Uncertainty in air stripping tower design: implications of the air-to-water ratio

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Abstract: Environmental engineers are frequently faced with uncertainty in making design decisions because the true value of many process parameters is unknown. In this study, the design of countercurrent air stripping towers was modeled using fuzzy numbers, taking into account uncertainties in mass transfer and Henry’s constant. It was found that, in addition to cost, the risk of failure is an important design consideration for stripping tower design. A significant over-design is both cost-effective and results in less risk of design failure. The air-to-water ratio that yielded the least risk of failure switched from low to high as the removal efficiency of the tower increased. An important result is that at lower removal efficiencies, tower design and operation is most sensitive to uncertainties in mass transfer and at higher removal efficiencies, tower design and operation is most sensitive to uncertainties in Henry’s constant. The implication is that low air-to-water ratios are best when the regulatory target removal efficiency is low and/or when the uncertainty in the value of the contaminant’s Henry’s constant is larger than the uncertainty in the mass transfer coefficient value. Otherwise a high air-to-water ratio results in the least risk of process failure.

Keywords: Air stripping; fuzzy numbers; gas transfer; uncertainty modeling

Introduction

Environmental engineers must design treatment systems in order to meet treatment goals for a wide range of contaminants in water, air and soil. Frequently, environmental engineers are faced with uncertainty in making design decisions because the true value of many process parameters is unknown. To avoid building a system that does not achieve the regulatory treatment goal, systems are over-designed (i.e. designed to achieve a treatment goal that is more stringent than the regulatory goal). For many processes, a range of designs can achieve the same treatment goal, but some of these designs will be more sensitive to uncertainty than others. Faced with this complexity, design engineers require a rational method for assessing and comparing the uncertainties inherent in each design.

In this research, packed tower air stripping was studied because it has been established as the most popular groundwater treatment method for removing volatile contaminants due to its low capital and operating costs. The tower is a tall cylinder filled with a porous packing material. Typically, the system operates in a countercurrent mode where the contaminated water is sprayed on top of the packing, while a blower forces air up through the packing from the bottom. As the water and air pass through the tower, the volatile contaminants transfer from the liquid phase into the gas phase. The contaminant-laden air is either discharged to the atmosphere or treated further, depending on the local air quality regulations.

(Risk of failure is an important design consideration for air stripping because it is more cost-effective to overdesign a tower than to retrofit an existing tower in order to increase its removal efficiency. Because air stripping tower design is based on Henry’s constant and mass transfer coefficients, fuzzy numbers were used to represent uncertainty in these process parameters. Thus, the primary objective of this study was to identify the air stripping tower design that offers the best combination of low cost and least risk of system failure due to uncertainties in important design parameters.)
Methodology

Air stripping involves the transfer of a contaminant from the liquid phase to the gas phase in a packed tower. Henry’s law describes the partitioning of the contaminant between its liquid and gas phase at equilibrium. Typically, only a limited number (less than ten) of experimentally determined Henry’s constant values exist for each compound, making it difficult to assess the parameter uncertainty (e.g., identity a probability density function with a true mean and variance).

An equation for designing countercurrent air stripping towers can be obtained from a mass balance over a control volume; the design equation assumes steady-state conditions, dilute solutions, chemical equilibrium and absence of the contaminant in the surrounding air. The design equation is often represented as the product of the height of a transfer unit (HTU) and the number of transfer units (NTU):

$$h_T = \frac{Q_L}{K_L a A} \left( \frac{S}{S-1} \right) \ln \left[ 1 + \left( \frac{S-1}{S} \right) \frac{C_L}{C_E} \right]$$  \hspace{1cm} (1)

HTU is the first fraction on the right-hand side of Eq. (1) ($Q_L / K_L a A$) and the remainder of the right-hand side is the NTU. Within Eq. (1), $A$ is the cross-sectional area of the tower, $K_L a$ is the overall mass transfer coefficient and $C_L$ and $C_E$ refer to the influent and effluent contaminant concentrations, respectively. The stripping factor $S$, is dimensionless and defined as follows:

$$S = \frac{Q_G H}{Q_L}$$  \hspace{1cm} (2)

where $Q_G$ and $Q_L$ are the volumetric gas (air) and liquid flow rates, respectively. The ratio $Q_G / Q_L$ is called the air-to-water ratio and is commonly used to characterize the quantity of air blown through the tower.

The Onda correlations (Onda et al., 1959, 1968) were used in this study for predicting the mass transfer coefficient ($K_L a$). The Onda correlations are three empirically based equations that estimate the liquid-phase mass transfer coefficient ($k_L$), gas-phase mass transfer coefficient ($k_G$) and specific interfacial area ($a$). These parameters and Henry’s constant ($H$) are used for calculating the overall mass transfer coefficient:

$$\frac{1}{K_L a} = \frac{1}{k_L a} + \frac{1}{H k_G a}$$  \hspace{1cm} (3)

Fuzzy numbers

Fuzzy set theory was used in this study in order to model the design uncertainty for two reasons. First, probabilistic methods (e.g., Monte Carlo simulations) require massive amounts of computer time, assumptions about the distribution of the parameters and assumptions concerning the independence of uncertainties in each parameter. In contrast, Schauble and Dvorak (1999) found that fuzzy set theory is easier to implement and requires less computing power than probabilistic methods (50,000–200,000 times less in this case). Schauble and Dvorak (1999) also found that probabilistic methods and fuzzy set theory resulted in similar conclusions concerning air stripping design. Fuzzy numbers, a subset of fuzzy set theory, can be used to represent imprecise parameters in analytical or empirical models. The membership value, as shown in Figure 1, represents the degree of membership of a given parameter value in a fuzzy number. The larger the membership value, the greater the possibility (or likelihood) of the possible value for that parameter. The exact shape of the fuzzy number is determined from the available data for the design parameters.
Design risk of failure analysis

The analysis of air stripping tower designs consisted of four steps. The first step was to model the uncertainty of the most important design parameters: Henry’s constant and the mass transfer coefficients. Fuzzy Henry’s constants were determined for the three compounds examined in this study: trichloroethylene (TCE), tetrachloroethylene (PCE) and bromoform (CHBr₃); these were chosen for this case study because they are common groundwater contaminants, they represent a wide range of volatilities and a significant quantity of Henry’s constant data is available for them. Data published by Freiburger et al. (1993) contained both the experimentally determined and thermodynamically calculated values of Henry’s constant at 10°C from a variety of sources. These shapes are illustrated in Figure 1. The value of the Henry’s constant corresponding to a cumulative probability of 0.5 was used as the “most likely” value of Henry’s constant. The width of Henry’s constant fuzzy numbers was determined from the data distribution. The Henry’s constant fuzzy number for TCE has a slightly larger width than that for PCE and is much larger than that for bromoform; this larger width means that there is more uncertainty in the true value of TCE’s Henry’s constant.

In contrast, the fuzzy numbers for the mass transfer coefficients were not determined in the same manner as Henry’s constant. “Crisp” values of the liquid- and gas-phase mass transfer coefficients were estimated using the Onda correlations (Onda et al., 1959, 1968). Then, the crisp mass transfer coefficients were multiplied by an error factor in order to represent uncertainty in the Onda correlations. The Onda correlations reported error between predicted and observed values for the liquid-phase mass transfer coefficient ($k_L$); this error was associated with a 90% confidence interval. From the error in the Onda correlations, the likely minimum and maximum error factors were chosen as 0.8 and 1.2, respectively and are illustrated in Figure 1. The extreme minimum and maximum values of the liquid-phase error factors were estimated from a graph of correlated data points (Onda et al., 1959). Because errors in the Onda correlations are assumed to be roughly normally distributed, the mean value of the error factor was assumed to be 1.0.

The fuzzy error factor for the gas-phase mass transfer coefficient ($k_G$) was determined using the same approach as used for the liquid-phase coefficient. Since Onda et al. (1968) reported a ±30% error in the estimate of the gas-phase mass transfer coefficient, the likely minimum and maximum error factors were 0.7 and 1.3, respectively. The extreme minimum and maximum values of the gas-phase error factor were estimated graphically from Onda et al. (1968) and are illustrated in Figure 1.

The second step used for analysing air stripping tower designs was to create a matrix of simulations that represented a wide range of tower designs; however, some of the
parameters in the air stripping design equation were held constant. The water flow rate \((Q_L)\) was fixed at 5.68 m\(^3\)/min (1,500 gallons/min). Both air and water temperatures were assumed to be 10ºC and the packing material was 3-inch plastic saddles. The air-to-water \((A/W)\) ratio \((A/W = \frac{HQ_G}{Q_L})\) examined ranged from 5.8 to 800. Since \(Q_L\) was constant in this study, changes in the \(A/W\) ratio also represented a change in \(Q_G\). The tower diameters varied from 1.55 to 3.47 m, while the height of the towers varied from 4.82 to 22.8 m. Contaminant removal efficiencies from 95.7% to 99.5% were included in the case study. Each unique combination of tower height, diameter and \(A/W\) ratio defined each tower design; varying the three parameters created a matrix of approximately 200 unique designs for each chemical.

Two removal efficiencies were determined for each design: the design (treatment) and regulatory target removal efficiencies. The design removal efficiency represented the contaminant removal achieved if the most likely values (membership = 1.0) of Henry’s constant and the mass transfer coefficients were used for the tower design. The target removal efficiency was the removal efficiency required to lower the influent concentration to the effluent concentration mandated by regulations.

The third step in analysing these air stripping tower designs was to calculate the risk of failure of each. The Fuzzy Air Stripping Analysis Program (FASAP) was developed in order to assess the risk of each design based on the inherent uncertainty in Henry’s constant and mass transfer coefficients. FASAP is described in detail in Schaubie and Dvorak (1999). Process performance of air strippers was modeled with Eq. (1) and the Onda correlations. Dong and Shah’s (1987) vertex method was chosen to solve Eq. (1) with a fuzzy Henry’s constant and fuzzy mass transfer coefficients. The solution for each unique tower design was a fuzzy number representing the expected removal efficiency. Once the fuzzy number for the removal efficiency was determined, FASAP was used to estimate the fraction of the area under the removal efficiency curve that is below the target regulatory removal efficiency. This function represents the risk of the design not achieving the required regulatory treatment goal, given the uncertainty in Henry’s constant and the mass transfer coefficients. In this study, three target regulatory removal efficiencies (92, 95 and 98% removal) were studied for each tower design. Risk of failure of air stripping towers did not include factors such as pump failure, fouling of the packing material or electrical failure.

Estimating the cost of each design was the fourth step in analysing air stripping tower designs for this study. A model by Dvorak et al. (1996) was used, which incorporates capital, operational and maintenance costs.

**Results**

**Optimal design strategies**

A wide range of simulations was examined in order to identify optimal design strategies for air stripping. Figure 2 shows the possibility of failure and cost of a range of designs for removing TCE. The possibilities of failure are associated with a target removal goal of 95%. The costs shown are for a five-year design life. Each symbol represents a unique combination of tower height, diameter and \(A/W\) ratio. Each group of like symbols represents designs with the same design removal efficiency. For each group of designs with the same removal, costs varied widely, but the reliabilities only varied within a small range. The larger the degree of over-design (represented by higher design removal efficiencies), the lower the possibility of failure and the higher the cost. Figure 2 shows that, for a small increase in cost, a significant increase in reliability was achieved. For example, the least expensive design at 95.7% removal was slightly less expensive than the least expensive design at 98% removal, but the 98% removal design was about 35% more reliable. Another important design parameter for air stripping towers is the \(A/W\) ratio. Figure 3A shows the
ratio for each design with a 96% removal efficiency; these designs represent all designs shown in Figure 2 with a 96% removal efficiency. Some designs shared the same A/W ratio, but they had different heights and diameters. The design in Figure 3A with the least risk of failure has an A/W ratio of 11. This figure indicates that, with lower removal efficiencies (<96.5%), it is better to maintain a lower A/W ratio, which would require the construction of a larger tower. A similar analysis of designs for 98% removal of TCE is illustrated in Figure 3B. In these cases, low A/W ratios corresponded to higher possibilities of failure. The design with the lowest risk of failure under these conditions had an A/W ratio of 44. This analysis showed that, at higher removal efficiencies (>96.5%), it is better to maintain a high A/W ratio, which would require the construction of a relatively small tower.

Air-to-water ratio switch
Previous research provides conflicting results as to the air-to-water ratio that results in the best combination of low cost and low risk of process failure. Results from Freiburger et al. (1993) stated that lower A/W ratios were the most reliable in all cases, although they examined only a narrow range of tower designs, in part due to limits on computational time due to the use of a probabilistic approach. As shown in Figure 3A, this result was observed for lower removal efficiencies in this study. However, the work of Roberts et al. (1985) has been interpreted to mean that larger A/W ratios result in designs with greater reliability. That result was found for higher removal efficiencies. The conditions under which this switch in the “best” A/W ratio occurred were investigated further in the present study.

A wide range of conditions were evaluated in this study, resulting in cases where both low A/W ratios and high A/W ratios resulted in the lowest risk of failure. Table 1
summarizes the study results. The stripping actors ($S = H \times A/W$ ratio) that yielded the lowest risk of failure are shown along with the $A/W$ ratios. The wide range of volatility ($H$) between chemicals made the $A/W$ ratios considerably different, but the stripping factors allowed a comparison between chemicals. Table 1 shows that the "$A/W$ ratio switch" occurred with both TCE and PCE, but not with bromoform. Two other removal goals were examined for the $A/W$ ratio switch. The results from the 92 and 98% target removal efficiencies were very similar to the 95% target removal, except that TCE did not exhibit the $A/W$ ratio switch at a removal goal of 92%.

To understand why the switch occurred and its implications, a sensitivity analysis was performed on the air stripping design equation (Eq. (1)). The sensitivity analysis consisted of measuring changes in the removal efficiency of a tower based on changes in the overall mass transfer coefficient and the stripping factor. A figure was created using data from a series of tower designs for removing TCE. The stripping factor (2.0), liquid loading rate ($0.036 \text{ m}^3/\text{m}^2/\text{s}$) and overall mass transfer coefficient ($0.019 \text{ s}$) were held constant for the base case. The base case represents the relationship between tower height and removal efficiency if the most likely values (membership value = 1.0) of Henry’s constant and the mass transfer coefficients were used. The resulting removal efficiency of each design is shown with a natural log scale, because the concentrations are in the logarithm term in Eq. (1).

For two sets of designs, the overall mass transfer coefficient ($K_L a$) was increased by 20 and 30%, corresponding to the likely maximum values of the liquid-phase and gas-phase mass transfer coefficients, respectively and Henry’s constant remained the same as the base case. For the other two sets of designs, the stripping factor was increased by 33 and 61%, corresponding to the likely maximum and extreme maximum value of Henry’s constant of TCE and the overall mass transfer coefficient remained the same as the base case. For all four sets of designs described, the tower design was identical to the base case with the exception of the increase in stripping factor or mass transfer coefficient.

The results from the base case and the sensitivity analysis are depicted in Figure 4. At lower design removal efficiencies (top portion of ordinate), a 20% increase in mass transfer rate ($K_L a$) resulted in a larger increase in tower height (from the base case) than a 33% increase in stripping factor ($S$). However, at higher removal efficiencies, the increase in stripping factor had a greater impact on the tower removal than the change in mass transfer. At lower design removal efficiencies, the air stripping tower design equation (Eq. (1)) is more sensitive to uncertainty in mass transfer than in Henry’s constant (the only

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<th>Target removal efficiency (%)</th>
<th>Design removal efficiency (%)</th>
<th>$A/W$ ratio (stripping factor) with lowest risk of failure</th>
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<td>5.9 (2) 11 (2) 200 (2)</td>
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component of the stripping factor which had uncertainty). However, at higher removals Eq. (1) is actually more sensitive to uncertainty in Henry’s constant than the mass transfer coefficients.

The reason the A/W ratio switch did not occur for bromoform (as listed in Table 1) was because the mass transfer uncertainty (roughly ±25%) was much larger than the low end uncertainty in bromoform’s Henry’s constant (~7.0%). This case can be observed in Figure 1 where the fuzzy number for bromoform’s Henry’s constant is the smallest of the three compounds. Since uncertainty in the mass transfer coefficients was dominating the total uncertainty in the design, low A/W ratios are more reliable at all removals. In addition, since TCE’s Henry’s constant had more uncertainty than PCE’s Henry’s constant (as shown in Figure 1 by the larger base), the A/W ratio switch occurred at a smaller removal efficiency.

The design removal efficiency where A/W ratio “switch” occurs will tend to be lower as the target removal efficiency is lower. The design removal efficiency where A/W ratio “switch” occurs will also tend to be lower when uncertainties in Henry’s constant (width of frizzy number) are greater than those in the mass transfer coefficients. Thus, if there is a great deal of uncertainty in the Henry’s constant of a compound (e.g. a wide fuzzy number), then there is a good chance that a large A/W ratio will result in the design with the smallest risk of design failure. On the other hand, if Henry’s constant is well very known (e.g. a narrow fuzzy number) and the uncertainty appears to be greater in the mass transfer, then a tower designed at a minimal A/W ratio (e.g. S = 2) may result in the most reliable design. Also, at lower target regulatory removal efficiency (e.g. <95%), a low A/W ratio may result in the design with the smallest risk of design failure, but, as the target regulatory removal increases, a large A/W ratio may be best. Note that the exact design removal efficiency where this switch occurs depends on the tower design, regulatory target removal efficiency and the dominant source of uncertainty.

An important side note is that, when off-gases from air stripping towers must be treated, then the least-cost tower design always has the lowest A/W ratio. Because off-gas treatment costs are a function of the volume of air treated, smaller A/W ratios mean less air must be treated. Since off-gas treatment is typically more costly than the actual air stripping, the tower design that results in the lowest cost of off-gas treatment will also have the lowest total cost of the treatment system (Dvorak et al., 1993). Many design engineers have resisted designing air strippers with off-gas treatment at low A/W ratios because they thought that those designs were less reliable. This work shows that, in many cases, not only will a low A/W ratio be the least-cost option, but it will also be the most reliable option.
Conclusions
This study shows that fuzzy set theory can enable engineers to incorporate uncertainty into air stripping tower design and optimization better. Furthermore, fuzzy set theory can he applied to other technologies where uncertainties exist in key parameters. This study also shows that, in addition to cost, the reliability of air stripping towers is an important design consideration. When a wide range of designs are examined, it is clear that a significant over-design is both cost-effective and results in less risk of process failure.

For TCE and PCE, the A/W ratio which yielded designs with the lowest possibility of failure switched from low to high as the design removal efficiency increased. At lower regulatory target removal efficiencies, it is often better to maintain a low A/W ratio. However, at higher regulatory target removal efficiencies, it may be better to use higher A/W ratios. The reason for the A/W ratio switch is that, at lower removal efficiencies, the tower design equation is more sensitive to uncertainties in the mass transfer coefficients and, at higher removal efficiencies, the tower design equation is more sensitive to uncertainties in Henry's constant. The exact removal efficiency where these competing factors switch in importance is dependent on the tower source of uncertainty.

References