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EFFECTS OF ORIFICE SIZE AND SURFACE CONDITIONS ON OXYGEN TRANSFER IN A BENCH SCALE DIFFUSED AERATION SYSTEM

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ABSTRACT

Non-steady state gas transfer methodology was used to examine the effect of orifice size and surface conditions on the rate of oxygen transfer in a 239 L bench scale tank. Each orifice size tested (40 μ, 397 μ and 1588 μ) increased the overall oxygen transfer coefficient (K_La_{20}, hr^{-1}); standard oxygen transfer rate (OT_s, g O_2/hr); transfer efficiency (E_o, %) and energy efficiency (E_p, g O_2/kW-hr) as orifice diameter decreased. The three surface conditions examined exerted a minor effect on oxygen transfer.

INTRODUCTION

Two important design variables capable of influencing the rate of oxygen transfer in diffused aeration systems are orifice size and the amount of induced turbulence within the aeration basin (1). Although the effect of bubble size on aeration efficiency is a well known phenomena that has been widely documented (2,3,4,5), the effect of different orifice sizes on bubble size, and subsequently on K_La, 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. Given the current interest in improving aeration efficiency, this aspect of diffused aeration system design requires further research attention (6).

In addition, although basin turbulence has received adequate research attention, the effect of varying the surface conditions and surface exchange area of the aeration basin has been less thoroughly documented. The purpose of this study was to examine the effect of the aforementioned variables on the overall oxygen transfer process under controlled laboratory conditions, using standard non-steady state oxygen transfer methodology. The tests were conducted in a bench scale tank (239 L), and the relative differences between treatments should remain valid during scale up to pilot and full scale systems. The usefulness of the data-base generated could manifest itself in increased oxygenation efficiencies in aeration tanks and in the emerging field of lake and stream reaeration systems (7).

EXPERIMENTAL METHODS

Tank Size, Geometry and Surface Conditions

The experiments were conducted in a rectangular translucent polyethylene tank, 0.89 m L x 0.59 m W x 0.57 m D filled with 239 L of municipal tap water (Figure 1). Both groups of diffusers were suspended in the center of the tank and hung 0.34 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. Three surface conditions were examined: cover, no cover and no cover plus wind generated from a vacuum exhaust port. The wind velocity was measured with a hot wire anemometer (Thermo-Air 1), and it was sufficient to create 0.5-1.0 cm waves in the tank and circulate dye across the long axis (0.89 m) of the tank surface in 10-15 seconds.

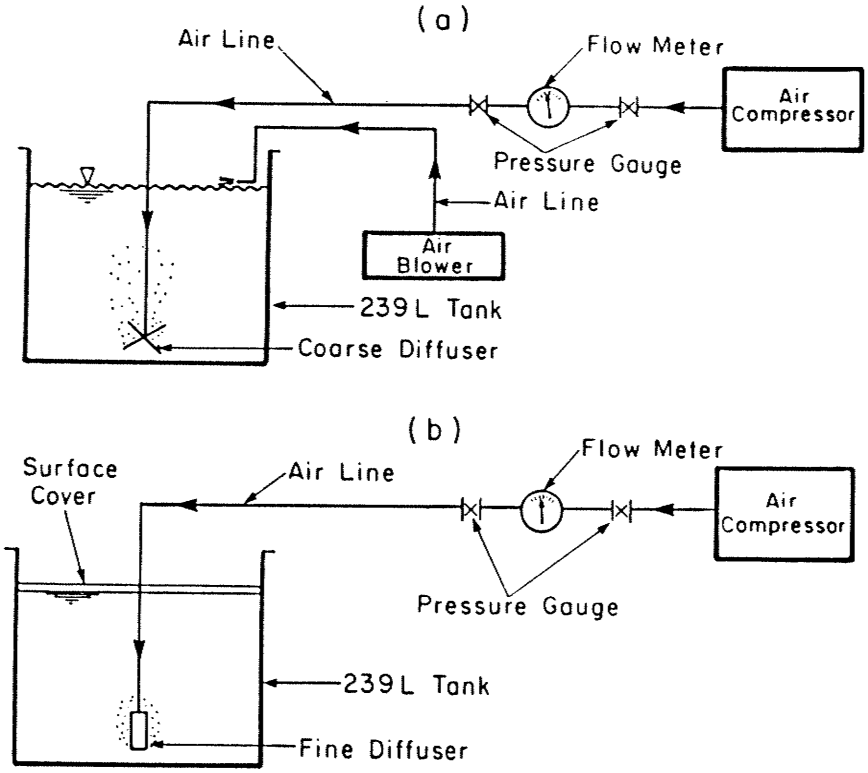

Figure 1: SCHEMATIC DIAGRAM OF THE EXPERIMENTAL AERATION SYSTEM WITH (a) COARSE BUBBLE DIFFUSER AND SURFACE WIND, (b) FINE BUBBLE DIFFUSER AND SURFACE COVER.

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 @ 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 at 1.0 kg/cm^2 and 21°C. Air pressure in the discharge line remained constant during each treatment test. The air flow valve was adjusted occasionally to maintain constant delivery of 28.3 L/min during each treatment test.

Reaeration Procedure

The deoxygenation-oxygenation procedure used was the non-steady state reaeration test (8). The test water was deoxygenated with 0.1 mg/L of cobalt chloride and 10.0 mg/L of sodium sulfite for each 1.0 mg/L of dissolved oxygen present in the water (9). The highest starting oxygen concentration was 10 mg/L, therefore a maximum concentration of 0.25 mg/L of cobalt ion was used. Since a polarographic probe was used for determining oxygen concentration, cobalt interference was not a problem. Theoretically only 7.9 mg/L of sodium sulfite is required for each mg/L of dissolved oxygen; however, due to partial oxidation during mixing, it is necessary to add up to 1.5 times the theoretical amount (10). The cobalt chloride was added first and thoroughly mixed into the test water. Sodium sulfite was mixed into a slurry in a 1 L flask, then added to the tank water and thoroughly mixed by a large paddle. A Winkler calibrated oxygen-temperature meter (YSI 54 ARC) was used to measure dissolved oxygen and water temperature in the test tank. The meter confirmed the tank water was rapidly deoxygenated as the dissolved oxygen concentration usually declined to 0.2-0.3 mg/L within 30 seconds. The air compressor was then turned on, and oxygen concentrations recorded every 30 seconds until the dissolved oxygen reached 6-7 mg/L. A maximum of five test runs were conducted on each batch of water to minimize interference from sodium sulfite accumulation (10).

Diffuser Type and Orifice Size

Two types of air diffusers were used in these experiments, coarse bubble diffusers (397 μ and 1588 μ diameter orifice) and fine bubble diffusers (40 μ). The coarse bubble diffusers were constructed of 1.27 cm ID schedule 40 PVC pipe. These diffusers were cross shaped, with 4 arms joining into a common center which was fitted with a 0.64 cm nipple for connecting the 0.64 cm air line. To ensure equivalent air delivery capability, pressure loss and orifice surface areas between the coarse bubble diffusers, the 1588 μ diffuser consisted of 4 orifices, 1 on each arm, and the 397 μ diffuser had 64 orifices, 16 on each arm. The fine bubble diffusers were obtained from Aquatic Eco-Systems Inc., and had a 40 μ maximum pore size (Model AS-8-0). The external dimensions were 7.6 cm L x 3.8 cm W x 3.8 cm D.

Experimental Design

The treatments examined in this experiment were the effect of orifice size (40 μ, 397 μ and 1588 μ) and the effect of surface conditions in the tank. This resulted in 9 combinations of orifice size and surface conditions (Table 1). Each of the treatments was assigned a number from 1 to 9, and the order in which the numbers were assigned was selected from a 10,000 digit random number table (11). Each set of nine treatments was completed in one day, then repeated the next day with a new set of random numbers. The purpose of this design was to remove random error that may occur during any given treatment day, and 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.

No.	Orifice Size (μ)	Surface Conditions
1	1588	cover
2	1588	no cover
3	1588	no cover + wind
4	397	cover
5	397	no cover
6	397	no cover + wind
7	40	cover
8	40	no cover
9	40	no cover + wind

Parameter Calculation

K_La_T was calculated according to (8) using linear least squares regression analysis. A range from 16 to 58 data points between 10 and 60% of saturation were used in the determination:

$$K_La_T = \frac{\ln [(C_s - C_1) / (C_s - C_2)]}{t_2 - t_1}$$

where:

ln = natural logarithm;
K_La_T = overall oxygen transfer coefficient at the temperature of the test water (hr^{-1});
C_1 = DO (mg/L) at t_1;
C_2 = DO (mg/L) at t_2;
C_s = DO saturation concentration (mg/L);
t_1 = time at point 1 on the semi-logarithmic plot (hr);
t_2 = time at point 2 on the semi-logarithmic plot (hr).

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 value for the test water, corrected for temperature and barometric pressure. This study used 10% and 60% saturation values for t_1 and t_2 as a sufficient number of data points (ie. 16 to 58) was collected between 10 and 60% without having to run the test to 80% saturation.

The dissolved oxygen saturation on test days was adjusted to current barometric pressure. Since the tests were conducted below 1000 m and 25°C, there was no correction in oxygen saturation for the vapor pressure of water (8). The saturation pressure was not corrected for mid-depth oxygen partial pressure as the test tank was only 0.34 m deep. K_La_T was corrected to K_La_{20} according to (9), and $\theta = 1.024$.

OT_s was calculated as follows (9):

$$OT_s = K_La_{20}\ DO_{20}\ V\cdot$$

where:
OT_s = standard oxygen transfer rate (g O_2/hr);
DO_{20} = dissolved oxygen concentration (mg/L) 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 (8):

$$E_p = OT_s/P$$

where:
E_p = energy efficiency (g O_2/kW-hr);
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 therefore was 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 with a nameplate horsepower of 0.1243kW. The power input then used for these tests was 28.3 L/min / 36.8 L/min x 0.1243 kW = 0.0956 kW. A minimum power loss was expected in the short length of air tubing (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 x 100.

Bubble Size

Bubble size was determined by photographing rising bubbles in a 70 L clear plexiglass column (0.29 m dia. x 1.06 m) with a Pentax ME camera and flash attachment, synchronized at 1/100 second. 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 60-70x to determine bubble size. Approximately 20 bubbles were measured for each orifice size. The air flow rate was set at 18.8 L/min, as the 28.3 L/min air flow rate was too high for accurate photography. A spreadsheet program was then written to calculate the volume of the bubbles. Since most of the bubbles were oblate spheriod 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);

The spreadsheet then calculated the equivalent diameter, mean bubble size, and coefficient of variation (standard deviation expressed as a percentage of the mean) for each orifice size.

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 sin square root transform was used on the E_o Anova's to reduce the skewness of the percentage values (12). 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 $\alpha = 0.01$.

RESULTS AND DISCUSSION

Orifice Diameter

The effect of orifice diameter was highly significant. There were no significant interaction or replication effects from the experimental design. The cell means (± one standard deviation) for K_La_{20}, OT_s, E_o and E_p (all surface treatments combined) for the three orifice sizes studied (40 μ, 397 μ and 1588 μ) are shown in Table 2. Scheffe's test indicated each diffuser was significantly different from each other for K_La_{20}, OT_s, E_o and E_p, and that K_La_{20}, OT_s, E_p and E_o increased with decreasing orifice diameter.

Table 2. Effect of Orifice Diameter on K_La_{20}, OT_s, E_o and E_p

Treatment	K_La_{20} (hr^{-1})	OT_s (gO_2/hr)	E_o (%)	E_p ($g\ O_2/kW\text{-}hr$)	n
40 μ	6.3 ±0.5	13.3 ±1.0	2.6 ±0.2	140.1 ±10.4	15
397 μ	3.7 ±0.3	7.8 ±0.6	1.5 ±0.1	82.1 ±6.6	15
1588 μ	2.0 ±0.1	4.3 ±0.3	0.8 ±0.1	44.7 ±3.1	15

An examination of the bubble size analysis (Table 3) provides the explanation for this result. A definite trend toward increasing bubble size with increasing orifice diameter was obtained for the 40 μ to 1588 μ diameter orifice range (CV = coefficient of variation).

Table 3. Equivalent bubble diameter as a function of orifice size

Orifice (μ)	Mean Equivalent Diameter (mm)	n	CV (%)
40	3.8	20	15.5
397	5.0	20	16.6
1588	7.1	20	31.0

A reduction in bubble size produces three distinct results: (a) an increase in surface area per unit bubble volume (13); (b) a decrease in terminal rise velocity (14); (c) a decrease in the liquid film coefficient (K_L) (4).

An increase in bubble surface area per unit volume increases the "a" (the interfacial surface area per unit volume of water; m^2/m^3) in K_La and acts to increase K_La and OT_s. A decrease in terminal rise velocity increases the bubble contact time which acts to increase E_o and E_p. However, a decrease in terminal rise velocity decreases the liquid film coefficient (K_L), which will decrease K_La, OT_s, E_o and E_p.

The interaction between these opposing factors determines the net effect on K_La, OT_s, E_o and E_p of a decrease in bubble size. In this case, the net effect was an increase in K_La, OT_s, E_o and E_p, indicating that the effect of increased surface area and contact time more than compensated for the reduction in K_L due to lower terminal rise velocities and liquid film coefficients. This suggests that in a shallow tank, increased interfacial area and contact time are more important aspects of oxygen transfer in 4 to 7 mm diameter bubbles than reduced liquid film coefficients.

The effect of increasing E_o with decreasing bubble size is a well documented response. For example, Morgan and Bewtra (5) and

Bewtra and Nicholas (4) have observed increased E_o with fine bubble diffusers (Saran tubes) as compared to coarse bubble diffusers (Spargers). In contrast, less research has been conducted on the effect of specific orifice sizes on bubble size and subsequently on K_La, OT_s, E_o and E_p. Mavinic and Bewtra (3) examined K_La, E_o and E_p in a simple column with a fixed orifice diameter of 1600 μ. Their K_La_{20} and E_p results were considerably higher due to a smaller column size and different method of calculating E_p, however their E_o values for the simple column are in the same range as the results for the 1588 μ orifice. Barnhardt (15) did examine this aspect of gas transfer and observed a decline in K_La as bubble diameter increased above 2.2 mm. Although the minimum equivalent bubble diameter generated from this research was 3.8 mm, the same trend of decreasing K_La with increasing bubble size was clearly evident.

These results clearly demonstrate the efficacy of using smaller orifices to generate fine bubbles and maximize oxygen transfer from diffused air aeration. The 397 μ coarse bubble diffuser was nearly twice as efficient (E_o) as the the 1588 μ coarse bubble diffuser, while the 40 μ silica glass diffuser was more than three times as efficient. The bubble size which generates the highest K_La values is in the 2.0-2.5 mm diameter range (15). The smallest bubble size in this study was 3.8 mm in equivalent diameter, therefore further increases in E_o would be theoretically possible with a smaller matrix ceramic diffuser. However, increased air filtration requirements and diffuser clogging problems may become additional design factors at this stage (16).

An important aspect of the orifice size-bubble size relationship not examined in these experiments is the effect of air flow rate on bubble size. Above a critical gas flow rate, bubble size becomes dependent on gas flow rate and independent of orifice diameter (17). This aspect must also be taken into consideration when designing diffused aeration systems.

Surface Conditions

A marginally significant effect was produced by the surface conditions treatment. The three treatment (cover, no cover, no cover + wind) cell means (all orifice sizes combined) for K_La, OT_s, E_o and E_p are shown in Table 4 (± one standard deviation). However, Scheffe's test was unable to distinguish any significant difference between the three treatments ($\alpha = 0.01$) in the comparison among means test.

Table 4. Effect of Surface Conditions on KLa, OTs, Eo and Ep

Treatment	K_La (hr^{-1})	OT_s (g O2/hr)	E_o (%)	E_p (g O_2/kW-hr)	n
Cover	3.8 ±1.8	8.1 ±3.8	1.6 ±0.8	85.2 ±40.2	15
No Cover	4.3 ±2.0	9.0 ±4.1	1.8 ±0.8	94.5 ±43.2	15
No Cover + Wind	3.9 ±1.8	8.3 ±3.8	1.6 ±0.7	87.3 ±39.8	15

Given the conservative nature of Scheffe's test and the marginally significant effect (ie. F=10-12) of the surface conditions treatment, this result was expected. A larger sample size would be required to separate out the treatment effects.

It is interesting to speculate on the factors responsible for the observed result. Logically, the cover-no cover effect makes sense as the surface area to volume ratio of the 239 L tank ($A/V = 2.2\ m^{-1}$) should result in a more noticeable effect as the surface component of gas transfer increases relative to bubble formation, rise and burst (18). However, the negative effect of the no cover and wind treatment is puzzling. One would expect an increase in gas transfer from the wind and wave action (19).

A possible explanation is that the velocity and direction of the wind generated circulation currents changed the circulation within the 239 L tank to a less efficient pattern. For example, the maximum wind speed measured in the tank was 4.1 m/sec at a distance of 10 cm fom the air nozzle. The velocity of wind induced surface currents are approximately 3% of wind speed (20), therefore a surface velocity of 13 cm/sec was possible.

The velocity of the rising air-bubble mixture should approximate the rise velocity of individual bubbles, which ranged in size from 4 to 7 mm diameter. The rise velocity of spherical cap bubbles in this size range is described by:

$$u = 1.02 \sqrt{g\ r_e}$$

where:
u = terminal rise velocity (cm/sec);
g = acceleration of gravity (980 cm/sec^2);
r_e = equivalent bubble radius (cm) (21).

This formula predicts a rise velocity of approximately 14-19 cm/sec, hence the velocity of the outward flowing surface current should be similar. The effect of the outward flowing surface current meeting the wind-induced circulation current would be a 69-93% reduction in velocity for the surface current flowing directly into the wind-induced current in the upwind half of the tank. The net effect of reduced surface current velocity may be to reduce the entrainment of small bubbles and reduce K_La, OT_s, E_o and E_p. Bewtra and Nicholas (4) observed a similar "stilling phenomena" during their experimental work on diffuser arrangements. They attributed the decline in transfer efficiency under certain diffuser arrangements to decreased water velocities and less bubble entrainment when two opposing air-water mixture streams met. Huibregtse (6) also noted that particular diffuser arrangements resulted in abnormal mixing patterns which influenced E_o and E_p.

An alternative hypothesis is that the surface conditions treatments had no effect on K_La, OT_s, E_o and E_p, and the statistical results are simply a Type 1 error, ie. the probability of rejecting the null hypothesis when it is true. The overlap of the standard deviations of the three treatments indicates the treatment effect, if real, is quite small and variable. In addition, the wind speed may have been too low to significantly influence oxygen transfer. O'Connor (20) and Downing and Truesdale (19) both observed little change in oxygen transfer below wind speeds of 3 m/sec. Although the maximum wind speed measured in these experiments was 4.1 m/sec at a distance of 10 cm from the nozzle, this decreased quite rapidly and was only 2.4 m/sec at a distance of 20 cm and less than 1.0 m/sec at the mid-point of the tank. Further studies are required to clarify if this result is real or an artifact of the experimental system.

These experimental results agree with Bewtra and Nicholas (4), in that the majority of oxygen transfer occurs during bubble formation, rise and burst, and that natural surface aeration plays a relatively minor role in small diffused air aeration basins with relatively low surface area to volume ratios. This effect was also observed in a full-lift hypolimnetic aeration system in which the surface area of the separator box was varied (7). This is in contrast to reservoirs and lakes, in which the majority of oxygen introduced from compressed air destratification systems arises from natural surface aeration (18, 22). This situation does not apply to mechanical surface aeration (23) or flowing systems, where hydraulic jumps can increase surface roughness and effective surface area and significantly contribute to the oxygenation process (24). However, in diffused aeration basins with small surface area to volume ratios, the design criterion should focus on maximizing mass transfer from small orifice air diffuser systems. The application of these findings could improve the oxygenation efficiency of diffused aeration systems, particularly in the developing field of lake and stream aeration where efficient diffuser systems have traditionally been underutilized (25).

CONCLUSIONS

The effect of orifice diameter on K_La, OT_s, E_o and E_p was highly significant, as parameter values increased with decreasing orifice size. The 397 μ diffuser was approximately twice as efficient as the 1588 μ diffuser, while the 40 μ diffuser was over three times as efficient. The principle effect of a reduction in orifice size was a reduction in bubble size, which increased the aforementioned variables via increased surface area per unit volume and increased contact time. The surface conditions treatment was only marginally significant. This suggests that in diffused aeration basins with low surface area to volume ratios, the design criterion should focus on maximizing mass transfer by using small orifice air diffuser systems.

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