FACTORS INFLUENCING OXYGEN TRANSFER IN DIFFUSED AERATION SYSTEMS AND THEIR APPLICATION TO HYPOLIMNETIC AERATION

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Abstract

A series of laboratory and field experiments were conducted to examine the effect of several design variables on the oxygenation capacity of hypolimnetic aeration systems. The laboratory experiments used non-steady state gas transfer methodology to examine the effect of air flow rate, air flow rate per diffuser, orifice size and reduced tank surface area on the overall oxygen transfer coefficient $(K_L a_{20}, hr^{-1})$; standard oxygen transfer rate (OT_s, g O₂/hr); energy efficiency (E_p , g O₂/kW-hr) and transfer efficiency $(E_o, \%)$. The field experiments examined the effect of diffuser depth, orifice size and reduced separator box surface area on the oxygen input per cycle (mg/L), daily oxygen load (kg O₂/day), transfer efficiency (E_o, %), energy efficiency (E_p, kg O₂/kW-hr) and water velocity (m/sec) in a full lift hypolimnetic aerator. The laboratory experiments demonstrated that $K_L a_{20}$, OT_s , E_p and E_o increased with air flow rate in the orifice range of 397 μ to 3175 μ diameter. In the 40 μ and 140 μ diameter orifice range, K_La_{20} and OT, increased with air flow rate; however, E_o and E_p were not affected. A decrease in orifice size from 3175 μ to 140 μ diameter increased $K_L a_{20}$, OT_s , E_p and E_o ; however, there was no significant difference between the 140 μ and 40 μ diameter silica glass diffusers. Reducing the air flow rate per silica glass diffuser (40 μ and 140 μ diameter) significantly increased $K_L a_{20}$, OT_s , E_p and E_o . A reduction in tank surface area had a minimal effect on $K_L a_{20}$, OT_s , E_p and E_o in two tank configurations with different surface area to volume ratios (0.94 and 2.2 m^{-1}). The field experiments demonstrated that increased depth of air release increased the oxygen input per cycle and water velocity, which, in turn increased the daily oxygen load, E_p and E_o . Orifice size in the 140 μ range significantly increased oxygen input per cycle, daily O_2 load, E_p and E_o ; however, the size range from 794 μ to 3175 μ exhibited similar but reduced gas transfer characteristics. A reduction in surface area in the separator box had no effect on the oxygenation capacity of the hypolimnetic aerator. Design criteria for hypolimnetic aerators are discussed including several modifications which should increase the oxygenation capacity of full lift hypolimnetic aeration systems.

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Chapter 1

Introduction

Cultural eutrophication is caused by excessive addition of limiting nutrients such as phosphorus and nitrogen to lakes, streams, rivers, estuaries and coastal waters (Wetzel, 1975). In lakes, these additions result in increased aquatic plant growth, undesirable changes in species composition, oxygen depletions, fish kills and decreased water quality for recreational use (Lee and Jones, 1988). In terms of domestic and industrial impact, cultural eutrophication decreases raw water quality (Dorin, 1981; Walker, 1983), increases treatment costs (Clark and Dorsey, 1980) and introduces possible carcinogens (eg. trihalomethanes) into the distribution system (Cantor et al., 1978; Tuthill and Moore, 1980; Jones and Lee, 1982).

Following the limiting nutrient controversy of the late 1960's (see Vallentyne, 1974 for review), attention in the 1970's focused on reducing nutrient inputs (Lee and Jones, 1988) and rehabilitating culturally eutrophied lakes (Dunst et al., 1974). Many lakes recovered naturally from excessive nutrient loading after nutrient diversion eg. Lake Washington (Edmondson and Lehman, 1981); however, in some lakes the eutrophic status remained unchanged following nutrient diversion eg. Lake Trummen (Bjork et al., 1972). Lakes of this type were sufficiently eutrophic to maintain their present state via internal nutrient cycling after external nutrient sources were reduced. In addition, many lakes receive nutrients from non-point sources, which may prove difficult, if not impossible, to control (Lee and Jones, 1988).

As a result, the interdisciplinary field of lake restoration emerged as limnologists and

engineers began to develop techniques for restoring eutrophic lakes. Lake restoration refers to "... the manipulation of a lake ecosystem to effect an in-lake improvement in degraded or undesirable conditions" (Dunst et al., 1974).

Hypolimnetic aeration is a lake restoration technique that has received widespread application. Originally developed in postwar Switzerland (Mercier and Perret, 1949), and rediscovered in West Germany (Bernhardt, 1967), hypolimnetic aeration is now used throughout Western Europe and North America (Verner, 1984). At least three multinational companies (Atlas Copco AB, Locher and Kobe Steel) are now actively marketing hypolimnetic aeration systems.

Two of the main difficulties associated with hypolimnetic aeration are (1) estimating the oxygen consumption of the water body and (2) estimating the oxygen input capacity of the aeration system. This illustrates the true interdisciplinary nature of lake restoration, as the first problem lies within the realm of limnology, while the second is in the field of civil and environmental engineering. The lack of interaction between these traditional disciplines is responsible in part for the current paucity of information on factors influencing the oxygen transfer capabilities of various hypolimnetic aeration systems.

A fair amount a basic (eg. Cornett and Rigler, 1984; Babin and Prepas, 1985) and applied research (eg. Ashley, 1983; McQueen et al., 1984) has recently been conducted on whole-lake oxygen consumption. The general consensus from the applied research is that estimates of hypolimnetic oxygen depletion should be calculated from well oxygenated hypolimnia to ensure that maximum depletion rates are obtained (McQueen and Lean, 1986; Ashley et al., 1987).

Estimating the oxygen input capacity of hypolimnetic aeration systems has not received the same amount of attention. A wide range of oxygen input capacitites have been recorded (Taggart and McQueen, 1982) and an equally wide range of hypolimnetic aeration systems are available (Fast and Lorenzen, 1976). Although some attempt has been made to standardize aerator design specifications (Taggart and McQueen, 1982; Ashley, 1985; Ashley, 1988) this has not addressed the problem of variable oxygen input.

Aside from the obvious influence of variable hypolimnetic BOD's and aerator volumetric water flow rates, few researchers have experimentally examined the effect of different diffuser designs, air flow rates and separator box surface exchange areas on the oxygenation capacity of hypolimnetic aeration systems. The purpose of this experiment was to use civil engineering gas transfer methodology to address this research deficiency. Specifically, its objectives were to investigate five design variables which this researcher felt, after considerable literature review, were poorly understood in terms of their contribution to the oxygenation capacity of hypolimnetic aeration systems. These design variables were as follows:

1. Depth of air injection. The co-current method of bubble-water transport in the inflow tube of full lift hypolimnetic aerators becomes progressively less efficient at oxygen transfer throughout a given rise. Decreasing hydrostatic pressure is partly responsible for this decline; however, the decreasing oxygen content of rising air bubbles and the additive effect of vertical water velocity and buoyant bubble velocity contribute to poor oxygen transfer efficiency (Speece, 1975). The few field measurements available support this conclusion as most oxygen transfer has been found to occur in the lower half of inflow tubes (Bernhardt, 1967; Smith et al., 1975).

The effect of diffuser depth on water velocity has received little research attention. Small changes in water velocity can result in significant changes in induced volumetric flow, daily oxygen load, transfer efficiency (E_o ; %) and energy efficiency (E_p ; kg O₂/kW-hr). This aspect of hypolimnetic aeration oxygen transfer was examined by inserting various diffusers into a full lift hypolimnetic aeration system

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at different depths and measuring changes in water velocity and dissolved oxygen concentration in the outflow tube.

- 2. Water surface exchange area. Neilson (1974) examined oxygen transfer under laboratory conditions, and concluded the surface area of the tank available for gas transfer directly influenced the oxygenation rate of his laboratory system. Neilson (1974) also estimated that only 6 to 12 % of total oxygen transfer in natural systems originates from bubble formation, rise and bursting. However hypolimnetic aerators, with their relatively small degassing chambers, are critically dependent on oxygen transfer during bubble formation, rise and bursting. A floating surface cover was used in the laboratory and field experiments to vary the surface exchange area and determine the relative importance of water surface area and gas transfer in relation to the overall oxygen transfer in a diffused aeration system.
- 3. Air flow rate. The volume of air injected per unit time is an important factor influencing the rate of oxygen transfer in diffused aeration systems. Higher air flows increase the turbulence at the air-water interface and the total interfacial area available for oxygen transfer to the surrounding liquid (Mavinic and Bewtra, 1974). As a result, the overall oxygen transfer coefficient (K_La_{20} ; hr^{-1}) usually increases with air flow rate. However, the effect of increased air flow rate on E_p and E_o is dependent on orifice size. In these experiments, the air flow rate was varied by a factor of two to examine its influence on K_La_{20} , E_o and E_p .
- 4. Air flow rate per fine bubble diffuser. The effect of varying the air flow rate per fine bubble diffuser was examined as a number of researchers have demonstrated an increase in the K_La_{20} , E_o and E_p by reducing the air flow rate per fine bubble diffuser (eg. Doyle et al., 1983; Morgan and Bewtra, 1960; Ippen and Carver, 1954). The purpose of this experiment was to determine if the 40 μ and 140 μ

silica glass diffusers responded in a similar manner, and determine which factors were responsible for this behaviour.

5. Orifice size. The size of an orifice is one of the most important factors influencing the rate of oxygen transfer in diffused aeration systems, due to its influence on bubble size, contact time of the bubble in the liquid and turbulence in and around the gas-liquid interface (Bewtra and Mavinc, 1978). Large bubbles have a higher liquid film coefficient (K_L) than small bubbles; however, their larger size reduces their contact time in the liquid and their surface area to volume ratio. Small bubbles (ie. less than 0.5 mm diameter) have higher surface area to volume ratios for improved gas exchange; however, their slower rise velocity results in a lower liquid film coefficient (K_L) but a longer contact time.

This aspect of the experiment was examined by using a range of orifice sizes from 40 μ to 3175 μ diameter to determine which orifice size generated bubbles with the highest K_La₂₀, E_o and E_p.

A combination of laboratory and field testing was selected for this research project. This allowed for a detailed examination of several factors capable of influencing gas transfer under controlled conditions, followed by the selection of appropriate variables for further evaluation and testing under actual field conditions. Although this increased the cost and complexity of this project, it significantly improved the reliability and robustness of the conclusions. The transition from bench scale to pilot scale is a crucial step in engineering development, and provides considerable insight into factors influencing the scale-up process.

Chapter 2

Methods

2.1 Lab Experiments

The laboratory experiments were conducted at the South Campus Fisheries Compound at U.B.C.

2.1.1 Air Supply

Air was supplied by a 1/6 hp (0.12 kW) Gast rotary vane vacuum-pressure pump (model 0211-V36A-G8CX), rated at 1.3 ft³/min (36.8 L/min) @ 0 psig (0 kg/cm²). The compressor was oil lubricated and fitted with a 10 μ oil removing element to prevent oil mist from contaminating the delivered air. The compressor was run several times for extended periods (4-5 hrs) and no oil film was detected in the test tank water. A pressure gauge was attached to the compressor to monitor air pressure in the discharge line (0-30 psig or 0-2.1 kg/cm²).

2.1.2 Air Flow Rate Measurement

Air flow rate was measured by a Brooks flow meter (Sho-Rate 50 Purgemeter), specifically manufactured for the experiments. The meter was equipped with a pressure gauge (0-30 psig or 0-2.1 kg/cm²) at both inlet and outlet nipples, and calibrated to read 4.7 to 56.6 L/min (0.2-2.0 ft³/min) at S.T.P. (1.0 kg/cm², 21 degrees C).

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2.1.3 Oxygen and Temperature Measurements

Dissolved oxygen and temperature in the test tanks was measured with a YSI 54 ARC oxygen-temperature meter. The oxygen meter was calibrated with two replicate Winkler titrations (Azide modification) (Lind, 1979) at the start of each experimental period. The temperature probe was checked against two mercury thermometers and was accurate within 0.5 degrees C.

The oxygen-temperature probe was suspended in the center of each test tank (70 L and 239 L) approximately 5 cm below the suspension point for the diffuser being tested. The probe was weighted so it hung vertically and did not contact the sides of the tank when the experiments were in progress.

2.1.4 Deoxygenation-Oxygenation Procedure

The deoxygenation-oxygenation procedure used was the non-steady state reaeration test as outlined in APHA et al. (1980). Basically, the test involves deoxygenating a known volume of water with sodium sulfite (Na₂SO₃) and cobalt chloride (CoCl₂.6H₂O), and measuring the rate of reoxygenation. The chemical reaction is (Beak, 1977):

$$Na_2SO_3 + O_2 \longrightarrow Na_2SO_4$$
 (2.1)

The test water was deoxygenated with 0.1 mg/L cobalt chloride as a catalyst and 10.0 mg/L of sodium sulfite for each 1.0 mg/L of dissolved oxygen present in the water (Boyd, 1986). 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 (Beak, 1977). 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. The oxygen meter confirmed the tank water was rapidly deoxygenated as the dissolved oxygen

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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.

2.1.5 Tank Size and Geometry

Two sizes of tanks were used in the experiments. One tank was a clear plexiglass cylinder, with an inside diameter of 0.29 m and a height of 1.06 m. This tank was filled with 70 L of water during the experiments. The second tank was a rectangular translucent polyethylene tub, 0.89 m L x 0.59 m W x 0.57 m H filled with 239 L of water.

A floating surface cover of 2.5 cm polystyrene foam was fabricated for each tank. The foam was cut with sufficient clearance (1 cm) to allow rapid installation and removal, but cover as much of the water surface area as possible.

2.1.6 Diffuser Type and Orifice Size

Two types of air diffusers were used in these experiments; coarse bubble diffusers and silica glass diffusers. The coarse bubble diffusers were constructed of 1.27 cm Schedule 40 white PVC irrigation pipe. The diffusers were cross shaped, with 4 arms joining into a common center. The center was fitted with a 0.64 cm nipple for attaching 0.64 cm tygon tubing air line. The outside diameter of the diffusers was 25 cm , and they fit inside the plexiglass cylinder with 2 cm clearance on either side.

The coarse bubble diffusers were fabricated to cover the orifice diameter range normally encountered in shop built diffusers ie. 1/8" (3175 μ); 1/16" (1588 μ), 1/32" (794 μ) and 1/64" (397 μ). The surface area of a circle increases 4x as the diameter doubles, so the number of holes drilled in each diffuser was as follows:

• 1/8" $(3175 \ \mu) - 1$ hole

Orifi	ice Size	Air Flow Rate	
1/8"	$(3175 \ \mu)$	1.586 ft ³ /min (44.9 L/m	in)
1/16"	$(1588 \ \mu)$	$0.421 \text{ ft}^3/\text{min}$ (11.9 L/m	in)
1/32"	$(794 \ \mu)$	$0.099 \text{ ft}^3/\text{min}$ (2.8 L/m	in)
1/64"	$(397 \ \mu)$	$0.025 \text{ ft}^3/\text{min}$ (0.7 L/m	in)

Table 2.1: Air flow rate through an orifice at 2 psig (0.136 kg/cm^2) .

- 1/16" (1588 μ) 4 holes (one on each arm)
- 1/32" (794 μ) 16 holes (four on each arm)
- 1/64" (397 μ) 64 holes (sixteen on each arm)

Standard tables of air discharge through an orifice at 2 psig (0.136 kg/cm^2) (assuming a discharge coefficient of 0.65 for a sharp edged orifice) are shown in Table 2.1. The compressor was capable of a maximum output of 36.8 L/min @ 0 psig (0 kg/cm^2) . Each diffuser was capable of passing the following volumes of air:

- 1/8" (3175 μ) 1 x 1.586 ft³/min = 1.59 ft³/min (44.9 L/min) @ 2 psig (0.14 kg/cm²)
- 1/16" (1588 μ) 4 x 0.421 ft³/min = 1.68 ft³/min (47.6 L/min) @ 2 psig (0.14 kg/cm²)
- 1/32" (794 μ) 16 x 0.099 ft³/min = 1.58 ft³/min (44.8 L/min) @ 2 psig (0.14 kg/cm²)
- 1/64" (397 μ) 64 x 0.025 ft³/min = 1.60 ft³/min (44.8 L/min) @ 2 psig (0.14 kg/cm²)

Therefore, orifice size and number were not considered restrictive to air flow at the experimental flow rates.

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The silica glass diffusers were obtained from Aquatic Eco-Systems Inc. (Apopka, Florida) in two pore sizes: 140μ maximum pore size (Model AS-8) and 40μ maximum pore size (Model AS-8-0). The external dimensions of both diffuser groups were identical, 3" L x 1.5" W x 1.5" D (7.62 cm L x 3.8 cm W x 3.8 cm D). Each diffuser weighed 0.39 lbs (0.18 kg) and was fitted with a 1/4" (0.64 cm) hose nipple.

Both groups of diffusers (coarse and silica glass) were suspended in the center of each test tank (cylinder or rectangular tank) by tygon tubing air line. The diffusers hung 0.80 m below the water surface in the cylinder and 0.34 m below the surface in the rectangular tank. A 0.45 kg weight was attached to the coarse bubble diffusers to counter their positive buoyancy and stop them from swinging about when discharging air. The silica glass diffusers were sufficiently heavy and did not require additional weighting.

The coarse bubble diffusers were quickly lowered into position during testing with the compressor running. This avoided flooding the diffusers with water which caused an uneven discharge of air while the diffuser was purged of water. The silica glass diffusers did not have this problem and immediately purged themselves of water when the compressor was turned on.

Dye was added on several occasions to each test 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 seconds (n=16), and the 239 L tank required an average of 30 seconds (n=3) to mix completely. This confirms initial observations that complete mixing was quickly achieved, and the oxygen-temperature probe was adequately positioned to measure the rate of oxygen increase in the water column.

2.1.7 Experimental Design

The lab experiments were divided in three groups: Group 1 – coarse bubble diffusers in the 70 L cylinder; Group 2 – silica glass diffusers in the 70 L cylinder; and Group 3 –

No.	Air Flow Rate (L/min)	Orifice Size (μ)	Cover
1.	9.4	397	no
2.	9.4	397	yes
3.	18.8	397	no
4.	18.8	397	yes
5.	9.4	794	no
6.	9.4	794	yes
7.	18.8	794	no
8.	18.8	794	yes
9.	9.4	1588	no
10.	9.4	1588	yes
11.	18.8	1588	no
12.	18.8	1588	yes
13.	9.4	3175	no
14.	9.4	3175	yes
15.	18.8	3175	no
16.	18.8	3175	yes

Table 2.2: Group 1 experimental treatments.

coarse bubble and silica glass diffusers in the 239 L tank.

The treatments examined in Group 1 were: the effect of air flow rate (9.4 L/min or 18.8 L/min); the effect of surface cover (present or absent), and the effect of orifice size (397 μ , 794 μ , 1588 μ and 3175 μ). This resulted in 16 combinations of flow, cover and orifice size (Table 2.2). The experiments were carried out in a randomized complete block design. Each of the treatments was assigned a number from 1 to 16, and the order in which the treatments were tested were selected from a 10,000 digit random number table (Rohlf and Sokal, 1969). Each set of 16 treatments was completed in one day, then repeated the next day with a new set of random numbers. For example, on Day 1 the sequence of testing was: 7, 4, 11, 3, 1, 10, 12, 9, 15, 6, 2, 5, 14, 13, 8 and 16. On Day 2 the sequence was: 4, 12, 5, 16, 3, 10, 6, 7, 1, 13, 11, 14, 8, 9, 2 and 15.

The purpose of this design was to remove random error that may occur during any

No.	Air Flow Rate (L/min)	Orifice Size (μ)	Cover	Number of Diffusers
1.	9.4	40	no	1
2.	9.4	4 0	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

Table 2.3: Group 2 experimental treatments.

given treatment day and block the treatments over time (days) to remove any systematic error introduced over time. Each treatment was replicated 5 times, always on a different day. The Group 1 experiments were conducted on September 2, 3, 4, 9 and 10, 1987.

The treatments examined in Group 2 were: the effect of air flow rate (9.4 L/min or 18.8 L/min); the effect of surface cover (present or absent); the effect of orifice size (40 μ or 140 μ); and the effect of diffuser numbers (1 or 2). This again resulted in 16 combinations of flow, cover, orifice size and number of diffusers (Table 2.3). The Group 2 experiments were conducted in the same randomized complete block design as Group 1. The Group 2 experiments were conducted on October 20, 21, 22, 23 and 26, 1987.

The treatments examined in Group 3 were: the effect of orifice size (40 μ , 397 μ and 1588 μ) and the effect of surface cover in the 239 L tank. Three surface conditions were examined: no cover, cover and no cover plus wind generated from a 23 L vacuum exhaust

No.	Air Flow Rate (L/min)	Orifice Size (μ)	Cover
1.	28.3	1588	yes
2.	28.3	1588	no
3.	28.3	1588	no + wind
4.	28.3	397	yes
5.	28.3	397	no
6.	28.3	397	no + wind
7.	28.3	40	yes
8.	28.3	40	no
9.	28.3	40	no + wind

Table 2.4: Group 3 experimental treatments.

port. The velocity of the wind was measured with a hot wire anemometer (Thermo-Air 1) and was sufficient to create 0.5 to 1.0 cm waves on the 239 L tank and circulate dye across the surface of the tank in 10-15 seconds.

This resulted in 9 combinations of orifice size and surface conditions (Table 2.4). The Group 3 experiments were conducted in the randomized complete block design, and performed on November 6, 7, 8, 9 and 11, 1987.

At the start of each experimental day, the barometric pressure was obtained from the Vancouver Weather Office. A series of data sheets were designed and the following information was recorded for each oxygen transfer test:

1. Date

2. Time

3. Orifice size

4. Barometric pressure

5. Water temperature

6. Air temperature

7. Tank configuration

8. Tank volume

9. Type of surface cover

10. Number of diffusers

11. Air flow

12. Grams of Na₂SO₃ added

13. Random number order

14. Oxygen concentration at 30 second intervals

15. Compressor discharge pressure

16. Pressure at inlet of air flow meter

17. Pressure at outlet of air flow meter

A digital electronic balance (Ohaus, C-300 M) was used to weigh the deoxygenation chemicals required for the experiments. The Na₂SO₃ and CoCl₂.6H₂O were Reagent grade and were obtained from local suppliers (BDH Chemicals and Chemonics Scientific).

2.1.8 Bubble Size

Bubble size was determined by photographing rising bubbles in the 70 L column with a Pentax ME camera and flash attachment, synchronized at 1/100 second. A meter stick

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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 Bausch and Lomb dissecting microscope at 60-70x to determine bubble size.

Approximately 20 bubbles were measured for each orifice size and air flow setting. A spreadsheet program was then written to calculate the volume of the bubbles. Since most of the bubbles were oblate spheroid in shape, the following formula was used to calculate volume:

$$V = 4/3\pi a^2 b \tag{2.2}$$

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 program then calculated the equivalent diameter of the bubbles according to:

$$d = \sqrt[3]{\frac{V \ 6}{\pi}} \tag{2.3}$$

where:

d = equivalent diameter (mm)

 $V = volume in mm^3$

Finally, the program calculated the mean bubble size and standard deviation for each orifice size and air flow rate.

2.2 Field Experiments

The field experiments were conducted at Black Lake, midway between Keremeos and Kaledon B.C. on Highway 3A. Black Lake is a small (max. depth = 9.0 m; volume = 178,500 m³) naturally eutrophic lake that was formed approximatley 8900 years ago by

a major meltwater outflow which drained the Kaledon tongue of the main Okanagan ice lobe (Nasmith, 1962).

A full lift hypolimnetic aeration system was installed in Black Lake in 1978 (Ashley, 1981). The aerator consists of an open box (2.4 m L x 1.2 m W x 0.9 m D) with two 0.76 m x 7.3 m galvanized steel pipes attached through the bottom of the box.

2.2.1 Air Supply

Air was provided by a 7.5 kW rotary vane compressor (Hydrovane SR 4000 rated at 1.13 m³/min free air delivery (FAD) @ 100 psig or 7.0 kg/cm²). The compressor was oil lubricated and fitted with a 3 μ oil removing absorbent element. A pressure gauge was attached to the compressor to monitor discharge pressure at the outlet valve.

2.2.2 Air Flow Rate Measurement

Air flow rate was measured by a Brooks (1305 O Ring Seal) flowmeter, specifically manufactured for the experiments. The meter was equipped with a pressure gauge (0-8 kg/cm²) at both inlet and outlet ports, and calibrated to read 113-1133 L/min (4-40 ft³/min) at 7.0 kg/cm² (100 psig) and 21 degrees C.

2.2.3 Oxygen, Temperature and Current Measurements

Dissolved oxygen and temperature were measured with the YSI 54 ARC oxygen-temperature meter used in the lab experiments. Oxygen-temperature profiles were taken approximately 3 m from the aerator at the start of the experiment to establish the oxygen concentration and temperature of the lake. When the various diffusers were being tested, the oxygen-temperature probe was suspended at 3 m in the outflow tube to measure the oxygen concentration and temperature of the outflow water. A General Oceanics current

	September 24, 1987				September 25, 1987			
	Be	fore	A	fter	Be	fore	A	ter
Ζ	02	Т	02	T	O2	Т	O2	T
0	9.4	16.0	8.4	17.0	8.2	16.0	7.9	16.0
1	9.0	16.0	8.6	16.4	7.9	16.0	8.0	16.0
2	8.8	16.0	8.4	16.0	7.9	16.0	7.8	16.0
3	8.8	16.0	8.5	16.0	7.9	16.0	7.7	16.0
4	8.1	15.6	8.1	15.7	6.5	15.9	7.7	15.8
5	3.8	15.0	8.2	15.0	2.2	15.1	4.8	15.0
6	0.4	10.5	0.4	11.4	0.4	11.2	0.4	10.9
7	0.4	9.0	0.4	9.8	0.4	9.5	0.4	9.7
8	0.4	8.8	0.4	9.5	0.4	9.0	0.4	9.6

Table 2.5: Oxygen-temperature profiles at Black Lake during field experiments.

meter (Model 2035) was also suspended at this depth to measure outflow water velocity.

2.2.4 Oxygenation Procedure

The procedure used to measure oxygen input from various diffusers involved lowering a diffuser to 3 m or 7 m in the inflow tube and measuring the oxygen concentration at 3 m in the outflow tube. The difference in oxygen concentration between inflow and outflow water is the amount of dissolved oxygen transferred by a specific diffuser. The loading rate of each diffuser was calculated by multiplying the oxygen differential by the volumetric flow of the aerator as measured by the current meter.

Each diffuser was operated for several minutes before a final oxygen and current measurement were recorded. The temperature of the hypolimnetic water changed very little during the experiment, and the influent oxygen concentrations were essentially constant at 0.4 mg/L (Table 2.5).

Orifi	ce Size	Air Flow Rate			
1/8"	$(3175 \ \mu)$	$5.005 \text{ ft}^3/\text{min}$	(141.7 L/min)		
1/16"	$(1588 \ \mu)$	$1.255 \text{ ft}^3/\text{min}$	(35.5 L/min)		
1/32"	$(794 \mu$	$0.351 \text{ ft}^3/\text{min}$	(9.9 L/min)		

Table 2.6: Discharge of air through an orifice at 20 psig (1.4 kg/cm^2) .

2.2.5 Diffuser Type and Orifice Size

Two types of diffusers were used in the field experiments; coarse bubble diffusers and silica glass diffusers. The coarse bubble diffusers were constructed of 3.8 cm ID Schedule 80 PVC pipe. The diffusers were cross-shaped, with 4 arms joining into a common center. The center of the cross was fitted with a 1.9 cm hose nipple for attaching 1.9 cm ID compressed air hose. The outside dimensions of the diffusers were 69 cm and they fit inside the 0.76 m outlet tube with 3.5 cm clearance on either side.

The coarse bubble diffusers were fabricated in three orifice sizes: 1/8" (3175 μ); 1/16" (1588 μ); and 1/32" (794 μ). A 1/64" (397 μ) diffuser was not possible in this size range due to the large number of orifices required (1280) and the high breakage rate of 1/64" bits when drilling schedule 80 PVC pipe. The number of holes drilled in each diffuser was as follows:

• 1/8" (3175 μ) - 20 holes (5 on each arm)

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- 1/16" (1588 μ) 80 holes (20 on each arm)
- 1/32" (794 μ) 320 holes (80 on each arm)

Standard tables of air discharge through an orifice at 20 psig (1.4 kg/cm^2) (assuming a discharge coefficient of 0.65 for a sharp edged orifice) are shown in Table 2.6. The compressor was rated for a maximum output of 40 ft³/min FAD $(1.13 \text{ m}^3/\text{min})$ @ 100 psig

(7.0 kg/cm²), and was operated at 10 ft³/min (0.28 m³/min) @ 100 psig (7.0 kg/cm²) throughout the experiments. According to Boyle's Law, $P_1V_1 = P_2V_2$ at constant temperature (Atlas Copco, 1978). Therefore, 10 ft³/min (0.28 m³/min) @ 114.7 psia (8.1 kg/cm²) is equivalent to 33 ft³/min (0.93 m³/min) @ 34.7 psia (2.4 kg/cm²). Each diffuser was capable of passing the following amounts of air:

- 1/8" (3175 μ) 20 x 5.005 ft³/min = 100 ft³/min (2.8 m³/min) @ 20 psig (1.4 kg/cm²);
- 1/16" (1588 μ) 80 x 1.255 ft³/min = 100 ft³/min (2.8 m³/min) @ 20 psig (1.4 kg/cm²);
- 1/32" (794 μ) 320 x 0.351 ft³/min = 112 ft³/min (3.2 m³/min) @ 20 psig 1.4 kg/cm²).

Therefore, orifice size and number were not considered restrictive to air flow at the experimental flow rates.

The silica glass diffusers were obtained from Aquatic Ecosystems Inc. (Apoka, Florida) in the 140 μ maximum pore size (Model ALR-23). The external dimensions of the diffusers were 23 cm L x 3.8 cm W x 3.8 cm D. Each diffuser weighed 1.35 lb (0.61 kg) and was fitted with a 0.5" (1.27 cm) NPT fitting. The diffusers were connected to a 1.5" (3.81 cm) PVC 4 way center, and arranged in a spiral pattern.

As mentioned previously, the diffusers were lowered into the inflow tube to a depth of 3 m or 7 m, and suspended by the 3/4" (1.9 cm) air hose attached to the center hose nipple. The silica glass diffusers were sufficiently heavy to remain submerged when operating; however, the coarse bubble diffusers required 10 lbs (4.5 kg) of additional weight to remain submerged. Both coarse and glass diffusers were lowered into position with the compressor running, to avoid flooding the coarse bubble diffusers and causing an uneven discharge of air.

No.	Orifice Size (μ)	Depth (m)
1.	140	3
2.	140	7
3.	794	3
4.	794	7
5.	1588	3
6.	1588	7
7.	3175	3
8.	3175	7

Table 2.7: Group 4 experimental treatments.

2.2.6 Experimental Design

The field experiments were divided into two groups; Group 4 and Group 5. The treatments examined in Group 4 were: the effect of orifice size $(3175 \ \mu, 1588 \ \mu, 794 \ \mu$ and 140 μ) and depth of air release (3 m or 7 m). This resulted in 8 combinations of depth and orifice size (Table 2.7). The Group 4 experiments were conducted in the same randomized complete block design as Groups 1-3. Each treatment was replicated 5 times. The Group 4 experiments were conducted on September 24, 1987.

The treatments examined in Group 5 were: the effect of orifice size (140 μ and 3175 μ) and the effect of a floating surface cover of 2.5 cm styrene foam board (present or absent). This resulted in 4 combinations of orifice size and cover (depth fixed at 7 m) (Table 2.8). The Group 5 experiments were also conducted in a randomized complete block design, replicated five times and conducted on September 25, 1987.

No.	Orifice Size (μ)	Cover
1.	140	No
2.	140	Yes
3.	3175	No
4.	3175	Yes

Table 2.8: Group 5 experimental treatments.

2.3 Parameter Calculation

2.3.1 Lab Experiments

Calculation of the oxygen transfer coefficient (K_La) is usually done by plotting the dissolved oxygen (DO) deficit vs time data on one-cycle semi-logarithmic graph paper, and the slope of the line is the overall oxygen transfer coefficient (K_La_T) (APHA et al., 1980). The formula for calculating K_La_T is:

$$K_L a_T = \frac{\ln[C_s - C_1] / [C_s - C_2]}{t_2 - t_1}$$
(2.4)

where:

ln = natural logarithm

 $K_L a_T = oxygen transfer coefficient at the temperature of the testwater, (hr⁻¹)$ $<math>C_1 = DO (mg/L)$ at point 1 on the graph $C_2 = DO (mg/L)$ at point 2 on the graph $C_s = DO$ saturation concentration (mg/L)

 $t_1 = time at point 1 on the graph (hr)$

 $t_2 = time at point 2 on the graph (hr)$

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

$$C_s = C_{s760} \frac{Pb}{760} \tag{2.5}$$

where:

 $C_s = DO$ saturation concentration during test (mg/L)

 $C_{s 760} = DO$ saturation at 760 mm Hg total pressure (mg/L)

Pb = barometric pressure during test (mm Hg)

Since the tests were conducted below 1000 m elevation and 25 degrees C, there was no correction in C_s for the vapor pressure of water (APHA et al., 1980). The saturation pressure was not corrected for mid-depth oxygen partial pressure as the test tanks were very shallow (0.8 m in the cylinder and 0.34 m in the square tank).

The problems with the graphical method of K_L a estimation are threefold:

- 1. Errors generated when reading numbers off the x and y axis;
- Errors generated when plotting the line when the data points do not fall in a straight line;
- 3. The time required to draw the graphs, the main purpose of which is to obtain the time estimates of t_1 and t_2 , corresponding to 20% and 80% of oxygen saturation.

When this researcher began analyzing the data, it was clear that human error was introduced from the graphical determination of t_1 and t_2 , and the time required to draw 205 graphs was a major impediment to completing this project in a timely and unbiased manner. As a result, it was decided to eliminate the graphical procedure, and estimate t_1 and t_2 directly from a simple linear regression of time vs natural logarithm of the oxygen deficit. This researcher used 10% and 60% saturation values to calculate t_1 and t_2 , as the time required to reach 80% saturation in the 239 L tank exceeded the 30 minute time limit recommended by Beak (1977), especially when testing the larger coarse bubble diffusers.

The regression of time vs ln oxygen deficit and subsequent calculation of K_La was done on a DEC Professional 350 microcomputer with the Pro 20/20 spreadsheet. The time required to write the spreadsheet template and command procedure, enter and check the data and calculate K_La_T for 205 separate tests was 4 days. K_La_T was converted to K_La_{20} according to:

$$K_L a_{20} = K_L a_T / \theta^{T-20} \tag{2.6}$$

where:

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

The spreadsheet program also calculated the standard oxygen transfer rate (OT_s, in grams O_2/hr) and the energy efficiency (E_p, in grams O_2/kW -hr). OT_s was calculated as follows (Boyd, 1976):

$$OT_{s} = K_{L}a_{20} DO_{20} V \tag{2.7}$$

where:

 $OT_s = standard oxygen transfer rate (g O_2/hr);$

 $DO_{20} = DO$ concentration (mg/L) at saturation for 20 degrees C and standard pressure (760 mm Hg);

 $V = volume of water in tank, m^3$.

 E_p was calculated as follows (APHA et al., 1980):

$$E_p = OT_s / P \tag{2.8}$$

where:

 E_p = energy efficiency in grams O_2/kW -hr; P = power input, kW.
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The power input (P) for each air flow rate 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 @ 0 kg/cm² (psig) with a nameplate horsepower of 0.1243 kW. The following power inputs were used for the Group 1-3 E_p calculations:

1. 9.4 L/min =
$$\frac{9.4L/min}{36.8L/min} \ge 0.1243 \text{ kW} = 0.0317 \text{ kW};$$

2. 18.8 L/min =
$$\frac{18.8L/min}{36.8L/min} \ge 0.1243$$
 kW = 0.0635 kW;

3. 28.3 L/min =
$$\frac{28.3L/min}{36.8L/min}$$
 x 0.1243 kW = 0.0956 kW.

The oxygen transfer efficiency $(E_o, \%)$ (weight of oxygen dissolved / weight of oxygen supplied x 100) was calculated as follows:

Each air flow rate ie. 9.4 L/min, 18.9 L/min and 28.3 L/min was multiplied by 0.21 to reflect the percent oxygen composition by volume of air (Atlas Copco, 1978). These values were multiplied by 60 min/hr to derive the L/hr of O₂ gas supplied to the test tank, then divided by 22.4 L/mole to obtain the number of moles supplied, then multiplied by the molecular weight of O₂ (32 g/mole) to obtain the grams of O₂ supplied per hour. This value was divided into the OT_s (grams O₂/hr) and multiplied by 100 to derive a percent transfer efficiency (E_c). An example is:

18.9 L/min of air supplied x 0.21 = 3.97 L/min O₂ supplied;

and multiplied by 60 min/hr = 238.14 L/hr O₂ supplied;

and divided by 22.4 L/mole = 10.631 moles supplied; .

and multiplied by 32 g/mole = 340.19 g O₂/hr supplied.

 $OT_s = 16.16 \text{ g } O_2/hr$, therefore $E_o = 16.16 \text{ g } O_2/hr / 340.19 \text{ g } O_2/hr \times 100 = 4.75\%$.

2.3.2 Field Experiments

Four parameters were calculated or measured for the field experiments. Oxygen input per cycle (mg/L) is the measured difference in oxygen concentration between outflow water at 3 m in the outlet tube and inflow water at the entrance of the intake tube (8 m).

Daily oxygen load (kg O_2/day) is the product of the oxygen input per cycle (g/m³) and the daily volumetric flow (Q_w) (m³/day) as calculated by:

$$Q_w = \pi r^2 v \tag{2.9}$$

where:

r = radius of outflow tube (m)

v = velocity of outflow water (m/sec)

The oxygen transfer efficiency (E_o) for the field experiments was calculated as follows: The compressor was operated at a constant air flow of 0.28 m³/min (10 ft³/min) @ 8.1 kg/cm² (114.7 psia) throughout the experiments, as measured by a flowmeter and a series of pressure gauges. The volume of intake air was then calculated to be 2.21 m³/min (78 ft³/min) at 1.03 kg/cm² (14.7 psia) using Boyle's Law (P₁V₁ = P₂V₂ at constant temperature).

The weight of oxygen supplied per day was then calculated by the same procedure used in the laboratory oxygen transfer efficiency calculations ie. 2.21 m³/min x 1000 $L/m^3 x 60 min/hr x 24 hr/day x 0.21 (\% O_2) / 22.4 L/mole x 32 g/mole O_2 / 1000g/kg$ = kg O₂ supplied per day. The weight of oxygen transferred per day divided by the weight of oxygen supplied to the lake x 100 = the oxygen transfer efficiency for the field experiments (E_o).

The aeration efficiency (E_p) was calculated as the daily load divided by the daily power input. The power input was adjusted to reflect the fraction of the compressor's energy consumption required to deliver a fixed air flow rate. The compressor was rated at $1.13 \text{ m}^3/\text{min FAD}$ at 7.0 kg/cm² with a nameplate horsepower of 7.5 kW. The compressor delivered 0.28 m³/min @ 7.0 kg/cm² for the Group 4 and 5 experiments, so the adjusted power input was $0.28/1.13 \times 7.5 = 1.858 \text{ kW}$.

2.3.3 Statistical Analysis

The statistical procedure used to analyze experimental and field 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 Anova was conducted on $K_{La_{20}}$, OT_s , E_p and E_o for Groups 1, 2 and 3; and on water velocity, oxygen input per cycle, daily oxygen load, E_o and E_p for Groups 4 and 5. The arc sin square root transform was used on the E_o Anova's to reduce the skewness of the percentage values (Larkin, 1975).

In situations where the null hypothesis was rejected, a comparison among means test was conducted using Scheffé's test. The level of significance was also set at $\alpha = 0.01$ for Scheffé's test. This is the most rigorous a posteriori test and is recommended by statistical purists when doing comparison among means tests (Larkin, 1975).

The initial Anova was set up to show the significance of the first, second and third order interaction effects. The standard procedure was to examine the second and third order interactions for significant results, then add the second and third order interaction sum of squares into the residual sum of squares and recalculate the Anova if no significant results were obtained. This leaves the main and first order interactions, which are easier to explain, and avoids the convoluted statements associated with explaining higher order interactions. This procedure was recommended by Dr. J. Berkowitz, Co-ordinator of the Statistical Consulting and Research Laboratory (SCARL) at UBC.

The overall experimental design was as follows:

Group	Experimental System	Variables
1	Laboratory	Air flow rate (9.4, 18.8 L/min)
	(70 L cylinder)	Orifice size $(397, 794, 1588, 3175 \mu)$
		Cover (yes, no)
2	Laboratory	Air flow rate $(9.4, 18.8 \text{ L/min})$
	(70 L cylinder)	Orifice size $(40, 140 \mu)$
		No. of diffusers $(1, 2)$
		Cover (yes, no)
3	Laboratory	Orifice size (40, 397, 1588 μ)
	(239 L tank)	Cover (yes, no, no $+$ wind)
4	Field	Orifice size $(140, 794, 1588, 3175 \mu)$
	(Hypolimnetic aerator)	Diffuser depth (3, 7m)
5	Field	Orifice size $(140, 3175 \mu)$
	(Hypolimnetic aerator)	Cover (yes, no)

Chapter 3

Results

3.1 Group 1: $K_L a_{20}$ and OT_s

The results for the Anova on Group 1 $K_L a_{20}$ and OT_s are shown in Appendix A. Significant results ($\alpha \leq 0.01$) were obtained for air flow rate, orifice size, air flow rate by size interaction and replicate days. There was no significant effect of surface cover on $K_L a_{20}$ or OT_s . The significant and non-significant results are similar for $K_L a$ and OT_s as the values of OT_s are derived from the initial $K_L a_{20}$ calculation.

3.1.1 Air Flow Rate

The air flow rate supplied to the diffusers produced the most significant result (Figure 3.1). The cell means for $K_{L}a_{20}$ and OT_s (Standard Deviation in brackets) for the two air flow rates studied, low flow (9.4 L/min) and medium flow (18.8 L/min) are shown in Table 3.9. The net result is that doubling the air flow rate produced a 122% increase in $K_{L}a_{20}$ and OT_s .

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/hr)$	n
Low Flow	4.5 (1.7)	2.8 (1.1)	40
High Flow	10.0(3.7)	6.2(2.3)	40

Table 3.9: Effect of air flow rate on Group 1 K_La_{20} and OT_s .



9.4 L/min18.8 L/minFigure 3.1: Effect of air flow rate on Group 1 K_La_{20} , E_p and E_o .

Treatment	${ m K}_L{ m a_{20}}~({ m hr^{-1}})$	$OT_s (g O_2/hr)$	n
397μ	11.5 (4.5)	7.1 (2.8)	20
794 μ	7.3(2.9)	4.5(1.8)	20
$1588~\mu$	5.5(2.2)	3.4(1.4)	20
$3175 \ \mu$	4.8(2.1)	3.0(1.3)	20

Table 3.10: Effect of orifice size on Group 1 K_La_{20} OT_s.

3.1.2 Orifice Size

Orifice size produced the next most significant result (Figure 3.2). The cell means for $K_{La_{20}}$ and OT_s (Standard Deviation in brackets) for the four orifice sizes studied (397 μ , 794 μ , 1588 μ and 3175 μ) are shown in Table 3.10. Scheffé's test was used in the comparison among means test for the four orifice sizes. The Scheffé's test indicates that the 397 μ orifice diffuser is significantly greater ($\alpha = 0.01$) for $K_{La_{20}}$ and OT_{20} , and the remaining three diffusers (794 μ , 1588 μ and 3175 μ) are not significantly different from each other.

3.1.3 Air Flow Rate by Size Interaction

A significant air flow rate by size interaction effect was detected for K_La_{20} and OT_s . A graphical plot of the data (K_La vs orifice size) (Figure 3.3) reveals the magnitude of the difference between cell means for K_La_{20} at low and medium air flow rates increases as orifice size decreases.

3.1.4 Replication

A significant effect was observed for the replication procedure used in the experiments. The cell means for $K_{L}a_{20}$ and OT_s (Standard Deviation in brackets) for the five replicate days are shown in Table 3.11. A comparison among means using Scheffé's test was



Figure 3.2: Effect of orifice size on Group 1 K_La₂₀.



Figure 3.3: Group 1 air flow rate by size interaction effect for K_La_{20}

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/hr)$	n
Day 1	6.6(3.6)	4.1(2.2)	16
Day 2	7.8(4.4)	4.8(2.8)	16
Day 3	7.6(4.1)	4.7(2.5)	16
Day 4	7.2(4.1)	4.4(2.5)	16
Day 5	7.1(4.1)	4.4(2.5)	16

Table 3.11: Effect of replication on Group 1 K_La_{20} and OT_s .

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/hr)$	n
Cover	7.2 (4.0)	4.4 (2.5)	40
No Cover	7.4(4.0)	4.6~(2.5)	40

Table 3.12: Effect of surface cover on Group 1 $K_{La_{20}}$ and OT_s .

unable to distinguish any significant differences among the five replicate days on which the experiments were conducted.

3.1.5 Surface Cover

The presence or absence of a surface cover did not exert a significant effect. The cell means for $K_{L}a_{20}$ and OT_s (Standard Deviation in brackets) for the cover treatment are shown in Table 3.12. The data suggest that the presence of a surface cover may reduce $K_{L}a_{20}$ and OT_s ; however, a larger sample size is required to adequately assess this treatment.

3.2 Group 1: E_o and E_p

The results for the Anova on Group 1 E_o and E_p are shown in Appendix A. Significant results ($\alpha \leq 0.01$) were obtained for orifice size, air flow, replicate days and surface cover. There was no significant interaction effect on E_p and E_o .

Treatment	E_o (%)	$E_p (g O_2/kW-hr)$	n
397μ	2.8(0.21)	147.5(11.4)	20
$794 \ \mu$	1.7 (0.16)	93.0(8.4)	20
$1588~\mu$	1.3 (0.13)	70.4(7.3)	20
$3175~\mu$	1.1(0.14)	60.5(7.6)	20

Table 3.13: Effect of orifice size on Group 1 E_o and E_p .

Treatment	$\mathrm{E}_{o}(\%)$	$E_p (g O_2/kW-hr)$	n
Low Flow	1.6 (0.63)	87.6 (33.9)	40
Medium Flow	1.8(0.67)	98.2(35.7)	40

Table 3.14: Effect of air flow rate on Group 1 E_o and E_p .

3.2.1 Orifice Size

Orifice size produced the most significant result (Figure 3.4 and 3.5). The cell means for E_o and E_p (Standard Deviation in brackets) for the four orifice sizes examined (397 μ , 794 μ , 1588 μ and 3175 μ) are shown in Table 3.13. Scheffé's test was used in the comparison among means test for the four orifice sizes. The test indicates each orifice size is significantly different from each other ($\alpha = 0.01$) for E_o and E_p , and that both transfer efficiency and energy efficiency decrease with increasing orifice size.

3.2.2 Air Flow Rate

The air flow rate to the diffusers produced the next most significant result (Figure 3.1). The cell means for E_o and E_p (Standard Deviation in brackets) for the two air flow rates studied, low flow (9.4 L/min) and medium flow (18.8 L/min) are shown in Table 3.14.



Figure 3.4: Effect of orifice size on Group 1 E_o.



Figure 3.5: Effect of orifice size on Group 1 E_p .

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Treatment	E_o (%)	$E_p (g O_2/kW-hr)$	n
Cover	1.7(0.66)	91.4 (35.6)	40
No Cover	$1.8 \ (0.65)$	94.3 (34.8)	40

Table 3.15: Effect of surface cover on Group 1 E_o and E_p .

3.2.3 Replication

A significant result was observed for the replication procedure used in the experiments. The F value of the replication effects is small (≈ 20) in relation to the main experimental effects and does not change the overall conclusions of the experiment.

3.2.4 Surface Cover

A marginally significant result was observed for the cover-no cover treatment. The cell means for E_o and E_p (Standard Deviation in brackets) are shown in Table 3.15. The F value of the cover-no cover treatment is very small (\approx 7-11) in relation to the main experimental effects. The presence of a surface cover may reduce E_o and E_p ; however, a larger sample size is required to adequately assess this treatment.

3.3 Group 2: $K_L a_{20}$ and OT_s

The results for the Anova on Group 2 $K_L a_{20}$ and OT_s are shown in Appendix B. Significant results were obtained for air flow rate, number of diffusers, air flow rate by number of diffuser interaction and surface cover. There was no significant effect of orifice size or replicate days on $K_L a_{20}$ or OT_s .

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/kW-hr)$	n
Low Flow	11.6(1.7)	7.2 (1.0)	40
Medium Flow	22.9(3.8)	14.2 (2.3)	40

Table 3.16: Effect of air flow rate on Group 2 K_La_{20} and OT_s .

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/kW-hr)$	n
One Diffuser	15.3(5.5)	9.5 (3.4)	40
Two Diffuser	19.1 (6.7)	11.8(4.1)	40

Table 3.17: Effect of diffuser number on Group 2 $K_{La_{20}}$ and OT_s .

3.3.1 Air Flow Rate

The air flow rate supplied to the diffusers produced the most significant result (Figure 3.6). The cell means for $K_{L}a_{20}$ and OT_s (Standard Deviation in brackets) for the two air flow rates examined, low flow (9.4 L/min) and medium flow (18.8 L/min) are shown in Table 3.16. The net result is that doubling the air flow rate produced a 90% increase in $K_{L}a_{20}$ and OT_s .

3.3.2 Number of Diffusers

The number of silica glass diffusers used in the experiment (1 or 2) produced the next most significant result (Figure 3.7). The cell means for K_La_{20} and OT_s (Standard Deviation in brackets) are shown in Table 3.17. The net result is that increasing the numbers of diffusers from 1 to 2 at a constant air flow rate produced a 25% increase in K_La_{20} and OT_s .



Figure 3.6: Effect of air flow rate on Group 2 K_La_{20} , E_p and E_o .



Figure 3.7: Effect of diffuser number on Group 2 K_La_{20} and E_o .

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/kW-hr)$	n
Cover	17.8 (6.8)	11.0(4.2)	40
No Cover	16.6(5.9)	10.3 (3.7)	40

Table 3.18: Effect of surface cover on Group 2 $K_{La_{20}}$ and OT_s .

3.3.3 Air Flow Rate by Number of Diffusers Interaction

A significant air flow rate by number of diffusers interaction effect was observed for K_La_{20} and OT_s . A graphical plot of the data reveals that the magnitude of the difference, between the cell means for K_La_{20} at one or two diffusers, increases with increased air flow rate (Figure 3.8).

3.3.4 Surface Cover

A barely significant inverse result was observed for the cover-no cover treatment. The cell means for K_La_{20} and OT_s (Standard Deviation in brackets) are shown in Table 3.18.

3.3.5 Orifice Size and Replicate Days

There was no significant effect of orifice size or replicate days on $K_{La_{20}}$ and OT_{s} in the Group 2 experiments. The cell means for orifice size and replicate days (Standard Deviation in brackets) are shown in Table 3.19.

3.4 Group 2: E_o and E_p

The results for the Anova on Group 2 E_o and E_p are shown in Appendix B. A significant result ($\alpha \leq 0.01$) was obtained for the number of diffusers treatment. There were no significant results from the air flow rate, orifice size, surface cover, interaction or replication



Figure 3.8: Group 2 air flow rate by number of diffusers interaction effect on $K_{La_{20}}$.

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/kW-hr)$	n
40μ	17.5(6.6)	10.8 (4.1)	40
$140 \ \mu$	17.0(6.2)	10.5 (3.9)	40
Day 1	17.5 (8.2)	10.8(5.1)	16
Day 2	17.7 (6.4)	11.0(4.0)	16
Day 3	17.3(6.0)	10.7 (3.7)	16
Day 4	16.6(5.8)	10.3 (3.7)	16
Day 5	17.1 (5.9)	10.6(3.7)	16

Table 3.19: Effect of orifice size and replication on Group 2 K_La_{20} and OT_s .

Treatment	E_o (%)	$E_p (g O_2/kW-hr)$	n
One Diffuser	3.8(0.52)	201.1 (27.7)	40
Two Diffuser	4.6(0.41)	248.8(21.8)	40

Table 3.20: Effect of diffuser number on Group 2 E_o and E_p .

treatments.

3.4.1 Number of Diffusers

The number of silica glass diffusers (1 or 2) used produced the only significant effect on E_o and E_p from the Group 2 treatments (Figure 3.7). The cell means for E_o and E_p (Standard Deviation in brackets) are shown in Table 3.20.

3.5 Group 3: $K_L a_{20}$ and OT_s

The results for the Anova on Group 3 K_La_{20} and OT_s are shown in Appendix C. Significant effects ($\alpha \leq 0.01$) were observed for orifice size and surface cover. There were no significant effects of replication or interaction.

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/hr)$	n
40μ	6.3(0.5)	13.3 (1.0)	15
$397~\mu$	3.7(0.3)	7.8(0.6)	15
$1588 \ \mu$	2.0(0.1)	4.3(0.3)	15

Table 3.21: Effect of orifice size on Group 3 K_La_{20} and OT_s .

Treatment	$K_L a_{20} (hr^{-1})$	$OT_s (g O_2/hr)$	n
Cover	3.8 (1.8)	8.1 (3.8)	15
No cover	4.3(2.0)	9.0 (4.1)	15
No cover $+$ wind	3.9(1.8)	8.3(3.8)	15

Table 3.22: Effect of surface conditions on Group 3 K_La_{20} and OT_s .

3.5.1 Orifice Size

Orifice size was highly significant. The cell means for $K_{L}a_{20}$ and OT_s (Standard Deviation in brackets) for the three orifice sizes studied (40 μ , 397 μ and 1588 μ) are shown in Table 3.21. Scheffé's test was used in the comparison among means test for the three orifice sizes examined. Scheffé's test indicates each diffuser is significantly different ($\alpha = 0.01$) from each other for $K_{L}a_{20}$ and OT_s .

3.5.2 Surface Cover

A marginally significant effect was produced by the surface cover treatment. The three treatment (cover, no cover, no cover plus wind) cell means for K_La_{20} and OT_s (Standard Deviation in brackets) are shown in Table 3.22. Scheffé's test was used in the comparison among means test for the three surface treatments. The test indicates no two treatments were significantly different at the $\alpha = 0.01$ level.

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Treatment	E_o (%)	$E_p (g O_2/kW-hr)$	n
40μ	2.6(0.2)	140.1 (10.4)	15
$397~\mu$	1.5(0.1)	82.1 (6.6)	15
$1588~\mu$	0.8(0.1)	44.7(3.1)	15

Table 3.23: Effect of orifice size on Group 3 E_o and E_p .

3.6 Group 3: \mathbf{E}_o and \mathbf{E}_p

The results for the Anova on Group 3 E_o and E_p are shown in Appendix C. Significant results were obtained for orifice size and surface cover. There were no significant replication or interaction effects.

3.6.1 Orifice Size

Orifice size was highly significant, and the cell means for the three orifice sizes studied (40 μ , 397 μ and 1588 μ) (Standard Deviation in brackets) are shown in Table 3.23. Scheffé's test indicates each diffuser orifice size is significantly different ($\alpha = 0.01$) from each other for E_o and E_p , and that E_o and E_p increase with decreasing orifice size.

3.6.2 Surface Cover

A marginally significant effect was produced for the surface cover treatment, and the cell means for the three treatments (Standard Deviation in brackets) are shown in Table 3.24. Scheffé's test was unable to distinguish a significant difference between the treatments $(\alpha = 0.01)$ in the comparison among means test.

Treatment	E. (%)	$E_p (g O_2/kW-hr)$	n
Cover	1.6(0.8)	85.2 (40.2)	15
No cover	1.8(0.8)	94.5~(43.2)	15
No cover $+$ wind	1.6(0.7)	87.3 (39.8)	15

Table 3.24: Effect of surface conditions on Group 3 E_o and E_p .

Orifice (μ)	Air Flow (L/sec)	Mean Equivalent diameter (mm)	n	CV
40 µ	18.8	3.8	20	15.5
$40 \ \mu$	9.4	4.2	20	23.1
$140 \ \mu$	18.8	4.5	20	26.9
140 μ	9.4	3.8	20	21.8
$397~\mu$	18.8	5.0	20	16.6
$397~\mu$	9.4	4.4	20	21.4
794 μ	18.8	4.4	20	42.5
794μ	9.4	7.6	7	21.5
$1588~\mu$	18.8	7.1	20	31.8
$1588 \ \mu$	9.4	8.2	20	44.3
$3175~\mu$	18.8	7.8	20	31.0
$3175 \ \mu$	9.4	6.6	20	3 0. 3

Table 3.25: Equivalent bubble diameter as a function of air flow and orifice size.

3.7 Bubble Size

The results of the bubble size analysis from the lab experiments are shown in Table 3.25. The results confirm the visual observations that smaller orifice sizes generate smaller bubbles. A clear trend toward increasing bubble size with increasing orifice diameter was obtained (Figure 3.9). There was no obvious trend for the effect of air flow on bubble size for a given orifice size. The coefficient of variation increased with increasing bubble size. This is also in agreement with visual observations as orifice sizes larger than 397 μ generated a wider range of bubble sizes, which continuously coalesced and fragmented during their ascent through the water column.





Treatment	Water Velocity (m/sec)	Oxygen Input (mg/L)	Daily Load (kg)	n
3 m	0.17 (0.04)	0.62 (0.19)	4.0 (1.2)	20
7 m	0.38(0.02)	0.73 (0.15)	10.9(2.1)	20

Table 3.26: Effect of diffuser depth on Group 4 (field experiments) water velocity, oxygen input and daily load.

Treatment	E_o (%)	$E_p (kg O_2/kW-hr)$	n
3 m	0.4 (0.13)	0.09 (0.03)	20
7 m	1.2(0.23)	0.24(0.05)	20

Table 3.27: Effect of diffuser depth on Group 4 (field experiments) E_o and E_p .

3.8 Group 4: Water Velocity, Oxygen Increase Per Cycle, Daily Oxygen Load, E_o and E_p

The results for the Anova on Group 4 water velocity, oxygen increase per cycle, daily oxygen load, E_o and E_p are shown in Appendix D.

3.8.1 Depth of Air Diffuser

The depth of the air diffuser in the inflow tube had a significant effect on water velocity in the outflow tube, oxygen increase per cycle, daily oxygen load, E_o and E_p (Figure 3.10). The cell means (Standard Deviation in brackets) for the two depths of air release (3 m and 7 m) are shown in Table 3.26 and 3.27.

3.8.2 Orifice Size

Orifice size had a significant effect on oxygen increase per cycle, daily oxygen load, E_o and E_p , but did not significantly affect water velocity in the outflow tube (Figure 3.11). The cell means for water velocity, oxygen input, daily load, E_o and E_p (Standard Deviation in



Figure 3.10: Effect of diffuser depth on Group 4 (field experiments) water velocity, oxygen input and E_o .



Figure 3.11: Effect of Group 4 (field experiments) orifice size on water velocity, oxygen input and E_o .

Treatment	Water Velocity (m/sec)	Oxygen Input (mg/L)	Daily Load (kg)	n
140μ	0.27 (0.12)	0.89 (0.12)	9.4 (4.8)	10
$794~\mu$	0.30 (0.11)	$0.60 \ (0.14)$	7.1(3.1)	10
$1588 \ \mu$	0.27 (0.12)	0.59(0.10)	6.6(3.6)	10
$3175~\mu$	0.27(0.12)	0.61(0.12)	6.7(3.7)	10

Table 3.28: Effect of orifice size on Group 4 (field experiments) water velocity, oxygen input and daily load.

Treatment	E_o (%)	$E_p (kg O_2/kW-hr)$	n
140μ	1.0(0.52)	0.21 (0.11)	10
794 μ	0.8(0.34)	0.16 (0.07)	10
$1588~\mu$	0.7(0.40)	0.15(0.08)	10
$3175~\mu$	0.7(0.41)	0.15(0.08)	10

Table 3.29: Effect of orifice size on Group 4 (field experiments) E_o and E_p .

brackets) for the four orifice sizes examined (140 μ , 794 μ , 1588 μ and 3175 μ) are shown in Table 3.28 and 3.29. Scheffé's test was used in the comparison among means test for the four orifice sizes examined. The test indicated that the 140 μ orifice diffuser was significantly different ($\alpha = 0.01$) from the other three diffusers for oxygen input, and the remaining three diffusers (794 μ , 1588 μ and 3175 μ) were not significantly different from each other. Scheffé's test was unable to distinguish any significant differences among the four orifice sizes when applied to the cell means for daily oxygen load, E_o and E_p . The F values for daily oxygen load (≈ 12), E_o (≈ 10) and E_p (≈ 12) were barely significant in the Anova, however Scheffé's test is conservative by design and just misses separating the 140 μ diffuser from the other three diffusers.

Treatment	Water Velocity (m/sec)	Oxygen Input (mg/L)	Daily Load (kg)	n
140μ	0.40 (0.04)	0.92 (0.09)	14.5 (1.9)	10
$3175~\mu$	0.43(0.01)	0.24 (0.02)	10.5(1.0)	10

Table 3.30: Effect of orifice size on Group 5 (field experiments) water velocity, oxygen input and daily load.

Treatment	E ₀ (%)	$E_p (kg O_2/kW-hr)$	n
140μ	1.6 (0.21)	0.32(0.04)	10
$3175~\mu$	1.2(0.27)	0.63(0.05)	10

Table 3.31: Effect of orifice size on Group 5 (field experiments) E_o and E_p .

3.8.3 Replicate Days and Interactions

There were no significant effects of replicate days or interactions on water velocity, oxygen increase per cycle, daily oxygen load, E_o and E_p in the Group 4 experiments.

3.9 Group 5: Water Velocity, Oxygen Increase Per Cycle, Daily Load, E_o and E_p

The results for the Anova on Group 5 water velocity, oxygen increase per cycle, daily oxygen load, E_o and E_p are shown in Appendix E.

3.9.1 Orifice Size

Orifice size had a significant effect on oxygen increase per cycle, daily oxygen load, E_o and E_p but did not significantly influence water velocity in the outflow tube. The cell means (Standard Deviation in brackets) for the two orifice sizes (140 μ and 3175 μ) are shown in Table 3.30 and 3.31.

3.9.2 Surface Cover, Replicate Days and Interaction

Surface cover, replicate days and interactions had no significant effect on water velocity, oxygen increase per cycle, daily oxygen load, E_o and E_p in the Group 5 experiments. Although the cover-no cover treatment was not significant, the data trend suggests slightly higher values for all measured parameters occurred when the surface cover was absent.

Chapter 4

Discussion: Gas Transfer Theory

A brief review of gas transfer theory and the non-steady state aeration test is required before discussing the experimental results.

4.1 Gas Transfer Theory

Several theories have been proposed to describe the mass transfer of a sparingly soluble gas such as oxygen to water (Krenkel and Orlob, 1962). Although these theories are approximations of the actual physical process, the theory which best describes the transfer mechanism was proposed by Dobbins (1964). This theory is a combination of the classic Whitman Two Film theory (Lewis and Whitman, 1924) and the Surface Rejuvenation theory (Dankwertz, 1951).

The Two Film theory was developed in 1924 (Lewis and Whitman, 1924) and later revised by Ippen et al. (1952) for the computation of oxygen absorption rates in water (Mavinic and Bewtra, 1974). According to this theory, a gas passes through two films of gas and liquid, respectively, by molecular diffusion and the mass transfer is driven by a partial pressure gradient in the gas phase and a concentration gradient in the liquid phase. Initially oxygen molecules from the gas phase are transported to the liquid film surface, resulting in saturation conditions at the interface. For slightly soluble gases such as oxygen, the gas film offers very little resistance and this phase proceeds rapidly. The liquid interface or film is estimated to be at least three molecules thick and composed of water molecules oriented with their negative sides (ie. oxygen) facing the gas phase

(Eckenfelder and Ford, 1968).

In the next phase, oxygen molecules slowly pass through this film by molecular diffusion. All of the resistance to the passage of oxygen into the water is due to molecular diffusion across the liquid film (Eckenfelder, 1959). In the final stage, oxygen is mixed into the water by diffusion and convection currents. At low mixing levels (ie. laminar flow conditions) the rate of oxygen absorption is regulated by the rate of molecular diffusion through the undisturbed liquid film and the Two Film theory holds true. However, as turbulence levels increase, the surface film is disrupted and renewal of the film becomes responsible for transferring oxygen to the liquid (Eckenfelder, 1969).

Dobbins (1964) resolved this dilemma by developing the following equation to describe the liquid film coefficient (K_L) (King, 1970):

$$K_L = \sqrt[2]{D}_L r \ coth \ \frac{\sqrt[2]{r} \ l^2}{D_L} \tag{4.10}$$

where:

 K_L = liquid film coefficient (m/hr) D_L = diffusion coefficient for oxygen (m²/hr) r = rate of surface renewal l^2 = liquid film thickness (m).

When the rate of surface renewal (r) is near zero (ie. laminar flow conditions), equation [4.10] reduces to:

$$K_L = D_L/l \tag{4.11}$$

and the transfer is controlled by molecular diffusion through the liquid film according to the Two Film theory.

As the rate of renewal increases equation [4.10] reduces to:

$$K_L = \sqrt[2]{D_L r} \tag{4.12}$$

and the mass transfer becomes a function of the rate of surface renewal as described by the Dankwertz Surface Rejuvenation theory. These two models may be regarded as the limits between which both transfer mechanisms contribute to the overall oxygen transfer process. In the transitional zone between molecular diffusion and turbulent mixing, the process may be visualized as a transfer, in series, through the diffusional sublayer, at the interface whose boundary layer is subjected to turbulence and subsequent surface renewal (O'Connor, 1982).

Mathematically, this theory can be expressed as follows (Mavinic and Bewtra, 1974):

$$dm/dt = K_L A (C_i - C_L) \tag{4.13}$$

where:

dm/dt = time rate of mass transfer (g/hr)

 K_L = liquid film coefficient (m/hr)

A = interfacial or absorbing surface area of air (m^2)

 C_i = saturation value of dissolved oxygen at the interface between liquid and air bubble (mg/L)

 C_L = average concentration of dissolved oxygen in the bulk liquid (mg/L).

This mass equation may be expressed in concentration units by introducing the volume of the liquid (V):

$$dc/dt = 1/V \ dm/dt = K_L \frac{A}{V} (C_i - C_L) = K_L a (C_i - C_L)$$
(4.14)

where:

dc/dt = rate of oxygen transfer (g/L/hr)

V = volume of the liquid m^3

A/V = a = the interfacial surface area of the air through which diffusion can occur generated by the particular aeration system per unit volume of water (m^2/m^3) $K_L a =$ overall oxygen transfer coefficient (hr^{-1}) In practice, it is difficult to measure K_L and (a) directly due to the hypothetical nature of l in K_L (according to the Two Film theory) and the technical difficulties of measuring (a) (ie. A/V). Therefore, it has become standard practice to consider the aeration process in terms of the overall oxygen transfer coefficient (K_La) when evaluating aeration equipment (Nienow, 1980).

4.2 Non-Steady State Reaeration Test

The experimental procedure used to obtain $K_L a$ is the clean water non-steady state reaeration test as defined by APHA et al., (1980). As mentioned earlier, the non-steady state reaeration test involves deoxygenating a known volume of water and measuring the rate of reoxygenation. The slope of the DO deficit vs time data when plotted on onecycle semi-logarithmic paper is the overall oxygen transfer coefficient ($K_L a_T$). Although several different aeration tests exist (Beak, 1977), the non-steady state test is regarded as the most accepted method for comparing the performance of various aeration systems (Lakin and Salzman, 1979; Ewing et al., 1979).

The reason this test has become an industry standard is due to its relative simplicity and ability to generate reasonably accurate results. The use of clean water ensures the transfer process involves diffusion only and is not confounded by chemical or biological reactions. However, a number of assumptions and proper test procedures are required to ensure the test results are meaningful.

The following assumptions are implied by the non-steady state test:

- 1. The overall mass transfer process occurs according to the Whitman Two Film theory, and the main resistance to gas transfer is due to molecular diffusion across the liquid film.
- 2. The test basin is completely mixed throughout the test period.

- 3. The $K_L a$ of the aeration system is constant throughout the test and independent of test duration and dissolved oxygen concentration.
- 4. Environmental conditions of air temperature, wind velocity and relative humidity may be ignored during the test runs, due to the assumption that the main resistance to gas transfer is due to the liquid film.
- 5. The dissolved oxygen saturation concentration remains constant throughout the test duration, and is influenced only by changes in total dissolved solids, water temperature and atmospheric pressure (Landberg, et al. 1969).

The general acceptance of the non-steady state reaeration test by the scientific and industrial community indicates the Whitman Two Film theory is adequate for describing the gas transfer process and the stated assumptions are valid for the test procedures.

However, a number of precautions must be taken to ensure the non-steady state test is properly conducted. These include:

- 1. Limiting the test time to periods of 10-30 minutes.
- 2. Using an oxygen probe to avoid measurement of entrained gas bubbles.
- 3. Collecting at least 6 data points between 10% and 80% saturation.
- Adding the cobalt chloride first, only once, and maintaining its concentration below 0.05 mg/L.
- 5. Conducting a maximum of 10 tests on a single batch of water.
- 6. Using linear least squares analysis to eliminate hand drawn line errors (Beak, 1977).

Chapter 4. Discussion: Gas Transfer Theory

Air temperatures should be less than 10 degrees C different from water temperatures during the experiments and the sodium sulfite should be premixed in a slurry before adding it to the test water, as recommended by APHA et al. (1980).

In summary, although the non-steady state test is not perfect, it remains the best method for realistically comparing various aeration devices. Provided the proper test procedures are followed, the non-steady state test is capable of an accuracy of plus or minus 5% of the true K_La value (Beak, 1977), and is reproducible within 8% for tests involving a single aerator in a single basin (APHA et al., 1980).
Chapter 5

Discussion: Group 1–3 Laboratory Experiments

A variety of factors influence the rate of oxygen transfer into water in diffused aeration systems. These include:

1. Oxygen concentration gradient (C_i-C_L) .

2. Temperature of the liquid.

3. Turbulence in and around the gas-liquid interface.

4. Depth of the liquid.

5. Contact time of the air bubble in the liquid.

6. Size of the air bubble.

7. Rate of air flow.

8. Type of diffuser.

9. Position of the diffuser.

10. Tank geometry (Mavinic and Bewtra, 1974).

The individual or collective effect of these factors directly influences the liquid film coefficient (K_L) , the interfacial area for gas transfer (a), the overall oxygen transfer coefficient (K_La) and the oxygen concentration gradient (C_i-C_L) (Mavinic and Bewtra, 1976).

Although all of these factors are important, the three key factors controlling the mass transfer of oxygen are those included in equation [4.14]: $dc/dt = K_L a(C_i - C_L)$

- 1. the hydrodynamics of the system which influence K_L ;
- 2. the area of contact between the gas and the liquid (a);
- 3. the concentration gradient between the gas and liquid phase (C_i-C_L) (Nienow, 1980).

The rationale of the laboratory experiments (Groups 1 to 3) was to maintain a relatively constant concentration gradient (C_i-C_L) via the non-steady state deoxygenation procedure, and examine the effects of air flow rate, orifice size, diffuser number and surface conditions on K_La_{20} , OT_s , E_p and E_o . Although K_La_{20} is the parameter which provides the basic information on the characteristics of each experimental configuration, the two most relevant parameters for comparing aeration systems are E_p and E_o (Bewtra and Mavinic, 1978; Beak, 1977). The effect of varying these factors on K_La_{20} , OT_s , E_p and E_o are discussed below.

5.1 Group 1

The treatments examined in Group 1 were: air flow rate (9.4 L/min or 18.8 L/min); surface cover (present or absent) and orifice size (397 μ , 794 μ , 1588 μ and 3175 μ).

5.1.1 Air Flow Rate

The air flow rate (9.4 or 18.8 L/min) to the diffusers produced the most significant result, increasing K_La and OT_s 122% with a 100% increase in air flow rate (Q_a) . As mentioned earlier, the values for OT_s are derived from the K_La_{20} , so these values respond similarly to treatment effects.

A number of researchers have observed a similar effect of flow on K_La_{20} (eg. Bewtra et al., 1970; Schmit et al., 1978) and at least two mechanisms are responsible for this result. Firstly, the increased volume of air injected into the column greatly increases the turbulence of the air-water interface. As mentioned earlier, mass transfer becomes a function of the rate of renewal of the liquid film under highly turbulent conditions, as described by the Surface Rejuvenation theory (Dobbins, 1964) [4.12]: $K_L = \sqrt[3]{D_L r}$. As r (the rate of surface renewal) increases, K_L increases. Therefore, one mechanism by which higher air flow rates generate larger K_La_{20} values is through their effect on K_L .

Secondly, higher air flow rates increase the number of bubbles present in the water column per unit time. This increases the total interfacial area available for the transfer of oxygen to the surrounding liquid (Mavinic and Bewtra, 1974). Therefore higher air flow rates also influence $K_{L}a_{20}$ via their effect on (a).

Higher air flow rates produced a 12% increase in Eo and Ep. This effect is also a result of higher turbulence and A/V ratios in the aeration column as previously discussed, and the size of bubbles and type of circulation pattern in the aeration column.

Some of the literature surveyed reported decreased transfer efficiency with increased air flow rate (eg. Bewtra and Nicholas, 1964; Ellis and Stanbury, 1980; Mavinic and Bewtra, 1976). The general explanation for this response is that air bubbles become larger with an increase in Q_a . This results in less oxygen transfer due to the reduced ratio of interfacial area to bubble volume, and decreased bubble-water contact time resulting from increased rise velocities (Mavinic and Bewtra, 1976).

This effect was not seen in the Group 1 experiments for several reasons:

1. The type of water column used in the experiments has a low circulating water velocity, similar to the System I described by Bewtra and Mavinic (1978). As a result, there is less additive effect of water velocity and the bubbles are assumed to be rising at their terminal velocity. This results in longer contact times than in systems with a circulating water velocity (eg. System II; Mavinic and Bewtra, 1976), and is less subject to decreasing E_o with increased air flow rates. Among the 4 types of systems investigated by Mavinic and Bewtra (1976), the simple column of water (System I) exhibited the least E_o response to increasing air flow rate at shallow diffuser depths.

- 2. There was no obvious effect of air flow rate on bubble size (see Table 3.25). This negated the usual effect of decreased interfacial area and contact time resulting from increased air flow rate.
- 3. The type of diffusers and resultant bubble sizes generated in these experiments are less influenced by increased air flow rate than fine bubble diffusers. Bewtra and Nicholas (1964) observed no change with E_o with increased air flow rate when using coarse bubble diffusers (Spargers), but observed a decline in E_o with Q_a when using fine bubble diffusers (Saran tubes). Ellis and Stanbury (1980) reported no significant change in E_o with increasing Q_a for coarse bubble diffusers at depths less than 4 m. However, at depths exceeding 4 m, coarse bubble E_o increased with Q_a , due to longer contact time and increased bubble shear and turbulence. Schmit and Redmon (1975) and Schmit et al. (1978) also reported increased E_o with Q_a , when testing coarse bubble diffusers in deep tanks.
- 4. The type of circulation pattern in the simple column generates more turbulence than circulating systems. In a confined column, there is considerable turbulence generated between the centrally rising air-water mixture and the adjacent water flowing in the reverse direction, to replace the water which is carried up in the air-water stream (Morgan and Bewtra, 1960). Dye additions showed considerable turbulence and eddy formation in the zone between the opposing flows. Thus,

 $K_{L}a_{20}$ values would tend to increase with Q_a . Mavinic and Bewtra (1974) also concluded that the simple column (System I) generated the highest turbulence and $K_{L}a_{20}$ values.

In summary, E_o and E_p increased with air flow rate over the range of air flows tested. Although this appears contrary to the usual response, further investigation of the literature reveals a number of instances where E_o remains constant or increases with increasing Q_a , when using coarse bubble diffusers in deep tanks (greater than 4 m) or in simple columns.

5.1.2 Orifice Size

Orifice size exerted a significant effect on K_La_{20} , OT_s , E_p and E_o . Each parameter increased with a decrease in orifice size. An examination of Table 3.25 (Bubble Size) provides the explanation for this result. A clear trend towards increasing bubble size with increasing orifice diameter was obtained for the 397 μ to 3175 μ diameter orifice range. The mean bubble size for the 3175 μ diameter orifice appears slightly smaller than the 1588 μ diameter orifice (7.2 mm vs 7.7 mm); however, the bubble measuring procedure was unable to accurately estimate the high end of the 3175 μ diameter orifice bubbles due to their extremely large size.

A reduction in bubble size produces three distinct results:

- 1. An increase in surface area per unit bubble volume (Eckenfelder, 1969).
- 2. A decrease in terminal rise velocity (Stenstrom and Gilbert, 1981)
- 3. A decrease in the liquid film coefficient (K_L) (Bewtra and Nicholas, 1964).

An increase in bubble surface area per unit volume increases the (a) in K_L and acts to increase K_La_{20} , 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 $K_L a_{20}$, OT_s, E_p and E_o of a decrease in bubble size. In this case, the net effect was an increase in $K_L a_{20}$, OT_s, E_p and E_o, 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 simple column, interfacial area and contact time are important parameters for oxygen transfer in 4 to 8 mm diameter bubbles.

A number of researchers have reported a similar effect of increased E_o with decreasing bubble size. For example, Morgan and Bewtra (1960) and Bewtra and Nicholas (1964) both observed increased E_o with fine bubble diffusers (Saran tubes) as compared to coarse bubble diffusers (Spargers).

In contrast, few papers were located which examined the effect of bubble size on $K_L a_{20}$. Mavinic and Bewtra (1976) examined $K_L a_{20}$ in a simple column, however their diffuser orifice size was fixed at 1600 μ diameter, so a comparison with the bubble sizes generated in these experiments is not possible. Bernhardt (1969) was the only paper located which examined this aspect of gas transfer, and his study showed a clear decrease in $K_L a$ with increasing bubble diameters of 2 mm and larger.

The Scheffé's test used in the statistical analysis of Group 1 results indicated each orifice size was significantly different from each other with respect to E_o and E_p . However, Scheffé's test separated only the 397 μ diameter orifice from the rest of the orifice diameters (794 μ , 1588 μ and 3175 μ) with respect to K_La_{20} and OT_s . Scheffé's test is conservative by design, and is the most rigorous a posterior test for performing comparisons among means (Larkin, 1975). Although Scheffé's Test indicates K_La_{20} and OT_s are not significantly different for the 794 μ , 1588 μ and 3175 μ orifice diameters, a clear trend is present and a larger sample size should show significant separation at the $\alpha =$

0.01 level.

5.1.3 Surface Cover

The presence of a floating surface cover did not exert a significant effect on K_La_{20} and OTs, but a marginally significant effect was detected for E_o and E_p . The cell means for K_La_{20} , OT_s , E_p and E_o suggest that slightly lower values occur when a floating surface cover is present. However, due to the non-significance of K_La_{20} and OT_s and the marginal significance of E_p and E_o (F \approx 7-11), a larger sample size is required to adequately assess this treatment effect.

Theoretically, lower K_La , OT_s , E_p and E_o should occur with a floating surface cover, as this would tend to decrease the transfer of atmospheric oxygen at the turbulent airwater interface generated by the bursting air bubbles. Nielson (1974) observed reduced rates of oxygenation in similar laboratory experiments, using floating styrene foam.

One possible explanation for the marginal result observed in these experiments is the relatively small surface area to volume ratio of the experimental column $(A/V = 0.94 m^{-1})$ as compared to Nielson's (1974) tank $(A/V = 1-10 m^{-1})$. As the surface area to volume ratio increases, the effect of reducing the surface component of gas transfer should become more apparent. Nielson (1974) estimates that natural surface aeration induced by a rising bubble plume should account for 88 to 94% of the oxygen transfer to small water supply reservoirs; however, the surface area to volume ratio of lakes is considerably larger than the 70 L experimental tank.

5.1.4 Interaction

The significant air flow rate x orifice size interaction effect detected for K_La_{20} is graphically presented in Figure 3.3. This researcher's interpretation of this interaction effect is that higher turbulence generated by larger air flow rates caused small bubbles to remain trapped in vortices near the top of the 70 L cylinder. This effect was quite noticeable during the experiments, as the small bubbles generated from the 397 μ and 794 μ diffusers persisted much longer at the higher flows.

This resulted in a longer contact time in the water column, which increased the K_La_{20} and OT, above what would be normally be expected for a given air flow and orifice size. Although the effect is significant, its F value (≈ 100) is small in relation to the main effects of the experiment (air flow rate and orifice size), and it does not change the principle conclusions of the experiment. Bewtra and Nicholas (1964) observed a similar entrainment effect when downward water velocitites exceeded the rise velocities of small bubbles, resulting in longer detention times and increased oxygen transfer.

5.1.5 Replication

A significant replication effect was detected for K_La_{20} , OT_s , E_p and E_o . The F value of the replication effect is small ($\approx 15-20$) in relation to the main experimental results and does not change the overall conclusions of the experiment. The result simply indicates that the experimenter was somewhat variable in his experimental procedure during the first few days of the experimental period.

5.2 Group 2

The treatments examined in Group 2 were: air flow rate (9.4 L/min or 18.8 L/min), surface cover (present or absent), orifice size (40 μ or 140 μ) and diffuser number (1 or 2).

5.2.1 Air Flow Rate

The rate of air flow (9.4 or 18.8 L/min) to the diffusers produced the most significant result, increasing $K_{L}a_{20}$ and OT_s by 97% with a 100% increase in Q_a . The mechanisms responsible for this result are the same as in Group 1, i.e. increased turbulence and interfacial area. However, doubling the air flow rate had no effect on E_o and E_p . Unlike the Group 1 response where a 100% increase in air flow rate produced a 122% increase in $K_{L}a_{20}$ and OT_s and a 12% increase in E_o and E_p , the Group 2 response showed only a 97% increase in $K_{L}a_{20}$ and OT_s and OT_s and no increase in E_o and E_p .

This differential response is due to the smaller bubbles produced by the Group 2 silica glass diffusers. As shown in Table 3.25, the mean bubble diameter produced by the 40 μ and 140 μ silica glass diffusers was 4.0 and 4.2 mm respectively. A decline in transfer efficiency with increasing air flow is the usual response with fine bubble 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 most likely due to a combination 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).

The less than 1:1 response of increased Q_a on $K_L a_{20}$ and OT_s is also due to the smaller bubble size of the 40 μ and 140 μ diameter diffusers. As shown in Table 3.25, there was no clear effect of air flow rate on bubble size. As a result, higher air flow rates combined with the chimney effect did not produce a proportional increase in K_L , the net effect being a less than 1:1 response of $K_L a_{20}$ and OT_s to Q_a .

5.2.2 Number of Diffusers

The purpose of this treatment was to examine the effect of air flow rate per diffuser, which is different from air flow rate per se. Increasing the number of silica glass diffusers from 1 to 2 resulted in a 25% increase in K_La_{20} and OT_s and a 21-24% gain in E_o and E_p . This response is well documented throughout the civil engineering literature (eg. 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 obvious effect of air flow rate on bubble size in this set of experiments (Table 3.25), therefore reasons (2) and (3) from Bewtra and Nicholas (1964) may not be as important in this particular situation. It should be noted, however, that a maximum of 20 bubbles were measured for each combination of air flow and orifice size. Given the thousands of bubbles 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 Q_a .

This researcher believes the explanation for $K_L a_{20}$, OT_s , E_p and E_o increasing with reduced air flow rate per diffuser is related to (1) and (4) above ie. increased gas transfer during bubble formation and reduced air-bubble entrainment. A high rate of gas transfer occurs at this stage, due to the continued expansion of the fresh gas-liquid interface and subsequent steep oxygen concentration gradient across the 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 increases $K_L a_{20}$, OT_s , E_p and E_o .

5.2.3 Surface Cover

The presence of a floating surface cover exerted a marginally significant inverse effect on $K_{L}a_{20}$ and OT_s , and no effect on E_o and E_p . The cell means for $K_{L}a_{20}$ and OT_s suggest that slightly higher values occur when a floating surface cover is present. One possible explanation for this result is due to the longer path length that bubbles must take through the water due to the presence of a surface cover. Markofsky (1979) noticed a slight increase in E_o when a surface cover was present and attributed this to increased contact time. However, due to the non-significance of E_o and E_p and marginal significance of K_La_{20} and OT_s (F \approx 7) a larger sample size is required to adequately assess this treatment effect.

5.2.4 Orifice Size

The size of the silica glass diffuser orifices examined in the Group 2 experiments (40 and 140 μ) had no effect on K_La_{20} , OT_s , E_p or E_o . The bubble size analysis supports this conclusion, as the mean bubble size created by the 40 μ and 140 μ diameter orifice diffusers were similar (Table 3.25).

A scanning electron micrograph (SEM) of each diffuser surface revealed a distinct difference in the pore size and size of the silica granules that comprise the diffuser body. The SEM shows the orifices are not round holes, but rather irregular shaped openings in a bonded matrix of variable sized silica granules. The size of the bubble produced by a porous diffuser depends on the surface tension of the air-liquid interface, the porosity of the diffuser medium and the air flow rate through each diffuser, in addition to the pore size of the diffuser (Bewtra and Nicholas, 1964). The size of a single bubble formed at low air flow rates from a single orifice is the result of a balance between the buoyant force of the bubble and the surface tension holding the bubble to the orifice. The bubble increases in size until its buoyancy exceeds the surface tension forces and it then detaches itself (Bowers, 1955).

At low air flow rates, bubbles tend to emerge in single formation, with a relatively constant diameter of approximately 11 times the orifice diameter (Haney, 1954). However, as air flow rates increase, single bubbles cannot carry the gas away quickly enough so the bubbles become larger and leave the orifice in the form of a chain, with adjacent bubbles just touching (Bowers, 1955). The gas flow rate at which chain formation occurs is known as the critical point, above which bubble size becomes dependent on gas flow rate and is independent of orifice diameter. The mathematical derivation of the critical gas flow point for various sized bubbles is described by Bowers (1955).

Visual observations of bubble formation with the 40 μ and 140 μ silica glass diffusers indicated bubbles emerged in chain formation, so the gas flow rate per orifice was above the critical rate for single bubble formation. As a result, bubble size was dependent on gas flow rate and the resulting bubble sizes were similar for both the 40 μ and 140 μ diffusors. Markofsky (1979) observed a similar effect with 90 μ and 180 μ porous diffusers and concluded there was no significant difference in transfer efficiency between the two orifice sizes at the experimental gas flow rates.

5.2.5 Interaction

The significant air flow rate x number of diffusers interaction effect is shown in Figure 3.8. The cause of this interaction effect is the same as in Group 1, i.e. at higher air flow rates, smaller bubbles became trapped in the vortices near the top of the 70 L cylinder and inflated the K_La_{20} and OT, above what would be normally expected for a given air flow and number of diffusers.

Although the effect is significant, its F value (≈ 13) is small in relation to the main effects of the experiment (air flow rate and number of diffusers), and it does not alter the main conclusions of the experiments.

5.2.6 Replicate Days

There was no significant effect of replicate days on $K_L a_{20}$, OT_s , E_p and E_o . This indicates the experimenter was becoming more proficient in his experimental technique and/or the experimental equipment had stabilized from the initial Group 1 experiments.

5.3 Group 3

The treatments examined in Group 3 were: effect of orifice size $(40 \ \mu, 397 \ \mu \text{ and } 1588 \ \mu)$ and effect of surface conditions in the 239 L tank (cover, no cover, no cover and wind).

5.3.1 Orifice Size

Orifice size exerted a significant effect on $K_L a_{20}$, OT_s , E_p and E_o , with each parameter increasing in value with decreasing orifice size. Scheffé's test indicates each diffuser size was significantly different from each other for $K_L a_{20}$, OT_s , E_o and E_p .

These results are similar to the Group 1 and Group 2 results, and the factors responsible are the same ie. smaller bubbles increased interfacial area and contact time, thus increasing K_La_{20} , OT_s , E_p and E_o .

5.3.2 Cover

A marginally significant result for K_La_{20} , OT_s , E_p and E_o was produced by the surface cover treatment. The results (Table 3.22 and 3.24) indicate parameter values were highest

with no surface cover, and that the no cover and wind treatment effect was similar to the floating cover effect.

Scheffé's test was unable to detect a significant difference between the three treatment effects in the comparison among means test. Given the conservative nature of Scheffé's test and the marginally significant effect of the cover treatments, this result was expected. Therefore, a larger sample size is required to adequately assess the effect of surface cover.

Regardless, it is interesting to speculate on the factors responsible for the observed result. Logically, the cover-no cover effect makes sense as the increasing surface area to volume ratio of the 239 L tank ($A/V = 2.2 \text{ m}^{-1}$ for the 239 L tank, 0.94 m⁻¹ for the 70 L cylinder) should result in a more noticeable effect as the surface component of gas transfer increases in relative importance (eg. Nielson, 1974). However, the negative effect of the no cover and wind treatment effect is puzzling. One would expect an increase in gas transfer from the wind and wave action (Downing and Truesdale, 1955).

One 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 239 L tank was 4.1 m/sec at a distance of 10 cm from the nozzle. The velocity of wind induced surface currents are approximatley 3% of wind speed (O'Connor, 1982), 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 8 mm diameter. The rise velocity of bubbles in this size range is described by:

$$u = 1.02\sqrt[2]{g r_e} \tag{5.15}$$

where:

u = terminal rise velocity (cm/sec)

 $g = \text{acceleration of gravity (980 cm/sec}^2)$

 r_e = equivalent bubble radius (cm)

(Haberman and Morton, 1954).

This formula predicts a rise velocity of approximately 20-29 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 40 to 60% 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 may reduce the entrainment of small bubbles and reduce the K_La_{20} , OT_s , E_o and E_p . Bewtra and Nicholas (1964) observed a similar "stilling phenomena" during their experiments 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.

5.4 Summary Analysis: Group 1-3

5.4.1 Comparison of $K_L a_{20}$, OT_s , E_p and E_o

The results from the Group 1-3 laboratory experiments are in agreement with the civil engineering literature, with respect to the effects of air flow, orifice size, air flow rate per diffuser and surface cover on K_La_{20} , OT_s , E_p and E_o . An examination of the data summaries in the Appendix (Appendix A, B and C) clearly shows that, among comparable performance variables (ie. E_p and E_o), the highest values were obtained by discharging air through the largest number of diffusers, with the smallest (ie. $40-140 \mu$) orifice size. Within a given tank configuration (ie. 70 L or 239 L), the tank geometry sets the limits by which diffuser number and orifice size influence the hydrodynamics and contact time. This ultimately determines the K_La , OT_s , E_p and E_o for each combination of diffuser number and orifice size.

5.4.2 $K_L a_{20}$

The highest $K_L a_{20}$ values were obtained in the Group 2 experiments (ie. Treatment 16; 26.4 hr^{-1}), and the lowest values were found in the Group 3 experiments (ie. Treatment 1; 1.9 hr^{-1}). The main reason for this effect is the increased interfacial area of the smaller bubbles, combined with the increased turbulence of the higher air flow rate in the 70 L column. It is interesting to note that despite receiving the highest air flows (ie. 28.3 L/min), the Group 3 $K_L a_{20}$ values were quite low. This suggests the turbulence generated by the flow pattern in the 239 L tank was considerably less than in the 70 L cylinder. Morgan and Bewtra (1960) and Bewtra and Mavinic (1976) also reported considerable turbulence and high $K_L a_{20}$ values in simple columns.

5.4.3 E_p

The highest E_p values were also achieved in the Group 2 experiments (ie. Treatment 4; 263 g O₂/kW-hr). The combination of multiple small orifice diffusers is clearly the most efficient in terms of energy efficiency.

Despite having the lowest $K_{L}a_{20}$ values, the fine bubble diffusers in Group 3 (Treatments 7, 8 and 9) generated E_p values greater than 100 g O_2/kW -hr. This is due to the larger volume of the 239 L tank, which is taken into account in the calculation for E_p . This demonstrates the utility of using E_p , rather than K_La_{20} , when comparing the performance of aeration systems.

The range of E_p values from the Group 1-3 experiments were much lower than the values reported by Mavinic and Bewtra (1976) for a simple column system (53-263 g O_2/kW -hr vs 1,203-1,657 g O_2/kW -hr). There are several reasons for this wide range in E_p , including different diffuser submergence and size of aeration columns; however, one

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of the main reasons is the method in which energy consumption was calculated. Mavinic and Bewtra (1976) used the theoretical power required to compress the air, which does not include the efficiency of the electric motor and compressor. The power input for the Group 1-3 experiments was simply taken as the nameplate horsepower of the compressor, and adjusted for the fraction of air delivered. Pasveer (1966) estimates only 10% of the theoretical power is actually used in the transfer of oxygen, after correcting for compressor efficiency, motor efficiency, air line losses and diffuser resistance.

5.4.4 E_o

The highest E_o values were achieved in the Group 2 experiments (ie. Treatments 4, 8 and 16; 4.8-4.9%) while the lowest values were found in the Group 3 experiments (ie. Treatment 1, 2, and 3; 0.3%). The combination of multiple diffusers with small orifices was the most efficient at gas transfer. As previously mentioned, air flow rate had no significant effect on E_o in the Group 2 experiments.

The low E_o values in Group 3 were mainly a result of the reduced turbulence as previously mentioned and the shallow depth of air release (ie. 0.34 m); this reduces contact time and the driving force $(C_i - C_L)$ for oxygen transfer. The fine bubble diffuser used in the Group 3 experiments were nearly 3 times more efficient at oxygen transfer than the 1588 μ diameter diffuser; however their overall E_o was still quite low compared to their performance in the 70 L column in the Group 2 experiments.

5.4.5 Optimum Bubble Size

Given the observed increase in $K_L a_{20}$, OT_s , E_p and E_o with decreasing bubble size, and the competing effects of large and small bubbles on rise velocity, contact time, K_L and interfacial area, is there an optimum bubble size which generates the highest overall oxygen transfer coefficient? An examination of a rise velocity vs equivalent bubble diameter curve (eg. Figure 2; Andeen, 1974) reveals a distinct pattern and the solution to this question.

Initially, bubble velocity increases linearly with increasing size, to a local maximum of approximately 32 cm/sec for single bubbles of 1.2–1.4 mm diameter (Haney, 1954). Bubble velocity then decreases in the diameter range from 1.4 to 6 mm before increasing again with an increase in bubble diameter. This characteristic curve is due to the interaction between the hydrodynamic, viscous and interfacial forces acting on the bubbles (Haberman and Morton, 1954). Small bubbles assume a spherical shape as surface tension reduces the surface area to a minimum for a given volume. This spherical shape dictates that small bubbles rise according to Stoke's Law, and the viscosity of the liquid is the most important parameter influencing their rise velocity.

As bubble size increases, the viscous and hydrodynamic forces acting on the bubble become more important and flattening of the bubble occurs. This results in an oblate spheriod shape, which has a higher drag than a sphere of the same volume, and the rise velocity declines. As bubble size continues to increase, the viscous and surface tension forces become small relative to hydrodynamic forces and the bubble assumes a spheriod cap shape. The upper surface of these bubbles is essentially spherical, and they rise independently of the properties of the liquid (Haberman and Morton, 1954).

An examination of a liquid film coefficient (ie. K_L) vs bubble diameter graph reveals a sharply increasing K_L to a peak at 2-2.5 mm diameter, then a gradual decline with increasing bubble size (eg. Figure 6; Bernhart, 1969). A plot of surface area vs bubble diameter results in an exponential decay type of curve (Figure 5.12). The net result of these three effects on K_L a is a response profile similar to the K_L vs bubble size curve. The K_L a increases sharply to a peak at 2.0-2.5 mm diameter, then declines exponentially with increasing bubble size (see Figure 11; Barnhart, 1969). Therefore, the optimum bubble size for maximum K_L a is 2.0-2.5 mm diameter.



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This confirms the observed response of orifice size on K_La_{20} in the Group 1–3 experiments, and suggests that the bubble sizes generated by the silica glass diffusers in the Group 2 experiments were approximately twice as large as the optimum size. Eckenfelder and Ford (1968) state that silicon dioxide, aluminum oxide and Saran diffusers generally produce bubbles in the 2.0–2.5 mm range, which explains why these diffusers are so efficient at oxygen transfer. However, Downing (1966) states "... that practical difficulties, such as the clogging of orifices of air diffusers, limit the smallest size of bubble that it is feasible to produce by air diffusion alone to a diameter of about 2–3 mm." Therefore, the lower limit of practical bubble size formation from ceramic diffusers is also the optimum bubble size for oxygen transfer.

Chapter 6

Discussion: Group 4 and 5 Field Hypolimnetic Aeration Experiments

6.1 Group 4 Field Experiments

The treatments examined in the Group 4 field experiments were the effect of orifice size (140 μ , 794 μ , 1588 μ and 3175 μ) and depth of air release (3 m or 7 m).

6.1.1 Depth of Air Release

The depth of air release in the inflow tube had a significant effect on water velocity in the outflow tube, daily oxygen load, E_o , E_p and oxygen increase per cycle. The parameter most significantly influenced by the depth of air release was the water velocity in the outflow tube. The cell means (Table 3.26) indicate the water velocity at the 7 m release depth was 124% greater than the 3 m release depth (0.17 m/sec vs 0.38 m/sec). This effect is due to increased contact time in the inflow tube which influences the rise velocity of the air-water mixture. When air is injected at the 7 m depth, the period of contact is longer, thus allowing the hypolimnetic water additional time to accelerate and approach the rise velocity of the ascending bubbles. When air is injected at 3 m, the bubbles reach the surface and escape before the water mass has had enough time to approach the bubble rise velocity. This principle is known as riser efficiency and is used to describe the efficiency of air-lift pumps (Andeen, 1974):

$$n_r = \frac{V}{V + V_r} \tag{6.16}$$

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where:

 n_r = riser efficiency (%)

V = liquid velocity (m/sec)

 V_r = velocity difference between liquid and gas (m/sec)

Clearly it is desirable to maintain a minimum velocity difference to achieve high riser efficiency.

There is a paucity of published data to compare with these results, as the hypolimnetic aeration literature has not examined the effect of diffuser depth on water velocity. There are a number of papers which include water velocity as a function of air flow rate for a single fixed depth (eg. Smith et al., 1975); however, the effect of diffuser depth on water velocity per se cannot be determined, as each system has a different depth of air injection, rate of air flow and diffuser design. There are a number of reports in the civil engineering literature in which air was injected at different depths (eg. Morgan and Bewtra, 1960; Ippen and Carver, 1954; Schmit et al., 1978); however, these studies were generally concerned with the effect of diffuser submergence on transfer efficiency. Bewtra and Nicholas (1964) mention "that for a given liquid depth, the velocities are decreased when the diffuser submergence is decreased", but no data or explanation is given.

The oxygen increase per cycle, E_p , E_o and daily O_2 load were significantly influenced by the depth of air injection. Although the F value for oxygen increase per cycle is marginal (F=8), the trend is in the expected direction and a larger sample size or a greater range of injection depths would undoubtedly result in a more significant effect. The F value for transfer efficiency (E_o) (\approx 327) is much larger as E_o is calculated on a daily basis; therefore, the depth effect on velocity and subsequent induced flow is included in the E_o analysis. The E_o , E_p and daily load calculations are related and their statistical behaviour is similar.

This effect is well documented in the civil engineering literature. For example, Morgan

and Bewtra (1960), Bewtra and Nicholas (1964), Schmidt et al. (1978) and Doyle et al. (1983) all observed increased E_o with an increase in diffuser submergence. This effect is a result of increased contact time due to an increase in bubble travel distance. In addition, increased depth of air injection results in increased oxygen solubility due to greater hydrostatic pressure, which increases the driving force for gas transfer (C_i-C_L) (Mavinic and Bewtra, 1976).

Unfortunately, there are no published experimental studies in the hypolimnetic aeration literature to compare with these results. In a discussion of hypolimnetic aerator design, Taggart and McQueen (1982) suggested that greater rise distances would result in longer bubble-water contact periods and increased oxygen transfer. Given the universality of this response in the civil engineering literature, there is little doubt that increased depth of air injection will generate a similar response in hypolimnetic aeration systems, and that increased contact time, induced flow and hydrostatic pressure will be the causitive factors.

6.1.2 Orifice Size

The size of orifice had a significant effect on oxygen increase per cycle, daily oxygen load, E_o and E_p . Although the F values are marginal (F \approx 10-15), the trend is in the expected direction and a larger sample size should result in a more significant effect.

Bubble size was not measured in the field experiments. However, based on the results of the laboratory experiments, the bubble size emerging from the 140 μ diffuser should be smaller than from the coarse bubble diffusers. As mentioned in the Group 1 discussion, a reduction in bubble size increases interfacial area, decreases terminal rise velocity and decreases the liquid film coefficient (K_L). Since orifice size had no effect on water velocity (and subsequently K_L) in this test group (Table 3.28), the factor most likely responsible for the increase in oxygen per cycle, daily load, E_p and E_o was an increase in interfacial area. However, since the cell means for bubble velocity were similar (Table 3.28), and smaller bubbles should have a lower rise velocity (Andeen, 1974), the smaller bubbles must have coalesced soon after forming into a heterogeneous mixture of bubble sizes, in order to generate the same water velocity for each orifice size. Field observations lend support to this hypothesis, as it was difficult to distinguish which diffuser was being tested on the basis of surface bubble size.

How then are small bubbles more efficient at oxygen transfer when their existence is so ephemeral? This researcher believes the answer lies with the life span of a bubble, in which there are three distinct phases with three different rates of oxygen transfer. The first phase occurs during bubble formation at the interstitial openings of the diffuser. During formation and growth of the bubble, the liquid-gas interface surrounding the bubble is continually expanding and the concentration gradients in the liquid film remain high, resulting in an unusually high rate of oxygen absorption (Ippen and Carver, 1954). In the second stage, known as the intermediate steady-state phase, the concentration gradients in the surrounding liquid film attain lower values, hence a reduced transfer of oxygen occurs during the bubble's ascent through the water column. This phase is subject to deviations from the steady state, depending on shear and turbulence in the water column (Mancy and Okun, 1960). In the final phase, the bubble bursts when it reaches the surface and releases its gas contents to the atmosphere. The liquid film surrounding the bubble containing fairly high concentrations of dissolved oxygen is left behind, and the disturbance of the interface by the bursting bubbles tends to enhance atmospheric oxygen exchange at this point.

Therefore, the increase in transfer efficiency arising from smaller orifices occurs during the bubble formation phase, prior to the bubbles coalescing into a heterogenous mixture. Although this period of bubble formation is quite brief, it is sufficient to allow for increased gas transfer. Pasveer (1966) states that the liquid film becomes saturated with oxygen in a time span of 1 x 10^{-7} seconds, which is considerably faster than the time span of bubble formation.

Scheffé's test indicated that the 140 μ diffuser was significantly more efficient in terms of oxygen increase per cycle than the 794, 1588 and 3175 μ diffusers, and that the 794, 1588 and 3175 μ diffusers were not significantly different from each other. Given the aforementioned discussion on the transient nature of increased oxygen transfer during bubble formation, this analysis appears correct. In other words, the difference in bubble size generated by orifice diameters in the 794 to 3175 μ range is too small to have a significant effect on oxygen transfer in a hypolimnetic aerator, because of their smaller surface area to volume ratio and the coalescing nature of the air-water mixture in the inflow tube.

Scheffé's test was unable to distinguish any significant differences between the four orifice sizes, with respect to the cell means for daily oxygen load, E_p and E_o . The F values for daily oxygen load (≈ 12), E_o (≈ 10) and E_p (≈ 12) are significant in the ANOVA; however, Scheffé's test is conservative by design and just misses separating the 140 μ diffuser effects from the remaining diffusers. Given a larger sample size, this researcher believes Scheffé's test would generate the same result as was observed for oxygen input per cycle ie. the 140 μ diffuser would be significantly more efficient, and the 794 to 3175 μ range diffusers would be statistically similar in terms of daily oxygen load, transfer efficiency and aeration efficiency.

As mentioned in the Group 1 discussion, the effect of reduced orifice size and bubble size on transfer efficiency is well known in the civil engineering field (eg. Morgan and Bewtra, 1960; Bewtra and Nicholas, 1964). In the hypolimnetic aeration field, several researchers have discussed the theoretical effect of orifice size and bubble size on transfer efficiency (Smith et al., 1975; Speece, 1975; Ashley, 1985; Ashley et al., 1987); however most hypolimnetic aeration installations pay little attention to diffuser design, and if mentioned, it is usually in terms of orifice spacing for pressure loss, rather than transfer efficiency (eg. Fast, 1971).

6.2 Group 5 Field Experiments

6.2.1 Orifice Size

Orifice size significantly influenced oxygen increase per cycle, daily oxygen load, E_o and E_p . The mechanisms responsible for this result are identical to those mentioned in the Group 4 discussion, i.e. reduced bubble size and increased interfacial area due to the smaller orifice size of the silica glass diffusers. In addition, since orifice size had no effect on water velocity, the enhanced transfer must have occurred during the brief bubble formation phase as previously described.

It is useful to note how sensitive the area to volume ratio is to changes in bubble size. Since the area of a sphere of diameter d is πd^2 and its volume is $\pi d^3/6$, the A/V ratio =

$$\frac{\pi d^2}{\pi d^3/6}$$
 (6.17)

or 6/d. A graphical plot of this ratio (Figure 5.12) illustrates how quickly the A/V ratio declines with increasing bubble size. Since the rate of gas transfer is directly proportional to A/V (ie. a), the efficiency of gas transfer will decrease in approximately the same way as the A/V ratio in Figure 5.12. Haney (1954) discusses this aspect of gas transfer in more detail and shows that if only 1% of a group of bubbles are oversized by a factor of 5, the rate of gas transfer will be decreased by over 50%.

6.2.2 Surface Cover

The presence or absence of a floating styrene cover had no effect on water velocity, oxygen input, daily O_2 load, E_p and E_o . Given the small size of the separator box (2.4 m x 1.2

m) and the resulting low A/V ratio (ie. 0.36 m^{-1}), this result is not surprising. An A/V ratio of 0.94 m⁻¹ in the 70 L cylinder was also insignificant, and it was not until the 239 L tank was used (A/V = 2.2 m^{-1}) that surface cover exerted a marginally significant effect on oxygen transfer. It is clear from these experiments that the majority of oxygen transfer occurs in the inflow tube, and aerator design modifications would be required to increase the surface component of the overall oxygen transfer process.

6.3 Summary Analysis: Group 4 and 5

6.3.1 Diffuser Depth

The effect of diffuser depth on oxygen increase per cycle was significant, however the effect was less than expected (ie. 0.62 mg/L at 3 m vs 0.73 mg/L at 7 m). The two observations from the literature (Bernhardt, 1967 and Smith et al., 1975) indicate most oxygen transfer occurs in the lower half of the inflow tube, and that declining hydrostatic pressure, decreasing oxygen content of rising bubbles and the additive effect of bubble and water velocity are responsible for this effect (Speece, 1975).

The small difference between the 3 m and 7 m oxygen input suggests additional factors may be involved. For example, the amount of bubble coalescence in the inflow tube should influence oxygen input per cycle. Downing (1966) suggested the dissolved oxygen in the interstitial liquid rising with the dense bubble clouds becomes saturated very quickly, and is not dispersed rapidly enough into the main body of the liquid. This results in a lower rate of oxygen transfer than would be obtained from a single free rising bubble. This may occur in the inflow tube and the observed minor effect of depth on oxygen input may be partially explained by rapid saturation of the interstitial liquid.

The significant effect of diffuser depth on E_o , E_p and daily load was mainly a result of increased water velocity and subsequent volumetric flow, rather than increased oxygen

input per cycle. This is an interesting result that suggests hypolimnetic aerator design criteria should focus on obtaining maximum induced volumetric flow, in addition to achieving high oxygen inputs per cycle.

6.3.2 Surface Cover

The results of the Group 4 and 5 field experiments agree with the hypolimnetic aeration literature in that most oxygen transfer occurs within the inflow tube. There are at least two design modifications which could increase oxygen input per cycle by increasing the surface oxygen transfer component.

The obvious approach is to increase the surface area of the separator box so that more surface area is available for gas transfer. This approach may be theoretically feasible, however the practical considerations of separator box size, cost and installation difficulties would probably invalidate this approach.

A second approach would be to increase the turbulence within the separator box by installing additional aeration equipment. LaBaugh (1980) installed an electric surface aerator inside the separator box in the Spruce Knob Lake hypolimnetic aerator in an attempt to increase its oxygenation capacity. However, electric aerators are limited to situations where the power cable length does not exceed the voltage and phase restrictions of the motor. A more flexible approach would be to use an air driven aerator. A unit of this type could be powered by the main compressed air supply to the diffusor. An experimental program would be required to assess the cost effectiveness and net impact on E_o and E_p from this type of modification.

A third approach would be to place a series of baffles in the separator box to cause additional shearing and mixing. This modification would not require any additional power.

6.3.3 Air Flow Rate

The rate of air flow to a hypolimnetic aerator has an upper and lower limit. The lower limit is the amount of air required to overcome frictional losses in the distribution system and start the air-lift flow. The upper limit is determined by the transition from bubbly flow to plug flow, which usually occurs above an air void fraction (ie. air volume / water volume) of 10% (Andeen, 1974). Within these two limits, the induced water flow is a function of depth of air release and air flow (Taggart and McQueen, 1982):

$$Q_w = (Z^{1.16})(Q_a^{0.66})(1.85) \tag{6.18}$$

where:

 Q_w = water flow in L/sec Q_a = air flow in L/sec

Z = depth of air release in meters.

Therefore, the basic design guidelines for air flow are to inject air as deep as economically possible, up to a void fraction of 10% of the induced water flow. To obtain more accurate estimates of required air flow, an empirical sizing method should be used (eg. Lorenzen and Fast, 1977; Taggart and McQueen, 1982; Ashley, 1985).

6.3.4 Air Flow Rate per Diffuser and Orifice Size

The effect of orifice size and air flow rate per diffuser on E_p and E_o has been previously discussed. In terms of hypolimnetic aerator design, the solution is quite simple: install as many fine bubble diffusers as is physically and economically possible. Ceramic and Saran diffusers generally produce bubbles in the optimum 2.0-2.5 mm diameter range (Eckenfelder and Ford, 1968) and are well suited for this type of application. Speece (1975) also states that bubble diameter should be in the 2.0-2.5 mm range to achieve optimum E_o and E_p .

6.3.5 Comparison to Literature E_p

The highest E_p obtained was 0.34 kg O₂/kW-hr when using the 140 μ diffusers at the 7 m injection depth (Appendix D). Published values for full lift hypolimnetic aerators range between 0.18 to 1.1 kg O₂/kW-hr for very deep installations (eg. Wahnbach Reservoir) (Lorenzen and Fast, 1977). The value of 0.34 kg O₂/kW-hr was similar to the E_p reported from Larsen and Mirror Lakes (0.32 kg O₂/kW-hr) which used a similar design of aerator (Smith et al., 1975).

6.3.6 Retrofitting Undersized Systems

Once a system has been installed and found to be undersized, there are at least three solutions to increase oxygen input.

The first method is to supply additional air to the system. This generally increases the oxygen input per cycle due to increased turbulence and interfacial area in the inflow tube. More importantly, the velocity and induced volumetric flow increase with air flow rate (Ashley et al., 1987; Taggart and McQueen, 1982). This approach is more capital intensive ie. compressor purchase, operating and maintenance costs, and should be only used up to a void fraction (air volume/water volume) of 10%, at which point air-lift pump efficiency declines (Andeen, 1974).

A second approach is to inject pure oxygen or a mixture of compressed air and oxygen into the aeration system (eg. Smith et al., 1975). This approach is suitable when lakes are located near areas where liquid oxygen is available eg. Amisk Lake, Alberta (Dr. E. Prepas, Zoology Department, University of Alberta, pers. comm.). However, this method may be logistically impractical and too expensive for remote areas or for large lakes.

The third approach is to increase the oxygen transfer efficiency of the existing system.

This may be accomplished through improvements in diffuser design, which would be the most cost effective solution. In addition, the idea of adding surface aerators may be a viable option if excess air capacity is available and the diffuser is already an efficient design.

6.3.7 New Designs

A number of design ideas for full lift hypolimnetic aerators have emerged as a result of exposure to the civil engineering literature on gas transfer.

The first idea involves a modification to improve oxygen transfer from the rising air bubbles. This would be achieved by placing an open mesh screen in the inflow tube, approximately 1/3 to 1/2 the distance up the inflow tube. The idea behind this modification is to re-fragment the coalesced bubbles in the rising water column into a smaller size and increase their surface area to volume ratio. The declining hydrostatic pressure and reduced oxygen content of the air bubbles will obviously limit the effectiveness of this idea; however, given the sensitivity of the A/V ratio to changes in bubble diameter (Haney, 1954) it may be possible to extract additional oxygen without further increases in energy input. This modification would be susceptible to plugging of the mesh from natural debris in the lake.

The second idea involves increasing the contact time of the air-water mixture in the inflow tube, to improve oxygen transfer efficiency. This would be achieved by placing vane deflectors in the inflow tube to induce a corkscrew flow pattern to the rising air-water mixture. This should result in a longer bubble-water rise path, hence longer contact time. It may be necessary to place vanes in the outflow tube to spiral water in the opposite direction to reduce torque stress on the separator box.

The idea of increasing contact time to improve oxygen transfer has been used by Pasveer (1966) in oxidation ditches; Wirth et al. (1975) used a spiral flow riser tube in their hypolimnetic aeration experiments. The net result of the spiral helix used by Wirth et al. (1975) was a reduction in transfer efficiency, due to coalescence of bubbles on the underside of the helix plate; however, the concept of increasing transfer efficiency through increased contact time is theoretically sound.

The third idea involves injecting compressed air into the downflow tube to increase transfer efficiency. This idea would involve injecting very fine bubbles $(1-2 \ \mu \text{ diameter})$ near the outflow tube so, that the outflowing water velocity would entrain the small bubbles into the outflow tube. The bubbles would then be subjected to increasing hydrostatic pressure as they moved down the outflow tube; this should result in efficient gas transfer. Using this configuration, a hypolimnetic aerator would function as a co-current upflow, on the inflow side, and a counter-current downflow on the outflow side (Figure 6.13). This is roughly analogous to Mavinic's and Bewtra's (1976) System III, or Speece's (1971) U-Tube hypolimnetic aeration system.

Potential problems with this design include residual bubble escape, which may cause local destratification, and N_2 supersaturation in the hypolimnion, which could be detrimental to in-lake and downstream (if installed in a reservoir) populations of salmonids (Rucker, 1972). Further research on the N_2 saturation aspect of this idea is required.

In conclusion, there are a number of modifications which may increase the oxygen transfer efficiency and aeration efficiency of full lift hypolimnetic aeration systems. Some of these ideas may prove impractical; however, they certainly warrant further investigation in laboratory and pilot scale experiments, considering the in-situ cost of hypolimnetic aeration.



Figure 6.13: Conceptual drawing of co-current upflow and counter-current downflow hypolimnetic aerator

Chapter 7

Conclusions

- 1. Increased air flow rates through 397 μ to 3175 μ diameter orifices resulted in increased K_La₂₀, OT_s, E_p and E_o, due to increased turbulence and interfacial area in the water column.
- 2. A decrease in orifice size from 3175 μ diameter to 397 μ caused an increase in K_La_{20} , OT_s , E_p and E_o due, to smaller bubble size and a corresponding increase in interfacial area and contact time.
- 3. A floating surface cover exerted a minimal effect on K_La_{20} , OT_s , E_p and E_o , indicating surface oxygen exchange in low A/V ratio (0.94-2.2 m⁻¹) tanks is a small component of the overall oxygen transfer process.
- 4. Increased air flow rates through 40 μ and 140 μ orifice diameter silica glass diffusers caused a linear increase in $K_L a_{20}$ and OT_s , due to increased turbulence and interfacial area, but had no effect on E_p and E_o .
- 5. Reducing the air flow rate per fine bubble diffuser (40 μ and 140 μ diameter orifice) increased K_La₂₀, OT_s, E_o and E_p via smaller bubble size; it reduced the likelihood of bubble coalescence and increased bubble dispersion.
- 6. Orifice size in the range of 40 μ and 140 μ diameter did not influence K_La₂₀, OT_s, E_p and E_o, as the gas flow rate was above the critical rate and the bubble size generated was similar for both orifice sizes.

- 7. A greater depth of air release enhanced the oxygenation capacity of the hypolimnetic aerator through a combined effect of hydrostatic pressure and contact time related gains in oxygen increase per cycle, and an increase in water velocity and induced volumetric flow.
- 8. An orifice size of 140 μ diameter increased the oxygenation capacity of a hypolimnetic aerator; however, 794-3175 μ diffusers had no effect due to the coalescing environment in the inflow tube.
- 9. A floating surface cover had no effect on oxygenation capacity, indicating little oxygen transfer occurs in the separator box of a standard design, full lift hypolimnetic aerator.
- 10. Hypolimnetic aerator design criteria should focus on obtaining maximum volumetric flows, in addition to achieving high oxygen input per cycle values.
- 11. The aeration efficiency (E_p) of hypolimnetic aerators may be increased by enhancing the surface exchange component through design modifications, involving increased separator box size or additional mechanical surface aeration; however, these modifications may not be practical.
- 12. The design guidelines for diffuser flow rate and orifice size are to install as many fine bubble ($\approx 140 \ \mu$ diameter) diffusers as physically and economically feasible.
- 13. Undersized hypolimnetic aeration systems may be upgraded by injecting additional air, increasing the oxygen content of the injected air or improving the oxygen transfer efficiency of the existing system.
- 14. Three design modifications for full lift hypolimnetic aeators, which may increase

transfer and energy efficiency, are bubble-breakers in the inflow tube, counterrotating spiral flows in the inflow and outflow tubes and fine bubble down-flow air injection in the outflow tube.
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Appendix A

Group 1 ANOVA Results: $K_L a_{20}$, OT_s , E_o and E_p

	Source of variation	\mathbf{DF}	Mean Square	F	Significance of F
-	Residual	63	0.22	<u> </u>	
	Constant	1	4225.47	18906.58	0.000
	Air flow	1	614.83	2751.01	0.000
	Surface cover	1	0.84	3.74	0.058
20	Orifice size	3	181.02	809.96	0.000
	Flow by cover	1	0.09	0.40	0.531
	Flow by size	3	22.44	100.42	0.000
	Cover by size	3	0.08	0.34	0.794
	Replication	4	3.43	15.34	0.000

 $K_L a_{20}$

	Source of variation	\mathbf{DF}	Mean Square	F	Significance of F
	Residual	63	0.09		
	Constant	1	1617.30	18426.20	0.000
	Flow	1	235.64	2684.70	0.000
OT	Surface cover	1	0.38	4.31	0.042
01,	Orifice size	3	69.14	787.78	0.000
	Flow by cover	1	0.03	0.32	0.573
	Flow by size	3	8.44	96.18	0.000
	Cover by sie	. 3	0.03	0.33	0.802
	Replication	4	1.34	15.23	0.000

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
Đ	Residual	63	0.03		
	Constant	1	4430.05	135560.54	0.000
	Flow	1	3.72	113.80	0.000
	Surface cover	1	0.36	11.01	0.002
Ŀо	Orifice size	3	46.74	1430.31	0.000
	Flow by cover	1	0.00	0.07	0.794
	Flow by size	3	0.04	1.37	0.260
	Cover by size	3	0.05	1.53	0.215
	Replication	4	0.78	23.74	0.000

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
	Residual	63	23.45		
	Constant	1	689894.09	29416.05	0.000
	Flow	1	2241.90	95.59	0.000
Ð	Cover	1	174.94	7.46	0.008
\mathbf{L}_p	Orifice size	3	30237.38	1289.28	0.000
	Flow by cover	1	0.74	0.03	0.859
	Flow by size	3	25.34	1.08	0.364
	Cover by size	3	16.59	0.71	0.551
	Replication	4	472.04	20.13	0.000

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Appendix B

Group 2 ANOVA Results: $K_L a_{20}$, OT_s , E_o and E_p

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}^{+}	Significance of F
•	Residual	65	3.89		
	Constant	1	23767.95	6113.90	0.000
	Flow	1	2534.22	651.88	0.000
	Surface cover	1	29.00	7.46	0.008
	Orifice size	1	4.72	1.21	0.274
TZ .	Number of diffusers	1	287.34	73.91	0.000
$\mathbf{n}_L \mathbf{a}_{20}$	Flow by cover	1	12.79	3.29	0.074
	Flow by size	1	0.02	0.01	0.949
	Flow by diffusers	1	50.04	12.87	0.001
	Cover by size	1	8.44	2.17	0.145
	Cover by diffusers	1	1.76	0.45	0.504
	Size by diffusers	1	5.78	1.49	0.227
	Replication	4	2.90	0.75	0.565
				-	

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
	Residual	65	1.50		
	Constant	1	9103.64	6074.37	0.000
	Flow	1	970.22	647.38	0.000
	Surface cover	1	10.95	7.31	0.009
	Orifice size	1	1.74	1.16	0.285
OT	Number of diffusers	1	109.98	73.38	0.000
OI_s	Flow by cover	1	4.80	3.20	0.078
	Flow by size	1	0.00	0.00	0.985
	Flow by diffusers	1	19.40	12.95	0.001
	Cover by size	1	3.20	2.14	0.149
	Cover by diffusers	. 1	0.58	0.39	0.537
	Size by diffusers	1	2.24	1.50	0.225
	Replication	4	1.09	0.73	0.577

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
-	Residual	65	0.42		
	Constant	1	11115.49	26185.78	0.000
	Flow	1	0.20	0.47	0.494
	Surface cover	1	2.67	6.29	0.015
	Orifice size	1	0.60	1.40	0.240
Б	Number of diffusers	1	32.95	77.62	0.000
\mathbf{E}_{o}	Flow by cover	1	0.44	1.04	0.311
	Flow by size	1	0.08	0.18	0.672
	Flow by diffusers	1	0.45	1.05	0.309
	Cover by size	1	0.68	1.61	0.210
	Cover by diffusers	1	0.09	0.21	0.652
	Size by diffusers	1	1.63	1.63	0.206
	Replication	4	0.30	0.71	0.588

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	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
-	Residual	65	597.95		
	Constant	1	4048155.2	6770.10	0.000
	Flow	1	152.08	0.25	0.616
	Surface cover	1	3728.91	6.24	0.015
	Orifice size	1	962.58	1.61	0.209
T D	Number of diffusers	1	45557.13	76.19	0.000
\mathbf{L}_p	Flow by cover	1	668.05	1.12	0.294
	Flow by size	1	96.58	0.16	0.689
	Flow by diffusers	1	477.66	0.80	0.375
	Cover by size	1	1032.05	1.73	0.194
	Cover by diffusers	1	112.53	0.19	0.666
	Size by diffusers	1	942.02	1.58	0.214
	Replication	1	355.92	0.60	0.667

$\mathbf{Appendix} \ \mathbf{C}$

Group 3 ANOVA Results: $K_L a_{20}$, OT_s , E_o and E_p

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
	Residual	32	0.07	. <u></u>	
	Constant	1	724.31	10219.64	0.000
$\mathrm{K}_L\mathrm{a}_{20}$	Surface cover	2	0.77	10.93	0.000
	Orifice size	2	70.47	994.34	0.000
	Cover by orifice	4	0.09	1.27	0.304
	Replication	4	0.10	1.46	0.238

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
-	Residual	32	0.33		
	Constant	1	3232.58	9764.05	0.000
OT,	Surface cover	2	3.24	9.80	0.000
	Orifice size	2	314.46	949.84	0.000
	Cover by size	4	0.37	1.11	0.371
	Replication	4	0.44	1.37	0.278

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
	Residual	32	0.05		
	Constant	1	2345.62	46238.19	0.000
\mathbf{E}_{o}	Surface cover	2	0.60	11.88	. 0.000
	Orifice size	2	62.07	1223.58	0.000
	Cover by orifice	4	0.05	1.07	0.387
	Replication	4	0.07	1.41	0.254

	Source of variation	DF	Mean Square	\mathbf{F}	Significance of F
	Residual	32	36.50		·
	Constant	1	356391.60	9764.04	0.000
\mathbf{E}_{p}	Surface cover	2	357.68	9.80	0.000
	Orifice size	2	34699.53	949.84	0.000
	Cover by orifice	4	40.38	1.11	0.371
	Replication	4	48.78	1.34	0.278

Appendix D

Group 4 Results: Water Velocity, Oxygen Input, Daily Oxygen Load, E_o

and \mathbf{E}_p

	Source of variation	DF	Mean Square	\mathbf{F}	Significance of F
	Residual	28	0.00		
	Constant	1	3.06	2946.03	0.000
Water Velocity	Orifice size	3	0.00	2.03	0.132
	Diffuser depth	1	0.46	445.31	0.000
	Size by depth	3	0.00	0.49	0.691
	Replication	4	0.00	0.90	0.477

	Source of variation	DF	Mean Square	\mathbf{F}	Significance of F
	Residual	28	0.01	. <u></u>	
	Constant	1	18.09	1271.08	0.000
Oxygen Input	Orifice size	3	0.21	14.82	0.000
	Diffuser depth	1	0.11	7.75	0.010
	Size by depth	3	0.00	0.11	0.953
	Replication	4	0.00	0.24	0.915

Daily Oxygen Load							
Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F			
Residual	28	1.48					
$\mathbf{Constant}$	1	2203.74	1485.02	0.000			
Orifice size	3	17.41	11.73	0.000			
Diffuser depth	1	474.03	319.43	0.000			
Size by depth	3	4.32	2.91	0.052			
Replication	4	1.24	0.84	0.515			

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
	Residual	28	0.19	·	
	Constant	1	1000.13	5259.56	0.000
\mathbf{E}_{o}	Orifice size	3	1.95	10.27	0.000
	Diffuser depth	1	62.17	326.92	0.000
	Size by depth	3	0.25	1.33	0.294
	Replication	4	0.17	0.90	0.477

	Source of Variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
-	Residual	28	0.00		
	Constant	1	1.10	1485.02	0.000
\mathbf{E}_{p}	Orifice size	3	0.01	11.73	0.000
	Diffuser depth	1	0.24	319.43	0.000
	Size by depth	3	0.00	2.91	0.052
	Replication	4	0.00	0.83	0.515

Appendix E

Group 5 Results: Water Velocity, Oxygen Input, Daily Oxygen Load, E_o and E_p

	Source of variation	\mathbf{DF}	Mean Square	${f F}$	Significance of F
	Residual	12	0.00	······	
	Constant	1	3.42	3562.13	0.000
Water Velocity	Orifice size	1	0.00	3.26	0.096
	Surface cover	1	0.00	1.17	0.300
	Size by cover	1	0.00	0.63	0.443
	Replication	4	0.00	0.54	0.708

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
	Residual	12	0.00		
	Constant	1	12.01	2574.11	0.000
Oxygen Input	Surface cover	1	0.00	0.11	0.749
	Orifice size	1	0.42	90.11	0.000
	Cover by size	1	0.00	0.11	0.749
	Replication	4	0.01	2.14	0.138

Daily Oxygen Load								
Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F				
Residual	12	2.16						
Constant	1	3120.00	1443.73	0.000				
Surface cover	1	1.92	0.89	0.364				
Orifice size	1	76.83	35.55	0.000				
Cover by size	1	0.29	0.13	0.721				
Replication	4	3.11	1.44	0.280				

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
•	Residual	12	0.15		
	Constant	1	897.15	5912.03	0.000
E	Orifice size	1	5.57	36.71	0.000
	Surface cover	1	0.14	0.94	0.352
	Size by cover	1	0.02	0.11	0.745
	Replication	4	0.22	1.47	0.273

	Source of variation	\mathbf{DF}	Mean Square	\mathbf{F}	Significance of F
	Residual	12	0.00		
	Constant	1	1.56	1443.72	0.000
\mathbf{E}_{p}	Surface cover	1	0.00	0.89	0.364
	Orifice size	1	0.04	35.55	0.000
	Cover by size	1	0.00	0.13	0.721
	Replication	4	0.00	1.44	0.280

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PROFESSIONAL ASSOCIATIONS

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