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Recent advances in hypolimnetic aeration design

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Introduction

Hypolimnetic aeration has developed into a widely used lake restoration technique due to its ability to selectively oxygenate the hypolimnion of stratified lakes and reservoirs while maintaining thermal stratification. This feature is important for restoring cold water fish habitat, improving water quality and allowing pre-treatment of potable water supplies in eutrophic lakes and reservoirs. The technique was originally developed in post-war Switzerland (MERCIER & PERRET 1949), revised in Germany (BERNHARDT 1967) and extensively field tested throughout Western Europe (BERNHARDT 1974, VERNER 1984, STEINBERG & ARZET 1984, JAEGER 1990, LAPPALAINEN 1994) and North America (FAST 1975, SMITH et al. 1975, ASHLEY 1983, MCQUEEN & LEAN 1986). More recently, attention has focused on understanding oxygen transfer and hydraulic performance of various hypolimnetic aerator designs (TAGGART & MCQUEEN 1982, ASHLEY 1985, ASHLEY et al. 1987, LITTLE 1995) in an attempt to predict and ultimately improve oxygen transfer efficiency (E_o; %) and energy efficiency (E_p; g O_2 kWh^{-1}). This paper reviews some recent advances in hypolimnetic aerator design that have significant potential for improving the effectiveness of this important lake and reservoir restoration technique.

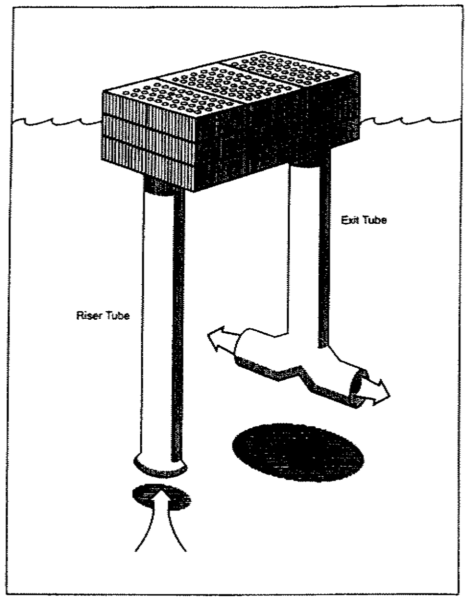

Fig. 1. "Bernhardt"-style full lift hypolimnetic aerator (from SOLTERO et al. 1994).

Full lift hypolimnetic aeration with compressed air

Although a variety of hypolimnetic aerator designs have been proposed and at least 13 designs subjected to full scale testing (FAST & LORENZEN 1976), the conventional full lift "Bernhardt" style (Fig. 1) has emerged as one of the more widely used due to its relatively simple design and availability of published data on oxygen transfer and energy efficiency (LORENZEN & FAST 1977, TAGGART & MCQUEEN 1982, ASHLEY 1985, ASHLEY et al. 1987, LITTLE 1995). Several design improvements have been suggested for full lift aerators (LORENZEN & FAST 1997, TAGGART & MCQUEEN 1982, ASHLEY 1989), however, relatively few have been subject to thorough laboratory and field testing. Three design parameters that have undergone limited laboratory and field trials include: (1) depth of air injection; (2) separator box surface exchange area and (3) diffuser orifice diameter (ASHLEY & HALL 1990). Surface exchange area of the separator box was found to have no effect on induced water velocity, oxygen input, daily O_2 load, energy efficiency (E_p; g O_2 kWh^{-1}) and oxygen transfer efficiency (E_o; %); the effect of diffuser depth on oxygen input was significant,

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however, the effect was less than expected; but orifice diameter did exert a significant influence on oxygen input, daily oxygen load, E_o and E_p (Ashley & Hall 1990).

Retrofitting high efficiency diffusers

A diffuser retrofit was undertaken on a large Bernhardt style full lift hypolimnetic aeration system to increase oxygen input. The original system installed in St. Mary Lake (Saltspring Island, B. C.) in 1985–1986 consisted of two open insulated fibreglass separator boxes (5.8 m L × 3.1 m W × 2.1 m D) with 1.5 m diameter × 12.0 m (inflow) and 9.5 m (outflow) galvanized steel pipes attached through the bottom of each separator box (Ashley 1988). Compressed air was provided by a 37 kW rotary screw compressor rated at 5.66 m^3 min^{-1} 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 pipe and two 207-m branch lines of 7.62 cm ID polyethylene and 31 m of 5.1 cm ID rubber air line.

The original pair of diffusers (one per inflow tube) installed in 1986 and 1987 were constructed of 3.81 cm ID galvanized steel water pipe and drilled with approximately eighty 3,175-µm diameter holes. This diffuser was replaced in March 1988 with a 5.1-cm ID aluminium ring structure slightly smaller than the diameter of the inflow tube and fitted with 24 140-µm diameter fine bubble silica glass diffusers (23 cm L × 3.8 cm D × 3.8 cm W). The diffuser depth was fixed at 12.5 m in each inflow tube. During the first 2 years of operation (1986–1987) with the coarse bubble diffusers, the hypolimnetic aeration system was unable to meet the hypolimnetic oxygen demand of St. Mary Lake. Following installation of the fine pore diffusers in 1988, the overall average daily oxygen input to St. Mary Lake increased from 311.24 kg day^{-1} to 512.07 kg day^{-1} (Table 1) with no corresponding increase in operational costs. Although the total daily oxygen input fluctuated in response to variations in hypolimnetic BOD and ambient oxygen concentrations, a definite trend towards higher daily loadings was observed with the 140 µm-diameter diffusers. Late summer hypolimnetic oxygen concentrations in St. Mary Lake increased from 0.4 mg L^{-1} in 1986 to 3.0–4.0 mg L^{-1} in 1990, and a classical "two-story" recreational fishery was created, with warmwater species in the epilimnion (*Micropterus dolomieui*) and cold-water species (*Oncorhynchus mykiss* and *Oncorhynchus clarki*) in the hypolimnion (personal communi-

Table 1. Daily oxygen input for St. Mary Lake (B.C.) full lift hypolimnetic aerator with coarse bubble (3,175-µm diameter: 1986–1987) and fine bubble (140-µm diameter: 1988–1990) diffusers.

	East Aerator		West Aerator		Total ($kg\ O_2$)	Ambient O_2 ($mg\ L^{-1}$ @ 13 m)
Date	Input ($kg\ O_2\ day^{-1}$)	Velocity ($m\ s^{-1}$)	Input ($kg\ O_2\ day^{-1}$)	Velocity ($m\ s^{-1}$)		
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	204.90	1.00	348.30	6.3
21/6/90	235.80	0.94	235.80	0.94	471.60	5.0

cation, P. LAW, Ministry of Environment, Lands and Parks, Nanaimo, B.C.). In addition, inspection divers noticed a hard, thin (2–3 mm) rust coloured crust had formed on the surface of the profundal sediments (personal observation, K. ASHLEY). Therefore, a relatively simple and inexpensive retrofit with high efficiency diffusers increased the daily oxygen input by 65% and changed the performance of the existing system from undersized to satisfactory without incurring additional operating costs.

An unknown factor in aquatic systems is the ageing of fine pore diffusers. At St. Mary Lake, divers scrubbed the diffusers with a coarse brush each spring on annual maintenance dives, and minimal fouling or performance loss was noted. Although lake environments are relatively pristine, significant changes in water chemistry do occur in the hypolimnion of eutrophic lakes. For example, in hard water lakes, whole lake precipitation reactions could deposit calcite on the diffuser surface, potentially changing bubble dynamics and influencing transfer efficiency. Annual inspections and cleanings are recommended to ensure the diffusers are operating properly. A new type of bubbleless hollow-fibre membrane aerator may resolve this problem (WEISS et al. 1998).

In extreme cases, the entire hypolimnetic aeration system may have to be replaced. This was the unfortunate situation in Medical Lake, Washington where a partial lift hypolimnetic aeration system with a coarse bubble diffuser was unable to meet the hypolimnetic oxygen demand. After retrofitting with a 600-µm diameter diffuser and a larger compressor, the partial lift unit was still undersized and then experienced structural failure. It was replaced with two Bernhardt style full lift hypolimnetic aerators which successfully oxygenated the hypolimnion (SOLTERO et al. 1994).

Hypolimnetic aeration with oxygen and air/oxygen mixtures

Pure oxygen has been used in several installations to increase the amount of oxygen transferred to the hypolimnion of eutrophic lakes and reservoirs. FAST & LORENZEN (1976) describe two examples of side stream pumping (SSP) where pure oxygen was added to water pumped from a lake and returned to the hypolimnion via a high pressure discharge line. This method increased the hypolimnetic oxygen concentration in Ottoville Quarry, Ohio to 21.5 mg L^{-1} which was the highest concentration recorded to date (FAST et al. 1977). SMITH et al. (1975) used supplemental oxygen in Mirror Lake, Wisconsin to overcome the high rate of hypolimnetic oxygen demand, and measured oxygen concentrations in the full lift separator box of 13.4 mg L^{-1} on pure oxygen and 8.6 mg L^{-1} using a blend of 0.45 m^3 min^{-1} compressed air and 0.16 m^3 min^{-1} liquid oxygen. PREPAS et al. (1997) successfully used liquid oxygen to oxygenate the north basin of naturally eutrophic Amisk Lake, Alberta using a deep oxygen bubble injection (DOBI) system originally proposed by SPEECE (1971). This system injected up to 1.3 t day^{-1} of fine oxygen bubbles (20–1,500-µm diameter) at 33 m and was able to maintain hypolimnetic oxygen concentrations >1.7 mg L^{-1} in summer and >5 mg L^{-1} in winter. The main limitations and concerns with the use of liquid oxygen are the high operating costs (FAST et al. 1976), availability in remote locations and site storage/security issues.

Downflow bubble contact aeration

A promising new design is the "Speece Cone" hypolimnetic aerator. This concept was originally proposed in 1971 as a downflow bubble contact aerator (DBCA) with an open cone (SPEECE 1971), re-designed in 1990–91 with a closed cone and field tested for the first time in 1992 in Newman Lake, Washington (DOKE et al. 1995). An innovative design of hypolimnetic aerator was required for Newman Lake as the lake is large (490 ha) but shallow, with a maximum depth of 9.1 m and a mean depth of 5.8 m, which was too shallow for any existing type of hypolimnetic aerator. The Speece Cone installed in Newman Lake was 2.8 m in diameter, 5.5 m tall, with a 45-kW submerged axial flow pump for water circulation and two 37-kW air compressors supplying compressed air to two pressure swing adsorption (PSA) on-site oxygen generation units. The system was designed to supply 1,361 kg day^{-1} of oxygen to the hypolimnion through a specially designed diffuser to avoid sediment disturbance (personal communication, G. LAWRENCE, UBC, Vancouver, B.C.). The system has performed extraordinarily well to date, with measured oxygen concentrations in the outlet pipe >30 mg L^{-1} despite being located in only 8.7 m of water. The system increased average summer hypolimnetic oxygen concentrations to 5.5 mg L^{-1} in 1992, however, thermal stratification was less stable due to two severe storm events (Thomas et al. 1994). An even larger Speece Cone (7 m tall) capable of supplying 8,000 kg day^{-1} of oxygen was installed and operated in Camanche Reservoir, California in 1993 and 1994 to improve water quality and prevent periodic fish kills in a salmonid hatchery relying on hypolimnetic water from the reservoir (personal communication, A. HORNE, University of California at Berkeley).

Conclusions

In the 21st century, hypolimnetic aeration will probably become standard practice for restoring water quality in eutrophic lakes and reservoirs which receive significant amounts of nutrients from internal loading and uncontrollable external sources. The three most widely used designs will probably be: (1) deep oxygen bubble injection; (2) downflow bubble contact aerations using the Speece Cone design; and (3) full lift hypolimnetic aerators, either using compressed air with high efficiency diffusers or supplemented with pure oxygen. The Speece Cone, with its relatively compact size, high oxygen input rate and deep or shallow water capability, represents one of the most significant advances in the design of hypolimnetic aeration since their inception over half a century ago. Equally important is the recent development of on-site PSA oxygen generating systems which remove many of the problems surrounding the storage/use of pure oxygen and allows for the development of smaller and more efficient designs of hypolimnetic aeration systems.

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