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Gas Transfer in Diffused Bubble Plumes

Steven C. Wilhelms¹ and Sandra K. Martin¹

Abstract

The gas transfer in aeration systems is broken into two processes: gas transfer at the bubble interface and gas transfer at the water surface. Experiments were conducted to separate these two sources of dissolved gas. Oxygen absorption was measured in a laboratory tank with air being diffused through a porous diffuser and then with nitrogen gas being diffused. The combination of these experiments along with reformulation of the theoretical transfer equation permit separation of the gas transfer at the water surface and in the rising bubble plume. Estimates of the exchange coefficient for the plume and surface are given.

Introduction

Diffused aeration systems for oxygen absorption are typically used in wastewater treatment. These systems usually use porous diffusers to generate a bubble plume that induces mixing and gas transfer. Design information for these diffuser systems is given as the product of the liquid film exchange coefficient, k_l , and the specific surface area, a . This product, $k_l a$, is generally referred to as the overall mass-transfer coefficient or the exchange coefficient and has units of hr^{-1} . It represents the sum of the oxygen absorption that occurs in the rising bubble plume and at the water surface of the test tank (Metcalf & Eddy, Inc. 1979).

Diffused aeration systems have been considered and have been installed at a few locations for improvement of dissolved oxygen (DO) in deep reservoirs and lakes. The level of confidence in applying manufacturer-supplied estimates of the exchange coefficient decreases with increasing reservoir depth since coefficients were derived from tank tests having water depths significantly less than those of deep

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reservoirs and lakes. While the relative contribution to the overall oxygen transfer by the water surface may be similar between laboratory flumes and shallow wastewater treatment facilities, the contribution to total gas transfer by absorption at the water surface would be significantly reduced for a very deep reservoir. For example, consider the oxygen transfer that occurs in a 5-m-deep test facility: part results from absorption from the bubbles and part from transfer with the atmosphere at the water surface. If the depth of the facility is 50 m, the mass of oxygen transferred across the water surface remains nearly the same (assuming no change in the overall mixing characteristics at the water surface). However, the total gas transfer would increase dramatically with the diffusers located at a 50-m depth due to the hydrostatic pressure on the bubbles. According to Henry's law, hydrostatic pressure enhances oxygen transfer by increasing the saturation concentration in the bubbles (Hydraulics Research Station 1978, McDonald and Gulliver 1990).

To design a diffused aeration system for a reservoir, the need exists to have separate estimates of the coefficients for gas transfer in the bubble plume and at the water surface. Once separated, the gas transfer due to the rising bubble plume can be calculated at any depth by varying the saturation constant due to the hydrostatic pressure and then integrating over the depth of the reservoir. The gas transfer due to the surface can then be added, resulting in a much improved diffuser design methodology. The work discussed herein, represents preliminary results of tests to separate the gas transfer at the water surface and in the bubble plume. The test procedure is presented, test results and analysis are shown, and future work is discussed.

Theoretical Basis

The gas transfer process for a diffused air plume can be broken into the two parts: oxygen absorption at the water surface and absorption from the air bubbles. Mathematically, the total process can be described by

$$\frac{dC}{dt} = \left[\frac{\partial C}{\partial t} \right]_{\text{Bub}} + \left[\frac{\partial C}{\partial t} \right]_{\text{Surf}} \quad (1)$$

where dC/dt is the total gas transfer and

$$\left[\frac{\partial C}{\partial t} \right]_{\text{Surf}} = [k_L a]_{\text{Surf}} (C_s - C) \quad (2)$$

is the oxygen absorption at the water surface and

$$\left[\frac{\partial C}{\partial t} \right]_{\text{Bub}} = [k_L a]_{\text{Bub}} (C_s - C) \quad (3)$$

is the oxygen absorption in the bubble plume, and C_s and C are the

saturation concentration and in-water concentration, respectively. An implicit assumption in this formulation is that the saturation concentration does not change for the bubbles.

Substituting Equations 2 and 3 into Equation 1 and integrating from an initial C_i to a final C_f oxygen concentration from time equal to zero to a lapse time of t , gives

$$\frac{C_s - C_f}{C_s - C_i} = e^{-([k_L a]_{\text{Surf}} + [k_L a]_{\text{Bub}}) t} = e^{-[k_L a]_{\text{Tot}} t} \quad (4)$$

which describes the oxygen absorption that would be measured in a test tank with a diffused air plume.

To separate the surface and bubble gas exchange in Equation 4, nitrogen gas was used instead of air. Equation 1 also describes the gas transfer for this condition. The surface exchange is described by Equation 2. However, the nitrogen bubbles actually strip oxygen from the water, thus the gas exchange is described by

$$\left[\frac{\partial C}{\partial t} \right]_{\text{Bub}} = -[k_L a]_{\text{Bub}} C \quad (5)$$

Substituting Equations 2 and 5 into Equation 1 and integrating over the same limits as defined in the previous paragraph gives

$$\frac{[k_L a]_{\text{Surf}} C_s - \{[k_L a]_{\text{Surf}} + [k_L a]_{\text{Bub}}\} C_f}{[k_L a]_{\text{Surf}} C_s - \{[k_L a]_{\text{Surf}} + [k_L a]_{\text{Bub}}\} C_i} = e^{-\{[k_L a]_{\text{Surf}} + [k_L a]_{\text{Bub}}\} t} \quad (6)$$

Equation 6 describes the oxygen transfer that would occur in a test tank with a diffused nitrogen gas plume. In this formulation $[k_L a]_{\text{Surf}}$ and $[k_L a]_{\text{Bub}}$ are separated from $[k_L a]_{\text{Tot}}$ allowing for the approximation of both of these coefficients using nonlinear regression.

Another way to formulate the problem is to evaluate the coefficients at equilibrium, when dC/dt equals zero or $[\partial C/\partial t]_{\text{Surf}} + [\partial C/\partial t]_{\text{Bub}} = 0$. Substituting the equilibrium value of the concentration, C_e , from the nitrogen tests for C results in the following proportionality:

$$\frac{[k_L a]_{\text{Surf}}}{[k_L a]_{\text{Bub}}} = \frac{C_e}{C_s - C_e} \quad (7)$$

Experimental Procedure

Standard procedures, established by the American Society of Civil Engineers (ASCE 1984) were used to conduct the tests. Sodium sulfite was used to deoxygenate water in a 1.3-m by 2.6-m rectangular laboratory test tank. The diffuser head was placed on the bottom of the tank at a water depth of 1.1 m. Compressed air was diffused through a 23-cm-diameter flexible-head diffuser at a rate of 18.9 l/m. Measurements of DO concentration were made over time at four locations in the tank. The same testing procedures were repeated as nitrogen gas was released through the diffuser.

Initially, a combination of both tests was expected to be necessary for the separation of the transfer coefficient into the contribution by the surface and by the bubbles. Before the theoretical formulation of the process had been developed, as shown in the previous section, the use of nitrogen was expected to eliminate the oxygen transfer in the bubble plume and hence, the oxygen uptake reflected in the measurements would be a result of oxygen transfer across the water surface only. After the formulation it became apparent, the nitrogen bubble plume stripped oxygen from the water, ultimately establishing steady-state between the oxygen absorbed at the water surface and the stripping action of the nitrogen plume. During the analysis, it was found that only the tests using nitrogen were needed to establish the contribution by the bubbles and the surface.

Results and Analysis

Using nonlinear multiple regression analysis and the formulation in Equation 4, the saturation concentration, C_s , and the total exchange coefficient, $[k_L a]_{Tot}$, were determined for the diffused air test to be approximately 8.0 mg/l and 1.08 hr^{-1} , respectively. The multiple linear regression analysis was repeated for the diffused nitrogen test such that an equilibrium concentration, C_e , and the combined mass transfer coefficient, $[k_L a]_{Tot}$ were determined to be approximately 2.95 mg/l and 1.08 hr^{-1} , respectively. This analysis did not result in separation of the total exchange coefficient into its parts, but did produce the equilibrium concentration resulting from the nitrogen tests. The observations of DO concentrations for the diffused air and diffused nitrogen tests and their fitted curves are shown in Figure 1. (These are actual observations and have not been adjusted for differences in temperature.)

Using the nonlinear regression technique, but formulating the problem using Equation 6 and the data from the nitrogen tests allowed the unknown values to be determined using one test. Analyzing the diffused nitrogen test, resulted in C_s , $[k_L a]_{Surf}$, and $[k_L a]_{Bub}$ values of approximately 8.85 mg/l, 0.36 hr^{-1} and 0.72 hr^{-1} , respectively. The total exchange coefficient agreed between tests and formulations.

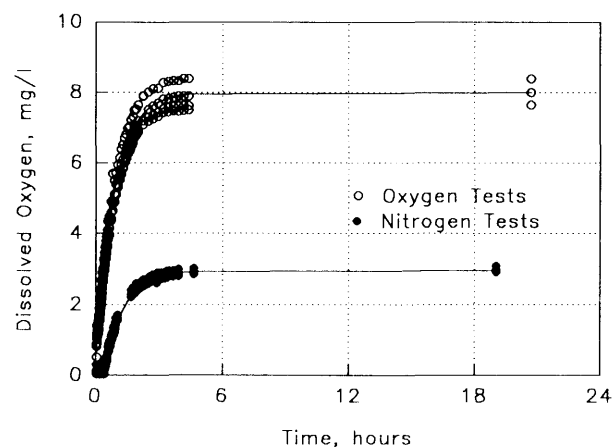


Figure 1. Dissolved oxygen concentration over time for diffused air and diffused nitrogen in laboratory tank

As can be seen, the ratio of the exchange coefficients for the surface to the bubbles is approximately 0.50. The same ratio can also be derived from Equation 7 by substituting 8.85 for C_s and 2.95 for C_e .

The results indicated that about one-third of the oxygen absorption in this tank test was due to surface exchange and two-thirds was absorbed from the bubble plume. Clearly, since the tank used in this test was approximately 1 m deep, the relative effect of surface absorption would be reduced as the depth increased.

Conclusions and Recommendations

In the design of deep-water aeration systems, the gas transfer resulting from the rising bubble plume should be determined separately from that caused by transfer at the surface. This is due to the impact that depth has on hydrostatic pressure, and consequently, the gas transfer efficiency. While the exchange coefficients for a variety of diffusers have been defined in tank tests by the manufacturers, these coefficients represent a total product of the liquid film coefficient and the specific surface area, $[k_L a]_{Tot}$, and do not represent the relative contribution to oxygen absorption by the bubbles and the surface.

Additional tests using nitrogen are in progress to determine the exchange coefficients associated with different diffuser flow rates. The total surface area of the bubbles for each air flow rate are being

determined from photographs of the bubble plume using a statistical analysis of bubble dimensions. Data from these tests will be used to assess the impact of the loading, or flow rate, on bubble size and its effect on the exchange coefficient k_L .

A numerical model will be developed to determine the concentration of oxygen in a reservoir resulting from a specific diffuser. The model will use the separate values obtained for the coefficients and integrate the effects of pressure over the depth of the reservoir. The model will be verified in a much deeper test facility. The results of this analysis should provide a more accurate means to design a deep reservoir aeration system for purposes of water quality.

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