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Air Stripping

Ju-Chang Huang and Chii Shang

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1. INTRODUCTION

Air stripping is a process by which a liquid, usually water or wastewater, is brought into intimate contact with a gas, usually air, so that some undesirable substances present in the liquid phase can be released and carried away by the gas.

In the past, the major objectives of wastewater treatment were the removal of SS (suspended solids), BOD (biochemical oxygen demand), and coliform bacteria. It is only very recently that the removal of inorganic nutrients, such as nitrogen and phosphorus, has been brought into focus. This is because it has been realized that the discharge of these nutrients into surface waters can result in excessive growths of algae and other aquatic plants, a phenomenon commonly referred to as "eutrophication."

Municipal wastewater and many industrial wastes are among the principal contributors of these nutrients to surface waters. For example, the average concentrations of nitrogen and phosphorus in typical domestic wastewater are, respectively, about 35–45 mg/L as N and 10–15 mg/L as P. Yet, nutrient concentrations of as low as 0.3–0.5 mg/L of nitrogen and 0.01–0.05 mg/L of phosphorus have been reported to cause eutrophication. Therefore, to eliminate this problem, a high efficiency of nutrient removal in the waste treatment process must be achieved. Conventional waste treatment processes are effective in

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removing only about 40–50% of the nitrogen and 25–30% of the phosphorus. Therefore, new treatment technologies must supplement conventional methods in order to improve the nutrient removal efficiencies.

In typical domestic wastewater, ammonia nitrogen represents about 55–60%, organic nitrogen about 40–45%, and nitrates plus nitrites together about 0–5% of the total nitrogen. Within a waste treatment plant, organic nitrogen is easily converted into ammonia species through hydrolysis, which can take place in various treatment units. A portion of ammonia is then utilized by bacteria for cell synthesis, and the remaining ammonia usually leaks out in the final plant effluent as residual ammonia nitrogen. In some situations, active biological nitrification may take place in the aeration tank. In such a case, most of the excess ammonia will be converted to nitrates.

The discovery of chlorinated hydrocarbons in remote global environments prompted researchers to re-examine the rates of evaporation of these compounds. These compounds, usually of high-molecular-weight and low vapor pressure, exhibit unexpectedly high evaporation rates due to their high equilibrium vapor partial pressures (1,2).

The presence of organic compounds that are potentially hazardous or toxic in water bodies is made increasingly evident by advances in analytical methods. This has resulted in the development of new technologies for the removal of these compounds from raw potable surface and groundwater supplies, as well as from process stream wastewater and effluent from groundwater remedial activities.

The removal of substances having reasonable equilibrium vapor pressures at ambient temperatures, including ammonia, carbon dioxide, hydrogen sulfide, and many VOCs (volatile organic compounds), by any of the processes known as air or gas stripping has proven to be efficient and cost effective. The Henry's law constant is a primary indicator of a compound's potential for removal by air stripping.

The countercurrent packed-tower type air stripper offers greater interfacial surface area for mass transfer of volatile compounds than do other gas-stripping processes. This method therefore offers significant advantages in efficiency and overall cost when used for the removal of volatile compounds from potable or wastewater streams. Equations have been developed to optimize system design for removal of specific compounds. In addition, a pilot study, scaled appropriately to the magnitude and sensitivity of the removal requirements of the air-stripping project, is recommended to enable the correct design specifications and overall cost estimates to be prepared. Secondary factors may affect the cost-effectiveness and removal efficiency of air-stripping processes, and therefore will require consideration. Cost modeling and system design to minimize power requirements should also be included in the design process.

2. HENRY'S LAW AND THE MASS-TRANSFER COEFFICIENT

Such processes as mechanical surface aeration, diffused aeration, spray fountains, spray or tray towers, open-channel cascades, and countercurrent packed towers are encompassed by the term air stripping. These procedures produce a condition in which a large surface area of the water to be treated is exposed to air, which promotes transfer of the contaminant from the liquid phase to the gaseous phase. This occurs because under normal conditions the concentration of the contaminant in ambient air is much lower than the concentration in contaminated water.

The ratio of the contaminant at equilibrium in the liquid phase, C_L , to the contaminant in the gaseous phase, C_G , is a relationship known as Henry's law:

$$H_c = \frac{C_G}{C_L} \quad (1)$$

where H_c is Henry's constant. Henry's constant is a property of the solute/solvent system and the temperature, and follows Van't Hoff's relationship (3).

$$\log H_c = \left(\frac{-H^\circ}{RT} \right) + k \quad (2)$$

where H° = enthalpy change resulting from the dissolution of the compound in water; R = the universal gas constant; T = the absolute temperature; and k = a compound-dependent constant.

The general form of the equation for the rate of mass transfer across the gas/liquid interface in a gas stripper is (4)

$$\frac{1}{V} \frac{dm}{dt} = -K_L a (C_L^* - C_L) \quad (3)$$

where V = the liquid volume, m^3 ; m = the mass of the solute, kg; t = time, s; K_L = the overall liquid mass transfer coefficient, m/s; a = the specific interfacial area, m^2/m^3 ; C_L = the bulk average concentration in the liquid phase, kg/m^3 ; C_L^* = the liquid concentration in equilibrium with the gas phase concentration, C_G , kg/m^3 ; and $K_L a$ = the transfer rate constant.

Several models exist for the characterization of gas transfer across the gas/liquid interface (5). According to the two-film model (6), laminar films exist at the gas/liquid interface. The resistance to the rate of mass transfer is given by R_T , and is estimated by summing the resistances offered by the liquid- and gas-phase boundary layers, R_L and R_G , respectively (4):

$$R_T = \frac{1}{K_L a} = R_L + R_G \quad (4)$$

The rate constants for the local liquid and gas phase transfers, k_L and k_G , respectively, are related to the overall transfer rate constant by

$$K_L a = \left(\frac{1}{k_L a} + \frac{1}{k_G a \cdot H_c} \right)^{-1} \quad (5)$$

For extremely volatile compounds, with high Henry's constants, the overall rate of transfer would therefore be controlled by the transfer rate at the liquid-phase boundary.

3. ANALYTICAL REQUIREMENTS FOR AN AIR-STRIPPING PROGRAM

An analytical program must be established, capable of identifying and quantifying contaminants in a water source to be treated, in order to assess remedial technologies. MCLs (maximum contaminant levels) for volatile organic pollutants in micrograms per liter have been prescribed by the US EPA (US Environmental Protection Agency), based on continual improvements in detection techniques.

US EPA published its initial list of 187 organic compounds found in US drinking water in 1975. Analyses were performed using GC-MS (gas chromatography with mass spectroscopy) and a packed column to separate organic compounds. Present-day analyses using a capillary column to separate compounds have increased the resolution of GC-MS detection several fold (7).

Multiple goals must be achieved by analytical methods intended to assess contaminated water bodies, particularly where treatment levels and options will be considered. Objectives must include at least the following (8):

1. Analytical programs must determine the types and concentrations of compounds present in order to allow the evaluation of various treatment methods. The relative economy of a particular technology is often dependent on the levels of contaminants to be treated.
2. The variability of contaminant levels in the water supply must be considered. Groundwater, surface water, and industrial wastewater may all show variations in quality with time due to the effects of pumping, recharge, or process flow. A potential system must be capable of treating the range of influent water qualities encountered to acceptable limits.
3. The concentrations of the contaminants in water immediately prior to and following treatment must be determined to allow analysis of the efficiency of the system. Pilot-study programs designed to determine the effects of varying system parameters are based on reliable water-quality analyses. Where rapid reporting of sampling results is a benefit, the portable GC instrument has found application.

For any analytical program selected, an appropriate quality assurance program must be implemented to minimize errors during the sampling and analysis process. The Federal Register contains the appropriate procedures for US EPA priority pollutants.

4. FEATURES AND DESIGN

4.1. Features of the Countercurrent Air Stripper

A countercurrent packed-tower air stripper has two major components (Fig. 1):

1. A vertical cylindrical tower, whose dimensions range from 6 in. (17 cm) to 9 ft (3 m) or larger in diameter, and from several feet (2 m) to 45 ft (15 m) or more in height. The tower contains a large number of packing elements whose surfaces provide the interface for mass transfer of volatile compounds from the aqueous to the gaseous phase. An aeration nozzle or liquid distributor at the top of the tower evenly distributes the influent water over the packing material in a fine spray. The shell of the tower is commonly made of FRP (fiberglass-reinforced plastic), aluminum, or stainless steel.
2. A high capacity blower forces ambient or heated air into the bottom of the air stripper where the volatile compounds are removed from the water covering the packing elements. The air continues to remove volatile constituents from the water as it is forced up through the column. A demister element at the top of the column prevents the escape of large amounts of water vapor with the exiting air.

The hydraulic head necessary to pump the influent water up to and through the aeration nozzle may be supplied by existing treatment or supply well pumps, or an additional water pump may be supplied.

4.2. Air-Stripper Design Parameters

Four key factors determine the efficiency with which volatile compounds may be removed from the liquid phase in an air stripper. Air-stripper design must include

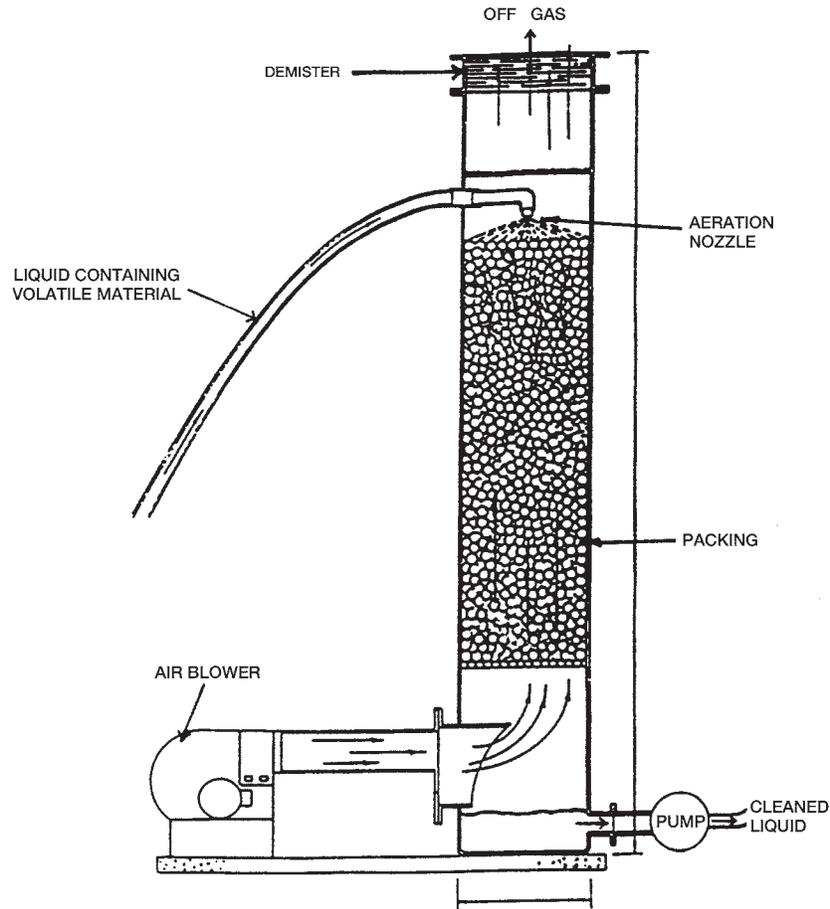


Fig. 1. Diagram of an air-stripping tower.

each of these factors and balance them with operational power requirements to optimize costs.

1. The ratio of air-to-water flow through the air stripper will control the removal rate of the contaminant. The ratio of air-to-water required to produce a desired removal efficiency is determined by the concentration and potential for removal of the contaminant by air stripping, indicated by the Henry constant. An increase in the air-to-water ratio will usually result in greater removal rates, up to a point at which entrainment of the liquid by the air flow occurs, resulting in a sharp increase in the air pressure drop through the stripping column. This phenomenon is known as flooding. The opposite condition occurs when the liquid flow rate is increased until the tower begins to fill with liquid. This is also referred to as flooding. Controlling the air pressure drop through the stripping tower will significantly reduce blower operation costs.
2. The height of the packed tower will also affect the removal efficiency of the contaminant. An optimum balance between the air-to-water ratio and the tower height results in acceptable removal efficiencies at the lowest combination of capital and operational cost.
3. The desired rate of flow of the liquid to be treated will determine the diameter of the air-stripping column.

4. The type of packing material will have an impact on the mass transfer rate, because the surface area of the packing provides the air-to-water interfacial area.

The size of the packing also affects the air pressure drop through the tower. Smaller size packing material offers more surface area than larger materials, but also offers more resistance to the air flow. The ratio of column diameter to nominal packing size should be greater than 12 to prevent channeling of the water along the walls of the air stripper (9).

Henry's constant, H_c , is an indication of how readily a compound will evaporate from a water body, and hence its potential for removal by air stripping. Although Henry's constants for many volatile organic compounds have been presented in the literature (4,8–10), it may be necessary to calculate the constant for compounds for which sufficient data do not exist. Application of regression analysis to equilibrium headspace concentrations of liquid samples of known concentration has been described as a method for empirically determining Henry's constant (8,9). Kavanaugh (9) demonstrated the van't Hoff effect, finding that for many volatile organic compounds Henry's constant increased approximately threefold for every 10°C rise in temperature.

It is the overall mass transfer coefficient, however, that ultimately controls the rate of removal of a substance by air stripping. For example, dichloroethane, which has a lower Henry's constant than trichloroethylene, has been found easier to remove by air stripping, owing to its higher mass transfer coefficient (10). The mass transfer coefficient for a specific substance in a specific air-stripping system may be calculated by (9):

$$K_L a = k_L a = \alpha \left(\frac{L_M}{U_L} \right)^{1-n} \left(\frac{U_L}{\rho_L D} \right)^{0.5D} \quad (6)$$

where L_M = the liquid mass flux rate, kg/m²-h; α and n = constants specific to the packing type; U_L = the liquid viscosity; ρ_L = the liquid density; and D = the molecular diffusion coefficient of the compound in water.

Information provided by the packing manufacturer is needed to apply Eq. (6) to calculate the mass transfer coefficient.

A quantity termed HTU (the height of a transfer unit) (9) characterizes the efficiency of mass transfer from water to air:

$$\text{HTU} = \frac{L}{K_L a \cdot C_o} \quad (7)$$

where L = the molar flux rate of the contaminant in the liquid phase, kmol/m²-s, and C_o = the molar density of water (55.6 kmol/m³). Analytical error may be introduced in the calculation of HTU due to uncertainties in various factors used to calculate the mass transfer coefficient. Commonly, existing field data are used for this design parameter. If such data are nonexistent for the contaminant to be removed, pilot study data may be analyzed to yield dependable mass transfer coefficient data suitable for final, full-scale design.

A design factor termed NTU (the number of transfer units) was also introduced by Kavanaugh (9) to characterize the difficulty of removing the contaminant from the liquid phase:

$$\text{NTU} = \left(\frac{S}{S-1} \right) \ln \left[\frac{C_{\text{inf}}(S-1)}{C_{\text{eff}}} + \frac{1}{S} \right] \quad (8)$$

where C_{inf} = the concentration of the contaminant in the influent water; C_{eff} = the concentration of the contaminant in the effluent water; and S = a concept known as the stripping factor. The stripping factor (4) is crucial in determining the ability of an air stripper to remove a specific contaminant. Theoretically, if $S > 1$, complete removal of the contaminant could be achieved by increasing the height of the packed tower to infinity. Conversely, if $S < 1$, the removal rate would have an upper limit despite further limits in tower height. It is necessary to design for a stripping factor greater than 1. Therefore, the stripping factor, S , is determined by

$$s = \frac{G'}{L'} H_c \quad (9)$$

where G'/L' = the volumetric air-to-water ratio. Thus, it may be seen that contaminants with lower Henry's constants will require higher air-to-water ratios to achieve successful removal rates.

A graphic comparison of the stripping factor (S) and the number of transfer units (NTU) shows that beyond $S = 4-5$, little additional contaminant removal occurs (9), as shown in Fig. 2. A stripping factor of 3 is suggested for most calculations of the required air-to-water ratio. NTU for air-stripper design can be calculated by substituting the desired removal efficiency into Eq. (8). The product of the HTU and the NTU yields the packed column height necessary to effect the desired removal of the contaminants:

$$Z = \text{HTU} \times \text{NTU} \quad (10)$$

where Z = the height of the packed column, m. A safety factor of 1.5 is recommended when implementing the tower height calculated by this method (9).

Air-stripping tower diameter is selected as a function of the liquid loading rates necessitated by the required design flow capability. The optimum tower diameter may be determined with the use of pressure-drop curves developed by Eckert (11) as shown in Fig. 3. The volumetric air-to-water ratio, calculated by Eq. (9), is converted to a weight-to-weight ratio and plotted on the abscissa in the form:

$$X = \left(\frac{L'}{G'} \right) \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{0.5} \quad (11)$$

where L'/G' = the volumetric water-to-air ratios and ρ_G and ρ_L = the densities of air and water, 1.205 kg/m³ and 998 kg/m³, respectively.

The ordinate value, corresponding to the intersection of the abscissa value with the appropriate pressure-drop curve (as supplied by the packing manufacturer), allows the determination of the allowable gas-flow rate from

$$Y = \frac{G'^2 C_f^{0.1}}{\rho_G (\rho_L - \rho_G)} \quad (12)$$

where G' = the optimum gas flow rate and C_f = the packing factor. From the volumetric ratio, the optimum liquid loading rate may also be determined.

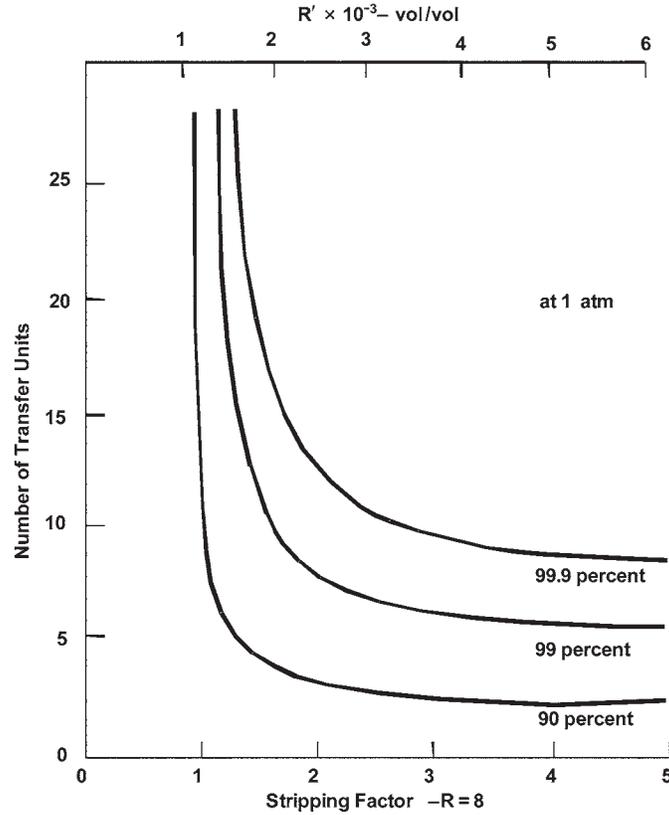


Fig. 2. General relationship between stripping factor and NTU.

The tower diameter may then be determined by:

$$\Phi = \left(\frac{4 Q_L \rho_L}{\pi L'} \right)^{0.5} \quad (13)$$

where Φ = the tower diameter, m; Q_L = the design flow, m^3/s ; and L' = the liquid loading rate, $\text{kg}/\text{m}^2\text{-s}$.

Typically, the air-stripper manufacturer will supply liquid flow ranges acceptable for a particular tower. Selecting an air stripper for which the design flow is at the lower end of the tower's rated capacity will produce high contaminant removal rates, but may not optimize power requirements. For large-scale systems where significant operational costs may be incurred by overdesigning the system, the use of pressure-drop curves and calculations such as Eqs. (1)–(13) are required.

4.3. Packing Material

The function of the packing material in an air stripper is to provide a large wetted surface area for mass transfer of contaminants to the gas phase, or ambient air. Several shapes and sizes are available, such as rings, saddles, and spheres. The packing material is commonly manufactured from polypropylene, PVC, or ceramic.

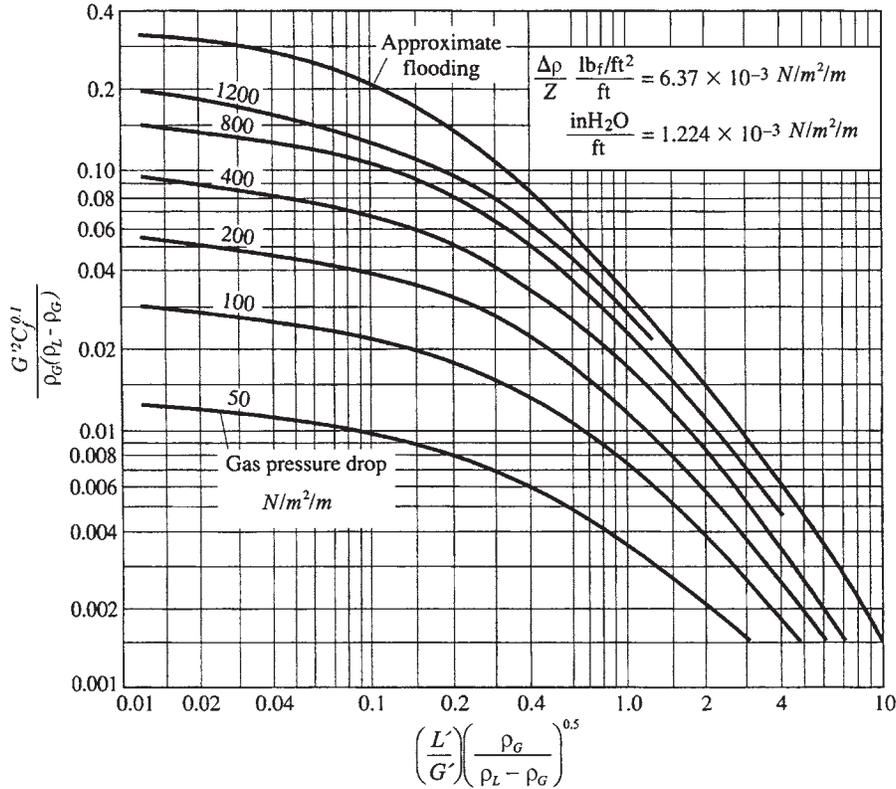


Fig. 3. Flooding and pressure drop correlations for packed towers.

When selecting a packing material, several factors must be balanced. A packing material that offers a large surface area for mass transfer will usually present more resistance to countercurrent air flow, causing a higher gas pressure drop. Different materials offer better resistance to corrosivity, encrustation, or unfavorable water conditions. Hand et al. (8) suggest an initial packing material selection offering a very low gas pressure drop, allowing the engineer to increase removal efficiency, if necessitated at some future time, by replacing the packing with a smaller or different-type packing material with more surface area.

5. PILOT STUDIES

The mass-transfer coefficient is sensitive to several factors, including Henry's constant of the contaminant, the packing factor, and the temperature of the ambient air and water to be treated. An HTU value, calculated at 20°C from Eq. (7), would require a fivefold increase if ambient water and air temperatures of 5°C and -12°C, respectively, were encountered (9). Therefore, the equations presented are recommended for initial design work and evaluation of pilot studies or field data. Data from pilot studies are required to provide dependable values for the mass-transfer coefficient and the effects on removal efficiencies produced by varying system parameters. An analytical program

capable of accurately indicating contaminant species and concentrations in influent and effluent water must also be employed.

A pilot study was performed by Bilello and Singley (3) using a 15 in. (38.1 cm) diameter PVC column, scaled up from a 6 in. (15.2 cm) column used in earlier studies. The effects of varying the air-to-water ratio, tower height, packing material, and temperature were studied. Good correlation between data obtained by each column was observed.

Prior to installation of a 9 ft (2.7 m) diameter packed column for removal of TCE (trichloroethylene), DIPE (diisopropyl ether), and MTBE (methyl tertiary butyl ether) from a municipal well water supply, a pilot study was performed using a 12 in. (30.5 cm) packed column. Packing material, liquid and air flow rates, and removal efficiencies were evaluated for the compounds present. In the pilot study, TCE, which has a higher Henry's constant than DIPE, was found to be more readily removed. Based on these findings, a full-scale design resulting in 99.9% removal of DIPE was implemented.

Air-stripper manufacturers and suppliers have assembled data banks based on similar pilot studies. For smaller-scale projects involving common volatile organic compounds, these existing data may be sufficient to specify air-stripper requirements based on the design engineer's experience with such systems and the provision of some system overcapacity. A pilot-scale program is required where it is uncertain that adequate removal of a contaminant may be achieved by existing designs, or where, owing to the economics of large-scale installations, incorrect specifications may later present unacceptable additional capital or operating expenses.

Example 1

A manufacturer of protective coatings (roof coatings, driveway sealers, and automotive undercoatings) uses 45 gpm (170 L/min) of groundwater, pumped from a well on the facility's property, for non-contact cooling purposes. The groundwater is contaminated with 5700 ppb of TCE (trichloroethylene), and therefore cannot be discharged to the local sewage treatment plant in accordance with the facility's NPDES permit, which specifies a maximum limit of 100 ppb TCE. Design an air stripper to reduce the TCE to within acceptable discharge limits.

1. A pilot study was performed by an air-stripper manufacturer using a pilot tower with the following specifications:
 - Diameter, 2 ft (0.61 m)
 - Packed height, 8.5 ft (2.59 m)
 - Air-to-water ratio, 160:1 (volumetric)
 - Henry's constant, 0.415 (from previous studies)
 - Packing material, #1 Tri-pack
 - During the pilot study the influent concentration of 2300 ppb TCE was reduced to 190 ppb in the effluent.
2. A value for HTU was calculated from the pilot test data:

$$\begin{aligned}
 S &= \frac{G'}{L'} H_c && \text{(Eq. 9)} \\
 &= 160 \times 0.415 \\
 &= 66.4
 \end{aligned}$$

$$\begin{aligned} \text{NTU} &= \left(\frac{S}{S-1} \right) \ln \left[\frac{C_{\text{inf}}(S-1)}{C_{\text{eff}}} + \frac{1}{S} \right] && \text{(Eq. 8)} \\ &= \left(\frac{66.4}{66.4-1} \right) \ln \left[\frac{2300 \times (66.4-1)}{190} + \frac{1}{66.4} \right] \\ &= 2.52 \end{aligned}$$

$$\begin{aligned} \text{HTU} &= \frac{Z}{\text{NTU}} && \text{(Eq. 10)} \\ &= \frac{2.59}{2.52} \\ &= 1.03 \text{ m} \end{aligned}$$

3. A production 2 ft (0.61 m) diameter tower has a packed height of 19 ft (5.49 m) and a rated flow of 15–60 gpm (56.8–227 L/min). The blower capacity of the stripper is 600 ft³/min (17 m³/min):

$$S = \frac{G'}{L'} H_c \quad \text{(Eq. 9)}$$

Using an in-between flow value of 45 gpm (0.17 m³/min),

$$\begin{aligned} S &= \frac{17}{0.17} \times 0.415 \\ &= 41.5 \end{aligned}$$

$$\begin{aligned} \text{NTU} &= \frac{Z}{\text{HTU}} && \text{(Eq. 10)} \\ &= \frac{5.49}{1.03} \\ &= 5.33 \end{aligned}$$

$$\begin{aligned} \text{NTU} &= \left(\frac{S}{S-1} \right) \ln \left[\frac{C_{\text{inf}}(S-1)}{C_{\text{eff}}} + \frac{1}{S} \right] && \text{(Eq. 8)} \\ 5.33 &= \left(\frac{41.5}{41.5-1} \right) \ln \left[\frac{5700 \times (41.5-1)}{C_{\text{eff}}} + \frac{1}{41.5} \right] \end{aligned}$$

Solving for the effluent concentration,

$$\begin{aligned} C_{\text{eff}} &= 30.2 \text{ ppb} \\ \% \text{ Removal} &= \frac{5700 - 30.2}{5700} (100) \\ &= 99.47 \end{aligned}$$

The calculations show the concentration of TCE would be reduced well below the permitted limit.

The value for the stripping factor, *S*, appears to be high in view of pressure-drop considerations. A reduction in the size of the blower would produce energy savings and still achieve an acceptable reduction in TCE.

The tendency with production units is to provide blowers of sufficient capacity to allow satisfactory removal of a wide range of compounds, many with Henry's constants much lower than that of TCE. Frequently, a sliding gate valve is provided as a means of reducing the air

flow, but unless the blower capacity is reduced, little power savings will result. For modest systems such as the example problem, the small power saving realized by down-sizing the blower is usually outweighed by the advantages of having excess capacity to handle colder temperatures, decreases in regulated discharge limits, or increases in influent contaminant levels.

6. AMMONIA STRIPPING

In addition to the volatile organic compounds found in water, ammonia is an inorganic compound that may occur in drinking water supplies and is frequently present in wastewaters. Ammonia nitrogen exists in both the dissolved gas form (NH_3) and in true solution (NH_4^+). These two species are present in a dynamic equilibrium according to the equation:



This equilibrium is controlled by the solubility product which varies with temperature. Therefore, the relative concentrations of these two species depend on both the pH of the solution and the temperature. In general, at a temperature of 20°C and a pH of 7 or below, only ammonium ions are present. As the pH increases above 7, the chemical equilibrium is gradually shifted to the left in favor of the ammonia gas formation. At a pH of about 11.5–12, only the dissolved gas is present. Figure 4 shows this relationship at 0, 20, and 40°C.

In addition to converting all the ammonia to the dissolved gas phase, efficient ammonia stripping requires proper conditions to facilitate a rapid transfer of the dissolved gas from the liquid phase to the air. This can be achieved by the creation of numerous small water droplets in conjunction with an ample supply of air flow. This is because the surface tension at the air–water interface is at a minimum when the water droplets or surface films are being formed, and transfer of dissolved gas from the liquid phase to the air flow is at a maximum at this instant. An ammonia stripping tower, similar to a conventional cooling tower, is normally used for ammonia removal (12).

The efficiency of an ammonia stripping operation depends primarily on five factors:

1. **pH.** As shown in Fig. 4, the relative distribution of the dissolved NH_3 gas vs the NH_4^+ ions in true solution depends greatly on pH. Because only the dissolved gas can be removed from solution, it is important to raise the pH to a value of 11 or higher so that at least 95% of the ammonia nitrogen is converted to the gas form. In full-scale operation, lime is usually the most economical, and thus is the most commonly used material for raising the pH. The amount of lime required to raise the pH depends on the characteristics of the water, primarily its bicarbonate concentration. Figure 5 illustrates the quantities of lime needed to raise the pH of two different domestic sewage samples. This must be determined for each situation.
2. **Temperature.** The liquid temperature can affect the ammonia stripping efficiency in two different ways. First, at a given pH, the percentage of ammonia nitrogen present as a dissolved gas increases with temperature as shown in Fig. 4. For example, at pH 10, at a temperature of 40°C about 95% of the ammonia nitrogen is present as the gas, but at 0°C only about 50% is present in the gaseous form. Second, the solubility of ammonia gas in water increases with decreasing temperature. The greater the solubility, the greater the amount of air required to remove a given amount of ammonia gas. Theoretically, the rate of ammonia stripping should be proportional to the difference in the partial pressures of ammonia between the liquid and the gaseous phases. Because a decrease of every 10°C in the process water would result in about a 40% decrease in the

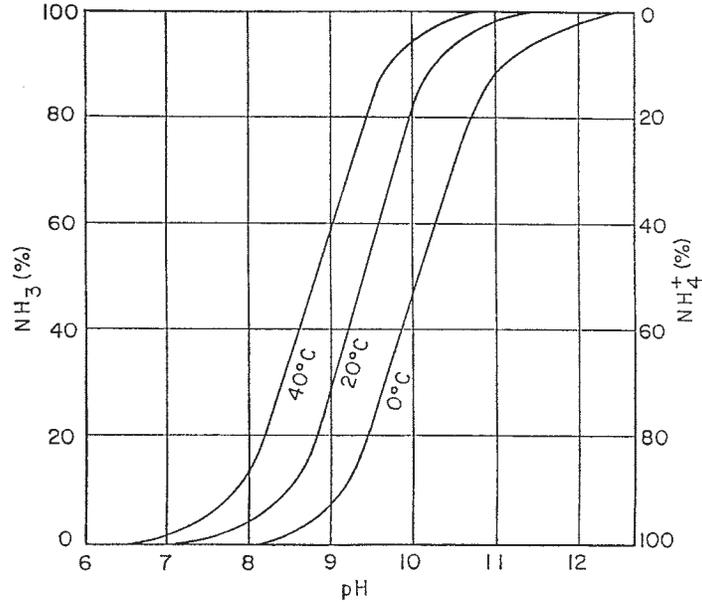


Fig. 4. Effects of pH and temperature on the distribution of ammonia and ammonium ion in water.

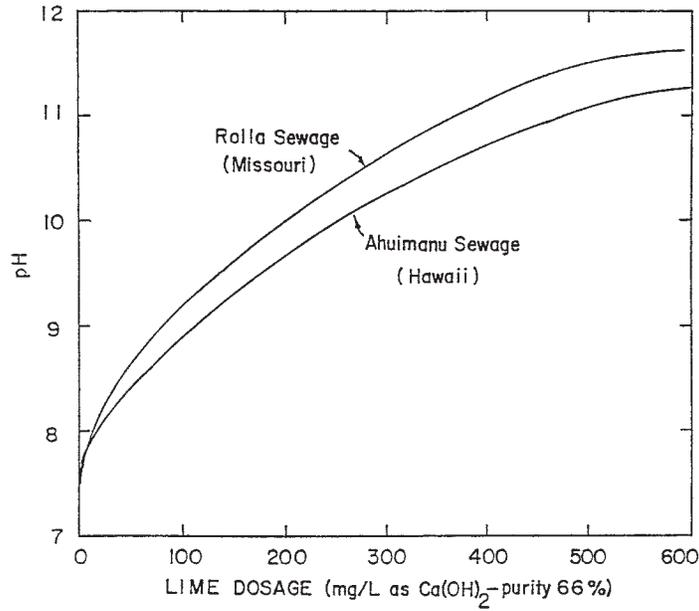


Fig. 5. Amounts of lime required to raise the pH of two sewage samples to various levels.

difference of the partial pressures, the rate of ammonia stripping can be expected to decrease in the same proportion. Therefore, if the operating efficiency must be maintained as high in the winter as in the summer, a substantial increase of air flow must be provided in order to reduce the ammonia partial pressure in the air stream and thus maintain a sufficient partial pressure difference between the liquid and the gaseous phases. If the ambient

air temperature drops below 0°C, freezing problems may occur, severely hampering the stripping operation. Even if icing and fogging do not occur at this temperature, the drastic decrease in removal efficiency, reported to be less than 30% (13), would make the ammonia stripping operation impractical and non-economical.

3. **Rate of Gas Transfer.** In order to remove ammonia from water, the dissolved NH_3 molecules must first move from the bulk liquid solution to the air–water interface, and then from the interface to the stripping air flow. Therefore, there are two factors that affect the rate of ammonia gas transfer from the liquid to the surrounding atmosphere.
 - a. Transport of the NH_3 molecules from the bulk liquid solution to the air–water interface. This is accomplished by molecular diffusion, but turbulent mixing is much more effective. If the distance of the transport is relatively short, such as that existing within a small water droplet, the rate of gas transport would seldom become a limiting factor governing the overall ammonia release rate.
 - b. Transfer of the ammonia molecules from the air–water interface to the gaseous phase. The maximum rate of the interfacial gas transfer takes place when the surface tension is at a minimum, which normally occurs when the water droplets are being formed. Once the water droplets are formed, the interfacial gas transfer becomes quite difficult. Therefore, by maintaining a condition in which there are repeated formations of water droplets of small size, the gas transfer rates within the droplets as well as on the droplet surfaces can both be maintained at the maximum rate. This is a fundamental necessity for the design of an ammonia stripping tower.

Besides the surface tension, the difference in the ammonia partial pressures between the liquid and the gaseous phases is actually the driving force causing the interfacial gas transfer. The maximum transfer rate will occur when there exists a maximum difference in the partial pressures. With a given ammonia concentration, the partial pressure in the liquid phase is constant. The ammonia partial pressure in the gaseous phase can be minimized by supplying an ample amount of air flow to dilute the concentration of the ammonia released into the gaseous phase. Therefore, the amount of air supply also affects the gas transfer rate.

4. **Air Supply Rate.** Because the difference in the ammonia pressures between the liquid and gaseous phases is the force for ammonia to transfer from the liquid to the air flow, an ample supply of air flow through the ammonia tower will dilute the concentration of the ammonia released thereby reducing its partial pressure in the gaseous phase and maximizing the ammonia release rate. The amount of air that is required to achieve a given degree of ammonia removal can be determined from the following analysis of the material balance (14):

$$L_q(x_1 - x_2) = G(y_1 - y_2) \quad (14)$$

where L_q = liquid flow through the stripping tower, moles water/unit time; x_1 = inlet water ammonia concentration, moles ammonia/mole water; x_2 = outlet water ammonia concentration, moles ammonia/mole water; G = air flow rate through the stripping tower, moles air/unit time; y_1 = outlet air ammonia concentration, moles ammonia/mole air; and y_2 = inlet air ammonia concentration, moles ammonia/mole air.

If it is assumed that the water leaving and the air entering the stripping tower have a zero ammonia concentration, then Eq. (14) can be rewritten as

$$L_q x_1 = G y_1 \quad \text{or} \quad \frac{G}{L_q} = \frac{x_1}{y_1} \quad (15)$$

That is, the amount of air requirement per unit volume of water, G/L_q , is equal to x_1/y_1 , or the concentration of ammonia in the inlet water (mole/mole) divided by the ammonia concentration in the outlet air.

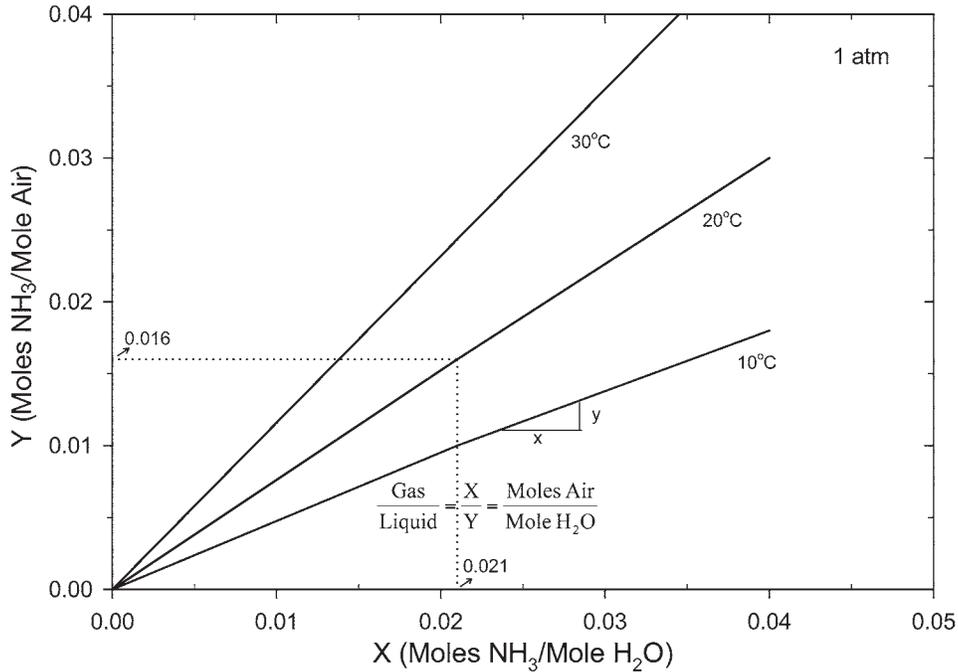


Fig. 6. Equilibrium distribution of ammonia in air and water under one atmospheric condition.

At a given temperature and atmospheric pressure, the molar ratio of ammonia saturated in the outlet air and in the inlet water can be assumed to remain constant according to Henry's law, which can thus be used to determine the respective moles of ammonia in a mole of air as a function of the moles of ammonia in a mole of water. Tchobanoglous (14) has prepared a set of curves showing the equilibrium distribution of ammonia in air and water at various temperatures under the condition of atmospheric pressure (Fig. 6). Using Eq. (15) and Fig. 6, the theoretical requirement of air for the ammonia-stripping operation at 100% efficiency can be calculated. For example, at a water temperature of 20°C and an influent ammonia concentration of 20 mg/L, the theoretical air requirement is calculated as follows:

$$\begin{aligned} \text{Inlet water NH}_3 \text{ conc.} &= 20 \text{ mg/L} = 20 \times 10^{-3} \text{ g/100g} \\ &= \frac{20 \times 10^{-3}}{17} \div \frac{1000}{18} \\ &= 0.021 \times 10^{-3} \text{ mole NH}_3/\text{mole H}_2\text{O} \end{aligned}$$

From Fig. 6, this corresponds to an ammonia concentration of 0.016×10^{-3} moles/mole in the outlet air when it is in complete equilibrium with the ammonia concentration in the influent water. Using Eq. (15), the theoretical air requirement becomes:

$$\begin{aligned} \frac{G}{L_q} = \frac{x_1}{y_1} &= \frac{0.021 \times 10^{-3}}{0.016 \times 10^{-3}} \\ &= 1.315 \text{ mole air/mole water} \end{aligned}$$

$$\begin{aligned} \text{and } 1.315 \text{ moles air} \times 22.4 \text{ liters/mole} \times 1 \text{ ft}^3/28.3 \text{ L} \\ = 1.04 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} \text{also, } 1.0 \text{ mole water} \times 18 \text{ gal/mole} \times 1 \text{ lb/454 g} \times 1 \text{ gal/8.34 lb} \\ = 0.00475 \text{ gal,} \end{aligned}$$

so

$$\begin{aligned} \frac{G}{L_q} &= \frac{1.04 \text{ ft}^3}{0.00475 \text{ gal}} \\ &= 219 \text{ ft}^3 \text{ air/gal water} \end{aligned}$$

Because all the curves in Fig. 6 are straight lines, and because the ratio of X/Y is a constant at a given temperature, regardless of the ammonia concentration in the influent water, the theoretical air requirement is dependent on only the water temperature and not on the influent ammonia concentration. This calculation of the theoretical air requirement is based on an operating efficiency of 100%, which is not achievable in actual practice. Therefore, for actual design, to obtain more than 90% ammonia-stripping efficiency it has been recommended that the design air requirement be 1.5 times the theoretical value (14). Another design approach is to use some empirical data or curves relating to the tower packing characteristics based on the concept of the height of a transfer unit vs the G/L_q ratio. These data can be obtained from the manufacturer.

5. **Hydraulic Loading Rate.** The hydraulic loading rate on the stripping tower can affect the ammonia removal in two ways. First, for a fixed tower depth, the larger the hydraulic loading rate, the shorter is the air–water contact period. Below a certain critical contact time the ammonia-stripping efficiency will be reduced drastically. Second, for a given internal packing configuration, if the hydraulic loading rate is too high, it may cause sheeting of the water, which reduces the intensity of droplet formation, thus decreasing the ammonia-stripping efficiency. For most ammonia-stripping operations, using a 6–7 m (20–24 ft) tower with an internal packing of 3.8×5 cm (1.5 \times 2 in.), a hydraulic loading rate between 0.04 and 0.12 $\text{m}^3/\text{min}/\text{m}^2$ (1 and 3 gpm/ft^2) is recommended.

Using Eq. (15) and Fig. 6 will give only a theoretical value for the air requirement for a given ammonia removal based on the assumption that the ammonia concentration in the outlet air is in absolute equilibrium with that present in the influent wastewater. This is rarely true in actual practice. Therefore, actual design calculations are somewhat more complicated.

Smith (15) has presented a practical ammonia-stripping tower design based on the concept of the height of transfer unit vs the gas/liquid ratio for a given type of tower packing. He has provided a sample design problem.

A. Design Information

1. Feed stream characteristics
 - a. average water flow, Q , MGD
 - b. peak water flow, Q_{max} , MGD
 - c. water temperature, T , °F
 - d. ammonia nitrogen concentration in water, X_1 , mg/L
 - e. pH of water
 - f. wet bulb temperature, °F
2. Required effluent characteristics
 - a. ammonia nitrogen concentration in water, X_2 , mg/L
3. Design decisions
 - a. liquid loading rate, L_q , lb $\text{H}_2\text{O}/\text{h}\text{-ft}^2$
 - b. gas loading rate, G , lb air/h-ft²

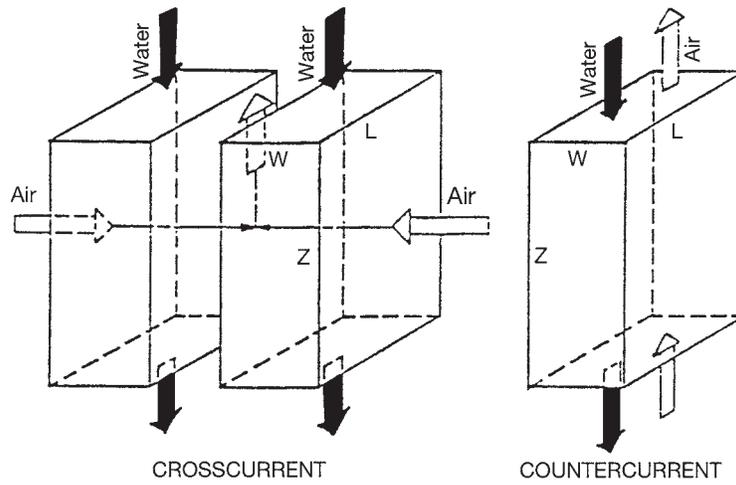


Fig. 7. Configuration of crosscurrent and countercurrent ammonia-stripping towers.

- c. tower width, W , ft
 - d. excess capacity factor
4. Packing characteristics (can be obtained from manufacturer)
 - a. ammonia-stripping height of a transfer unit (ft) vs gas/liquid ratio
 - b. height of a transfer unit (ft) for cooling vs gas and liquid loading rates
 - c. pressure drop characteristics as a function of gas loading
- B. Design Procedure**
1. *Selection of a Pretreatment Method:* This includes the determination of the chemical to be used for raising the liquid pH and also the level to which it must be raised. In general, lime is the cheapest chemical to raise the pH. If the pretreatment is also intended for removing both phosphorus and suspended solids, the pH should be raised to between 10.5 and 11.0, which normally requires a hydrated lime dosage of about 400 mg/L for domestic sewage, as shown in Fig. 5.
 2. *Determination of the Ammonia Removal Efficiency Required:* Design is generally based on the average concentration of ammonia nitrogen present in the tower effluent. This value is normally dictated by the required regulation.
 3. *Selection of Tower Type, Geometry, and Areal Loading Rate:* The first design decision is whether to use crosscurrent or countercurrent flow, which are illustrated in Fig. 7. Next, the liquid loading rate must be fixed in the general range of 500–1000 lb $H_2O/h\text{-ft}^2$. The gas/liquid loading ratio, G/L_q [(lb air/h-ft²)/(lb water/h-ft²)], is selected next with a normal value between 2 and 4. For countercurrent towers, the G/L_q ratio will determine the maximum percentage removal possible. The tower width must also be selected by the designer. In general, the wider the tower, the less efficient is the stripping operation for the crosscurrent tower. However, for the countercurrent tower, the effectiveness is independent of the tower width. Both the ammonia concentration and the flow are likely to vary diurnally and seasonally. The design can be based on either the average (usually) or the peak conditions depending on the nature of the effluent requirement. In any case some excess or duplicate capacity should be provided for shut-down and repair or cleaning.
 4. *Determination of Packing Characteristics:* The packing characteristics are normally obtained from the tower manufacturer. Figure 8 illustrates the relationship between the height of a transfer unit for ammonia stripping and the G/L_q ratio for one type of packing

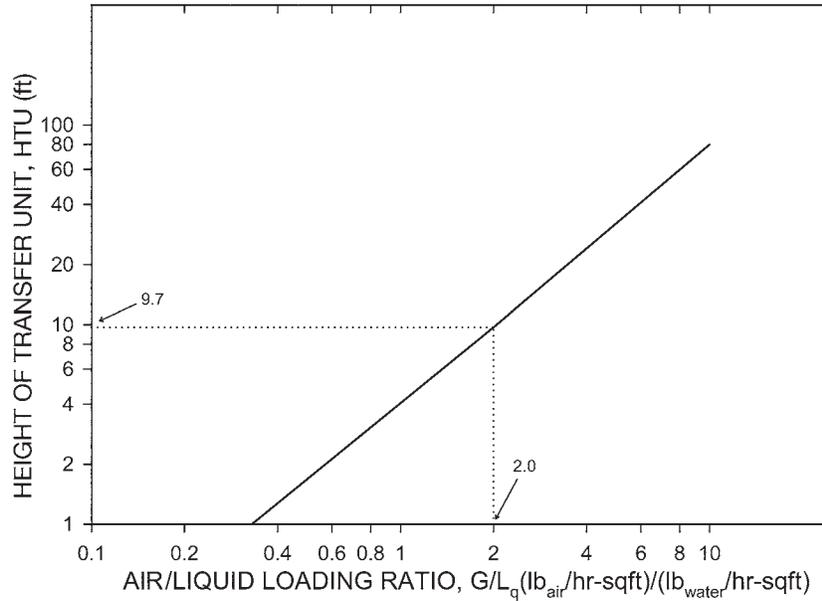


Fig. 8. Typical relationship between the height of transfer unit and the gas/liquid ratio for one type of packing for crosscurrent tower (15).

used in the crosscurrent operation (15). The use of this relationship in the actual stripping tower design is explained in the following example. It must be noted that these data must be obtained from actual test observations for a specific packing.

5. *Sizing of Countercurrent Towers:* The cross-sectional, or plan, area of the tower must be calculated first. For this, the liquid loading rate for the tower, Q_w , lb/h, is determined from the flow rate, Q , MGD, by the equation:

$$Q_w = Q \times \left(\frac{8.34}{24} \right) \times 10^6 \quad (16)$$

where 8.34 is the water density in lb/gal and 24 converts days to hours.

Using the liquid loading rate, L_q , (lb/h-ft²) selected in step 3, the plan area can be calculated using

$$\text{Plan area} = \frac{Q_w}{L_q} \quad (17)$$

The length and width of the tower can be selected in any way that gives the required plan area (referring to standard manufacturers' equipment design).

Based on the plan area, the height of the tower required to give the desired degree of ammonia removal can be calculated. For a countercurrent tower assuming a constant water temperature throughout the towers:

$$Z = \frac{\text{HTU}}{A-1} \ln \left[\frac{(A-1)X_1 + X_2 - (G_m/L_q)Y_2}{(A-1)X_2 + X_2 - (G_m/L_q)Y_2} \right] \quad (18)$$

where Z = countercurrent tower height, ft; HTU = height of a transfer unit, ft; $A = H_c G_m / L_m$ or $H_c (G/29) / (L/18)$, where H_c is Henry's constant = $0.1117e^{0.02612T}$, T is the temperature,

$^{\circ}\text{F}$, G_m is the gas loading rate, lb-moles/ft²-h, L_m is the liquid loading rate, lb moles/ft²-h; X_1 = ammonia concentration in the inlet water, mg-N/L; X_2 = ammonia concentration in the outlet water, mg-N/L; Y_1 = ammonia concentration in the outlet air, mg-N/L; Y_2 = ammonia concentration in the inlet air, mg-N/L (normally considered to be zero).

6. *Calculation of Pressure Drop through the Tower:* The electrical power requirement for the fan is determined by the pressure drop through the tower packing. The pressure drop is directly proportional to the air velocity head, $(1/2\rho)v^2$. Concentration of mass can be expressed as $Q = \rho Av$, where Q is lb air/h; A = area, ft²; v is air velocity, ft/h; and ρ is the air density, lb/ft³. The gas loading rate, G , in units of lb/h-ft² is, therefore, equal to ρv . The pressure drop through the tower will therefore be expressed as a constant times G^2/ρ . The constant is a characteristic of the packing and must be obtained from the manufacturer of the packing.
7. *Sizing of Crosscurrent Towers:* Crosscurrent towers are normally built in two identical sections as shown in Fig. 7 so that the air can flow into a common central channel between the two sections and out the top of the tower. For a crosscurrent tower, the liquid loading rate is selected first. The total flow through the tower is divided by 2 and this flow is used to size one of the two sections. Therefore, the plan area of each section is computed as follows:

$$\text{Area of each section} = \frac{Q}{2L_q} \times \frac{8.34}{24} \times 10^6 \quad (19)$$

The width of the tower must be selected by the designer. Because the plan area of one section has been computed by Eq. (19), the length equals the plan area divided by the tower width. Both sections have the same height, Z , and the procedure for finding height is as follows. For a tower of infinitesimal width, the removal of ammonia nitrogen down the tower can be represented by:

$$X = X_1 \exp \left[\frac{-(H_c G_m) \times Z}{L_m \times \text{HTU}} \right] \quad (20)$$

where Z = tower height, ft and X = ammonia concentration at Z ft down the tower, mg-N/L and all other terms the same as for Eq. (18).

Because the term $H_c G_m / L_m$ is a constant based on the temperature and the preselected air/liquid loading, X/X_1 vs Z/HTU should plot as a straight line on semi-log paper as shown in Fig. 9. Various plots will result depending on the temperature and the G/L_q ratio. Therefore, if X/X_1 is known and HTU has been determined as a function of the G/L_q ratio in Fig. 8, the value of Z/HTU can be selected from Fig. 9. Subsequently, the tower height, Z , can be calculated as

$$Z = \text{HTU (from Fig. 10)} \times Z/\text{HTU (from Fig. 9)}$$

The difficult part of the design is developing the plot of X/X_1 vs Z/HTU (Fig. 9). Because the plot is known to be a straight line, only two points need to be determined to obtain the desired plot. One point can be at the top of the tower where $Z/\text{HTU} = 0$ and $X/X_1 = 1.0$. Therefore, only one other point needs to be calculated to establish the desired line. It has been found by means of computation that the value of X/X_1 at the $Z/\text{HTU} = 1.0$ level from the top of the tower can be correlated to W/HTU as shown in Fig. 10. Therefore, Fig. 9 can be obtained by selecting a G/L_q ratio, obtaining an HTU value from Fig. 8, selecting a width, calculating W/HTU , and determining X/X_1 from Fig. 10. At the selected G/L_q ratio and temperature, the value of X/X_1 can be plotted vs $Z/\text{HTU} = 1$ to obtain Fig. 9. This design relationship holds over a range of influent ammonia concentrations from 20 to 2000 mg-N/L.

8. *Costs of Installing and Operating the Tower:* The capital and operating costs of the ammonia-stripping tower will depend on the design, but reliable cost information must be obtained

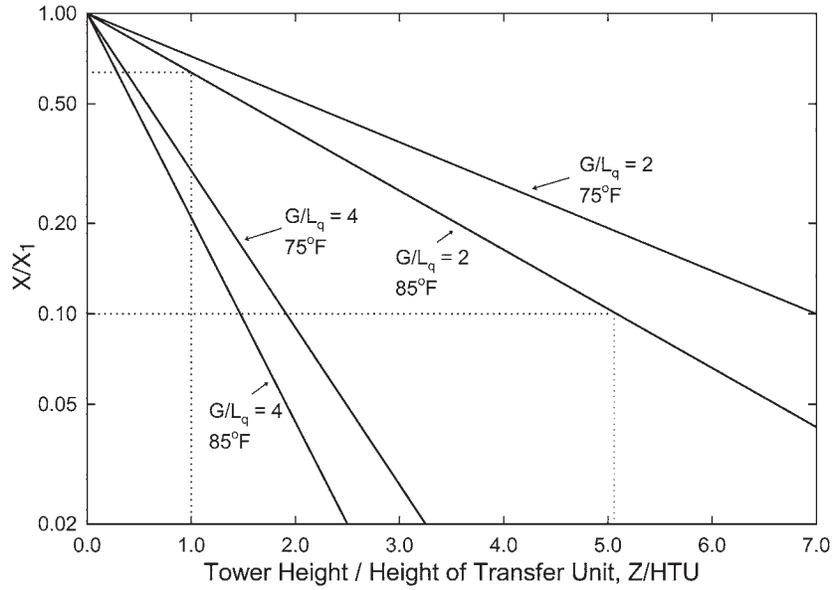


Fig. 9. Example of design relationship of Z/HTU vs X/X_1 for ammonia stripping tower (15).

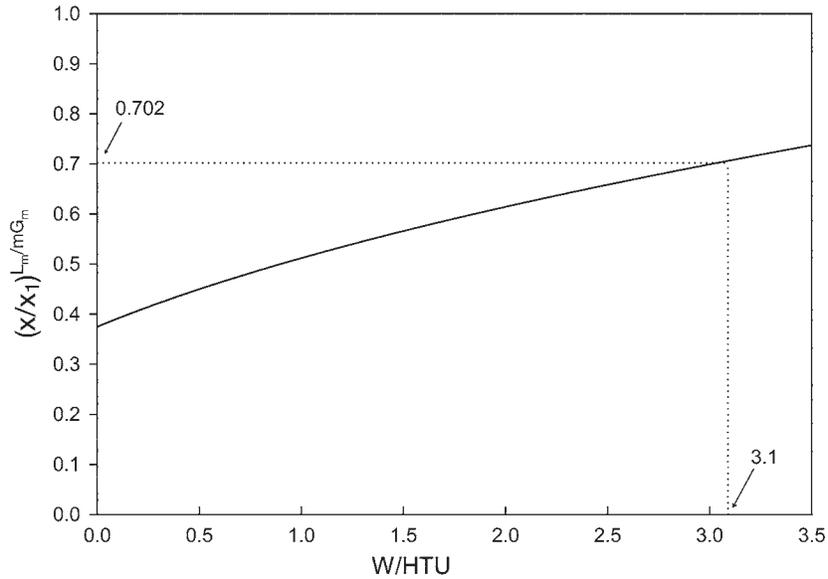


Fig. 10. Typical design relationship of W/HTU vs $(X/X_1)^{L_m/mG_m}$ at $Z/HTU = 1.0$ (15).

from the equipment manufacturer. In South Tahoe, a tower having a plan area of 900 ft² and a height of 24 ft with a nominal capacity of 3.75 MGD was installed at a cost of \$310,000 based on the 1969 FWPCA STP Construction Cost Index of 127.1 (12). This is equivalent to about \$8.00/MG if the investment is amortized at 5% interest over 25 yr. Costs for operation and maintenance are about \$8.75/MG.

Table 1
Required Design Data for the Example Problem

1. Feed Stream Characteristics:
a. average water flow, Q , 10 MGD
b. peak water flow, 25 MGD
c. water temperature, T , 85°F
d. ammonia concentration in water, X_1 , 20 mg/L as N
e. pH of water, 11.0
f. wet bulb air temperature, 75°F
2. Required Effluent Stream Characteristics:
a. ammonia concentration, X_2 , 2.0 mg/L as N
3. Design Decisions:
a. liquid loading rate, L_q , 500 lb H ₂ O/h-ft ²
b. gas loading rate, G , 1000 lb air/h-ft ²
c. tower width, W , 60 ft
d. excess capacity factor, 1.2
4. Packing Characteristics (from manufacturer):
a. ammonia stripping height of a transfer unit (ft) vs gas/liquid ratio (see Fig. 8)
b. height of a transfer unit (ft) for cooling vs gas and liquid loading rates
c. pressure drop characteristics as function of gas loading

Some other representative cost relationships can also be found in this reference (12), but these cannot be used as a substitute for data from the supplier. In general, the equipment costs include the following components: fans, water pumps to deliver the water to the top of the tower, tower structure and packing, exterior covering, and electrical installation. The principal operating and maintenance costs are electrical power for pumping water and air, operating and maintenance labor, and chemicals to raise the pH.

C. Example Design Problem for a Crosscurrent Tower

The design data shown in Table 1 are to be used to design a crosscurrent ammonia-stripping tower. The wastewater to be treated is municipal sewage that has been treated by activated sludge followed by lime clarification. A 90% ammonia removal efficiency is desired. The packing is assumed to have the characteristics shown in Fig. 8.

1. Calculate the gas/liquid loading rate ratio:

$$\frac{G}{L_q} = \frac{1000 \text{ lb air/h} \cdot \text{ft}^2}{500 \text{ lb H}_2\text{O/h} \cdot \text{ft}^2} = 2.0$$

2. Calculate the plan area of the tower and its length:

$$\begin{aligned} \text{Plan area of each section} &= \frac{Q}{2L_q} \times \frac{8.34 \times 10^6}{24} \\ &= \frac{10}{2 \times 500} \times \frac{8.34 \times 10^6}{24} \\ &= 3475 \text{ ft}^2 \end{aligned}$$

Because the total tower width is 60 ft (in two sections), the width of each section is 30 ft. Thus, the length of the tower is 3475/30 = 116 ft. That is, the crosscurrent tower will consist of two sections, each 30 ft wide and 116 ft long.

3. Calculate tower height, Z :
- $G/L_q = 2.0$
 - Calculate Henry's law constant, H_c , at 85°F and $H_c G_m/L_m$:

$$H_c = 0.1117e^{0.02612 \times 85} = 1.02866$$

$$G_m = 1,000/29 = 34.5$$

$$L_m = 500/18 = 27.8$$

$$H_c G_m / L_m = 1.029 \times 34.5 \div 27.8 = 1.277$$

- Obtain the value of HTU from Fig. 8:
 $G/L_q = 2.0$; thus, from Fig. 8, HTU = 9.7 ft
- Calculate W/HTU :
 $W/HTU = 30/9.7 = 3.1$
- From Fig. 10 at $W/HTU = 3.1$, obtain:

$$\left(\frac{X}{X_1} \right)^{\frac{L_m}{H_c G_m}} = 0.702 \text{ at } Z/HTU = 1.0$$

Thus, to obtain X/X_1 at $Z/HTU = 1.0$, the value of 0.702 must be raised to the $H_c G_m / L_m$ power:

$$\frac{X}{X_1} = (0.702)^{1.277} = 0.636 \text{ at } Z/HTU = 1.0$$

- Correlate X/X_1 vs Z/HTU :
At the top of the tower, $Z/HTU = 0$; $X/X_1 = 1.0$
At $Z/HTU = 1.0$, $X/X_1 = 0.636$
With these two points, plot a straight line as shown in Fig. 9 (for $G/L_q = 2.0$ and $T = 85^\circ\text{F}$)
- Obtain the value of Z/HTU from Fig. 9:
At $X/X_1 = 0.1$ (for 90% ammonia removal efficiency),
 $Z/HTU = 5.1$
- Calculate the tower height:
 $Z = (\text{HTU from Fig. 8}) \times (Z/HTU \text{ from Fig. 9})$
 $= 9.7 \times 4.5 = 49.5 \text{ ft.}$

The above calculation has assumed that the water temperature (85°F) has remained unchanged down the tower. In reality, the water temperature will tend to approach the wet bulb temperature of the air. Because the water temperature will never drop below the wet bulb temperature, the wet bulb temperature can thus be used as a limit of reduced performance.

Therefore, the above computation procedure can be repeated with the water temperature of 75°F. Henry's law constant, H_c , will have a value of 0.793 and $H_c G_m / L_m$ will have a value of 0.985. Raising 0.702 to this power gives 0.706. The upper line for a G/L_q ratio of 2 in Fig. 9 would represent the limit of reduced performance due to cooling of the water. With this temperature cooling effect, the maximum tower height required is:

$$Z = 9.7 \times 6.8 = 66 \text{ ft}$$

4. Optimization of tower height and the G/L_q ratio: Because these tower heights are large, it is necessary to examine the effect of increasing the G/L_q ratio to 4. From Fig. 8, read HTU as 23.5 ft. Thus, width/23.5 is 1.278. Enter Fig. 10 and read 0.545 for

$(X/X_1)^{L_m/H_c G_m}$. For 85°F, $H_c G_m/L_m = 2.56$ and the intercept is 0.21. At 75°F, $H_c G_m/L_m = 1.97$, and the intercept is 0.302. These two lines are also shown in Fig. 9. Thus, for a value of G/L_q of 4.0, the values of Z/HTU for $X/X_1 = 0.1$ are 1.49 for 85°F and 1.95 for 75°F. The height of the tower at 85°F is $1.48 \times 23.5 = 34.8$ ft, whereas at 75°F it becomes $1.95 \times 23.5 = 45.8$ ft. This shows that setting the G/L_q ratio to 4.0 instead of 2.0 would result in a shorter tower. The amount of air required, however, is not doubled: 34.8×2 divided by $49.5 = 1.40$. Thus, at this higher air loading rate, only 40% more air is required. To find the optimum G/L_q ratio, the entire design must be priced and the minimum cost tower selected. This requires repetitive calculations using a computer and incorporating reasonably accurate cost data as well as mass transfer, enthalpy transfer, and pressure drop characteristics on the detailed analysis. To complete the design, the pressure drop through the two sections must be computed from the manufacturer's data. The cost of the structure, packing, and pumps must be computed. The electrical power consumption can be computed from the air pressure drop and the height of the tower together with the volume flows of air and water.

D. Example Design Problem for a Countercurrent Tower

The same design conditions used for the crosscurrent tower will also apply to the countercurrent tower in this problem. Because we have no valid data for the height of a transfer unit for the packing used in the countercurrent configuration, we will use the same value of 9.7 ft for the purpose of illustration.

1. The values of $G/L_q = 2.0$, $H_c = 1.02866$ at 85°F and 0.793 at 75°F, and total plan area = 6950 ft² are calculated the same as for the crosscurrent tower. The term $A = H_c G_m/L_m$ has a value of 1.277 at 85°F and 0.985 at 75°F.
2. Using Eq. (18) for a removal of 90%, the value of Z/HTU at 85°F is 3.906; so the tower height is $3.906 \times 9.7 = 37.9$ ft. The corresponding crosscurrent tower height was calculated to be 49.5 ft. However, at 75°F, the value of Z/HTU is 9.82; so the tower height becomes $9.82 \times 9.7 = 95.3$ ft. This is larger than the value of 66 ft calculated for the crosscurrent tower.

This demonstrates how the countercurrent design may become prohibitive if performance above a certain level is required. Furthermore, in most instances the water within the tower will be cooled, and Henry's law constant will be lower. This would result in less efficient gas transfer near the bottom of the tower. This effect can be evaluated on the computer program, but not in hand calculations. This example simply delineates the maximum and minimum possible tower heights, and shows the necessity for consideration of the effect of cooling.

7. WATER QUALITY PROBLEMS

When the water entering an air stripper contains inorganic substances near the limits of their solubility, precipitation of these metals or minerals within the air stripper may occur. At the aeration nozzle, ferrous iron in solution oxidizes and precipitates as insoluble ferric oxides. Manganese may also be oxidized to an insoluble form within the air stripper. Carbonate or bicarbonate ions may form an insoluble scale. The result is that the nozzle and packing material in the air stripper may become encrusted, and the efficiency of mass transfer is reduced. In a case study at a hazardous waste site, poor removal of benzene, trichloroethylene, and other volatile organics were achieved by air stripping (16). Coating of the packing material by iron and manganese was cited as the culprit.

Where air stripping is used in conjunction with other water treatment processes such as flocculation, the positioning of the air stripper in the supply flow stream may be important. Positioning of the stripping tower downstream of the flocculation unit has been accomplished successfully where strict control over the quantities of floc particles released into the water stream has been maintained.

Two approaches are used to prevent precipitation of inorganics in the air stripper. A chelating system introduces an agent that binds with the inorganic material that would otherwise precipitate. Citric acid is often used to keep iron in solution as it passes through the air stripper. A second approach is the use of a sequestering agent that reduces surface tension within the system and thereby prevents encrustation.

The efficiency of an air stripper may also be impeded by biological fouling. Large populations of microorganisms are often found in water contaminated by volatile organic compounds, because these compounds serve as a nutrient source for certain species of bacteria. At installations in metropolitan areas or proximate to sewage treatment facilities, coliform bacteria are often present in large numbers. The organisms are not destroyed by the air-stripping process; rather, the air stripper may provide an environment conducive to their progeneration. Hand et al. (8) reported increases in coliform counts between air stripper influent and effluent on three sampling dates. Field inspections under these conditions often reveal accumulations of these organisms on the packing material, drastically reducing removal efficiency.

The most common method for reducing the numbers of these organisms is by chlorination of the influent water. Periodically, it may be necessary to clean and disinfect the air stripper by “shocking” the tower with acid or chlorine, or by surging the tower with peroxide. Routine inspections and cleaning of the air stripper must be considered normal maintenance and a part of the operational expense. In addition, corrosional effects and an increase in the formation potential of THMs (trihalomethanes: chloroform and bromoform) may result from chlorination.

8. OFF-GAS EMISSIONS

Air stripping removes VOCs (volatile organic compounds) from water by facilitating their transfer to the gaseous phase where presumably by dilution they become less hazardous. In some cases, however, the ambient air quality is sensitive enough to require discharge limitations on point sources as small as an air stripper. Although it is easier to control the air effluent from an air stripper than from a process such as mechanical aeration, the potential environmental impacts and costs for treatment of such emissions, if required, require consideration from the earliest design phases.

Dispersion modeling techniques have been developed over the past decade that allow accurate evaluation of the ground-level concentrations of a pollutant emanating from a single point source. One such method is PTPLU (from PoinT PLUme), an algorithm based on Gaussian plume modeling concepts, developed by the US EPA (17). The model has input parameters for the height of the discharge stack, the quantity and concentration of pollutant, the wind speed and meteorological stability, the height of the receptor, and other variables. This program permits the analysis of potential air quality effects that would originate as a result of an air stripper installation.

When it is determined that an air-stripper gas effluent will require treatment, a conventional method for the reduction of air emissions is the use of GAC (granular activated carbon). GAC will usually provide suitable adsorption of airborne VOCs (16).

In a report produced for the API (American Petroleum Institute) (10), the annual cost estimate presented for the treatment of off-gas using GAC was shown to approach 50% of the total annual cost for removal and treatment of phase-separated hydrocarbons and groundwater at a petroleum spill site. Although the cost of treating the air stripper off-gas in this fashion in some cases equals the cost of using GAC as the primary water treatment method, the two technologies are frequently used in conjunction when the influent levels of VOCs are high. Some states require that air-stripper gas effluent be treated, but do not specify a treatment level, posing a theoretical, but not substantial, cost obstacle to the use of air stripping as a viable treatment alternative.

A technology that has recently been applied to the abatement of off-gas emissions is catalytic incineration. At this time the unit cost is high (approaching \$30,000) and yearly operational costs uncertain due to the necessity of supplying heat to promote complete combustion of the VOCs. This technology will nonetheless provide substantial cost savings over GAC, particularly for large systems where high concentrations of contaminants are encountered in the air effluent.

Even where off-gas treatment adds significant costs to the treatment process, air stripping may still be clearly indicated as a primary treatment technology. GAC and other treatment methods are not capable of sufficient removal of some species of volatile organic compounds, and are often used in conjunction with gas stripping.

9. CAPITAL AND OPERATIONAL COST ANALYSIS

9.1. *Minimizing Power Costs*

Methods to select the correct tower dimensions and operating parameters were discussed previously. Some latitude exists in the selection of the air-to-water ratio, gas-pressure drop, and tower height that will produce desired removal rates of a target compound. The goal of design, using these concepts, is to produce a system operating in a region favorable to each parameter, and therefore, not overly sensitive to small variations in each.

Increasing tower height or air-to-water ratio was shown by the design equations to effect greater removals of volatile contaminants. Hand et al. (8) showed that for trichloroethylene at three different gas-pressure drops, decreasing the air-to-water ratio below approx 30:1 necessitated exponential increases in the height of the air stripper to maintain removal efficiency. Figure 11 illustrates the typical relationship between tower height and the air-to-water ratio at various gas pressure drops. Hand et al. (8) shows that for air stripping of trichloroethylene at air-to-water ratios below approx 30:1, water pump brake power requirements increased sharply as did tower height, but that at higher air-to-water ratios, blower requirements increased. Typical relationships between pump and blower break power and the air-to-water ratio at various gas pressure drops are shown in Fig. 12. Roberts and Levy (4) performed a similar energy-cost analysis for removal of chloroform by air stripping. He achieved results similar to Hand et al., finding that energy requirements for removal of chloroform were minimized by maintaining an air-to-water ratio of approx 30:1.

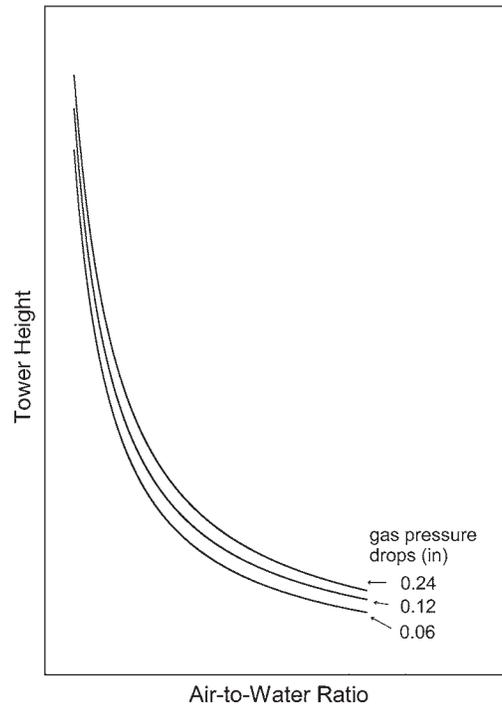


Fig. 11. Typical relationship between tower height and the air-to-water ratio at various gas pressure drops.

Selection of an appropriate packing material will have a direct effect on the capital cost of the air-stripper system and an indirect effect on the operational cost. Selecting a packing with a high packing factor such as Berl Saddles or Raschig Rings may provide the maximum available surface area for mass transfer and thereby minimize tower dimensions, but may also produce an unacceptable pressure drop and associated operational costs. More detailed information of the packing materials can be found in ref. 18 or obtained from the manufacturers. A packing factor with a high unit price may offer a large surface area combined with a reasonably low pressure drop, and thereby compensate for the initial price differential by offering increased removal efficiency and lower blower power requirements. Hand et al. (8) found that for a twofold increase in tower volume a gas-pressure drop from 0.49 to 0.06 in. H_2O/ft occurred, resulting in a 70% decrease in power requirements.

Design equations are combined with cost-modeling techniques described in the literature (19) to optimize system design and minimize energy requirements. The capital cost savings afforded by using readily available production air-stripper assemblies must be balanced against the operational cost savings represented by the most efficient design in order to assess the total system cost.

9.2. Comparisons of Capital and Operational Costs

The large surface area of the packing in an air stripper promotes the transfer of volatile organic compounds to the vapor phase without undergoing any reaction with

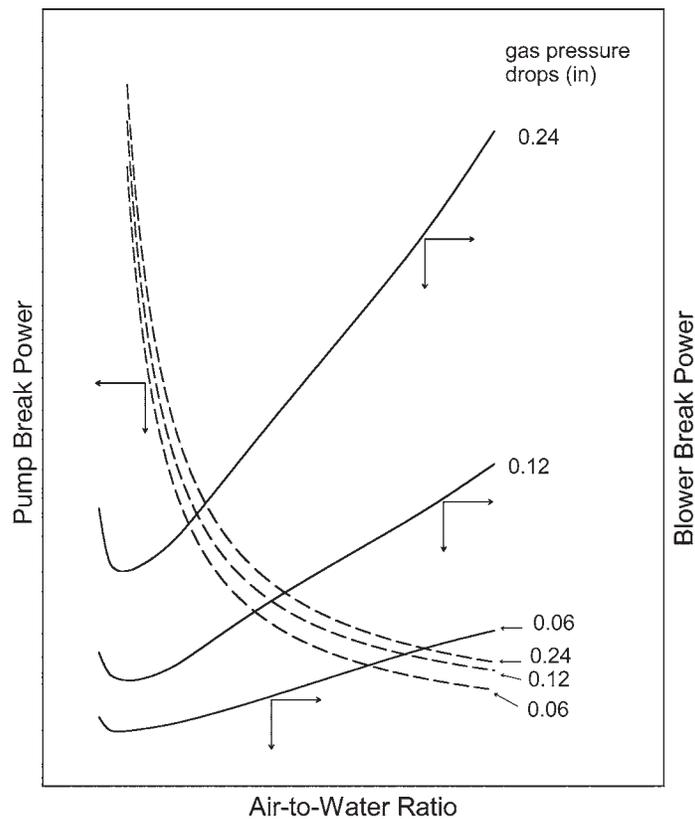


Fig. 12. Typical relationship between pump and blower break power and the air-to-water ratio at various gas pressure drops.

these compounds. An air stripper may be expected to remove contaminants from a water for years provided that maintenance to prevent and remove fouling of the packing is performed. Cost comparisons with treatment mechanisms that require regeneration, such as GAC, are favorable.

Influent water quality, effluent water quality requirements, and total system capacity are the major factors that determine the cost of a water treatment system. Capital and operational costs for air-stripper systems increase with the concentrations of the volatile organic compounds to be removed. Taller packed towers and higher air-to-water ratios required for greater removals increase the blower and pump power requirements. At low concentrations, however, operating costs appear to be equally affected by the mass-transfer coefficient of the target compound (18). The costs for removing low levels of TCE are nearly twice those for removing vinylidene chloride, a compound with a much higher Henry's constant.

Prior to installation of an air stripper (20) to remove TCE, DIPE, and MTBE from a municipal water supply, GAC had been used for this purpose. Carbon bed life had decreased to 4–6 wk shortly before the air stripper was put on-line, at a regeneration cost of \$32,000 per replacement. The total capital cost for the GAC system was approx \$200,000, while the installed cost of the air stripper was approx \$375,000. The yearly

operational cost savings provided by switching to air stripping exceeded \$100,000. Following air stripper start-up, the GAC system was initially maintained to “polish” the air-stripper effluent, but the air stripper proved to be so effective that the carbon units were placed on stand-by. The production wells were capable of increased yield as a result of the elimination of the head loss imposed by the carbon units.

Analysis of influent water quality prompted the selection of air stripping over GAC for treatment of a contaminated surface water supply (7). Although the carbon units provided good adsorption of TCE, rapid breakthrough of 1,1-dichloroethane and 1,1,1-trichloroethane was noted.

An air-stripping system designed to minimize energy requirements (8) was installed to remove volatile organic compounds at levels between 200 and 250 $\mu\text{g/L}$ from drinking water supplied by a municipal well field. The system was capable of treating 2.16 MGD (8,176 m^3/d) at effluent levels not exceeding 10 $\mu\text{g/L}$ total VOCs. Total installed cost was approx \$200,000, and operational costs were less than \$20,000/yr.

Sites where petroleum losses to the subsurface have occurred are typified by high levels of dissolved hydrocarbons in the groundwater. Increasingly, the presence of gasoline additives, such as MTBE, is also found. When used to treat groundwater contaminated by these volatile organic compounds, rapid breakthrough of GAC systems occurs. Air stripping offers substantial capital cost savings and overwhelming operational cost savings when compared to GAC under these conditions (10). Capital and operational costs for air stripping are not as sensitive to influent water quality and flow rate as are costs for carbon.

Air stripping is not suited to the removal of non-volatile organic compounds. These compounds may be successfully removed by adsorption on carbon, however. The installation of an air stripper and GAC in a water treatment system is a frequent practice. The air stripper greatly extends the bed life of the carbon by removing the bulk of the volatile organic compounds, while the carbon unit removes the remaining compounds that are not amenable to air stripping. The resulting operational costs are higher than the costs for air stripping alone, but significantly lower than the costs for treatment with GAC alone (10,38).

10. RECENT ADVANCEMENTS

Air-stripping processes using crosscurrent and countercurrent packed towers have been well developed and practiced in the last decade. The processes have been extensively applied for ammonia stripping, groundwater remediation, and industrial wastewater (ammonia and VOCs) stripping (21–24,38). Crosscurrent stripping was found to be an advantage over the conventional countercurrent stripping because the mass-transfer coefficient in crosscurrent operation is insensitive to the gas flow rate, thereby allowing a high air-to-water ratio, G'/L' , without chances of flooding (21). Crosscurrent stripping also offers a significant economic advantage over countercurrent stripping due to the savings in energy costs, when the target contaminants are considerably less volatile (23). However, the drawback of applying a high air-to-water ratio in crosscurrent stripping is the increased cost of off-gas treatment. Details can be found in Tables 4 and 5 in ref. 23.

With progressive development of the computer technology, substantial advancement has been made in the area of developing models to simplify the air-stripping tower design

procedure so that the tower configuration associated with tower performance can be optimized and the overall cost (sum of capital and operating costs) associated with installation and operation can be minimized (22,23,25–29). The relationships of optimum design parameters to Henry's law constants and the sensitivity of tower overall cost to specific design parameters can be well demonstrated by computer simulation (23). By computer iteration, these programs provide a quick prediction of the tower performance with limited inputs of design parameters. However, these models may suffer from underestimation or overestimation of the actual costs (23), especially when the designing engineers are facing unfamiliar packing materials or contaminants. Under this circumstance, these models may only be used as a preliminary screening and evaluation tool. In most cases, further pilot-scale testing is needed.

One limitation of these proposed models comes from the uncertainty of the estimated mass-transfer coefficients. The Onda correlations (30) are most commonly used for estimating mass transfer of volatile chemicals from water during air stripping with random packings. However, the correlations are only valid for liquid loading rates between 1.1 and 63 gpm/ft² (0.8 and 43 kg/m²-s), gas loading rates between 2.206 and 267.9 cfm/ft² (0.014 and 1.7 kg/m²-s), and nominal packing sized up to 2 in. (0.0508 m). The Onda correlations were found to be fairly inaccurate to predict mass transfer with large random packings, especially at high gas flow rates and when the gas-side resistance is large (31). It has been reported that the Onda correlations under-predicted k_G for the saddles by about 40% on average and over-predicted k_G for the spheres by more than 50% (32). Advancement in estimating mass-transfer coefficients has been made. Little and Selleck (33) have proposed new mass-transfer correlations for two types of packing in a crossflow tower based on experimental data, while Piche et al. (34) applied artificial neural network (ANN) modeling to predict mass-transfer coefficients.

Thom and Byers (35) discussed the design and construction issues that can lead to the inaccurate model predictions compared to field observations in that liquid distribution, packing materials, fouling, chemical reaction, and end effects were of great importance.

Another limitation and restriction of these models are the data reliability of the Henry's law constants. It is very important that accurate Henry's law constants shall be available for modeling an air stripper as all design parameters and costs are strongly sensitive to the Henry's law constants (22). For many common VOCs, the constants are available in books as well as the literature. For uncommon contaminants, the constants may be looked up in an extensive database by Sander (36) or predicted by using quantitative structure-activity relationship (QSAR) model for Henry's law constant (37). However, if the data are absent or data reliability is of question, pilot testing or laboratory measurement of the Henry's law constant is recommended (38).

11. CONCLUSIONS

Volatile compounds exhibit high activity coefficients in water and are easily evaporated. The countercurrent air stripper provides a large wetted surface area for mass transfer in a compact unit. Although routine maintenance is required, the components of the air stripper should have long service lives. The air stripper is capable of removing large numbers of volatile compounds at relatively low cost.

The design of an air stripping tower is essentially similar to that of the conventional cooling tower (12). There are two basic types of tower configuration: crosscurrent and countercurrent, with the former being more common at the present time.

Although the ammonia-stripping operation is both reliable and flexible in its routine operation, it has some shortcomings which must be carefully considered by the design engineer. Some major problems are:

1. Problems associated with cold weather operation. Low temperature increases the ammonia solubility making the ammonia more difficult to release from the liquid to the gaseous phase. In severe winter conditions, fogging and icing may occur, which hamper the tower operation.
2. Problems associated with calcium carbonate scale formation. Because ammonia stripping is operated at a high pH (11 or above), calcium deposits on the packing materials can be expected. If these deposits are not periodically dislodged and broken up by the hydraulic force, excessive accumulation can restrict the flow of both the wastewater and the air, thereby reducing the effectiveness of the system.

There has also been concern over the potential air pollution problem that can be caused by the ammonia present in the off-gas. However, it has been reported (12) that the ammonia concentration in the off-gas from a stripping tower seldom exceeds 10 mg/m^3 even before its dispersion in the surrounding air. The threshold for odor is about 35 mg/m^3 ; therefore, there is little likelihood for the ammonia-stripping operation to cause an odor problem. However, small concentrations of ammonia in air may react with sulfur dioxide to form aerosols or fog. Under such a situation, ammonia can be removed from the off-gas by a scrubber or by bubbling it through a dilute sulfuric acid solution.

Operating costs can be minimized and operating efficiency maximized by applying the principles herein outlined in the design of an air-stripping system. For small systems designed to remove relatively common contaminants, existing engineering data may be sufficient to design a suitable air stripper. Production units are designed to remove a wide range of compounds over the normal range of ambient temperatures. Where the target compounds are difficult to remove or the mass-transfer coefficients are not well known, pilot studies are required to furnish data for final, full-scale design. Large systems require extensive design work and pilot study data to minimize potential excessive operating costs.

Accurate characterization of the influent water quality is required before air-stripper parameters can be specified. In addition, the presence of substances other than the target compounds may reduce the efficiency of removal of the target compounds. Modifications to and maintenance of the system will usually permit good removal efficiency under these conditions.

Treatment of the air effluent from a packed tower adds an additional cost factor to the process. Use of GAC to remove the volatilized compounds from the air effluent, although an apparent redundancy, may be less expensive than the use of GAC alone.

Non-volatile compounds are not removed from water by air stripping. Air stripping may be used in conjunction with another treatment method, such as GAC, flocculation, or chlorination, to achieve treatment levels at an operating cost below that possible by the use of a single technology. Consideration of the factors herein presented allows an accurate assessment of the effectiveness of air stripping for specific water treatment objectives.

NOMENCLATURE

a	specific interfacial area, m^2/m^3
C_o	molar density of water ($55.6 \text{ kmol}/m^3$)
C_{inf}	concentration of the contaminant in the influent water
C_{eff}	concentration of the contaminant in the effluent water
C_f	packing factor
C_G	concentration of contaminant at equilibrium in the gaseous phase
C_L	concentration of contaminant at equilibrium in the liquid phase, kg/m^3
C_L^*	liquid concentration in equilibrium with the gas phase concentration, kg/m^3
D	molecular diffusion coefficient of the compound in water
G	air flow rate through the stripping tower, moles air/unit time
G'	optimum gas flow rate
G'/L'	volumetric air-to-water ratio
G_m	gas loading rate, lb moles/ ft^2 -h
H^o	enthalpy change resulting from the dissolution of the compound in water
H_c	Henry's law constant, atm m^3 /mole
HTU	height of a transfer unit, ft or m
k	a compound-dependent constant, unitless
k_G	gas mass transfer coefficient, m/s
k_L	liquid mass transfer coefficient, m/s
K_L	overall liquid mass transfer coefficient, m/s
$K_L a$	transfer rate constant, s^{-1}
L	molar flux rate of the contaminant in the liquid phase, $kmol/m^2$ -s
L'	liquid loading rate, kg/m^2 -s
L'/G'	volumetric water-to-air ratios
L_M	liquid mass flux rate, kg/m^2 -h
L_m	liquid loading rate, lb moles/ ft^2 -h
L_q	liquid flow through the stripping tower, moles water/unit time
m	mass of the solute, kg
n	constants specific to the packing type
NTU	Number of transfer units
Q	average water flow, MGD
Q_L	design flow, m^3/s
Q_{max}	peak water flow, MGD
Q_w	liquid loading rate for the tower, lb/h
R	universal gas constant, $0.000082057 \text{ atm } m^3/\text{mole}\cdot\text{K}$
R_G	resistance to the rate of mass-transfer by the gas-phase boundary layer, s
R_L	resistance to the rate of mass-transfer by the liquid-phase boundary layer, s
R_T	total resistance to the rate of mass-transfer, s
S	a concept known as the stripping factor
T	temperature, Kelvin (K)
U_L	liquid viscosity
V	liquid volume, m^3
W	tower width, ft
X	ammonia concentration at Z ft down the tower, mg-N/L

X_1	ammonia concentration in the inlet water, mg-N/L
x_1	inlet water ammonia concentration, moles ammonia/mole water
X_2	ammonia concentration in the outlet water, mg-N/L
x_2	outlet water ammonia concentration, moles ammonia/mole water
Y_1	ammonia concentration in the outlet air, mg-N/L
y_1	outlet air ammonia concentration, moles ammonia/mole air
Y_2	ammonia concentration in the inlet air, mg-N/L
y_2	inlet air ammonia concentration, moles ammonia/mole air
Z	height of the packed column, m or ft
α	constants specific to the packing type
ρ_G	air density, 1.205 kg/m ³
ρ_L	liquid density, 998 kg/m ³
ϕ	tower diameter, m

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