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FACTORS INFLUENCING OXYGEN TRANSFER IN FINE PORE DIFFUSED AERATION

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Abstract—A bench-scale experiment was conducted in a 70 l. tank of tap water to examine the effect of four design variables on oxygen transfer in a fine pore diffused aeration system. The experiment used non-steady state gas transfer methodology to examine the effect of air flow rate, air flow rate per diffuser, orifice diameter and reduced tank surface area on the overall oxygen transfer coefficient (K_La_{20}, h^{-1}); standard oxygen transfer rate (OT$_s$, g O$_2$ h^{-1}); energy efficiency (E_p, g O$_2$ kWh^{-1}) and oxygen transfer efficiency (E_o, %). The experiments demonstrated that K_La_{20} and OT$_s$ increased with air flow rate (9.4–18.8 l min^{-1}) in the 40 and 140 μ diameter orifice range; however, E_p and E_0 were not affected. Reducing the air flow rate per fine pore diffuser (40 and 140 μ diameter pore size) significantly increased K_La_{20}, OT$_s$, E_p and E_o. A decrease in orifice diameter from 140 to 40 μ had no effect on K_La_{20}, OT$_s$, E_p and E_0. A reduction in tank surface area had a marginally significant inverse effect on K_La_{20} and OT$_s$, and no effect on E_p and E_o. The mean bubble size produced by the 40 and 140 μ diffusers was 4.0 and 4.2 mm, respectively. There was no consistent effect of air flow rate on bubble size within the range of air flow rates used in this experiment. In clean water aeration applications, the optimum system efficiency will be obtained using the largest number of fine pore diffusers operated at low air flow rates per diffuser. In wastewater treatment plants, higher air flow rates per diffuser should be used to prevent diffuser biofouling and keep biological solids in suspension. Wastewater systems are purposely operated at less than optimum transfer efficiencies in exchange for reduced diffuser maintenance and improved mixing. In either situation, changes in tank surface area and diffuser pore size (provided that pore diameter remains between 40 and 140 μ) are unlikely to have any significant effect on aeration system efficiency.

Key words—oxygen transfer efficiency, non-steady state reaeration, fine pore aeration systems, diffuser design

NOMENCLATURE

$a = \frac{1}{2}$ long axis of an air bubble (mm)
$b = \frac{1}{2}$ short axis of an air bubble (mm)
C_1 = dissolved oxygen concentration at t_1 (mg l^{-1})
C_2 = dissolved oxygen concentration at t_2 (mg l^{-1})
C_s = dissolved oxygen saturation concentration at ambient temperature and barometric pressure (mg l^{-1})
C_{s760} = dissolved oxygen saturation concentration at 760 mm Hg (mg l^{-1})
DO$_{20}$ = dissolved oxygen saturation concentration at 760 mm Hg and 20°C (mg l^{-1})
d = equivalent diameter of an air bubble (mm)
E_o = oxygen transfer efficiency (%)
E_p = energy efficiency (g O$_2$ kWh^{-1})
K_La_T = overall dissolved oxygen transfer coefficient at the temperature of the test water (h^{-1})
K_La_{20} = overall dissolved oxygen transfer coefficient at 20°C (h^{-1})
OT$_s$ = standard dissolved oxygen transfer rate (g O$_2$ h^{-1})
P_b = barometric pressure (mm Hg)
Q_a = air flow rate (l min^{-1})
t_1 = time when dissolved oxygen concentration equals 10% of C_s (h)
t_2 = time when dissolved oxygen concentration equals 60% of C_s (h)

INTRODUCTION

A renewed emphasis on energy efficient aeration has rekindled considerable interest in fine pore (fine bubble) aeration systems in North America (EPA, 1989). Aeration systems are among the most energy intensive operations in wastewater treatment systems, consuming between 50–90% of the total energy costs of typical municipal installations (Wesner *et al.*, 1977). A 1982 survey of North American municipal and industrial wastewater treatment plants indicates that approx. 1.3 million kW of aeration equipment is in place, with a capital value of $0.6–0.8 billion, and annual operating costs of $0.6 billion in 1982 (Barnhart, 1985). However, fine pore aeration systems have historically been associated with clogging and maintenance problems (EPA, 1985), and considerable research is currently directed at developing high efficiency systems with low maintenance requirements (WPCF, 1988).

A considerably smaller, but environmentally significant amount of aeration equipment is also being used to increase oxygen concentrations in the hypolimnion of eutrophic lakes and ponds (Lorenzen and Fast, 1977; Pastorok *et al.*, 1981). Originally developed in postwar Switzerland and rediscovered in Germany (Bernhardt, 1967), hypolimnetic aeration is now used throughout Western Europe and North America (McQueen and Lean, 1986). Although the basic designs of hypolimnetic aeration systems have been well documented (Fast and Lorenzen, 1976; Taggart and McQueen, 1982; Ashley, 1985), minimal research effort has been directed at improving diffuser design and increasing oxygen transfer efficiency (Ashley and Hall, 1990).

The purpose of this research was to examine four basic factors capable of influencing oxygen transfer in fine pore diffused aeration systems: orifice diameter, air flow rate, air flow rate per diffuser and surface area of the aeration tank, and determine which of these factors would be important in developing higher efficiency systems for use in lake restoration and wastewater treatment. Although the effect of bubble size on aeration efficiency is a well known phenomenon that has been widely documented (Morgan and Bewtra, 1960; Bewtra and Nicholas, 1964; Mavinic and Bewtra, 1974, 1976), the effect of different orifice sizes, air flow rates and tank surface area on bubble size, and subsequently on the overall oxygen transfer coefficient ($K_L a$), standard oxygen transfer rate (OT_s) energy efficiency (E_p) and oxygen transfer efficiency (E_o), under similar experimental conditions, has been less widely researched. This is particularly evident in the fine pore aeration literature, where the term "fine bubble diffused aeration" is not well defined and the distinction between fine and coarse bubbles is not clearly stated (EPA, 1985, 1989). For these experiments, fine pore diffusers are defined as those diffusers, which when new, produce bubbles of 2–5 mm diameter in clean water (EPA, 1989).

MATERIALS AND METHODS

Tank size, geometry and surface conditions

The experiments were conducted in a clear Plexiglas cylinder, with an inside diameter of 0.29 m and a height of 1.06 m, and filled with 70 l. of municipal tap water (Fig. 1). The diffusers were suspended in the center of the tank and hung 0.8 m below the water surface. A floating surface cover of 2.5 cm polystyrene was fabricated for the tank. The cover was cut with sufficient clearance (1 cm) to allow rapid installation and removal, but cover as much of the water surface as possible. Two surface conditions were examined; cover and no cover. Dye was added on several occasions to the tank to examine circulation patterns and determine if any stagnant zones existed. The water in the 70 l. cylinder was completely mixed within an average of 17 s ($n = 16$), thus confirming initial observations that complete mixing was quickly achieved.

Air supply and flow measurement

Air was supplied by a 0.12 kW Gast rotary vane vacuum-pressure pump, rated at 36.8 l min^{-1} @ 0 kg cm^{-2}. The compressor was oil lubricated and fitted with a 10 μ oil-removing element to prevent oil mist from contaminating the delivered air. Air flow rate was measured by a Brooks flow meter, fitted with a pressure gauge (0–2.1 kg cm^{-2}) at both inlet and outlet nipples, and calibrated to read 4.7–56.6 l min^{-1} at 1.0 kg cm^{-2} and 21°C. Air pressure in the discharge line remained constant during each treatment test. The two air flow rates selected for the experiments were 9.4 and 18.8 l min^{-1}. The air flow valve was adjusted occasionally to maintain constant delivery of 9.4 or 18.8 l min^{-1} during each treatment test.

Reaeration procedure

The deoxygenation–oxygenation procedure used was the non-steady state reaeration test (APHA, 1980). The test water was deoxygenated with 0.1 mg l^{-1} of cobalt chloride and 10.0 mg l^{-1} of sodium sulfite for each 1.0 mg l^{-1} of dissolved oxygen present in the water (Boyd, 1986). The highest starting oxygen concentration was 10 mg l^{-1}; therefore a maximum concentration of 0.25 mg l^{-1} of cobalt ion was used. Since a polarographic probe was used for determining oxygen concentration, cobalt interference was not a problem. The cobalt chloride was added first and thoroughly mixed into the test water. Sodium sulfite was then mixed into a slurry in a 1 liter flask, added to the tank water and thoroughly mixed by a large paddle. Theoretically

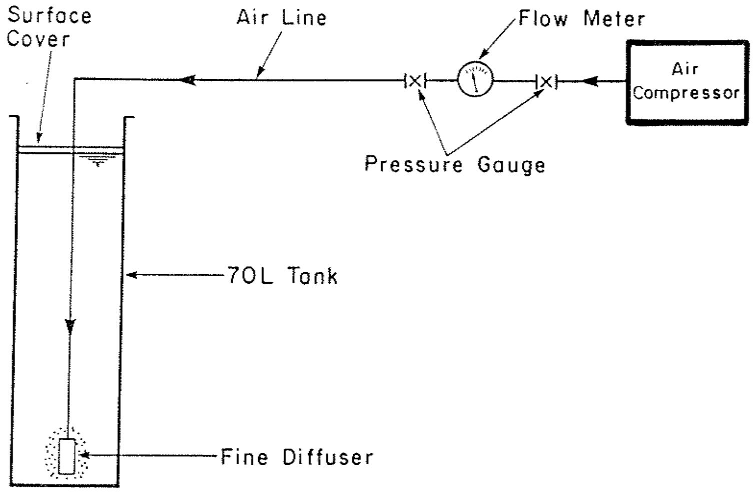

Fig. 1. Schematic diagram of the experimental aeration system.

only 7.9 mg l^{-1} is required for each mg l^{-1} of dissolved oxygen; however, due to partial oxidation during mixing it is necessary to add up to 1.5 times the stoichiometric amount (Beak, 1977). A Winkler calibrated oxygen–temperature meter (YSI 54 ARC) was used to measure dissolved oxygen and water temperature in the test tank. The oxygen–temperature probe was suspended in the center of the tank approx. 5 cm below the suspension point for the diffuser being tested. The meter confirmed the tank water was rapidly deoxygenated as the dissolved oxygen concentration usually declined to 0.2–0.3 mg l^{-1} within 30 s. The air compressor was then turned on, and oxygen concentrations recorded every 30 s until the dissolved oxygen reached 6–7 mg l^{-1}. A maximum of five test runs were conducted on each batch of water to minimize interference from sodium sulfite accumulation (Beak, 1977).

Diffuser type and orifice size

Two sizes of fine pore air diffusers were used in these experiments: 140 μ maximum pore size (Model AS-8) and 40 μ maximum pore size (Model AS-8-0). The diffusers were made of fused silica glass and were obtained from Aquatic Eco-Systems Inc. (Apopka, Fla, U.S.A.). Scanning electron micrographs (SEMs) of the 40 and 140 μ silica diffusers revealed a distinct difference in pore size and grain size between the 40 μ and the 140 μ sizes (Fig. 2). The external dimensions of both diffuser sizes were identical, 7.6 cm L × 3.8 cm W × 3.8 cm D. Each diffuser weighed 0.18 kg and was fitted with a 0.64 cm hose nipple.

Experimental design

The treatments examined in this experiment were: the effect of orifice pore diameter (40 or 140 μ); the effect of surface cover (present or absent); the effect of air flow rate (9.4 or 18.8 l min^{-1}); and the effect of diffuser number (1 or 2). This resulted in 16 combinations of orifice size, surface cover, air flow rate and diffuser number (Table 1). The experiments were carried out in a randomized complete block design. Each of the treatments was randomly assigned a number from 1 to 16. Each set of 16 treatments was completed in 1 day, then repeated the next day with a new set of random numbers. The purpose of this design was (a) to remove random error that may occur during any given treatment day, and (b) to block the treatments over time to remove any systematic error introduced over time. Each treatment was replicated 5 times, always on a different day.

Table 1. Experimental treatments for fine pore diffusers

No.	Flow rate (l min^{-1})	Orifice size (μ)	Cover	Diffusers
1	9.4	40	no	1
2	9.4	40	yes	1
3	9.4	40	no	2
4	9.4	40	yes	2
5	18.8	40	no	1
6	18.8	40	yes	1
7	18.8	40	no	2
8	18.8	40	yes	2
9	9.4	140	no	1
10	9.4	140	yes	1
11	9.4	140	no	2
12	9.4	140	yes	2
13	18.8	140	no	1
14	18.8	140	yes	1
15	18.8	140	no	2
16	18.8	140	yes	2

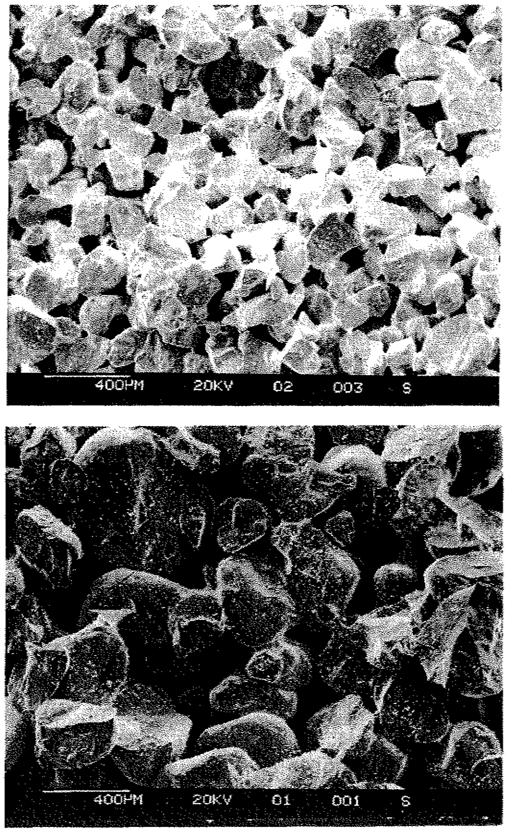

Fig. 2. Scanning electron micrographs of the 40 and 140 μ pore diameter diffusers.

Parameter calculation

$K_{\rm L}a_{\rm T}$ was calculated according to (APHA, 1980):

$$K_{\rm L}a{\rm T} = \frac{\ln[(C_s - C_1)/(C_s - C_2)]}{t_2 - t_1}$$

where

ln = natural logarithm
$K_{\rm L}a_{\rm T}$ = overall oxygen transfer coefficient at the temperature of the test water (h^{-1})
C_1 = DO (mg l^{-1}) at t_1
C_2 = DO (mg l^{-1}) at t_2
C_s = DO saturation concentration during test (mg l^{-1})
t_1 = time at point 1 on the semi-logarithmic plot (h)
t_2 = time at point 2 on the semi-logarithmic plot (h).

t_1 and t_2 are usually chosen as the times at which the measured oxygen concentration is 20% (t_1) and 80% (t_2) of the saturation values for the test water, corrected for temperature and barometric pressure. This study used 10 and 60% saturation values for t_1 and t_2, since a sufficient number of data points (i.e. 11) was collected between 10 and 60% without having to run each test to 80% saturation.

The dissolved oxygen saturation on test days was adjusted to current barometric pressure according to:

$$C_s = C_{s760} \times P_b/760$$

where

C_s = DO saturation concentration during test (mg l^{-1})
C_{s760} = DO saturation at 760 mm Hg total pressure (mg l^{-1})
P_b = barometric pressure during test (mm Hg).

Since the tests were conducted below 1000 m and 25°C, there was no correction in oxygen saturation for the vapor pressure of water (APHA, 1980). The saturation pressure was not corrected for mid-depth oxygen partial pressure as the test tank was only 1 m deep. $K_{\rm L}a_{\rm T}$ was corrected to $K_{\rm L}a_{20}$ according to:

$$K_{\rm L}a_{20} = K_{\rm L}a_{\rm T}/\theta^{T-20}$$

where

$\theta = 1.024$ and T = water temperature in °C (Boyd, 1986).

OT_s was calculated as follows (Boyd, 1986):

$$OT_s = K_L a_{20} DO_{20} V$$

where

OT_s = standard oxygen transfer rate (g O_2 h^{-1})
DO_{20} = dissolved oxygen concentration (mg l^{-1}) at saturation for 20°C; and standard pressure (760 mm Hg)
V = volume of water in the tank (m^3).

E_p was calculated as follows (APHA, 1980):

$$E_p = OT_s/P$$

where

E_p = energy efficiency (g O_2 kWh^{-1})
P = power input (nameplate horsepower) (kW).

During the experiments, the desired air flow was obtained by wasting the excess compressor output. As a result, it was not possible to measure actual power consumption. The power input was therefore adjusted to reflect the fraction of the compressor's energy consumption required to deliver a given air flow rate. The compressor was rated at 36.8 l min^{-1}, with a nameplate horsepower of 0.1243 kW. The power input then used for these tests was:

$$9.4\,l\,min^{-1} = 9.4\,l\,min^{-1}/36.\,l\,min^{-1} \times 0.1243\,kW = 0.0317\,kW;$$

$$18.8\,l\,min^{-1} = 18.8\,l\,min^{-1}/36.8\,l\,min \times 0.1243\,kW = 0.0635\,kW.$$

A minimum power loss was expected in the short length of air delivery tubing (i.e. 1 m), hence the relative differences between treatments was considered the important result, even though wire horsepower was not measured.

E_o (oxygen transfer efficiency, %) was calculated as OT_s/weight of oxygen supplied per hour at standard conditions × 100.

Bubble size and photography

Bubble size was determined by photographing rising bubbles in the 70 l. clear Plexiglas column (0.29 m dia × 1.06 m) with a Pentax ME camera and flash attachment, synchronized at 1/100 s. A meter stick graduated with 1 mm increments was suspended in the cylinder and bubbles were photographed against the meter stick for scale. The slide photographs were then examined with a Baush and Lomb dissecting microscope at 60–70 × to determine bubble size. Approximately 20 bubbles were measured for each orifice size. Bubbles were photographed at air flow rates of 9.4 and 18.8 l min^{-1}. Since most of the bubbles were oblate spheroid in shape, the following formula was used to calculate volume:

$$V = 4/3\,\pi a^2 b$$

where

V = volume in mm^3
a = 1/2 long axis of the bubble (mm)
b = 1/2 short axis of the bubble (mm).

Equivalent bubble diameter was calculated according to:

$$d = (V6/\pi)^{1/3}$$

where

d = equivalent diameter (mm)
V = bubble volume in mm^3.

Mean bubble size and coefficient of variation (standard deviation expressed as a percentage of the mean) was also calculated for each orifice size and air flow rate.

Statistical analysis

The statistical procedure used to analyze the experimental data was an analysis of variance program (MANOVA) in the SSPS statistical package. The level of significance was set at $\alpha = 0.01$ for each statistical test. The arc sine square root transform was used on the E_o ANOVAs, to reduce the skewness of the percentage values (Larkin, 1975). In situations where the null hypothesis was rejected, an *a posteriori* comparison among means test was conducted using Scheffe's test and the level of significance was also set at $\alpha = 0.01$.

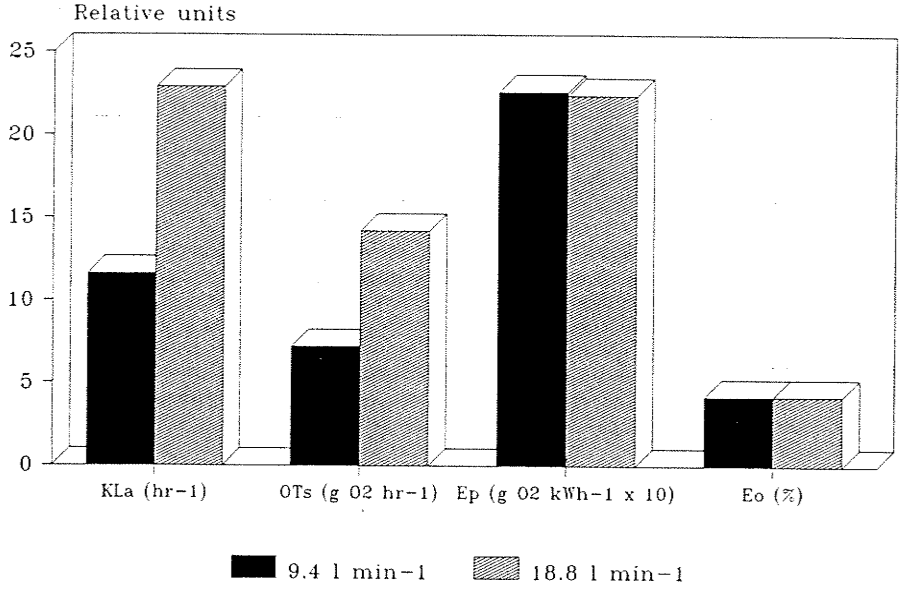

Fig. 3. Effect of air flow rate (9.4 or 18.8 l min^{-1}) on overall oxygen transfer coefficient ($K_L a_{20}$, h^{-1}); standard oxygen transfer rate (OT_s, g O_2 h^{-1}); energy efficiency (E_p, g O_2 kWh^{-1}) and oxygen transfer efficiency (E_o, %) using combined data from the orifice diameter, diffuser number and surface cover treatments.

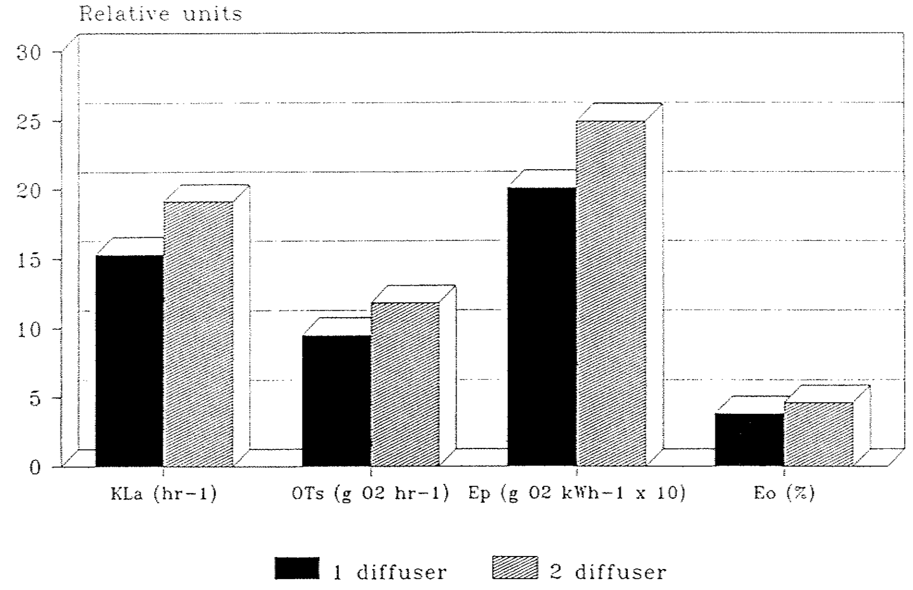

Fig. 4. Effect of diffuser number (1 or 2) on overall oxygen transfer coefficient ($K_L a_{20}$, h^{-1}); standard oxygen transfer rate (OT_s g O_2 h^{-1}); energy efficiency (E_p, g O_2 kWh^{-1}) and oxygen transfer efficiency (E_o, %) using combined data from the orifice diameter, air flow rate and surface cover treatments.

RESULTS

Air flow rate

Changes in the air flow rate supplied to the diffusers produced the largest changes in $K_L a_{20}$ and OT_s. Doubling the air flow from low flow (9.4 l min^{-1}) to medium flow (18.8 l min^{-1}) produced a 90% increase in $K_L a_{20}$ and OT_s. Air flow rate had no effect on E_o and E_p (Fig. 3).

Number of diffusers

The number of diffusers that were used (1 or 2) produced the next most significant result (Fig. 4). Increasing the number of diffusers from 1 to 2 at a constant air flow rate produced a 25% increase in $K_L a_{20}$ and OT_s. The number of diffusers used (1 or 2) also produced the only significant effect on E_o and E_p that was observed during the entire experimental program (Fig. 4).

Orifice and bubble size

There was no significant effect of orifice size (40 and 140 μ) on $K_L a_{20}$, OT_s, E_o and E_p. The cell means for $K_L a_{20}$, OT_s, E_o and E_p (all other treatments combined) are shown in Fig. 5. There was a minor

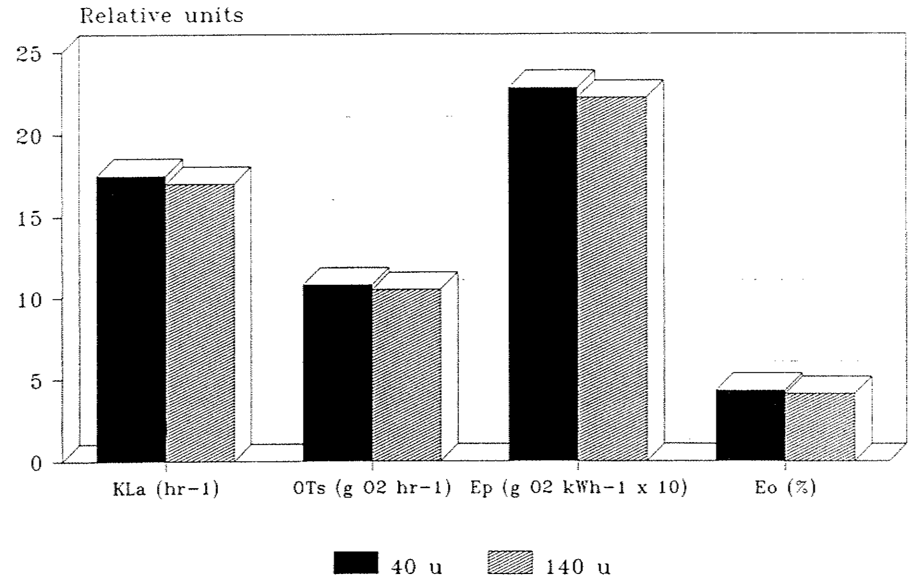

Fig. 5. Effect of orifice diameter (40 or 140 μ) on overall oxygen transfer coefficient ($K_L a_{20}$, h^{-1}); standard oxygen transfer rate (OT_s, g O_2 h^{-1}); energy efficiency (E_p, g O_2 kWh^{-1}) and oxygen transfer efficiency (E_o, %) using combined data from the air flow rate, diffuser number and surface cover treatments.

difference between the bubble sizes generated by the $40\,\mu$ (3.8–4.2 mm) and $140\,\mu$ diffusers (3.8–4.5 mm) (Fig. 6), and no consistent effect of air flow rate on bubble size for a given orifice diameter. Statistical tests (ANOVA) performed on the bubble size data indicated there was no significant effect of orifice size or air flow rate on equivalent bubble diameter.

Surface cover

A significant result ($P = 0.008$) was observed for $K_L a$ and OT_s in the cover–no cover treatment ($F = 7$, $K_L a_{20}$ and OT_s), with each value increasing slightly in value in the presence of the surface cover. There was no significant effect of the surface cover treatment on E_o and E_p.

Interaction effect

A significant air flow rate x number of diffusers interaction effect ($P = 0.001$) was observed for $K_L a_{20}$ and OT_s ($F = 13$, $K_L a_{20}$ and OT_s). The data indicate the difference between the cell means for $K_L a_{20}$ or OT_s, at one or two diffusers, increases with air flow rate. The combined effect of two diffusers and the medium air flow rate ($18.8\,\mathrm{l\,min^{-1}}$) inflated $K_L a$ and OT_s above what would be normally expected for a given air flow rate and number of diffusers.

DISCUSSION

Air flow rate

The rate of air flow (9.4 or $18.8\,\mathrm{l\,min^{-1}}$) to the diffusers produced a significant response in the overall oxygen transfer coefficient ($K_L a_{20}$, $\mathrm{h^{-1}}$) and standard oxygen transfer rate (OT_s, $\mathrm{g\ O_2\,h^{-1}}$). The principal mechanisms responsible for this result are increased turbulence (Schmit *et al.*, 1978) and interfacial area (Mavinic and Bewtra, 1974) in the experimental column. However, doubling the air flow rate had no effect on energy efficiency (E_p, $\mathrm{g\ O_2\ kWh^{-1}}$) and oxygen transfer efficiency (E_o, %). This differential response is a result of the small bubbles produced by the fine pore diffusers. As shown in Fig. 6, the mean bubble diameters produced by the 40 and $140\,\mu$ diffusers were 3.8–4.2 and 3.8–4.5 mm, respectively. A decline in transfer efficiency with increasing air flow is the usual response with fine pore diffusers. Morgan and Bewtra (1960), Bewtra and Nicholas (1964) and Ellis and Stanbury (1980) observed decreased E_o with increasing Q_a. This response is likely due to a combined effect of decreased oxygen absorption during bubble formation and interference from adjacent rising bubbles (Ellis and Stanbury, 1980). Increased air flow rates create a greater concentration of bubbles with relatively restricted lateral diffusion; this causes the so called "chimney effect", where oxygen transfer does not increase in proportion to Q_a, due to the resulting increase in resistance to lateral diffusion (Ippen and Carver, 1954).

Number of diffusers

Doubling the number of diffusers resulted in a 25% increase in $K_L a$ and OT_s and a 21–24% gain in E_o and E_p. This response is well documented in the civil

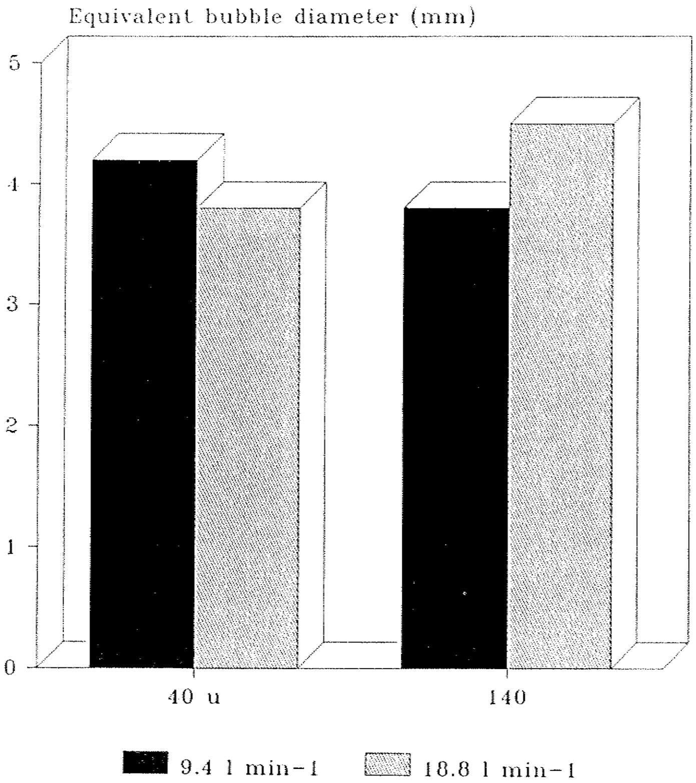

Fig. 6. Equivalent bubble diameter in relation to orifice size and air flow rate.

engineering literature (e.g. Huibregtse *et al.*, 1983; Doyle *et al.*, 1983; Morgan and Bewtra, 1960; Leary *et al.*, 1969; Ippen and Carver, 1954). Bewtra and Nicholas (1964) concluded that this response was a combined effect of (1) an increase in oxygen absorption during bubble formation, (2) a change in bubble rise velocity with Q_a, (3) a change in bubble diameter and K_L with Q_a and (4) a decrease in air–bubble entrainment with reduced Q_a. There was no consistent effect of air flow rate on bubble size (Fig. 6); therefore changes in bubble rise velocity, bubble diameter and K_L with Q_a may not be as important in this particular experimental system. It should be noted, however, that a maximum of 20 bubbles were measured for each combination of air flow rate and orifice size. Given the thousands of bubbles present in the aeration column at any time, it is possible that the sample size estimation procedure was unable to detect an increase in bubble size with increasing air flow.

The authors believe that the explanation for $K_L a$, OT_s, E_p and E_o increasing with reduced air flow rate per diffuser is a function of increased gas transfer during bubble formation and reduced air–bubble entrainment. A high rate of gas transfer occurs at the bubble formation stage, due to the continued expansion of the fresh gas–liquid interface (Mancy and Okun, 1960). A reduction in gas flow rate per diffuser results in the production of smaller bubbles, reduces the likelihood of coalescence and allows better lateral diffusion through more uniform bubble dispersion (Ippen and Carver, 1954). The combined effect of these factors results in more interfacial area and contact time, which in turn, increases $K_L a$, OT_s, E_p and E_0.

Orifice and bubble size

The pore size of the silica glass diffuser orifices examined in these experiments (40 and 140 μ) had no effect on $K_L a$, OT_s, E_p and E_o. Visual observations of bubble formation with the 40 and 140 μ diffusers indicated bubbles emerged in chain formation, so the gas flow rate per orifice was above the critical rate for single bubble formation (Bowers, 1955). As a result, bubble size was dependent on gas flow rate and the resulting bubble sizes were similar for both the 40 and 140 μ diffusers. The bubble size analysis supports this conclusion, as the mean bubble size generated by the 40 and 140 μ diameter orifice diffusers were not significantly different (Fig. 6). Markofsky (1979) observed a similar effect with 90 and 180 μ porous media diffusers and concluded there was no significant difference in transfer efficiency between the two sizes at the experimental gas flow rates.

Surface cover

The presence of a floating surface cover exerted a minor inverse effect on $K_L a$ and OT_s, and no effect on E_0 and E_p. In theory, lower $K_L a$, OT_s, E_p and E_o should result with a floating surface cover, as this would tend to decrease the transfer of atmospheric oxygen at the turbulent air–water interface generated by the bursting bubbles. Nielson (1974) observed reduced rates of oxygenation in similar laboratory experiments, using floating styrene foam. However, the surface area to volume ratio of Nielson's (1974) tank ($A/V = 1$–$10\ \mathrm{m}^{-1}$) was larger than the ratio in the 70 l. column ($A/V = 0.94\ \mathrm{m}^{-1}$). As the surface area to volume ratio increases, the effect of reducing the surface component of gas transfer should become more apparent.

One explanation may be the longer path length that bubbles must take to reach the surface due to the trapping effect of a surface cover. Markofsky (1979) noticed a slight increase in E_o when a surface cover was present and attributed this to increased bubble contact time. Regardless, the marginal results observed in these experiments confirm previous laboratory (Ashley *et al.*, 1990) and field (Ashley and Hall, 1990) experiments, and suggest that surface area modifications are unlikely to exert any significant influence on oxygen transfer in standard sized diffused aeration basins or hypolimnetic aeration systems.

Interaction

The significant air flow rate × number of diffusers interaction effect was a result of small bubbles becoming trapped in the vortices near the top of the 70 l. cylinder, when higher air flow rates were used. This resulted in longer contact times and inflated the $K_L a$ and OT_s above what would be normally expected for a given air flow rate and number of diffusers. Although the effect is significant, its F value (approx. 13) is small in relation to the main effects of the experiments and it does not alter the principle conclusions of the experiment. E_o and E_p did not show a significant interaction effect as the extra power required to deliver the higher air flow rate is included in their parameter calculation.

Applications

In order to achieve an interdisciplinary goal of improving the efficiencies of wastewater treatment plants and hypolimnetic aeration systems, the preceding general conclusions must be modified to suit site-specific applications. For example, in wastewater treatment plants, low air flow rates per diffuser may lead to diffuser biofouling (Boyle and Redmon, 1983) and insufficient mixing to suspend biological solids (Rooney and Huibregtse, 1980). These systems may be purposely operated at less than optimum transfer efficiencies, in exchange for reduced diffuser maintenance and improved mixing.

In contrast, hypolimnetic aeration systems generally operate in relatively clean environments, hence the general conclusion of many fine pore diffusers operated at low air flow rates per diffuser is valid. The principal constraint in hypolimnetic aeration systems is the small area available to mount diffusers.

Innovative diffuser designs are therefore required to fit the maximum number of diffusers within the confines of the aeration system. An unknown factor in aquatic systems is the aging of fine pore diffusers. Although lake environments are relatively pristine in comparison to wastewater, significant changes in water chemistry do occur in the hypolimnion of eutrophic lakes. For example, in hard water lakes, whole lake precipitation reactions could deposit significant amounts of calcite on the diffuser surface, thus changing bubble dynamics and influencing transfer efficiency. This aspect of diffuser design requires further study under actual field conditions.

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REFERENCES

APHA (1980) *Standard Methods for Examination of Water and Wastewater*, 15th edition. American Public Health Association, Washington, D.C.

Ashley K. I. (1985) Hypolimnetic aeration: practical design and application. *Wat. Res.* **19,** 735–740.

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

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

Barnhart E. L. (1985) An overview of oxygen transfer systems. Proceedings of seminar workshop on aeration system design testing, operation and control. U.S. Environmental Protection Agency Report, EPA-600 9-85-005.

Beak Consultants Ltd (1977) CPAR Project Report 542-1. State of the art review: aeration. Beak Consultants Ltd Report, Montreal, Quebec.

Bernhardt H. (1967) Aeration of Wahnbach Reservoir without changing the temperature profile. *J. Am. Wat. Wks Ass.* **59,** 943–964.

Bewtra J. K. and Nicholas W. R. (1964) Oxygenation from diffused air in aeration tanks. *J. Wat. Pollut. Control Fed.* **36,** 1195–1224.

Bowers R. H. (1955) The mechanics of bubble formation. *J. appl. Chem.* **5,** 542–548.

Boyd C. E. (1986) A method for testing aerators for fish tanks. *Prog. Fish Cult.* **48,** 68–70.

Boyle W. C. and Redmon D. T. (1983) Biological fouling of fine bubble diffusers; state-of-art. *J. envir. Engng* **109,** 991–1005.

Doyle M. L., Boyle W. C., Rooney T. and Huibregtse G. L. (1983) Pilot plant determination of oxygen transfer in fine bubble aeration. *J. Wat. Pollut. Control Fed.* **55,** 1435–1440.

Ellis S. E. and Stanbury R. (1980) The scale-up of aerators. Paper No. 3, Symposium on The Profitable Aeration of Waste Water. BHRA Fluid Engineering Report, Cranfield, Bedford, England.

EPA (1985) Summary Report. Fine pore (fine bubble) aeration systems. U.S. Environmental Protection Agency Report, EPA-625 8-85-010.

EPA (1989) Design manual. Fine pore aeration systems. U.S. Environmental Protection Agency Report, EPA-625 1-89-023.

Fast A. W. and Lorenzen M. W. (1976) Synoptic survey of hypolimnetic aeration. *J. envir. Engng* **106,** 1161–1173.

Huibregtse G. L., Rooney T. C. and Rasmussen D. C. (1983) Factors affecting fine bubble diffused aeration. *J. Wat. Pollut. Control Fed.* **55,** 1057–1064.

Ippen A. T. and Carver C. E. (1954) Basic factors of oxygen transfer in aeration systems. *Swge Indust. Wastes* **26,** 813–829.

Larkin P. A. (1975) *Biometrics*. University of British Columbia, Vancouver, British Columbia, Canada.

Leary R. D., Ernest L. A. and Katz W. J. (1969) Full scale oxygen transfer studies of seven diffuser systems. *J. Wat. Pollut. Control Fed.* **41,** 459–473.

Lorenzen M. W. and Fast A. W. (1977) A guide to aeration/circulation techniques for lake management. U.S. Environmental Protection Agency Report, EPA-600 3-77-004.

Mancy K. H. and Okun D. A. (1960) Effects of surface active agents on bubble aeration. *J. Wat. Pollut. Control. Fed.* **32,** 351–364.

Markofsky M. (1979) On the reoxygenation efficiency of diffused air aeration. *Wat. Res.* **13,** 1339–1346.

Mavinic D. S. and Bewtra J. K. (1974) Mass transfer of oxygen in diffused aeration systems. *Can J. civ. Engng* **1,** 71–84.

Mavinic D. S. and Bewtra J. K. (1976) Efficiency of diffused aeration systems in wastewater treatment. *J. Wat. Pollut. Control Fed.* **48,** 2273–2283.

McQueen D. J. and Lean D. R. S. (1986) Hypolimnetic aeration: an overview. *Wat. Pollut. Res. J. Can.* **21,** 205–217.

Morgan P. F. and Bewtra J. K. (1960) Air diffuser efficiencies. *J. Wat. Pollut. Control Fed.* **32,** 1047–1059.

Neilson B. J. (1974) Reaeration dynamics of reservoir destratification. *J. Am. Wat. Wks Ass.* **66,** 617–620.

Pastorok R. A., Ginn T. C. and Lorenzen M. W. (1981) Evaluation of aeration/circulation as a lake restoration technique. U.S. Environmental Protection Agency Report, EPA-600 3-81-014.

Rooney T. C. and Huibregtse G. L. (1983) Increased oxygen transfer efficiency with coarse bubble diffusers. *J. Wat. Pollut. Control Fed.* **52,** 2315–2326.

Schmit F. L., Wren J. D. and Redmon D. T. (1978) The effect of tank dimensions and diffuser placement on oxygen transfer. *J. Wat. Pollut. Control Fed.* **50,** 1750–1767.

Taggart C. T. and McQueen D. J. (1982) A model for the design of hypolimnetic aerators. *Wat. Res.* **16,** 643–654.

Water Pollution Control Federation/American Society of Civil Engineers (1988) Aeration, a wastewater treatment process. WPCF Manual of Practice No. FD-13, ASCE Manuals and Reports on Engineering Practice No. 63.

Wesner G. M., Ewing L. J. and Hinrichs D. J. (1977) Energy conservation in municipal wastewater treatment. U.S. Environmental Protection Agency Report, EPA-430 9-77-011.