

M64

Gas Transfer Applications in Water— **Addition and Removal**



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Gas Transfer Applications in Water: Addition and Removal



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Preface



A group of volunteers from the Inorganics Committee of the American Water Works Association (AWWA) prepared this manual of practice. The need for a manual on aeration and air stripping was brought to the attention of the committee at the 2010 Inorganic Contaminants Workshop. It was discussed at the workshop that a standalone manual on aeration and air stripping did not exist. The goal of this first edition of M64 is to provide the reader with a general understanding of the principles of aeration and air stripping, providing knowledge regarding the applications of aeration and air stripping, and providing operators guidance on the operation and maintenance of aeration and air stripping equipment, including case studies. The manual includes Henry's law constants for several contaminants of interest in drinking water applications. We encourage interested readers to pursue additional information on aeration and air stripping topics through other AWWA resources.

The contents of this Manual include the importance of gas transfer operations in water treatment, including a definition of aeration (Chapter 1), the physical mechanism of gas transfer, including Henry's law constants and information regarding blower selection (Chapter 2), the principles and applications for gas addition (Chapter 3), the principles and applications for gas removal (Chapter 4), and the installation, operation, and maintenance of aeration and air stripping equipment (Chapter 5). Chapter 2 contains a summary table of Henry's law constants, and Chapter 5 includes case studies of existing system operation and maintenance. The index can be helpful in finding information on a subject of interest presented in different context throughout the manual.

This manual is designed to provide operators and engineering staff with an understanding of aeration and air stripping systems, with a comprehensive look at different technologies and applications of gas addition and gas removal. The Inorganics Committee is hopeful that M64 will meet industry needs and will be a useful resource for a broad audience. As this is the first edition of AWWA Manual M64, *Gas Transfer Applications in Water: Addition and Removal*, the Inorganics Committee and AWWA welcome comments and suggestions for improving future editions of this manual. Please contact the AWWA Water Quality Engineer, 6666 West Quincy Avenue, Denver, CO 80235-3098 to provide feedback on the contents of this manual.

Jennifer Baldwin, Ph.D., P.E.
Chair, M64 Committee

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Chapter **1**

Importance of Gas Transfer Operations in Water Treatment

OVERVIEW

Aeration is a well-established and relatively common process that has been used for producing drinking water for many centuries. The industry definition of aeration per the AWWA Water Dictionary is “a gas transfer unit process that allows for the absorption of gas (frequently oxygen or disinfectant) by water, the air stripping of volatile compounds, and the precipitation of inorganic contaminants.”

This short definition covers a broad range of processes that involves gas transfer into and out of water. This chapter is intended to provide an overview of the aeration process, how it was developed and has been refined to its current design, why it has been used, what gases are added into or removed from water, and contaminants it can be used to remove. From this overview and introduction, readers should gain a basic understanding of the aeration process before seeking out the more topic-specific chapters later in the manual to address their individual questions and requirements.

HISTORY AND FUTURE

Aeration has been used since the earliest civilizations as people recognized the benefit of mixing water with air. Those humans found that adding air removed odors and improved the taste of surface and groundwaters. In those earliest aeration applications, the aeration

process was initiated by bubbling air through basins full of water, having water cascade across manmade waterfalls, or simply exposing basins of water to windy conditions. All of these ancient uses were to address taste and odor issues before drinking the water, via a combination of transferring oxygen into the water (oxygenation) and the removal of noxious dissolved gases out of the water (air stripping).

Until the 1970s, aeration was still primarily used to address aesthetic issues, such as taste and odors and iron oxidation before filtration. Its use for other water treatment in North America generally started in the late 1970s when the United States Environmental Protection Agency (USEPA) began the regulation of volatile organic compounds (VOCs) as a result of the mandated cleanup of VOC-contaminated sites. The VOC contamination entered groundwater at many of these sites, with subsurface plumes oftentimes extending close to or into the drinking water supplies. Many VOCs are hydrophobic and readily removed using aeration. As a result, numerous “pump-and-treat” aeration systems were installed to remove the contaminants.

Since then, aeration has been identified by USEPA as one of the best available technologies to directly treat many primary drinking water contaminants, including synthetic organic chemicals (SOCs) and radon. In addition, aeration has been identified as a process to indirectly address several other drinking water rules. Examples include the Lead and Copper Rule for the removal of carbon dioxide in membrane-treated waters and to address plumbing corrosion issues associated with low-pH waters and lower total inorganic carbon. Another example is using aeration to remove total trihalomethanes (TTHMs), as the means for utilities to achieve compliance with the Stage 1 and Stage 2 Disinfectants and Disinfection Byproducts Rules. Finally, aeration is often used to remove methane, an unregulated contaminant, from groundwater in order to prevent hazardous conditions from developing due to the flammability of methane.

Looking forward at the time of this writing, USEPA’s proposed carcinogenic VOCs (cVOCs) rule and potential reductions in regulatory limits for individual VOCs could lead more utilities to implement aeration. Also, more utilities are facing the dilemma of continuing to meet their communities’ water demands without any available high-quality water sources. Meeting the demand means that these utilities may need to reconsider the use of previously ignored or bypassed water sources. These sources are generally of poorer quality and often contain contaminants for which aeration can be a viable treatment solution.

COMPARATIVE BENEFITS AND DISADVANTAGES OF AERATION VERSUS OTHER TREATMENT PROCESSES

The aeration process is a very appealing treatment as it is often inexpensive compared to other processes. Also, it most often uses no chemicals, thereby eliminating the expense of chemical delivery systems, storage tanks, transfer pumps, and piping. The lack of chemicals also eliminates the community and operator exposure risks associated with delivering chemicals, cleaning up chemical spills, and potential chemical over- or under-dosing. This inherent safety makes aeration a more attractive option than caustic soda addition for pH adjustment or hypochlorite/permanganate for iron oxidation (its use for solely manganese oxidation is not as common due to the longer reaction times).

Aeration also has a distinct advantage over activated carbon processes in addressing SOCs and TTHMs. Aeration does not produce a waste residual from the treatment process except in cases where air quality regulations require removal of the contaminant from the vapor phase. In comparison, activated carbon needs to be removed, replaced, and properly landfilled once the carbon’s absorptive capacity is exhausted (unless it is possible

to regenerate the carbon either thermally or through biodegradation). In addition, aeration requires considerably less energy compared to reverse osmosis membranes.

The aeration system does have some disadvantages associated with it. Aeration systems can be quite large, especially when treatment flowrates are large, the required amount of contaminant removal is great, or if the required treated water discharge concentration is very low, i.e., $<1 \mu\text{g/L}$. These conditions result in large diameter, tall vessels if packed towers are used. Such towers may conflict with local zoning requirements and neighborhood concerns over visual impacts and the release of contaminants into the air, especially if the installation could be located in a residential area. Large diffuser array basins can be used but the footprint may be prohibitive, and there may be construction difficulties if the basins need to be deep. Once the requisite blowers, air piping, and electrical panels are included, aeration towers or basins often require more land than do some other treatment processes. Aeration systems often operate at atmospheric pressure, so pumping into and out of these systems is often required. The additional pumps add process complexity, capital costs, energy costs, and further increase the space requirements. Chemicals may be required to treat the contaminants stripped from the water (hydrogen sulfide is an example).

Aeration systems generally have a higher capital cost than liquid (caustic soda, sodium hypochlorite, or permanganate) feed systems but may offer lower lifecycle costs and may be preferred because of safety considerations. The costs of aeration systems versus activated carbon absorption are dictated by the relative difference between aeration's pumping and blower energy costs and the labor and materials costs for activated carbon replacement, though aeration has historically been the less expensive of the two.

MANUAL PURPOSE, ORGANIZATION, AND USE

This manual is intended to provide guidance to water quality specialists and engineers with theoretical and practical understanding and concepts for using aeration systems to meet current and potentially future regulatory requirements. To assist the reader, this manual has been organized into distinct, separate chapters relating to specific contaminants or groups of contaminants, aeration system design, and operation and maintenance. As a result, a reader does not necessarily need to read the entire manual to gain the knowledge needed to complete their required tasks. These chapters are:

1. Importance of gas transfer operations in water treatment – this chapter.
2. Physical mechanism of gas transfer – this chapter explains the fundamental chemical equations and reactions in the process followed by the major physical features and considerations for various forms of aeration systems, including weir, cascade, and tray aerators, packed towers, staged diffused bubble systems, and blowers.
3. Gas addition – the processes to add gases to water to improve water quality and/or downstream processes are discussed in this chapter, including air/oxygen, gaseous chlorine, ozone, anhydrous ammonia, sulfur dioxide, and carbon dioxide.
4. Gas removal – also known as “air stripping,” this chapter describes how the aeration process can be used to remove various dissolved contaminants, including carbon dioxide, hydrogen sulfide, radon, VOCs, and TTHMs.
5. Installation, operation, and maintenance – this manual's final chapter reviews the issues associated with installing, operating, and maintaining an aeration system.

RESOURCES

As with any design manual and reference material, the authors have made their best effort to provide a comprehensive source of knowledge to the reader, but it is the readers' responsibility to use their professional judgment to properly apply the information provided for their specific requirements. The authors encourage readers to independently verify the information contained herein with other, and potentially more current, sources of information. In addition, readers should review other design guidance manuals. A partial list of other manuals with aeration information includes:

American Water Works Association and American Society of Civil Engineers. 2011 (6th ed.). *Water Quality and Treatment: A Handbook on Drinking Water* (J.K. Edzwald, editor. New York: McGraw-Hill.

American Water Works Association and American Society of Civil Engineers. 2005 (4th ed.). *Water Treatment Plant Design*. New York: McGraw-Hill.

Crittenden, J.C.; Trussel, R.R.; Hand, D.W.; Howe, K.J.; and Tchobanoglous, G. 2012 (3rd ed.). *MWH's Water Treatment: Principles and Design*. New York: John Wiley & Sons.

Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. 2012. *Recommended Standards for Water Works ("Ten States Standards")*, Health Research Inc.

HDR Engineering, Inc. 2001 (2nd ed.). *Handbook of Public Water Systems*. New York: John Wiley & Sons.

In addition, a good source of drinking water-related research for specific contaminants is the Water Research Foundation (www.waterrf.org).

Chapter **2**

Physical Mechanism of Gas Transfer

INTRODUCTION

This chapter describes (1) the basic mechanisms of gas transfer into or out of drinking water and (2) the equipment that is designed to carry out the gas transfer. The physical mechanism of gas transfer plays a critical role in water treatment techniques used for contaminant removal and chemical conditioning. Gas transfer mechanisms can be categorized as either (1) air stripping (desorption) or (2) aeration (gas absorption). Air stripping is the transfer of a gas or volatile organic compound from water to air, whereas aeration is the transfer of a gas to water. Air stripping has been used for the removal of carbon dioxide, radon, nitrogen trichloride, oxygen gas, hydrogen sulfide, methane, and many volatile organic compounds (VOCs) from water. Common aeration practices include the addition of carbon dioxide, oxygen, ozone, and chlorine. A full spectrum of water treatment applications of air stripping and aeration are summarized in Table 2-1.

Design of gas transfer equipment requires a basic understanding of gas-water equilibrium described by Henry's law, and the kinetics of mass transfer across the water-gas interface. Gas transfer equipment is designed to optimize the mass transfer for a particular compound while balancing capital and operating costs and footprint requirements.

EQUILIBRIUM AND HENRY'S LAW

In gas transfer, air and water are brought into contact with each other to take advantage of the relative solubility of the gas in water and air. Equilibrium describes the final state of solubility in each phase after the mass rate of transfer between water and air are equal. A system not in equilibrium will always move toward equilibrium. The rate at which the

Table 2-1 Water treatment air stripping and aeration applications

Phase Transfer Type/Compound	Water Treatment Goals
Gas absorption	
O ₂ addition	• Oxidation of inorganics, lake destratification
O ₃ addition	• Oxidation of organics, disinfection, and color removal
Cl ₂ addition	• Oxidation of inorganics and disinfection
ClO ₂ addition	• Disinfection
CO ₂ addition	• pH control
SO ₂ addition	• Dechlorination
NH ₃ addition	• Chloramine formation for disinfection
Air stripping	
CO ₂ stripping	• Corrosion control
O ₂ stripping	• Corrosion control
H ₂ S stripping	• Odor control
NH ₃ stripping	• Nutrient removal
VOC stripping	• Taste and odor removal, VOC removal

Source: Montgomery 1985

liquid-gas system approaches equilibrium is a function of how far the system is from equilibrium. Equilibrium in aeration applications is not typically reached because it is usually not cost-effective to add or remove more than is required by the application.

For gas transfer applications in drinking water, the equilibrium partitioning between water and air can be described by Henry's law:

$$P_a = K_{H,a} x_a \quad (\text{Eq 2-1})$$

At equilibrium, the partial pressure or concentration of a compound in the gas phase (P_a) is proportional to the mole fraction of the compound in the liquid phase (x_a). The proportionality constant, $K_{H,a}$, is also known as the Henry's law constant. The equation is valid for dissolved organic and inorganic compounds that are able to move between the water phase and air phase in drinking water up to near the solubility of the compound. Typical concentrations of gaseous compounds in drinking water solutions are far below levels that would influence the Henry's law constant. Further, drinking water is generally of such high quality that the ionic strength or surfactants are not factors that will alter the Henry's law constant.

The value of the Henry's law constant provides insight into the relative ease of a compound to move from the water phase to the air phase or vice versa. Air stripping processes are more effective for compounds with higher Henry's law constants, and aeration processes are more effective for compounds with lower Henry's law constants.

The Henry's law constant describes only the equilibrium state and does not describe the rate of transfer. Further, it must be pointed out that the reported Henry's law constants in the literature can vary over a wide range, depending on the research source. This range can be an order of magnitude or more, so different sources should be consulted. The same is true for the temperature factors reported in the literature. For this reason, the efficiency of any gas transfer equipment should be determined in real application or piloting over the temperature range of the application. Manufacturers often test their equipment designs to generate design data so that they can accurately predict performance for different applications.

Dimensionless Henry's constants are frequently used in engineering design. However, Henry's law constants reported in the literature can be reported in a number of units including but not limited to atm, atm-L/mole, bar, and bar-L/mole. Conversion from units reported in the literature is often required; Table 2-2 provides a number of calculations that can be used to convert from commonly reported units to dimensionless units. Table 2-3 provides dimensionless Henry's law constants for a number of organic compounds and gases that can be encountered in drinking water treatment.

In the event that Henry's Law constants are not readily available, the Henry's law constant can be estimated. However, the estimation technique only provides values within ± 50 to 100 percent of experimental values and should therefore only be used if measured values are not available. The following equation can be used to estimate the Henry's law constant when the mole fraction of the compound is equal to 1 and the compound is perfectly miscible in solution (Hand 1999):

$$K_H = P_{v,A} \quad (\text{Eq 2-2})$$

where $P_{v,A}$ is the vapor pressure of compound A at a specified temperature (atm).

Variations in ionic strength and temperature may change the Henry's law constant. As temperature increases, the solubility of gases in water decreases and the partial pressure of a specific compound in the gas phase increases, thereby increasing the Henry's law constant. As temperature decreases, the solubility of gases in water increases and the partial pressure of a specific compound in the gas phase decreases, thereby decreasing the Henry's law constant. Temperature effects are generally driven by the water temperature rather than the air temperature, as air rapidly approaches the water temperature during initial contact, due to the relatively high heat capacity of water compared to air.

Solution pH affects the distribution of species between un-ionized and ionized forms, which influences the volatility of compounds. Only un-ionized species (e.g., NH_3 rather than NH_4^+ and CO_2 rather than HCO_3^-) are volatile, which makes them amenable to air-water equilibrium partitioning.

Table 2-2 Henry's law constant conversions

Units for Henry's Law Constant	Conversion to Dimensionless Henry's Law Constant	Forms of Universal Gas Constant
atm	$= \frac{K_H [\text{atm}]}{RT \times 55.56 \frac{\text{mol}}{\text{L}}}$	$R = 0.08205 \frac{\text{atm} \cdot \text{L}}{\text{mol} \cdot \text{K}}$
$\frac{\text{atm} \cdot \text{L}}{\text{mol}}$	$= \frac{K_H \left[\frac{\text{atm} \cdot \text{L}}{\text{mol}} \right]}{RT}$	$R = 0.08205 \frac{\text{atm} \cdot \text{L}}{\text{mol} \cdot \text{K}}$
bar	$= \frac{K_H [\text{bar}]}{RT \times 55.56 \frac{\text{mol}}{\text{L}}}$	$R = 0.083145 \frac{\text{bar} \cdot \text{L}}{\text{mol} \cdot \text{K}}$
$\frac{\text{bar} \cdot \text{L}}{\text{mol}}$	$= \frac{K_H \left[\frac{\text{bar} \cdot \text{L}}{\text{mol}} \right]}{RT}$	$R = 0.083145 \frac{\text{bar} \cdot \text{L}}{\text{mol} \cdot \text{K}}$

T = temperature [K]

Table 2-3 Henry's law constants for select volatile organic compounds and gases encountered in drinking water treatment

Component	KH (-)	T (°C)	Source
1,1,1-trichloroethane	0.416	10	Hand 1999, Ashworth 1988
	0.487	15	Hand 1999, Ashworth 1988
	0.607	20	Hand 1999, Ashworth 1988
	0.712	25	Hand 1999, Ashworth 1988
	0.849	30	Hand 1999, Ashworth 1988
1,1,2,2-tetrachloroethane	0.014	10	Hand 1999, Ashworth 1988
	0.008	15	Hand 1999, Ashworth 1988
	0.030	20	Hand 1999, Ashworth 1988
	0.010	25	Hand 1999, Ashworth 1988
	0.028	30	Hand 1999, Ashworth 1988
1,1,2-trichloroethane	0.017	10	Hand 1999, Ashworth 1988
	0.027	15	Hand 1999, Ashworth 1988
	0.031	20	Hand 1999, Ashworth 1988
	0.037	25	Hand 1999, Ashworth 1988
	0.054	30	Hand 1999, Ashworth 1988
1,1,2-trichlorotrifluoroethane	6.63	10	Hand 1999, Ashworth 1988
	9.1	15	Hand 1999, Ashworth 1988
	10.2	20	Hand 1999, Ashworth 1988
	13	25	Hand 1999, Ashworth 1988
	12.9	30	Hand 1999, Ashworth 1988
1,1-dichloroethane	0.158	10	Hand 1999, Ashworth 1988
	0.192	15	Hand 1999, Ashworth 1988
	0.234	20	Hand 1999, Ashworth 1988
	0.256	25	Hand 1999, Ashworth 1988
	0.312	30	Hand 1999, Ashworth 1988
1,1-dichloroethylene	0.663	10	Hand 1999, Ashworth 1988
	8.59	15	Hand 1999, Ashworth 1988
	0.907	20	Hand 1999, Ashworth 1988
	1.06	25	Hand 1999, Ashworth 1988
	1.28	30	Hand 1999, Ashworth 1988
1,2,4-trichlorobenzene	0.056	10	Hand 1999, Ashworth 1988
	0.044	15	Hand 1999, Ashworth 1988
	0.076	20	Hand 1999, Ashworth 1988
	0.079	25	Hand 1999, Ashworth 1988
	0.119	30	Hand 1999, Ashworth 1988
1,2-dichloroethane	0.050	10	Hand 1999, Ashworth 1988
	0.055	15	Hand 1999, Ashworth 1988
	0.061	20	Hand 1999, Ashworth 1988
	0.058	25	Hand 1999, Ashworth 1988
	0.07	30	Hand 1999, Ashworth 1988

Continued

Table 2-3 Henry's law constants for select volatile organic compounds and gases encountered in drinking water treatment (*continued*)

Component	KH (-)	T (°C)	Source
1,2-dichloropropane	0.053	10	Hand 1999, Ashworth 1988
	0.053	15	Hand 1999, Ashworth 1988
	0.079	20	Hand 1999, Ashworth 1988
	0.146	25	Hand 1999, Ashworth 1988
	0.115	30	Hand 1999, Ashworth 1988
1,3,5-trimethylbenzene	0.174	10	Hand 1999, Ashworth 1988
	0.195	15	Hand 1999, Ashworth 1988
	0.238	20	Hand 1999, Ashworth 1988
	0.275	25	Hand 1999, Ashworth 1988
	0.387	30	Hand 1999, Ashworth 1988
1,4-dichlorobenzene	0.091	10	Hand 1999, Ashworth 1988
	0.092	15	Hand 1999, Ashworth 1988
	0.108	20	Hand 1999, Ashworth 1988
	0.13	25	Hand 1999, Ashworth 1988
	0.156	30	Hand 1999, Ashworth 1988
2,4-dimethylphenol	0.357	10	Hand 1999, Ashworth 1988
	0.285	15	Hand 1999, Ashworth 1988
	0.42	20	Hand 1999, Ashworth 1988
	0.202	25	Hand 1999, Ashworth 1988
	0.151	30	Hand 1999, Ashworth 1988
2-methylpentane	30	10	Hand 1999, Ashworth 1988
	29.4	15	Hand 1999, Ashworth 1988
	26.3	20	Hand 1999, Ashworth 1988
	33.7	25	Hand 1999, Ashworth 1988
	34.1	30	Hand 1999, Ashworth 1988
1,2-dichlorobenzene	0.070	10	Hand 1999, Ashworth 1988
	0.061	15	Hand 1999, Ashworth 1988
	0.070	20	Hand 1999, Ashworth 1988
	0.064	25	Hand 1999, Ashworth 1988
	0.095	30	Hand 1999, Ashworth 1988
1,3-dichlorobenzene	0.095	10	Hand 1999, Ashworth 1988
	0.098	15	Hand 1999, Ashworth 1988
	0.122	20	Hand 1999, Ashworth 1988
	0.117	25	Hand 1999, Ashworth 1988
	0.17	30	Hand 1999, Ashworth 1988
ammonia	0.001	20	Hand 1999, Montgomery 1985
benzene	0.142	10	Hand 1999, Ashworth 1988
	0.164	15	Hand 1999, Ashworth 1988
	0.188	20	Hand 1999, Ashworth 1988
	0.216	25	Hand 1999, Ashworth 1988
	0.29	30	Hand 1999, Ashworth 1988

Continued

Table 2-3 Henry's law constants for select volatile organic compounds and gases encountered in drinking water treatment (*continued*)

Component	KH (-)	T (°C)	Source
carbon dioxide	1.14	20	Hand 1999, Montgomery 1985
carbon tetrachloride	0.637	10	Hand 1999, Ashworth 1988
	0.808	15	Hand 1999, Ashworth 1988
	0.965	20	Hand 1999, Ashworth 1988
	1.21	25	Hand 1999, Ashworth 1988
	1.52	30	Hand 1999, Ashworth 1988
chlorine	0.442	20	Hand 1999, Montgomery 1985
chlorine dioxide	0.041	20	Hand 1999, Montgomery 1985
chloroethane	0.327	10	Hand 1999, Ashworth 1988
	0.405	15	Hand 1999, Ashworth 1988
	0.458	20	Hand 1999, Ashworth 1988
	0.495	25	Hand 1999, Ashworth 1988
	0.575	30	Hand 1999, Ashworth 1988
chlorobenzene	0.105	10	Hand 1999, Ashworth 1988
	0.119	15	Hand 1999, Ashworth 1988
	0.142	20	Hand 1999, Ashworth 1988
	0.147	25	Hand 1999, Ashworth 1988
	0.19	30	Hand 1999, Ashworth 1988
chloroform	0.074	10	Hand 1999, Ashworth 1988
	0.986	15	Hand 1999, Ashworth 1988
	0.138	20	Hand 1999, Ashworth 1988
	0.172	25	Hand 1999, Ashworth 1988
	0.223	30	Hand 1999, Ashworth 1988
cis- 1,2-dichloroethylene	0.116	10	Hand 1999, Ashworth 1988
	0.138	15	Hand 1999, Ashworth 1988
	0.15	20	Hand 1999, Ashworth 1988
	0.186	25	Hand 1999, Ashworth 1988
	0.231	30	Hand 1999, Ashworth 1988
cyclohexane	4.44	10	Hand 1999, Ashworth 1988
	5.33	15	Hand 1999, Ashworth 1988
	5.82	20	Hand 1999, Ashworth 1988
	7.24	25	Hand 1999, Ashworth 1988
	8.97	30	Hand 1999, Ashworth 1988
dibromochloromethane	0.016	10	Hand 1999, Ashworth 1988
	0.019	15	Hand 1999, Ashworth 1988
	0.043	20	Hand 1999, Ashworth 1988
	0.048	25	Hand 1999, Ashworth 1988
	0.061	30	Hand 1999, Ashworth 1988

Continued

Table 2-3 Henry's law constants for select volatile organic compounds and gases encountered in drinking water treatment (*continued*)

Component	KH (-)	T (°C)	Source
ethylbenzene	0.14	10	Hand 1999, Ashworth 1988
	0.191	15	Hand 1999, Ashworth 1988
	0.25	20	Hand 1999, Ashworth 1988
	0.322	25	Hand 1999, Ashworth 1988
	0.422	30	Hand 1999, Ashworth 1988
ethylene dibromide	0.013	10	Hand 1999, Ashworth 1988
	0.020	15	Hand 1999, Ashworth 1988
	0.025	20	Hand 1999, Ashworth 1988
	0.027	25	Hand 1999, Ashworth 1988
	0.032	30	Hand 1999, Ashworth 1988
hydrogen sulfide	0.389	20	Hand 1999, Montgomery 1985
m-xylene	0.177	10	Hand 1999, Ashworth 1988
	0.21	15	Hand 1999, Ashworth 1988
	0.249	20	Hand 1999, Ashworth 1988
	0.304	25	Hand 1999, Ashworth 1988
	0.357	30	Hand 1999, Ashworth 1988
methane	28.7	20	Hand 1999, Montgomery 1985
methyl cellosolve	1.9	10	Hand 1999, Ashworth 1988
	1.54	15	Hand 1999, Ashworth 1988
	4.83	20	Hand 1999, Ashworth 1988
	1.26	25	Hand 1999, Ashworth 1988
	1.53	30	Hand 1999, Ashworth 1988
methylene chloride	0.060	10	Hand 1999, Ashworth 1988
	0.072	15	Hand 1999, Ashworth 1988
	0.102	20	Hand 1999, Ashworth 1988
	0.121	25	Hand 1999, Ashworth 1988
	0.145	30	Hand 1999, Ashworth 1988
methyl ethylbenzene	0.151	10	Hand 1999, Ashworth 1988
	0.178	15	Hand 1999, Ashworth 1988
	0.209	20	Hand 1999, Ashworth 1988
	0.228	25	Hand 1999, Ashworth 1988
	0.31	30	Hand 1999, Ashworth 1988
methyl ethyl ketone	0.012	10	Hand 1999, Ashworth 1988
	0.017	15	Hand 1999, Ashworth 1988
	0.008	20	Hand 1999, Ashworth 1988
	0.005	25	Hand 1999, Ashworth 1988
	0.004	30	Hand 1999, Ashworth 1988

Continued

Table 2-3 Henry's law constants for select volatile organic compounds and gases encountered in drinking water treatment (*continued*)

Component	KH (-)	T (°C)	Source
methyl isobutyl ketone	0.028	10	Hand 1999, Ashworth 1988
	0.016	15	Hand 1999, Ashworth 1988
	0.012	20	Hand 1999, Ashworth 1988
	0.016	25	Hand 1999, Ashworth 1988
	0.027	30	Hand 1999, Ashworth 1988
n-hexane	10.3	10	Hand 1999, Ashworth 1988
	17.5	15	Hand 1999, Ashworth 1988
	36.7	20	Hand 1999, Ashworth 1988
	31.4	25	Hand 1999, Ashworth 1988
	62.7	30	Hand 1999, Ashworth 1988
nonane	17.2	10	Hand 1999, Ashworth 1988
	21	15	Hand 1999, Ashworth 1988
	13.8	20	Hand 1999, Ashworth 1988
	16.9	25	Hand 1999, Ashworth 1988
	18.7	30	Hand 1999, Ashworth 1988
o-xylene	0.123	10	Hand 1999, Ashworth 1988
	0.153	15	Hand 1999, Ashworth 1988
	0.197	20	Hand 1999, Ashworth 1988
	0.199	25	Hand 1999, Ashworth 1988
	0.252	30	Hand 1999, Ashworth 1988
oxygen	32.5	20	Hand 1999, Montgomery 1985
ozone	3.77	20	Hand 1999, Montgomery 1985
p-xylene	0.181	10	Hand 1999, Montgomery 1985
	0.204	15	Hand 1999, Montgomery 1985
	0.268	20	Hand 1999, Montgomery 1985
	0.304	25	Hand 1999, Montgomery 1985
	0.38	30	Hand 1999, Montgomery 1985
propylbenzene	0.245	10	Hand 1999, Ashworth 1988
	0.309	15	Hand 1999, Ashworth 1988
	0.366	20	Hand 1999, Ashworth 1988
	0.442	25	Hand 1999, Ashworth 1988
	0.551	30	Hand 1999, Ashworth 1988
radon	1.69	20	Hand 1999, Montgomery 1985
sulfur dioxide	0.029	20	Hand 1999, Montgomery 1985
tetrachloroethylene	0.364	10	Hand 1999, Ashworth 1988
	0.467	15	Hand 1999, Ashworth 1988
	0.587	20	Hand 1999, Ashworth 1988
	0.699	25	Hand 1999, Ashworth 1988
	0.985	30	Hand 1999, Ashworth 1988

Continued

Table 2-3 Henry's law constants for select volatile organic compounds and gases encountered in drinking water treatment (*continued*)

Component	K _H (-)	T (°C)	Source
toluene	0.164	10	Hand 1999, Ashworth 1988
	0.21	15	Hand 1999, Ashworth 1988
	0.231	20	Hand 1999, Ashworth 1988
	0.263	25	Hand 1999, Ashworth 1988
	0.325	30	Hand 1999, Ashworth 1988
trans- 1,2-dichloroethylene	0.025	10	Hand 1999, Ashworth 1988
	0.298	15	Hand 1999, Ashworth 1988
	0.356	20	Hand 1999, Ashworth 1988
	0.386	25	Hand 1999, Ashworth 1988
	0.469	30	Hand 1999, Ashworth 1988
trichloroethylene	0.237	10	Hand 1999, Ashworth 1988
	0.282	15	Hand 1999, Ashworth 1988
	0.350	20	Hand 1999, Ashworth 1988
	0.417	25	Hand 1999, Ashworth 1988
	0.515	30	Hand 1999, Ashworth 1988
trichlorofluoromethane	2.31	10	Hand 1999, Ashworth 1988
	2.88	15	Hand 1999, Ashworth 1988
	3.34	20	Hand 1999, Ashworth 1988
	4.13	25	Hand 1999, Ashworth 1988
	4.91	30	Hand 1999, Ashworth 1988
vinyl chloride	0.646	10	Hand 1999, Ashworth 1988
	0.711	15	Hand 1999, Ashworth 1988
	0.903	20	Hand 1999, Ashworth 1988
	1.08	25	Hand 1999, Ashworth 1988

Note: Refer to "Other References" in Chapter 1 if compound of interest is not found in this table.

Surfactants, if present, would decrease the Henry's law constant of the compounds of interest (thereby decreasing ability to volatilize). In drinking water applications, water supplies do not typically have concentrations of surfactants that would affect the design of air stripping equipment.

If literature values are not available for a specific temperature, the van 't Hoff equation can be used to calculate the change in K_H with temperature. For the temperatures encountered in water treatment, K_H generally increases with increasing temperature because the aqueous solubility of the component decreases while its vapor pressure increases.

$$\log K_H = \frac{-\Delta H^0}{RT} + E \quad (\text{Eq 2-3})$$

where:

K_H = calculated Henry's law constant

$-\Delta H^0$ = heat absorbed in the evaporation of 1 mole of component A from solution at constant temperature and pressure

R = universal gas constant $\left(1.987 \frac{\text{kcal}}{\text{kmol} \cdot \text{K}}\right)$

T = temperature

E = empirical constant

The standard enthalpy change, ΔH , for the dissolution of a compound in water is assumed to be constant over the temperature range of interest in the previous equation.

Tables 2-4 and 2-5 include values of ΔH and E for several volatile organic compounds and gases.

Temperature dependence of the Henry's law constant can also be expressed using the following temperature regression equation:

$$K_H = \exp\left(A - \frac{B}{T}\right) \quad (\text{Eq 2-4})$$

where A and B are fitting parameters, T is temperature (K), and K_H is the Henry's law constant ($\text{atm}\cdot\text{m}^3/\text{gmole}$).

Table 2-6 provides values of the fitting parameters for a selection of compounds that can be encountered in drinking water treatment. Note that this table is not comprehensive, so other references, such as those listed in Chapter 1, may be needed if a compound is not listed in this table.

Table 2-4 Henry's constants and temperature dependence for select volatile organic compounds in water

Gas	Molecular Formula	Henry's Constant at 20°C (atm)*	Temperature Dependence	
			ΔH^0 (kcal/kmol, $\times 10^{-3}$)	E
Carbon tetrachloride	CCl_4	1.29×10^3	4.05	10.06
Tetrachloroethylene	C_2Cl_4	1.10×10^3	4.29	10.38
Trichloroethylene	CCHCl_3	550	3.41	8.59
Benzene	C_6H_6	240	3.68	8.68
Chloroform	CHCl_3	170	4.00	9.10

* Calculated from water solubility data and pure liquid partial pressure at specified temperature (Landolt-Boernstein 1976, Montgomery 1985)

Note: Refer to "Resources" in Chapter 1 if compound of interest is not found in this table.

Table 2-5 Henry's constants and temperature dependence for gases in water

Gas	Molecular Formula	Henry's Constant at 20°C (atm)	Temperature Dependence	
			ΔH^0 (kcal/kmol, $\times 10^{-3}$)	E
Oxygen	O_2	4.3×10^4	1.45	7.11
Nitrogen	N_2	8.6×10^4	1.12	6.85
Methane	CH_4	3.8×10^4	1.54	7.22
Ozone	O_3	5.0×10^3	2.52	8.05
Carbon dioxide	CO_2	1.51×10^2	2.07	6.73
Hydrogen sulfide	H_2S	5.15×10^2	1.85	5.88
Chlorine	Cl_2	5.85×10^2	1.74	5.75
Chlorine dioxide	ClO_2	54	2.93	6.76
Sulfur dioxide	SO_2	38	2.40	5.68
Ammonia	NH_3	0.76	3.75	6.31

(Landolt-Boernstein 1976 and International Critical Tables, Montgomery 1985)

Note: Refer to "Resources" in Chapter 1 if compound of interest is not found in this table.

Table 2-6 Fitting parameters for the temperature regression equation

Component	A	B	R ²
1,2-dichloropropane	9.843	4,708	0.820
1,3-dichlorobenzene	2.882	2,564	0.850
1,1,2-trichlorotrifluoroethane	9.649	3,243	0.932
1,1,1-trichloroethane	7.351	3,399	0.998
1,1,2-trichloroethane	9.320	4,843	0.968
1,1-dichloroethane	5.484	3,137	0.993
1,1-dichloroethylene	6.123	2,907	0.974
1,2,4-trichlorobenzene	7.361	4,028	0.819
1,2-dichloroethane	-1.371	1,522	0.878
1,3,5-trimethylbenzene	7.241	3,628	0.962
1,4-dichlorobenzene	3.373	2,720	0.941
Benzene	5.534	3,194	0.968
carbon tetrachloride	9.739	3,951	0.997
Chlorobenzene	3.469	2,689	0.965
Chloroethane	4.265	2,580	0.984
Chloroform	11.41	5,030	0.997
<i>cis</i> -1,2-dichloroethylene	5.164	3,143	0.974
Cyclohexane	9.141	3,238	0.982
Decalin	11.85	4,125	0.919
dibromochloromethane	14.62	6,373	0.914
Ethylbenzene	11.92	4,994	0.999
ethylene dibromide	5.703	3,876	0.928
<i>m</i> -xylene	6.280	3,337	0.998
methylene chloride	8.483	4,268	0.988
methyl ethylbenzene	5.557	3,179	0.968
methyl ethyl ketone	-26.32	-5,214	0.797
n-hexane	25.25	7,530	0.917
<i>o</i> -xylene	5.541	3,220	0.966
<i>p</i> -xylene	6.931	3,520	0.989
Propylbenzene	7.835	3,681	0.997
tetrachloroethylene	10.65	4,368	0.987
Tetralin	11.83	5,392	0.996
Toluene	5.133	3,024	0.982
<i>trans</i> -1,2-dichloroethylene	5.333	2,964	0.985
trichloroethylene	7.845	3,702	0.998
trichlorofluoromethane	9.480	3,513	0.998
vinyl chloride	6.138	2,931	0.970

Source: Ashworth 1988

Note: Refer to "Resources" in Chapter 1 if compound of interest is not found in this table.

GAS TRANSFER

Film Diffusion

Transfer of material in air stripping and aeration applications occurs from one bulk phase to another across a gas-liquid interface. The portion of each media where concentrations differ from the bulk phase is referred to as the boundary layer, and transfer from one bulk media to another is often conceptualized as having to overcome a resistance in a thin film in the boundary layer of each phase. These liquid and gas film resistances control the rate of mass transfer. In general, the liquid film has a greater influence on the transfer of low solubility gases like carbon dioxide and oxygen. Turbulence and temperature are the most important factors in film resistance. Gas transfer is enhanced as temperature and turbulence increase (thereby reducing the boundary layer thickness and increasing rate of molecular diffusion).

The differential between the saturation value of a compound (that is its equilibrium concentration as described by Henry's law) and its actual concentration in the water or air provides the driving force for phase transfer. The phase transfer occurs in the direction of decreasing the difference between the actual concentration and the saturation concentration. In air stripping applications, the concentration of the target compound in water must exceed the saturation concentration. The more that the concentration exceeds the saturation concentration, the greater the driver for phase transfer from the water phase to air phase. In aeration applications, the concentration of the target compound in water must be below saturation, and the concentration of a gas in air, the greater driver for phase transfer from the air phase to water phase.

Gas Transfer Without Chemical Reaction

The overall resistance to mass transfer can be described as the sum of the liquid-phase resistance and gas-phase resistance to mass transfer. The overall resistance to mass transfer is described as follows:

$$\frac{1}{K_L a} = \frac{1}{k_l a} + \frac{1}{K_H k_g a} \quad (\text{Eq 2-5})$$

where:

- K_L = overall liquid phase mass transfer coefficient (ft/h) [m/h]
- k_l = liquid phase mass transfer coefficient (ft/h) [m/h]
- k_g = gas phase mass transfer coefficient (ft/h) [m/h]
- K_H = Henry's law constant
- a = effective area for mass transfer (ft²) [m²]

The effective area for mass transfer, a , describes the interfacial area of the system in which mass transfer occurs. The mass transfer coefficient, K_L , is a function of the compound's Henry's law constant, the geometry and physical characteristics of the air stripping system, system temperature, contact time, and liquid-phase and gas-phase resistances to mass transfer (k_g and k_l).

For gas scrubbing operations, the previous equation can also be written to describe the overall mass transfer coefficient for the gas phase:

$$\frac{1}{K_G a} = \frac{K_H}{k_l a} + \frac{1}{k_g a} \quad (\text{Eq 2-6})$$

where:

- K_G = overall gas phase mass transfer coefficient (L/T)
- a = effective area for mass transfer (ft²) [m²]

K_H = Henry's law constant

k_l = liquid phase mass transfer coefficient (ft/h) [m/h]

k_g = gas phase mass transfer coefficient (ft/h) [m/h]

The product of the mass transfer coefficient, K_L or K_G , and the effective area for mass transfer, a , is commonly evaluated as one constant, $K_L a$ or $K_G a$.

In turbulent flow regimes, mass transfer coefficients must be determined experimentally. When experimental data are not available, mass transfer correlations can be used for the design of various aeration and air stripping equipment.

The volumetric rate of transfer of a volatile compound from water to air can be expressed by the following first-order equation:

$$M = K_L a (C_i^* - D_i) \quad (\text{Eq 2-7})$$

where:

M = mass of substance transferred per unit of time per unit of volume (lb/h)/ft³ [kg/h)/m³]

K_L = overall liquid mass transfer coefficient (ft/h) [m/h]

a = effective area for mass transfer (ft²/ft³) [m²/m³]

C_i^* = liquid-phase concentration in equilibrium with gas-phase concentration (lb/ft³) [kg/m³]

D_i = bulk liquid-phase concentration (lb/ft³) [kg/m³]

The rate of mass transfer is a function of the difference between the existing concentration and the equilibrium concentration of the substance in solution. Increasing the effective area for mass transfer will increase the mass transfer rate; however, capital and operating costs will also increase as more surface area will be required (e.g., additional packing). Designers typically design aeration equipment to optimize mass transfer while balancing capital and energy costs.

The mass transfer rate will be controlled by either the liquid or gas phase. Understanding the controlling phase is important for design and operations refinement. A concentration gradient is required to exist in the direction of transfer of each phase, so designers and operators need to know the controlling phase in order to keep the concentration gradient moving in the controlling direction. Table 2-7 identifies the controlling phase for select VOCs and gases. The following rule of thumb can be used to determine which phase controls the mass transfer rate for a compound:

- $K_H > 0.05$ and low liquid solubility: liquid-phase controls
- $K_H < 0.002$ and high liquid solubility: gas-phase controls
- $0.0002 < K_H < 0.05$: both liquid and gas phase may affect mass transfer rate

Table 2-7 Controlling phase for select compounds

Compound	K_H (25°C)	Controlling Phase
Oxygen	29.29	Liquid
Carbon tetrachloride	1.2	Liquid
Trichloroethylene	0.40	Liquid
Chloroform	0.15	Liquid
Acetone	0.001	Gas

Source: Hand 2011

Gas Transfer With Chemical Reaction

Chemical reactions can occur in gas transfers through the gas–water interface resulting in an increased absorption rate. Gases used in the water treatment industry that can undergo chemical reactions include sulfur dioxide, carbon dioxide, ozone, and chlorine. Design of aeration equipment needs to account for these chemical reactions.

The impact on the rate of absorption due to chemical reactions is a function of the chemical reaction type, the reactant concentrations, rate constant, reaction order, and solute molecular diffusion constants. Montgomery (1985), Danckwerts (1970), and Sherwood (1975) present methods for calculating the volumetric rate of mass transfer.

It is important to emphasize that there are removal and addition limitations when air is used to bring about gas transfer. The atmosphere is made up of several natural gases, and in the vicinity of contamination sites, air can contain various amounts of other volatile contaminants. To the extent that these atmospheric gases are present, removal and addition are limited by the equilibration given by Henry's constant. In other words, if the air used in a process contains that which is being transferred, it is not possible to remove all of the constituents. Of interest with regard to drinking water is that air always naturally contains oxygen, carbon dioxide, and radon. At a given water temperature, the saturation of these gases with respect to the air–water equilibrium defines the concentrations that will remain with any amount of aeration or air stripping. For radon, this will likely be a few tenths to 0.5 pCi/L (average air concentration near ground of 1.5 pCi/L); for oxygen, it is in the range of $\approx$ 8–14 mg/L; and for carbon dioxide, it is in the range of 0.4–0.8 mg/L. These values are meant to cover the range of typical drinking water temperatures.

Air containing the constituent that is being transferred is most important in the location of the blower air filter intake relative to the discharging air vent. It is not unheard of that a partial return of vent air comes back into a blower and limits the removal efficiency. A reasonable separation of the two air streams is needed to ensure that this does not occur and typically 10 feet, with opposing direction for the air flows, is sufficient to avoid this potential problem.

GAS TRANSFER EQUIPMENT

This section discusses the various types of gas addition and removal technologies and their general application, design, and operational considerations. The order of presentation of equipment types is based on the general historical chronology of development.

Some of the first techniques used to aerate water employed a simple cascade or waterfall. It was recognized early on that water was “freshened” by cascading it over rocks, wooden slats, and sequential trays. This practice was an attempt to equilibrate the water with air, to add oxygen, to remove carbon dioxide and hydrogen sulfide, and to start the process of iron oxidation as a prelude to filtration of the precipitated iron. As the process was developed, coke trays were often used to improve the removal of manganese, which much later was found to need a manganese dioxide coating on surfaces to carry out oxidation and removal on filters. Coke tray aerators are a series of activated carbon trays where water passes through each plate through small holes. This type of aeration also raised the pH and reduced corrosivity for waters that had significant carbon dioxide. The majority of these operations focused on groundwater treatment. The “Resources” section in Chapter 1 lists reference materials that offer more information on the historical aspects of aeration.

The development of more sophisticated equipment that was designed for specific reactor applications requiring much higher removal efficiency largely occurred in the 1940s through the 1960s in the field of chemical engineering. The equipment included

packed towers, spray devices, and multi-staged bubble reactors in both horizontal and in stacked tray configurations. During the 1970s, while USEPA and states began establishing maximum concentration levels (MCLs) for a variety of VOCs, engineers in the drinking water field began using the more efficient equipment. Packed towers were the most common equipment applied to the removal of VOCs, both in the groundwater remediation effort associated with the Superfund program and leaking underground fuel storage and in drinking water supplies that were contaminated. At the same time, lower-profile air strippers in the form of multi-staged bubble equipment were used as alternatives to packed towers. These low-profile systems were easier to locate inside buildings and did not cause an industrial-looking installation in more highly populated areas. In addition, there were some advantages for easier maintenance. The staged bubble systems used two basic designs: (1) a cascade of vertical trays employing countercurrent air:water flow, and (2) a staged horizontal vessel using air diffusers in each stage with blower air distributed evenly to all stages. Packed towers and low-profile air strippers can be designed to achieve almost complete removal of volatile contaminants with a single pass.

It should be noted that other types of less efficient equipment, including venturizers/eductors, spray, cascades, etc., can also attain high removals, but they would often require multiple-pass configurations that are not cost-effective when isolated batch processing and re-pumping requirements are included.

There are specific applications in which the lower removal devices offer practical advantages and are employed in drinking water treatment. One example is where only a low degree of removal is required to meet the treatment goal (see Table 2-8). A second example is where an existing deep storage tank is used for the removal of THHMs (see Chapter 4). In this case, the energy required for a blower or compressor is cost prohibitive because of excess depth, and a surface or a spray device with continuous circulation may be sufficient to provide a cost-effective treatment. This may be more economical in some cases, such as when the cost of an additional air stripper after storage and a possible re-pumping step is required. Lastly, for very small water systems, an educator or a venturi device is sometimes used for the addition of a small amount of oxygen to oxidize dissolved iron.

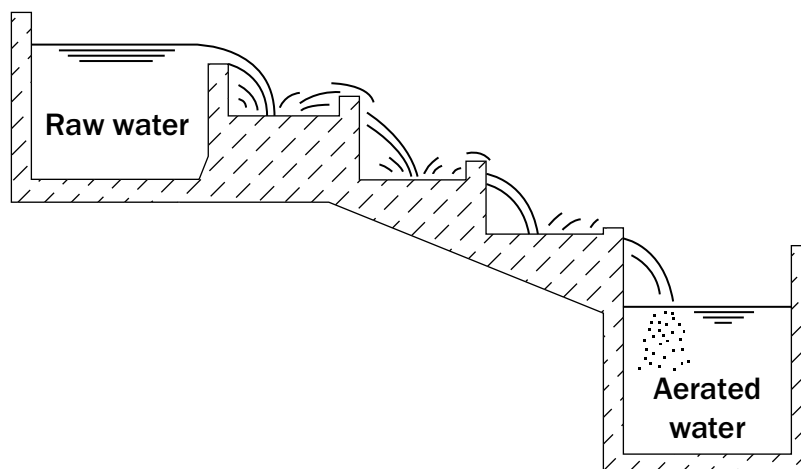
Finally, many of the installations of gas transfer equipment used in drinking water are predesigned by the manufacturer. The design engineer works with the manufacturer to select the appropriate capacity system and ensure that the unit selected will perform as specified.

Weir, Cascade, and Tray Aerators

In weir, cascade, and tray aerators, water drops by gravity onto several steps. Each step contains an overflow weir and a receiving gutter. When water passes over a weir, an interface between air and water is created. When the falling water submerges into the receiving body of water, significant amounts of air are entrained. The entrained air is then dispersed in the form of bubbles throughout the receiving body of water, which leads to the transfer of gases. Figure 2-1 shows a schematic of a typical cascade aerator.

Table 2-8 Efficiency coefficient k of different gases as a function of the weir height, in percent

Gas	$h = 1 \text{ ft (0.4m)}$	$h = 2 \text{ ft (0.8 m)}$	$h = 4 \text{ ft (1.2)}$
O ₂	25	46	55
CO ₂	14	15	15
CH ₄	27	48	62



Source: Appropedia article entitled "Original: Slow sand filtration water treatment plants"

Figure 2-1 Schematic of a cascade aerator

The gas transfer takes place at the interface between the water and the air bubbles. Because the amount of air that is entrained is limited, the air-to-water ratio is also limited, typically about 0.4 to 1.

An estimate of the efficiency for a cascade can be made, assuming that there is a relationship between the measured fall height and the efficiency. The efficiency of a cascade depends on the fall height of each cascade step and the number of steps:

$$K = \frac{c_{we} - c_{wo}}{C_s - c_{wo}} = 1 - (1 - k)^n \quad (\text{Eq 2-8})$$

where:

- K = overall efficiency of the cascade
- c_{wo} = initial concentration of gas in water [g/m³]
- c_{we} = final concentration of gas in water [g/m³]
- C_s = concentration of gas in water at saturation [g/m³]
- k = efficiency for each step [%]
- n = number of steps

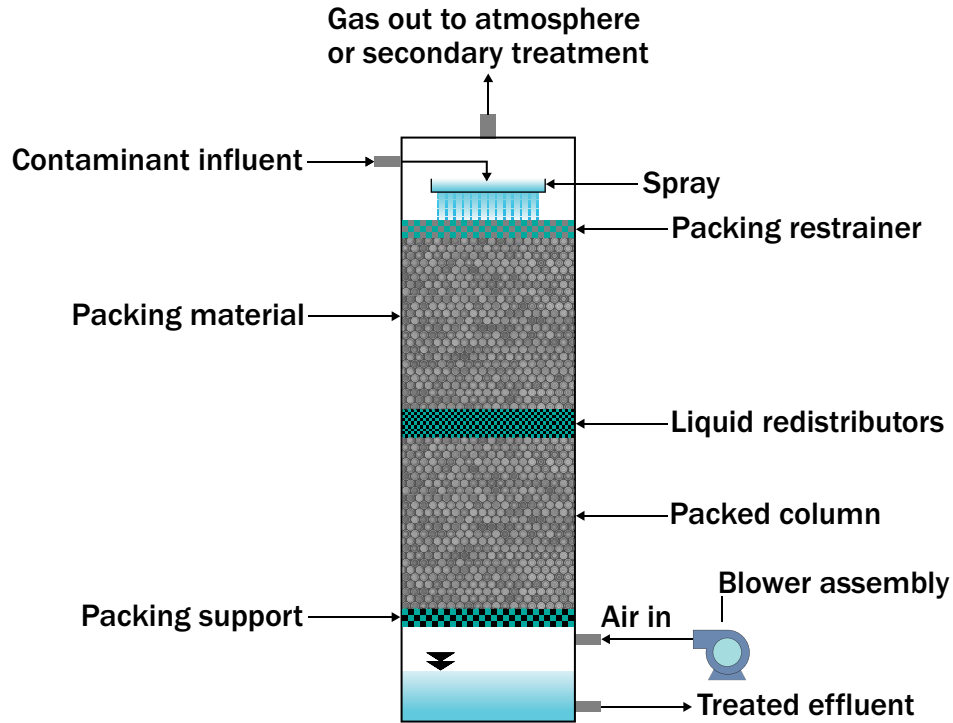
In Table 2-8, the efficiency is given for oxygen, carbon dioxide, and methane as a function of the fall height of a step. With the data from Table 2-8 and Equation 2-8, the efficiency of a cascade with n number of steps can be calculated. In practice, the total fall height of all the cascade steps together typically varies between 5 to 20 feet (2 to 7 m).

Packed Towers

Packed tower aeration (PTA) involves passing water down through a column of packing material while forcing air up through the packing media as shown in Figure 2-2.

Generally, aeration is feasible for removing compounds with a Henry's law constant greater than 100 (expressed in atm mol/mol) but not normally feasible for removing compounds with a Henry's constant of less than 10. For values between 10 and 100, PTA or other forced-air systems are used but should be evaluated using pilot studies or modeling. Table 2-9 shows categories of compounds in water classified by ease of aeration.

Because the Henry's law constant for each compound decreases with decreasing temperature, the system should be designed for the coldest air and water temperatures expected during operation.



Source: USEPA

Figure 2-2 Schematic of a packed tower aerator

Table 2-9 Aerated compounds in water (based on Henry's constant at 20°C)

Henry's Constant	Compounds
>100; readily aerated	Vinyl chloride, nitrogen, methane, ozone, toxaphene, carbon dioxide, radon, carbon tetrachloride, tetrachloroethylene, trichloroethylene, hydrogen sulfide, chloromethane, 1,1,1-trichloroethylene, toluene, 1,2,4-trimethylbenzene, benzene, 1,4-dichlorobenzene, chloroform
>10 and <100; potentially removed with packed tower aeration	1,2-dichloromethane, 1,1,2-trichloroethene, sulfide dioxide, bromoform
<10; not readily aerated	Ammonia, oxygen, pentachlorophenol, dieldrin, benzene, aldicarb, chlordane, polychlorinated biphenols

Source: Odell 2010

A tower aerator consists of a cylinder of steel or synthetic material filled with a packing medium (see Figure 2-2). Packing media can consist of stacked slats or tubes, or specially designed packing material like the Pall-ring and the Berl-saddle. In the top section of the tower, the water is divided over the packing media and flows down over the media surface. As a result of the flow of water over the packing media, a large contact surface between the air and water is created for gas transfer. In addition, the water falls in drops from one packing element to the other, continuously forming new drops and renewing the air-water interface for additional gas transfer (Delft University of Technology 2019).

The air can be renewed by natural ventilation or with the help of a ventilator. If a ventilator is used, the air can have a co- or counter-current flow in the tower, as a ventilator can help to distribute the air if it is in a co-current flow with water. With natural ventilation, the air is required to be counter-current with water. The packing material can be produced

from synthetic material, metal, carbon, or ceramic material. The dimensions of the individual pieces vary from 6 mm to 75 mm. In practice, installations used for purifying drinking water use mostly synthetic packing material with a dimension of 25–50 mm.

The surface loading (flow divided by surface area) that in practice is used in tower aerators is 40–100 m³/(m²·h). The applied packing height, which determines the retention time of the water in the tower aerator, varies between 3 and 5 m.

A disadvantage of the tower aerator is that the system is sensitive to clogging. If iron (Fe²⁺) is present in groundwater, it will oxidize in the tower aerator (Fe³⁺) and accumulate on the packing material as iron hydroxide (Fe(OH)₃). Because the oxidized iron influences the gas transfer negatively, it will be necessary to back flush the tower aerator. Water with a high velocity, or a combination of water and air, is then flushed through the tower aerator, removing the iron contamination from the packing material. In addition to flushing, it will be necessary to periodically clean the packing material chemically. In this case, the packing material must be removed from the tower aerator.

CO₂ can be stripped and pH subsequently increased through air stripping. In groundwater that has high calcium hardness and alkalinity, this pH increase can result in conditions that result in calcium carbonate precipitation on the packing media. Periodic cleaning of the media or use of a sequestering chemical (like a polyphosphate) would be necessary to avoid solidification on the media and reduced gas transfer.

The procedure to design a packed tower system is described by El-Belhil, El-Gezawi and Sbri (2012) here:

1. Identify a target contaminant or select the contaminant whose final water quality standard is the most difficult to achieve (usually the least volatile contaminant).
2. Select removal efficiency needed.
3. Select the lowest water temperature and determine Henry's law constant from the literature or calculations previously described in this chapter.
4. Select air-to-water (A/W) ratio: typical air-to-water ratios for groundwater are between 10 and 100. Compute the stripping factor S , where K_H' is the Henry's law constant for the selected contaminant at the lowest water temperature, Q_g is the gas flow rate, and Q_w is the water flow rate.

$$S = K_H' \frac{Q_g}{Q_w} \quad (\text{Eq 2-9})$$

Most designs used a stripping factor in the range 3 – 5. However, S as high as 10 has been used.

5. Compute the number of transfer units NTU , where $C_{L,in}$ is the concentration of the contaminant L into the packed tower and $C_{L,out}$ is the concentration of the contaminant L out of the packed tower.

$$NTU = \left(\frac{S}{S-1} \right) \ln \left[\frac{S}{S-1} \frac{C_{L,in}}{C_{L,out}} + \frac{1}{S} \right] \ln \left[\frac{S}{S-1} \frac{C_{L,in}}{C_{L,out}} + \frac{1}{S} \right] \quad (\text{Eq 2-10})$$

6. Select a hydraulic loading rate and compute the cross-sectional area and the diameter of the tower. Hydraulic loading rates may vary between 5 and 50 gpm/ft² (3.4×10^{-3} to 0.034 m³/m²·s). Hydraulic loading rates between 20 and 35 gpm/ft² are usually used.
7. Select the packing material and the mass transfer correlations to be used, such as Sherwood and Holloway's correlation (1940), which considers only the resistance in the liquid film, or Onda's correlation (1968), which includes both gas and liquid film resistances.

8. Compute the wetted surface area.

$$\frac{a_w}{a_t} = 1 - \exp \left[-1.45 \left(\frac{\sigma_c}{\sigma_L} \right)^{0.75} \left(\frac{L_w^*}{a_t \mu_L} \right)^{0.1} \left(\frac{L_w^{*2}}{\rho_L^2 g} \right)^{-0.05} \left(\frac{L_w^{*2}}{\rho_L \sigma_L a_t} \right)^{0.2} \right] \quad (\text{Eq 2-11})$$

where:

- a_w = effective interfacial area of packing per unit volume
- a_t = actual area of packing per unit volume
- σ_c = critical surface tension for the particular packing material
- σ_L = liquid surface tension
- L_w^* = liquid mass flow rate per unit cross-sectional area
- ρ_L = density of water
- μ_L = viscosity of water
- g = gravity constant

The actual area of packing per unit volume (a_t) is usually obtained from the manufacturer, while the critical surface tension of the packing is assumed to be that of water. Several other pieces of information such as the density and viscosity of air and water can be obtained from standard textbooks or handbooks. Note that the equations use mass flux ($\text{kg/m}^2\cdot\text{s}$).

9. If liquid and gas diffusivity of contaminant is not available, estimate the diffusivity of the contaminant in liquid and air phases with the Wilke and Chang (1955) equation and Hirschfelder, Bird, and Spotz (1946) equation, respectively.
10. With information from items 7 and 8, calculate the liquid and air phase mass transfer coefficients (k_L and k_G).

$$\frac{k_G}{a_t} \frac{RT}{D_G} = 5.23 \left[\frac{V_w^*}{a_t \mu_G} \right]^{0.7} \left[\frac{\mu_G}{\rho_G D_G} \right]^{\frac{1}{3}} [a_t d_p]^{-2} \quad (\text{Eq 2-12})$$

$$k_L \left[\frac{\rho_L}{\mu_L g} \right]^{\frac{1}{3}} = 0.0051 \left[\frac{L_w^*}{a_w \mu_L} \right]^{\frac{2}{3}} \left[\frac{\mu_L}{\rho_L D_L} \right]^{-0.5} [a_t d_p]^{0.4} \quad (\text{Eq 2-13})$$

where:

- V_w^* = air mass flow rate per unit column cross-sectional area
- ρ_G = density of air
- μ_G = viscosity of air
- D_G = gas-phase binary diffusivity
- D_L = liquid-phase binary diffusivity
- d_p = packing size

11. The overall mass transfer K_L is then computed.

$$\frac{1}{K_L} = \frac{1}{K_L} + \frac{1}{k_g K_H} \quad (\text{Eq 2-14})$$

12. Compute the height of a transfer unit (HTU), assuming $a = a_w$.

$$HTU = \frac{L_w^*}{\rho_L K_L a} \quad (\text{Eq 2-15})$$

13. The height of the tower required is then computed. A safety factor can be added to the height of packing, if required.

$$Z = HTU \times NTU \quad (\text{Eq 2-16})$$

14. Head losses through the packing itself can be estimated from manufacturers' literature. The pressure drop across the demister packing support plate, duct work, and tower inlet and outlet is calculated.

$$\Delta P = k_p \left(\frac{Q_g}{A_x} \right)^2 \quad (\text{Eq 2-17})$$

where:

A_x = the cross-sectional area of the packet tower aerator

15. The total horsepower requirement can be estimated from

$$\text{AirHP} = \frac{144 Q_g (p_1 - p_2)}{33,000 (E)} \quad (\text{Eq 2-18})$$

where an assumed fan and motor efficiency of 50 and 70 percent, respectively, can be used to yield an overall efficiency of 35 percent.

The tower air outlet in PTA systems must be designed to prevent noise from becoming a nuisance to neighbors. Sound regulations vary by site and zoning, but often the design must meet a decibel level at the property line. Air quality permitting may also be required depending on the contaminants removed and the location of the facility (ASCE/AWWA 2012).

Residuals from aeration systems are off-gases. In some applications, the off-gas must be collected and contaminants removed prior to discharge to the atmosphere. GAC canisters are most commonly used to collect and treat off-gases, with heating of the air flow to maximize efficiency and GAC life. Specific requirements for off-gas treatment from aeration facilities vary by location and with air quality standards.

Vacuum Degassers

A vacuum gas transfer system is usually executed as a tower aerator filled with a packing material in which the pressure is lowered by a vacuum pump. Membrane degassers are also used, where a vacuum is placed across a membrane and the gas is pulled from the water through the membrane (Macklin 2019).

Due to the vacuum pump, gas is removed from the water, resulting in lower gas concentrations. Because the gas concentrations in the water are lower than in the atmosphere, the saturation concentrations in the water are also lower. Because of the low saturation concentrations, it is possible to remove higher levels of gas from the water than is possible under atmospheric conditions. This makes a vacuum gas transfer system ideal for removing dissolved nitrogen and oxygen from the water and is frequently applied before the denitrification process. The efficiency of the vacuum gas transfer system depends on the vacuum pressure that is maintained in the treatment unit. The primary drawback of this technology is a higher energy use compared with packed tower aeration systems.

Staged Diffused Bubble Systems

There are two basic variations of bubble equipment as defined by the reactor and air introduction. Both of these designs use completely mixed (aerated) stages in series flow to approach a plug-flow efficiency. A completely mixed reactor is relatively inefficient compared to a plug-flow reactor because the mixing allows some portion of the influent to exit the reactor with minimal detention time in which treatment may occur. Therefore, the completely mixed stages must be placed in series to avoid back mixing and to achieve high efficiency. In this way, a plug-flow efficiency is closely approached if stages are greater than 3–6, depending on the contaminant and other factors. These systems are designed to maintain a relatively low profile compared to packed towers.

Diffused bubble systems almost exclusively use large orifices for bubble introduction to minimize maintenance. Air intensities are very high to minimize the equipment footprint, and this requires a high air velocity and a specific head loss at each orifice to maintain even air distribution without unnecessarily high pressure drop. For this type of equipment, a fine air bubble is not possible. Further, much lower maintenance is realized using coarse bubbles. Manufacturers simply design around any loss of transfer due to larger bubble size (Lowry and Lowry 1988).

The other important design parameter for these systems is depth. In testing many volatile contaminants during the 1970s and 1980s, it was learned that excessive depth was not needed for efficient bubble systems. Bubble rise depth has to be a balance of two factors: transfer efficiency and blower head (power required). Data show that there are a wide range of optimum depths when balancing these two requirements, based on the constituent being removed. For example, for the very poorly stripped methyl tertiary-butyl ether (MTBE), there is no significant advantage (transfer) beyond a depth of several inches. Transfer is minimal for this low Henry's constant VOC and it is transferred into an air bubble very rapidly. On the other extreme, carbon dioxide and radon transfer benefits from increasing depth up to several feet. The most important aspect of water depth is that several feet of depth is ample for optimum removal, and deeper water only results in an unnecessary increase in capital and operating cost associated with higher-pressure air blowers. This statement is valid for all applications of interest in drinking water treatment and for coarse bubbles.

The key to the design of this type of diffused bubble equipment is (1) limited depth and (2) coarse bubbles. Both of these parameters are fixed by the manufacturers of the equipment. Bubble aeration equipment that is designed using deep basins and finer bubble orifices are inherently expensive and less effective in drinking water applications (Lowry and Lowry 1988).

Vertically stacked bubble trays. This equipment uses vertically stacked successive shallow-depth trays with the water flowing downward by gravity and the air flowing in a counter-current, upward direction. A common name for this equipment is shallow tray air strippers. Depending upon the number of trays, each with 1–2 in. of water depth, the total static water depth varies from a few inches to tens of inches. Similar to packed towers, more height (trays) yields increased removal and increased blower pressure. Trays have holes for air flow (coarse bubbles), and downcomer pipes for water flow from tray to tray. An advantage of this design over packed towers is lower vertical height. Ease of maintenance is also reported to be an advantage, as trays are designed to be unstacked and packing is avoided (Ahmed et al. 2014).

Hundreds of these low-profile shallow tray air strippers have been used in pump-and-treat and drinking water applications for the removal of VOCs, radon, methane, hydrogen sulfides, and carbon dioxide.

General mathematical modeling for this type of equipment was described in 1958 in the *Handbook of Chemical Engineering*. However, each manufacturer has proprietary empirical design data and modeling available for its specific equipment.

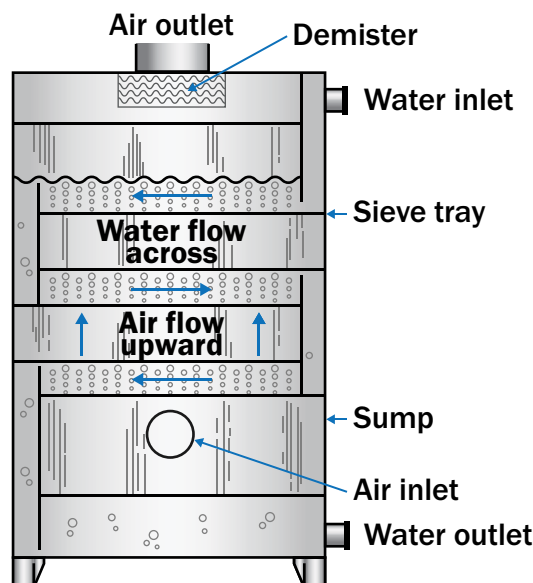
A schematic and a photo of a stacked tray unit are shown in Figures 2-3 and 2-4, respectively.

Horizontal multi-staged bubble systems. Multi-staged bubble air stripping (MSBAS) and aeration have been used in drinking water treatment for 30 years. This type of system employs a vessel that is divided into stages using flow-through dividers and aerators in each stage. Water flows end to end, and air flows equally into each stage. This system was first applied to drinking water for very small water systems requiring extremely high removal (>99.999%) of VOCs in gasoline-contaminated wells (Lowry and Lowry 1984, Lowry and Lowry 1988) in the early 1980s. It has been used in larger systems for the removal of radon, carbon dioxide, VOCs, sulfides, methane, and nitrogen trichloride and for the addition of oxygen in the oxidation of iron (Lowry et al. 1984, Dixon et al. 1991, Schock et al. 1999). Several hundred systems are treating drinking water supplies. Recently, USEPA commissioned a study to define the performance of this system for the removal of 13 VOCs being considered for future regulation of carcinogenic VOCs (Lowry 2013).

Given a specific contaminant (Henry's constant) and water temperature, the basic design parameters for the process are

- air:water (A:W) ratio
- depth of bubble rise
- size of bubbles
- number of stages

The stages in the process are what create an efficiency far beyond what a single completely mixed vessel would produce. As the number of stages increases, the process



Courtesy of Carbonair.

Figure 2-3 Schematic of a stacked tray unit



Courtesy of Milt Larsen.

Figure 2-4 A stacked tray unit

efficiency approaches that of a theoretical plug-flow process. The two processes are shown below in Eq 2-19 and Eq 2-20.

Completely mixed stages in series:

$$C/C_o = [1/(1+kt)]^m \quad (\text{Eq 2-19})$$

where:

C = concentration at steady state

C_o = inlet concentration

k = the first-order rate constant for a single stage, time^{-1} (directly proportional to air intensity, AI)

t = detention time, volume/flow, of a single stage

m = number of stages in series

Plug-flow:

$$C_t/C_o = e^{-kt} \quad (\text{Eq 2-20})$$

where:

C_t = concentration at time t

Air is generally introduced to each stage at a high rate to minimize the equipment footprint. The Reynold's number for this type of air flow at an orifice is far greater than 5,000; therefore, the air exits the orifice as a continuous airstream and the bubbles do not form at the orifice. While the bubble size is influenced and proportional to orifice size, it is generally much larger, and the actual bubble size range and distribution are determined by the hydrodynamics of the mixing intensity in the stage.

It is important to note that the detention time in a completely mixed diffused bubble reactor is not important, as long as a specific A:W ratio is achieved. The first-order rate constant is directly proportional to the air intensity, all other factors being equal. For a fixed depth and aerator device, a doubling of the air intensity is a doubling of the rate constant for the range of practical application of these processes. The rate constant is an empirical quantity that is estimated using either a continuous pilot vessel or a batch reactor. As long as the depth, bubble size, and temperature are representative, then this constant is much more accurate than using a general theoretical model as described by others (AWWA 1999). The rate is exactly first-order ($r^2 \approx 0.99$), and design removal prediction is very accurate. Lowry has described this process in several publications, including those previously cited in this section (Lowry et al. 1984, Lowry 2013).

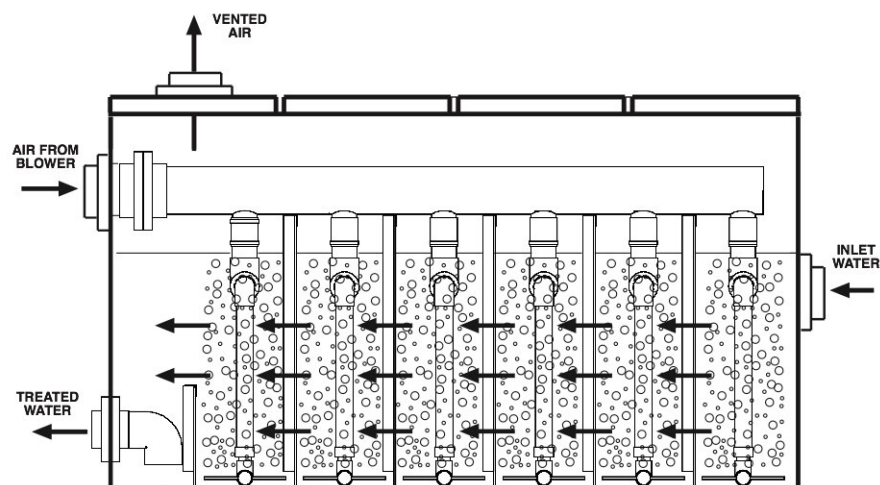
A schematic of a multi-stage bubble air stripper is shown in Figure 2-5. Example removal relations for carbon dioxide are shown in Figures 2-6 and 2-7. Figure 2-6 shows the first order relation for a single stage, and Figure 2-7 shows the resulting removal relation by application of the model for removal by completely mixed stages in series.

Summary

All of the types of gas transfer equipment described previously have their place in drinking water treatment. While packed towers and cascade type aerators are the most numerous throughout the United States, other types of equipment are applicable to many water supplies and are used routinely. Where high removal is required, packed towers and low-profile bubble systems are often required. Ease of maintenance, installed footprint, indoor installation, and overall height can be important factors in the determination of which equipment to use.

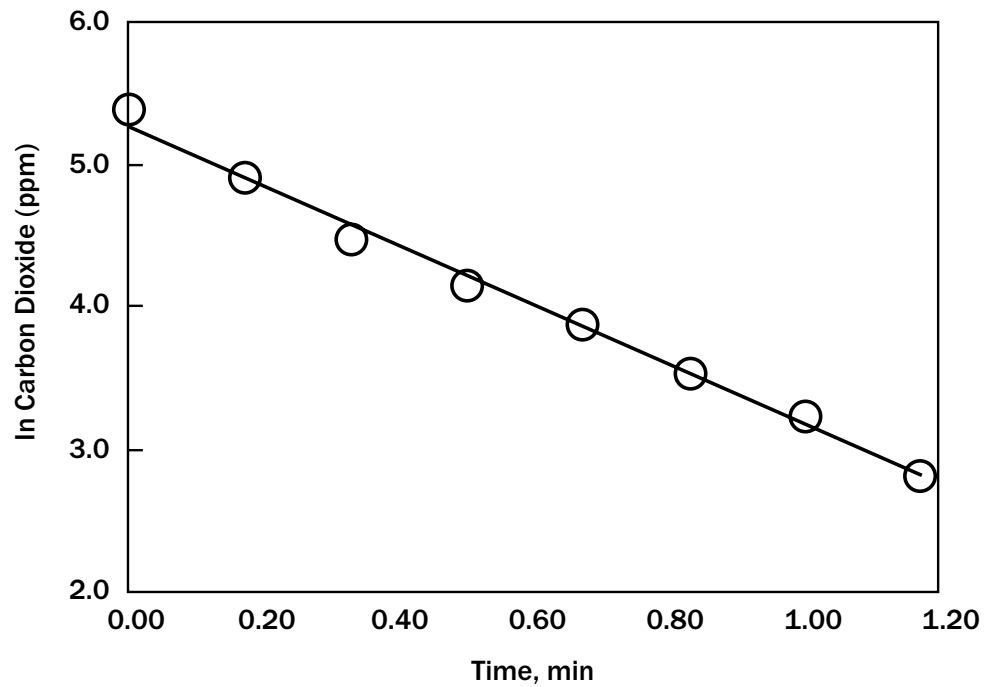
For special situations such as TTHM removal in relatively deep storage tanks, a surface or spray device can offer a solution without adding another step in treatment and/or additional pumping.

A photo of a multi-stage bubble system is shown in Figure 2-8.



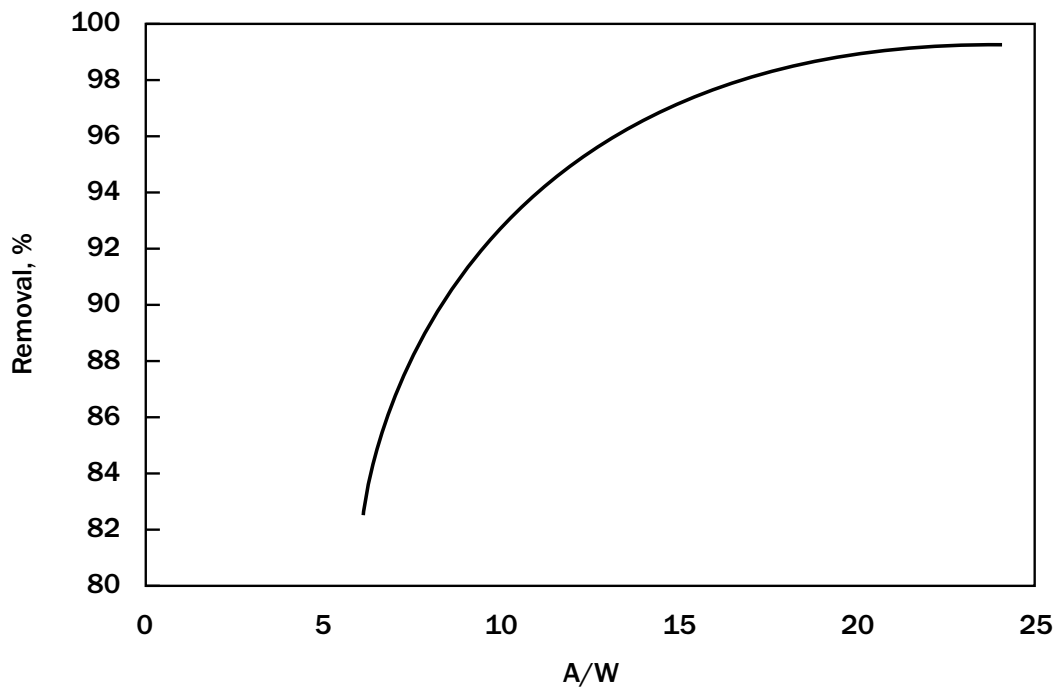
Courtesy of Lowry Aeration Systems, Inc.

Figure 2-5 Schematic of a multi-staged bubble air stripper



Courtesy of Lowry Aeration Systems, Inc.

Figure 2-6 First-order removal of carbon dioxide in batch test (k equals the slope of the fitted line)



Courtesy of Lowry Aeration Systems, Inc.
A/W—air:water ratio

Figure 2-7 Removal of carbon dioxide in six-stage bubble reactor



Figure 2-8 Multi-stage bubble system for the removal of carbon dioxide at 500 gpm (Searsport, Maine)

BLOWER SELECTION

The terms *fan*, *blower*, and *compressor* have been used interchangeably over the years in various applications. In general, these terms are typically used for devices that span a wide range of pressure, with axial fans being on the low-pressure end and compressors being on the high-pressure end of the spectrum. These devices are negative-displacement or positive-displacement. Centrifugal and regenerative blowers are negative-displacement, where accelerating and decelerating the air achieve compression. Positive-displacement devices directly compress air by reciprocating pistons, rotary vanes, or turbines. For this chapter, the term *blower* will be used, as it is most appropriate for the majority of equipment being considered.

The selection of the air blower is based on several design and operating parameters. The blower must be able to provide

- clean, oil-free air,
- the required amount of air as dictated by the design A:W,
- the required design head for the application, and
- a noise level below an acceptable design value.

In addition to meeting design and operating parameters, the blower should be selected to minimize

- the energy required for the specific air stripping process that is used and
- the maintenance required for long-term operation.

Types of Blowers

The blower categories that are suitable for drinking water applications are axial fans, single and multiple stage centrifugal blowers, regenerative blowers, and positive displacement blowers. The range of blower types is a result of air volume and pressure requirements for a given application. Fans produce airflow at very low pressures and are appropriate for exchange of the air headspace in an enclosed storage tank using a spray device to air strip contaminants. At the opposite end of the application spectrum is the positive displacement blower. This type of blower is used for applications requiring relatively high air pressures to overcome the static pressure head of deep storage tanks. Between these two extremes are the blowers that are used most often for air-stripping applications involving packed towers and low-profile bubble and tray processes. These blowers are used to provide air at pressures in a range of a few inches of WC to several psi. The same blowers can also be applied to produce a vacuum in the process, as in specially designed packed towers where enhanced mass transfer may result from a negative pressure.

Each of the blower types described previously is shown in Figures 2-9 through 2-12.

The types of blowers most suited for aeration and air stripping are regenerative (lower flow rates) and centrifugal. These blowers provide air at the most reasonable power cost. Excess water depth or packing losses should be avoided, to minimize the blower pressure that is required. The theoretical power a blower uses is related to head by:

$$AHP = (Q \times P) \div 6,356 \quad (\text{Eq 2-21})$$

where:

- AHP = air horsepower
- Q = volumetric flow rate (SCFM)
- P = pressure (inches of water gauge) or resistance



Source: Cincinnati Fan

Figure 2-9 An axial fan



Courtesy of Lowry Systems, Inc.

Figure 2-10 A centrifugal blower



Courtesy of Lowry Aeration Systems, Inc.

Figure 2-11 A regenerative blower

Diffused bubble vessels or trays should not require a design using a positive-displacement blower but instead typically use a centrifugal or regenerative blower. Water depth and blower head do not need to be greater than 3–4 ft for aeration or air stripping applications, based on fundamental transfer kinetics and efficient design. As previously explained, detention time, per se, is not important to removal with diffused bubble systems. Water



Courtesy of Lowry Aeration Systems, Inc.

Figure 2-12 A positive displacement-type blower

depth greater than 3–4 ft is not beneficial from a treatment standpoint and is extremely costly on an energy and capital cost basis.

Deep tank aeration or air stripping is a wasteful practice and should not be used. While it may be tempting to use an existing deep tank, it is always far more cost-effective to use a smaller and more cost-efficient design. For example, a tank that is 15 ft deep would require approximately 5 times the power of a vessel with a depth of 3 ft, and the blower type would be significantly more costly to operate and maintain. Higher water depths and blower pressures are not required for bubble systems and should be avoided.

Since packed towers have relatively low head for airflow, they typically use a centrifugal blower or fan. Packed towers normally require less blower head than bubble systems because they do not have a static water depth to overcome.

SCFM, ACFM, and ICFM

Air is compressible and its movement is typically expressed as a volume rate rather than a mass flow rate. In the US, the blower industry traditionally uses units of standard cubic feet per minute (SCFM), actual cubic feet per minute (ACFM), and inlet cubic feet per minute (ICFM). SCFM is the flow of air in cubic feet per minute at standard temperature and pressure. It must be noted that various temperatures and pressures have been referred to as “standard,” depending on manufacturer and industrial application. The Compressed Air & Gas Institute (CAGI) and the American Society of Mechanical Engineers (ASME) standards state that standard air is at a temperature of 68°F, a barometric pressure of 29.92 (sea level), and a relative humidity of 36 percent. The density of standard air is 0.075 pounds per cubic foot. ACFM is the actual cubic feet per minute of air. ICFM is the inlet cubic feet per minute of air and is equivalent to the ACFM.

The ACFM is the actual volume of air moving at any temperature, pressure, and relative humidity, and is related to SCFM as follows:

$$SCFM = ACFM \left(\frac{T_1 + 460}{T_2 + 460} \right) \left(\frac{P_{atm}}{14.7} \right) \quad (\text{Eq 2-22})$$

where:

$$\begin{aligned} T_1 &= \text{standard temperature, } ^\circ\text{F} \\ T_2 &= \text{temperature of inlet air, } ^\circ\text{F} \\ P_{atm} &= \text{atmospheric pressure at blower altitude, psi} \end{aligned}$$

Note that temperature and altitude are the main influences on converting ACFM to SCFM. It is common to disregard the correction for relative humidity because it is not a significant factor in most applications.

Once a blower is selected for the operating point at a given altitude, the changes in SCFM are almost entirely related to the inlet air temperature. The coldest seasonal temperature (highest air density) dictates the maximum power required (motor hp) and the warmest seasonal temperature (lowest air density) dictates the minimum pressure that the blower can generate at maximum speed (60 Hz). Both conditions must be checked to ensure the motor is adequate for the load and that the blower airflow will not drop below the surge point in the case of a centrifugal blower.

Affinity Laws

Blower speed influences the airflow, head produced, and the power required. The affinity laws, sometimes referred to as fan laws, can be used to correct a blower performance curve for speed change from N_1 to N_2 , where N = speed in rpm or Hz. This applies to a blower operating on a variable-frequency drive (VFD). The affinity laws are as follow:

$$\left(\frac{Q_1}{Q_2} \right) = \left(\frac{N_1}{N_2} \right) \quad (\text{Eq 2-23a})$$

$$\left(\frac{H_1}{H_2} \right) = \left(\frac{N_1}{N_2} \right)^2 \quad (\text{Eq 2-23b})$$

$$\left(\frac{P_1}{P_2} \right) = \left(\frac{N_1}{N_2} \right)^3 \quad (\text{Eq 2-23c})$$

where:

$$\begin{aligned} Q_1 &= \text{blower flow at speed } N_1 \\ Q_2 &= \text{blower flow at speed } N_2 \\ H_1 &= \text{blower head at speed } N_1 \\ H_2 &= \text{blower head at speed } N_2 \\ P_1 &= \text{blower power at speed } N_1 \\ P_2 &= \text{blower power at speed } N_2 \end{aligned}$$

Minimum Speed, Airflow, and Blower Surge

When the speed of the blower is reduced, there are definite limits related to the head produced so that the blower pressure does not fall below the static head. This applies to types of air strippers that must overcome a minimum head to produce airflow. Diffused bubble and stacked tray air strippers have a fixed static water head that must be overcome to produce bubbles, and to distribute bubbles uniformly. This head is slightly higher during operation if an overflow weir is involved and the maximum water depth must

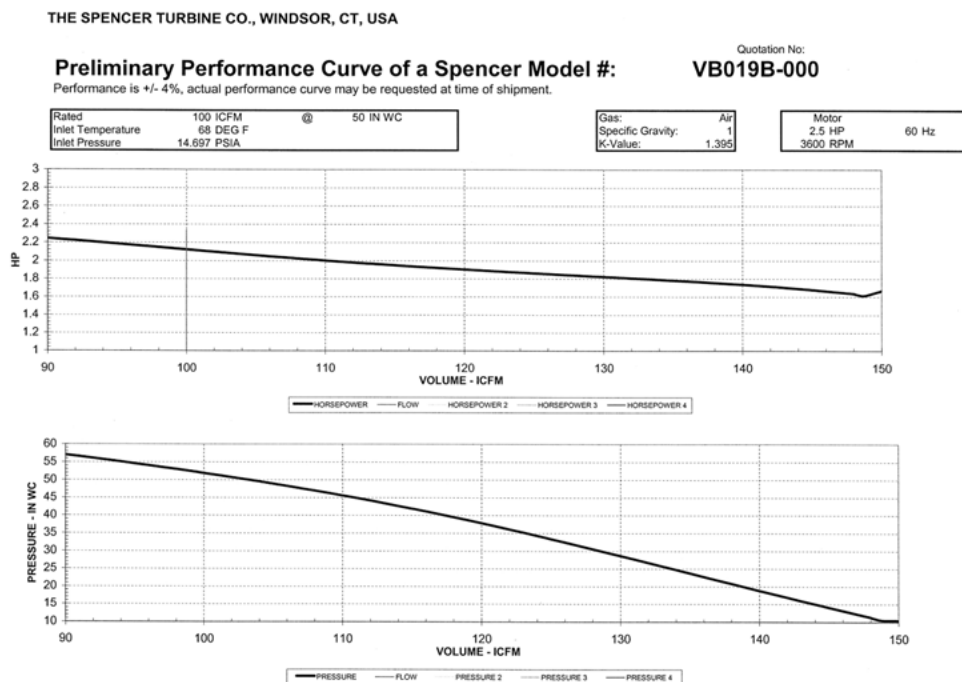
be considered when a blower is operated at reduced speeds. The blower must always be operated at a pressure that is sufficiently high to avoid a deadhead condition.

Centrifugal and axial compressors will surge when forward flow through the compressor can no longer be maintained, due to an increase in pressure across the compressor, and a momentary flow reversal occurs. Once a surge occurs, the reversal of flow reduces the discharge pressure or increases the suction pressure, thus allowing forward flow to resume again until the pressure reaches the surge point again. This surge cycle will continue until some change is made in the process or compressor conditions. Severe damage to the thrust bearings, seals, and the impeller can occur with a severe surge condition. A centrifugal blower must not be turned down to a flow rate that puts it into a surge condition. The surge airflow limit is related to the internal design of the specific machine.

The extent of the damage is particular to the specific design of the blower, but total failure can occur with acute surge. An example would be if the blower inlet filter or intake screen becomes partially or totally blocked for period of time. When a blower is selected, the manufacturer normally provides the blower curve with minimum flow shown for each speed being considered. The minimum flow rates take into account blower surge and include a safety factor.

Surge can be an issue with a centrifugal blower because it is routine to throttle a centrifugal blower to produce a specific airflow and save power. Throttling a centrifugal blower reduces the power required, as power is related to the mass flow of air passing through the machine. The opposite is true for a regenerative blower, where throttling increases the power draw.

Blower surge is not a factor with a regenerative blower, and the lower limit on airflow is normally dictated by power draw and temperature rise. In the case of reduced motor speed for a regenerative blower, it is the required minimum airflow or the deadhead condition that dictates the minimum speed.



Courtesy of Lowry Aeration Systems, Inc.

Figure 2-13 Regenerative blower—scfm, pressure, power (Spencer Turbine Co., Windsor, Conn.)