Hypolimnetic Aerators: Predicting Oxygen Transfer and Water Flow Rate

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Predicting Oxygen Transfer and Water Flow Rate in Hypolimnetic Aerators

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(ABSTRACT)

The objective of this research was to characterize the performance of hypolimnetic aerators with respect to oxygen transfer and water flow rate to allow the development of two comprehensive process models. The oxygen transfer model is the first model that applies discrete-bubble principles to a hypolimnetic aerator, and the water flow rate model is the first that applies an energy balance to this particular type of lake aeration device. Both models use fundamental principles to predict hypolimnetic aerator performance, as opposed to empirical correlations.

The models were verified with data collected from a full-scale hypolimnetic aerator installed in Lake Prince, which is a water supply reservoir for the City of Norfolk, Virginia. Water flow rate, gas-phase holdup and dissolved oxygen profiles were measured as a function of air flow rate.

The initial bubble size was calculated by the oxygen transfer model using field data. The range of bubble diameters obtained using the model was 2.3-3.1 mm. The Sauter mean diameters of bubbles measured in a laboratory system ranged from 2.7-3.9 mm. The riser and downcomer DO profiles and gas holdups predicted by the model are in close agreement with experimental results.

The water flow rate model was fitted to the experimental water velocity by varying the frictional loss coefficient for the air-water separator. An empirical correlation that predicts the loss coefficient as a function of superficial water velocity was obtained. The results of the correlation were similar to those predicted by literature equations developed for external airlift bioreactors.

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CHAPTER 1. LITERATURE REVIEW

Background

Thermal stratification of lakes and reservoirs can lead to severe water-quality problems. This phenomenon usually occurs in the summer months. During the winter and early spring, the water column is typically uniformly cold and easily mixed by the wind. As spring progresses, the days become warmer. On a calm, hot day, the surface waters warm rapidly because of increased solar radiation and become less dense. The surface water then cannot be mixed with the denser, colder water beneath except by severe winds. At this point, the water body can be classified as thermally stratified (Cooke and Carlson, 1989).

When a water body becomes stratified, three layers develop. The warm upper layer is termed the epilimnion. This region continues to circulate on windy days and exchanges gasses, primarily nitrogen and oxygen, with the atmosphere. The second layer is the metalimnion in which water temperature drops rapidly with increasing depth. The bottom layer of colder, denser water is the hypolimnion. The hypolimnion is essentially unaffected by the atmosphere or the epilimnion and is considered to be relatively stagnant. In addition, this region usually does not have enough sunlight penetration for photosynthesis to occur. Because of these factors, the dissolved oxygen supply in this layer cannot be replenished continually (Cooke and Carlson, 1989). Oxygen in the hypolimnion is depleted by plant, animal, and bacteria respiration and by sediment reactions (Cole, 1994). If the amount of dissolved oxygen in this stratum is not adequate to meet these demands, then anoxic conditions soon result. Low dissolved oxygen levels in the hypolimnion limit the use of the water body as a cold-water fishery. This condition can also lead to the production of hydrogen sulfide gas. In addition, it can cause iron and manganese accumulated in the sediments to solubilize. These compounds produce considerable taste, odor, and color problems if hypolimnetic water is to be treated for potable uses (Cooke and Carlson, 1989). The removal of these compounds creates an increased oxidant demand at the water treatment plant, which can be quite expensive. Chlorine can also react with certain organics in raw water to produce disinfection-by-products such as trihalomethanes, which are suspected carcinogens and therefore must be under strict regulatory levels in finished water (Tate and Arnold, 1990).

To combat anoxia in the hypolimnion and subsequently lower the dosage of chlorine or other oxidants applied at the treatment plant, artificial aeration is commonly used. Hypolimnetic aeration and destratification, or artificial circulation, are the two primary methods of artificial aeration (Fast *et al.*, 1975a). Hypolimnetic aeration involves oxygenation of the hypolimnion without disturbing the thermal-density gradient associated with stratification (Kortmann *et al.*, 1994a). The goal of artificial circulation is either to prevent a water body from stratifying or to mix an already stratified one by introducing sufficient energy to disrupt the thermal gradient. If properly designed, an artificial circulation system will create isothermal and isochemical conditions in a lake or reservoir, which may greatly improve water quality; however, an undersized or poorly designed destratification system can actually increase algal blooms, nutrient concentrations, and turbidity in the water body (Cooke and Carlson, 1989). Hypolimnetic aeration has several advantages over artificial circulation. This type of aeration does not transport nutrients into the epilimnion where they can contribute to algal growth. In addition, an oxygen-enriched, cold-water habitat is created for fish species such as trout and salmon. Hypolimnetic aeration requires less energy than artificial circulation to attain a given oxygen level. Lastly, this type of aeration allows the use of depth-selective withdrawal from water distribution reservoirs (Fast *et al*., 1975a).

Hypolimnetic Aeration Methods

Various methods have been developed to achieve hypolimnetic aeration. The methods can be grouped into three different categories: mechanical agitation, oxygen injection, and air injection (Lorenzen and Fast, 1977; see also Cooke and Carlson, 1989). Mercier and Perret (1949) developed one of the earliest mechanical agitation aeration systems. During mechanical agitation, water is pumped from the hypolimnion into a splash basin that is located on the surface of the lake or reservoir. The water is then mechanically agitated, which creates a high level of turbulence at the air-water interface. This action increases oxygen transfer from the gas phase to the liquid phase. In addition, air is entrained into the water by the agitating motion. The entrained air forms bubbles in the water, which continue to transfer gaseous oxygen into the liquid. The aerated water is then returned to the hypolimnion. This type of aeration system is relatively inefficient, but it has proven to be successful in a limited number of cases (Cooke and Carlson, 1989).

Oxygen injection can be accomplished through several different methods. Hypolimnetic water can be withdrawn, exposed to pure oxygen under high pressure, then delivered back to the hypolimnion. Another method involves introducing pure oxygen into the hypolimnion through the use of a diffuser to form a rising unconfined oxygen bubble plume. However, measures must be taken to ensure that the oxygen bubbles formed are small enough to dissolve completely before reaching the epilimnion or destratification can occur. A third method involves pumping hypolimnetic water downward with sufficient velocity that injected oxygen is forced downward as well. The oxygen bubbles that do not dissolve entirely must then be separated from the water in the hypolimnion. A Speece Cone oxygenator, originally called a downflow bubble contactor, is an example of a hypolimnetic aerator that utilizes this principle (Speece et al., 1973).

Air injection systems include several different methods as well. Bubble plume diffusers can be used to aerate a water body by dispersing injected air into the hypolimnion. Using air as opposed to pure oxygen is less efficient, but the gas supply is less costly. A relatively new technique, layer aeration, uses air injection to oxygenate and to redistribute available dissolved oxygen obtained from photosynthesis and contact with the atmosphere (Kortmann *et al*., 1994a, 1994b). Downflow systems are similar to the one described above for oxygen injection, with the exception of air being utilized instead of pure oxygen.

Another method of air injection is an upflow system. Upflow systems can be classified into two principle types: partial airlift and full airlift. Partial airlift systems operate by injecting compressed air near the bottom of the hypolimnion. The air-water mixture travels up a vertical pipe to a given depth in the lake where gasses are vented to the atmosphere through a pipe to the water surface. The aerated water is then returned downward to the hypolimnion. In a full airlift injection system, the same process occurs except that the air-water mixture rises to the surface of the lake before gasses are vented to the atmosphere. This allows the air bubbles to be in contact with the water longer than in a partial-lift system and the water to be in contact with the atmosphere for a short time. These occurrences increase oxygen transfer from the gas phase to the liquid phase. Many of the hypolimnetic aerators studied have been of the full airlift type. Since the focus of this work is full airlift hypolimnetic aeration systems, they will be described in greater detail. For simplicity, the term “hypolimnetic aerator” will be used in the remainder of this thesis to represent full airlift systems.

Hypolimnetic Aerator Operation

Full airlift hypolimnetic aerators typically consist of (1) a vertical pipe commonly called a riser tube, (2) a diffuser unit located inside the bottom of the riser tube, (3) an air-water separation chamber located at the top of the riser on the lake surface, and (4) a return pipe, commonly called a downcomer, that leads from the separation chamber back to the hypolimnion (McQueen and Lean, 1986). For the operation of a hypolimnetic aerator, there is a source of compressed air. Compressed air that is delivered to the aerator is allowed to bubble freely from the diffuser unit located at the bottom of the riser tube. When gas is introduced to the water column in the riser, it creates a gas/water mixture that is less dense than the surrounding water. This causes the mixture to travel up the riser tube. Once the mixture reaches the top of the riser, a portion of the bubbles continues to rise and enter the atmosphere. The remainder of the bubbles is entrained in the flow of water that enters the downcomer. The aerated water then flows through the downcomer and is released back into the hypolimnion.

Hypolimnetic Aeration Studies

The first full airlift hypolimnetic aeration study published in the literature was conducted by Bernhardt (1967). Since that time, there have been numerous works completed on hypolimnetic aeration systems. These can be classified by the particular lakes where the aeration systems have been installed: Wahnbach Reservoir, Germany (Bernhardt, 1967, 1974; Bernhardt and Wilhelm, 1975), Lakes Järlasjön and Tulligesjön, Sweden (Bjork, 1973; Bengtsson and Gelin, 1975), Hemlock Lake, Michigan, U.S.A. (Fast 1975a, b), Silver Lake, Mirror Lake and Larson Lake, Wisconsin, U.S.A. (Wirth *et al*., 1975), Tory Lake, Ontario, Canada (Taggart and McQueen, 1981, 1982; Taggart, 1984), Black Lake, British Columbia, Canada (Ashley, 1983, 1985; Ashley and Hall, 1990), Spruce Knob

Lake, West Virginia, U.S.A. (Hess, 1975; LaBaugh, 1980), Lake St. George, Ontario, Canada (McQueen and Lean, 1983, 1984; McQueen and Story, 1986; McQueen *et al*., 1984, 1986; Lean *et al*., 1986), Wesslinger See, Germany (Steinberg and Arzet, 1984), Glen Lake (Ashley *et al*., 1987), Lake Hütten, Lake Türlen, and Lake Wilen, Switzerland (Favre, 1991), Lake Krupunder, Germany (Jaeger, 1994), Medical Lake, Washington, U.S.A. (Soltero *et al*., 1994), Lake Prince and Lake Western Branch, Virginia, U.S.A. (Cumbie *et al*., 1994), Lake Stevens, Washington, U.S.A. (Gibbons *et al*., 1994), Lake Tegal, Germany (Hamblin and Lindenschmidt, 1995), St. Mary Lake, British Columbia, Canada (Nordin *et al*., 1995), and Newman Lake, Washington, U.S.A. (Moore *et al*., 1996). Theoretical models have been proposed by Little (1995) and Nakamura and Inoue (1996). Experimental techniques and results have been thoroughly reviewed by Fast and Lorenzen (1976), Lorenzen and Fast (1977), and McQueen and Lean (1986).

Effects of Hypolimnetic Aeration

The majority of the investigaters listed previously have examined the effects of hypolimnetic aeration on water quality and the lake ecosystem. In their extensive review of literature on hypolimnetic aeration, McQueen and Lean (1986) summarized the results of the studies: (1) well-designed aeration systems have maintained stratification and have not increased hypolimnetic water temperature significantly; (2) hypolimnetic oxygen levels increased, (3) iron, manganese, hydrogen sulfide, and methane levels decreased; (4) zooplankton populations were generally unaffected; (5) chlorophyll levels were usually not altered; and (6) depth distributions of cold-water fish populations increased. The effects of hypolimnetic aeration on phosphorus levels have been more variable. McQueen *et al*. (1986) attribute this to pH levels and iron availability for phosphorus sedimentation. The published effects of aeration on nitrogen levels have not been consistent either; ammonium and total nitrogen decreased in some studies, but they increased in others. McQueen and Lean (1986) also concluded that this occurrence is related to pH levels. It has been reported that gaseous nitrogen concentrations were elevated to supersaturation levels during hypolimnetic aeration with compressed air, and some concern has been expressed over causing gas bubble disease in fish (Fast *et al*., 1975b). However, no adverse effects of hypolimnetic aeration on fish populations have been reported (McQueen and Lean, 1986). A literature survey published since the review of McQueen and Lean (1986) supports the results presented above (Favre, 1991; Gibbons, 1994; Jaeger, 1994; Soltero *et al*., 1994; Gemza, 1995; Nordin *et al*., 1995).

Aerator Design

While many studies of hypolimnetic aerators have focused on their effects on water quality, stratification, and lake biota, relatively few studies have been undertaken to examine the parameters that affect aerator performance. Likewise, only a few researchers have attempted to develop methods for designing a full-lift hypolimnetic aeration system. The information regarding hypolimnetic aerator design is limited to the following works.

Ashley and Hall (1990)

Ashley and Hall (1990) conducted a series of experiments in Black Lake with a pilot-scale, full-airlift hypolimnetic aerator to investigate the effect of diffuser depth, diffuser orifice diameter, and air-water separator box surface cover on a number of operational parameters. These parameters included oxygen transfer, daily oxygen load, transfer efficiency, energy efficiency, and water velocity. After the authors analyzed the data, they retrofitted a full-scale aerator with fine pore diffusers to test the results obtained with the pilot-scale system. The depth of the air diffuser was found to have a significant effect on water velocity, oxygen transfer, daily oxygen load, transfer efficiency, and energy efficiency. All of these values increased as the depth of the air release was increased. The authors concluded that the increased water velocity was primarily responsible for the increases in the latter three variables, rather than oxygen transfer. Orifice size was also found to have a considerable effect on oxygen transfer, thus daily oxygen load, transfer efficiency, and energy efficiency as well. Orifice size, however, did not have any effect on induced water velocity. The diffuser with the smallest diameter, 140 micrometers (μm), produced the highest oxygen transfer in the pilot-scale aerator. Because of this, the 140 μm fine-pore diffuser was installed in the full-scale aerator, which significantly increased the oxygenation performance. The authors hypothesized that these events were caused by a momentary increase in the bubble interfacial area, which increased oxygen transfer. Surface cover on the separator box did not seem to have an appreciable effect on any of the parameters. Ashley *et al*. (1990, 1991, 1992) have also conducted studies examining the effects of orifice size, surface cover, and air flow rate on oxygen transfer in bench-scale systems and obtained similar results.

Lorenzen and Fast (1977)

The first published hypolimnetic aerator sizing method was proposed by Lorenzen and Fast (1977). The authors discussed various design considerations including hypolimnetic volume estimates, oxygen consumption rates, oxygen input capacity, compressor selection, and diffuser design. They also addressed potential problems and available types of hypolimnetic aeration devices.

The first step of Lorenzen and Fast's hypolimnetic aerator sizing method involved determination of the minimum air flow, $Q_{a,\ min}$ ($ft^3\ d^{-1}$), required to maintain a given dissolved oxygen level. The air flow rate is calculated using the following formula:

$$Q_{a,min} = \frac{ODR(V_h)}{8.2}$$

where ODR is the oxygen depletion rate ($g\ m^{-3}\ d^{-1}$), V_h is the volume of the hypolimnion (m^3), and 8.2 is the mass of oxygen in a cubic foot of air ($g\ ft^{-3}$). The previous equation assumes 100% oxygen transfer efficiency. Lorenzen and Fast assumed that the water is saturated with oxygen when it reaches the top of the riser tube in a full-lift hypolimnetic aerator. Therefore, the water flow rate required to achieve saturated dissolved oxygen conditions can be computed from the following equation:

$$Q_w = \frac{ODR(V_h)}{(DO_{sat} - DO_{req})}$$

where Q_w is water flow rate (l d^{-1}), DO_{sat} is the saturated dissolved oxygen concentration at a given temperature (g m^{-3}), and DO_{req} is the required dissolved oxygen concentration (g m^{-3}). To determine the air flow rate necessary to induce the calculated water flow rate, the following formula is used:

$$Q_a = \frac{(Q_w)^3\left(1 + \frac{fL}{D} + K_L\right)}{673D^4 \ln\left(\frac{L+34}{34}\right)}$$

where Q_a is air flow rate (cfs), Q_w is water flow rate (cfs), f is a friction factor (-), L is the depth of air release (m), D is the riser diameter (m), and K_L is a constant for entrance friction loss (-). In developing the previous equation, Lorenzen and Fast assumed that the theoretical head available results from the density difference between the air-water mixture in the riser and the ambient water. It was also assumed that half of the theoretical head is used to move water to the top of the riser and that the other half is used to return the aerated water to the hypolimnion. The authors developed a series of curves that depicted Q_w^3/Q_a as a function of riser diameter for various depths of air release.

Taggart and McQueen (1982)

Taggart and McQueen (1982) developed a simple model for the design of a full-lift hypolimnetic aerator. The method focuses on determination of the length and diameter of the riser and downcomer tubes when compressor capacity is known. Diffuser depth, applied air flow rate, water velocity, and cross-sectional area of the riser tube are the principle variables in the empirical model. The authors presented a step-wise approach for determining the required riser diameter. First, the amount of air delivered to the aerator from an on-shore compressor must be estimated with the formula:

$$F_a = 58\left(\frac{pd^5}{WL}\right)^{\frac{1}{2}}$$

where F_a is air flow (ft^3 min^{-1}), p is the pressure drop along the delivery pipe (lb in^{-2}), d is the diameter of the delivery pipe (in.), W is the weight of 1 ft^3 of entering air at ambient temperature (lb), and L is the length of the delivery pipe (ft). Next, the water flow rate is estimated by the following empirical equation:

$$F_w = 1.85 \cdot Z^{1.16} \cdot F_a^{0.66}$$

where F_w is water flow rate (l s^{-1}), Z is the rise distance of the air-water mixture (m), and F_a is the air flow rate (l s^{-1}). This relationship was determined by application of a proportionality equation from the literature and a step-wise regression of data collected from 20 other published experiments. Based on this equation, Taggart and McQueen concluded that the riser tube should be as long as possible to optimize water flow rate and that relatively small systems are more efficient than larger ones. The next step is to determine the cross-sectional area of the riser with the equation:

$$r = \left(\frac{F_w}{\pi v}\right)^{\frac{1}{2}}$$

where r is the radius of the riser tube (m), F_w is the water flow rate (m^3 s^{-1}), and v is the median bubble rise velocity (m s^{-1}). This equation assumes that the bubble rise velocity determines the maximum water velocity. Taggart and McQueen (1982) assumed an average rise velocity of 0.46 m s^{-1} based on observed bubble sizes and literature results obtained with similar sized bubbles.

The previous equations are required in the design of a new hypolimnetic aerator based on the depth of the diffuser in the riser and the air flow capacity of the compressor system. If the water flow rate in an existing aerator must be determined, the following formula can be utilized:

$$F_w = 5.14(Z)^{0.698}(F_a)^{0.459}(5.75)^r$$

This correlation was derived from a step-wise regression of literature data from about 10 published studies.

Once the size of the riser tube is known, the cross-sectional area of the downcomer tubes can be found from the following set of equations:

$$h = \frac{\left(\frac{v}{c}\right)^2 (L_t + 16.46D)}{D}$$

$$v = \frac{F_w}{\pi\left(\frac{D}{2}\right)^2}$$

$$c = -7.98(\log_{10} D) + 18.74$$

where h is height of head above the riser (m), v is the water velocity (m s^{-1}), c is a constant, L_t is the length of the downcomer tube, D is the downcomer diameter (m), and F_w is the water flow rate (m^3 s^{-1}). When more than one downcomer is considered, an equivalent value of D can be calculated from the total area M (m^2):

$$D = 2\left(\frac{M}{\pi}\right)^{\frac{1}{2}}$$

The previous set of equations should be solved to minimize the head height above the riser.

<u>Ashley (1985)</u>

Another empirical hypolimnetic aerator design model was proposed by Ashley (1985). In addition to aerator design and sizing, Ashley also discussed other practical aspects of hypolimnetic aeration including the air supply, rated and actual air flow, and performance specifications. The aerator model he presented was derived from the work of Lorenzen and Fast (1977) and Taggart and McQueen (1982) and experience with the Black Lake hypolimnetic aeration system. Ashley developed a nine-step procedure for sizing compressors and hypolimnetic aerators that includes the following tasks: 1) estimate hypolimnetic volume, 2) estimate hypolimnetic oxygen consumption rate, 3) calculate water flow rate, 4) calculate riser and downcomer tube sizes, 5) determine entrance, exit, and friction losses, 6) determine the density of the air-water mixture, 7) calculate air flow requirements, 8) estimate compressor pressure and power requirements, and 9) calculate separator box size and floatation requirements.

Once the volume and oxygen consumption rate of the hypolimnion have been determined through analysis of the water body and its ecosystem, the water flow rate required from a hypolimnetic aerator can be found from the following equation:

$$Q_w = \frac{OCR}{\Delta C}$$

where Q_w is the water flow rate (l d^{-1}), OCR is the daily oxygen consumption rate (mg d^{-1}), and ΔC is the increase in the dissolved oxygen concentration produced by the aerator (mg l^{-1}). This equation assumes that the induced water flow rate will completely satisfy the daily oxygen consumption in the hypolimnion. Determination of the dissolved oxygen increase produced by the aerator is an important part of the equation. Ashley (1985) stated that values of this parameter can range from 0.7 and 9.0 mg L^{-1} and that it may be difficult to predict. Next, the diameter of the riser tube can be calculated from the following formula:

$$r = \sqrt{\frac{Q_w}{\pi v}}$$

where r is the radius of the riser tube (m), Q_w is the water flow rate ($m^3\ s^{-1}$), and v is the bubble-water velocity ($m\ s^{-1}$). Ashley estimated v to be approximately 1.2 $m\ s^{-1}$. The author recommended that the total cross-sectional area of the downcomers equal or exceed the area of the riser to avoid a high amount of head loss in the air-water separator that would impede the water flow rate. The entrance, exit, and friction loss coefficients are then determined from a set of equations that are functions of water flow rate. The presence of bubbles in the riser tube is assumed to have a negligible effect on head loss. The loss coefficients are used to estimate the total headloss for the aerator. The headloss is used to calculate the density of the air-water mixture in the riser tube. Once the density of the air-water dispersion is obtained, the air flow required to pump water through the aerator at the designated flow rate can be determined from the following:

$$\overline{Q}_a = \frac{10.4 Q_a \ln\left(\frac{L + 10.4}{10.4}\right)}{L} \quad \text{and} \quad Q_a = \frac{Q_w \rho_w - Q_w \rho_{aw}}{0.662 \rho_{aw} - \rho_a}$$

where $\overline{Q}_a$ is the mean air flow rate ($m^3\ s^{-1}$), Q_a is the air flow rate ($m^3\ s^{-1}$), L is the depth of the diffuser in the riser, ρ_w is the density of water ($kg\ m^{-3}$), ρ_a is the density of air ($kg\ m^{-3}$), and ρ_{aw} is the density of the air-water mixture ($kg\ m^{-3}$). To obtain the compressor pressure and power requirements, the pressure drops in the air supply system are summed, and standard engineering formulas are used, respectively. Lastly, Ashley stated that the weight of the box, riser and downcomer tubes, and water head must be taken into consideration when determining the floatation requirements of the air-water separator box.

<u>Kortmann *et al*. (1994a)</u>

A more recent hypolimnetic aerator design method was developed by Kortmann *et al*. (1994a). The primary focus of the model is on determining an accurate value of the total oxygen demand from respiratory and nonrespiratory sources within the lake ecosystem. Once this parameter is estimated, the amount of air flow required to satisfy the oxygen demand can be found. The first step of the model is to calculate the oxygen deficit rate with dissolved oxygen profiles. Next, the respiratory oxygen demand is determined using the oxygen deficit rate and the ecosystem respiratory coefficient. The nitrogenous oxygen demand is then calculated and added to the respiratory oxygen demand to obtain the total oxygen demand. Once the total oxygen demand has been calculated, the amount of air flow required can be obtained with the following equation:

$$Q_{air} = \left(\frac{1.5 \cdot TOD \cdot A_z \cdot 10^{-6}}{1.205 \cdot 0.2}\right)\left(\frac{100}{depth \cdot E}\right)$$

where Q_{air} is the required air flow ($m^3\ d^{-1}$), 1.5 is the optional 50 % safety factor, TOD is the total oxygen demand ($mg\ m^{-2}\ d^{-1}$), A_z is surface the area of the hypolimnion (m^2), 10^{-6} is a conversion factor ($kg\ mg^{-1}$), 1.205 is the density of air at 1.01 bar and 20°C, 0.2 is the fraction of oxygen in air, depth is the depth of the diffuser, and E is aerator gas-solute transfer efficiency per meter (%). The aerator transfer efficiency can be estimated from a linear relationship that the authors developed from a regression of performance test data. Efficiency is given as a function of the ambient dissolved oxygen concentration desired. The formula shown above will provide the amount of air that must be supplied to the riser diffusers at the depth which they are installed. The air flow rate must be converted to a flow at standard conditions to determine the size of the compressor required.

Little (1995)

A relatively simple model was developed by Little (1995) to predict induced water flow rate and the increase in the dissolved oxygen concentration produced by a hypolimnetic aerator. Cocurrent flow of water and gas, variation of the saturated dissolved oxygen concentration as a function of depth, and depletion of gaseous oxygen are accounted for in the model. Input parameters to the model include the aerator dimensions, volumetric air flow rate, depth of the diffuser in the riser, and intake water conditions. To calculate water flow rate, the following equation is used:

$$U_L = 0.70\left(U_G\right)^{0.53}\left(L\right)^{0.56}$$

where U_L is the superficial liquid velocity in the riser, U_G is the superficial gas velocity in the riser ($m\ s^{-1}$), and L is the length of the riser tube (m). This correlation was derived from the same data set that Taggart and McQueen (1982) used to develop their formula for predicting water flow rate, with the exception being that dependence on riser diameter has been eliminated. To determine the amount of oxygen transferred from the gas phase to the liquid phase, a mass balance was performed on water flowing in the riser:

$$\frac{dC}{dz} = \frac{K_L a}{U_L}\left(C^* - C\right)$$

where C is the bulk dissolved oxygen concentration ($mg\ l^{-1}$), z is the distance from the diffuser, K_La is the volumetric mass transfer coefficient, and C^* is the saturated aqueous oxygen concentration at the air-water interface. This equation assumes that the amount of oxygen transferred from the air bubbles to the water is small relative to the amount available, the gas-phase holdup is small, and the air-water mixture is in plug flow. In addition, nitrogen transfer is ignored. To determine the amount of oxygen transferred relative to the amount available in the air, a mass balance is made on the total amount transferred:

$$\frac{Y_{out}}{1-Y_{out}} = \frac{Y_{in}}{1-Y_{in}} - \frac{(C_{out} - C_{in})Q_L}{MG_0}$$

where Q_L is the liquid flow rate, M is the molar mass of oxygen, and G_0 is the molar flow rate of nitrogen in the air flow. To calculate the saturated aqueous oxygen concentration in equilibrium with the bubbles at any depth the following formula is used:

$$C^* = \frac{Y}{m}\left(1 + \frac{\rho_L g(H-z)}{P}\right)$$

where Y is the mole fraction of oxygen in air (-), m is a Henry's Law constant, ρ_L is density of the liquid (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), H is the depth of the air diffuser (m), and P is a conversion factor (101325 Pa atm^{-1}). The volumetric mass transfer coefficient must be known to solve the mass balance equation. Little used a set of four correlation equations from the literature to obtain an estimate of the mass transfer coefficient and gas holdup in the riser. These correlations were developed using data collected during mass transfer studies in bubble columns and airlift reactors.

Summary of Hypolimnetic Aerator Design Methods

The literature dealing with full airlift hypolimnetic aerator design methods is limited. Taggart and McQueen (1982) stated that two primary issues need to be considered when designing an aerator: (1) the required capacity of the air compressor and (2) the dimensions of the aerator. The volume of the hypolimnion, summer oxygen depletion rate, and target hypolimnion dissolved oxygen level must be known to determine the capacity of the air compressor. Lorenzen and Fast (1977) conducted a thorough review of hypolimnetic aeration systems available at the time and developed a complex aerator sizing method. In an attempt to provide a simpler analysis of oxygen transfer mechanisms, Taggart and McQueen (1982) proposed an empirically based model intended for use by biologists, limnologists, and environmentalists. Their model focuses on determining the length and cross-sectional area of the riser tube and the cross-sectional area of the downcomer tube once the compressor capacity is known. The model's most important assumption is that the superficial water velocity is equal to the bubble rise velocity. The aerator design method of Ashley (1985) was derived from the work of Lorenzen and Fast (1977) and Taggart and McQueen (1982) and observations of the Black Lake hypolimnetic aeration system. A couple of critical assumptions were also made in this model including: (1) the daily water flow rate will balance the maximum daily oxygen consumption measured during spring stratification and (2) the velocity of the air-water mixture is approximately 1.2 m s^{-1}. The model also requires an estimate of the increase in the dissolved oxygen concentration produced by the aerator. The aerator sizing method developed by Kortmann *et al*. (1994a) is focused on obtaining an accurate value of the total oxygen demand of a given lake or reservoir. Once the oxygen demand is known, the amount of air flow required to satisfy the demand can be calculated. Little (1995) proposed a model based on a mass balance of oxygen in the dissolved and gas phase. Correlation equations are used to calculate input parameters to the model such as the water flow rate, mass transfer coefficient, and the gas-phase holdup.

Although the models and sizing methods reviewed thus far provide useful insight into the design of hypolimnetic aerators, the operation of these devices is not fully understood. The model developed by Lorenzen and Fast (1977) contains two important assumptions that may not be applicable to a number of hypolimnetic aeration systems. It was assumed that the aerator achieves 100% oxygen transfer efficiency and that aerated water at the top of the riser tube is saturated with dissolved oxygen. Neither of these assumptions is valid for aerators where the depth of air release is relatively shallow. The models of Taggart and McQueen (1982) and Ashley (1985) are primarily empirically based and involve a number of critical assumptions that are unproven. Taggart and McQueen's (1982) assumption that the superficial water velocity is equal to the bubble rise velocity is questionable. The concept of a "slip" velocity between ascending bubbles and the water flow has been well established (Haberman and Morton, 1954; Turner, 1966; Heijen and Van't Riet, 1984; Siegel *et al*., 1986). Ashley's (1985) model was field tested by Ashley *et al*. (1987) in a small eutrophic lake. The aeration system was unable to satisfy the daily oxygen demand of the lake because the induced water velocity was overestimated during design. The oxygen input of the aerator also was overestimated. The aerator-sizing method of Kortmann *et al*. (1994a) only calculates the amount of air flow required to meet daily oxygen demands; the model does not provide a method for determining the dimensions of a hypolimnetic aerator or for predicting its performance. The model proposed by Little (1995) represents one of the first attempts to develop a theoretical approach for predicting oxygen transfer in full airlift hypolimnetic aerators, but it relies upon empirical correlations to calculate important input variables. A more fundamental model is needed to aid in the design of new hypolimnetic aerators and to predict the performance of existing aerators. A more theoretical approach would ensure that the model is applicable to a variety of aerator designs and lake ambient conditions. In addition, more accurate and precise measurements of induced water flow rate, oxygen input, and intake water conditions from aerators operated under carefully controlled conditions are required to properly validate the model.

REFERENCES

Ashley, K. I., Hypolimnetic aeration of a naturally eutrophic lake: Physical and chemical effects, *Can. J. Fish. Aquat. Sci*., *40*, 1343-1359, 1983.

Ashley, K. I., Hypolimnetic aeration: Practical design and application, *Wat. Res*., *19*, 735-740, 1985.

Ashley, K. I. and K. J. Hall, Factors influencing oxygen transfer in hypolimnetic aeration systems, *Verh. Int. Verein. Limnol*., *24*, 179-183, 1990.

Ashley, K. I., S. Hay, and G. H. Scholten, Hypolimnetic aeration: Field test of the empirical sizing method, *Wat. Res*., *2*, 223-227, 1987.

Ashley, K. I., D. S. Mavinic, and K. J. Hall, Effects of orifice size and surface conditions on oxygen transfer in a bench scale diffused aeration system, *Envir. Tech., 11*, 609-618, 1990.

Ashley, K. I., K. J. Hall, and D. S. Mavinic, Factors influencing oxygen transfer in fine pore diffused aeration, *Wat. Res.*, *25*, 1479-1486, 1991.

Ashley, K. I., D. S. Mavinic, and K. J. Hall, Bench-scale study of oxygen transfer in course bubble diffused aeration, *Wat. Res.*, *26*, 1289-1295, 1992.

Bengtsson, L. and C. Gelin, Artificial aeration and suction dredging methods for controlling water quality, *Proceedings on Water Quality Symposium*, 313-342, 1975.

Bernhardt, H., Aeration of Wahnbach Reservoir without changing the temperature profile, *AWWA, 59*, 943-964, 1967.

Bernhardt, H., Ten years experience of reservoir aeration, paper presented at Seventh Inter. Conf. On Water Pollution Research, Paris, 1974.

Bernhardt, H. and A. Wilhelms, Hypolimnetic aeration as a means of controlling redox processes on the bottom of a eutrophic reservoir, *Verh. Internat. Verein. Limnol., 19*, 1957-1959, 1975.

Bjork, S., Restoring lakes in Sweden, *Tech. Rev., 76*, 1-10, 1973.

Cole, G. A., *Textbook of Limnology*, 4th ed., 412 pp., Waveland Press, Inc., Prospect Heights, IL, 1994.

Cooke, G. D. and R. E. Carlson, *Reservoir Management for Water Quality and THM Precursor Control*, 387 pp., AWWA Research Foundation, Denver, CO, 1989.

Cumbie, W. E., D. Rosenthal, and B. Welsh, Hypolimnetic aeration of Norfolk, Va. reservoirs improves lake quality while reducing problems at treatment plant (abstract), *Lake and Reserv. Manage.*, 9, 67, 1994.

Fast, A. W. and M. W. Lorenzen, Synoptic survey of hypolimnetic aeration, *J. Envr. Eng. Div., Am. Soc. Civ. Eng., 102,* 1161-1173, 1976.

Fast, A. W., V. A. Dorr, and R. J. Rosen, A submerged hypolimnion aerator, *Wat. Resour. Res.*, *11*, 287-293, 1975a.

Fast, A.W., W. J. Overholtz, and R. A. Tubb, Hypolimnetic oxygenation using liquid oxygen, *Wat. Resour. Res.*, *11*, 294-299, 1975b.

Favre, R. P., Hypolimnetic aeration in three Swiss lakes, in *Air-Water Mass Transfer-Selected Papers from the Second International Symposium on Gas Transfer at Water Surfaces*, pp. 660-669, ASCE, New York, NY, 1991.

Gemza, A., Some practical aspects of whole lake mixing and hypolimnetic oxygenation. Ecological impacts of aeration on lakes and reservoirs in southern Ontario (abstract), *Lake and Reserv. Manage.*, 11, 141, 1995.

Gibbons, H. L., B. Bogus, and G. Williams, World’s largest attempt at hypolimnetic aeration (abstract), *Lake and Reserv. Manage., 9,* 76, 1994.

Haberman, W. L. and R. K. Morton, An experimental study of bubbles moving in liquids, *Proc. Am. Soc. Civ. Eng., 80,* 379-427, 1954.

Hamblin, P. F. and K. E. Lindenschmidt, Observations and model of the thermal impact of hypolimnetic aeration on a shallow urban lake, Lake Tegal, Germany (abstract), *Lake and Reserv. Manage.*, *11*, 146, 1995.

Heijnen, J. J. and K. Van't Riet, Mass transfer, mixing, and heat transfer phenomena in low viscosity bubble column reactors, *Chem. Eng. J., 28,* B21-42, 1984.

Hess, L., The effect of the 1st year of artificial hypolimnion aeration on oxygen, temperature and the depth distribution of rainbow trout Salmo gairdneri in Spruce Knob Lake, West Virginia, U.S.A., *Proc. W. Va. Acad. Sci., 47,* 176-183, 1975.

Jaeger, D., Effects of hypolimnetic water aeration and iron-phosphate precipitation on the trophic level of Lake Krupunder, *Hydrobiol.*, *275/276*, 433-444, 1994.

Kortmann, R. W., G. W. Knoecklein, C. H. and Bonnell, Aeration of stratified lakes: Theory and practice, *Lake and Reserv. Manage.*, *8*, 99-120, 1994a.

Kortmann, R. W., Oligotrophication of Lake Shenipsit by layer aeration, *Lake and Reserv. Manage.*, *9*, 94-97, 1994b.

La Baugh, J. W., Water chemistry changes during artificial aeration of Spruce Knob Lake, West Virginia, *Hydrobiologia, 70,* 201-216, 1980.

Lean, D. R. S., D. J. McQueen, and V. A. Story, Phosphate transport during hypolimnetic aeration, *Arch. Hydrobiol.*, *108*, 209-280, 1986.

Little, J. C., Hypolimnetic aerators: Predicting oxygen transfer and hydrodynamics, *Wat. Res.*, *29*, 2475-2482, 1995.

Lorenzen, M. W. and A. W. Fast, *A Guide to Aeration/Circulation Techniques for Lake Management*, Ecol. Res. Ser. EPA 600/3-77-004, 126 pp., USEPA, 1977.

Mercier, P. and J Perret, Aeration station of Lake Bret, Monastbull, Schwiez, *Ver. Gas. Wasser-Fachm, 29,* 25, 1949.

McQueen, D. J. and D. R. S. Lean, Hypolimnetic aeration and dissolved gas concentrations, *Wat. Res*., *17,* 1781-1790, 1983.

McQueen, D. J. and D. R. S. Lean, Aeration of anoxic hypolimnetic water: effects on nitrogen and phosphorus concentrations, *Verh. Int. Verein. Limnol., 12,* 268-276, 1984.

McQueen, D. J. and D. R. S. Lean, Hypolimnetic aeration: An overview, *Water Poll. Res. J. Can.*, *21*, 205-217, 1986.

McQueen, D. J., D. R. S. Lean, and M. N. Charlton, The effects of hypolimnetic aeration on iron-phosphorus interactions, *Water Res*., *20*, 1129-1135, 1986.

McQueen, D. J., S. S. Rao, and D. R. S. Lean, Hypolimnetic aeration: Changes in bacterial populations and oxygen demand, *Arch. Hydrobiol.*, *99*, 498-514, 1984.

McQueen, D. J. and V. A. Story, Impact of hypolimnetic aeration on zooplankton and

phytoplankton populations, *Envir. Tech. Lett., 7,* 31-44, 1986.
Moore, B. C., P. H. Chen, W. H. Funk, and D. Yonge, A model for predicting lake sediment oxygen demand following hypolimnetic aeration, *Wat. Res. Bull., 32,* 723-731, 1996.
Nakamura, Y. and T. Inoue, A theoretical study on operational condition of hypolimnetic aerators, *Wat. Sci. Tech.*, *34*, 211-218, 1996.
Nordin, R., K. Ashley, and P. Law, Hypolimnetic aeration of St. Mary Lake, British Columbia, Canada (abstract), *Lake and Reserv. Manage.*, 11, 176, 1995.
Siegel, M. H., J. C. Merchuk, and K. Schügerl, Airlift reactor analysis: interrelationships between riser, downcomer, and gas liquid separator, *AIChE, 32*, 1585-1596, 1986.
Soltero, R. A., L. M. Sexton, K. I. Ashley, and K. O. McKee, Partial and full lift aeration of Medical Lake, WA to improve water quality, *Wat. Res*., *28*, 2297-2308, 1994.
Speece, R. E., F. Rayyan, and G. Murfee, Alternative considerations in the oxygenation of reservoir discharges and rivers, in *Applications of Commercial Oxygen to Water and Wastewater Systems,* edited by R. E. Speece and J. F. Malina, pp. 342-361, Center for Research in Water Resources, Austin, Texas, 1973.
Steinberg, C. and K. Arzet, Impact of hypolimnetic aeration on abiotic and biotic conditions in small kettle lake, *Envir. Tech. Lett*., *5*, 151-162, 1984.
Taggart, C. T., Hypolimnetic aeration and zooplankton: A possible limitation to the restoration of cold-water fish production, *Can. J. Fish. Aquat. Sci*., *41*, 191-198, 1984.
Taggart, C. T. and D. J. McQueen, Hypolimnetic aeration of a small kettle lake: Physical and chemical changes, *Arch. Hydrobiol*., *91*, 150-180, 1981.
Taggart, C. T. and D. J. McQueen, A model for the design of hypolimnetic aerators, *Wat. Res*., *16*, 949-956, 1982.
Tate, C. H. and K. F. Arnold, Health and aesthetic aspects of water quality, in *Water Quality and Treatment*, edited by F. W. Pontius, pp. 63-154, McGraw-Hill, Inc., New York, 1990.
Turner, J. C., On bubble flow in liquids and fluidised beds, *Chem. Eng. Sci*., *21*, 971, 1966.
Wirth, T. L., D. R. Knauer, and S. A. Smith, Total and hypolimnetic aeration of lakes in Wisconsin, *Verh. Internat. Verein. Limnol*., *19*, 1960-1970, 1975.

CHAPTER 2. PREDICTING OXYGEN TRANSFER IN HYPOLIMNETIC AERATORS

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ABSTRACT

Hypolimnetic aerators have been installed in Lakes Prince and Western Branch, two water supply reservoirs for the City of Norfolk, Virginia. Data collected from these systems were used to verify a process model that predicts aerator performance based on air flow rate and intake water conditions. Water flow rate, gas-phase holdup, and dissolved oxygen (DO) profiles were measured as a function of air flow rate. The data were utilized in calculations of initial bubble size by application of a model originally developed to predict oxygen transfer in a bubble-plume diffuser. The model was extended to account for oxygen transfer in the air-water separator and the downcomers. The range of bubble diameters obtained using the model was 2.3-3.1 mm. The Sauter mean diameters of bubbles measured in a laboratory system ranged from 2.7-3.9 mm. The riser and downcomer DO profiles and gas holdups predicted by the model were in close agreement with experimental results.

INTRODUCTION

Thermal stratification of lakes and reservoirs can lead to severe problems in water quality. Most inland water bodies stratify into three layers during the summer months: the epilimnion, metalimnion, and hypolimnion. The bottom layer of colder, denser water is the hypolimnion. The hypolimnion is essentially unaffected by the atmosphere and is relatively stagnant. In addition, this region usually does not receive enough sunlight for photosynthesis to occur. Because of these factors, the dissolved oxygen (DO) in this layer is not continually replenished [*Cooke and Carlson*, 1989]. Oxygen in the hypolimnion is depleted by plant, animal, and bacterial respiration and by sediment reactions [*Cole*, 1994]. If the amount of dissolved oxygen in this strata is inadequate to meet these demands, then anoxic conditions result. Low DO levels in the hypolimnion limit the use of the water body as a cold-water fishery. This condition can also lead to the production of hydrogen sulfide gas. In addition, it can cause iron and manganese accumulated in the sediments to solubilize. These compounds can result in taste, odor, and color problems if hypolimnetic water is to be treated for potable uses. [*Cooke and Carlson*, 1989]. The removal of these compounds creates an increased oxidant demand at the water treatment plant, which can be quite expensive. If chlorine is the oxidant, increased levels can also react with certain organics in the raw water to produce disinfection-by-products, such as trihalomethanes, which are suspected carcinogens and, therefore, are under strict regulatory control [*Tate and Arnold*, 1990].

Artificial aeration is commonly used to prevent anoxia in the hypolimnion. Three principal devices are used in lake aeration: hypolimnetic aerators, Speece Cones, and bubble-plume diffusers. Hypolimnetic aerators and Speece Cones are designed to oxygenate only the hypolimnion without disturbing thermal stratification. Bubble-plume diffusers can also be used for hypolimnetic oxygenation. In addition, they can provide aeration by destratification, which involves upwelling of hypolimnetic water to the surface where it mixes with oxygen-rich epilimnetic water. Hypolimnetic aeration and destratification are the two primary methods of artificial aeration [*Fast et al*., 1975a].

Hypolimnetic aeration has several advantages over destratification. One of them is that nutrients, such as nitrogen and phosphorus, are not carried to the epilimnion where they can stimulate algal growth. Another advantage is that this type of aeration can create or preserve a cold-water fishery habitat for species such as trout or salmon [*Fast et al*., 1975a]. Hypolimnetic aeration also allows the use of depth-selective withdrawal for maximizing the water quality from potable water sources [*Kortmann et al*., 1994]. This type of aeration consumes less energy than destratification. Numerous studies conducted documenting the physical, chemical, and biological effects of this type of lake aeration have been conducted [*Fast et al*., 1975a, b; *Wirth et al*., 1975; *Taggart and McQueen*, 1981; *Ashley*, 1983; *McQueen and Lean*, 1983; *McQueen et al*., 1984; *Steinberg and Arzet*, 1984; *Taggart*, 1984; *McQueen and Story*, 1986; *McQueen et al*., 1986; *Favre*, 1991; *Cumbie et al*., 1994; *Jaeger*, 1994; *Kortmann et al*., 1994; *Soltero et al*., 1994; *Gemza*, 1995; *Hamblin and Lindenschmidt*, 1995; *Nordin et al*., 1995].

Two of the major difficulties associated with hypolimnetic aeration are estimating the hypolimnetic oxygen demand and predicting aerator oxygen input rates [*Ashley and Hall*, 1990]. The oxygen input rate can be determined if the induced water flow rate and the increase in the dissolved oxygen concentration produced by the aerator are known. In contrast to the study of the effects of aeration, only a few researchers have attempted to develop methods to estimate oxygen input rates for aeration systems [*Lorenzen and Fast*, 1977; *Taggart and McQueen*, 1982; *Ashley*, 1985; *Ashley et al.*, 1987; *Little*, 1995]. *Taggart and McQueen* [1982] reported that it might be difficult to accurately predict the oxygen transfer efficiency of an aerator. To avoid undersizing aerator installations, *Ashley et al.* [1987] recommended that oxygen addition should be set conservatively between 1.0-4.0 mg/L. All of these methodologies are primarily empirically based, which casts some doubt on their general applicability. *Little* [1995] developed a model based on fundamental principles; however, it requires the use of correlation equations to predict key variables.

Burris and Little [1997] presented a model that provides a more fundamentally based approach in determining hypolimnetic aerator oxygen transfer. It was patterned after the bubble-plume model of *Wuest et al*. [1992]. The oxygen transfer model was based on the conservation of mass of oxygen and nitrogen in the dissolved and gas phase. It utilized discrete-bubble principles, which have been previously applied to other types of aeration systems, such as those used in wastewater treatment and ozonation, in addition to bubble plume diffusers [*Pöpel and Wagner,* 1991; *Tsang*, 1991; *Bischof et al*., 1994; *Bin*, 1995]. In this paper, the model and additional experimental data verifying the model are presented. The hypolimnetic oxygen transfer model represents the first documented attempt to apply discrete-bubble principles to this particular type of lake aeration device.

EQUIPMENT AND METHODS

Validation of the model was attempted with experimental data that were collected from a full-scale hypolimnetic aerator. The aerator was part of the City of Norfolk's hypolimnetic aeration system installed in two of its water supply reservoirs, Lake Prince and Lake Western Branch. The lakes are located in Suffolk County, Virginia and have a total capacity of approximately 49×10^6 m^3. The City of Norfolk supplies potable water to a significant portion of the Tidewater Virginia area. In the past, anoxic conditions have developed in both lakes during the stratification period. Aerators were installed in an effort to increase dissolved oxygen levels and, hence, to improve water quality.

Hypolimnetic Aeration System

Ten hypolimnetic aerators in Lake Prince and 17 in Lake Western Branch were operating at the time of this study. The aerators were placed in the former river channel, the deepest part of the reservoirs, to maximize efficiency. Compressed air was supplied from two sets of on-shore compressors. The set at Lake Western Branch consisted of four 37-kW compressors, while the other set consisted of four 75-kW compressors. The compressors at Lake Western Branch provided air for Western Branch aerators 1-10, and the other set supplied the remaining Western Branch aerators and all of the Lake Prince aerators. Once the air left the compressor, it traveled through a metering manifold. Each line was equipped with a mass flow meter, pressure reducing valve, pressure gauge, and shut-off valve. After entering the reservoir, the air flowed through a 5.1-cm diameter polyethylene pipe to the individual aerators.

The most recent aerator design was selected for testing because of its relatively well-defined flow pattern through the aerator and the fact that its structure facilitated field data collection (Figure 1). The bulk of the aerator consisted of three vertical pipes and an air-water separator box, all constructed of fiberglass. The center pipe was the riser tube, and a pair of diffusers was located at the bottom as described by *Burris et al*. [submitted]. The riser tube had a telescoping feature that allowed the top of the aerator to remain floating and the bottom to rest on the sediments. The two outer pipes were the downcomers, which discharged aerated water to a specified lake depth. In addition to the diffuser unit located in the riser, two auxiliary diffusers were also located in each of the downcomers. The downcomers were equipped with baffles at their outlets to deflect the discharge jet away from the sediments. The air-water separator had doors that allowed access inside the riser and downcomers from the lake surface. The aerator was also outfitted with a destratification diffuser that could be used during the winter months to enhance circulation of the entire water column to increase oxygen transfer with the atmosphere. This diffuser was located near the sediments outside of the aerator. The destratification diffuser could be activated by diverting the flow of air from the main portion of the aerator with a valve. The data used to verify the model were obtained specifically from Lake Prince Aerator 1 (LPA1). Table 1 gives a summary of the relevant dimensions of this aerator during testing.

When air was introduced to the water column in the riser, it created an air-water mixture that was less dense than the surrounding water. This buoyant mixture traveled up the riser tube. Once the mixture reached the top of the riser, some of the bubbles continued to rise and enter the atmosphere. The remainder was entrained in the flow of water that entered either of the two downcomers. The aerated water then flowed through the downcomers and was discharged at a specific depth in the lake. The discharge depth was approximately equal to the depth at which water was withdrawn from the lakes for treatment.

Field Equipment and Methods

Two main pieces of experimental equipment were used to collect field data from the aerators. One was a YSI Model 610 data logger equipped with a dissolved oxygen and temperature probe. The DO probe was calibrated at the beginning of a testing day, and the calibration was checked at the end of the day for any drift.

The other piece of field equipment was a Swoffer Model 2100 stream current propeller meter. This meter was modified to obtain readings in both vertical directions for use in the riser and downcomers. Prior to testing, the performance of the meter was evaluated in a laboratory flume, and good agreement (±10%) between readings was obtained. The propeller meter was also calibrated in the field during each sampling trip, as recommended by the manufacturer.

Since the only parameter other than structural modifications that could be adjusted on LPA1 was the air flow rate, a series of field experiments was conducted over a wide range of air flow rates (0.019 $m^3\ s^{-1}$ - 0.066 $m^3\ s^{-1}$). During the tests, air was supplied only to the diffuser unit in the riser; the auxiliary diffusers in the downcomers were not used. Tests were performed in duplicate, and the data recorded during each run included air flow rate, water temperature, riser and downcomer gas-phase holdup, water velocity, and dissolved oxygen (DO) profiles in the riser and both downcomers. In addition, a background DO profile in the water column was determined outside the aerator on each day of testing.

Air flow rate was measured so that its effect on oxygen transfer could be determined. It was also needed as an input for the model. Water temperature was measured so that the assumption of isothermal conditions in the aerator could be verified and the appropriate physical properties of the water and air could be determined. Overall gas-phase holdup was determined by the volume expansion technique. The height of the gas-liquid dispersion during aeration was measured with a measuring tape. The volume expansion technique is a simple and reliable method that has been used by a number of researchers examining airlift bioreactors [*Chisti*, 1989], which are hydrodynamically similar to hypolimnetic aerators. Water velocity is another important parameter required by the model, and velocity measurement during the experiments is described by *Burris et al.* [submitted].

Laboratory Equipment and Methods

Bubble size was measured in a large cylindrical tank located in the Tennessee Valley Authority engineering laboratory. The height of the tank was 14 m with an internal diameter of 2.1 m. A water depth of 10 m was used during the tests to simulate field conditions. The tank was equipped with transparent portholes that allowed visual observations to be made during the experiments. The diameter of the portholes was about 0.28 m. The centers of the first and second portholes were located 0.61 m and 1.8 m, respectively, from the bottom of the tank. Subsequent portholes were located approximately every 1.8 m.

During the bubble-size determination, compressed air was supplied to a diffuser mount inside the tank. The diffuser mount consisted of two sections of 3.8 cm schedule 80 PVC with the same orifice layout as the field units. The two diffusers were spaced 0.46 m apart and were of differing length, 0.86 m and 0.71 m. They were constructed this way so that the orifices of the shorter one could be viewed through the first porthole. The diffuser unit rested on the tank bottom, and the 0.71 m diffuser was placed approximately 0.36 m directly behind the first porthole. Two scales with different graduations, 2.0 mm and 3.2 mm, were placed at the second porthole to facilitate measurement of bubble size. The second porthole, as opposed to the first, was used to collect data because individual bubbles did not form immediately at the orifices because jets caused by a very high air flow rate per orifice were present. The scales were placed on a white background to facilitate observation of the bubbles and were located 0.20 m behind the second porthole.

Photographs of the bubble swarm were taken at the second porthole and used to determine bubble size. A 35-mm single-lens reflex camera with a 50-mm macro lens and attached ring flash were used. Three different ISO film speeds were used: 1600, 400, and 200. A 1/1000 s shutter speed was selected, and the camera automatically adjusted the aperture. Bubble photographs were taken over the same range of air flow rates that were used in the field tests. The camera was focused on the measurement scales prior to the tests because of the difficulty viewing them through the bubble plume at the higher air flow rates. At least four pictures were obtained during each experiment. The procedure was repeated in triplicate, once at each film speed.

After the film was developed and printed, an image-processing technique was used to determine bubble size electronically. First, the photographs were digitized with a color scanner. The digitized images were viewed on a color monitor and processed with Microsoft PhotoEditor. After the images were displayed on the screen, the number of pixels in a graduation of the scale was determined. Twenty bubbles were randomly selected for measurement from each photograph to determine average bubble size for a given air flow rate. This number of bubbles was used by other researchers in determining mean diameters [*Ashley et al*., 1990; *Ashley et al*., 1991; *Chen et al*., 1993]. Only bubbles that were in-focus were analyzed because their boundaries were easily discernible and no correction for distance from the scale had to made. Since the shapes of the rising bubbles were not spherical, the horizontal and vertical diameters of each one were measured. Typically, the horizontal diameter was greater than the vertical one. The equivalent circular cross-sectional area (A_c) was calculated with the following formula:

$$A_c = \frac{\pi xy}{4} \quad (\text{mm}^2) \tag{1}$$

where x is the length of the horizontal diameter of the bubble (mm), and y is the length of the vertical diameter (mm). The equivalent circular diameter (d_c) was found from the relationship:

$$d_c = \sqrt{\frac{4A_c}{\pi}} \quad (\text{mm}) \tag{2}$$

To determine the volume to surface area ratio of the bubbles sampled, the Sauter mean diameter ($d_{3,2}$) was calculated by:

$$d_{3,2} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \quad (\text{mm}) \tag{3}$$

where d_i is the diameter of bubble i (mm) and n is the number of bubbles in the sample.

OXYGEN TRANSFER MODEL

The oxygen transfer model developed in this paper is similar to the model *Wüest et al.* [1992] used to predict the performance of a bubble-plume diffuser. The plume model consists of a set of eight differential equations that describe plume characteristics on the basis of the conservation laws for mass, momentum, and heat. The plume model also uses additional equations of state and literature correlations to calculate various parameters [*Wuest et al.*, 1992]. The hypolimnetic aerator model is based on the conservation of mass of molecular species in the dissolved and gas phase. Since the conditions in a hypolimnetic aerator differ from those encountered in a bubble plume, the model and associated assumptions were adjusted accordingly.

Model Assumptions

- Flow is fully turbulent.
- Gas movement is dominated by advective transport, which is determined from the mean flow; and dispersion is neglected.
- The diffusers produce bubbles at a constant rate.
- The bubbles are evenly distributed over the cross-section of the riser.
- Bubble coalescence is neglected, and the bubble number flux remains constant throughout the riser.
- The diameter of all bubbles is the same at a given depth.
- Initial dissolved concentrations of the molecular species are equal to the properties of lake water at the aerator intake.
- Mass transfer of gasses other than nitrogen or oxygen is neglected.
- The water temperature, gas temperature, and volumetric water flow rate are all constant.
- The bubble size remains constant from the top of the riser dispersion to the top of the downcomer dispersion.
- The flow of water and bubbles from the riser is assumed to be divided equally between the two downcomers, after bubble loss to the atmosphere is accounted for.
- If the bubble rise velocity in the downcomers is equal to or greater than the actual water velocity, then gas holdup is negligible, and, thus, no oxygen transfer occurs in the downcomers.

Model Equations

The model provides a fundamental approach for determining oxygen transfer since it utilizes the discrete-bubble concept. The local mass transfer flux of a molecular species associated with a single bubble, J_i, is given by:

$$J_i = K_{OLi}\,(C_{si} - C_i) \quad (\text{mol m}^{-2}\text{ s}^{-1}) \tag{4}$$

where K_{OLi} is the overall mass transfer coefficient (m s^{-1}), C_{si} is the dissolved saturation concentration (mol m^{-3}), and C_i is the dissolved bulk concentration (mol m^{-3}). The subscript i refers to the two molecular species of interest, oxygen and nitrogen. The mass transfer coefficient is determined from an empirical correlation that is a function of bubble radius (Table 2). The same correlation is used for oxygen and nitrogen since the molecules have similar diffusivities. The saturation concentration of a given species is calculated using Henry's Law:

$$C_{si} = K_i P_i \quad (\text{mol m}^{-3}) \tag{5}$$

where K_i is Henry's constant (mol m^{-3} bar^{-1}) and P_i is the partial pressure (bar). Henry's constant is available as a function of temperature (Table 2).

To determine the total mass transfer flux per unit height, the number flux of bubbles, N (s^{-1}), is used. The number flux remains constant throughout the riser and is calculated from the initial bubble radius, initial total gas flow rate, and diffuser depth. The number of bubbles per unit height is found by dividing the number flux by the bubble velocity relative to the walls of the riser (V_L + V_b), where V_L is the actual liquid velocity (m s^{-1}) and V_b is the bubble rise velocity (m s^{-1}). The total mass transfer per unit height is obtained by multiplying the number of bubbles per unit height, the surface area of a single bubble, and the local mass transfer flux, or:

$$K_{OLi}(K_i P_i - C_i)\frac{4\pi r^2 N}{V_L + V_b} \quad (\text{mol m}^{-1}\text{ s}^{-1}) \tag{6}$$

where r is the bubble radius (m).

As mentioned previously, the oxygen transfer model is based upon the law of conservation of mass. Assuming steady-state conditions, a differential mass balance on the dissolved mass flux yields:

$$\frac{dM_{Di}}{dz} = K_{OLi}\,(K_i P_i - C_i)\,\frac{4\pi r^2 N}{(V_L + V_b)(1-\varepsilon)} \quad (\text{mol m}^{-1}\text{ s}^{-1}) \tag{7}$$

where A_r is the cross-sectional area of the riser (m^2) and the dissolved mass flux is defined as:

$$(\text{mol s}^{-1}) \tag{8}$$

A similar derivation can be applied to the gaseous components, producing:

$$\frac{dM_{Gi}}{dz} = -K_{OLi}\,(K_i P_i - C_i)\,\frac{4\pi r^2 N}{V_L + V_b} \quad (\text{mol m}^{-1}\text{ s}^{-1}) \tag{9}$$

where the mass flux of gaseous species is defined as:

$$M_{Gi} = A_r(V_L + V_b)Y_i \quad (\text{mol s}^{-1}) \tag{10}$$

The mass flux equation for the gas phase contains the total bubble velocity relative to the riser walls, whereas the flux equation for the dissolved phase contains only the water velocity. In the above mass balance equations, the total mass transfer term appears as a gain in the dissolved phase and a loss in the gas phase. Applying the mass flux equations to each phase and to each molecular species of interest (oxygen and nitrogen) yields a set of four differential equations. Table 2 provides the parameter correlations that are required to solve the model, and Table 3 shows the equations of state.

In addition to being used for the riser, the model equations were extended to enable prediction of downcomer oxygen transfer. Oxygen transfer occurs in the downcomers because of carry-over of bubbles from the riser. The conservation and state equations used for the downcomers are identical to those applied to the riser except that the bubble rise velocity is negative since the bubbles are moving in the opposite direction to the water flow. Also, the number flux of bubbles in the downcomers takes into account flow splitting and bubble loss to the atmosphere. The fraction of bubbles lost (FL) as the dispersion travels across the air-water separator, or top section, of the aerator is estimated using a settling-tank approach as described in the following equation:

$$FL = \frac{V_b}{V_t} \tag{11}$$

where V_t (m s^{-1}) is the actual water velocity in the top section of the aerator.

Oxygen transfer that occurs in the top section of the aerator as the bubble-water mixture flows from the riser to each of the downcomers is also calculated. Oxygen transfer in this region is assumed to be caused only by reaeration with the atmosphere; gas transfer from the bubbles is accounted for in solving the riser and downcomer equations. The final DO concentration when the flow reaches the end of the separator (C_f) is given by:

$$C_f = \frac{K_{Lt} A_t}{Q_t + K_{Lt} A_t} C_s + C_o \quad (\text{g m}^{-3}) \tag{12}$$

where K_{Lt} (m s^{-1}) is the liquid-side mass transfer coefficient for the top section, A_t (m^2) is the surface area of the water in contact with the atmosphere in the top section, Q_t (m^3 s^{-1}) is the water flow rate through the top section, C_s is the DO saturation concentration at the surface, and C_o (g m^{-3}) is the initial DO concentration. In deriving the above equation, the average DO concentration of the water was used in determining the mass flux of oxygen from the atmosphere.

Since the mass transfer coefficient in the top section was unknown, it was calculated using the experimental data and the dimensions of the aerator. The saturation concentration was calculated using Henry's Law. The initial DO concentration was assumed to be equal to the experimental value at the top of the riser. For each test, the final DO concentration was set equal to the average of the measured concentrations at the top of each downcomer. Therefore, a single mass transfer coefficient was determined for each run. These were graphed as a function of applied air flow rate, and a linear regression was performed. The resulting correlation equation is:

$$K_{Lt} = 0.2304 Q_G + 0.0171 \quad (\text{m s}^{-1}) \tag{13}$$

where Q_G is the applied gas flow rate (m s^{-1}). The above equation is only valid for this particular hypolimnetic aerator design and air flow rates in the range of 0.019-0.066 $m^3\ s^{-1}$. The R^2 value of the linear regression was relatively low at 0.52. Therefore, the oxygen transfer prediction for the top section of the aerator should only be used as a rough estimate.

Model Solution Procedure

Before the model can be solved, the initial conditions at the bottom of the riser tube must be determined. As stated in the assumptions, the initial values of the dissolved oxygen and dissolved nitrogen concentrations are assumed to be equal to the ambient water conditions at the depth of the diffuser. The initial fluxes for these components are determined by multiplying their initial actual concentrations by the actual initial water velocity and the riser cross-sectional area. The gaseous oxygen and nitrogen fluxes are calculated from the air input rate and the initial fraction of each molecular species. The initial gas holdup is determined by use of the initial gaseous species concentration, total pressure, and temperature. The number flux of bubbles is obtained from the air input rate, initial bubble size, and total pressure. The initial total pressure is determined from the depth of the diffuser and the water density. The water and gas temperatures are equal to the ambient lake temperature at the diffuser depth.

The mass flux equations are solved iteratively in three steps by application of the standard Euler method. The equations are first integrated using the initial values described previously. Next, the equations of state are calculated for the partial pressure of oxygen and nitrogen (P_O and P_N, respectively) and the bubble radius (r). Lastly, the remaining parameters required by the model are determined: bubble slip velocity (V_b), mass transfer coefficients (K_{OLO} and K_{OLN}), and Henry's constants (K_O and K_N). The total mass transfer terms are then computed and used to obtain the change in the mass fluxes over a small increment in the vertical coordinate. The new mass fluxes are used as the initial conditions for the next step, and the process is repeated. The iteration for the riser is completed when the flow reaches the top of the riser dispersion.

Because equal amounts of flow and bubbles are assumed to enter each downcomer, the analyses for both are identical. The model, therefore, predicts oxygen transfer in only one half of the aerator after the riser iteration. Oxygen transfer in the air-water separator of the aerator is estimated by use of equations 12 and 13. The water flow rate in the top section is equal to half of that in the riser. The surface area for mass transfer with the atmosphere is set equal to one-half of the separator plan area. The initial DO concentration is equivalent to the value calculated by the model for the top of the riser dispersion.

The same procedure used in the riser is applied to determine oxygen transfer in the downcomers. The iteration begins at the top of the downcomer dispersion. The initial conditions are determined from the dissolved species' concentrations and the gaseous species' molar fractions after oxygen transfer has occurred in the top section. The model iterations stop when the flow reaches the outlet of the downcomer.

RESULTS AND DISCUSSION

The water flow rate and temperature for each applied air flow rate measured in the hypolimnetic aerator were used to fit the DO profiles in the riser by application of the oxygen transfer model. A least-squares analysis was used to determine the DO profile that provided the best fit to the experimental profiles. The model fit for the riser was accomplished by varying the initial bubble size created by the diffuser, which was the only unknown in the system that was studied. The measured profiles and best-fit model predictions are given in Figure 2. (Note: Average measured water temperature during the tests was approximately 21 ^{o}C). The model follows the oxygen concentration profiles well over the entire range of experimental air flow rates. The data show an initial rapid transfer of oxygen to the water in the bottom portion of the riser tube. This phenomenon is caused by a high driving force produced by the increased hydrostatic pressure coupled with the relatively low dissolved oxygen concentration in the water. As the water travels up the riser, the hydrostatic pressure decreases while the dissolved oxygen concentration increases. Both act to lower the driving force, hence decreasing the rate of oxygen transfer.

Since the downcomer DO profiles were not used in the model fits, they were predicted with the bubble diameters determined by the model. These downcomer predictions are also shown in Figure 2. Both the model and experimental profiles are nearly linear with similar slopes. The model seems to perform better at the higher air flow rates, which is most likely the result of error in the estimation of oxygen transfer in the top section at lower air flow rates. The error affects the initial dissolved oxygen concentration used by the model in determining the downcomer profile.

Figure 3 shows the initial bubble diameters that provided the best fit of the model to the experimental data and the corresponding experimentally measured Sauter mean diameters. The measured values were obtained from two independent sets of tests over the entire range of air flow rates. The values calculated by the model and those measured during the laboratory experiments seem to be relatively independent of applied air flow rate, an effect also observed by *Ashley et al.* [1992]. The range of fitted initial bubble diameters is 2.3-3.1 mm, and the range of experimentally observed diameters is 2.7-3.9 mm. One possible cause for the discrepancy between measured and fitted values is the difference in hydrodynamic conditions between the field and the laboratory tests. In the hypolimnetic aerators, there is an induced water flow rate that produces flow across the diffuser orifices. The flow would tend to cause greater shear and hence smaller bubbles than if there was no flow. The flow rate would produce bubbles with a smaller volume, and hence a smaller diameter. Also, one of the assumptions of the model is that the bubbles do not coalesce. If bubble coalescence does occur, then the number flux of bubbles (N) decreases, which, in turn, would cause the bubble size to increase.

Figure 3 also shows the standard deviations for each of the measured bubble diameters. From the graph, it can be seen that most of the deviations are approximately 30%. All of the fitted bubble sizes, with the exception of one at the lowest air flow rate, fall within ±30% of the measured values. The standard deviations of the measured bubble sizes indicate that the assumption of uniform bubble size may be invalid. However, a modeling analysis was performed using a bubble size distribution instead of a single value, and the oxygen transfer values obtained did not differ significantly from those resulting from use of a constant bubble diameter.

An analysis was performed to determine the sensitivity of riser DO profiles to initial bubble sizes created by the diffuser, the only unknown for the system studied. Two cases were investigated, one with the lowest fitted bubble diameter and the other with the highest fitted diameter. Table 4 provides the baseline conditions for the each case. The effect of bubble size on the mean square error (MSE) between predicted and measured riser DO profiles is shown in Figures 4 and 5 for each set of conditions. From the graphs, it can be seen that bubbles sizes less than the fitted diameter have a greater effect on the MSE than diameters above the fitted value. This is primarily due to the fact that the number flux of bubbles increases as the bubble size decreases. The bubble slip velocity decreases as the diameter decreases below 1.4 mm. From Equation 7, it can be seen that both of these occurrences act to increase the change in DO concentration per unit height. Figures 4 and 5 also indicate that the model is less sensitive to bubble size for Case 2 than for Case 1. The results of the sensitivity analysis suggest that more accurate DO profiles will be predicted by the model if: 1) the initial bubble size is overestimated rather than underestimated and 2) the bubble diameter that provides the best fit is relatively large.

Overall gas phase holdup was also calculated by the model using the bubble diameters obtained when the riser DO profiles were fitted. The predicted results are compared to experimental values in Figure 6. Good agreement is seen between measured and calculated gas holdup, with all of the predicted values within ± 30% of the observed. A possible cause for the deviation may be error associated with the experimental water velocity. The equipment used to obtain water velocity readings (stream propeller meter) has not been fully verified for use in gas-liquid flow. If the measured velocity is slightly higher than the actual value, then the gaseous species' concentrations calculated by the model would be lower than expected. This would cause the gas holdup determined by the model to be lower than the experimental value.

SUMMARY AND CONCLUSIONS

Data from a full-lift hypolimnetic aerator have been collected over a wide range of applied air flow rates. Dissolved oxygen concentration profiles, water flow rates, and gas holdup were measured. A model that was developed to describe bubble dynamics and oxygen transfer in a bubble plume diffuser was applied to the conditions of a hypolimnetic aerator. By varying a single parameter (the initial bubble size) the model was found to provide a close fit to the experimental DO profiles as well as reasonable agreement with the observed gas holdup in the riser. The bubble sizes predicted by the model agree well with the Sauter mean diameters obtained during laboratory experiments. The model was also extended to account for oxygen transfer in the air-water separator and to predict DO profiles in the downcomers; again, the model output compares well with the experimental data. The model was found to be more sensitive when the initial bubble size was underestimated rather than overestimated and when the bubble size that provided the best fit was relatively large. These results represents a significant advance in the understanding of hypolimnetic aerator performance and, because of the fundamental nature of the model, suggest that this approach may be successfully applied to other types of aeration devices.

ACKNOWLEDGMENTS

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NOTATION

Variables

A	area, m^2.
C	dissolved concentration, mol m^{-3}, g m^{-3}.
d	diameter, m.
FL	fraction lost.
H	height, m.
J	mass transfer flux through single bubble surface, mol m^{-2} s^{-1}.
K	solubility constant, mol m^{-3} bar^{-1}.
K_L	liquid-side mass transfer coefficient, m s^{-1}.
K_{OL}	overall mass transfer coefficient, mol s^{-1}.

L	length, m.
M	mass flux, mol s^{-1}.
N	number flux of bubbles, s^{-1}.
P	pressure, bar.
Q	volumetric flow rate, $m^3 s^{-1}$.
r	bubble radius, m.
t	time, s.
V	actual velocity, m s^{-1}.
x	horizontal length, mm.
y	vertical length, mm.
Y	gaseous concentration, mol m^{-3}.
z	depth, m.

Greek Letters

ε	gas holdup.
ρ	density, kg m^{-3}.

Subscripts

3,2	Sauter mean
atm	atmospheric
avg	average
c	circular
d	downcomer
D	dissolved
e	exit
G	gaseous
i	molecular species
L	liquid
N	nitrogen
o	initial
O	oxygen
r	riser
s	saturation
t	top
tot	total

REFERENCES

Ashley, K. I., Hypolimnetic aeration of a naturally eutrophic lake: Physical and chemical effects, *Can. J. Fish. Aquat. Sci.*, *40*, 1343-1359, 1983.

Ashley, K. I., Hypolimnetic aeration: Practical design and application, *Wat. Res.*, *19*, 735-740, 1985.

Ashley, K. I. and K. J. Hall, Factors influencing oxygen transfer in hypolimnetic aeration systems, *Verh. Int. Verein. Limnol*., *24*, 179-183, 1990.

Ashley, K. I., S. Hay, and G. H. Scholten, Hypolimnetic aeration: Field test of the empirical sizing method, *Wat. Res*., *2*, 223-227, 1987.

Ashley, K. I., D. S. Mavinic, and K. J. Hall, Effects of orifice size and surface conditions on oxygen transfer in a bench scale diffused aeration system, *Envir. Tech.*, *11*, 609-618, 1990.

Ashley, K. I., K. J. Hall, and D. S. Mavinic, Factors influencing oxygen transfer in fine pore diffused aeration, *Wat. Res.*, *25*, 1479-1486, 1991.

Ashley, K. I., D. S. Mavinic, and K. J. Hall, Bench-scale study of oxygen transfer in course bubble diffused aeration, *Wat. Res.*, *26*, 1289-1295, 1992.

Bin, A. K., Application of a single-bubble model in estimation of ozone transfer efficiency in water, *Ozone Sci. Eng.*, *17*, 469-484, 1995.

Bischof, F., Durst, F., Höfken, M., and Sommerfeld, M., Theoretical considerations about the development of efficient aeration systems for activated sludge treatment, *Aeration Tech.*, *187*, 27-38, 1994.

Burris, V. L. and J. C. Little, Bubble dynamics and oxygen transfer in a hypolimnetic aerator, paper presented at Reservoir Management and Water Supply - An Integrated System, IAWQ/IWSA, Prague, Czech Republic, May 3-8, 1997.

Chen, S., M. B. Timmons, D. J. Aneshansley, and J. J. Bisogni, Jr., Bubble size distribution in a bubble column applied to aquaculture systems, *Aquaculture Eng.*, *11*, 267-280, 1993.

Chisti, M. Y., *Airlift Bioreactors,* 345 pp., Elsevier Science Publishing, New York, NY, 1989.

Cole, G. A., *Textbook of Limnology*, 4th ed., 412 pp., Waveland Press, Inc., Prospect Heights, IL, 1994.

Cooke, G. D. and R. E. Carlson, *Reservoir Management for Water Quality and THM Precursor Control,* 387 pp., AWWA Research Foundation, Denver, CO, 1989.

Cumbie, W. E., D. Rosenthal, and B. Welsh, Hypolimnetic aeration of Norfolk, Va. reservoirs improves lake quality while reducing problems at treatment plant (abstract), *Lake and Reserv. Manage.*, 9, 67, 1994.

Fast, A. W., V. A. Dorr, and R. J. Rosen, A submerged hypolimnion aerator, *Wat. Resour. Res.*, *11*, 287-293, 1975a.

Fast, A.W., W. J. Overholtz, and R. A. Tubb, Hypolimnetic oxygenation using liquid oxygen, *Wat. Resour. Res.*, *11*, 294-299, 1975b.

Favre, R. P., Hypolimnetic aeration in three Swiss lakes, in *Air-Water Mass Transfer-Selected Papers from the Second International Symposium on Gas Transfer at Water Surfaces*, pp. 660-669, ASCE, New York, NY, 1991.

Gemza, A., Some practical aspects of whole lake mixing and hypolimnetic oxygenation. Ecological impacts of aeration on lakes and reservoirs in southern Ontario (abstract), *Lake and Reserv. Manage.*, 11, 141, 1995.

Hamblin, P. F. and K. E. Lindenschmidt, Observations and model of the thermal impact of hypolimnetic aeration on a shallow urban lake, Lake Tegal, Germany (abstract), *Lake and Reserv. Manage.*, 11, 146, 1995.

Little, J. C., Hypolimnetic aerators: Predicting oxygen transfer and hydrodynamics, *Wat. Res.*, *29*, 2475-2482, 1995.

Lorenzen, M. W. and A. W. Fast, *A Guide to Aeration/Circulation Techniques for Lake Management*, Ecol. Res. Ser. EPA 600/3-77-004, 126 pp., USEPA, 1977.

Nordin, R., K. Ashley, and P. Law, Hypolimnetic aeration of St. Mary Lake, British Columbia, Canada (abstract), *Lake and Reserv. Manage.*, 11, 176, 1995.

Jaeger, D., Effects of hypolimnetic water aeration and iron-phosphate precipitation on the trophic level of Lake Krupunder, *Hydrobiol.*, *275/276*, 433-444, 1994.

Kortmann, R. W., G. W. Knoecklein, C. H. and Bonnell, Aeration of stratified lakes: Theory and practice, *Lake and Reserv. Manage.*, *8*, 99-120, 1994.

McQueen, D. J. and D. R. S. Lean, Hypolimnetic aeration and dissolved gas concentrations, *Wat. Res.*, *17*, 1781-1790, 1983.

McQueen, D. J. and D. R. S. Lean, Hypolimnetic aeration: An overview, *Water Poll. Res. J. Can.*, *21*, 205-217, 1986.

McQueen, D. J., D. R. S. Lean, and M. N. Charlton, The effects of hypolimnetic aeration on iron-phosphorus interactions, *Water Res.*, *20*, 1129-1135, 1986.

McQueen, D. J., S. S. Rao, and D. R. S. Lean, Hypolimnetic aeration: Changes in bacterial populations and oxygen demand, *Arch. Hydrobiol.*, *99*, 498-514, 1984.

McQueen, D. J. and V. A. Story, Impact of hypolimnetic aeration on zooplankton and phytoplankton populations, *Envir. Tech. Lett., 7,* 31-44, 1986.

Pöpel, H. J. and M. Wagner, Prediction of oxygen transfer from simple measurements of bubble characteristics, *Wat. Sci. Tech.*, *23*, 1941-1950, 1991.

Soltero, R. A., L. M. Sexton, K. I. Ashley, and K. O. McKee, Partial and full lift aeration of Medical Lake, WA to improve water quality, *Wat. Res.*, *28*, 2297-2308, 1994.

Steinberg, C. and K. Arzet, Impact of hypolimnetic aeration on abiotic and biotic conditions in small kettle lake, *Envir. Tech. Lett.*, *5*, 151-162, 1984.

Taggart, C. T., Hypolimnetic aeration and zooplankton: A possible limitation to the restoration of cold-water fish production, *Can. J. Fish. Aquat. Sci.*, *41*, 191-198, 1984.

Taggart, C. T. and D. J. McQueen, Hypolimnetic aeration of a small kettle lake: Physical and chemical changes, *Arch. Hydrobiol*., *91*, 150-180, 1981.

Taggart, C. T. and D. J. McQueen, A model for the design of hypolimnetic aerators, *Wat. Res*., *16*, 949-956, 1982.

Tate, C. H. and K. F. Arnold, Health and aesthetic aspects of water quality, in *Water Quality and Treatment*, edited by F. W. Pontius, pp. 63-154, McGraw-Hill, Inc., New York, 1990.

Tsang, G., Theoretical investigation of oxygenating bubble plumes, in *Air-Water Mass Transfer-Selected Papers from the Second International Symposium on Gas Transfer at Water Surfaces*, pp. 715-727, ASCE, New York, NY, 1991.

Wirth, T. L., D. R. Knauer, and S. A. Smith, Total and hypolimnetic aeration of lakes in Wisconsin, *Verh. Internat. Verein. Limnol*., *19*, 1960-1970, 1975.

Wuest, A., N. H. Brooks, D. M. and Imboden, Bubble plume modeling for lake restoration, *Wat. Resour. Res*., *28*, 3235-3250, 1992.

Table 1. LPA1 Dimensions.

Parameter	Value (m)
riser length	10
downcomer length	5
riser diameter	1.1
downcomer diameter	1.1

Table 2. Parameter Correlations (*Wüest et al*., 1992).

Parameter	Correlation		Units
Bubble slip velocity	$V_b = 4474r^{1.357}$	$r < 7.0 \times 10^{-4}$	$m\ s^{-1}$
	$V_b = 0.23$	$7.0 \times 10^{-4} < r < 5.1 \times 10^{-3}$	r units: m
	$V_b = 4.202r^{0.547}$	$r > 5.1 \times 10^{-3}$	
Oxygen and nitrogen	$K_{OL} = 0.6r$	$r < 6.67 \times 10^{-4}$	$m\ s^{-1}$
mass transfer coefficient	$K_{OL} = 4.0 \times 10^{-4}$	$r > 6.67 \times 10^{-4}$	r units: m
Oxygen solubility	$K_O = 2.125 - 0.05021T + 5.77 \times 10^{-4}T^2$		$mol\ m^{-3}\ bar^{-1}$
constant			T units: ^oC
Nitrogen solubility	$K_N = 1.042 - 0.0245T + 3.171 \times 10^{-4}T^2$		$mol\ m^{-3}\ bar^{-1}$
constant			T units: ^oC

Table 3. Equations of State (*Wüest et al*., 1992).

Parameter	Equation	Units
Total pressure	$P_{tot} = P_{atm} + 10^{-5}\rho_{avg} gz$	bar ρ units: kg m^{-3} g units: m s^{-2} z units: m
Partial pressure	$P_i = \left(\frac{Y_i}{Y_O + Y_N}\right) P_{tot} = \left(\frac{M_{Gi}}{M_{GO} + M_{GN}}\right) P_{tot}$	bar Y units: mol m^{-3} M units: mol s^{-1}
Gas holdup	$\varepsilon = \left[\frac{(Y_O + Y_N)}{P_{tot}}\right] RT$	dimensionless Y units: mol m^{-3} P units: Pa R units: J mol^{-1} K^{-1} T units: K
Bubble radius	$r = \left[\frac{3\varepsilon A_r (V_L + V_b)}{4\pi N}\right]^{\frac{1}{3}}$	m A_r units: m^2 v units: m s^{-1} N units: s^{-1}

Table 4. Baseline Conditions for Sensitivity Analysis.

Parameter	Case 1	Case 2
Air flow rate (m^3 s^{-1})	0.019	0.049
Water flow rate (m^3 s^{-1})	0.43	0.73
Initial DO concentration (mg l^{-1})	0.32	0.24
Water temperature (^oC)	21.1	21.2
Fitted bubble diameter (mm)	2.3	3.1

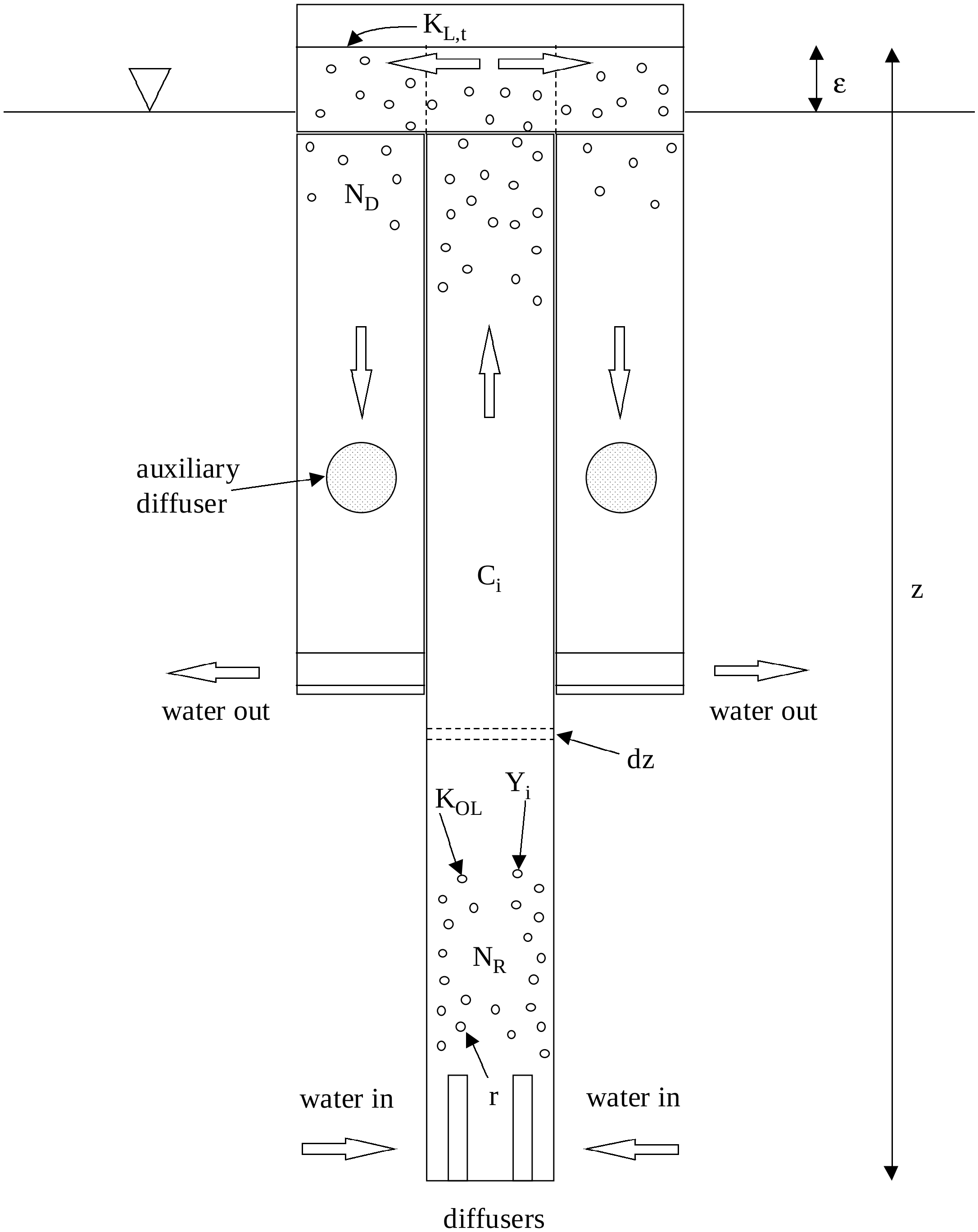

Figure 1. Schematic representation of hypolimnetic aerator LPA1.

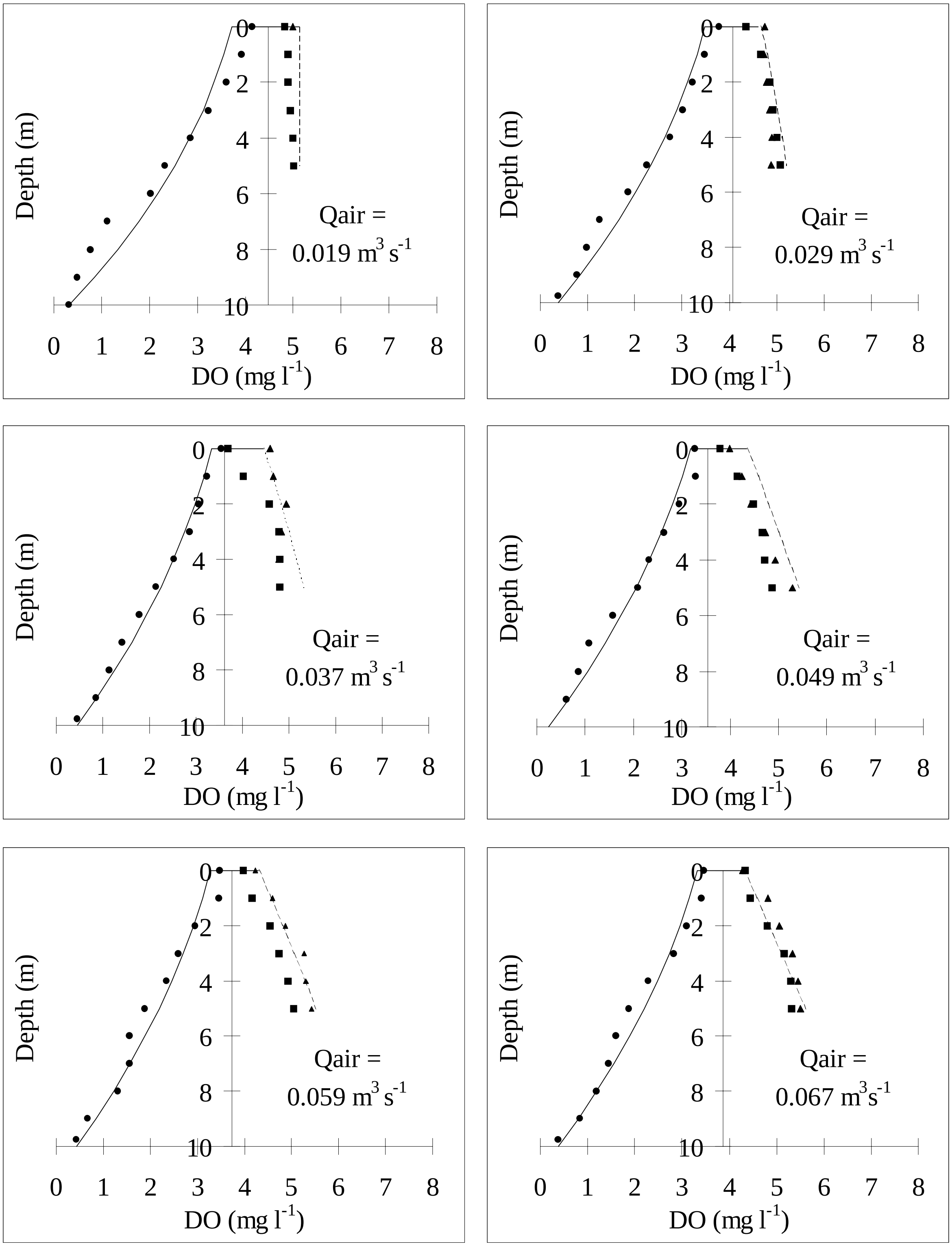

Figure 2. Experimental and model DO profiles at range of air flow rates (— model fit, ···· model prediction,● riser data, ▲ downcomer 1 data, ■ downcomer 2 data).

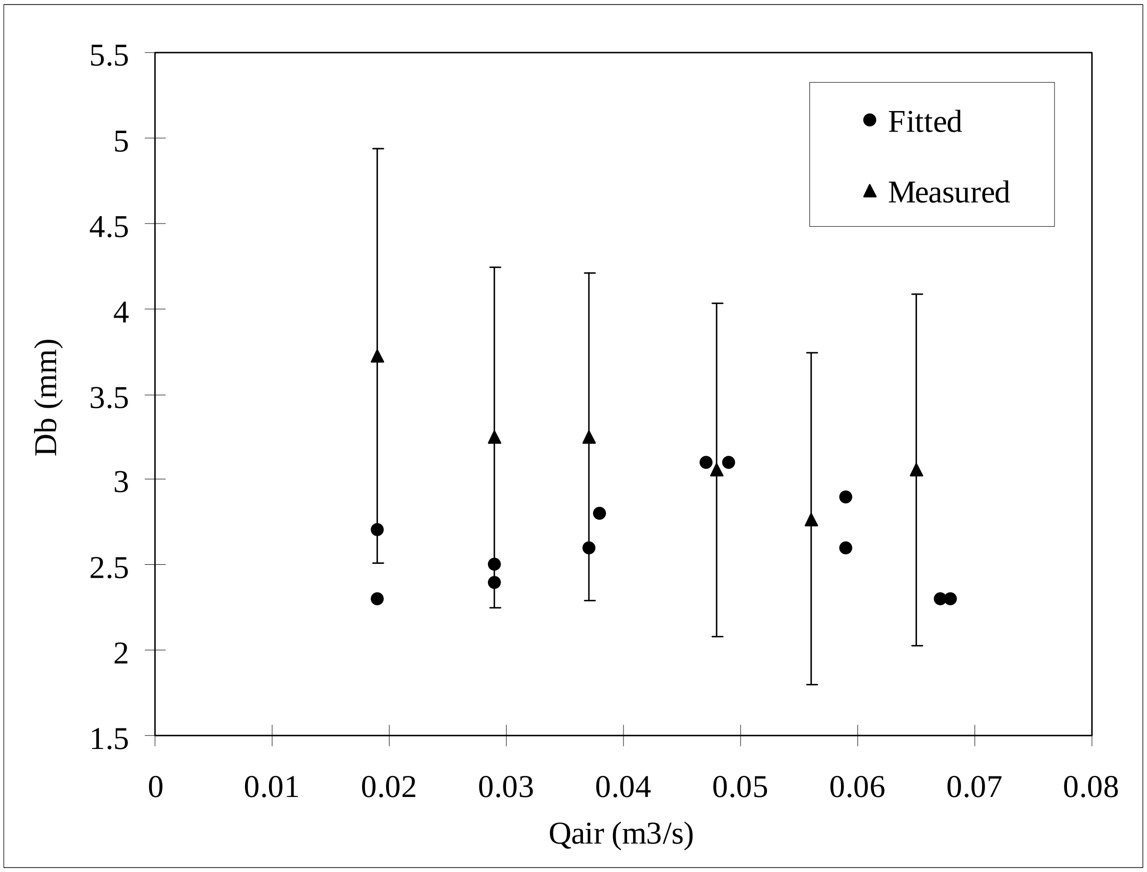

Figure 3. Comparison of fitted and measured bubble diameters. Vertical lines represent standard deviations of measured bubble sizes.

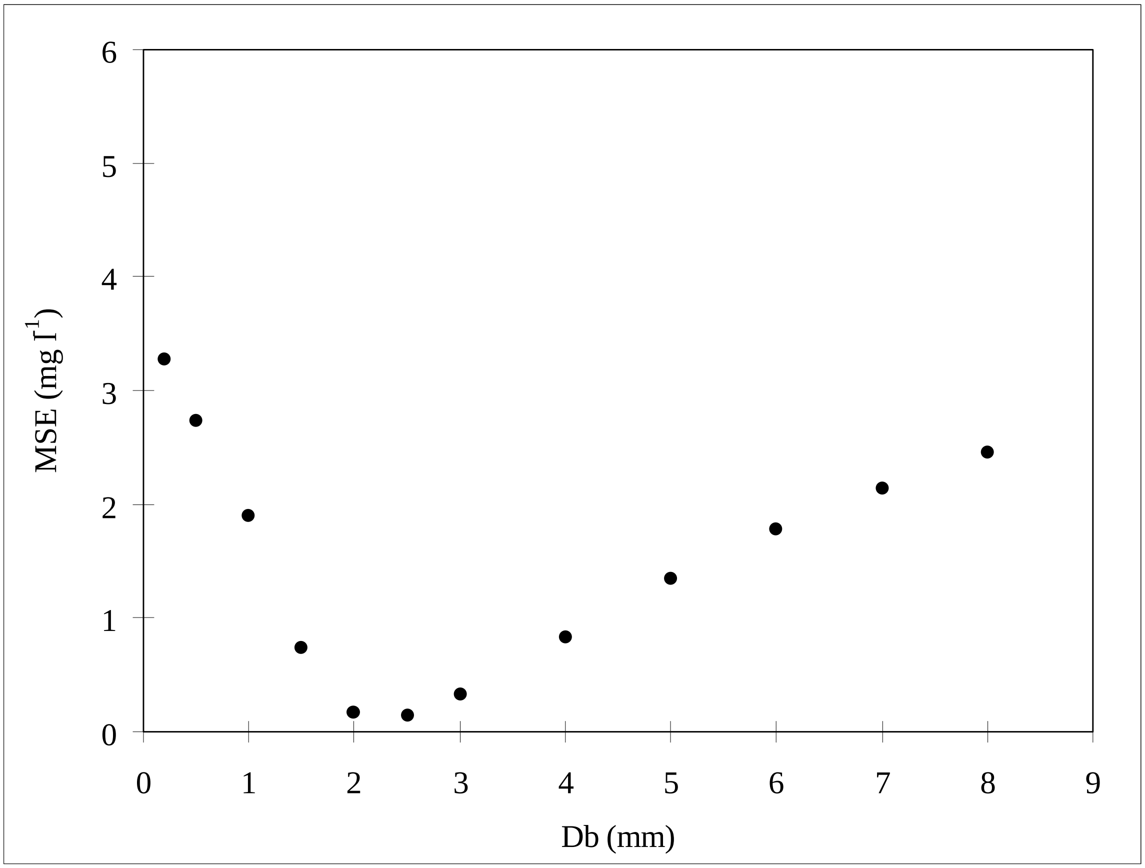

Figure 4. Sensitivity of riser DO profile predicted by oxygen transfer model to initial bubble diameter for Case 1.

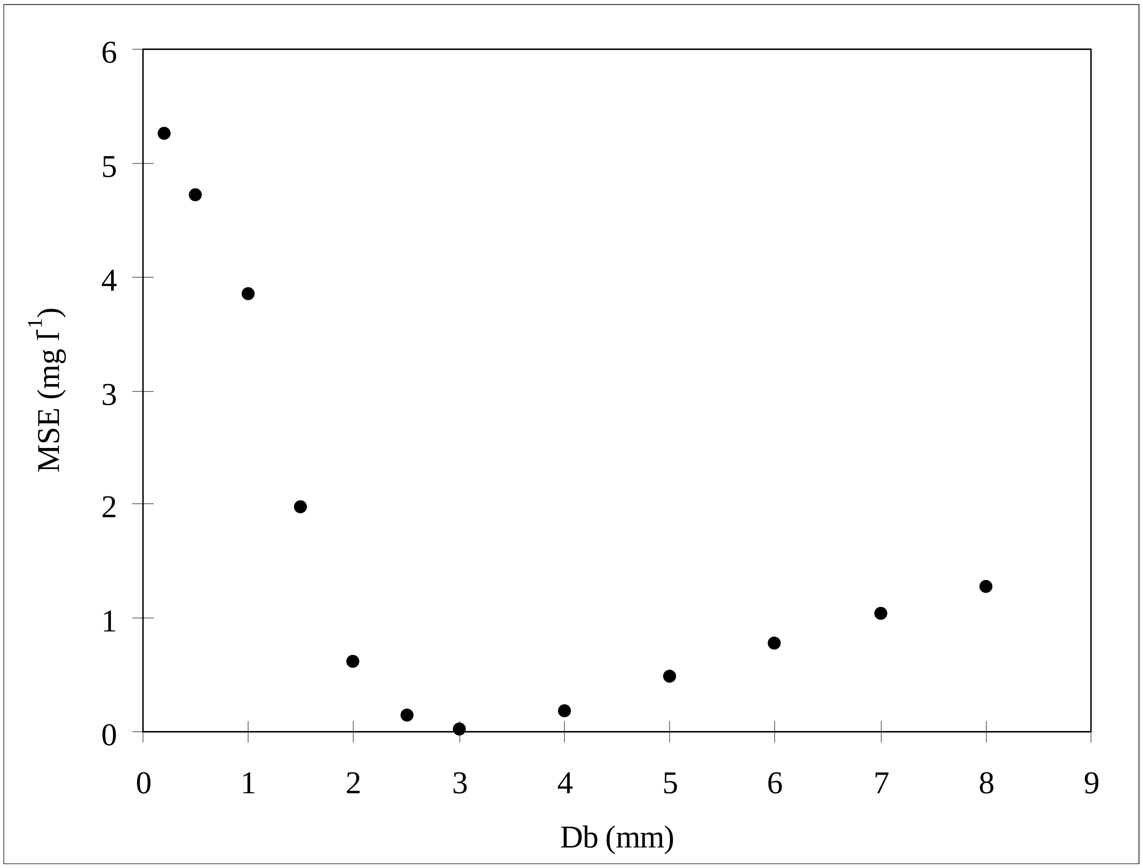

Figure 5. Sensitivity of riser DO profile predicted by oxygen transfer model to initial bubble diameter for Case 2.

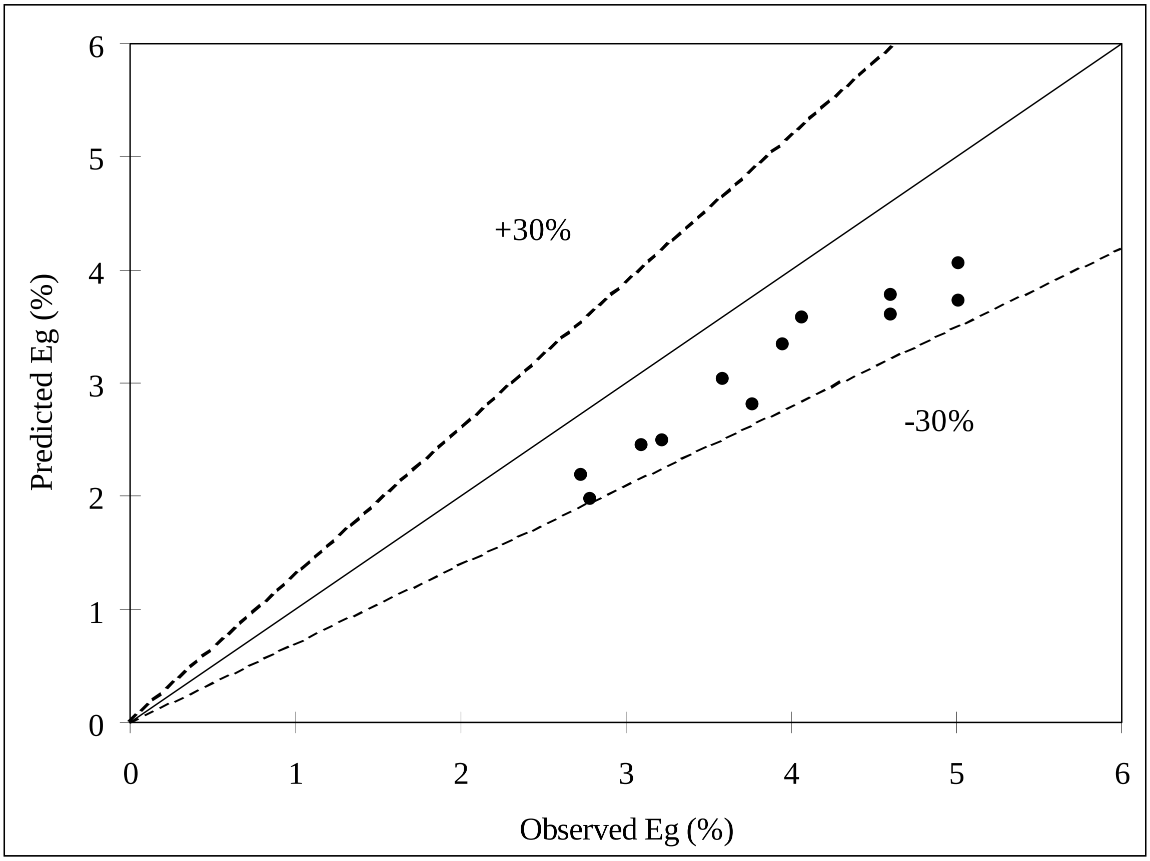

Figure 6. Comparison of observed and predicted gas holdup in riser.

CHAPTER 3. PREDICTING WATER FLOW RATE IN HYPOLIMNETIC AERATORS

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ABSTRACT

Data used to verify a model that predicts water flow rate when given the air flow rate and intake water conditions were collected from a full-scale hypolimnetic aerator installed in a water supply reservoir owned by the City of Norfolk, Virginia. Water flow rate and gas-phase holdup were measured as a function of air flow rate. Tests were performed with air supplied only to the riser and with varying air flow to the downcomers. The downcomer diffusers did not significantly affect water flow rate for this aerator design. The model was fitted to the experimental water velocity by varying the frictional loss coefficient for the air-water separator. An empirical correlation that predicts the loss coefficient as a function of superficial water velocity was obtained. Results of the correlation were similar to that obtained from a review of the literature on external airlift bioreactors.

INTRODUCTION

Anoxic conditions in the hypolimnion that develop during thermal stratification of lakes and reservoirs can lead to severe water quality problems [*Burris et al*., 1998]. Hypolimnetic aeration commonly is used to increase oxygen levels in this layer. This type of aeration is designed to oxygenate only the hypolimnion without disturbing thermal stratification. Two of the major difficulties associated with hypolimnetic aeration are estimating the hypolimnetic oxygen demand and predicting the aerator oxygen input rate, which is highly dependent on the water flow rate induced by the aerator [*Ashley and Hall*, 1990]. Several researchers have attempted to develop models to predict hypolimnetic aerator performance [*Lorenzen and Fast*, 1977; *Taggart and McQueen*, 1982; *Ashley*, 1985]. *Taggart and McQueen* developed an empirical equation for estimating water flow rate as a function of aerator riser tube height and volumetric air flow rate. *Ashley* proposed that water flow rate should be determined by dividing daily oxygen consumption by the aerator's input rate. To avoid undersizing aerators, *Ashley et* *al*. [1987] suggested that a water velocity of 0.45-0.50 m s^{-1} be used if there is no bubble size or velocity data available.

A more fundamentally based model for predicting water flow rate in hypolimnetic aerators was developed based on an energy balance over the entire aerator [*Del Vecchio and Little*, 1995]. The model takes into account energy introduced by isothermal gas expansion and energy loss due to bubble wakes, friction, and isothermal gas compression. The model is similar to those developed for external-loop airlift bioreactors, which are hydrodynamically similar to hypolimnetic aerators. The energy balance approach has been used extensively in predicting airlift reactor performance [*Chakravarty et al*., 1974; *Lee et al*., 1986; *Calvo*, 1989; *Chisti*, 1989; *Calvo and Letón*, 1991; *Kemblowski*, 1993; *Akita et al*., 1994; *Merchuk and Berzin*, 1995]. This paper presents modifications to the model and verification using data from a full-scale hypolimnetic aerator. The previously documented methods of predicting induced water flow rate are primarily empirically based. This new approach represents a more fundamental method for determining induced water flow rate in a hypolimnetic aerator.

EQUIPMENT AND METHODS

In order to validate the model, experimental data were collected from an operational full-scale hypolimnetic aerator. The aerator was part of Norfolk's hypolimnetic aeration system installed in Lake Prince, one of its water supply reservoirs. Norfolk supplies potable water to a significant portion of Virginia's Tidewater area. In the past, anoxic conditions have developed in the lake during the stratification period. Aerators were installed to increase dissolved oxygen levels, thereby improving water quality.

Hypolimnetic Aeration System

Details of the hypolimnetic aeration system are described by *Burris et al*. [submitted]. The most recent aerator design was selected for testing because of its relatively well-defined flow pattern through the aerator and because its structure facilitated field data collection (Figure 1). The data used to verify the model were obtained from Lake Prince Aerator 1 (LPA1). Table 1 provides a summary of the relevant dimensions of this aerator during testing. The bulk of the aerator was fiberglass, consisting of three vertical pipes and an air-water separator box. The center pipe was the riser tube. Water and gas bubbles traveled up this tube, which had a telescoping feature that allowed the separator to remain floating and the bottom to rest on the sediments with fluctuating lake levels. The two outer pipes were the downcomers, which discharged aerated water to a specified lake depth. The downcomers were equipped with baffles on their outlets to deflect water flow away from the sediments. The air-water separator had doors that permitted access inside the riser and downcomers from the lake surface.

When used for hypolimnetic aeration, compressed air bubbled freely from a diffuser mount located at the bottom of the riser tube. The diffuser unit consisted of two pieces of 3.8 cm, schedule 80 polyvinyl chloride (PVC) pipe mounted vertically on the ends of a tee. The length of each diffuser piece was approximately 0.86 m with 3.2 mm orifices located towards the top. The openings were placed in five vertical rows approximately 1.3 cm apart. There were 12 holes per row spaced 2.5 cm apart. The holes were oriented only on one side of each diffuser, and the diffuser pieces were mounted with the orifices opposite one another. The manufacturer's intention was to create a spiral flow of water up the riser tube with this configuration. In addition to the diffuser unit in the riser, two auxiliary diffusers are also in each of the downcomers. The purpose of the auxiliary diffusers was to increase overall oxygen transfer from the aerator.

When air was introduced to the water column in the riser, an air-water mixture less dense than the surrounding water traveled up the riser tube. Once the mixture reached the top of the riser, some of the bubbles continued to rise and enter the atmosphere. The remainder were entrained in the flow of water that entered either of the two downcomers. The aerated water then flowed through the downcomers and was released at a specified lake depth. The discharge depth was approximately equal to the depth at which raw water was being withdrawn for treatment.

Experimental Equipment

Data were collected from the aerator using two main pieces of experimental equipment, a YSI Model 610 data logger equipped with a temperature probe and a Swoffer Model 2100 stream current propeller meter. The meter was modified to obtain readings in both vertical directions in the riser and downcomers. Prior to testing, the performance of the meter was evaluated in a laboratory flume, and good agreement between readings was obtained. In accordance with manufacturer's guidelines, the propeller meter was calibrated in the field during each sampling trip.

Experimental Method

Since the only parameter other than structural modifications that could be adjusted on LPA1 was the air flow rate, experiments were conducted in a wide range of air flow rates (0.019 m^3 s^{-1} - 0.066 m^3 s^{-1}) to the riser diffuser. Tests were performed in duplicate, and the data recorded during each run included air flow rate, water temperature, overall gas-phase holdup, and water velocity.

In addition to the tests performed with air flow supplied to the riser diffuser only, two sets of experiments were conducted with a portion of the riser air flow diverted to the auxiliary diffusers in the downcomers. During both series of tests a constant air flow rate (0.047 m^3 s^{-1} and 0.066 m^3 s^{-1}) was delivered to the entire aerator with varying amounts of the flow directed to the downcomers. An equal air flow rate was delivered to each downcomer diffuser. The data collected and procedures followed during these experiments were identical to those of the testing series with air flow supplied to the riser diffuser only.

The effect of air flow rate on induced water velocity was measured. Water temperature was required to determine the appropriate physical properties of the water and air. Gas-phase holdup was needed to calculate water flow rate with the model. Gas holdup in the riser and both of the downcomers was determined by the volume-expansion technique. The height of the gas-liquid dispersion during aeration was measured with a measuring tape. The volume expansion technique is a simple and reliable method that has been used by a number of researchers examining airlift bioreactors, which are hydrodynamically similar to hypolimnetic aerators [*Chisti*, 1989].

Water flow rate was determined using the velocity-area method. Velocity measurements were obtained within the riser at a depth of approximately 1.4 m to avoid objects (diffuser mount cable and air supply hose) that would impede the movement of the velocity meter propeller. Data were obtained from a single location within the cross-section for each run because few areas were unaffected by the obstructions. Ten readings were taken for each run, with each reading a 30-second average of the actual velocity at that point. The readings were then averaged to calculate the induced water velocity for the run. Water velocity data were used to calculate observed water flow rate knowing the cross-sectional area of the riser.

MODEL DEVELOPMENT

The water flow rate model presented in this paper is based upon that developed by *Del Vecchio and Little* [1996]; the original model was modified for the conditions encountered in the particular aerator design studied. The main equations for the model came from literature on airlift bioreactor performance. Airlift reactors are comprised of a volume of liquid separated into two distinct portions, only one of which is sparged with gas to induce a liquid flow rate. There are two main classifications of airlift reactors, internal-loop and external- or outer-loop. Internal-loop airlifts are bubble columns divided by an internal baffle. External-loop airlifts are comprised of two distinct vertical pipes connected by horizontal sections at the top and bottom [*Chisti*, 1989]. Structurally and hydrodynamically, hypolimnetic aerators are similar to external-loop airlift reactors, and the same principles should be applicable to both devices.

The water flow rate model is based upon a macroscopic energy balance over the entire aerator. The rate of energy input due to gas flow is equal to the rate of energy dissipation due to fluid flow [*Lee et al.*, 1986]. The balance can be written as follows:

$$E_I = E_W + E_F + E_E + E_T + E_D + E_C \tag{1}$$

where E_I is the energy input due to isothermal gas expansion; E_W is the energy dissipation due to wakes created by the bubbles in the riser; E_F is the energy loss due to friction in the riser and downcomer; E_E is the energy loss due to local disturbances in the flow (entrance and exit); E_T is the energy loss due to fluid turn-around and friction at the top of the riser; E_D is the energy loss due to the upward rise of bubbles in the downcomer relative to the liquid flow; and E_C is the energy loss due to isothermal gas compression in the downcomer.

Model Assumptions

Several simplifying assumptions were made in developing the water flow rate model equations. The energy balance equation assumes that the system is operating at steady state and that the energy introduced by the gas as it is dispersed by the diffuser into the surrounding liquid is negligible. In solving the model, it is assumed that there is equal flow in each downcomer and that the water temperature remains constant throughout the aerator. Lastly, it is assumed that all bubbles that enter the downcomers exit through the bottom.

Model Equations

The energy input due to isothermal gas expansion as the bubbles travel up the riser can be defined as [*Chisti*, 1989]:

$$E_I = Q_{Gr} P_{atm} \ln\left(1 + \frac{\rho_{GLr} g H_{GLr}}{P_{atm}}\right) \tag{2}$$

where Q_{Gr} is the volumetric gas flow rate in the riser measured at atmospheric pressure ($m^3\ s^{-1}$), P_{atm} is atmospheric pressure (Pa), ρ_{GLr} is the average density of the gas-liquid dispersion in the riser ($kg\ m^{-3}$), g is gravitational acceleration ($m\ s^{-2}$), and H_{GLr} is the height of the gas-liquid dispersion in the riser (m). The average dispersion density is

$$\rho_{GLr} = \rho_L (1 - \varepsilon_r) + \rho_{G_r} \varepsilon_r \tag{3}$$

and the height of the dispersion is obtained from

$$H_{GLr} = \frac{H_L}{(1 - \varepsilon_r)} \tag{4}$$

where ρ_L is the density of the liquid ($kg\ m^{-3}$), ε_r is the average gas-phase holdup in the riser (-), ρ_{Gr} is the average density of the gas in the riser ($kg\ m^{-3}$), and H_L is the height of the unaerated liquid (m). The average gas density in the riser can be computed from:

$$\rho_{Gr} = \left(\frac{MW}{RT}\right)\left(P_{atm} + \rho_{GLr} g \frac{H_{GLr}}{2}\right) \tag{5}$$

where MW is the molecular weight of the gas ($g\ mol^{-1}$), R is the ideal gas constant ($J\ mol^{-1}\ K^{-1}$), and T is the absolute temperature (K).

The energy dissipation created by the bubble wakes in the riser is obtained by equating the rate of loss of pressure energy of the gas and liquid with the rate of gain in potential energy of the liquid [*Lee et al.*, 1986] giving:

$$E_W = \rho_L g H_L A_r \varepsilon_r \left[\frac{U_{Gr}}{\varepsilon_r} - \frac{U_{Lr}}{(1-\varepsilon_r)} \right] \tag{6}$$

where A_r is the cross-sectional area of the riser, U_G is the average superficial gas velocity in the riser (m s^{-1}), and U_{Lr} is the superficial liquid velocity in the riser (m s^{-1}). The bracketed term is equivalent to the bubble slip velocity, the velocity of the bubbles relative to the liquid. Using Turner's assumption [*Turner*, 1966], the slip velocity is equal to the terminal rise velocity of the bubbles (V_b). Substituting for this term, the above equation becomes:

$$E_W = \rho_L g H_L A_r \varepsilon_r V_b \tag{7}$$

For the range of bubble sizes typically produced by diffusers with similar sized orifices, V_b can be approximated to be a constant value of 0.23 m s^{-1} [*Wuest et al.*, 1992].

The energy loss due to friction between the dispersion and the wall of the riser can be calculated from [*Merchuk and Stein*, 1981]:

$$E_{Fr} = 2 C_{fr} \rho_L U_{Lr} (U_{Lr} + U_{Gr}) \frac{H_L}{D_r} (U_{Lr} A_r) \tag{8}$$

where C_{fr} is the riser flow Fanning friction factor (-) and D_r is the diameter of the riser (m). The Fanning friction factor may be determined from:

$$C_{fr} = \frac{0.046}{Re_r^{0.2}} \quad \text{and} \quad Re_r = \frac{U_{Lr} D_r}{(1-\varepsilon_r)\nu_L} \tag{9}$$

where Re_r is the riser flow Reynolds number and ν_L is the kinematic viscosity of the liquid (m s^{-2}). The same equations can be applied to calculate the energy loss due to downcomer wall friction:

$$E_{Fd} = 2 C_{fd} \rho_L \frac{L_d}{D_d} (U_{Ld}^3 A_d) \tag{10}$$

where C_{fd} is the downcomer Fanning friction factor (-), L_d is the length of the downcomer (m), D_d is the diameter of the downcomer (m), U_{Ld} is the superficial downcomer liquid velocity (m s^{-1}), and A_d is the cross-sectional area of the downcomer (m^2). Similarly, the respective Fanning friction factors can be obtained from:

$$C_{fd} = \frac{0.046}{Re_d^{0.2}} \quad \text{and} \quad Re_d = \frac{U_{Ld} D_d}{(1-\varepsilon_d)\nu_L} \tag{11}$$

where Re_d is the downcomer flow Reynolds number (-) and ε_d is the average downcomer gas holdup (-).

The energy dissipated by local flow disturbances is obtained from the following equation [*Del Vecchio and Little*, 1996]:

$$E_E = \frac{1}{2}\rho_L\left[V_{Lr}^3 K_{en} A_r \left(1-\varepsilon_r\right) + U_{Lex}^3 K_{ex} A_{ex}\right] \tag{12}$$

where V_{Lr} is the actual liquid velocity in the riser (m s^{-1}), K_{en} is the entrance loss coefficient (-), U_{Lex} is the superficial liquid velocity through the exit (m s^{-1}), K_{ex} is the exit loss coefficient (-), and A_{ex} is the cross-sectional area of the exit (m^2). The entrance and exit loss coefficients were estimated from the equations presented in *Fried and Idelchick* [1989]. The actual liquid velocity is related to the superficial velocity by

$$V_{Lr} = \frac{U_{Lr}}{\left(1-\varepsilon_r\right)} \tag{13}$$

Since there is no loss of liquid as the flow passes through the aerator, the continuity equation can be applied:

$$U_{Lr} A_r = N_d U_{Ld} A_d = N_{ex} U_{Lex} A_{ex} \tag{14}$$

where N_d is the number of downcomers and N_{ex} is the number of aerator exits.

The energy loss due to turnaround and friction at the top of the aerator is defined by [*Chisti*, 1989]:

$$E_T = \frac{1}{2}\rho_L V_{Lr}^3 K_t A_r \left(1-\varepsilon_r\right) \tag{15}$$

where K_t (-) is the loss coefficient for the top portion of the aerator.

The energy dissipated by the presence of rising bubbles in the downcomer liquid flow can be represented by [*Kemblowski et al.*, 1993]:

$$E_D = \rho_L g H_{GL} U_{Ld} A_d \varepsilon_d \tag{16}$$

where ε_d is the average gas-phase holdup in the downcomer (-).

The energy loss due to isothermal compression of bubbles in the downcomer is:

$$E_C = Q_{Gd} P_{atm} \ln\left(\frac{P_{atm}}{P_{atm} + \rho_{GLd} g H_{GLd}}\right) \tag{17}$$

where Q_{Gd} is the volumetric gas flow rate in the downcomer measured at atmospheric pressure (m^3 s^{-1}), ρ_{GLd} is the average density of the gas-liquid dispersion in the downcomer (kg m^{-3}), and H_{GLd} is the height of the gas-liquid dispersion in the downcomer (m). The average dispersion density may be written as:

$$\rho_{GLd} = \rho_L (1 - \varepsilon_d) + \rho_{Gd} \varepsilon_d \tag{18}$$

and the height of the dispersion is obtained from the following equation:

$$H_{GLd} = \frac{L_D}{(1 - \varepsilon_d)} \tag{19}$$

where ρ_{Gd} is the average density of the gas in the downcomer (kg m^{-3}). The average gas density in the downcomer can be computed from:

$$\rho_{Gd} = \left(\frac{MW}{RT}\right)\left(P_{atm} + \rho_{GLd} g \frac{H_{GLd}}{2}\right) \tag{20}$$

Model Solution Procedure

The aerator design and dimensions were available, and the actual water velocity, riser gas holdup, and water temperature were measured for each applied volumetric air flow rate. In addition, the entrance and exit loss coefficients were approximated using pressure loss equations for internal fluid systems. Therefore, the only unknown with respect to the model was the loss coefficient for the top section of the aerator. The model was fitted to the experimental water velocity by varying K_t. The fit was accomplished using a Newton-Raphson iteration scheme on the energy balance equation.

RESULTS AND DISCUSSION

Figure 2 shows the induced water flow rate data that were collected during each run of the three series of experiments. As illustrated in the graph, the induced water flow rate increases linearly as the applied riser air flow rate is increased. The data from all of the experiments follow the same trend, independent of the amount of air that was applied to the downcomer diffusers. These results suggest that, for this particular aerator design and range of air flow rates, the downcomers do not have a significant impact on the water flow rate that is induced in the riser tube. Therefore, the terms that are a function of downcomer gas holdup in the energy balance equation (Equation 1) were assumed to be zero, resulting in the following:

$$E_I = E_W + E_F + E_E + E_T \tag{21}$$

This new energy balance equation was solved using the Newton-Raphson iteration approach as described previously. For simplicity, only the data collected when the air flow rate was supplied solely to the riser was analyzed with the model.

Using the measured riser gas holdup for each applied air flow rate, the water flow rate model was fitted to the experimental water velocity. The model fit was accomplished by varying the frictional loss coefficient for the top section of the aerator, the only unknown for the device studied. Figure 3 shows the friction coefficients that provided the best fit of the model to the experimental water flow rate data; the results are plotted as a function of induced superficial water velocity in the riser. From Figure 3, it can be seen that the loss coefficient for the top section appears to be higher at the lower superficial water velocities, becoming less affected by the parameter as velocity increases. The results may be explained by small (about 0.13 m high) weir-like structures at the top of the riser tube of LPA1 that were present during testing. The forms were installed to measure induced water flow rate. They were constructed of the same thin fiberglass sheets as used for the riser and downcomers; therefore, they most closely resembled thin-plate weirs. The weirs were located on both sides of the riser between each downcomer, and they spanned the entire width of the top section of the aerator. Water had to flow over the weirs before it entered the downcomers. At low water velocities, flow over the devices approximated true weir flow. At higher velocities, however, the flow did not resemble weir flow because of the lack of a defined nappe. The structures had a greater impact on the water flow rate at the lower velocities; at the higher water velocities, the weirs acted merely as small flow obstructions.

When a function was applied to the results of the model fit, the following correlation, with an R^2 value of 0.90, was obtained:

$$K_t = 4.2U_L^{-1.5} \tag{22}$$

Figure 3 shows how the present correlation compares to that of *Chisti et al*. [1988]. *Chisti et al*. conducted a review of the available literature on external-loop airlift bioreactor performance. The authors assumed that since the top and bottom sections of an external-loop reactor have similar geometries, the loss coefficients are approximately equal. They noted that, despite widely varying reactor dimensions, the value of the loss coefficient for the bottom section is within a range defined by the reactors utilized by *Onken and Weiland* [1980], *Bello* [1981], and *Merchuk and Stein* [1981]. *Chisti et al*. [1988] assumed an average value for the top and bottom loss coefficients of 5.5. Referring to Figure 3, it can be seen that the hypolimnetic aerator correlation predicts results similar to the *Chisti et al*. value at low superficial water velocities. At higher water velocities, the hypolimnetic aerator results deviate from the *Chisti et al*. coefficient value. The difference is probably due to the water flow pattern over the weirs in the top section of the aerator as described previously.

The hypolimnetic aerator correlation shows the trend of K_t decreasing with increasing water velocity in Figure 3. Similarly, the Fanning friction factor in wholly turbulent flow decreases as the Reynolds number increases and approaches an asymptotic value. Referring to Equation 9, it can be seen that Reynolds number is a function of water velocity, pipe diameter, liquid kinematic viscosity, gas holdup. All of these parameters remained relatively constant except the induced water velocity for the hypolimnetic aerator studied. Since Reynolds number is directly proportional to water velocity (Equation 9), the trend exhibited by the present correlation parallels the behavior of the Fanning friction factor with increasing Re [*Akita et al*., 1994]. However, the present correlation does not predict a finite value for K_t. The reason is probably that the Reynolds number range during the experiments was relatively small (4×10^5 to 1×10^6) and extrapolating values of K_t using the correlation beyond this range is subject to error.

The differences between the K_t values predicted by the hypolimnetic and airlift reactor correlations can probably be explained by the fact that the two aeration devices, while similar in some ways, are also significantly different in others. The riser length to diameter ratio (L_R/D_R) for an airlift reactor is generally much greater than the value for the hypolimnetic aerator tested. The riser length to diameter ratios of the experimental units used by and *Onken and Weiland* [1980] and *Merchuk and Stein* [1981] were 85 and 29, respectively. These values compare with a ratio of 9 for the hypolimnetic aerator tested. Also, a hypolimnetic aerator does not have the effect of recirculating water like an external-loop airlift.

SUMMARY AND CONCLUSIONS

Data from a full-lift hypolimnetic aerator have been collected over a wide range of applied air flow rates. Water flow rate, gas-phase holdup, and water temperature were measured. Experiments were conducted with air supplied only to the riser diffuser and also with a portion of the air flow diverted to the downcomer diffusers. Operation of the downcomer diffusers had relatively little impact on the measured water flow rate in the riser. An energy balance model that was developed to predict induced water flow rate in external airlift bioreactors was applied to a hypolimnetic aerator. By varying a single parameter (the frictional loss coefficient of the air-water separator) the model was found to provide results similar to those obtained from a review of the literature on external-loop airlift bioreactors. These results support the use of an energy balance approach to determine water flow rate in hypolimnetic aerators. However, additional research is required to verify the accuracy of the correlation developed and to extend this model to other full- and partial-lift hypolimnetic aerator designs.

ACKNOWLEDGMENTS

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NOTATION

Variables

A	area, m^2.
C_f	Fanning friction factor.
D	diameter, m.
E	energy input/loss rate, J s^{-1}.
g	gravitational acceleration, m s^{-2}.
H	height, m.
K	frictional loss coefficient.
L	length, m.
MW	molecular weight, g mol^{-1}.
N	number of items.
P	pressure, bar.
Q	volumetric flow rate, m^3 s^{-1}.
Re	Reynolds number.
t	time, s.
U	superficial velocity, m s^{-1}.
V	actual velocity, m s^{-1}.

Greek Letters

ε	gas-holdup.
ν	kinematic viscosity, m^2 s^{-1}.
ρ	density, kg m^{-3}.

Subscripts

atm	atmospheric
C	gas compression
D, d	downcomer
E	entrance/exit
ex	exit
en	entrance
F	friction
G	gaseous, gas
GL	gas-liquid dispersion
I	input
L	liquid
R, r	riser
T, t	top
tot	total
W	bubble wakes

REFERENCES

Akita, K., O. Nakanishi, and K. Tsuchiya, Turn-around energy losses in an external-loop airlift reactor, *Chem. Eng. Sci.*, *49*, 2521-2533, 1994.

Ashley, K. I., Hypolimnetic aeration: Practical design and application, *Wat. Res*., *19*, 735-740, 1985.

Ashley, K. I. and K. J. Hall, Factors influencing oxygen transfer in hypolimnetic aeration systems, *Verh. Int. Verein. Limnol*., *24*, 179-183, 1990.

Ashley, K. I., S. Hay, and G. H. Scholten, Hypolimnetic aeration: Field test of the empirical sizing method, *Wat. Res*., *2*, 223-227, 1987.

Bello, R. A., A characterization study of airlift contactors for applications to fermentations, Ph.D. thesis, Univ. of Waterloo, Canada, 1981.

Burris, V. L., J. C. Little, and D. McGinnis, Predicting oxygen transfer in hypolimnetic aerators, submitted.

Calvo, E. G., A fluid dynamic model for airlift loop reactors, *Chem. Eng. Sci.*, *44*, 321-323, 1989.

Calvo, E. G. and P. Leton, A fluid dynamic model for bubble columns and airlift reactors, *Chem. Eng. Sci.*, *46*, 2947-2951, 1991.

Chakravarty, M., H. D. Singh, J. N. Baruah, and M. S. Iyengar, Liquid velocity in a gas-lift column, *Indian Chemical Engineer*, *16*, 17-22, 1974.

Chisti, M. Y., *Airlift Bioreactors*, 345 pp., Elsevier Science Publishing, New York, NY, 1989.

Chisti, M. Y., B. Halard, and M. Moo-Young, Liquid circulation in airlift reactors, *Chem Eng. Sci.*, *44*, 321-323, 1988.

Cole, G. A., *Textbook of Limnology*, 4th ed., 412 pp., Waveland Press, Inc., Prospect Heights, IL, 1994.

Cooke, G. D. and R. E. Carlson, *Reservoir Management for Water Quality and THM Precursor Control*, 387 pp., AWWA Research Foundation, Denver, CO, 1989.

Del Vecchio, D. C. and J. C. Little, Predicting water flow rate in hypolimnetic aerators, poster presented at International Association on Water Quality, Biennial Conference, Singapore, July 1995.

Fast, A. W., V. A. Dorr, and R. J. Rosen, A submerged hypolimnion aerator, *Wat. Resour. Res.*, *11*, 287-293, 1975.

Fried, E. and I. E. Idelchick, *Flow Resistance: A Design Guide for Engineers*, 400 pp., Hemisphere Publishing, New York, NY, 1989.

Kemblowski, Z., J. Przywarski, and A. Diab, An average gas hold-up and liquid circulation velocity in airlift reactors with external loop, *Chem. Eng. Sci*., *48*, 4023-4035, 1993.

Kortmann, R. W., G. W. Knoecklein, C. H. and Bonnell, Aeration of stratified lakes: Theory and practice, *Lake and Reserv. Manage.*, *8*, 99-120, 1994.

Lee, C. H., L. A. Glasgow, L. E. Erickson, and S. A. Patel, Liquid-circulation in airlift fermentors, in *Biotechnology Processes: Scale-Up and Mixing*, edited by C. S. Ho and J. Y. Oldshue, pp. 50-59, American Institute of Chemical Engineers, New Jersey, 1986.

Lorenzen, M. W. and A. W. Fast, *A Guide to Aeration/Circulation Techniques for Lake Management*, Ecol. Res. Ser. EPA 600/3-77-004, 126 pp., USEPA, 1977.

Merchuk, J. C. and I. Berzin, Distribution of energy dissipation in airlift reactors, *Chem. Eng. Sci.*, *50*, 2225-2233, 1995.

Merchuk, J. C. and Y. Stein, Local hold-up and liquid velocity in airlift reactors, *AICHE Journal*, *27*, 377-388, 1981.

Onken, U. and P. Weiland, Hydrodynamics and mass transfer in an airlift loop fermentor, *Eur. J. Appl. Microbiol. Biotechnol.*, *10*, 31-40, 1980.

Taggart, C. T. and D. J. McQueen, A model for the design of hypolimnetic aerators, *Wat. Res.*, *16*, 949-956, 1982.

Turner, J. C., On bubble flow in liquids and fluidised beds, *Chem. Eng. Sci.*, *21*, 971, 1966.

Table 1. LPA1 Dimensions.

Parameter	Value (m)
riser length	10
downcomer length	5
riser diameter	1.1
downcomer diameter	1.1

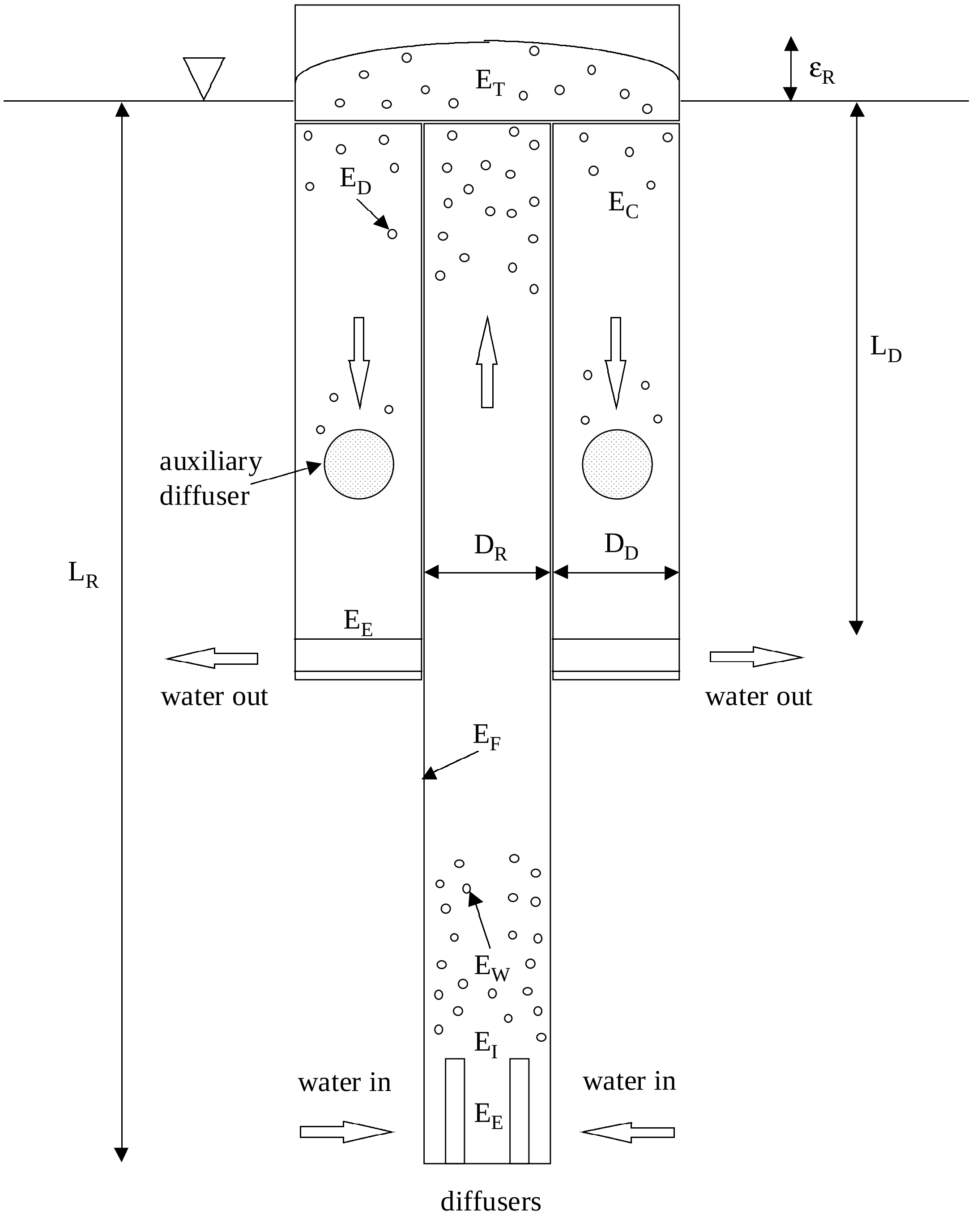

Figure 1. Schematic representation of hypolimnetic aerator LPA1.

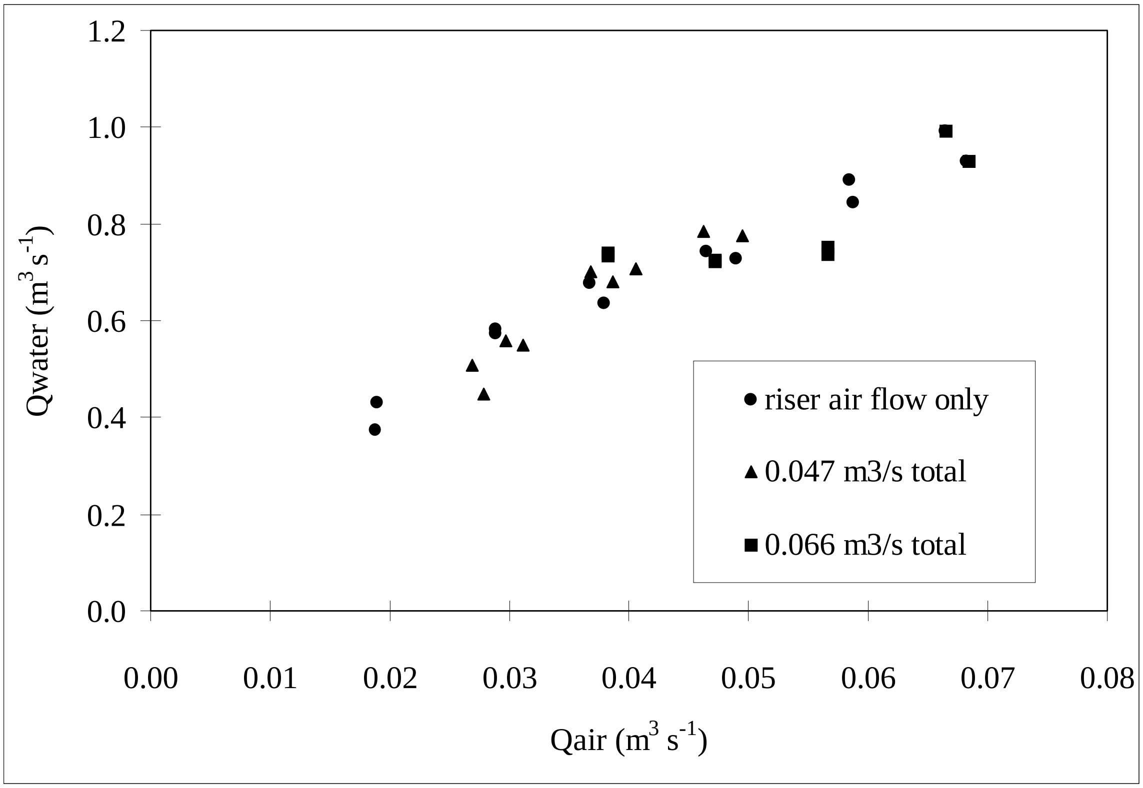

Figure 2. Effect of riser applied air flow rate on induced water flow rate.

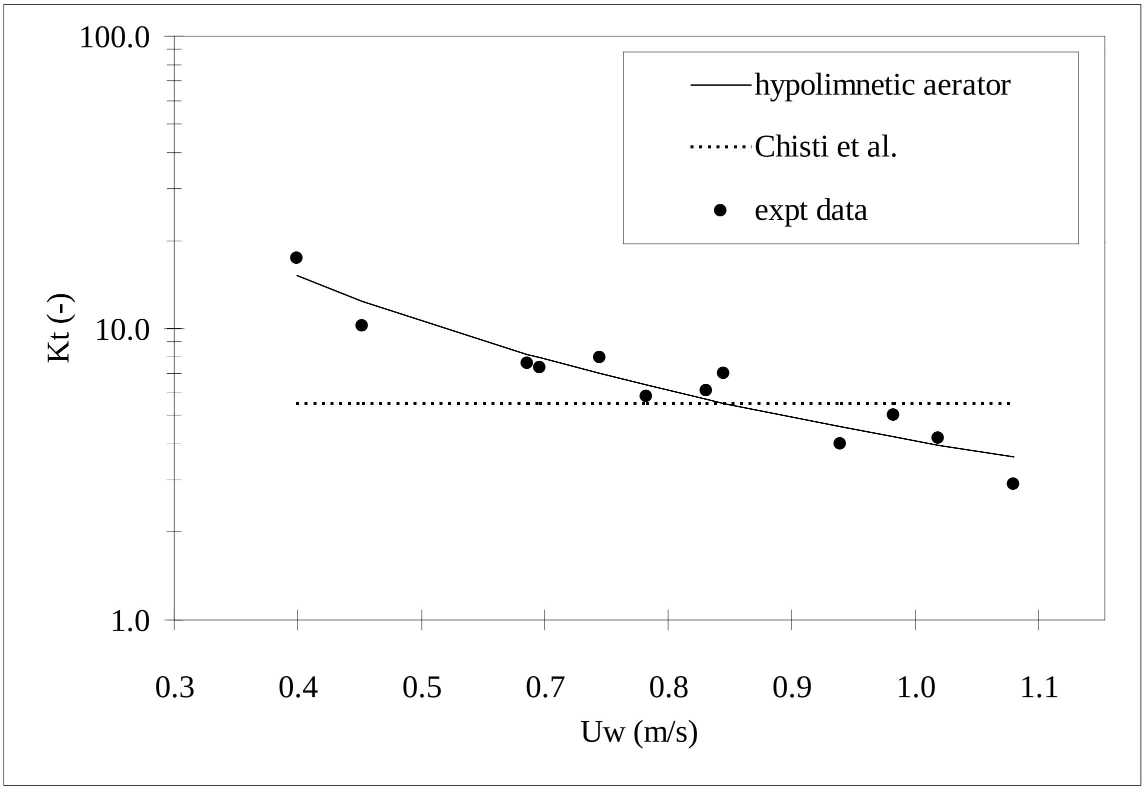

Figure 3. Comparison of present hypolimnetic aerator and Chisti *et al*. (1988) correlations.

VITA

Vickie Lien Burris was born on January 2, 1973 in Lynchburg, Virginia. She attended West Virginia University in Morgantown, West Virginia from 1991 to 1995 and graduated with a Bachelor of Science Degree in Mechanical Engineering, Magna Cum Laude. Subsequently, she attended Virginia Tech in Blacksburg, Virginia to pursue a Master of Science Degree in Environmental Engineering. Before defending, Vickie began working as a Staff Engineer for Black and Veatch Corporation in the Greenville, South Carolina office.