5	—	0.1–1 L air/L water
Dispersed air	Compressed air is created through a stationary sparger orifice-type dispersion apparatus located directly below a submerged high-speed turbine.	Compressed air or ozone	Ozonation, especially when high concentrations of Fe and Mn are present. Used due to clogging of porous diffusers	1.5	1–2		
Hydraulic aspirator	A gas stream is educted into the liquid stream with a venturi-type device.	Compressed ozone, CO ₂ , Cl ₂	Ozonation, CO ₂ addition, Cl ₂ disinfection	1.5–3.5	—	3–6 (10–20)	
Mechanical aspirator	A hollow-blade impeller rotates at a speed sufficient to aspirate and discharge a gas stream into the water.	Compressed air or ozone	Ozonation, CO ₂ addition	0.7			
Mechanical aerator	Surface aerators (brush or turbine types) sweep air into the water and fling water into the air. Aeration pumps pull air into the water.	Mechanical agitation of water into surrounding air	O ₂ absorption, VOC removal when <90% removal required	1.5–4.5 (turbine) 2.5 (brush)			

trays, columns, or towers and between trays. The thin liquid film that forms as water flows downward is disrupted continuously by the irregular surfaces of the packing material, maximizing the exposure of the water to the atmosphere and encouraging air–water mixing.

Cascade aerators

Cascade aerators are commonly used for treating groundwater and may be located at the groundwater source or reservoir. Cascade aerators are also called step aerators as water flows downward in a thin film over a series of steps or baffles, sometimes constructed of concrete. Cascade aerators are generally less efficient than other types of thin-film aerators because water flow is less turbulent, resulting in less air–water mixing.

Multiple-tray aerators

There are several types of multiple-tray aerators, all based on the same design concept of stacked trays, where water is distributed over the top tray with a spray nozzle or special distribution trough and then flows from the upper tray over the tray sides into lower trays. Tray-type aerators may be either natural draft type such as coke tray aerators or forced draft type such as wood slat aerators.

Of all the types of multiple-tray aerators, wood slat towers are the most efficient. The slat towers are either forced or induced draft and are enclosed in a wood, fiberglass, or metal shell, as shown on Fig. 14-6. The slats are generally stacked and centered vertically and the horizontal spaces between the slats are staggered so that the water trickling down one tray strikes the middle of the slat of the next tray.

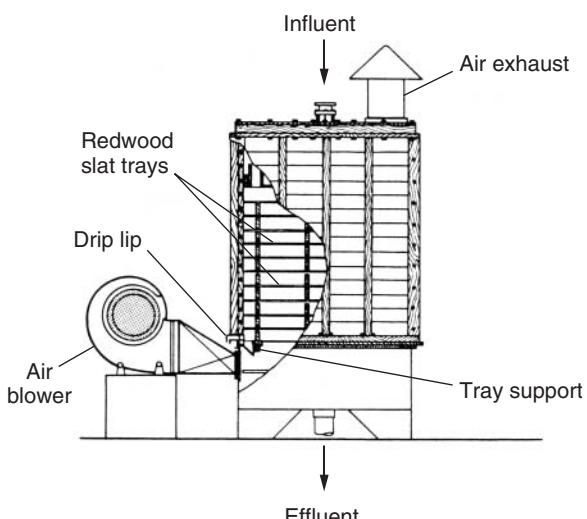


Figure 14-6
Forced-draft multiple-slat tower cascade aerator.

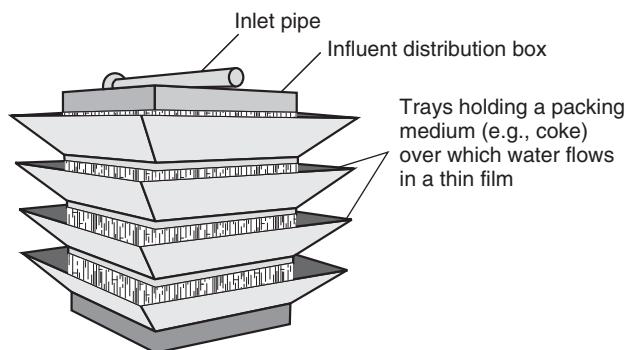


Figure 14-7
Natural draft coke tray aerator.

Tray aerators are typically designed for natural draft, as shown on Fig. 14-7, and typically the tray is filled with packing material such as coke. Coke tray aerators provide somewhat more turbulence in air–water contact because the large surface area of the coke provides a large air–water contact area. Tray aerators are built with splash skirts to reduce the water loss and icing of the protective retaining screens.

A type of multiple-tray aerator that has recently grown in use for removal of VOCs from contaminated waters is the low-profile air stripper, also called the sieve tray column, as shown on Fig. 14-8a. Because the water flows horizontally across each tray, the desired removal efficiency can be obtained by increasing the length or width of the trays instead of the height.

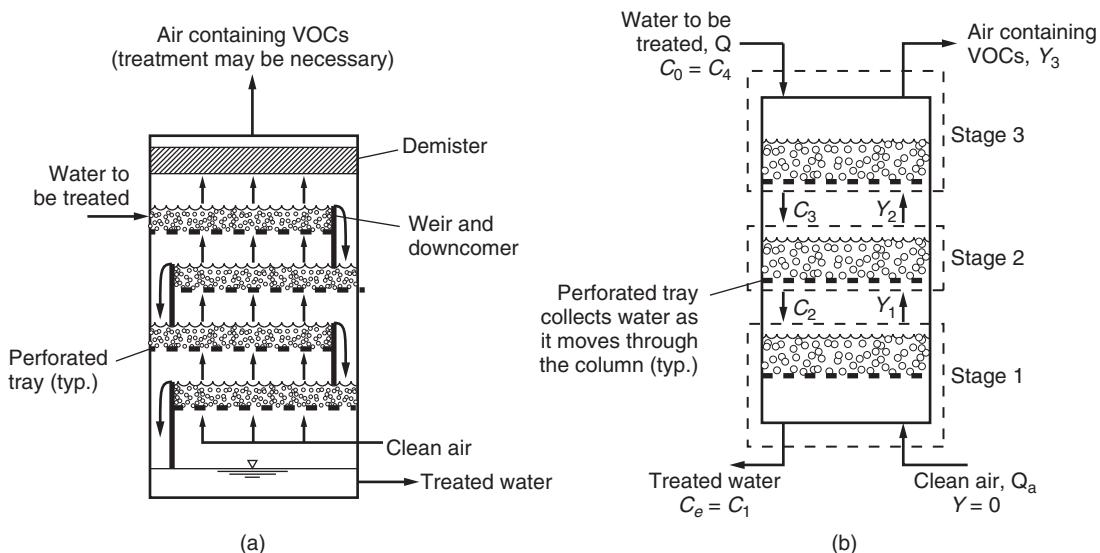


Figure 14-8
Low-profile air stripping: (a) schematic (adapted from U.S. ACE, 2001) and (b) diagram of low-profile air stripping as multistage, countercurrent process.

Packed towers

Packed towers are circular or square towers that are filled with an irregular shaped inert packing material, as shown on Fig. 14-9. Packing material is available in a wide variety of sizes and shapes depending on the manufacturer. Operationally, water is pumped to the top of the tower and into a liquid distributor where it is dispersed as uniformly as possible across the packing surface, and then it flows by gravity through the packing material and is collected at the bottom of the tower. Airflow may be in the same direction as the water (co-current), in the opposite direction as the water (countercurrent), or across the water (cross flow). For countercurrent operation, a blower is used to introduce fresh air into the bottom of the tower and the air flows countercurrent to the water up through the void spaces between the wetted packing material, as shown on Fig. 14-9.

An important part of the packed tower system that is not shown on Fig 14-9 is a demistor, which eliminates entrained water drops and aerosols in the off-gas of a packed tower. Aerosols must be eliminated because they can be displeasing to local communities from an aesthetic point of view and they can freeze in cold climates, causing icing problems.

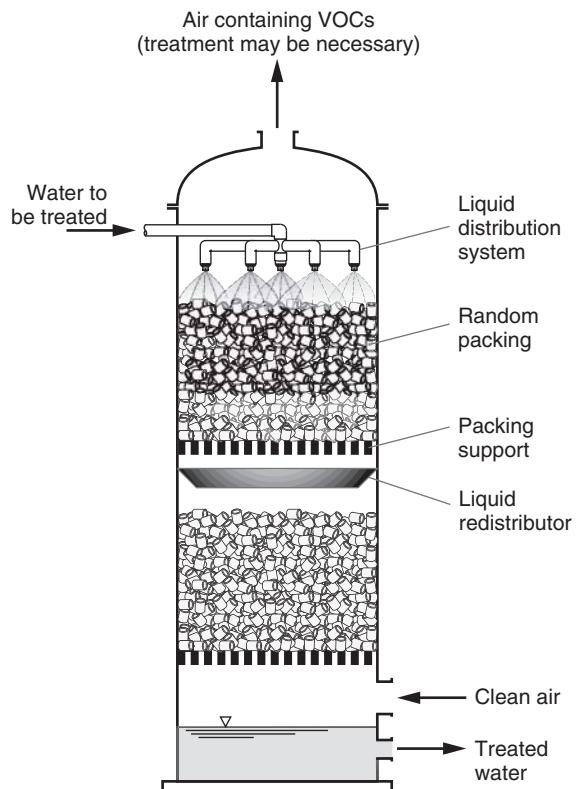


Figure 14-9
Schematic of a countercurrent packed tower.

Diffusion-type aeration systems (either diffused-air or dispersed-air systems) force air into the water using compressed air. Blowers used for aerating systems are either multiple-stage or single-stage centrifugal or rotary positive displacement. Rotary blowers are often used for small installations, where water depth varies significantly.

Diffusion and Dispersion Aerators

DIFFUSED AIR

Compressed air is generally introduced through porous membranes, porous plates or tubes, or wound fiber or metallic filaments at the bottom of a basin or tank, as illustrated by the bubble column on Fig. 14-10a. Diffused-air systems generally require filters to screen out particulates in the air because the air is forced to flow through very fine pores, which can easily plug.

DISPERSED AIR

Mechanical mixers and a stationary orifice-type sparger air dispersion system are used to force air into water in dispersed-air systems, as shown on Fig. 14-10b. The mechanical mixer in the contactor aids in the air–water mixing and, therefore, the gas transfer efficiencies are generally much better than in simple diffused-air systems. The air dispersion outlet is generally located a small distance above the tank bottom to reduce the pressure requirements of the air compressor. Dispersed-air systems usually do not require air filtration as the orifice-type spargers do not readily plug.

Air aspiration is commonly accomplished with either hydraulic aspirators or mechanical devices. A typical hydraulic aspirator is a type of hydraulic eductor or injector in which pressurized water flows through a throat similar to a venturi tube to create a low-pressure condition that in turn draws atmospheric air or gas into the water. A second type of aspirator is a mechanical aspirator that consists of a hollow-blade impeller that rotates at a speed sufficient to aspirate and discharge atmospheric air into the

Aspirators

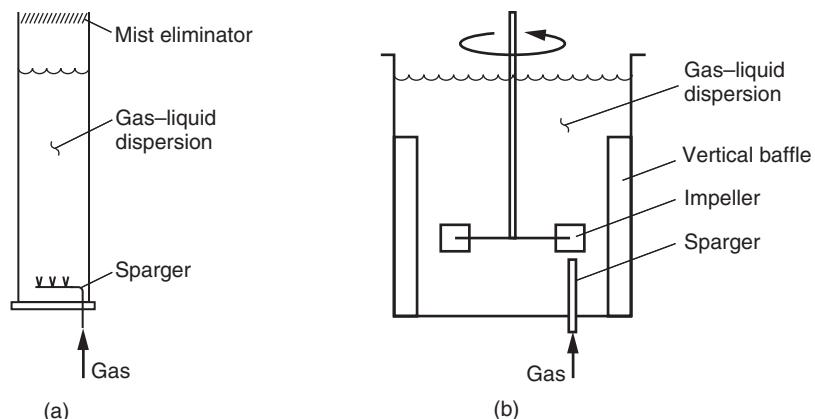


Figure 14-10
Common diffused aeration systems: (a) bubble column and (b) agitated vessel.

water. Hydraulic aspirators are mostly small in size, but a single unit under favorable conditions and operating with atmospheric air produces twice the oxygen transfer rate of ordinary mechanical aspirators.

Mechanical Aerators

Advantages and Disadvantages of Various Air-Stripping and Aeration Systems

Surface aerators and aeration pumps are the two basic types of mechanical aerators. Surface aerators may be of the turbine type or the brush type, as shown on Fig. 14-11. Aeration pumps consist of a turbine mixer with a draft tube. A number of patented mechanical aerators can be purchased from manufacturers.

Each type of air-stripping and aeration system offers process and cost advantages for a specific mass transfer problem. Low-profile air strippers versus packed towers and diffusion-type aerators versus droplet and thin-film aerators are compared in the following discussion.

LOW-PROFILE AIR STRIPPERS VERSUS PACKED TOWERS

The advantages of using a low-profile air stripper over a conventional packed tower stripper are that (1) the low-profile air stripper is smaller and more compact and (2) periodic maintenance is easier to perform on the low-profile air stripper. The disadvantage is that for a given removal the low-profile air stripper requires a significantly higher airflow than a conventional countercurrent packed tower. Consequently, the operational costs can be greater for the low-profile air stripper. In addition, low-profile air strippers are limited to lower water flow rates than countercurrent packed towers.

DIFFUSION-TYPE AERATORS VERSUS DROPLET AND THIN-FILM AERATORS

The advantages of diffusion-type aerators include (1) negligible head loss for the process water system and (2) less space requirements than for

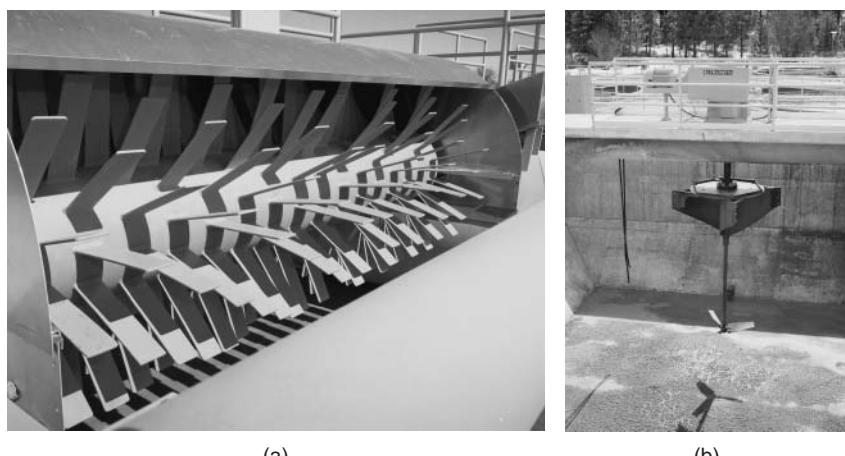


Figure 14-11
Typical examples of surface aeration devices:
(a) brush type and (b) turbine type.

the droplet and thin-film aerators. Diffused-air systems may be extremely effective for reservoir management. Many successful diffused-air applications for reservoir destratification have been reported in the literature (AWWA, 1978a,b; Biederman and Fulton, 1971; Garton, 1978; Laverty and Nielsen, 1970; Steichen et al., 1979; Symons et al., 1970).

Selection of the appropriate equipment is based on relative transfer efficiencies, available hydraulic head, ease of maintenance, and cost considerations (capital and operating costs). Transfer efficiency and some cost considerations are considered below.

Selection of Appropriate Equipment

TRANSFER EFFICIENCY

An important consideration in selecting a process for a specific application is the upper limit of transfer efficiency that can be economically achieved by the process. Many of the processes described in Table 14-5 have limited transfer efficiency. Commercially available cascade aerators cannot achieve greater than 50 or 60 percent removal of chloroform, a relatively volatile organic contaminant. In contrast, packed towers can achieve >99% removal of chloroform. Cascade and multiple-tray aerators encounter corrosion and algae and slime growth problems, particularly if the process water contains hydrogen sulfide. Chlorination and copper sulfate treatment of the process water may help control these problems, but that is an additional operational issue with which to contend.

COST CONSIDERATIONS

For many applications of air–water mass transfer in water treatment, such as stripping of volatile contaminants or addition of a reactant gas, one or more of the four types of air–water contacting systems described above may be used. When more than one system may be appropriate to address the air–water mass transfer issue, capital and operating costs generally are the deciding factors.

Capital cost

The capital cost of each of the processes discussed is closely related to the mass transfer efficiency of the process. In general, the lower the transfer efficiency, the larger the facility required for achieving a certain removal.

Operating cost

Operating cost is primarily a function of the hydraulics of the process and the method of gas dispersion. Equipment complexity or heavy maintenance is typically not a major consideration because most mass transfer equipment is relatively simple, although it should be noted that fouling by chemical precipitation and/or biological growth must be controlled.

When adding a reactive gas such as oxygen, the operating cost must also include chemical costs. The principal cost may be the chemical itself

and/or generation of the compound and to a lesser degree the feeding equipment and gas transfer contact tank (if any).

14-4 Fundamentals of Packed-Tower Air Stripping

Packed towers are either cylindrical columns or rectangular towers containing packing that disrupts the flow of liquid, thus producing and renewing the air–water interface. A schematic of a countercurrent cylindrical packed tower is shown on Fig 14-9, and the operation was described in Sec. 14-3. Packed towers have high liquid interfacial areas and void volumes greater than 90 percent, which minimizes air pressure drop through the tower.

The random packing material is important to the efficient transfer of volatile contaminants from the water to the air because it provides a large air–water interfacial area. Various types of packing shapes, sizes, and their physical properties are available commercially, as shown on Fig. 14-12. The packing can be structured packing or individual pieces that are randomly placed in the tower.

Mass Balance Analysis for a Countercurrent Packed Tower

The model for countercurrent packed towers requires the relationship that relates the bulk water-phase concentration to the bulk air-phase concentration. To obtain a relationship between the bulk air and water concentrations that are shown on Fig. 14-13, a mass balance is written around the lower half of the tower as follows:

1. The general statement of mass balance in words is

$$\begin{aligned} & \text{Mass of chemical entering in liquid phase per unit time} \\ & + \text{mass of chemical entering in gas phase per unit time} \\ & = \text{mass of chemical exiting in liquid phase per unit time} \\ & + \text{mass of chemical exiting in gas phase per unit time} \end{aligned} \quad (14-18)$$

2. The mass balance representation using symbols on Fig. 14-13 is

$$QC_b(z) + Q_a Y_0 = QC_e + Q_a Y_b(z) \quad (14-19)$$

where Q = liquid flow rate, m^3/s

$C_b(z)$ = bulk liquid-phase concentration at axial position z
along tower, mg/L

Q_a = gas flow rate, m^3/s

Y_0 = gas-phase concentration entering tower, mg/L

C_e = effluent liquid-phase concentration, mg/L

$Y_b(z)$ = bulk gas-phase concentration at axial position z
along tower, mg/L

Intalox Saddles		Jaeger Tri-Packs			
		d_p	5.08 cm (2.0 in.)	7.62 cm (3.0 in.)	8.89 cm (3.5 in.)
		C_f	69 m ⁻¹ (21 ft ⁻¹)	52 m ⁻¹ (16 ft ⁻¹)	39 m ⁻¹ (12 ft ⁻¹)
		a_t	98 m ⁻¹ (30 ft ⁻¹)	66 m ⁻¹ (20 ft ⁻¹)	125 m ⁻¹ (38 ft ⁻¹)

Tellerettes (Type K)		No. 2	No. 3	Lantec Q-PAC		
		d_p	5.08 cm (2.0 in.)	7.62 cm (3.0 in.)	d_p	8.89 cm (3.5 in.)
		C_f	36 m ⁻¹ (11 ft ⁻¹)	30 m ⁻¹ (9 ft ⁻¹)	C_f	23 m ⁻¹ (7 ft ⁻¹)
		a_t	52 m ⁻¹ (28 ft ⁻¹)	72 m ⁻¹ (22 ft ⁻¹)	a_t	98 m ⁻¹ (30 ft ⁻¹)

Lantec NUPAC		Lantec LANPAC		
		d_p	5.84 cm (2.3 in.)	8.89 cm (3.5 in.)
		C_f	53 m ⁻¹ (16 ft ⁻¹)	26 m ⁻¹ (8 ft ⁻¹)
		a_t	180 m ⁻¹ (55 ft ⁻¹)	131 m ⁻¹ (40 ft ⁻¹)

Lantec LANPAC-XL		Plastic rings		
		d_p	5.08 cm (2.0 in.)	7.62 cm (3.0 in.)
		C_f	33 m ⁻¹ (10 ft ⁻¹)	30 m ⁻¹ (9 ft ⁻¹)
		a_t	242 m ⁻¹ (74 ft ⁻¹)	72 m ⁻¹ (22 ft ⁻¹)

Critical surface tension depends on material, for polypropylene, $\sigma_c = 0.033 \text{ N/m}$

Figure 14-12

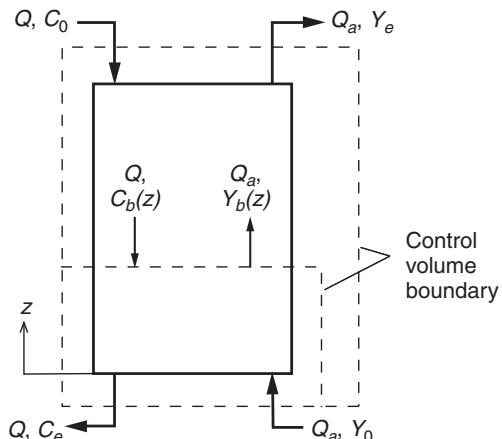
Typical examples of polyethylene packing materials used in air-stripping towers and their physical characteristics.

Combining terms, Eq. 14-19 can be written as

$$[Y_b(z) - Y_0] = \left(\frac{Q}{Q_a} \right) [C_b(z) - C_e] \quad (14-20)$$

A mass balance on the overall tower shown in Fig. 14-13 is

$$QC_0 + Q_a Y_0 = QC_e + Q_a Y_e \quad (14-21)$$

**Figure 14-13**

Definition drawing for mass balances on a packed tower.

Combining terms, Eq. 14-21 can be written as

$$Y_e - Y_0 = \left(\frac{Q}{Q_a} \right) (C_0 - C_e) \quad (14-22)$$

where C_0 = influent liquid-phase concentration to tower, mg/L

Y_e = effluent gas-phase concentration from tower, mg/L

Assuming clean air entering the bottom of the tower ($Y_0 = 0$), Eq. 14-20 becomes

$$Y_b(z) = \left(\frac{Q}{Q_a} \right) [C_b(z) - C_e] \quad (14-23)$$

Under the same assumption, Eq. 14-22 can be written as

$$Y_e = \left(\frac{Q}{Q_a} \right) (C_0 - C_e) \quad (14-24)$$

Equations 14-23 and 14-24 represent the operating line equation for packed-tower aeration (see Chap. 7 for an introduction to operating lines). The operating and equilibrium lines for packed-tower aeration are presented on Fig. 14-14, which is known as a McCabe–Thiele diagram (McCabe and Thiele, 1925). The operating line is labeled 1 on Fig. 14-14, and the equilibrium line is labeled 2. Equilibrium is described by a straight line known as Henry's law (see Sec. 14-2):

$$Y = H_{YC}C \quad (14-25)$$

where Y = gas-phase concentration, mg/L

C = liquid-phase concentration in equilibrium with gas-phase concentration Y , mg/L

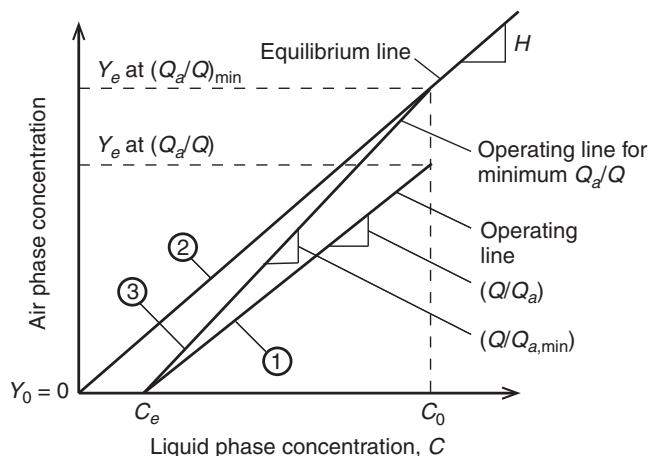


Figure 14-14
Operating line diagram for packed tower.

As discussed in Chap. 7, the operating and equilibrium lines are an important concept in separation processes, such as air stripping, because they can be used to determine the minimum amount of extracting phase (e.g., air in packed-tower aeration), in terms of mass or volume required to remove a component (e.g., from water in packed-tower aeration) to a desired removal efficiency.

STRIPPING FACTOR

A parameter commonly used in the evaluation of packed towers is the stripping factor (S); S is defined as the ratio of the slope of the equilibrium line to the operating line slope. As shown in Fig. 14-14, the equilibrium line divided by the operating line yields the following expression for the S :

$$S = \frac{\text{slope of equilibrium line}}{\text{slope of operating line}} = \frac{H_{YC}}{Q/Q_a} = \left(\frac{Q_a}{Q} \right) H_{YC} \quad (14-26)$$

where S = stripping factor, dimensionless

Q_a/Q = operating air-to-water ratio of tower

Q_a = air flow rate, m^3/s

Q = water flow rate, m^3/s

When $S = 1$, the slopes of the equilibrium and operating lines are parallel to one another and removal to the treatment objective is possible but will require a very long or infinite tower length. When $S < 1$, the slope of the operating line is greater than the slope of the equilibrium line, the desired removal will be equilibrium limited and the treatment objective will not be obtained if a very low effluent concentration is needed. When $S > 1$, the slope of the operating line is less than the slope of the equilibrium line and the treatment objective can be met using stripping.

MINIMUM AIR-TO-WATER RATIO

A special case of the operating line shown in Fig. 14-14 is line number 3. This line intersects the equilibrium line where the influent concentration, C_0 , is in equilibrium with the exiting gas-phase concentration (i.e., $Y_e = H_{YC}C_0$). The slope of this line represents the inverse of the minimum air-to-water ratio that can meet the treatment objective if the packed-tower length is infinite. If it is assumed the influent gas-phase concentration, Y_0 , is equal to zero, and the influent liquid-phase concentration is in equilibrium with the exiting air according to Eq. 14-25, then Eq. 14-22 can be rearranged to yield the following expression for the minimum air-to-water ratio:

$$\left(\frac{Q_a}{Q}\right)_{\min} = \frac{C_0 - C_e}{H_{YC}C_0} \quad (14-27)$$

where $(Q_a/Q)_{\min}$ = minimum air-to-water ratio, dimensionless

C_0 = influent liquid-phase concentration, mg/L

C_e = treatment objective, mg/L

The minimum air-to-water ratio $(Q_a/Q)_{\min}$ represents the minimum air-to-water ratio that can be applied for a packed tower to meet its treatment objective C_e . If the air-to-water ratio applied is less than the minimum air-to-water ratio, it will not be possible to design a packed tower capable of meeting the treatment objective because equilibrium will be established in the tower before the treatment objective is reached.

With respect to the selection of the optimum air-to-water ratio, it has been demonstrated that minimum tower volume and power requirements are achieved using approximately 3.5 times the minimum air-to-water ratio for contaminants with Henry's law constants greater than 0.05 for high percentage removals, corresponding to a stripping factor of 3.5 (Hand et al., 1986).

RELATIONSHIP BETWEEN S AND $(Q_a/Q)_{\min}$

The stripping factor can be related to the minimum air-to-water ratio when the treatment efficiency is very high, and Eq. 14-27 can be approximated as

$$\left(\frac{Q_a}{Q}\right)_{\min} = \frac{C_0 - C_e}{H_{YC}C_0} \approx \frac{1}{H_{YC}} \quad (C_e \ll C_0) \quad (14-28)$$

Substitution of Eq. 14-28 into Eq. 14-26 yields a relationship for stripping factor in terms of minimum air to water ratio

$$S = \frac{Q_a/Q}{(Q_a/Q)_{\min}} \quad (14-29)$$

When $C_e \ll C_0$, the stripping factor is approximately equal to the ratio of the actual air flow rate to the minimum air flow rate for treating a given flow of water.

Example 14-3 Calculation of minimum air-to-water ratio and stripping factor

Calculate the minimum air-to-water ratio and operating air-to-water ratio for 1,2-dichloropropane (DCP) and tetrachloroethylene (PCE) with 90 percent removal at 10°C for a countercurrent packed tower. Calculate the operating air-to-water ratio for a packed tower that minimizes the tower volume and power requirements, and the stripping factor for each compound at the operating air-to-water ratio.

Solution

- Determine H_{PC} for each compound using data in Table 14-3.

a. DCP:

$$H_{YC,DCP} = 0.0525 \text{ (dimensionless)}$$

b. PCE:

$$H_{YC,PCE} = 0.364 \text{ (dimensionless)}$$

- Calculate the minimum air-to-water ratio for each compound using Eq. 14-28.

a. DCP:

$$\left(\frac{Q_a}{Q}\right)_{min,DCP} = \frac{C_0 - C_e}{H_{YC,DCP} C_0} = \frac{C_0 - 0.1C_0}{0.0525C_0} = 17.14$$

b. PCE:

$$\left(\frac{Q_a}{Q}\right)_{min,PCE} = \frac{C_0 - C_e}{H_{YC,PCE} C_0} = \frac{C_0 - 0.1C_0}{0.364C_0} = 2.47$$

- To calculate the operating air-to-water ratio that minimizes tower volume and power consumption, multiply the minimum air-to-water ratio by 3.5.

a. DCP:

$$\left(\frac{Q_a}{Q}\right)_{DCP} = 3.5 \left(\frac{Q_a}{Q}\right)_{DCP,min} = (3.5)(17.14) = 60$$

b. PCE:

$$\left(\frac{Q_a}{Q}\right)_{PCE} = 3.5 \left(\frac{Q_a}{Q}\right)_{PCE,min} = (3.5)(2.47) = 8.65$$

4. Calculate the stripping factor for each compound using Eq. 14-26. Note that the largest air-to-water ratio from step 3 applies to all compounds being stripped in the tower.

a. DCP:

$$S_{DCP} = \left(\frac{Q_a}{Q} \right) H_{YC,DCP} = (60) (0.0525) = 3.15$$

b. PCE:

$$S_{PCE} = \left(\frac{Q_a}{Q} \right) H_{YC,PCE} = (60) (0.364) = 21.8$$

Comment

The compound with the lower Henry's law constant (DCP) requires much larger minimum and operating air-to-water ratios to achieve the desired removal. This is expected because a smaller Henry's constant indicates lower volatility, i.e. that is, a greater preference of the compound for the water phase and a lower tendency for stripping from the water phase to the air phase.

Mass Balance for Multistage Stripping Tower

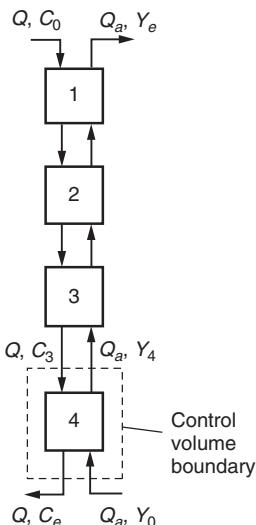


Figure 14-15
Definition drawing for mass balances on multistage stripping tower.

In the design of air-stripping towers, the number of equilibrium stages required for stripping is often determined. Determining the number of equilibrium stages is analogous to representing plug flow as a series of completely mixed flow reactors (CMFRs), as described in Chap. 6. It is assumed that equilibrium conditions prevail within each stage.

A mass balance on the lower section of a staged countercurrent tower shown in Fig. 14-15 is

$$QC_3 + Q_a Y_0 = QC_e + Q_a Y_4 \quad (14-30)$$

Assuming clean air enters the tower ($Y_0 = 0$) and rearranging Eq. 14-30,

$$Y_4 = \left(\frac{Q}{Q_a} \right) (C_3 - C_e) \quad (14-31)$$

The McCabe–Thiele (1925) graphical method for determining the number of equilibrium stages is demonstrated on Fig. 14-16 for a four-stage stripping tower. Both the operating line and the equilibrium line are shown on Fig. 14-16. The method for constructing the McCabe–Thiele diagram for finding the number of equilibrium stages or number of transfer units is described as follows:

1. The point (C_0, Y_e) represents the influent water-phase concentration and exiting air-phase concentration of the contaminant of interest at the top of the tower. Draw a horizontal line from the point (C_0, Y_e) to the point (C_1, Y_e) , which represents the

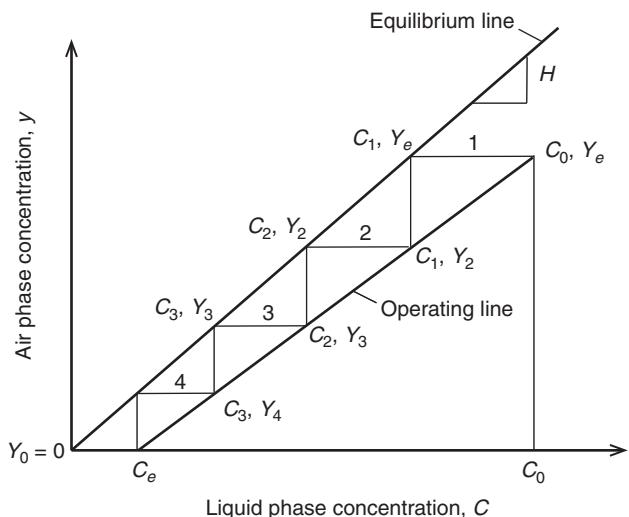


Figure 14-16
Operating line diagram for multistage stripping tower.

location where the water-phase concentration of the constituent is in equilibrium with the exiting air, as shown on Fig. 14-16.

2. Draw a vertical line from the point (C_1, Y_e) to the point (C_1, Y_2) on the operating line. The numerical value of Y_2 can be determined based on a mass balance around stage 1 shown on Fig. 14-16:

$$Y_2 = \left(\frac{Q}{Q_a} \right) C_1 + Y_e - \left(\frac{Q}{Q_a} \right) C_0 \quad (14-32)$$

3. Draw a horizontal line from the point (C_1, Y_2) on the operating line to the point (C_2, Y_2) on the equilibrium line.
4. Draw a vertical line from the point (C_2, Y_2) on the equilibrium line to the point (C_2, Y_3) on the operating line.
5. Draw a horizontal line from the point (C_2, Y_3) on the operating line to the point (C_3, Y_3) on the equilibrium line.
6. Draw a vertical line from the point (C_3, Y_3) on the equilibrium line to the point (C_3, Y_4) on the operating line.
7. Continue until point (C_n, Y_{n+1}) is reached and the effluent concentration C_e is surpassed.

If the final stage does not intersect the effluent concentration, then the minimum number of stages would include the stage that overshoots the effluent concentration. This procedure is used to estimate the minimum number of stages or transfer units, because equilibrium is not usually attained and additional stages are required beyond the minimum number.

The McCabe–Thiele method described above can also be used to determine the minimum number of trays required in low-profile air stripping, which is a countercurrent, staged process and is discussed in Sec. 14-6.

Design Equation for Determining Packed-Tower Height

Predicting the required height of a packed tower to meet a given air-stripping treatment objective is one of the goals of packed-tower design. The design equation for tower height can be derived using these assumptions: (1) steady-state conditions prevail in the tower, (2) air flow rate and water flow rate are constant through the column, (3) no chemical reactions occur, and (4) plug flow conditions prevail for both the air and water.

LIQUID-PHASE MASS BALANCE AROUND A DIFFERENTIAL ELEMENT

A liquid-phase mass balance around the differential element surrounded by a dashed box on Fig. 14-17a serves as the basis for the design equation. A schematic of the differential element applicable to the case of a liquid-side mass balance is presented on Fig. 14-17b.

The liquid-phase mass balance around the differential element is written in words as

$$\begin{aligned} & \text{Mass of organic entering per unit time} \\ & - \text{mass of organic leaving per unit time} \\ & + \text{mass of organic generated per unit time} \\ & = \text{mass of organic accumulated per unit time} \end{aligned} \quad (14-33)$$

Equation 14-33 can be written symbolically as

$$[QC_b(z + \Delta z)] - [QC_b(z)] + 0 - [J_A(a\Delta V)] = 0 \quad (14-34)$$

where

Q = water flow rate, m^3/s

C_b = bulk liquid-phase concentration, mg/L

z = axial position along tower, m

Δz = height of differential element, m

J_A = flux across air–water interface, $\text{mg}/\text{m}^2 \cdot \text{s}$

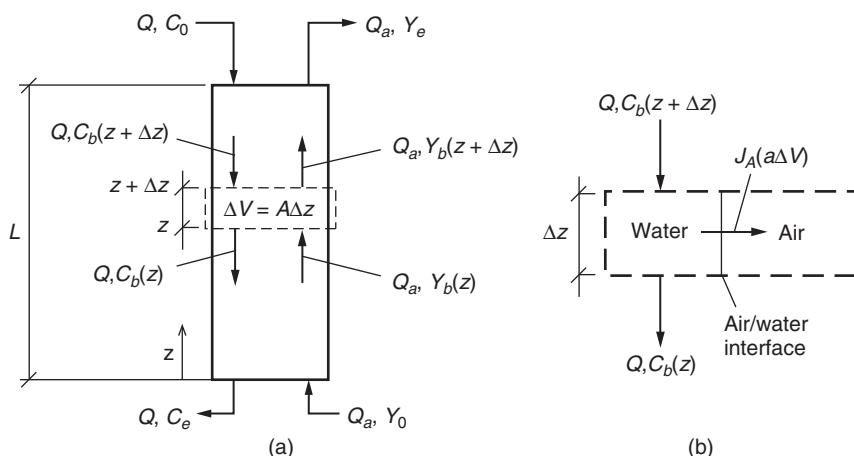


Figure 14-17
Packed-tower design equation definition drawing: (a) schematic of packed tower showing differential element and (b) schematic of differential element used in liquid-side mass balance.

a = area available for mass transfer divided by vessel volume,
 m^2/m^3

ΔV = volume of differential element, m^3

As shown in Chap. 7, the term J_A in Eq. 14-34 is obtained from the two-film theory:

$$J_A = K_L [C_b(z) - C_s^*(z)] \quad (14-35)$$

where K_L = overall liquid-phase mass transfer coefficient, m/s

$C_s^*(z)$ = liquid-phase concentration at air–water interface in equilibrium with the bulk gas-phase concentration, mg/L

Inserting Eq. 14-35 and $\Delta V = A \Delta z$ into Eq. 14-34 yields

$$[QC_b(z + \Delta z)] - [QC_b(z)] - \{K_L [C_b(z) - C_s^*(z)](aA \Delta z)\} = 0 \quad (14-36)$$

where A = cross-sectional area of packed tower, m^2

Rearranging Eq. 14-36 and dividing by $A \Delta z$ yields the equation

$$\frac{Q}{AK_L a} \left[\frac{C_b(z + \Delta z) - C_b(z)}{\Delta z} \right] = C_b(z) - C_s^*(z) \quad (14-37)$$

where $K_L a$ = overall mass transfer rate constant, s^{-1}

Taking the limit as Δz approaches zero results in

$$\frac{Q}{AK_L a} \lim_{\Delta z \rightarrow 0} \left[\frac{C_b(z + \Delta z) - C_b(z)}{\Delta z} \right] = \frac{Q}{AK_L a} \frac{dC_b}{dz} = [C_b(z) - C_s^*(z)] \quad (14-38)$$

Separating variables in Eq. 14-39 results in

$$\frac{Q}{AK_L a} \int_{C_e}^{C_0} \frac{dC_b}{C_b - C_s^*} = \int_0^L dz = L \quad (14-39)$$

where L = height of packed tower, m

C_0 = influent liquid-phase concentration, mg/L

C_e = treatment objective, mg/L

RELATING CONCENTRATION AT AIR–WATER INTERFACE TO CONCENTRATION IN BULK LIQUID

To solve Eq. 14-39, C_s^* needs to be expressed in terms of C_b . The following relationship, obtained by using the definition of C_s^* and the operating line, can be used:

$$C_s^* = \frac{Y_b}{H_{YC}} = \frac{Y_b(z)}{H_{YC}} \quad (14-40)$$

where Y_b = bulk gas-phase concentration, $Y_b(z)$, mg/L

Substituting Eq. 14-25 into Eq. 14-40 yields the desired result:

$$C_s^* = \frac{Y_b}{H_{YC}} = \frac{(Q/Q_a)(C_b - C_e)}{H_{YC}} \quad (14-41)$$

where Q_a = air flow rate, m^3/s

DETERMINATION OF TOWER HEIGHT

Substituting Eq. 14-41 into Eq. 14-39 results in the following:

$$L = \frac{Q}{AK_L a} \int_{C_e}^{C_0} \frac{dC_b}{C_b [1 - (Q/Q_a)/H_{YC}] + C_e (Q/Q_a)/H_{YC}} \quad (14-42)$$

$$= \frac{Q}{AK_L a} \left[\frac{1}{1 - (Q/Q_a)/H_{YC}} \right] \ln \left[C_b \left(1 - \frac{Q/Q_a}{H_{YC}} \right) + C_e \left(\frac{Q}{Q_a} \right) / H_{YC} \right]_{C_e}^{C_0} \quad (14-43)$$

$$= \frac{Q}{AK_L a} \left[\frac{1}{1 - (Q/Q_a)/H_{YC}} \right] \ln \left[\frac{C_0 + (C_e - C_0)(Q/Q_a)/H_{YC}}{C_e} \right] \quad (14-44)$$

Additional details on the development of the design equation for countercurrent packed-tower aeration may be found in the literature (Ball and Edwards, 1992; Ball et al., 1984; Cummins and Westrick, 1983; Dzombak et al., 1993; Gross and TerMaath, 1985; Hand et al., 1986; Kavanaugh and Trussell, 1980, 1981; McKinnon and Dyksen, 1984; Roberts and Levy, 1985; Roberts et al., 1985; Sherwood and Hollaway, 1940; Singley et al., 1980, 1981; Treybal, 1980; Umphres et al., 1983).

Expressing tower height in terms of stripping factor

Equation 14-44 can be further simplified using the definition of the stripping factor, $S = (Q_a/Q)H_{YC}$ (see Eq. 14-26):

$$L = \frac{Q}{AK_L a} \left[\frac{1}{1 - (1/S)} \right] \ln \left[\frac{(1/S)(C_e - C_0) + (C_0)}{C_e} \right] \quad (14-45)$$

$$= \frac{Q}{AK_L a} \left(\frac{S}{S - 1} \right) \ln \left[\frac{(C_e - C_0) + S(C_0)}{SC_e} \right] \quad (14-46)$$

The design equation for packed-tower aeration is given by

$$L = \frac{Q}{AK_L a} \left[\frac{S}{(S - 1)} \right] \ln \left[\frac{1 + (C_0/C_e)(S - 1)}{S} \right] \quad (14-47)$$

where L = packed-tower height, m

A = cross-sectional area of packed tower, m^2

$K_L a$ = overall liquid-phase mass transfer rate constant, $1/\text{s}$

S = stripping factor, dimensionless

C_0 = influent liquid-phase concentration, mg/L

C_e = treatment objective, mg/L

Expressing tower height in terms of transfer units

In packed-tower aeration, the tower length is often defined as

$$L = \text{HTU} \times \text{NTU} \quad (14-48)$$

where HTU = height of transfer unit, m

NTU = number of transfer units or number of equilibrium stages

With additional algebraic rearranging, the HTU and NTU are defined as

$$\text{HTU} = \frac{Q}{AK_L a} \quad (14-49)$$

$$\text{NTU} = \frac{S}{S-1} \ln \left[\frac{1 + (C_0/C_e)(S-1)}{S} \right] \quad (14-50)$$

The height of a transfer unit is determined by the superficial velocity (Q/A) divided by the overall mass transfer rate constant. For packed towers, the height of a transfer unit is a measure of the stripping effectiveness of particular packings for a given stripping process. Packing that is typically smaller in size has higher specific surface area causing more efficient transfer of solute from one phase to another, thereby increasing $K_L a$ and decreasing the HTU. The HTU and tower length will decrease as the superficial velocity decreases or the rate of mass transfer increases.

The number of transfer units can be thought of as a measure of the difficulty of stripping a solute from the liquid to the gas phase. The more difficult it is to strip the solute, the more NTUs needed to achieve a given removal efficiency. The number of transfer units in a packed column can be determined from Fig. 14-18, which is a plot of numerous solutions of Eq. 14-50. For a given S , the removal efficiency increases with increasing

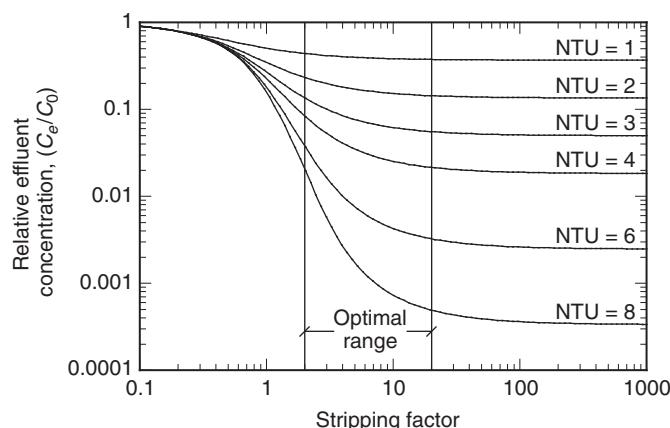


Figure 14-18
Dependence of relative effluent concentration on NTU and stripping factor.

NTU (or number of hypothetical completely mixed tanks). In addition, for a given removal efficiency, increasing S or the air-to-water ratio will decrease the NTU required. As shown on Fig. 14-18, the optimal range for the stripping factor might be considered between 2 and 20 because high removal efficiency is not possible at S less than 1, and no additional improvements in removal occurs at values of S greater than about 20. The best efficiency point for minimum power requirements and tower volume tends to occur at an air-to-water ratio of 3.5 times the minimum air-to-water ratio required for stripping, which would correspond to a low value of the stripping factor (Hand et al., 1986).

The NTU concept bridges the gap between continuous fluid contact and stage operation (see discussion in Chap. 7). For the hypothetical driving force shown on Fig. 14-19a, four equilibrium counter-current stages would be required to meet an effluent concentration of 2.5 mg/L for an influent concentration of 12.5 mg/L. The stripping factor and Henry's constant for this situation are 1.0 and 0.5, respectively.

The operating and equilibrium lines are parallel, and $C_b - C_s^*$ differs by exactly 2.5 mg/L, resulting in exactly four equilibrium stages. The NTU for continuous contact can be determined from this equation and the integration of $1/(C_b - C_s^*)$, which is shown on Fig. 14-19b:

$$\text{NTU} = \int_{C_e}^{C_0} \frac{dC_b}{C_b - C_s^*} \quad (14-51)$$

where $C_s^* = C_s^*(z)$ represents the liquid-phase concentration at the air-water interface in equilibrium with $Y_b(z)$ (see Eq. 14-41) in milligrams per liter and $C_b = C_b(z)$, which is defined above.

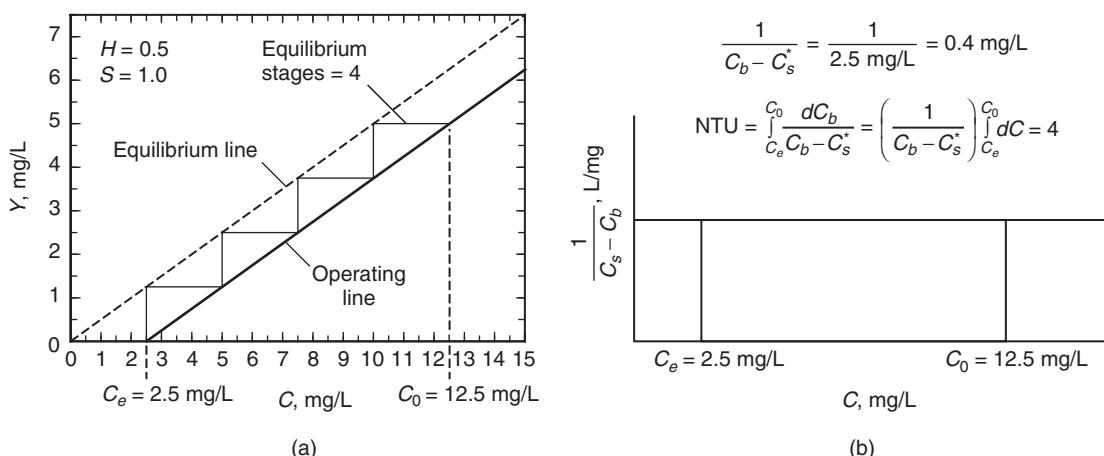


Figure 14-19

(a) Determination of the number of equilibrium stages (NTU) using an operating line diagram for a packed tower. (b) Sample integration to determine the number of transfer units (NTU).

In this case, the NTU for equilibrium stages and continuous contact are equal. In general, this will not be true, but this does establish the relationship between NTU and the number of equilibrium tanks in series. The HTU is the height of one equivalent stage at equilibrium.

14-5 Analysis and Design of Packed-Tower Air Stripping

The two main design categories for packed-tower air stripping are (1) modifications to existing towers (rating analysis) and (2) designing new towers (design analysis). Modifications are made to existing towers to either treat greater volumes of water or modify constituent removal (e.g., lower levels, different constituents). Process efficiency may be improved by increasing the air flow rate, decreasing the water flow rate, replacing the packing with a more efficient packing type, or increasing the packed-tower height. Designing new towers includes the selection of packing type, air-to-water ratio, gas pressure drop, and operational flexibility.

Because packed-tower analysis involves repetitive calculations and the opportunity for introducing errors, commercially available software is commonly used to evaluate the impact of process variables on process performance. Software design tools typically contain the design equations, Henry's constants, mass transfer correlations, databases for many commercially available packing types, and physical properties of many VOCs that have been encountered in water supplies. In addition, graphical user interfaces make the software user friendly (Dzombak et al., 1993; Hokanson, 1996).

Packed-tower air stripping is analyzed in this section including (1) determination of properties required to calculate packed-tower height, (2) description of process variables, and (3) representation of the equations applicable to design versus rating analysis of packed towers. The following design considerations for packed-tower air stripping are also discussed: (1) design variables, (2) design approach, and (3) factors influencing packed-tower performance.

To determine the packed-tower height as described above, the following properties are needed: (1) gas pressure drop, (2) cross-sectional area of the tower, and (3) mass transfer rate constant. Determination of the properties required to calculate packed-tower height is discussed below.

Properties Needed to Determine Packed-Tower Height

GAS PRESSURE DROP

The gas pressure drop in packed columns is an important design and operational parameter because the electrical costs of the blower account for a significant fraction of the operational costs. Consequently, it is important to operate at a low gas pressure drop to minimize the blower costs. Methods used to determine the gas pressure drop through the packing includes: pilot

and full-scale data collection, manufacturer's pressure drop specifications, and generalized Eckert pressure drop curves. Pressure drop data obtained from pilot and full-scale testing is the best way to determine the operating gas pressure drop. However, in many instances engineers use software programs and spreadsheets to design these systems because much of the design information is known or can be easily calculated.

Manufacturers provide gas pressure drop information on most all of their packing materials, which can be used to determine the pressure drop through the packing. The pressure drop of gas rising countercurrent to liquid flowing through a packed tower typically follows the pattern illustrated on Fig. 14-20. This pressure drop data is for Jaeger 3.5-in. nominal diameter Tripack plastic packing. The pressure drop per unit depth of packing is typically plotted in terms of a C factor, which is defined by the following equation:

$$\text{C factor} = V_S ((\rho_L - \rho_g)/(\rho_g))^{0.5} \quad (14-52)$$

where V_S = superficial gas velocity, m/s

ρ_g = gas density, kg/m³

ρ_L = liquid density, kg/m³

C factor is the density-corrected superficial gas velocity through the column packing and describes the balance between the gas momentum force, which acts to entrain bundles of liquid droplets, and the gravity force, which resists the upward entrainment of water (Kister et al., 2007). Given

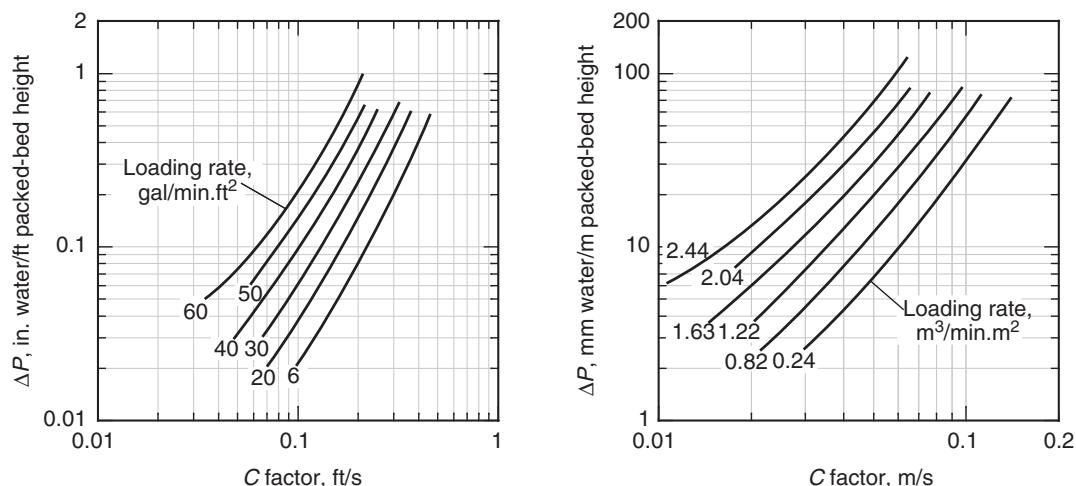


Figure 14-20

Gas pressure drop curves as a function of C factor for 3.5-in. nominal diameter plastic tripacks (Adapted from Jaeger Products, Brochure 600).

the temperature, packed-tower area, packing height, gas and liquid loading rates, Fig. 14-20 can be used to determine the pressure drop across the packing material. Manufacturers typically supply pressure drop information on their various packing materials.

When manufacturers data is not available, a common method of estimating the gas pressure drop through random packing in towers is the use of the generalized Eckert pressure drop correlation (see Fig. 14-21). The Eckert correlation relates the gas pressure drop to the capacity parameter on the ordinate (y axis) as a function of the flow parameter on the abscissa (x axis). For high gas loading rates, entrainment of the liquid by the rising gas can occur, characterized by a sudden rapid increase in the gas pressure drop, and eventually the column will become a flooded contactor because of the back pressure caused by the rising gas. However, as discussed above, most all air-stripping applications operate at low gas pressure drops to minimize energy costs associated with the blower operation and flooding is never a problem.

The Eckert correlation shown in Fig. 14-21 was developed based on data for packings such as small intalox saddles, rashig, and pall rings. Incorporated in the capacity parameter on the ordinate scale is an empirical parameter characteristic of the shape, size, and material property of the packing type and is called the packing factor (C_f). C_f has units of inverse length and is used to relate the packing type to the relative gas pressure drop through the packing in the tower. Figure 14-12 displays C_f values for several commonly used plastic packing types. Since C_f is incorporated in the numerator of the capacity parameter on the ordinate scale, packing

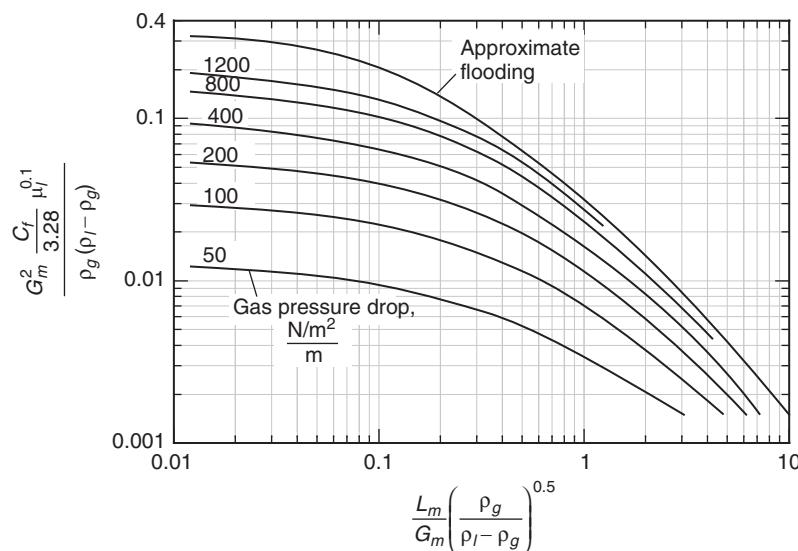


Figure 14-21
Generalized Eckert gas pressure drop and liquid and gas loading correlation in SI units for random packed tower. The coefficient 3.28 is a conversion factor when the packing factor in SI units (m^{-1}) is used because the Eckert diagram was originally drawn in English units. (Adapted from Eckert, 1961; Treybal, 1980).

materials with a higher C_f value will have a higher gas pressure drop than packing materials with a lower C_f value. In general, the gas pressure drop will increase with increasing packing factor.

The practical operating range for packed towers is between abscissa (x axis) values of 0.02 and 4.0 on the generalized Eckert pressure drop curves (see Fig. 14-21). For abscissa values greater than 4, large water loading rates can reduce the water-air contact area provided by the packing surface and inhibit proper airflow through the column, causing a decrease in removal efficiency. Similarly, high air flow rates (abscissa values less than about 0.02) can cause entrained water in the tower as well as channeling of the air through the tower. For situations where high air flow rates are required for high removal efficiencies (>95 percent), it is important to provide an even air inlet distribution at the bottom of the tower (Thom and Byers, 1993). Towers operating in the regions described above may require additional packing depth to compensate for efficiency reductions.

For an air-water system at 20°C and 1 atm and S value of 3, the dimensionless Henry's constants can only range from about 0.0021 to 0.42, corresponding to an abscissa between 0.02 and 4 on the Eckert curves. Thus, use of Fig. 14-21 for stripping tower design is restricted, and pilot studies are recommended for tower design when the abscissa values are greater than 4, unless manufacturer's data on gas pressure drop applies in that higher range. Nonvolatile compounds with Henry's constants below 0.0021 should not be used as the basis for a packed-tower aeration design given the difficulty of their removal in the air-stripping process.

In summary, the best method for evaluating gas pressure drop for a given design is from pilot or full-scale studies. If these studies are not available, the next best way would be to use manufacturer's data for gas pressure drop, followed by the use of the Eckert curves. The Eckert curves could be applied initially to estimate the tower diameter followed by the use of the manufacturers data to determine the actual pressure drop for the given tower diameter.

CROSS-SECTIONAL AREA

The cross-sectional area of a packed tower can be estimated from the generalized Eckert pressure drop curves shown on Fig. 14-21 (see above discussion of gas pressure drop). The gas loading rate, liquid loading rate, and tower area may be determined from Fig. 14-21 using the following procedure:

1. Specify the following design parameters:
 - a. Packing factor for the media (see Fig. 14-12)
 - b. Air-to-water ratio [typically 3.5 times $(Q_a/Q)_{\min}$]
 - c. Gas pressure drop (typically 50 N/m²/m)

2. Determine the value on the x axis on the Eckert curve shown on Fig. 14-21:

$$x = \left(\frac{1}{G_m/L_m} \right) \left(\frac{\rho_g}{\rho_l - \rho_g} \right)^{0.5} \quad (14-53)$$

where x = value on x axis on Eckert curve

G_m = air mass loading rate, $\text{kg}/\text{m}^2 \cdot \text{s}$

L_m = water mass loading rate, $\text{kg}/\text{m}^2 \cdot \text{s}$

ρ_g = air density, kg/m^3

ρ_l = water density, kg/m^3

The value of G_m/L_m can be determined knowing the air-to-water ratio, water density, and air density:

$$\frac{G_m}{L_m} = \left(\frac{Q_a}{Q} \right) \left(\frac{\rho_g}{\rho_l} \right) \quad (14-54)$$

3. Graphically determine the numerical value y on the y axis on the Eckert curve shown on Fig. 14-21 knowing the gas pressure drop and x .
4. Determine the gas loading rate based on the following relationship for the y -axis value on the Eckert curve shown on Fig. 14-21:

$$y = \frac{G_m^2 (C_f/3.28) \mu_l^{0.1}}{\rho_g (\rho_l - \rho_g)} \quad (14-55)$$

Rearrange Eq. 14-55 and solve for G_m :

$$G_m = \left[\frac{y \rho_g (\rho_l - \rho_g)}{(C_f/3.28) \mu_l^{0.1}} \right]^{0.5} \quad (14-56)$$

where y = numerical value on y axis of Eckert curve
determined in step 3

C_f = packing factor, m^{-1}

μ_l = dynamic viscosity of water, $\text{kg}/\text{m} \cdot \text{s}$

5. Determine the water mass loading rate based on the following relationship:

$$L_m = \frac{G_m}{(Q_a/Q)(\rho_g/\rho_l)} \quad (14-57)$$

6. Determine the cross-sectional area of the packed tower based on the following relationship:

$$A = \frac{Q \rho_l}{L_m} \quad (14-58)$$

where A = cross-sectional area of packed tower, m^2

Q = water flow rate, m^3/s

Correlations describing the Eckert pressure drop curves to predict gas loading rate and tower area were fit by Cummins and Westrick (1983). The Eckert pressure drop correlations are useful for performing packed-tower aeration design calculations using spreadsheets or computer programs, but the correlations are beyond the scope of this book.

Example 14-4 Diameter, area, and pressure drop of a packed tower

Determine the cross-sectional area and tower diameter for a packed-tower design based on 1,2-dichloropropane (DCP) at 10°C for a water flow rate Q of 0.1 m³/s (1585 gal/min). The basis for design is given by the operating air-to-water ratio of 60 (see Example 14-3), gas pressure drop $\Delta P/L = 50 \text{ N/m}^2 \cdot \text{m}$, and the 8.9-cm (3.5-in.) plastic tripacks. The physical properties of air and water at 10°C are as follows: water density $\rho_l = 999.7 \text{ kg/m}^3$, water viscosity $\mu_l = 1.307 \times 10^{-3} \text{ kg/m} \cdot \text{s}$, and air density, $\rho_g = 1.247 \text{ kg/m}^3$ (see Apps. B and C). The packing factor from Fig. 14-12, C_f , for 8.9-cm (3.5-in.) plastic tripacks is 39.0 m⁻¹. The dimensionless Henry's law constant of DCP is $H_{YC,DCP} = 0.0525$ (see Table 14-3).

Solution

1. Specify the packing factor, air-to-water ratio, and gas pressure drop.
 - a. *Packing factor:* Given in problem statement:

$$C_f = 39 \text{ m}^{-1}$$

- b. *Air-to-water ratio:* Determined in Example 14-3 for 90 percent removal:

$$\left(\frac{Q_a}{Q}\right)_{DCP} = 60$$

- c. *Gas pressure drop:* Given in problem statement:

$$\frac{\Delta P}{L} = 50 \text{ N/m}^2 \cdot \text{m}$$

2. Determine the value on the x axis on the Eckert curve shown on Fig. 14-21:

- a. Determine G_m/L_m using Eq. 14-54:

$$\begin{aligned} \frac{G_m}{L_m} &= \left(\frac{Q_a}{Q}\right) \left(\frac{\rho_g}{\rho_l}\right) = 60 \left(\frac{1.247}{999.7}\right) \\ &= 0.075 \text{ kg air/kg water} \end{aligned}$$

b. Determine x using Eq. 14-53:

$$x = \left[\frac{1}{(G_m/L_m)} \right] \left(\frac{\rho_g}{\rho_l - \rho_g} \right)^{0.5} = \left(\frac{1}{0.075} \right) \left(\frac{1.247}{999.7 - 1.247} \right)^{0.5} \\ = 0.47$$

3. Graphically determine the numerical value y on the y axis on the Eckert curve shown on Fig. 14-21 knowing the gas pressure drop and x . At the location on Fig. 14-21 where $x = 1.13$ and $\Delta P/L = 50 \text{ N/m}^2 \cdot \text{m}$,

$$y = 0.005$$

4. Determine the gas loading rate based on the relationship for the y -axis value on the Eckert curve shown on Fig. 14-21. Solve for G_m using Eq. 14-56:

$$G_m = \left[\frac{y \rho_g (\rho_l - \rho_g)}{(C_f/3.28) \mu_l^{0.1}} \right]^{0.5} = \left[\frac{0.005(1.247)(999.7 - 1.247)}{(39.0/3.28)(1.307 \times 10^{-3})^{0.1}} \right]^{0.5} \\ = 1.01 \text{ kg/m}^2 \cdot \text{s}$$

5. Determine the water mass loading rate using Eq. 14-57:

$$L_m = \frac{G_m}{(Q_a/Q)(\rho_g/\rho_l)} = \frac{1.01 \text{ kg/m}^2 \cdot \text{s}}{(60)(1.247 \text{ kg/m}^3/999.7 \text{ kg/m}^3)} \\ = 13.5 \text{ kg/m}^2 \cdot \text{s}$$

6. Determine the cross-sectional area of the packed tower using Eq. 14-58:

$$A = \frac{Q}{L_m} = \frac{(0.1 \text{ m}^3/\text{s})(999.7 \text{ kg/m}^3)}{13.5 \text{ kg/m}^2 \cdot \text{s}} \\ = 7.4 \text{ m}^2$$

7. Determine the tower diameter assuming a circular tower area.

$$D = \sqrt{\frac{4A^2}{\pi}} = \sqrt{\frac{4(7.4 \text{ m}^2)}{\pi}} = 3.07 \text{ m}$$

Standard tower sizes of 1.22 m (4 ft), 1.83 m (6 ft), 2.44 m (8 ft), 3.048 m (10 ft), 3.66 m (12 ft), and sometimes 4.27 m (14 ft) in diameter are usually the norm for most packed-tower equipment manufacturers. For this case we will use a 3.048-m (10-ft) diameter tower. For a tower diameter of 3.048 m, the operating values of G_m and L_m are 1.02 kg/m² · s and 13.7 kg/m² · s, respectively.

8. Determine the tower gas pressure drop based on the manufacturer's data presented in Fig. 14-20.

- a. Calculate the C-factor from Eq. 14-52,

$$\begin{aligned} \text{C factor} &= V_S ((\rho_L - \rho_g)/(\rho_g))^{0.5} \\ &= \left(\frac{1.02 \text{ kg/m}^2 \cdot \text{s}}{1.247 \text{ kg/m}^3} \right) (999.7 - 1.247/1.247)^{0.5} \\ &= 0.03 \text{ m/s} \end{aligned}$$

- b. Calculate the liquid loading rate in $\text{L/m}^2 \cdot \text{min}$ for a tower diameter of 3.048 m (10 ft):

$$\frac{Q}{A} = \frac{0.1 \text{ m}^3/\text{s}}{\pi (3.048 \text{ m})^2/4} \frac{1000 \text{ L}}{\text{m}^3} \frac{60 \text{ s}}{\text{min}} = 822 \frac{\text{L}}{\text{m}^2 \cdot \text{min}}$$

- c. Determine the relative head loss through the packing using Fig. 14-20.

For a C factor of 0.03 m/s and a volumetric liquid loading of 822 $\text{L/m}^2 \cdot \text{min}$, the head loss per unit length of packing is about 4.5 mm water per m of packing height or 44 $\text{N/m}^2 \cdot \text{m}$. In this case the gas pressure drop determined from the Eckert correlation is in close agreement with the manufacturer's gas pressure drop data.

Comment

If multiple compounds are to be removed, the compound with the lower Henry's law constant in the water to be treated is used as the basis for determining the cross-sectional area of the tower, because it will require the highest air-to-water ratio to have a stripping factor in the optimal range.

MASS TRANSFER RATE CONSTANT

The general equation for calculating the overall mass transfer rate constant $K_L a$ in aeration processes was derived earlier based on the two-film theory of mass transfer in Chap. 7:

$$\frac{1}{K_L a} = \frac{1}{k_l a} + \frac{1}{H_{YC} k_g a} \quad (7-88)$$

where $K_L a$ = overall mass transfer rate constant, s^{-1}

k_l = liquid-phase mass transfer coefficient, m/s

k_g = gas-phase mass transfer coefficient, m/s

a = area available for mass transfer divided by vessel volume, m^2/m^3

The K_{La} values for packed towers can be determined by performing pilot plant studies or from packing manufacturers and previously reported field studies. They can also be estimated from mass transfer correlations.

Determination by pilot plant studies

A pilot plant study is the preferred way to determine K_{La} for a given VOC in water, but, as discussed below, fairly accurate estimates can be made from the correlations. Pilot-scale packed towers range in size from 2 to 6 m (6.5 to 20 ft) in height and 0.3 to 0.6 m (1 to 2 ft) in diameter. The column diameter used will depend upon the desired packing size. It is generally recommended that ratios of column diameter to nominal packing diameter be greater than 10:1 (>15:1 desired) to minimize error caused by channeling of the water down the walls of the column (Treybal, 1980). It is also recommended that the packed-column height-to-diameter ratio be greater than 1:1 to provide for proper liquid distribution (Treybal, 1980; Roberts et al., 1985).

Equation 14-48 is used in conjunction with pilot plant data to determine K_{La} for a given VOC. The value of K_{La} is based on VOC removal due to the packed height portion of the tower. However, VOC removal also occurs as the water contacts the air above the packing at the top of the tower and at the bottom as the water falls into the clearwell below the packing. This incidental additional removal is sometimes referred to as "end effects" (Umphres et al., 1983). To determine the K_{La} , $NTU_{measured}$ is plotted versus the packing height and the NTU value corresponding to zero packing depth is referred to as $NTU_{end\ effects}$ (dimensionless):

$$NTU_{measured} = \left(\frac{1}{HTU} \right) \times Z + NTU_{end\ effects} \quad (14-59)$$

where Z = distance from top of packing to sample port location
along packed portion of tower, L

For a given water and air loading rate, aqueous-phase concentration measurements are evaluated at the influent, effluent, and various sample port locations along the packed column and $NTU_{measured}$ is calculated from Eq. 14-50. The plot of $NTU_{measured}$ versus Z should result in a straight line (Eq. 14-59), and K_{La} is determined from the slope (1/HTU). Experimentally determined K_{La} values can be correlated as a function of water loading rate for several air-to-water ratios that would be expected during operation of the full-scale column. The full-scale packed-tower height can be determined from K_{La} and the design equations.

A full-scale packed-tower height calculated using a K_{La} value determined from a pilot study is generally conservative. For a given packing size, K_{La} values generally increase as the tower diameter increases (Roberts et al., 1985). The increase is caused by minimizing channeling of the water down the inside of the column walls (wall effects), which occurs to a greater degree in small columns. The VOC removal rate is lower along the walls

Table 14-6Packed-tower air-stripping pilot plant studies that determined $K_L a$ values for several VOCs

Water Matrix	VOCs	Reference
Sacramento–San Joaquin Delta water in northern California	Chloroform, dibromochloromethane, bromodichloromethane, bromoform	Umphres et al. (1983)
Potomac tidal fresh estuary water mixed with nitrified effluent wastewater	Carbon tetrachloride, tetrachloroethene, trichloroethene, chloroform, bromoform	Ball et al. (1984)
City of Tacoma, WA, groundwater	1,1,2,2-Tetrachloroethane, trans-1,2-dichloroethene, trichloroethene, tetrachloroethene	Byers and Morton (1985)
Laboratory-grade organic free water	Oxygen, tetrachloroethene, Freon-12, 1,1,1-trichloroethane, trichloroethene, carbon tetrachloride	Roberts et al. (1985)
North Miami Beach, FL, groundwater and City of Gainsville, FL, groundwater	Chloroform	Bilello and Singley (1986)
Village of Brewster, NY, groundwater	cis-1,2-Dichloroethene, trichloroethene, tetrachloroethene	Wallman and Cummins (1986)
Gloucester, Ottawa, Ontario, groundwater	Chloroform, toluene, 1,2-dichloroethane, 1,1-dichloroethane, trichloroethene, diethyl ether	Lamarche and Droste (1989)
Miami, FL, tap water	Bromoform, bromodichloromethane, chloroform, dibromochloromethane, carbontetrachloride, tetrachloroethene, trichloroethene, 1,1,1-trichloroethane, chlorobenzene, m-dichlorobenzene, m-xylene, toluene	Narbaitz et al. (2002)

of the column than within the packing because the air/water contact time, surface area, and mixing are smaller. As the tower diameter increases, the percentage of flow down the walls of the column decreases, minimizing the wall effects.

Based on the results from several packed-tower field studies (see Table 14-6), experimentally determined $K_L a$ values for several VOCs and various contaminated water sources can be obtained. The $K_L a$ values reported in these studies can be used to design towers if the operating conditions (temperature, water and air loading rate) and packing type and size are identical.

Estimation with empirical correlations

From an evaluation of available mass transfer models for packed-tower aeration (Onda et al., 1968; Sherwood and Hollaway, 1940; Shulman et al., 1955), it has been found that the Onda model or a modification of it provides the best predictions of mass transfer coefficients (Lamarche and Droste, 1989; Djebbar and Narbaitz, 1995, 1998). For several VOCs, it has been demonstrated that $K_L a$ values obtained from the Onda correlations compare favorably to pilot plant data using smaller packing sizes (Cummins

and Westrick, 1983; Roberts et al., 1985). The Onda correlations for determination of the liquid-phase mass transfer coefficient (k_l), gas-phase mass transfer coefficient (k_g), and specific interfacial area (a) are presented in Chap. 7. The packing properties needed for the Onda correlations are shown in Fig. 14-12. The Onda correlations were developed for nominal packing sizes up to 5.1 cm (2 in.).

Studies have found that the Onda correlations for mass transfer coefficients overestimate the $K_L a$ values for larger packing sizes [greater than 2.5 cm (1 in.) nominal diameter] (Djebbar and Narbaitz, 1995; Lenzo et al., 1990; Thom and Byers, 1993; Dvorak et al., 1996). Djebbar and Narbaitz (1998) modified the Onda model in an effort to improve its predictive capabilities. The modified Onda model included recalibration to a new extensive set of mass transfer data that included adjustments to the constants and exponents in the model, incorporation of an additional dimensionless parameter (L/d_p) into the liquid-phase mass transfer correlation k_l , and incorporation of the gas-phase Reynolds number (RE_g) and the packing efficiency number (a/d_p) into the interfacial area equation. As compared to the Onda model, the modified Onda model reduced the average absolute error to 21 percent as compared to 30 percent for the Onda model, which is about a 30 percent reduction in the error. The modified Onda model requires a trial-and-error method for design because an initial guess of the tower length is needed to calculate the k_l . More recently Dejebar and Narbaitz (2002) used neural network nonparametric approach to analyze gas and liquid mass transfer data from packed tower technology to predict $K_L a$ values. They were able to improve upon the predictions for $K_L a$ with an average absolute error of less than 19 percent, which is perhaps the best prediction to date. Unfortunately, it would be too time consuming for design engineers to use this technique to obtain $K_L a$ values.

At present, there is no correlation that can be used to predict $K_L a$ within ± 10 percent for larger packing sizes. Thus, based on the literature cited above, it is recommended that a safety factor of 0.70 (design $K_L a$ /Onda $K_L a$) be applied for packing diameters greater than 2.5 cm (1 in.) as a conservative estimate of packing height required.

Example 14-5 Mass transfer coefficients in packed-tower aeration

Determine the mass transfer coefficients for DCP and PCE at 10°C in packed-tower aeration for the air mass loading rate and water mass loading rate determined in Example 14-4 using the Onda correlations and a safety factor of 0.70 (design $K_L a$ /Onda $K_L a$) for 8.9 cm (3.5 in.) plastic tripacks. The water flow rate, Q , is 0.1 m³/s (1585 gal/min). The physical properties of air and water from Apps. B and C at 10°C are water density $\rho_l = 999.7$

kg/m^3 , the dynamic viscosity of water $\mu_l = 1.307 \times 10^{-3} \text{ kg/m} \cdot \text{s}$, water surface tension $\sigma = 0.0742 \text{ N/m}$, air density $\rho_g = 1.247 \text{ kg/m}^3$, and air viscosity $\mu_g = 1.79 \times 10^{-5} \text{ kg/m} \cdot \text{s}$. The properties of the packing material from Fig. 14-12 are nominal diameter of packing $d_p = 0.0889 \text{ m}$, packing factor $C_f = 39.0 \text{ m}^{-1}$, specific surface area of packing $a_t = 125.0 \text{ m}^2/\text{m}^3$, and critical surface tension of packing $\sigma_c = 0.033 \text{ N/m}$. The liquid diffusivity D_l and gas diffusivity D_g for DCP and PCE were determined from the Hayduk–Laudie correlation and the Wilke–Lee modification of the Hirschfelder–Bird–Spotz method, respectively, to be equal to $D_{l,\text{DCP}} = 6.08 \times 10^{-10} \text{ m}^2/\text{s}$, $D_{l,\text{PCE}} = 5.86 \times 10^{-10} \text{ m}^2/\text{s}$, $D_{g,\text{DCP}} = 7.65 \times 10^{-6} \text{ m}^2/\text{s}$, and $D_{g,\text{PCE}} = 7.13 \times 10^{-6} \text{ m}^2/\text{s}$ (see Chap. 7). From Example 14-4, the air loading rate G_m and water loading rate L_m are equal to 1.02 and $13.7 \text{ kg/m}^2 \cdot \text{s}$, respectively. As obtained in Table 14-3 at 10°C , the dimensionless Henry's law constants of DCP and PCE are $H_{Y,\text{DCP}} = 0.0525$ and $H_{Y,\text{DCE}} = 0.364$.

Solution

- Calculate the specific surface area available for mass transfer a_w , which is determined from the Onda correlations (see Table 7-5):

$$a_w = a_t \left\{ 1 - \exp \left[-1.45 \left(\frac{\sigma_c}{\sigma} \right)^{0.75} \left(\frac{L_m}{a_t \mu_l} \right)^{0.1} \left(\frac{L_m^2 a_t}{\rho_l^2 g} \right)^{-0.05} \left(\frac{L_m^2}{\rho_l a_t \sigma} \right)^{0.2} \right] \right\}$$

$$= 125 \left\{ 1 - \exp \left[\begin{aligned} & -1.45 \left(\frac{0.0330}{0.0742} \right)^{0.75} \left(\frac{13.7}{125.0 \times 1.307 \times 10^{-3}} \right)^{0.1} \\ & \times \left(\frac{13.7^2 \times 125.0}{999.7^2 \times 9.81} \right)^{-0.05} \\ & \times \left(\frac{13.7^2}{999.7 \times 125.0 \times 0.0742} \right)^{0.2} \end{aligned} \right] \right\}$$

$$= 67 \text{ m}^2/\text{m}^3$$

- Calculate the liquid-phase mass transfer coefficient k_ℓ using the Onda correlations (see Table 7-5).

a. DCP:

$$k_\ell = 0.0051 \left(\frac{L_m}{a_w \mu_l} \right)^{2/3} \left(\frac{\mu_l}{\rho_l D_l} \right)^{-0.5} (a_t d_p)^{0.4} \left(\frac{\rho_l}{\mu_l g} \right)^{-1/3}$$

$$= 0.0051 \left\{ \left[\frac{13.7}{67 \times (1.307 \times 10^{-3})} \right]^{2/3} \left[\frac{1.307 \times 10^{-3}}{999.7 \times (6.08 \times 10^{-10})} \right]^{-0.5} \right. \\ \left. \times (125.0 \times 0.0889)^{0.4} \left[\frac{999.7}{(1.307 \times 10^{-3}) \times 9.81} \right]^{-1/3} \right\} \\ = 1.95 \times 10^{-4} \text{ m/s}$$

b. PCE:

$$k_\ell = 0.0051 \left(\frac{L_m}{a_w \mu_l} \right)^{2/3} \left(\frac{\mu_l}{\rho_l D_l} \right)^{-0.5} (a_t d_p)^{0.4} \left(\frac{\rho_l}{\mu_l g} \right)^{-1/3} \\ = 0.0051 \left\{ \left[\frac{13.7}{67 \times (1.307 \times 10^{-3})} \right]^{2/3} \left[\frac{1.307 \times 10^{-3}}{999.7 \times (5.87 \times 10^{-10})} \right]^{-0.5} \right. \\ \left. \times (125.0 \times 0.0889)^{0.4} \left[\frac{999.7}{(1.307 \times 10^{-3}) \times 9.81} \right]^{-1/3} \right\} \\ = 1.92 \times 10^{-4} \text{ m/s}$$

3. Calculate the gas-phase mass transfer coefficient k_g using the Onda correlations (see Table 7-5).

a. DCP:

$$k_g = 5.23 (a_t D_g) \left(\frac{G_m}{a_t \mu_g} \right)^{0.7} \left(\frac{\mu_g}{\rho_g D_g} \right)^{1/3} (a_t d_p)^{-2} \\ = 5.23 \left\{ \left[125.0 \times (7.65 \times 10^{-6}) \right] \left[\frac{1.02}{125.0 \times (1.79 \times 10^{-5})} \right]^{0.7} \right. \\ \left. \times \left[\frac{1.79 \times 10^{-5}}{1.247 \times (7.65 \times 10^{-6})} \right]^{1/3} (125.0 \times 0.0889 \text{ m})^{-2} \right\} \\ = 3.63 \times 10^{-3} \text{ m/s}$$

b. PCE:

$$k_g = 5.23 (a_t D_g) \left(\frac{G_m}{a_t \mu_g} \right)^{0.7} \left(\frac{\mu_g}{\rho_g D_g} \right)^{1/3} (a_t d_p)^{-2} \\ = 5.23 \left\{ \left[125.0 \times (7.13 \times 10^{-6}) \right] \left[\frac{1.02}{125.0 \times (1.79 \times 10^{-5})} \right]^{0.7} \right. \\ \left. \times \left[\frac{1.79 \times 10^{-5}}{1.247 \times (7.13 \times 10^{-6})} \right]^{1/3} (125.0 \times 0.0889 \text{ m})^{-2} \right\} \\ = 3.46 \times 10^{-3} \text{ m/s}$$

4. Calculate the overall mass transfer rate constant $K_L a$ based on a_w , k_l , and k_g from the Onda correlations using Eq. 7-88.

a. DCP:

$$\begin{aligned}\frac{1}{K_L a} &= \frac{1}{k_1 a_w} + \frac{1}{k_g a_w H_{YC}} \\ &= \frac{1}{(1.95 \times 10^{-4}) \times 67} + \frac{1}{(3.63 \times 10^{-3}) \times 67 \times 0.0525} \\ \Rightarrow K_L a &= 0.00645 \text{ s}^{-1} \quad (\text{based on Onda correlations})\end{aligned}$$

b. PCE:

$$\begin{aligned}\frac{1}{K_L a} &= \frac{1}{k_1 a_w} + \frac{1}{k_g a_w H_{YC}} \\ &= \frac{1}{(1.92 \times 10^{-4}) \times 67} + \frac{1}{(3.46 \times 10^{-3}) \times 67 \times 0.364} \\ \Rightarrow K_L a &= 0.011 \text{ s}^{-1} \quad (\text{based on Onda correlations})\end{aligned}$$

5. Calculate actual $K_L a$ applying a safety factor (SF) of 0.70 on the Onda $K_L a$.

a. DCP:

$$\begin{aligned}K_L a &= K_L a(\text{Onda}) \times (\text{SF}) = (0.00645 \text{ s}^{-1}) \times 0.70 \\ &= 0.00452 \text{ s}^{-1}\end{aligned}$$

b. PCE:

$$\begin{aligned}K_L a &= K_L a(\text{Onda}) \times (\text{SF})_{K_L a} = (0.011 \text{ s}^{-1}) \times 0.70 \\ &= 0.0077 \text{ s}^{-1}\end{aligned}$$

Power Requirements

The total operating power for a single air-stripping packed-tower system is the sum of the blower and pump brake power requirements. The blower brake power P_{blower} can be determined from the following relationship (Tchobanoglou et al., 2003):

$$P_{\text{blower}} = \left(\frac{G_{\text{me}} R T_{\text{air}}}{\text{MW} n_a \text{Eff}_b} \right) \left[\left(\frac{P_{\text{in}}}{P_{\text{out}}} \right)^{0.283} - 1 \right] \quad (14-60)$$

where P_{blower} = blower brake power, kW

Eff_b = blower net efficiency, expressed as decimal fraction, which accounts for both fan and motor on blower

G_{me} = mass flow rate of air, kg/s

n_a = constant used in determining blower brake power,
= 0.283 for air

P_{in} = inlet air pressure in packed tower (bottom of tower),
atm or N/m²

P_{out} = outlet air pressure in packed tower (top of the tower),
usually equal to ambient pressure, atm or N/m²

R = universal gas constant, 8.314 J/mol · K

T_{air} = absolute air temperature, typically assumed equal to
 T , K (273 + °C)

T = absolute water temperature, K (273 + °C)

MW = molecular weight of air, 28.97 g/mol

The term P_{in} refers to the pressure at the bottom of the tower, which is the inlet for the airstream:

$$P_{in} = P_{ambient} + [(\Delta P/L) \times L] + \Delta P_{losses} \quad (14-61)$$

where $P_{ambient}$ = ambient pressure, atm or N/m²

ΔP = pressure drop caused by packing media, atm or N/m²

L = packing height, m

ΔP_{losses} = pressure drop by demister, packing support plate,
duct work, inlet and outlet of tower, atm or N/m²

The pressure drop ΔP_{losses} may be estimated by using the empirical constant k_p , which was determined by fitting full-scale tower data (Hand et al., 1986):

$$\Delta P_{losses} = \left(\frac{Q_a}{A} \right)^2 k_p \quad (14-62)$$

where Q_a = volumetric air flow rate, m³/s

A = tower cross-sectional area, m²

k_p = empirical constant, 275 N · s²/m⁴

The air pressure drop through the demister, packing support plate, duct work, and inlet and outlet of the tower is accounted for in Eq. 14-62. It is assumed that turbulent-flow conditions prevail and most of the losses occur in the tower (i.e., in the packing support plate and the demister).

The pump power requirement can be determined from the equation

$$P_{pump} = \frac{\rho_l Q H g}{Eff_p} \quad (14-63)$$

where P_{pump} = power required to pump water to top of tower, W

ρ_l = water density, kg/m³

Q = water flow rate, m^3/s

H = vertical distance from pump to liquid distributor at top of tower, m

g = acceleration due to gravity, 9.81 m/s^2

Eff_p = pump efficiency, expressed as fraction

Equation 14-63 only accounts for the additional head required to pump the water to the top of the tower.

Example 14-6 Power requirements for packed-tower aeration

Determine the total power requirement (blower and pump brake power) and specific energy per unit volume of water treated for a packed tower aeration design removing DCP at 10°C and 1 atm ($101,325 \text{ N/m}^2$) for a water flow rate of $0.1 \text{ m}^3/\text{s}$, a stripping factor of 3.5, and a gas pressure drop of $50 \text{ (N/m}^2\text{)}/\text{m}$. Assume the blower efficiency is 35 percent ($\text{Eff}_b = 0.35$) and the pump efficiency is 80 percent ($\text{Eff}_p = 0.80$).

From Example 14-4, the air-to-water ratio $Q_a/Q = 60$ and the tower area $A = 7.3 \text{ m}^2$ (based on a 3.048-m (10-ft) tower diameter). From Example 14-7, the tower length $L = 7.8 \text{ m}$. The water density and air density at 10°C are $\rho_l = 999.7 \text{ kg/m}^3$ and $\rho_g = 1.247 \text{ kg/m}^3$.

Solution

1. Calculate blower power requirements.
 - a. Calculate the air mass flow rate from the volumetric air flow rate.
 - i. Calculate volumetric air flow rate Q_a :

$$\begin{aligned} Q_a &= \left(\frac{Q_a}{Q} \right) Q = (60)(0.1 \text{ m}^3/\text{s}) \\ &= 6.0 \text{ m}^3/\text{s} \end{aligned}$$

- ii. Calculate the air mass flow rate G_{me} :

$$\begin{aligned} G_{me} &= Q_a \rho_g = (6.0 \text{ m}^3/\text{s})(1.247 \text{ kg/m}^3) \\ &= 7.48 \text{ kg/s} \end{aligned}$$

- b. Calculate the pressure drop through the demister, the packing support plate, duct work, and inlet and outlet (ΔP_{losses}) using Eq. 14-62:

$$\begin{aligned} \Delta P_{losses} &= \left(\frac{Q_a}{A} \right)^2 k_p = \left(\frac{6.0 \text{ m}^3/\text{s}}{7.3 \text{ m}^2} \right)^2 (275 \text{ N} \cdot \text{s}^2/\text{m}^4) \\ &= 186 \text{ N/m}^2 \end{aligned}$$

- c. Calculate the inlet pressure to the packed tower, P_{in} , using Eq. 14-61:

$$\begin{aligned} P_{in} &= P_{ambient} + \left(\frac{\Delta P}{L} \right) L + \Delta P_{losses} = 101,325 \text{ N/m}^2 \\ &+ \left\{ [(50 \text{ N/m}^2)/m] \times 7.66 \text{ m} \right\} + 186 \text{ N/m}^2 \\ &= 101,894 \text{ N/m}^2 \end{aligned}$$

- d. Calculate the blower brake power P_{blower} using Eq. 14-60:

$$\begin{aligned} P_{blower} &= \left(\frac{G_{me}RT_{air}}{\text{MW } n_a \text{ Eff}_b} \right) \left[\left(\frac{P_{in}}{P_{out}} \right)^{n_a} - 1 \right] \\ &= \left[\frac{(7.48)(8.314) \times (273 + 10)}{(28.97)(0.283)(0.35)} \right] \left[\left(\frac{101,894}{101,325} \right)^{0.283} - 1 \right] \\ &= 9.73 \text{ kW} \end{aligned}$$

2. Calculate pump power requirements P_{pump} to move the water to the top of the tower using Eq. 14-63:

$$\begin{aligned} P_{pump} &= \frac{\rho_l Q L g}{\text{Eff}_p} \\ &= \left[\frac{(999.7 \text{ kg/m}^3)(0.1 \text{ m}^3/\text{s})(7.8 \text{ m})(9.81 \text{ m/s}^2)}{0.80} \right] \left(\frac{1 \text{ W}}{1 \text{ kg} \cdot \text{m}^2/\text{s}^3} \right) \\ &= 9,561 \text{ W} = 9.56 \text{ kW} \end{aligned}$$

3. Calculate total power requirements P_{total} :

$$P_{total} = P_{blower} + P_{pump} = 9.56 \text{ kW} + 9.73 \text{ kW} = 19.3 \text{ kW}$$

4. Calculate the specific energy:

$$E = \frac{19.3 \text{ kW}}{(0.1 \text{ m}^3/\text{s}) (3600 \text{ s/h})} = 0.0536 \frac{\text{kWh}}{\text{m}^3}$$

There are two types of analyses commonly performed for packed-tower air stripping, termed *design analysis* and *rating analysis*. In a design analysis, it is desired to *size a new packed tower* to exactly meet the treatment objective C_{TO} . Substituting $C_{TO} = C_e$ into Eq. 14-47 results in the design equation for packed tower aeration:

$$L = \frac{Q}{AK_{La}} \left(\frac{S}{S-1} \right) \ln \left[\frac{1 + (C_0/C_{TO})(S-1)}{S} \right] \quad (14-64)$$

Design versus Rating Analysis of Packed Towers

where L = packed tower height, m
 Q = water flow rate, m^3/s
 A = cross-sectional area of packed tower, m^2
 $K_L a$ = overall liquid-phase mass transfer rate constant, s^{-1}
 S = stripping factor, dimensionless
 C_0 = influent liquid-phase concentration, mg/L
 C_{TO} = treatment objective, mg/L

Estimation of mass transfer rate constant $K_L a$ and cross-sectional area A for packed-tower air stripping is described above.

In a rating analysis, the effluent concentrations of various compounds *for an existing tower* can be determined. The following variables are known in a rating analysis: (1) tower height, (2) tower diameter, (3) type of packing, (4) water flow rate, (5) air flow rate, (6) pressure, (7) temperature, (8) influent concentration, and (9) mass transfer coefficient. Knowing these variables, it is possible to determine effluent concentration and gas pressure drop for the tower. The effluent concentration is found by rearranging Eq. 14-47 and solving for effluent concentration C_e :

$$C_e = \frac{C_0(S - 1)}{S \exp[LK_L a(S - 1)/(Q/A)S] - 1} \quad (14-65)$$

where C_e = effluent liquid-phase concentration, mg/L

In a rating analysis, the pressure drop for the tower can be calculated using an iterative method based on correlations for the Eckert curves.

Design Variables

Design variables for packed-tower air stripping include (1) the air-to-water ratio, (2) the gas pressure drop, and (3) the type of packing material. Once the physical properties of the contaminant(s) of interest, the influent concentration(s), treatment objective(s), water, and air properties are known, design parameters can be selected to obtain the lowest capital and operation and maintenance costs.

AIR-TO-WATER RATIO

It has been shown that air-to-water ratios of approximately 3.5 times the minimum air-to-water ratio provide the minimum tower volume and power requirement, which corresponds to a stripping factor of about 3.5 for a range of Henry's law constants from 0.003 to 0.3 (Hand et al., 1986).

GAS PRESSURE DROP

A low gas pressure drop should be chosen to minimize the blower power consumption. Packed towers are usually designed to operate with a gas pressure drop well below flooding conditions. Many stripping towers are designed for gas pressure drops of 200 to 400 (N/m^2)/m of packing depth (0.25 to 0.5 in. $\text{H}_2\text{O}/\text{ft}$ of packing) (Treybal, 1980). Based on detailed

cost analyses, it has been found that using a lower gas pressure drop between 50 and 100 (N/m^2)/m and a stripping factor of 3.5 yields the lowest total annual treatment cost for removal of volatile compounds with dimensionless H_{YC} values greater than 0.05 (Cummins and Westrick, 1983; Dzombak et al., 1993; Hand et al., 1986). Towers have been constructed with gas pressure drops as low as 30 (N/m^2)/m, but gas pressure drops that are too low may result in very low liquid loading and poor water distribution across the packing, which will reduce the area available for mass transfer and tower performance.

An additional advantage of operating at a low gas pressure drop is that, if the blower is sized conservatively, the air flow rate can be increased to improve removal efficiency without major changes in the process operation. However, the required tower height may sometimes be too large for a particular application (mostly for aesthetic reasons, the local community may object to tall towers). To obtain a smaller tower height for a given removal, the air-to-water ratio can be increased.

TYPE AND SIZE OF PACKING MATERIAL

The competing requirements of a low gas pressure drop and high surface area available for mass transfer per vessel volume must be weighed when selecting packing because the preferred packing characteristics work against each other as high surface area per volume causes higher gas pressure drop. The surface area per volume and packing factor for commonly available packing materials are reported on Fig. 14-12. For a given type of packing, the packing factor and surface area increase as the size of packing decreases. However, different types of packing can have lower packing factors for the same surface area per volume. For example, the 75-mm (3-in.) saddles and 50-mm (2-in.) tripacks have packing factors of 16 and 15, respectively, and yet the tripacks have 76 percent more surface area per volume because of their unique shape, which is shown on Fig. 14-12. A packing material with a low packing factor and a high specific surface area is desired for optimal tower performance.

Tower volume and power requirements have been compared for a number of packing types and sizes reported in Fig. 14-12. The comparisons show that the type of packing media does not have a large impact on the tower volume or the total operating power requirements. However, it has been shown for the same type of packing (e.g., plastic tripacks), smaller nominal diameters result in lower tower volume and power requirements (Hand et al., 1986).

A major concern with respect to choosing the type and size of packing is the possibility of calcium, iron, and manganese precipitates forming on the packing during extended periods of operation and causing reduced removals and higher gas pressure drops, which is discussed in this section. To alleviate precipitation problems, larger packing sizes, which have smaller specific surface area, may be preferable because there would be less

surface area upon which precipitate can form as well as larger spaces for airflow.

The criteria for choosing the type and size of packing will depend upon the water flow rate and the desired degree of operational flexibility of the design. For small water flow rates, it is recommended that nominal diameter packing of 50 mm (2 in.) or less be used to minimize channeling or short circuiting of the water down the wall of the tower. Minimizing the impact of channeling requires that the ratio of tower diameter to nominal packing diameter be greater than 10:1 ($> 15:1$ is desired).

Design Approach

In most situations in water treatment, multiple contaminants are present in the water, and the packed tower must be designed to remove all the contaminants to some specified treatment level. At the design stage, the limiting contaminant that controls the design must first be determined. In general, the contaminant with the lowest Henry's constant is used to determine the required air-to-water ratio and the contaminant with the highest removal efficiency is used to determine the required packing height.

Once the influent concentration of the organic contaminant, treatment objective, flow rate, and design temperature are known, the following steps are followed for design:

1. Select an efficient packing material that is expected to give good mass transfer at low gas head loss. For the selected packing, determine head loss and mass transfer characteristics from commercially available data. Based on the data provided in Table 14-5, tripacks and lantec packing are among the best packing material.
2. Select a gas-phase pressure drop per unit tower length. A value of $50 \text{ N/m}^2/\text{m}$ usually provides an economical choice and the largest flexibility.
3. Select an operating air-to-water ratio. For most situations, an operating air-to-water ratio that is 3.5 times the minimum air-to-water ratio required for stripping provides the most economical design. For multicomponent systems, the compound with the lowest Henry's constant is used to calculate the operating air-to-water ratio.
4. Given the packing type, stripping factor, and gas pressure drop, the gas loading rate, liquid loading rate, and tower diameter can be determined based on the Eckert curve.
5. Compare the liquid loading rate to allowable liquid loading rates in commercially available equipment. If the liquid loading rate exceeds recommended values, reduce the gas pressure drop and repeat the computation. If the liquid loading rate is less than recommended values, increase the gas pressure drop and repeat the computation.
6. Determine the K_{La} from the Onda correlation using a safety factor of 0.70.

7. Determine the HTU from Eq. 14-49.
8. Determine the NTU from Eq. 14-50. For multicomponent systems, the contaminant with the highest degree of removal is used to determine the NTU.
9. Determine the height of the tower from Eq. 14-48. Typical packed-tower heights usually do not exceed about 9.0 m (30 ft). Should the calculated tower length exceed 9.0 m, the air-to-water ratio could be increased by increasing the air flow rate to achieve the same treatment objective but with a smaller tower height.
10. Repeat for various values of the stripping factor and the gas pressure drop and determine the optimum or least-cost design. The optimal design will usually be obtained with an operating air-to-water ratio equal to 3.5 times the minimum air-to-water ratio required for stripping and a gas pressure drop of 50 N/m²/m.
11. At this point, preliminary design is complete and a pilot test should be conducted to be certain that the mass transfer correlations are correct.
12. Once the mass transfer parameters are confirmed to be correct, the design can be finalized by examining the operational flexibility of the system.

Several of these steps have been demonstrated in previous examples. Calculation of HTU, NTU, and height of the tower is demonstrated in Example 14.7.

Example 14-7 Height of a packed tower

Determine the packed-tower height required to remove DCP and PCE at 10°C for a water flow rate Q of 0.1 m³/s (1585 gal/min). The basis for design is DCP removal, gas pressure drop $\Delta P/L = 50 \text{ N/m}^2 \cdot \text{m}$, and 8.9-cm (3.5-in.) plastic tripacks. From Table 14-3, the dimensionless Henry's constants of DCP and PCE at 10°C are $H_{YC,DCP} = 0.0525$ and $H_{YC,PCE} = 0.364$. As shown in Example 14-4, the air-to-water ratio is determined based on the contaminant with lower Henry constant, DCP, and a factor of $3.5(Q_a/Q)_{\min,DCP} = 60$. From Example 14-4, the tower area based on DCP (the compound with the lower Henry constant), for the conditions described above, is 7.3 m² [based on a tower diameter of 3.048 m (10 ft)]. From Example 14-5, the actual liquid-phase mass transfer rate constants after applying a safety factor of 0.70 on the Onda $K_L a$ values for DCP and PCE at 10°C for the conditions described above are $K_{La,DCP} = 0.0045 \text{ s}^{-1}$ and $K_{La,PCE} = 0.0077 \text{ s}^{-1}$. The influent concentrations of DCP and PCE are $C_{0,DCP} = 40 \mu\text{g/L}$ and $C_{0,PCE} = 35 \mu\text{g/L}$. Both DCP and PCE have a treatment objective C_e equal to 5 $\mu\text{g/L}$.

Solution

1. The tower length is calculated based on the compound with the greatest of removal requirement which is DCP
- a. Calculate the stripping factor, S, from Eq. 14-26:

$$S = \frac{Q_a}{Q} H_{YC} = (60)(0.0525) = 3.15$$

- b. Calculate the height of a transfer unit, HTU, using Eq. 14-49:

$$\text{HTU} = \frac{Q}{AK_L a_{DCP}} = \frac{0.1 \text{ m}^3/\text{s}}{(7.3 \text{ m}^2)(0.0045 \text{ s}^{-1})} = 3.04 \text{ m}$$

- c. Calculate the number of transfer units, NTU, using Eq. 14-50:

$$\begin{aligned} \text{NTU} &= \frac{S}{S-1} \ln \left[\frac{1 + (C_0/C_e)(S-1)}{S} \right] \\ &= \frac{3.15}{3.15-1} \ln \left[\frac{1 + (40/5)(3.15-1)}{3.15} \right] \\ &= 2.57 \end{aligned}$$

- d. Calculate the packed-tower height L using Eq. 14-48:

$$L = (\text{HTU})(\text{NTU}) = (2.57 \text{ m})(3.04) = 7.8 \text{ m}$$

2. Determine the effluent concentration of PCE for the given design tower area and height to make sure it meets its treatment objective.

- a. Calculate the stripping factor for PCE given the air-to-water ratio and Henry's constant using Eq. 14-26:

$$S_{\text{PCE}} = \left(\frac{Q_a}{Q} \right) H_{YC,\text{PCE}} = (60)(0.364) = 21.8$$

- b. Calculate the effluent concentration C_e of PCE using Eq. 14-65:

$$\begin{aligned} C_e &= \frac{C_{0,\text{PCE}}(S_{\text{PCE}} - 1)}{S_{\text{PCE}} \exp[LK_L a_{\text{PCE}}(S_{\text{PCE}} - 1)/(Q \times S_{\text{PCE}}/A)] - 1} \\ &= \frac{(35 \mu\text{g/L})(21.8 - 1)}{21.8 \exp[(7.8 \text{ m})(0.0077 \text{ s}^{-1})(21.8 - 1)/[(0.1 \text{ m}^3/\text{s})(21.8)/(7.3 \text{ m}^2)]] - 1} \\ &= 0.51 \mu\text{g/L} \end{aligned}$$

Comments

The design based on DCP for this example resulted in both components meeting their treatment objectives. While calculation of tower height based on the compound with the highest removal efficiency is suggested as a

guideline, there are cases where the guideline will break down because tower height depends on more than just removal efficiency (see Eqs. 14-49 to 14-51) and a design based on the compound with the higher removal efficiency may not allow the treatment objectives of the other compounds to be met. The situation described above is particularly likely to occur if the compound with the highest removal efficiency has a dimensionless Henry's law constant much higher than one or more of the other compounds. The examples in this chapter demonstrate that the design of countercurrent packed towers is a computationally-intensive process. The spreadsheet identified as Resource E10 at the website listed in App. E can be used to perform the calculations.

Packed-tower performance may be impacted by environmental conditions such as water temperature and water quality such as dissolved solids.

TEMPERATURE

Temperature influences both the rate of mass transfer and Henry's constant and thus impacts equipment size, as well as the removal efficiency, in an existing packed tower. A packed tower that is designed to meet treatment objectives at one temperature may not be able to achieve the same treatment objectives at a lower temperature, as shown in Table 14-7. For example, if the temperature decreases from 15 to 5°C, the effluent concentration increases threefold. The information in Table 14-7 is based on a packed tower designed with the following specifications:

1. Trichloroethylene removal with an influent concentration of 100 µg/L = 95 percent. The 95 percent removal value is used to determine the NTU, as shown in Eq. 14-50
2. Design temperature 15°C
3. $H_{YC} = 0.282$
4. $Q_a/Q = 12$

Factors Influencing Packed-Tower Performance

Table 14-7
Effect of temperature on packed-tower operation

Temperature T , °C	$C_{E,T}/C_{E,15^\circ\text{C}}$
0	5.2
5	3.3
10	2.0
15	1
20	0.45

5. Packing: Plastic tripacks = 0.089 m (3.5 in.)
6. Flow rate 0.095 m³/s (1500 gal/min)
7. Pressure drop 50 N/m²/m

DISSOLVED SOLIDS

During operation of a packed tower, dissolved inorganic chemicals such as calcium, iron, and manganese may precipitate onto packing media, which can cause a pressure drop increase and a void volume decrease in the tower. The main methods for controlling the negative effects of chemical precipitates are cleaning the precipitate off the packing and controlling precipitate formation.

Precipitate potential

The potential for fouling of packing material by precipitates is especially great in waters containing appreciable amounts of carbon dioxide. Ground-water often contains 30 to 50 mg/L of carbon dioxide. Carbon dioxide can be removed in an air-stripping tower, particularly at high air-to-water ratios, but removal of carbon dioxide tends to raise the pH of the water. As pH increases, bicarbonate is converted to carbonate. In natural waters containing significant quantities of calcium ion, calcium carbonate will precipitate when the carbonate ion concentration is high enough that the solubility product of calcium carbonate is surpassed.

Based on a dimensionless Henry's constant for carbon dioxide of 1.3 at 25°C (calculated using data given in Table 14-4) and the fact that air contains about 0.035 percent by volume of carbon dioxide, the aqueous concentration of carbon dioxide in equilibrium with air can be determined as 0.48 mg/L. The concentration of free carbon dioxide can be reduced to its equilibrium concentration with air via air stripping. The amount of carbonate in the tower effluent depends on both the final carbon dioxide contration and the pH.

Since carbon dioxide (carbonic acid when in solution) is a weak acid, the rate of stripping depends on the apparent Henry's law constant and pH as presented earlier in this chapter. As carbon dioxide is stripped, the pH will rise and the rate of total carbonate stripping will decrease as water flows through the packing. Acid-base chemistry can be incorporated into the design equations presented earlier in this chapter to develop equations that predict the rate of carbonate stripping and pH of the tower effluent (Howe and Lawler, 1989). Once the tower effluent pH is known, the maximum amount and rate of precipitation that will result in fouling of the tower can be estimated using theoretical precipitation calculations [e.g., using a chemical equilibrium model such as MINTEQA2 (U.S. EPA, 1999) or Visual MINTEQ (Gustafsson, 2002)]. Because the free carbon dioxide concentration is most often reduced to a level greater than the concentration in equilibrium with air, the time taken to foul the tower will be much longer than predicted by the theoretical maximum precipitation

calculations. Pilot plant testing is the only method available for determining the actual precipitation rate.

Cleaning

Plastic packing can be removed periodically and put into a tumbler so that the precipitate can be broken off. Acid treatment dramatically deteriorates the plastic packing (making it very brittle) over time and is not recommended. In some instances, conditioning chemicals may be necessary to add to the cleaning process because precipitates can form within weeks in hard water.

Controlling precipitate

Larger packing size, which has smaller specific surface area, may be preferable because there is less surface area upon which precipitate can form as well as larger spaces for airflow. Controlling precipitation with scale inhibitors represents a significant cost in certain situations; therefore, the potential for precipitation must be carefully analyzed.

14-6 Analysis of Low-Profile Air Strippers

Over the past 20 years, low-profile air stripping has become increasingly common. Unit compactness is a key advantage of low-profile air strippers compared to packed towers. Design guidelines for low-profile air strippers, including a comparison with countercurrent packed-tower air strippers, are presented in the following discussion.

A schematic of a low-profile air stripper, which consists of a stack of sieve trays with contaminated water entering the top of the unit and exiting the bottom as treated water and clean air entering the bottom of the unit and exiting at the top containing VOCs, is shown on Fig. 14-8. The operation of a low-profile air stripper has been described by Treybal (1980), and several other researchers have expanded upon that seminal work to explain sieve tray (low-profile) air-stripping columns in detail (LaBranche and Collins, 1996; Mead and Leibbert, 1998; Nothakun et al., 1994; U.S. ACE, 2001). Low-profile air strippers operate as a countercurrent process with water entering at the top of the unit and flowing across each sieve tray, as shown on Fig. 14-8a. Inlet and outlet channels or downcomers are placed at the ends of each tray to allow the water to flow from tray to tray. Fresh air flows upward from a blower positioned beneath the bottom tray through perforated holes into a water layer on each tray. Large air flow rates are typically used, causing very small bubbles or frothing to form upon air contact with the water. The frothing provides a high air–water surface area for mass transfer to occur. Low-profile air stripping can be described conceptually as a countercurrent, staged operation, as demonstrated on Fig. 14-8b.

Description

Both packed towers and low-profile air strippers are capable of providing greater than 99 percent removal of most VOCs. There are numerous advantages and disadvantages of low-profile air strippers when compared to packed towers. Advantages include the following:

- ❑ *Unit Compactness.* Because the water flows horizontally across each tray, augmenting the length or width of the trays, instead of the height of the unit, will increase the removal efficiency. A typical low-profile air stripper is less than 3 m (10 ft) tall, whereas packed towers are often on the order of 8 m (26 ft) in height. There are many situations when architectural or height restrictions require use of a compact, low-profile air stripper even when cost analysis favors a packed tower.
- ❑ *Fouling.* Low-profile air strippers are less susceptible to fouling by inorganics because there is no packing. Low-profile air strippers are also much easier to disassemble and clean, compared to packed towers, as the trays are stackable and can be easily removed for cleaning.

Disadvantages include:

- ❑ *Narrow Range of Air Flow Rates.* A low-profile air stripper must operate under a narrow range of air flow rates. If the air flow rate is too high, a flooding condition results. If the air flow rate is too low, water will flow through the holes in the sieve trays, a condition known as weeping. Because of the importance of operating the low-profile air stripper under proper conditions, it is necessary that the manufacturer design the sieve tray columns to assure proper performance. Because the air flow rate is finely tuned by the manufacturer, it is not possible to adjust the air flow rate downward should the amount of water treated decrease. In contrast, the air flow rate for a packed tower can be more readily adjusted should a shift in water flow rate occur.
- ❑ *Higher Air-to-Water Ratios.* The air-to-water ratio required for a low-profile air stripper is on the order of 100 to 900 (LaBranche and Collins, 1996), compared to a typical air-to-water ratio of 30 for a packed tower. The higher air flow rate for low-profile air strippers is an important consideration, especially when off-gas treatment is required. The higher air-to-water ratio for low-profile air strippers will result in higher costs to operate the blower due to a higher pressure drop and higher costs to treat the off-gas.
- ❑ *Foaming.* If the water has a tendency to foam, then packed-tower aeration must be used.

Design Approach

Design equations for low-profile air stripping are not currently available in the literature. The diffused aeration approach is not applicable because of the frothing that occurs in low-profile air stripping. An empirical Fickian approach to mass transfer was applied to low-profile air stripping, and it was shown that the mass transfer rate constants for low-profile air stripping of

TCE and PCE compare favorably to mass transfer rate constants of VOCs in packed-tower aeration and mechanical aeration (LaBranche and Collins, 1996).

The following methods are available for determining the size of a low-profile air stripper:

- Analytical equations: Treybal (1980)
- Manufacturer-supplied software: Carbonair Environmental Systems (2003); North East Environmental Products (2003).
- McCabe–Thiele graphical method: See Sec. 14-4

A description of the recommended method for preliminary sizing of a low-profile air stripper from the U.S. ACE (2001) design manual follows:

1. Determine the minimum and maximum volume of water to be treated, the minimum temperature of the water, and the maximum concentration of VOCs in the untreated water.
2. Determine the desired concentration (percent removed) of the VOCs in the treated water.
3. Calculate the theoretical number of sieve trays needed to remove the VOCs to the desired concentration.
4. Estimate the tray efficiency and the number of actual trays needed.
5. Estimate the size (cross-sectional area) of the perforated plate section of each tray.
6. Estimate the pressure drop through the air stripper.
7. Estimate the size of the air blower motor (in kilowatts).

The McCabe–Thiele graphical approach for determining the number of equilibrium stages (theoretical trays) for low-profile air stripping was discussed in Sec. 14-4. It is also possible to determine the number of theoretical trays from the following relationship (Li and Hsiao, 1990; Treybal, 1980):

$$N_{\text{th}} = \frac{\ln[1 + (C_0/C_{\text{TO}})(S - 1)]}{\ln(S)} - 1 \quad (14-66)$$

where N_{th} = number of theoretical trays

S = stripping factor, dimensionless

C_0 = influent liquid-phase concentration, mg/L

C_{TO} = treatment objective, mg/L

Once the number of theoretical trays is known, the number of actual trays can be calculated based on the tray efficiency:

$$N_{\text{act}} = \frac{N_{\text{th}}}{\text{Eff}_{\text{tray}}} \quad (14-67)$$

where N_{act} = number of actual trays

Eff_{tray} = tray efficiency, expressed as decimal fraction

Example 14-8 Low-profile air stripping

Determine the actual number of trays needed for a low-profile air stripper compared to the theoretical number of trays for the following conditions. The influent concentration of PCE is 15 mg/L and the treatment objective is 0.005 mg/L. The water flow rate is 0.003 m³/s (48 gpm) and the water temperature is 10°C. The air flow rate is 0.7 m³/s (1500 cfm). The dimensionless Henry's constant of PCE at 10°C is equal to 0.364.

Solution

1. Calculate the theoretical number of sieve trays required to remove the compound to the desired concentration.
 - a. Determine air-to-water ratio and the stripping factor:

$$\frac{Q_a}{Q} = \frac{0.7 \text{ m}^3/\text{s}}{0.003 \text{ m}^3/\text{s}} = 233 \quad S = \frac{Q_a}{Q} \times H_{YC,PCE} = 233 \times 0.364 = 85$$

- b. Use Eq. 14-66 to determine the number of theoretical trays:

$$N_{th} = \frac{\ln[1 + (C_0/C_{T0})(S - 1)]}{\ln(S)} - 1$$

$$= \frac{\ln[1 + (15/0.005)(85 - 1)]}{\ln(85)} - 1 = 1.8$$

- c. The appropriate number of theoretical trays is thus equal to 2.
2. Determine the number of actual trays using Eq. 14-67. Use a tray efficiency of 0.5, which is within the appropriate range of 0.4 to 0.6:

$$N_{act} = \frac{N_{th}}{\text{Eff}_{tray}} = \frac{2}{0.5} = 4$$

Comment

The actual number of trays needed for low-profile air stripping is greater than the theoretical number of trays by a factor of approximately 2 based on manufacturer's data.

Based on manufacturers' data, an appropriate Eff_{tray} value appears to be in the range of 0.4 to 0.6 (U.S. ACE, 2001).

14-7 Analysis of Spray Aerators

Spray towers and spray fountains are the two main types of spray aerators. A fixed grid of nozzles is used to either spray water in towers (spray

towers) or spray water vertically into the air from the water surface (spray fountains), as shown on Fig. 14-5. The primary type of spray aerator used in water treatment is a fountain spray aerator, which is popular because existing reservoirs and large basins may be readily retrofit with them. When used in reservoirs and large basins, spray aerators are used to strip taste- and odor-causing compounds from raw water stored in reservoirs, oxygenate groundwater to remove iron and manganese, and strip VOCs. Spray fountain aerators are considered in this section; spray towers are discussed in Sec. 14-8.

Air–water contact occurs by spraying fine water droplets from pressurized nozzles into the air, which creates a large air–water surface for mass transfer. Three types of pressurized spray nozzles are typically used in water treatment applications: (1) hollow cone, (2) full cone, and (3) fan spray (see Fig. 14-22). Full-cone nozzles create a uniform pattern of droplets over the entire angle of spray, while hollow-cone nozzles create a circular pattern of droplets, primarily around the circumference of the angle of spray. Although hollow-cone nozzles do not distribute droplets as well as full-cone nozzles and have a larger pressure drop requirement, hollow cones are generally preferred over full cones because they create smaller diameter drops and have a larger nozzle orifice. Hollow-cone spray nozzles are also prone to plugging and may require strainers upstream of the nozzle to discourage nozzle plugging.

Contaminant removal occurs during the time the water droplet is in contact with the air, so the basis for spray aeration design equations is the mass transfer from the droplet across the air–water interface. A mass balance on water droplets of equal size and equal air exposure is given in words in Eq. 14-68 and mathematically in Eq. 14-69 (Hand et al., 1999):

$$\frac{\text{Mass lost from water drop per unit time}}{\text{Mass transferred across air–water interface of water drop per unit time}} = \text{ (14-68)}$$

Description

Design Approach

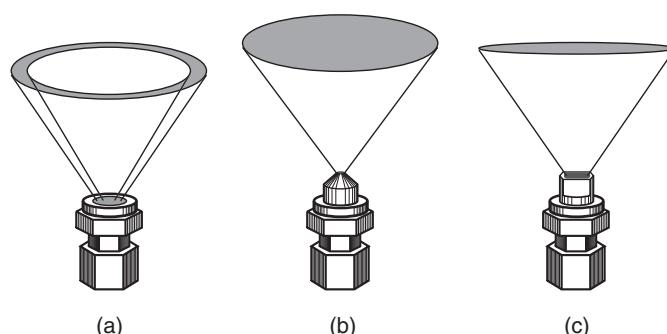


Figure 14-22
Common spray nozzles: (a) hollow cone, (b) full cone, and (c) fan spray.

$$V_d \frac{dC}{dt} = K_L a [C(t) - C_s(t)] V_d \quad (14-69)$$

where V_d = volume of drop, m^3
 K_L = overall mass transfer coefficient, m/s
 a = interfacial surface area available for mass transfer for water drop, m^2/m^3
 $C(t)$ = concentration in water drop at time t , mg/L
 $C_s(t)$ = concentration at air–water interface at time t , mg/L

The gas-phase contaminant concentration in the open air is assumed to be zero, and the concentration at the air–water interface, C_s , is assumed to be in equilibrium with the air, so it is also zero. The final contaminant concentration of the water drop after exposure to air may be determined by rearranging Eq. 14-69 and integrating over the time the drop is exposed to the air:

$$C_e = C_0 e^{-K_L a \theta} \quad (14-70)$$

where C_e = final contaminant concentration of water drop after being exposed to air, mg/L
 C_0 = initial contaminant liquid-phase concentration of drop before being exposed to air, mg/L
 θ = time of contact between water drop and air, s

The time of contact between the water drop and the air, θ , is dependent upon the exiting velocity and trajectory and can be estimated from the equation

$$\theta = \frac{2v_d \sin \alpha}{g} \quad (14-71)$$

where α = angle of spray measured from horizontal, deg
 g = acceleration due to gravity, 9.81 m/s^2
 v_d = exit velocity of water drop from nozzle, m/s

The exit velocity v_d can be determined using the orifice equation

$$v_d = C_v \sqrt{2gh} \quad (14-72)$$

where C_v = coefficient of velocity for orifice, unitless
 h = total head of nozzle, m

The coefficient of velocity C_v is provided by the nozzle manufacturer and typically varies from 0.4 to 0.65. The area of flow is typically less than the nozzle area so the flow rate Q may be calculated by using a revised form of Eq. 14-72, as shown in the equation

$$Q_n = C_d A_n \sqrt{2gh} \quad (14-73)$$

where Q_n = flow rate through nozzle, m^3/s

A_n = area of nozzle opening, m^2

C_d = coefficient of discharge from nozzle, which is supplied by nozzle manufacturer, unitless

The overall mass transfer coefficient may be computed from either Eq. 14-74 or Eq. 14-75, depending on the value of the dimensionless quantity $[2(D_l\theta)^{0.5}/d_d]$ (Calvert et al., 1972; Higbie, 1935; Jury, 1967):

$$K_L = \begin{cases} 2 \left(\frac{D_l}{\pi\theta} \right)^{1/2} & \text{for } \frac{2(D_l\theta)^{1/2}}{d_d} < 0.22 \\ \frac{10D_l}{d_d} & \text{for } \frac{2(D_l\theta)^{1/2}}{d_d} > 0.22 \end{cases} \quad (14-74)$$

where K_L = overall mass transfer coefficient, m/s

d_d = Sauter mean diameter (SMD) of water drop, equal to total volume of spray divided by total surface area, m

D_l = contaminant liquid diffusivity, m^2/s

θ = contact time of water drop with air, s

The Sauter mean diameter is a design parameter provided by the nozzle manufacturers. The area on the water droplets that is available for mass transfer can be calculated as

$$a = \frac{6}{d_d} \quad (14-76)$$

where a = interfacial surface area available for mass transfer, m^2/m^3

Example 14-9 Spray aeration

It is necessary to strip carbon dioxide, CO_2 , from a groundwater. Determine the number of nozzles required and the expected carbon dioxide removal efficiency for treating the water with a spray aeration system. The groundwater has a temperature of 25°C and a dissolved CO_2 concentration of 100 mg/L . The water is pumped from the well at a flow rate of $0.050 \text{ m}^3/\text{s}$, and the pump has the capacity to deliver an additional 30 m of head. The nozzle manufacturer has supplied the following data: $\text{SMD} = 0.0010 \text{ m}$, $\alpha = 90^\circ$, $C_v = 0.45$, $C_d = 0.25$, nozzle diameter = 0.0125 m . Refer to Table 7-1 in Chap. 7 for diffusion coefficients.

Solution

1. Determine the number of nozzles required.

- a. Calculate the area of one nozzle:

$$A_n = \left(\frac{1}{4} \pi \right) (0.0125 \text{ m})^2 = 1.2 \times 10^{-4} \text{ m}^2$$

- b. Calculate the flow rate through one nozzle, Q_n , using Eq. 14-73:

$$Q_n = C_d A_n \sqrt{2gh} = 0.25(1.2 \times 10^{-4} \text{ m}^2) \sqrt{2(9.81 \text{ m/s}^2)(30 \text{ m})} \\ = 7.3 \times 10^{-4} \text{ m}^3/\text{s}$$

- c. The number of nozzles can be calculated by dividing the total flow by the flow through each nozzle:

$$\text{Required number of nozzles} = \frac{Q}{Q_n} = \frac{0.050 \text{ m}^3/\text{s}}{7.3 \times 10^{-4} \text{ m}^3/\text{s}} = 68$$

2. Determine the CO₂ removal efficiency.

- a. Calculate the velocity of the water exiting the nozzle, v_d , using Eq. 14-72:

$$v_d = C_v \sqrt{2gh} = 0.45 \sqrt{2(9.81 \text{ m/s}^2)(30 \text{ m})} = 11 \text{ m/s}$$

- b. Determine the contact time of the water drop with the air, t , using Eq. 14-71:

$$\theta = \frac{2v_d \sin \alpha}{g} = \frac{2(11 \text{ m/s}) \sin(90^\circ)}{9.81 \text{ m/s}^2} = 2.2 \text{ s}$$

- c. Calculate the overall liquid-phase mass transfer coefficient K_L . From Table 7-1, the liquid-phase diffusion coefficient of CO₂ is $2.0 \times 10^{-9} \text{ m}^2/\text{s}$.

- i. Calculate the dimensionless quantity $2(D_l\theta)^{1/2}/d_d$:

$$\frac{2(D_l\theta)^{1/2}}{d_d} = \frac{2[(2.0 \times 10^{-9} \text{ m}^2/\text{s})(2.2 \text{ s})]^{1/2}}{0.0010 \text{ m}} = 0.13 < 0.22$$

- ii. Because the dimensionless quantity determined in the previous step is less than 0.22, calculate the overall liquid-phase mass transfer coefficient K_L using Eq. 14-74:

$$K_L = 2 \left(\frac{D_l}{\pi \theta} \right)^{0.5} = 2 \left(\frac{2.0 \times 10^{-9} \text{ m}^2/\text{s}}{\pi \times 2.2 \text{ s}} \right)^{0.5} \\ = 3.4 \times 10^{-5} \text{ m/s}$$

- d. Calculate the interfacial area for mass transfer, a , using Eq. 14-76:

$$a = \frac{6}{d_d} = \frac{6}{0.0010 \text{ m}} = 6.0 \times 10^3 / \text{m}$$

- e. Calculate $K_L a$:

$$K_L a = (3.4 \times 10^{-5} \text{ m/s})(6.0 \times 10^3 / \text{m}) \\ = 0.20 \text{ s}^{-1}$$

- f. Calculate the effluent liquid-phase CO₂ concentration after stripping using Eq. 14-70:

$$C_e = C_0 e^{-K_L a \times \theta} = (100 \text{ mg/L}) e^{-0.20 \text{ s}^{-1} \times 2.2 \text{ s}} \\ = 64 \text{ mg/L}$$

- g. Calculate the carbon dioxide removal efficiency due to stripping:

$$\text{Carbon dioxide removal efficiency} = \frac{C_0 - C_e}{C_0} \times 100 \\ = \frac{100 - 64}{100} = 36\%$$

14-8 Other Air-Stripping and Aeration Processes

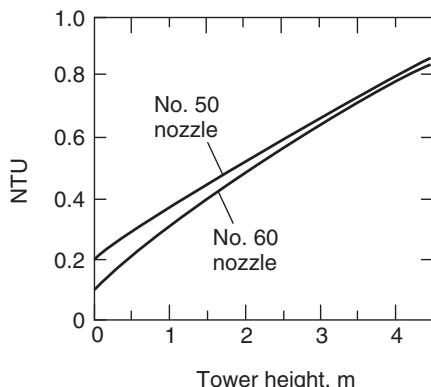
Other types of air-stripping and aeration processes, such as spray towers, diffused aerators, and mechanical aerators, are introduced and discussed briefly in this section.

There are a variety of configurations in which spraying can be used. Some configurations are analogous to packed-tower designs, and some are more complex designs, which are typically used for air pollution control such as cyclone scrubbers and Venturi scrubbers. Historically, spray systems have been used in water treatment for aeration, degasification of well water, and odor removal.

Spray Towers

Only a few studies of spray towers have been conducted on mass transfer in clean-water systems. Based on these studies, it has been found that spray systems are limited with respect to the removals that can be achieved, and a substantial portion of removal in a spray system may occur at the nozzle. Typically, one to three transfer units are reported as a maximum limit that can be achieved in spraying systems. The apparent limitation in percent removal is the product of backmixing of air and spray disturbance due to wall or adjacent spray contact (Davies and Ip, 1981; Ip and Raper, 1977; Pigford and Pyle, 1951).

The NTU as a function of the height of the spray tower is shown on Fig. 14-23. The residual NTU at zero height, in this case between 0.1 and 0.2 transfer units, is the result of the removal occurring at the nozzle. Some process designs may take advantage of the removal occurring at the nozzles by recycling flow or by incorporating several banks of nozzles. The aforementioned nonideal effects have hindered development of a general empirical design model. With the data presently available, a spray tower cannot be designed for a precise removal. Rather, the design approach

**Figure 14-23**

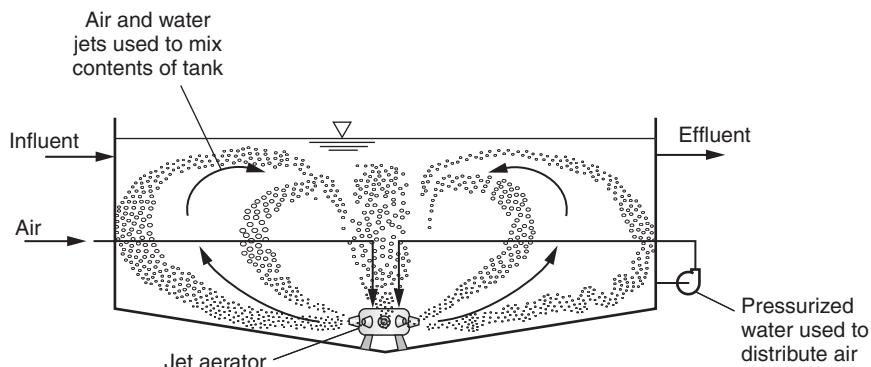
Number of transfer units in pilot spray tower as function of tower height
(Adapted from Davies and Ip, 1981).

serves merely as a basis to estimate the approximate removal efficiency of a spray system.

Diffused Aeration

The diffused, or bubble, aeration process consists of contacting water with gas bubbles for the purposes of transferring gas to the water (e.g., O₃, CO₂, O₂) or removing VOCs from the water by stripping. The process can be carried out in a clearwell or special rectangular concrete tanks (contactors) typically 2.7 to 4.6 m (9 to 15 ft) in depth.

A typical diffused-air aeration system is shown on Fig. 14-24. The most commonly used diffuser system consists of a matrix of perforated tubes (or membranes) or porous plates arranged near the bottom of the tank to provide maximum gas-to-water contact. Various types of diffusers and diffuser system layouts are presented in the U.S. EPA's (1989) technology transfer design manual on fine pore aeration systems. Jet aerators, which consist of jets that discharge fine gas bubbles and provide enhanced mixing

**Figure 14-24**

Typical example of a diffused-air aeration system.

for increased absorption efficiency, are used to provide good air-to-water contact (Mandt and Bathija, 1977). Model development for bubble aeration has been described in the literature (Matter-Müller et al., 1981; Munz and Roberts, 1982; Roberts et al., 1984).

Mechanical aerators typically used in water treatment are surface or submerged turbines or brushes, as shown on Fig. 14-11. Surface aerators can be used in water treatment as an alternative to diffused aeration systems for stripping of volatile contaminants. Surface aeration has been primarily used for oxygen absorption and the stripping of gases and volatile contaminants when the required removals are less than about 90 percent.

The brush-type aerator consists of several blades attached to a rotary drum that is half submerged in water in the center of the tank, as shown on Fig. 14-11. As the drum rotates, it disperses the water into the surrounding air, thus providing interfacial contact between the air and water for mass transfer to take place.

The turbine-type aerator consists of a submerged propeller system located in the center of the tank and surrounded by a draft tube. As the submerged propeller rotates, it draws water from outside the draft tube through the inner section and into the air, creating contact between the air and water.

Model development for surface aeration as applied to water treatment has been described in the literature (Matter-Müller et al., 1981; Munz and Roberts, 1989; Roberts and Dändliker, 1983; Roberts et al., 1984, 1985).

Mechanical Aerators

Problems and Discussion Topics

Note: Several of these problems pertain to the design of countercurrent packed towers, which is a computationally-intensive process. The spreadsheet identified as Resource E10 at the website listed in App. E can be used to perform the calculations.

- 14-1 What is the dimensionless Henry's law constant for a compound that has a value of 400 atm? What is the Henry's law constant in atmospheres and atm/(mol/L) for a compound that has a dimensionless Henry's law constant of 0.2? Assume the temperature is 15°C.
- 14-2 What is the Henry's law constant in dimensionless form and atmospheres for a compound that has a Henry's law constant of 2.0 atm/ (mol/L)? What is the dimensionless Henry's law constant for a compound that has a value of 200 atm? Assume the temperature is 10°C.
- 14-3 Calculate the dimensionless Henry's law constant at 10 and 25°C for benzene.

- 14-4 Calculate the dimensionless Henry's law constant at 5 and 15°C for chloroform.
- 14-5 Calculate the apparent Henry's constant of hydrogen sulfide at pH 6.3 at 25°C.
- 14-6 Calculate the minimum air-to-water ratio for chloroform and benzene with 95 percent removal at 10°C for a countercurrent packed tower.
- 14-7 Using the McCabe–Thiele graphical method, determine the number of equilibrium stages required to strip chloroform from an influent concentration of 200 µg/L to its treatment objective of 5 µg/L in a countercurrent, packed tower at 5°C. Assume clean air enters the tower and $S = 3.5$.
- 14-8 Determine the cross-sectional area and diameter for a packed-tower design based on chloroform at 20°C for a water flow rate Q of 0.15 m³/s (2400 gal/min). The basis for design is stripping factor $S = 3.5$, gas pressure drop $\Delta P/L = 50 \text{ N/m}^2 \cdot \text{m}$, and 5.1-cm (2-in.) plastic saddles.
- 14-9 Determine the cross-sectional area and diameter for a packed-tower design based on benzene at 10°C for a water flow rate Q of 0.05 m³/s (800 gal/min). The basis for design is stripping factor $S = 3.5$, gas pressure drop $\Delta P/L = 50 \text{ N/m}^2 \cdot \text{m}$, and 5.8-cm (2.3-in.) LANPAC packing material.
- 14-10 Determine the mass transfer coefficients for benzene and chloroform at 20°C in packed-tower aeration for the air mass loading rate and water mass loading rate determined in Problem 14-8 using the Onda correlations and a safety factor of 0.75 (actual $K_L a$ /Onda $K_L a$) for 5.1-cm (2-in.) plastic saddles. The water flow rate Q is 0.15 m³/s (2400 gal/min). Determine the liquid diffusivity D_l and gas diffusivity D_g for benzene and chloroform using the Hayduk–Laudie correlation and the Wilke–Lee modification of the Hirschfelder–Bird–Spotz method, respectively. The viscosity of air, μ_g , at 20°C is $1.77 \times 10^{-5} \text{ kg/m} \cdot \text{s}$.
- 14-11 Determine the mass transfer coefficients for benzene and chloroform at 10°C in packed-tower aeration for the air mass loading rate and water mass loading rate determined in Problem 14-9 using the Onda correlations and a safety factor of 0.75 (actual $K_L a$ /Onda $K_L a$) for 5.8-cm (2.3-in.) LANPAC packing material. The water flow rate Q is 0.05 m³/s (800 gal/min). Determine the liquid diffusivity D_l and gas diffusivity D_g for benzene and chloroform using the Hayduk–Laudie correlation and the Wilke–Lee modification of the Hirschfelder–Bird–Spotz method, respectively. The viscosity of air, μ_g , of 10°C is $1.72 \times 10^{-5} \text{ kg/m} \cdot \text{s}$.

- 14-12 Determine the packed-tower height required to remove chloroform at 20°C for a water flow rate Q of 0.15 m³/s (2400 gal/min). Use the tower area determined in Problem 14-8 and the mass transfer coefficients determined in Problem 14-10 in the solution of the problem. The influent concentration for benzene is 50 µg/L and its treatment objective is 5 µg/L. The influent concentration for chloroform is 100 µg/L and its treatment objective is 5 µg/L.
- 14-13 Determine the packed-tower height required to remove benzene at 20°C for a water flow rate Q of 0.15 m³/s (2400 gal/min). Use the tower area determined in Problem 14-8 and the mass transfer coefficients determined in Problem 14-10 in the solution of the problem. The influent concentration for benzene is 50 µg/L and its treatment objective is 5 µg/L. The influent concentration for chloroform is 100 µg/L and its treatment objective is 5 µg/L.
- 14-14 Determine the packed-tower height required to remove chloroform at 10°C for a water flow rate Q of 0.05 m³/s (800 gal/min). Use the tower area determined in Problem 14-9 and the mass transfer coefficients determined in Problem 14-11 in the solution of the problem. The influent concentration for benzene is 75 µg/L and its treatment objective is 5 µg/L. The influent concentration for chloroform is 100 µg/L and its treatment objective is 5 µg/L.
- 14-15 Determine the packed-tower height required to remove benzene at 10°C for a water flow rate Q of 0.05 m³/s (800 gal/min). Use the tower area determined in Problem 14-9 and the mass transfer coefficients determined in Problem 14-11 in the solution of the problem. The influent concentration for benzene is 75 µg/L and its treatment objective is 5 µg/L. The influent concentration for chloroform is 75 µg/L and its treatment objective is 5 µg/L.
- 14-16 Using the packed-tower height and conditions in Problem 14-12, perform a rating analysis to determine if benzene will be removed to meet its treatment objective.
- 14-17 Using the packed-tower height and conditions in Problem 14-13, perform a rating analysis to determine if chloroform will be removed to meet its treatment objective.
- 14-18 Using the packed-tower height and conditions in Problem 14-14, perform a rating analysis to determine if benzene will be removed to meet its treatment objective.
- 14-19 Using the packed-tower height and conditions in Problem 14-15, perform a rating analysis to determine if chloroform will be removed to meet its treatment objective.
- 14-20 Determine the total power requirement (blower and pump brake power) for a packed-tower aeration design removing chloroform at 20°C and 1 atm (101,325 N/m²) for a water flow rate of 0.15 m³/s,

- a stripping factor of 3.5, and a gas pressure drop of $50 \text{ N/m}^2/\text{m}$. Assume the blower efficiency is 35 percent ($\text{Eff}_b = 0.35$) and the pump efficiency is 80 percent ($\text{Eff}_p = 0.80$). Use the air-to-water ratio and tower area determined in Problem 14-8. Use the tower length determined in Problem 14-12.
- 14-21 Determine the total power requirement (blower and pump brake power) for a packed-tower aeration design removing benzene at 10°C and 1 atm ($101,325 \text{ N/m}^2$) for a water flow rate of $0.05 \text{ m}^3/\text{s}$, a stripping factor of 3.5, and a gas pressure drop of $50 \text{ N/m}^2/\text{m}$. Assume the blower efficiency is 35 percent ($\text{Eff}_b = 0.35$) and the pump efficiency is 80 percent $\text{Eff}_p = 0.80$. Use the air-to-water ratio and tower area determined in Problem 14-9. Use the tower length determined in Problem 14-13.
- 14-22 Design a packed-tower aeration system to treat $0.075 \text{ m}^3/\text{s}$ of water at 15°C and remove benzene (influent concentration that equals $40 \mu\text{g/L}$), chloroform (influent concentration equals $60 \mu\text{g/L}$), and carbon tetrachloride (influent concentration equals $30 \mu\text{g/L}$) to a treatment objective of total VOC concentration that equals $5 \mu\text{g/L}$. Determine an appropriate tower diameter and tower length. Use 0.0508-m (2-in.) plastic tripacks as the packing material. The viscosity of air at 15°C is $1.75 \times 10^{-5} \text{ kg/m} \cdot \text{s}$.
- 14-23 Determine the actual number of trays needed for a low-profile air stripper for the following conditions. The influent concentration of trichloroethylene (TCE) is 30 mg/L and the treatment objective is 0.005 mg/L . The water flow rate is $0.00630 \text{ m}^3/\text{s}$ (100 gpm) and the water temperature is 10°C . The air flow rate is $1.42 \text{ m}^3/\text{s}$ (3000 cfm). The Henry's constant of TCE at 10°C is 0.230.
- 14-24 A well water contains 1.0 mg/L of methane with temperature of 10°C . The well pumps $0.0600 \text{ m}^3/\text{s}$ (950 gpm) and the pump has the capacity to deliver an additional 28 m (40 psi) of head. Determine the number of nozzles required and the expected methane removal efficiency. The following information was obtained from the nozzle manufacturer: $SMD = 0.10 \text{ cm}$, $\alpha = 90^\circ$, $C_v = 0.45$, $C_d = 0.25$, nozzle diameter = 1.25 cm . Let D_l for methane be $1.1 \times 10^{-5} \text{ cm}^2/\text{s}$ at 10°C .

References

- Ashworth, R. A., Howe, G. B., Mullins, M. E., and Rogers, T. N. (1988) "Air-Water Partitioning Coefficients of Organics in Dilute Aqueous Solutions," *J. Hazardous Mat.*, **18**, 1, 25–36.
- AWWA (1978a) "Water Treatment Plant Sludges—An Update of the State of the Art, Part 1, American Water Works Association Sludge Disposal Committee Report", *J. AWWA*, **70**, 9, 498–503.

- AWWA (1978b) "Water Treatment Plant Sludges—An Update of the State of the Art, Part 2, American Water Works Association Sludge Disposal Committee Report", *J. AWWA*, **70**, 10, 548–554.
- Ayuttaya, P. C. N., Rogers, T. N., Mullins, M. E., and Kline, A. A., (2001) "Henry's Law Constants Derived from Equilibrium Static Cell Measurements for Dilute Organic-Water Mixtures," *Fluid Phase Equilibria*, **185**, 359–377.
- Ball, B. R., and Edwards, M. D. (1992) "Air Stripping VOCs from Groundwater: Process Design Considerations," *Environ. Progr.*, **11**, 1, 39–48.
- Ball, W. P., Jones, M. D., and Kavanaugh, M. C. (1984) "Mass Transfer of Volatile Organic Compounds in Packed Tower Aeration," *J. WPCF*, **56**, 2, 127–135.
- Biederman, W. J., and Fulton, E. E. (1971) "Destratification Using Air," *J. AWWA*, **63**, 7, 462–466.
- Bilello, L. J., and Singley, J. E. (1986) "Removing Trihalomethanes by Packed-Column and Diffused Aeration," *J. AWWA*, **78**, 2, 62–71.
- Byers, W. D., and Morton, C. M. (1985) "Removing VOC from Groundwater; Pilot, Scale-up, and Operating Experience," *Environ. Progr.*, **4**, 2, 112–118.
- Calvert, S., Lundgren, D., and Mehta, D. S. (1972) "Venturi Scrubber Performance," *J. Air Pollut. Control Assoc.*, **22**, 7, 529–532.
- Carbonair Environmental Systems (2003) 2731 Nevada Avenue North, New Hope, MN.
- Cummins, M. D., and Westrick, J. J. (1983) "Trichlorethylene Removal by Packed Column Air Stripping: Field Verified Design Procedure," in Proceedings, American Society of Civil Engineers Environmental Engineering Conference, Boulder, CO, pp. 442–449.
- Davies, T. H., and Ip, S. Y. (1981) "Droplet Size and Height Effects in Ammonia Removal in a Spray Tower," *Water Res.*, **15**, 5, 525–533.
- Dewulf, J., Drijvers, D., and Langenhove, H. V., (1995) "Measurement of Henry's Law Constant as Function of Temperature and Salinity for the Low Temperature Range," *Atmosph. Environ.*, **29**, 4, 323–331.
- Djebbar, Y., and Narbaitz, R. M. (1995) "Mass Transfer Correlations for Air Stripping Towers," *Environ. Progr.*, **14**, 3, 137–145.
- Djebbar, Y., and Narbaitz, R. M. (1998) "Improved Correlations in Packed Towers," *Water Sci. Technol.*, **38**, 6, 295–302.
- Djebbar, Y., and Narbaitz, R. M. (2002) "Neural Network Prediction of Air Stripping KLa," *J. Environ. Eng. ASCE*, **128**, 5, 451–460.
- Dvorak, B. I., Lawler, D. F., Fair, J. R., and Handler, N. E. (1996) "Evaluation of the Onda Correlations for Mass Transfer with Large Random Packings," *Environ. Sci. Technol.*, **30**, 2, 945–953.
- Dzombak, D. A., Roy, S. B., and Fang, H.-J. (1993) "Air Stripper Design and Costing Computer Program," *J. AWWA*, **85**, 10, 68–72.
- Eckert, J. S. (1961) "Design Techniques for Sizing Packed Towers," *Chem. Eng. Progr.*, **57**, 9, 54–58.
- Garton, J. E. (1978) "Improve Water Quality through Lake Destratification," *Water Wastes Eng.*, **15**, 5, 42–44.
- Gossett, J. M. (1987) "Measurement of Henry's Law Constants for C1 and C2 Chlorinated Hydrocarbons," *Environ. Sci. Technol.*, **21**, 2, 202–208.

- Gross, R. L., and TerMaath, S. G. (1985) "Packed Tower Aeration Strips Trichloroethylene from Groundwater," *Environ. Progr.*, **4**, 2, 119–124.
- Gustafsson, J. P. (2002) *Visual MINTEQ, Version 2.12a*, KTH Royal Institute of Technology, Stockholm, Sweden.
- Hand, D. W., Crittenden, J. C., Gehin, J. L., and Lykins, B. W., Jr. (1986) "Design and Evaluation of an Air Stripping Tower for Removing VOCs from Groundwater," *J. AWWA*, **78**, 9, 87–97.
- Hand, D. W., Hokanson, D. R., and Crittenden, J. C. (1999) Air Stripping and Aeration, Chap. 5 in R. D. Letterman (ed.), *Water Quality and Treatment: A Handbook of Community Water Supplies*, 5th ed., American Water Works Association, McGraw-Hill, New York.
- Heron, G., Christensen, T. H., and Enfield, C. G. (1998) "Henry's Law Constant for Trichloroethylene between 10 and 95 °C," *Environ. Sci. Technol.*, **32**, 10, 1433–1437.
- Higbie, R. (1935) "The Rate of Absorption of a Pure Gas into a Still Liquid During Short Periods of Exposure," *Trans. Am. Inst. Chem. Eng.*, **31**, 365–389.
- Hine, J., and Mookerjee, P. K. (1975) "The Intrinsic Hydrophobic Character of Organic Compounds, Correlations in Terms of Structural Contributions," *J. Org. Chem.*, **40**, 3, 292–298.
- Hokanson, D. R. (1996) Development of Software Design Tools for Physical Property Estimation, Aeration, and Adsorption, M.S. Thesis, Michigan Technological University, Houghton, MI (<http://cpas.mtu.edu/etdot/>).
- Howe, K. J., and Lawler, D. L. (1989) "Acid-Base Reactions in Gas Transfer: A Mathematical Approach," *J. AWWA*, **81**, 1, 61–66.
- Ip, S. Y., and Raper, W. (1977) "Ammonia Stripping with Spray Towers," *Progr. Water Technol.*, **10**, 587–605.
- Jury, S. H. (1967) "An Improved Version of the Rate Equation for Molecular Diffusion in a Dispersed Phase," *AICHE J.*, **13**, 6, 1124–1126.
- Kavanaugh, M. C., and Trussell, R. R. (1980) "Design of Aeration Towers to Strip Volatile Contaminants from Drinking Water," *J. AWWA*, **72**, 12, 684–692.
- Kavanaugh, M. C., and Trussell, R. R. (1981) Air Stripping as a Treatment Process, in Proceedings of AWWA Symposium on Organic Contaminants in Groundwater, St. Louis, MO. American Water Works Association, Denver, CO. Paper S2-6, pp. 83–106.
- Kister, H. Z., Scherffius, J., Afshar, K., and Abkar, E. (2007) "Realistically Predict Capacity and Pressure Drop for Packed Columns," *Chem. Eng. Prog.*, **103**, 7, 28–38.
- LaBranche, D. F., and Collins, M. R. (1996) "Stripping Volatile Organic Compounds and Petroleum Hydrocarbons from Water," *Water Environ. Res.*, **68**, 3, 348–358.
- Lamarche, P., and Droste, R. L. (1989) "Air Stripping Mass Transfer Correlations for Volatile Organics," *J. AWWA*, **81**, 1, 78–89.
- Lau, K. A. (2009) Theoretical and Experimental Studies of the Temperature Dependence of the Henry's Law Constant of Organic Solutes in Water, Ph.D. Dissertation, Michigan Technological University, Houghton, MI.
- Laverty, G. L., and Nielsen, H. L. (1970) "Quality Improvements by Reservoir Aeration," *J. AWWA*, **62**, 11, 711–714.

- Lenzo, F. C., Frielinghaus, T. J., and Zienkiewicz, A. W. (1990) The Application of the Onda Correlation to Packed Column Air Stripper Design: Theory Versus Reality, pp. 1301–1321, in Proceedings American Water Works Association Annual Conference, Cincinnati, OH.
- Li, K. Y., and Hsiao, K. J. (1990) “VOC Strippers: How Many Trays?” *Hydrocarbon Process.*, **69**, 2, 79–81.
- Lin, S. T., and Sandler, S. I. (2000) “Multipole Corrections to Account for Structure and Proximity Effects in Group Contribution Methods: Octanol-water Partition Coefficients,” *J. Phys. Chem.*, **104**, 30, 7099–7105.
- Lin, S. T., and Sandler, S. I. (2002) “Henry’s Law Constant of Organic Compounds in Water from Group Contribution Model with Multipole Corrections,” *Chem. Eng. Sci.*, **57**, 2727–2733.
- Lincoff, A. H., and Gossett, J. M. (1984) “The Determination of Henry’s Law Constant for Volatile Organics by Equilibrium Partitioning in Closed Systems,” pp. 17–25 in *Gas Transfer at Water Surfaces*, W. Brutsaert and G. H. Jurka (eds.) Reidel, Germany.
- Mackay, D., and Shiu, W. Y. (1981) “A Critical Review of Henry’s Law Constants for Chemicals of Environmental Interest,” *J. Phys. Chem. Ref. Data*, **10**, 1175–1199.
- Mackay, D., Shiu, W. Y., and Sutherland, R. P. (1979) “Determination of Air-Water Henry’s Law Constant for Hydrophobic Pollutants,” *Environ. Sci. Technol.*, **13**, 3, 333–337.
- Mandt, M. G., and Bathija, P. R. (1977) “Jet Fluid Gas/Liquid Contacting and Mixing,” *AICHE Symp. Ser.*, **73**, 167, 15–22.
- Matter-Müller, C., Gujer, W., and Giger, W. (1981) “Transfer of Volatile Substances from Water to the Atmosphere,” *Water Res.*, **15**, 11, 1271–1279.
- McCabe, W. L., and Thiele, E. W. (1925) “Graphical Design of Fractionating Columns,” *Ind. Eng. Chem.*, **17**, 6, 605–611.
- McKinnon, R. J., and Dyksen, J. E. (1984) “Removal of Organics from Groundwater through Aeration Plus GAC,” *J. AWWA*, **76**, 5, 42–47.
- Mead, E., and Leibbert, J. (1998) A Comparison of Packed-Column and Low-Profile Sieve Tray Air Strippers, in Proceedings of the 1998 Conference on Hazardous Waste Research, The Great Plains/Rocky Mountain Hazardous Substance Research Center, Snowbird, UT, pp. 328–334.
- Meylan, W. M. (1999) HENRYWIN v 3.05, Syracuse Research Corporation, Syracuse, NY.
- Meylan, W. M., and Howard, P. H. (1991) “Bond Contribution Method for Estimating Henry’s Law Constants,” *Environ. Toxicol. Chem.*, **10**, 10, 1283–1293.
- Miller, D. J., and Hawthorne, S. B. (2000) “Solubility of Liquid Organic Flavor and Fragrance Compounds in Subcritical (Hot/Liquid) Water from 298 K to 473 K,” *J. Chem. Eng. Data*, **45**, 2, 315–318.
- Munz, C., and Roberts, P. V. (1982) Mass Transfer and Phase Equilibria in a Bubble Column, paper presented at the American Water Works Association Annual Conference, Miami, FL.
- Munz, C., and Roberts, P. V. (1989) “Gas and Liquid-Phase Mass Transfer Resistance of Organic Compounds During Mechanical Surface Aeration,” *Water Res.*, **23**, 5, 589–601.

- Narbaitz, R. M., Mayorga, W. J., Torres, F. D., Greenfield, J. H., Amy, G. L., Minear, R. A. (2002) "Evaluating Aeration Stripping Media on the Pilot Scale," *J. AWWA*, **94**, 9, 97–111.
- Nicholson, B. C., Maguire, B. P., and Bursell, D. B. (1984) "Henry's Law for the Trihalomethanes: Effects of Water Composition and Temperature," *Environ. Sci. Technol.*, **18**, 7, 518–521.
- Nirmalakhandan, N. N., and Speece, R. E. (1988) "QSAR Model for Predicting Henry's Constant," *Environ. Sci. Technol.*, **22**, 11, 1349–1357.
- NIST (2011) Accessed at <http://webbook.nist.gov/chemistry/> on Jan. 3, 2011.
- North East Environmental Products (2003) 17 Technology Drive, West Lebanon, NH.
- Notthakun, S., Bros, D. E., and Riddle, C. S. (1994) *Sieve Tray Air Strippers*, Carbonair Environmental Systems, Minneapolis, MN.
- Onda, K., Takeuchi, H., and Okumoto, Y. (1968) "Mass Transfer Coefficients between Gas and Liquid Phases in Packed Columns," *J. Chem. Eng. Jpn.*, **1**, 1, 56–62.
- Pigford, R. L., and Pyle, C. (1951) "Performance Characteristics of Spray-Type Absorption Equipment," *Ind. Eng. Chem. Process Des. Devel.*, **43**, 1649–1662.
- Roberts, P. V., and Dändliker, P. G. (1983) "Mass Transfer of Volatile Organic Contaminants from Aqueous Solution to the Atmosphere During Surface Aeration," *Environ. Sci. Technol.*, **17**, 8, 484–489.
- Roberts, P. V., Hopkins, G. D., Munz, C., and Riojas, A. H. (1985) "Evaluating Two-Resistance Models for Air Stripping of Volatile Organic Contaminants in a Countercurrent, Packed Column," *Environ. Sci. Technol.*, **19**, 2, 164–173.
- Roberts, P. V., and Levy, J. A. (1985) "Energy Requirements for Air Stripping Trihalomethanes," *J. AWWA*, **77**, 4, 138–146.
- Roberts, P. V., Munz, C., and Dändliker, P. (1984) "Modeling Volatile Organic Solute Removal by Surface and Bubble Aeration," *J. WPCF*, **56**, 2, 157–163.
- Robbins, G. A., Wang, S., and Stuart, J. D. (1993) "Using Static Headspace Method to Determine Henry's Law Constants," *Anal. Chem.*, **65**, 21, 3113–3118.
- Rogers, T. N. (1994) Predicting Environmental Physical Properties from Chemical Structure Using a Modified Unifac Model, Ph.D. Dissertation, Michigan Technological University, Houghton, MI.
- Sander, R. (1999) "Compilation of Henry's Law Constants for Inorganic and Organic Species of Potential Importance in Environmental Chemistry (Version 3)," Accessed at <http://www.henrys-law.org> on Jan. 3, 2011.
- Schwarzenbach, R. P., Gschwend, P. M., and Imboden, D. M. (1993) *Environmental Organic Chemistry*, Wiley, New York.
- Sherwood, T. K., and Hollaway, F. A. (1940) "Performance of Packed Towers—Liquid Film Data for Several Packings," *Trans. Am. Inst. Chem. Eng.*, **36**, 39–70.
- Shulman, H. L., Ullrich, C. F., and Wells, N. (1955) "Performance of Packed Columns I. Total, Static, and Operating Holdups," *AICHE J.*, **1**, 2, 247.
- Singley, J. E., Ervin, A. L., and Mangone, M. A. (1980) Trace Organics Removal by Air Stripping, report to AWWA Research Foundation, Denver, CO.

- Singley, J. E., Ervin, A. L., and Mangone, M. A. (1981) Trace Organics Removal by Air Stripping, supplemental report to AWWA Research Foundation, Denver, CO.
- SRC (2011). Accessed at <http://www.syrres.com/what-we-do/databaseforms.aspx?id=386> on Jan. 3, 2011.
- Steichen, J. M., Garton, J. E., and Rice, C. E. (1979) "Effect of Lake Destratification on Water Quality," *J. AWWA*, **71**, 4, 219–225.
- Suzuki, T., Ohtaguchi, K., and Koide, K. (1992) "Application of Principle Components Analysis to Calculate Henry's Constant from Molecular Structure," *Computer Chem.*, **16**, 1, 41–52.
- Symons, J. M., Carswell, J. K., and Robeck, G. G. (1970) "Mixing of Water Supply Reservoirs for Quality Control," *J. AWWA*, **62**, 5, 322–334.
- Tchobanoglous, G., Burton, F. L., and Stensel, H. D. (2003) *Wastewater Engineering: Treatment and Reuse*, 4th ed., McGraw-Hill, New York.
- Thom, J. E., and Byers, W. D. (1993) "Limitations and Practical Use of a Mass Transfer Model for Predicting Air Stripper Performance," *Environ. Progr.*, **12**, 1, 61–66.
- Treybal, R. E. (1980) *Mass-Transfer Operations*, 3rd ed., McGraw-Hill, New York.
- Umphres, M. D., Tate, C. H., Kavanaugh, M. C., and Trussell, R. R. (1983) "Trihalomethane Removal by Packed Tower Aeration," *J. AWWA*, **75**, 8, 414–418.
- U.S. ACE (2001) *Engineering and Design: Air Stripping*, No. 1110-1-3, U.S. Army Corps of Engineers, Department of the Army, Washington, DC.
- U.S. EPA (1986) *Superfund Public Health Evaluation Manual*, EPA/540/1-86/060 U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, D.C.
- U.S. EPA (1989) *Design Manual: Fine Pore Aeration Systems*, EPA 625/1-89/023, U.S. Environmental Protection Agency, Washington, DC.
- U.S. EPA (1999) *MINTEQA2*, Version 4.0, U.S. Environmental Protection Agency, Washington, DC.
- Wallman, H., and Cummins, M. D. (1986) "Design Scale-up Suitability for Air-Stripping Columns," *Public Works*, **117**, 10, 74–78.
- Yaws, C. L., Miller, J. W., Shah, P. N., Schorr, G. R., and Patel, P. M. (1976) "Correlation Constants for Chemical Compounds," *Chem. Eng.*, **83**, 25, 153–162.

