Oxygen Transfer in Full Lift Hypolimnetic Aeration Systems

Kenneth I. Ashley [1], Donald S. Mavinic and Kenneth J. Hall [2]

Abstract

A series of experiments were conducted to examine the effect of diffuser depth, diffuser orifice diameter and separator box surface area on oxygen transfer (mg/L), daily oxygen load (kg O_2/day), transfer efficiency (E_o, %), energy efficiency (E_p, kg O_2/kW-hr) and water velocity (m/sec) in a small full lift hypolimnetic aerator (tube dia. = 0.76 m). A large hypolimnetic aerator (tube dia. = 1.5 m) was then retrofitted with 140 μ fine pore diffusers to test the pilot scale observations. The experiments demonstrated that oxygen transfer and water velocity increased with the depth of air release. This in turn increased daily oxygen load, E_o and E_p. The orifice size experiments indicated that the 140 μ diameter fine pore diffuser significantly increased oxygen transfer, daily oxygen load, E_o and E_p, however, the differences in bubble size generated by the 794 μ to 3175 μ coarse bubble diffusers were too small to have any significant effect on the aforementioned parameters. A reduction in surface area of the separator box had no effect on the oxygenation capacity of the aeration system. Retrofitting a large hypolimnetic aerator with 140 μ diffusers markedly increased its oxygenation capacity.

Introduction

Hypolimnetic aeration is a lake restoration technique that is achieving widespread application in the industrialized world. Originally developed in postwar Switzerland and rediscovered in West Germany (Bernhardt, 1967), hypolimnetic aeration is now used throughout Western Europe and North America (McQueen and Lean, 1986). At least three multi-national companies (Ecoflox, Locher and Kobe Steel) and a few regional companies (eg. TIBEAN) 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 problem has traditionally been associated with civil and environmental engineering.

[1] Fisheries Research and Development Section,
Ministry of Environment, Province of British Columbia,
University of British Columbia, Vancouver, B.C., Canada, V6T 1W5
(604)-660-1812

[2] Environmental Engineering Group, Dept. of Civil Engineering,
University of British Columbia, Vancouver, B.C., Canada, V6T 1W5

Reprinted from Air-Water Mass Transfer
Second International Symposium
U.S. Army Waterways Experiment Station/ASCE
Minneapolis, MN, Sept. 11-14, 1990

A fair amount of basic (eg. Cornett and Rigler, 1980; Babin and Prepas, 1985) and applied limnology (eg. Ashley, 1983; McQueen et al., 1984) has been conducted on whole-lake oxygen consumption. The general consensus from the applied limnology 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 capacities 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 full lift aerator design specifications (Lorenzen and Fast, 1977; Taggart and McQueen, 1982; Ashley, 1985) this has not addressed the problem of variable oxygen input.

Aside from the obvious influence of variable hypolimnetic BOD's and aerator size, 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 full lift hypolimnetic aeration systems. The purpose of this experiment was to investigate three design variables which these researchers felt, after considerable literature review, were poorly understood in terms of their contribution to the oxygenation capacity of full lift hypolimnetic aeration systems. These design variables were as follows:

(1) Orifice size. Orifice size 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 (Mavinic and Bewtra, 1976; Bewtra and Mavinic, 1978). Large bubbles have a higher liquid film coefficient (K_L; m/hr) than small bubbles, however, their larger size reduces their contact time in the liquid and their surface area to volume ratio is smaller. Small bubbles (ie. < 0.5 mm dia.) have higher surface area to volume ratios for improved gas exchange, however, their slower rise velocity results in a lower K_L but a longer contact time. This aspect of the experiment was examined by using a range of diffuser orifice sizes from 140 μ to 3175 μ to determine which orifice size generated bubbles with the highest transfer efficiency (E_o) and energy efficiency (E_p).

(2) 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 as the mixture rises through the water column. Decreasing hydrostatic pressure is partly responsible for this decline, however, the decreasing oxygen content of rising bubbles and the additive effect of vertical water velocity and buoyant bubble velocity contribute to poor oxygen transfer efficiency (Speece, 1975). A limited number

of field measurements support this hypothesis as the majority of 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, which in turn influences daily oxygen load, E_o and E_p. This aspect of hypolimnetic aeration oxygen transfer was examined by inserting various diffusers into a full lift hypolimnetic aeration system at two different depths and measuring changes in water velocity and dissolved oxygen concentration in the outflow tube.

(3) Separator box surface exchange area. Full lift hypolimnetic aerators, with their relatively small degassing chambers, are dependent on oxygen transfer during bubble formation, rise and bursting. A floating surface cover was used in these experiments to vary the surface exchange area and determine the relative importance of separator box surface area to the overall oxygenation capacity of a full lift hypolimnetic aeration system.

Methods

The pilot scale experiments were conducted at Black Lake, a small (area = 3.9 ha; max. depth = 9.0 m; volume = 178,500 m^3) naturally eutrophic lake located (elev. = 750 m, 49°20'30"N, 119°44'05"W) in southern interior B.C. A full lift hypolimnetic aeration system was installed in Black Lake in 1978 (Ashley, 1983). The aerator consisted of an open insulated box (2.4 m L x 1.2 m W x 0.9 m D) with two 0.76 m diameter x 7.3 m L galvanized steel pipes attached through the bottom of the box.

Compressed air was provided by a 7.5 kW rotary vane compressor rated at 1.13 m^3/min free air delivery at 7.0 kg/cm^2. Air flow rate was measured by a Brooks flowmeter, equipped with a pressure gauge (0-8 kg/cm^2) at both inlet and outlet ports, and calibrated to read 113-1133 L/min at 7.0 kg/cm^2 and 21 °C.

Dissolved oxygen and temperature were measured with a Winkler calibrated YSI 54 ARC oxygen-temperature meter. Oxygen-temperature profiles were taken approximately 3 m from the aerator at the start of the experiment to establish baseline oxygen and temperature profiles. When the experiments were in progress, 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 meter (Model 2035) was also suspended at this depth to measure outflow water velocity.

The difference in oxygen concentration between inflow and outflow water is the amount of oxygen transferred by a specific treatment. The loading rate of each treatment was calculated by multiplying the oxygen differential by the volumetric flow of the aerator as measured by the current meter. Each treatment was operated for several minutes before a final oxygen and current measurement were recorded. The temperature of the hypolimnetic water changed little during the experiment, and the influent oxygen concentration was essentially constant at 0.4 mg/L (Ashley, 1989).

The Black Lake experiments were divided into two groups. The parameters examined in Group 1 were: the effect of orifice size (3175 μ, 1588 μ, 794 μ and 140 μ), and depth of air release (3 m or 7 m). This resulted in 8 combinations of depth and orifice size. The coarse bubble diffusers (794 μ - 3175 μ) were fabricated from 3.8 cm dia. PVC pipe. The diffusers were cross-shaped, with 4 arms joining into a common centre. The number of holes drilled in each diffuser was adjusted to maintain a constant discharge capacity ie. 3175 μ - 20 holes; 1588 μ - 80 holes; 794 μ - 320 holes. The outside dimensions of the diffusers were 0.69 m and they fitted inside the 0.76 m inlet tube with 3.5 cm clearance on either side. The fine bubble diffusers were constructed of fused silica glass with a 140 μ maximum pore size. Four 140 μ silica glass diffusers (23 cm L x 3.8 cm W x 3.8 cm D) were connected to a 3.8 cm PVC 4 way centre, and arranged in a spiral pattern.

The parameters examined in Group 2 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. The diffuser depth was fixed at 7 m. The Group 1 and 2 experiments were conducted in a complete randomized block design, and performed in September, 1987.

The statistical procedure used to analyze the Black Lake data was an analysis of variance program in the SSPS statistical package (α = 0.01). The statistical analysis was conducted on water velocity, oxygen transfer, daily oxygen load, E_o and E_p. The arc sin square root transform was used in the E_o analysis to reduce the skewness of the percentage values. Scheffe's test (alpha = 0.01) was used for the "a posteriori" comparison among means test.

Full scale application of the experimental results was conducted at St. Mary Lake, a mid-size (area = 182 ha, max. depth = 16.7 m; volume = 16,300,000 m^3) culturally eutrophic lake located (elev. = 46 m, 48°53'30"N, 123°32'15"W) in the Gulf Islands region of British Columbia. A full lift hypolimnetic aeration system was installed in St. Mary Lake in 1985-86. This system was considerably larger than the unit in Black Lake, and consisted of two open insulated fibreglass boxes (5.8 m L x 3.1 m W x 2.1 m D) with 1.5 m diameter x 12.0 m (inflow) and 9.5 m (outflow) galvanized steel pipes attached through the bottom of each separator box.

Compressed air was provided by a 37 kW rotary screw compressor rated at 5.66 m^3/min free air delivery at 7.0 kg/cm^2, and delivered to the two aerators via a 621 m main line of 7.62 cm ID polyethylene air line and two branch lines of 207 m 7.62 cm ID polyethylene and 31 m of 5.1 cm ID rubber air line. The original diffuser used in 1986 and 1987 was constructed of 3.81 cm ID galvanized steel pipe, drilled with approximately 80 3175 μ holes. This diffuser was replaced in March 1988 with a 5.1 cm ID aluminum ring structure, fitted with 24 of the same 140 μ fine bubble diffusers as used in the pilot scale experiments. The diffuser depth was fixed at 12.5 m. Field measurements and calculations were done in the same manner as the Black Lake experiments.

Results

Black Lake

Group 1. The depth of the air diffuser in the inflow tube had a significant effect on water velocity in the outflow tube, oxygen transfer, daily oxygen load, E_o and E_p. The mean values (Standard Deviation in brackets) for the two depths of air release (3 m and 7 m) are shown in Table 1.

Orifice size also had a significant effect on oxygen transfer, daily oxygen load, E_o and E_p, but did not significantly affect water velocity in the outflow tube. The mean values for water velocity, oxygen transfer, daily load, E_o and E_p (Standard Deviation in brackets) for the four orifice sizes are shown in Table 2.

Scheffe's test was used in the comparison among means test for the four orifice sizes. The test indicated that the 140 μ orifice diffuser was significantly more efficient ($\alpha = 0.01$) than the other three diffusers for oxygen transfer, but the remaining three diffusers were not significantly different from each other. Due to its conservative nature, Scheffe's test was unable to distinguish any significant differences among the four orifice sizes when applied to the mean values for daily oxygen load, E_o and E_p.

Group 2. The cover-no cover experiments had no significant effect on the measured Group 2 parameters. However, the orifice size results in this test (ie. 140 μ and 3175 μ) were similar to the Group 1 results, ie. a significant increase in oxygen transfer, daily oxygen load, E_o and E_p with the 140 μ diffuser but no significant effect on water velocity in the outflow tube.

St. Mary Lake

The installation of the fine pore diffusers markedly increased the daily oxygen input to St. Mary Lake (Table 3). Although the total daily input fluctuated considerably in response to variations in hypolimnetic BOD and ambient oxygen concentrations, a definite trend towards higher daily loadings was observed with the 140 μ diffusers. Late summer hypolimnetic oxygen concentrations in St. Mary Lake have increased from 0.4 mg/L in 1986 to 2.0-3.4 mg/L in 1989, and a summer fishery for introduced steelhead trout (Oncorhynchus mykiss) has been created (pers. comm., P. Law, Ministry of Environment, Nanaimo, B.C.). A complete analysis of the St. Mary Lake hypolimnetic aeration project will begin in 1991.

Discussion

Depth of air release. The effect of diffuser depth on oxygen input 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; Table 1). Observations from the literature (Bernhardt, 1967; Smith et al., 1975) indicate most oxygen transfer occurs in the lower half of the inflow tube. Declining hydrostatic pressure, decreasing oxygen content of rising bubbles and the additive effect of bubble and water velocity appear to be responsible for this effect (Speece, 1975).

Transfer efficiency values for full lift hypolimnetic aerators apparently range between 9 and 50% (Smith et al., 1975). The E_o values obtained in this study were considerably lower, and there is no obvious explanation for this discrepancy. One explanation is an error in determining the mass of oxygen delivered per unit time when converting from compressed air to air at standard conditions. 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 may influence oxygen transfer. 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 single free rising bubbles. This may occur in the inflow tube and the observed minor effect of depth on oxygen transfer, and the very low E_o's and E_p's may be partially explained by rapid saturation of the interstitial liquid. Transfer efficiencies of 28-40% are normal for clean water transfer efficiencies in secondary treatment plants (EPA, 1989), however, the air-bubble plumes in these systems are not constrained within riser tubes and are free to entrain additional water.

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 transfer per se. Presumably, this is a result of longer contact time in the inflow tube which minimizes the slip velocity between rising bubbles and water and increases riser efficiency (Andeen, 1974). This result suggests that hypolimnetic aerator design criteria should focus on maximizing induced volumetric flow, in addition to achieving high oxygen transfer.

Orifice size. Orifice size had a significant effect on oxygen transfer, daily oxygen load, E_o and E_p. Bubble size was not measured in the field experiments; however, based on the results of a concurrent set of laboratory experiments, the mean bubble size emerging from the 140 μ diffuser should be smaller than from the coarse bubble diffusers (ie. 140 μ - 4.2 mm; 794 μ - 6.0 mm; 1588

μ - 7.7 mm; 3175 μ - 7.2 mm) (Ashley, 1989). 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 2), the factor most likely responsible for the increase in oxygen transfer, daily O_2 load, E_o and E_p was an momentary increase in interfacial area. However, the cell means for bubble velocity were similar (Table 2), and smaller bubbles should have a lower rise velocity (Andeen, 1974). Therefore, 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 observed surface bubble size.

Surface cover. The presence of a floating styrene cover had no effect on water velocity, oxygen transfer, daily O_2 load, E_o and E_p. This result agrees with literature reports in that most oxygen transfer occurs within the inflow tubes in full lift designs. However, there are at least two design modifications which could increase oxygen transfer by increasing the surface exchange component. An 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 in rigid full lift designs. Flexible fabric type hypolimnetic aerators may be able to utilize this type of design modification.

A second approach would be to increase the turbulence within the separator box by installing baffles or 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 motors are limited to situations where the power cable length does not exceed voltage and phase restrictions of the motor. A more flexible approach would be to use a photovoltaic (Ward et al., 1986) or air driven surface aerators. An air driven unit could be powered from the main compressed air supply to the diffuser. 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.

Full scale application in St. Mary Lake confirmed the pilot scale observations that 140 μ fine pore diffusers are considerably more efficient at oxygen transfer than coarse bubble diffusers. Hypolimnetic oxygen concentrations have increased to 3-4 mg/L, and a classical "two-story" fishery now exists, with warmwater species in the epilimnion and cold-water species in the hypolimnion. Spring turnover phosphorus concentrations and summer phytoplankton chlorphyll a concentrations have also declined significantly since 1989 (pers. comm., R. Nordin, Ministry of Environment, Victoria, B.C.).

Conclusions

In conclusion, there are at least two engineering modifications which were found to increase the oxygenation capacity of full lift hypolimnetic aeration systems. Increased depth of air injection and the use of 140 μ fine pore diffusers significantly increased the oxygenation capacity of a pilot scale hypolimnetic aeration system. Retrofitting 140 μ fine pore diffusers to a full scale system markedly increased daily oxygen load and summer hypolimnetic oxygen concentrations. Design modifications to increase the surface transfer component may be possible; however, they warrant further investigation.

Acknowledgements

This project would not have been possible without the assistance of many individuals. We would like to thank Dr. R.N. Nordin, Dr. W.K. Oldham, Dr. G.A. Lawrence, Dr. N.T. Johnston, Dr. J. Berkowitz, Mr. A. Facchin, Mr. P. Law, Mr. D. Oliver, Mr. G. Scholten, Mr. G. Reid and Mr. B.R. Ward for their support and assistance. This study was supported by the Ministry of Environment (Province of British Columbia) and an NSERC grant to Dr. K.J. Hall.

References

Andeen, G.B. 1974. "Bubble pumps". Compressed Air Magazine 79:16-19.

Ashley, K.I. 1983. "Hypolimnetic aeration of a naturally eutrophic lake:physical and chemical effects". Can. J. Fish. Aquat. Sci. 40(9):1343-1359.

Ashley, K.I. 1985. "Hypolimnetic aeration:practical design and application". Water Research 19(5):735-740.

Ashley, K.I., Hay, S., & Scholten, G.H. 1987. "Hypolimnetic aeration:field test of the empirical sizing method". Water Research 21(2):223-227.

Ashley, K.I. 1989. "Factors influencing oxygen transfer in diffused aeration systems and their application to hypolimnetic aeration". M.A.Sc. Thesis, Dept. of Civil Engineering, University of British Columbia. Vancouver, British Columbia. 115 pp.

Babin, J. & Prepas, E.E. 1985. "Modelling winter oxygen depletion rates in ice-covered temperate zone lakes in Canada". Can. J. Fish. Aquat. Sci. 42(2):239-249.

Bernhardt, H. 1967. "Aeration of Wahnbach Reservoir without changing the temperature profile". J. Amer. Water Works Assn. 59:943-964.

Bewtra, J.K. & Mavinic, D.S. 1978. "Diffused aeration systems from theory to design". Can. J. Civil Eng. 5(1):32-41.

Cornett, R.J. & Rigler, F.H. 1980. "The areal hypolimnetic oxygen deficit:An empirical test of the model". Limnol. Oceanogr. 25(4):672-679.

Downing, A.L. 1966. Response to Pasveer, A. "Considerations on the efficiency of the aeration process." Air and Water Pollution International 10:448-449.

EPA. 1989. Design Manual: Fine Pore Aeration Systems. EPA/625/1-89/023. Cincinnati, Ohio. 305 p.

Fast, A.W. & Lorenzen, M.W. 1976. "Synoptic survey of hypolimnetic aeration". J. Environ. Eng. Div., Proc. Amer. Soc. Civil Eng. 106 (EE6):1161-1173.

LaBaugh, J.W. 1980. "Water chemistry changes during artificial aeration of Spruce Knob Lake, West Virginia". Hydrobiologia 70:201-216.

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

Mavinic, D.S. & Bewtra, J.K. 1976. "Efficiency of diffused aeration systems in wastewater treatment". J. Water Poll. Control Fed. 48(10):2273-2283.

McQueen, D.J., Rao, S.S. & Lean, D.R.S. 1984. "Hypolimnetic aeration:changes in bacterial populations and oxygen demand". Arch. Hydrobiol. 99(4):498-514.

McQueen, D.J. & Lean, D.R.S. 1986. "Hypolimnetic aeration:An overview". Water Poll. Res. J. Canada 21(2):205-217.

Smith, S.A., Knauer, D.R. & Wirth, T. 1975. "Aeration as a lake management technique". Wisconsin Dept. Natural Resources. Tech Bull. No. 87.

Speece, R.E. 1975. "Ten Year's experience of reservoir aeration." Reply to H. Bernhardt. Prog. Water Technol. 7:489-494.

Taggart, C.T. & McQueen, D.J. 1982. "A model for the design of hypolimnetic aerators". Water Research 16:643-654.

Ward, P.R.B., Dunford, W.G. & Ashley, K.I. 1986. "Ice control in lakes by photovoltaics powered water circulation". In: Proceedings of the 15th Annual Conference of the Solar Energy Society of Canada:41-46. Winnipeg, Manitoba, Canada. June 22-25, 1986.

Table 1. Effect of diffuser depth on Group 1 water velocity, oxygen transfer, daily O_2 load, E_o and E_p (all orifice sizes combined).

Treatment	Water Velocity (m/s)	Oxygen Input (mg/L)	Daily Load (kg)	E_o (%)	E_p (kg O_2/kW-hr)	n
3 m	0.17 (0.04)	0.62 (0.19)	4.0 (1.2)	0.4 (0.13)	0.09 (0.03)	20
7 m	0.38 (0.02)	0.73 (0.15)	10.9 (2.1)	1.2 (0.23)	0.24 (0.05)	20

Table 2. Effect of orifice size on Group 1 water velocity, oxygen transfer, daily O_2 load, E_o and E_p (both depths combined).

Treatment	Water Velocity (m/s)	Oxygen Input (mg/L)	Daily Load (kg)	E_o (%)	E_p (kg O_2/kW-hr)	n
140 u	0.27 (0.12)	0.89 (0.12)	9.4 (4.8)	1.0 (0.52)	0.21 (0.11)	10
794 u	0.30 (0.11)	0.60 (0.14)	7.1 (3.1)	0.8 (0.34)	0.16 (0.07)	10
1588 u	0.27 (0.12)	0.59 (0.10)	6.6 (3.6)	0.7 (0.40)	0.15 (0.08)	10
3175 u	0.27 (0.12)	0.61 (0.12)	6.7 (3.7)	0.7 (0.41)	0.15 (0.08)	10

Table 3. Oxygen input for St. Mary Lake hypolimnetic aerator with coarse (1986-87) and fine pore (1988-90) diffusers.

	East Aerator		West Aerator			
Date	Input (kg O_2/day)	Velocity (m/sec)	Input (kg O_2/day)	Velocity (m/sec)	Total (kg O_2)	Ambient O_2 (mg/L @13 m)
27/8/86	44.13	0.7	236.09	1.07	280.22	4.1
10/6/87	110.95	0.88	124.82	0.88	235.77	7.0
24/6/87	138.69	0.88	83.22	0.88	221.91	5.3
12/8/87	208.04	0.88	166.43	0.88	374.47	1.5
8/8/87	249.65	0.88	194.17	0.88	443.82	0.5
Fine pore diffusers installed in March, 1988.						
29/7/88	218.44	0.77	410.41	0.93	628.85	2.1
10/8/88	182.04	0.77	351.78	0.93	533.82	1.4
22/8/88	182.04	0.77	395.75	0.93	577.79	1.1
12/11/89	143.40	0.70	204.9	1.00	348.30	6.3
21/6/90	235.80	0.94	235.80	0.94	471.60	5.0

APPENDIX. NOTATION

E_o - transfer efficiency (%)
E_p - energy efficiency (kg O_2/kW-hr)