Oxygenation performance of a laboratory-scale Speece Cone hypolimnetic aerator: preliminary assessment

K.I. Ashley, D.S. Mavinic, and K.J. Hall

Abstract: A prototype laboratory-scale Speece Cone hypolimnetic aerator was used to examine the effect of oxygen input rate and outlet port water velocity on oxygen transfer, using four standard units of measure for quantifying oxygen transfer: (*i*) the oxygen transfer coefficient at 20 °C, K_La_{20} (h^{-1}); (*ii*) the standard oxygen transfer rate (SOTR) (g $O_2 \cdot h^{-1}$); (*iii*) the standard aeration efficiency (SAE) (g O_2 $kW \cdot h^{-1}$); and (*iv*) the standard oxygen transfer efficiency (SOTE) (%). The maximum inlet velocity (i.e., 70 $cm \cdot s^{-1}$) was only 23% of the recommended design velocity (i.e., 305 $cm \cdot s^{-1}$), and the two-phase bubble swarm did not properly develop inside the cone, but remained as a gas pocket at the top of the cone, resulting in a drastically reduced bubble surface area to water ratio. Therefore, all of the performance measures from this prototype Speece Cone were much lower than would be expected with the recommended design inlet velocity of 305 $cm \cdot s^{-1}$. Despite this difference, the system was still capable of oxygen transfer efficiencies of about 61%, under low gas flow rates, which is still higher than any full-lift design hypolimnetic aerator operating on air. Future research efforts are focused on building a pilot-scale Speece Cone, with as close to the correct inlet and outlet velocities, hydraulic residence time, and physical dimensions as possible, such that a two-phase bubble swarm could be generated. Once this experimental data is collected and analyzed, it can be properly compared with predictive models.

Key words: hypolimnetic aeration, Speece Cone, oxygen transfer, re-aeration.

Résumé : Un prototype de laboratoire d'aérateur hypolimnétique à cône de Speece a été utilisée pour étudier l'effet du taux d'oxygène en entrée et de la vélocité de l'eau en sortie sur le transfert d'oxygène, en utilisant quatre unités standard de mesure pour quantifier le transfert d'oxygène : (*i*) le coefficient de transfert d'oxygène à 20 °C, K_La_{20} (h^{-1}); (*ii*) le taux de transfert d'oxygène standard (« SOTR ») (g O_2 /h); (*iii*) l'efficacité d'aération standard (« SAE ») (g O_2 kW/h), et (*iv*) l'efficacité du transfert d'oxygène standard (« SOTE ») (%). La vitesse maximale en entrée (c'est à dire 70 $cm \cdot s^{-1}$) atteignait seulement 23 % de la vitesse recommandée (c'est à dire 305 $cm \cdot s^{-1}$), et l'essaim de bulles à deux phases ne s'est pas développé correctement à l'intérieur du cône, mais est resté une poche de gaz au sommet du cône, ce qui a considérablement réduit le rapport de surface entre la bulle et l'eau. Par conséquent, toutes les mesures de performance de ce prototype de cône de Speece étaient beaucoup plus basses que l'on pourrait s'attendre avec la vitesse en entrée recommandée de 305 $cm \cdot s^{-1}$. Malgré cette différence, le système était encore capable d'une efficacité de transfert d'oxygène d'environ 61 %, avec de bas débits de gaz, ce qui est encore plus élevé que n'importe quel aérateur hypolimnétique à levée complète (« full-lift design ») fonctionnant sur l'air. Les futurs efforts de recherche sont concentrés sur la construction d'un cône de Speece pilote, avec des vitesses d'entrée et de sortie, un temps de résidence hydraulique et des dimensions physiques aussi proches des bonnes valeurs que possible, de telle sorte que l'essaim de bulle à deux phases puisse être généré. Une fois que ces données expérimentales sont recueillies et analysées, il peut être correctement comparé à des modèles prédictifs.

Mots-clés : aération hypolimnétique, cône de Speece, transfert d'oxygène, ré-aération.

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Introduction

Hypolimnetic aeration is an important water quality improvement technique because of its ability to selectively oxygenate the hypolimnion of stratified lakes and reservoirs, while maintaining thermal stratification. This capability is desirable in eutrophic lakes and reservoirs as the presence of a cold, aerobic hypolimnion significantly improves (*i*) water quality for domestic and industrial applications and (*ii*) the management of freshwater fisheries. Hypolimnetic aeration systems can be grouped into seven general categories: (*i*) mechanical agitation systems, (*ii*) full-lift designs using compressed air or oxygen (or both), (*iii*) partial-lift designs using compressed air or oxy-

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gen (or both), (*iv*) downflow air injection (DAI), (*v*) deep oxygen bubble injection (DOBI) using oxygen, (*vi*) side-stream injection (SSI) systems using oxygen, and (*vii*) downflow bubble contact aeration (DBCA) or “Speece Cone” aerators using oxygen (Lorenzen and Fast 1977). The DOBI, SSI, and DBCA designs utilize oxygen only, due to concerns about nitrogen gas supersaturation and low oxygen transfer performance if operated on air.

Hypolimnetic aeration systems, by definition, are deployed in lakes and reservoirs that are thermally stratified, but are usually greater than 15–20 m in depth, to ensure sufficient depth is available to physically contain the works and provide adequate hydrostatic pressure; this is especially important when operating on air only, to achieve acceptable oxygen transfer rates. Hypolimnetic aeration systems are rarely installed in water bodies shallower than 10 m, and virtually never installed in depths less than 9 m, even if these water bodies have a definable, albeit occasionally transient, hypolimnion. Consequently, no in situ engineering solutions have been available to oxygenate the hypolimnia of eutrophic lakes and reservoirs at the shallow end of the depth – thermal stratification spectrum. A variety of lake restoration techniques and watershed nutrient reduction strategies are available to eventually improve water quality in eutrophic ecosystems (Dunst et al. 1974; Cook et al. 2005); however, none of these are capable of providing rapid oxygenation of anoxic hypolimnia.

Recently, the Speece Cone design has generated considerable interest, because of its ability to discharge oxygenated water with unusually high concentrations of dissolved oxygen (i.e., > 30 mg/L), even when operating at depths traditionally considered too shallow (i.e., <10 m) for conventional hypolimnetic aerator designs. The Speece Cone design was originally proposed in 1971, as a downflow bubble contact aerator (DBCA) with an open cone (Speece 1971), but was never field tested. The concept was redesigned with a closed cone and subsequently field tested in 1990, for the Alabama Power Company, at the outlet of the Logan Martin Dam, Alabama.

The first Speece Cone designed for in situ lake water quality improvement was tested in 1992 in Newman Lake, Washington (Doke et al. 1995). An innovative design of a hypolimnetic aerator was necessary as Newman Lake is large (490 ha), but quite shallow, with a maximum depth of 9.1 m and a mean depth of only 5.8 m. As such, it was too shallow for conventional full-lift, partial-lift, DAI, mechanical or DOBI hypolimnetic aerator designs, and the high energy discharge jet from a SSI system may have destratified the lake. The Speece Cone installed in Newman Lake was 2.8 m in diameter, 5.5 m high, with a 45 kW submerged axial flow pump for water circulation. Two, 37 kW compressors supplied compressed air to two pressure swing adsorption (PSA), on-site, oxygen generation units. The system was designed to distribute 1360 kg·d^{-1} of oxygen to the hypolimnion via an extended diffuser, to avoid sediment disturbance and unintentional destratification [G. Lawrence, Civil Engineering Dept., The University of British Columbia (UBC), Vancouver, B.C., personal communication, 1991]. The system has performed exceptionally well to date, with oxygen concentrations >30 mg/L routinely measured in the outlet ports, despite being located in only 8.7 m of water. The system also increased average summer hypolimnetic oxygen concentrations to 5.5 mg/L in 1992; however, thermal stratification was less stable, due to occasional severe storm events (Thomas et al. 1994).

An even larger Speece Cone (7 m in height), capable of supplying 8000 kg·d^{-1} of oxygen, was installed in Camanche Reservoir, California, in 1993 to improve water quality and prevent periodic fish kills in a salmonid hatchery; the latter was relying on hypolimnetic water discharged from the anoxic hypolimnion. Unpublished reports indicate that this system has also performed extremely well to date (A. Horne, University of California at Berkeley, personal communication, 1994). Speece Cone installations have also been considered for oxygenation of the deep water ship channel at the Port of Stockton, California (HDR Engineering 2004), the hypolimnion of Onondaga Lake, New York (G. Lawrence, Civil Engineering, UBC, Vancouver, B.C., personal communication, 2004), and the seasonally anoxic sections of Hood Canal in Washington State (M. Beutel, Civil Engineering, Washington State University, Pullman, Washington, personal communication, 2004). Two large Speece Cones capable of dissolving 6800 kg·d^{-1} of oxygen were installed in Savannah Harbour, Georgia, in 2007.

Remarkably, there is no information in the primary published literature examining the oxygenation characteristics of Speece Cone hypolimnetic aeration systems. McGinnis and Little (1998) developed a model that predicts bubble dynamics and oxygen transfer in a Speece Cone; however, there is no published field or laboratory data available to examine the model’s predictions. Accordingly, this current research effort, although preliminary in nature, provides the first detailed analysis of two design factors capable of influencing the oxygen transfer capabilities of a Speece Cone. The experiments utilized nonsteady-state gas transfer methodology in a laboratory-scale system. Specifically, the research examined the effect of oxygen input rate and outlet port water velocity on oxygen transfer, using four standard units of measure for quantifying oxygen transfer: (*i*) the oxygen transfer coefficient at 20 °C, K_La_{20} (h^{-1}); (*ii*) the standard oxygen transfer rate (SOTR) (g O_2·h^{-1}); (*iii*) the standard aeration efficiency (SAE) (g O_2 kW·h^{-1}), and (*iv*) and the standard oxygen transfer efficiency (SOTE) (%). The purpose of this initial research work was to determine which combination(s) of design factors was most effective at dissolving oxygen into water, under laboratory test conditions, in a Speece Cone.

Methods

Speece Cone and tank dimensions

The laboratory-scale Speece Cone consisted of a submersible pump and a DBCA cone (Fig. 1). The intake port was connected to the pump by 40 cm of clear 5.08 cm inside diameter (ID) hose. The dimensions were 75 cm (overall height) × 34 cm (base diameter), with a clear viewing panel (12 cm × 30 cm) in the tapered portion of the cone. The lower section of the cone was 15 cm high, and the tapered upper section was 60 cm in height. There was a 90° upward facing elbow at the distal end of the outlet port. Oxygen entered the cone at an operating depth of 2.3 m, immediately downstream of the 180° elbow in the inlet port, through a

Fig. 1. Schematic of Speece Cone aerator with several probe locations shown. PSA, pressure swing adsorption.

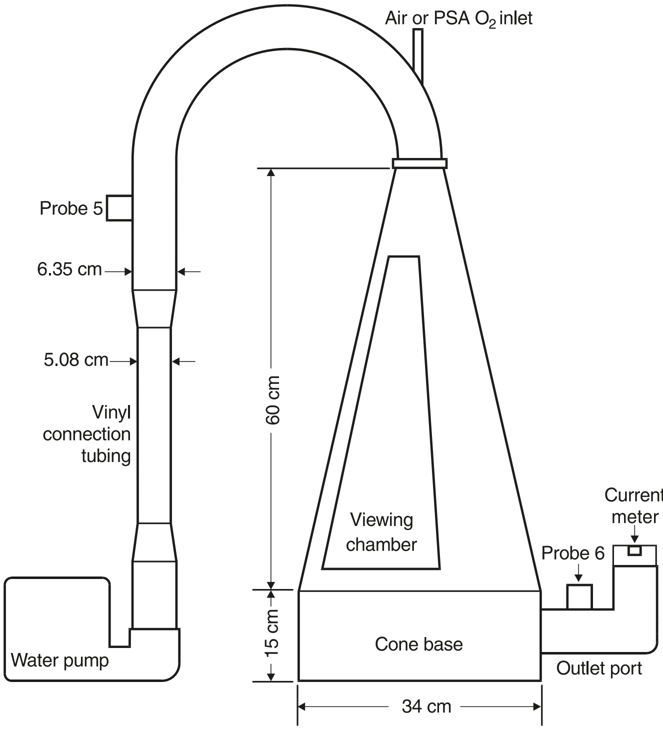
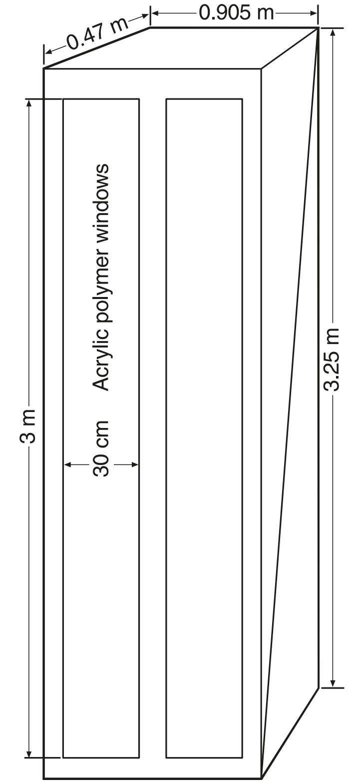


Fig. 2. Schematic diagram of aeration tank



6.4 mm brass fitting and hose nipple (Fig. 1). The unit was constructed of aluminum, and was attached to an 80 cm × 34 cm base plate. The main circulating pump for the Speece Cone was a 10 400 $L \cdot h^{-1}$ submersible pump (Little Giant 6-CIM-R) connected to a Variac voltage control unit that allowed pump voltage to be varied from 50% to 110% of rated power. The operating depth of the cone ranged from 310.5 cm (cone bottom) to 235.5 cm (cone top). The interior tank dimensions were as shown in Fig. 2. The tank was filled to a depth of 3.105 m for the tests; hence, the operational volume was 1194 L. The tank was equipped with two sections (300 cm × 30 cm × 25.4 mm) of clear acrylic on the front panel, to allow viewing of the tank interior.

Tank mixing, velocity measurement, and probe locations

An acrylic divider (200 cm high × 38 cm wide) was also inserted into the tank, to prevent short-circuiting of water discharged from the cone outlet port back into the inlet port. Dye tests indicated the divider sheet was an effective barrier to short-circuiting (Ashley 2002). Three additional 4500 $L \cdot h^{-1}$ submersible mixing pumps were positioned throughout the tank, to ensure complete mixing. Dye tests and oxygen probe readings confirmed that the tank was rapidly mixed with all four pumps operating (maximum pumping rate = 23 900 $L \cdot h^{-1}$), as the oxygen concentration throughout the tank was reduced to < 1% within an average of 3 min, following the addition of a sodium sulfite solution. A velocity sensor for the Speece Cone was positioned in the centre of the discharge flow, 10 cm from the end of the outlet port. The oxygen probes were arranged in the tank to ensure that the tank was completely mixed, to validate the nonsteady-state re-aeration test (ASCE 1992). The probes were numbered according to their position in the tank and the Speece Cone as follows: probe 1, suspended in the tank at 1.5 m; probe 2, suspended in the tank at 0.5 m; probe 3, suspended in the tank at 1.0 m; probe 4, suspended in the tank at 2.0 m; probe 5, inlet to the Speece Cone (Fig. 1), operating depth of 2.39 m, and probe 6, outlet to the Speece Cone (Fig. 1), operating depth of 2.95 m. Probe 7 was the percentage oxygen by volume probe, used to track the purity of the introduced oxygen gas, and probe 8 was a temperature probe located at a depth of 3.0 m.

Water, compressed air, and oxygen supply

The water used in the tests was taken directly from the water supply system to UBC, which is low in total dissolved solids (22 $mg \cdot L^{-1}$), slightly acidic (mean pH of 6.1), and typically of high quality. A 44.74 kW Quincy rotary screw compressor (Model QNW 260-D), rated at 6800 $L \cdot min^{-1}$ [240 standard cubic feet per minute measured at 1 atmosphere pressure (101.325 kPa), 0% relative humidity, and 21.1 °C] supplied the compressed air for the building. A nominal efficiency filter and water-cooled aftercooler was fitted to the discharge end of the compressor. Oxygen gas for the experiments was produced by an AS-20 oxygen generator, manufactured by the AirSep Corporation (Buffalo, New York), and stored in a 227 L receiver. The purity of oxygen generated ranged from 90% to 95%. A reference cylinder of certified oxygen gas (>99.99% oxygen), obtained from Air Liquide Canada (Vancouver, B.C.), was used to calibrate the oxygen gas probe (i.e., probe 7) and continuously monitor the purity of the oxygen generated by the AirSep unit.

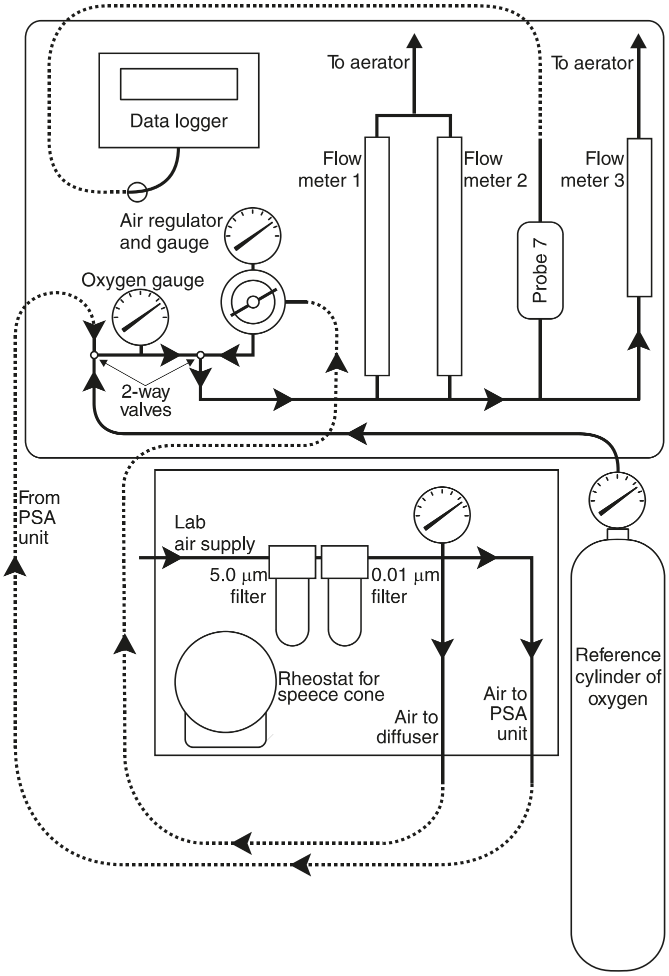
Instrumentation, parameter measurement, and data logging

A manifold board (Point Four Systems Inc., Richmond, B.C.) distributed and regulated the flow and delivery pressure of the various gases being tested (Fig. 3). Inflowing compressed air from the laboratory supply passed through a Wilkerson 5.0 μm particulate and oil–water filter, then a 0.01 μm particulate filter and oil–water filter. Filtered air was then routed to the PSA unit or straight to the manifold, via a pair of on–off ball valves. The filtered gas (air or oxygen) was then routed via separate regulators to an array of three mechanical flow indicators, which could be operated independently or in any combination. Pressure gauges were fitted to each regulator on the manifold board, on a single-stage regulator fitted to the PSA oxygen receiver and on a two-stage regulator fitted to the reference cylinder of high purity compressed oxygen. The coarse-scale flow meter was a Brooks Sho-rate flow indicator, with 150 mm scale, 2 to 46 L·min^{-1}; the medium scale meter was a Brooks Sho-rate flow indicator with 150 mm scale, 2 to 12 L·min^{-1}; and the fine scale meter was a Key Instruments flow indicator with 80 mm scale, 0 to 3.5 L·min^{-1}, all calibrated for 100% oxygen. The Brooks flow indicators were designed to operate at 3.2 bar (45 psig) (1 bar = 100 kPa), and the Key Instruments flow indicator was designed for 3.5 bar (50 psig), although it was operated at 3.2 bar.

Flow meter readings were corrected by a specific density correction factor (i.e., $\sqrt{1.105/1.0}$) when operated on compressed air. The Key Instruments meter was corrected by a pressure correction factor (i.e., $\sqrt{59.7/64.7}$) to compensate for the lower operating pressure (i.e., 3.2 versus 3.5 bar). All of the flow meters were calibrated for 21 °C; hence, no temperature correction factor was required. The manifold board was fitted with two, two-way ball valves so that compressed air, PSA oxygen or high purity reference oxygen could be delivered to the diffusers. The gas supply for the percent volume probe cup (i.e., probe 7) (Fig. 3) was located downstream of the three flow indicators; however, the volumetric flow rate of gas to the probe cup was so low that it did not introduce a bias to the various flow meter readings. The gas exiting the probe cup was vented into an 11 cm water-filled cylinder, so that the gas flow could be directly observed in a bubble stream and adjusted to maintain a low, but constant, discharge rate (Fig. 3). Water velocity was measured by a Marsh McBirney model 2000 flow meter, using a fixed point averaging (FPA) program to dampen the output variation. A time duration of 120 s was used for the averaging period.

A PT4 monitor (Point Four Systems Inc., Richmond, B.C.) was supplied with seven OxyGuard probes, which are membrane-covered, self-polarizing, galvanic measuring elements with a built-in temperature compensation. Preliminary tests revealed that dissolved oxygen concentrations in the water were changing too quickly to register with the standard mg·L^{-1} membranes. Therefore, the Oxyguard probes were configured to measure dissolved oxygen in percent saturation, rather than mg·L^{-1}, as the percent saturation probe membranes were 50% thinner than the mg·L^{-1} membranes, resulting in a faster probe response time. Water temperature was measured with a dedicated stainless steel thermister

Fig. 3. Schematic diagram of manifold board with data logger and flow meters. PSA, pressure swing adsorption.



probe (channel 8) on the PT4 monitor, and a secondary temperature probe on the Yello Springs Instruments (YSI) meter (Yellow Springs, Ohio). Both probes were typically within ~0.2 °C, and the PT4 temperature reading was used for the probe calibration procedure. The PT4 temperature probe was checked in an ice bath (0 °C) and room temperature (20 °C) water, as determined by a mercury calibration thermometer, and found to be accurate within 0.5 °C. An eight-channel, microprocessor-based PT4 monitor (Point Four Systems Inc., Richmond, B.C.) was used to record and log data collected during the experiments. The unit was configured with 6 channels for measuring dissolved oxygen in water (channels 1–6), one percent-oxygen channel (channel 7) for measuring the purity of the oxygen gas, and one temperature channel (channel 8). Continuous visual checks were made during each test to ensure the upstream gas pressure remained constant at 3.2 bar, and that gas flow remained at the desired delivery rate.

Experimental design

The design variables examined were the effect of oxygen flow rate (1, 2, and 3) L·min^{-1} and the effect of outlet port discharge velocity (20, 30, 40, 50, 60, and 70 cm·s^{-1}). This was equivalent to pumping rates of 38, 57, 76, 95, 114, and

133 L·min^{-1}. These design variables were based on the capacity of the main circulating pump and oxygen generator. The treatments were arranged into six experimental groups. A single, miscellaneous test was conducted, where the Speece Cone was operated on compressed air at 3 L/min, at a discharge velocity of 50 cm·s^{-1}. This resulted in six principal treatment groups and one minor treatment group (Table 1). The experiments were carried out in a randomized complete block design. This resulted in three combinations of gas flow rate × discharge velocity. Each set of three combinations was completed, then repeated in a different randomly selected order, to remove any random error that may have occurred during any given treatment day. Each treatment was replicated four times, three being the minimum replicate recommended for nonsteady-state re-aeration tests (ASCE 1992). A total of 76 individual re-aeration tests were completed (Table 2).

Test procedure, oxygen calibration, and oxygenation protocol

The basic test procedure started with filling the tank with clean water, turning on the submersible mixing pumps, and allowing the tank water to circulate for 5–6 min. Replicate samples of water were then collected from 10 cm below the tank surface in 300 mL biochemical oxygen demand (BOD) bottles, and analyzed for dissolved oxygen, using the Winkler titration procedure (Azide modification; Lind 1979). The two Winkler readings were then averaged to provide the reference oxygen concentration to calibrate the PT4 unit and probes for the day. The YSI meter was calibrated in mg·L^{-1} to the average of the two Winkler readings. The percent saturation for dissolved oxygen on each test day was calculated according to Colt (1984):

$$[1] \qquad C_s^* = C_{s\,760}^*(\mathrm{BP} - P_{\mathrm{H2O}})/(760.0 - P_{\mathrm{H2O}})$$

where C_s* is the dissolved oxygen air-solubility value (mg·L^{-1}) for the ambient barometric pressure, temperature, and vapor pressure of water; C_s*_{760} is the dissolved oxygen air-solubility value (mg·L^{-1}) for the barometric pressure equal to 760.0 mm Hg (1 mm Hg = 133.322 Pa) and ambient temperature; BP is the barometric pressure in mm Hg; and P_{H2O} is the vapor pressure of water in mm Hg for the ambient temperature.

Values for C_s*_{760} and P_{H2O} were taken from reference tables in Colt (1984), and the barometric pressure for each test day was taken from the Vancouver weather station on the Environment Canada Web page (at www.weatheroffice.com).

The percent oxygen saturation of the test water was then determined using eq. [2], on each day:

$$[2] \qquad \frac{[(\text{Winkler 1}) + (\text{Winkler 2})]/2}{C_s^*} \times 100 = \%\ \text{oxygen saturation}$$

where Winkler 1 and Winkler 2 are the mg·L^{-1} of oxygen in Winkler sample 1 and 2, respectively.

The PT4 monitor was then calibrated with this value, using the single-point calibration procedure outlined in the PT4 software (Point Four Systems 1997). The probe response was examined from 0% saturation (sulfite bath) to 100% saturation (AirLiquide certified > 99.99% oxygen gas) and found to be essentially linear; hence, this calibration procedure was satisfactory. Once calibrated, the probes were quite stable, but were still re-calibrated each test day. The purity of the oxygen gas (percent volume) produced by the PSA unit was monitored by a dedicated probe (channel 7) in the PT4 monitor. This probe was calibrated daily using the reference cylinder of certified oxygen gas (>99.99% oxygen). The probe was then calibrated to this reference standard, using the same single-point calibration procedure. The probe also monitored the oxygen concentration in air, when tests were being conducted on compressed air.

The deoxygenation–oxygenation procedure used was the nonsteady-state re-aeration test (Boyd and Watten 1989; ASCE 1992). The test water was deoxygenated with 0.1 mg·L^{-1} of cobalt chloride (certified grade of $CoCl_2·6H_2O$) and 10.0 mg·L^{-1} of sodium sulfite (trade acronym: Sulftech catalyzed Na_2SO_3; code 098–3393) for each 1.0 mg·L^{-1} of dissolved oxygen present in the water (Boyd 1986); an additional 10% weight of Na_2SO_3 was added, to ensure rapid deoxygenation at the colder test temperatures. Mixing details can be found elsewhere (Ashley 2002). Theoretically, only 7.9 mg·L^{-1} of sodium sulfite is required for each mg·L^{-1} of dissolved oxygen; however, due to partial oxidation during mixing, it is necessary to add up to 1.5 times the stoichiometric amount (Beak 1977). The YSI meter and PT4 monitor confirmed that the tank water was rapidly deoxygenated, as the percent oxygen saturation invariably declined to < 1.0%

Table 1. List of treatments for Speece Cone experiments.

Test No.	Discharge velocity (cm·s^{-1})	Pumping rate (L·min^{-1})	PSA O_2 flow rate (L·min^{-1})
1	20	38	1, 2, 3
2	30	57	1, 2, 3
3	40	76	1, 2, 3
4	50	95	1, 2, 3
5	60	114	1, 2, 3
6	70	133	1, 2, 3
Misc. 1	50	95	3 (air only)

Note: Misc., miscellaneous.

Table 2. List of treatment combinations for Speece Cone experiments.

Test No.	No. of combinations	Replicates	Total No. of tests
1	3	4	12
2	3	4	12
3	3	4	12
4	3	4	12
5	3	4	12
6	3	4	12
Subtotal			72
Misc. 1	1	4	4
Subtotal			4
Total			76

Note: Misc., miscellaneous.

within 2.5 min. The tank was allowed to mix for 8 min before re-aeration treatments were initiated.

The oxygen differential between the inlet and outlet of the Speece Cone was often quite large; hence, the oxygen flow was terminated when the percent saturation at the intake port (i.e., probe 5) reached 65% saturation; however, the mixing pumps remained operating. This allowed the pumps to continue circulating water within the tank and purge oxygenated water out of the Speece Cone into the bulk water. The percent saturation recorded at probe 5 (see Fig. 1), following 2 min of circulation with zero oxygen flow, was then used to represent the terminal percent oxygen saturation for the experiment. The 2 min period, following termination of oxygen flow, was not included in the various oxygen transfer calculations, as no "new" oxygen was added during this procedure, only a redistribution of existing oxygen that had already been transferred within the Speece Cone and tank. A maximum of six test runs was conducted on each tank of water, before draining and refilling, to minimize interference from sodium sulfite accumulation (Beak 1977; ASCE 1992).

Electrical measurements and power calculations

The electrical current and line voltage for the PSA unit and Speece Cone main pump was measured with a Data Hold digital clamp meter (Model DM 266) and Fluke digital multimeter. The PSA current draw was measured during oxygen production and nitrogen venting cycles, and the average measured amperage (i.e., 0.15 A) was multiplied by the line voltage (i.e., 110 V) to determine the energy requirement of the PSA unit (i.e., 16.5 W). The Speece Cone main pump power requirements were calculated by taking the average of two amperage readings and three voltage readings at each 0.5 increment on the Variac voltage control unit (0–100 scale) from 65 to 85. During the Speece Cone tests, the Variac voltage control unit setting at the end of each test was recorded, and the mean setting determined for each measured water discharge velocity × gas flow combination (i.e., four readings). A linear regression equation was used to predict the energy consumption for each of the mean water discharge velocity settings used in the Speece Cone tests:

$$[3] \qquad y = 0.0153x - 0.3386 \qquad r^2 = 0.99$$

where y is the kW energy consumption of the Speece Cone main pump, x is the Variac voltage control unit setting, and r^2 is the correlation coefficient.

Parameter estimation procedure

The log deficit method of parameter estimation was used to determine K_La, as the experimental tests were terminated at 60%–65% saturation, due to the time impracticality of running all tests to 98% of saturation [as is mandatory for the nonlinear regression method of parameter estimation (ASCE 1992)]. This method is the recommended American Society of Civil Engineers (ASCE) method of parameter estimation for the measurement of oxygen transfer in clean water; "however, if the engineer/owner so specifies, the log deficit method described in Annex E shall be permitted in lieu of the nonlinear regression method" (ASCE 1992, p. 9). The log deficit method is also the recommended technique for parameter estimation within the aquacultural and aquatic sciences community (Boyd 1986; Boyd and Watten 1989) and was listed as a tentative standard in the 15th edition of *Standard methods for the examination of water and wastewater* (APHA 1980).

The oxygen transfer coefficient at the temperature T (°C) of the test water, K_La_T (h^{-1}), was calculated according to:

$$[4] \qquad K_La_T = \frac{\log n[(C_s^* - C_1)/C_s^* - C_2]}{t_2 - t_1}$$

where C_s* is the dissolved oxygen air-solubility value (mg·L^{-1}) for the ambient barometric pressure, temperature, and vapor pressure of water; C_1 is the dissolved oxygen concentration at time t_1 (mg·L^{-1}); and C_2 is the dissolved oxygen concentration at time t_2 (mg·L^{-1}); 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, barometric pressure, and vapor pressure of water. This study used approximately 10% (t_1) and 65% (t_2) saturation values for t_1 and t_2, as a sufficient number of data points (i.e., 11) was collected and it was not practical, from a time perspective, to run each test to 80% saturation.

K_La_T was corrected to K_La_{20} according to (ASCE 1992):

$$[5] \qquad K_La_{20} = K_La_T\theta^{(20-T)}$$

where θ is the Arrhenius temperature correction coefficient (= 1.024).

The SOTR was calculated as:

$$[6] \qquad \mathrm{SOTR} = K_La_{20}\, C_{s20}\, V$$

where C_{s20} is the dissolved oxygen concentration (mg·L^{-1}) at saturation for 20 °C and standard pressure (760 mm Hg) and V is the volume of water in the tank (m^3).

The SAE was calculated as:

$$[7] \qquad \mathrm{SAE} = \mathrm{SOTR/power\ input}$$

where power input is the total delivered power (kW).

Power input calculations

For the Speece Cone experiments, the power input was separated into four components plus an expansion factor for the weight of air flow. This was based on the published air input to oxygen output ratio of the AirSep AS-20 PSA unit (i.e., 15.9 to 1). The first energy component, E_1, is the delivered blower power required to deliver the mass flow of gas at the absolute minimum pressure requirement of the PSA unit (7.2 bar). Delivered blower power is the "theoretical power required at a blower discharge to deliver a given mass flow of gas at a given discharge pressure, calculated based upon adiabatic compression" (ASCE 1992, p. 15). The delivered blower power was calculated according to the adiabatic compression formula (ASCE 1992):

$$[8] \qquad P_w = wRT_1/29.7ne[(p_2/p_1)^{0.283} - 1]$$

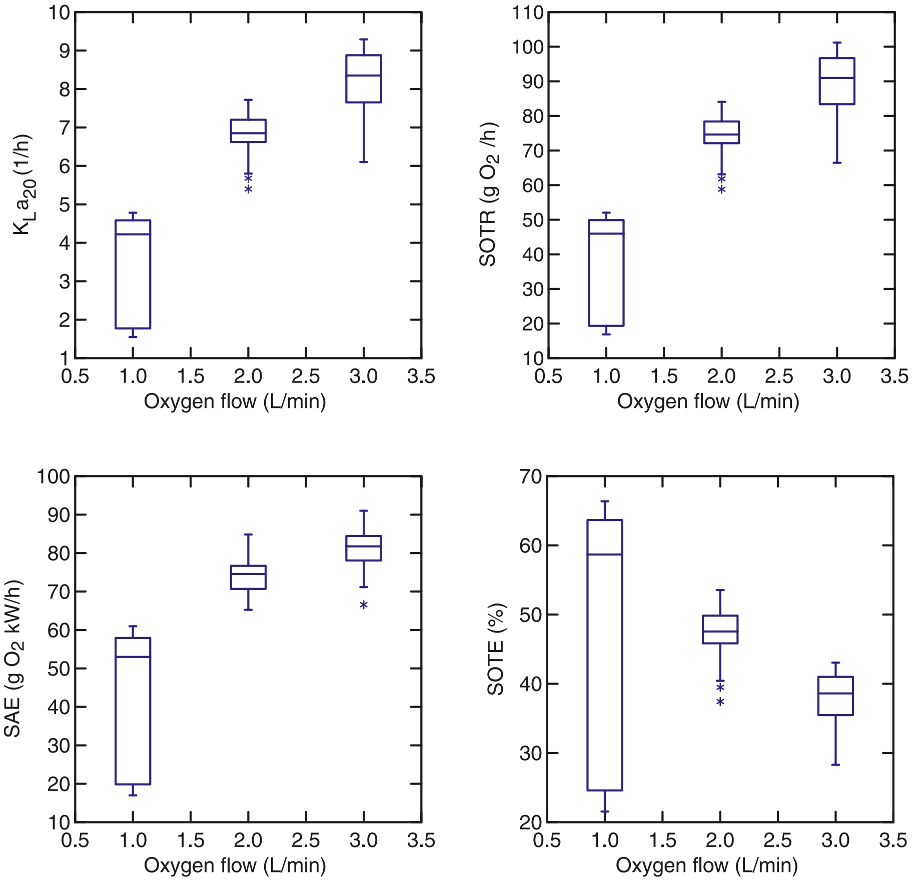
where P_w is the power input (kW); w is the weight of air flow (kg·s^{-1}) (i.e., 1.2927 g·L^{-1}); R is the engineering gas constant for air [= 8.314 kJ/(k·mol·K)]; T_1 is the absolute inlet temperature before compression (K); n is a constant [= (k-1)/k = 0.283 for air (and oxygen), where k = 1.395

Table 3. Summary of energy calculations for Speece Cone experiments.

Treatment	E_1	E_2	E_3	E_4
Speece Cone – PSA	Adiabatic compression at 7.2 bar	Adiabatic compression at 2.9 m depth	Average measured wire power of main circulation pump	Average PSA measured wire power
Speece Cone – air	Adiabatic compression at 4.1 bar	Adiabatic compression at 2.9 m depth	Average measured wire power of main circulation pump	Not applicable

Note: PSA, pressure swing adsorption.

Fig. 4. Box and whisker plots showing effect of pressure swing adsorption O_2 flowrate on (*a*) K_La_{20}, (*b*) standard oxygen transfer rate (SOTR), (*c*) standard aeration efficiency (SAE), and (*d*) standard oxygen transfer efficiency (SOTE). *, outlier.



for air (and oxygen)]; 29.7 is the constant for SI conversion; e is the compressor efficiency (= 0.80); and p_1 and p_2 are the absolute inlet pressures before compression (= 1.0 bar) and after compression (= 4.1 bar), respectively.

The second energy component, E_2, is the same adiabatic compression formula adjusted to the absolute ambient hydrostatic pressure of gas release (i.e., 2.9 m), rather than the absolute minimum pressure requirement of the PSA unit. The third energy component, E_3, is the average measured wire power of the main Speece Cone pump, as derived from the linear regression equation between control unit setting and measured energy consumption. The fourth energy component, E_4, is the average measured wire power of the AirSep AS-20 PSA unit (i.e., 0.0165 kW). The sum of E_1, E_2, E_3, and E_4 equals the total delivered power (Table 3).

For the Speece Cone experiment on air, the power input was separated into three components. The first energy component, E_1, is the delivered blower power based upon adiabatic compression, from the manifold board regulator (i.e., 4.1 bar). The second energy component, E_2, is the same adiabatic compression formula adjusted to the absolute ambient hydrostatic pressure of gas release (i.e., 2.9 m). The third energy component, E_3, is the average measured wire power of the main Speece Cone pump derived from the linear regression equation between control unit setting and measured energy consumption. The sum of E_1, E_2, and E_3 equals the total delivered power (Table 3).

Finally, SOTE was calculated as:

$$[9] \qquad \text{SOTE} = \text{SOTR}/W_{O2}$$

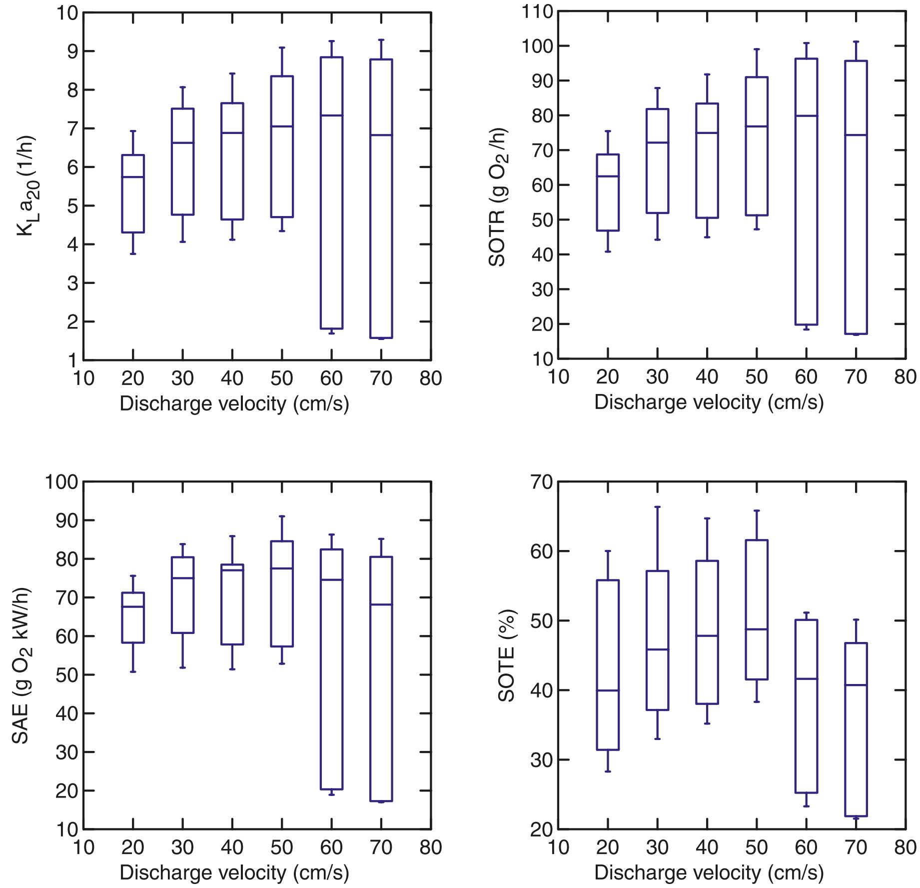
where W_{O2} is the mass flow rate of oxygen in the gas flow stream (g $O_2 \cdot h^{-1}$).

The detailed calculation of W_{O2} for the various experimental treatments can be found elsewhere (Ashley 2002).

Statistical analysis

The statistical model used to analyze the experimental

Fig. 5. Box and whisker plots showing effect of water discharge velocity on (*a*) K_La_{20}, (*b*) standard oxygen transfer rate (SOTR), (*c*) standard aeration efficiency (SAE), and (*d*) standard oxygen transfer efficiency (SOTE).



data was the general linear model (GLM) in the SYSTAT 10 statistical package (Systat Software, Inc., San Jose, Calif.). This model can estimate any univariate or multivariate general linear model, including analysis of variance or covariance (Wilkinson and Coward 2000). The level of significance was set at α = 0.01 for each statistical test. The first step in the analysis was to plot a frequency distribution of K_La_{20}, SOTR, SAE. and SOTE, to determine if the values were normally distributed. An initial box and whisker plot of the covariate and treatments (e.g., gas flow rate and discharge velocity) was then plotted against K_La_{20}, SOTR, SAE, and SOTE, to examine for outliers. No extreme outliers were detected in the 76 trials conducted in these tests (Ashley 2002).

Results

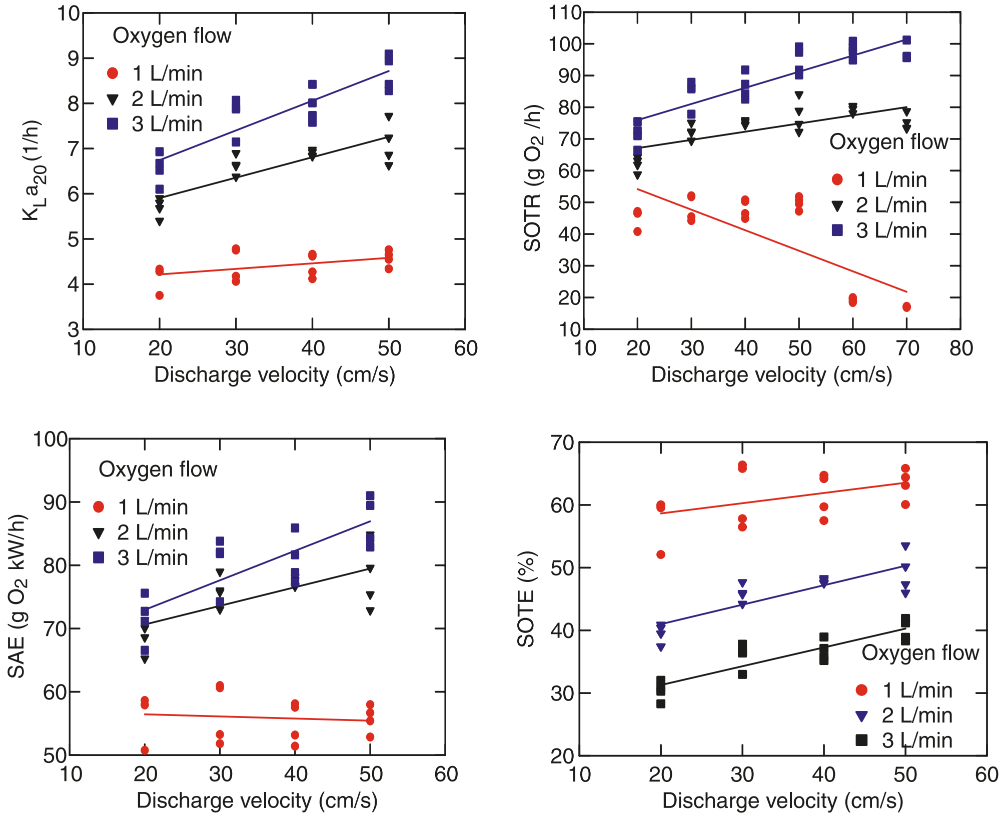
The initial box and whisker plots of K_La_{20}, SOTR, SAE, and SOTE, as a function of oxygen flow rate and discharge water velocity, showed a pattern of increased variance for the 1 L·min^{-1} oxygen flow rate (Fig. 4) and discharge velocities of 60 and 70 cm·s^{-1} (Fig. 5). The untransformed plots of K_La_{20}, SOTR, SAE, and SOTE indicated that the performance of the Speece Cone was highly variable at these treatment combinations; therefore, the data was analysed without the two highest discharge velocities (i.e., 60 and 70 cm·s^{-1}) in an attempt to determine homogeneity of slopes. The analysis indicated a significant interaction effect (Fig. 6); hence the data was log transformed and re-analyzed (Fig. 7).

A significant result ($\alpha \leq 0.01$) was obtained for the discharge velocity covariate effect for K_La_{20}, SOTR, SAE, and SOTE, and the oxygen gas flow rate for K_La_{20}, SOTR, and SOTE (Table 4). The SAE performance of the Speece Cone was not significantly influenced by oxygen gas flow rate, within this truncated data set. However, a significant oxygen flow rate × discharge velocity interaction effect was observed for K_La_{20}, SOTR, SAE, and SOTE (Table 4).

While statistically valid, this approach did not provide sufficient insight into the overall performance of the Speece Cone; therefore, three-dimensional (3-D) graphing was used to understand the behaviour of K_La_{20}, SOTR, SAE, and SOTE under the full range of experimental treatments in this preliminary work. The 3-D graphs indicate K_La_{20} and SOTR increased as oxygen flow rates increased from 1 to 2 L·min^{-1}, over the range of velocities from 20 to 50 cm·s^{-1}; then there was a reduced slope as oxygen flow increased to 3 L·min^{-1} (Ashley 2002). However, when operated at a combined oxygen flow rate < 2 L·min^{-1} and discharge velocities > 50 cm·s^{-1}, the K_La_{20} and SOTR decreased precipitously.

The SAE response manifold was similar to K_La_{20} and SOTR responses (Ashley 2002). The most dramatic response was for SOTE, which indicated increasing oxygen transfer efficiency as oxygen flow rate decreased from 3 to 1 L·min^{-1},

Fig. 6. Effect of pressure swing adsorption O_2 flow rate (1, 2, and 3 L·min^{-1}) and water discharge velocity (20–50 cm·s^{-1}) on (*a*) K_La_{20}, (*b*) standard oxygen transfer rate (SOTR), (*c*) standard aeration efficiency (SAE), and (*d*) standard oxygen transfer efficiency (SOTE).



over the range of discharge velocities of 20 to 50 cm·s^{-1} (Ashley 2002). However, when operated at combined oxygen flow rates < 2 L·min^{-1} and velocities > 50 cm·s^{-1}, SOTE decreased abruptly, indicating a collapse of the high oxygen transfer efficiencies normally associated with Speece Cone aerators.

Experiments with air

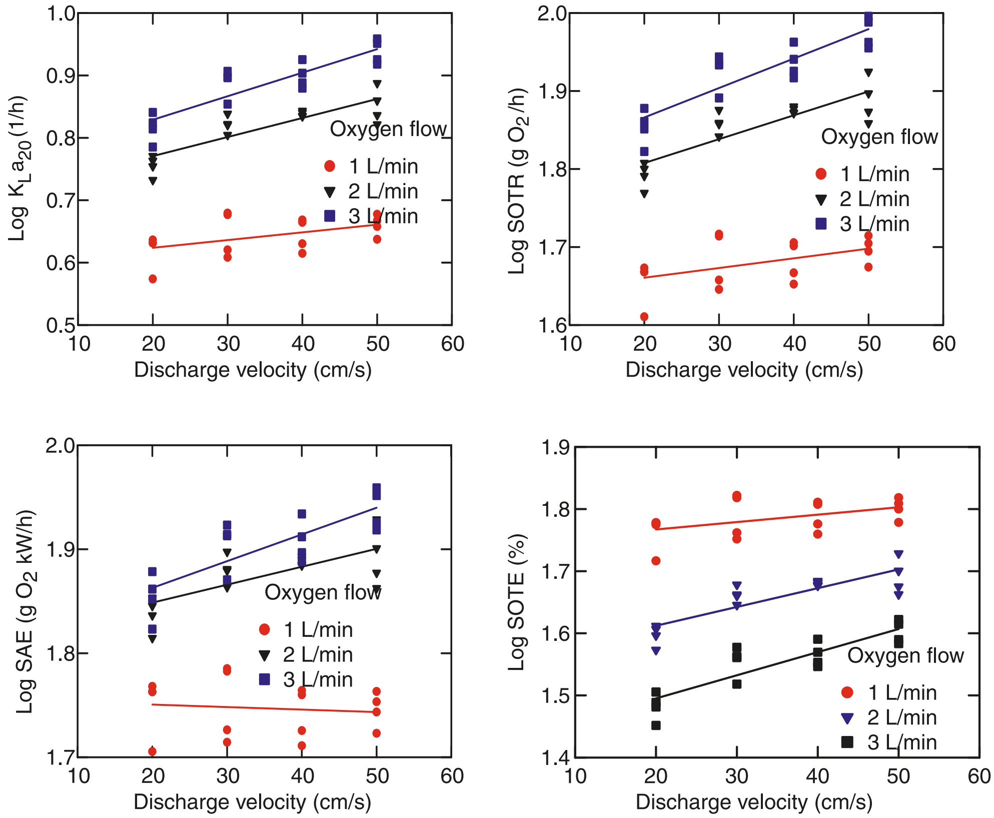
The results of the Speece Cone tests using air were considerably different from the performance on PSA-generated oxygen. The tests were conducted only at 3 L·min^{-1} air at 50 cm·s^{-1}, as this was among the most efficient oxygen gas flow rate × discharge velocity combination for the Speece Cone. The mean values obtained for K_La_{20}, SOTR, SAE, and SOTE at this setting, on air, were lower than any values recorded on PSA oxygen (Table 5). For comparative purposes, the air results are shown alongside the 3 L·min^{-1} × 50 cm·s^{-1} data, for the Speece Cone operating on oxygen.

Discussion

This research effort was an attempt to examine the oxygen transfer capabilities of a laboratory-scale Speece Cone. Unlike published design guidelines for full-lift hypolimnetic aerators (e.g., Lorenzen and Fast 1977; Taggart and McQueen 1982; Ashley 1985), there is no experimental data from Speece Cone operation available in the primary published literature. McGinnis and Little (1998) developed a model that predicts oxygen transfer in a Speece Cone, and acknowledged the absence of any experimental data to validate their model. Their model assumed no bubble coalescence or breakup occurs, and that both gas and water are in plug flow mode; these assumptions were not valid for this study.

A Speece Cone functions by having three distinct zones within the aeration chamber: an energizing zone at the top of the cone, a gas transfer zone in the middle, and a bubble–water separation zone near the bottom. All of these zones must exist simultaneously, to achieve the high dissolved oxygen transfer capability that has been reported in the published literature (e.g., Thomas et al. 1994; Doke et al. 1995). Water must enter the energizing zone with sufficient velocity to entrain injected oxygen gas and initiate a two-phase bubble swarm in the cone. The gas transfer zone is the intensely turbulent area, which maintains the two-phase bubble swarm, i.e., where the downward water velocity matches the rise velocity of the bubbles. As only oxygen is normally used in a Speece Cone, the gas flow rate must be matched to the oxygen dissolution rate in a given volume of water; otherwise, the bubble swarm will increase in size, eventually coalescing into a gas pocket and collapsing the gas transfer process. The bubble–water separation zone at the bottom of the Speece Cone is required to prevent residual bubbles from being discharged in the outlet port, and avoiding localized destratification upon their release. Therefore, the key design parameters for a Speece Cone are (*i*) a critical minimum inlet water velocity; (*ii*) a critical maximum outlet water velocity; (*iii*) a critical ratio of oxygen to water flow rates to allow complete gas dissolution and prevent bubble coalescence;

Fig. 7. Effect of pressure swing adsorption O_2 flow rate (1, 2, and 3 L·min^{-1}) and water discharge velocity (20–50 cm·s^{-1}) on (*a*) K_La_{20}, (*b*) standard oxygen transfer rate (SOTR), (*c*) standard aeration efficiency (SAE), and (*d*) standard oxygen transfer efficiency (SOTE) using log transformed data.



and (*iv*) sufficient cone dimensions to maintain a two-phase bubble swarm and allow residual bubble separation, while providing sufficient residence time for 100% gas transfer. Speece et al. (1990) provided the following, initial design criteria: 3.05 m·s^{-1} for the inlet velocity, ≤ 0.305 m·s^{-1} for the outlet velocity, and a residence time of about 10 s. No information was presented on gas to water ratios, and neither have these design criteria been updated in the published literature.

Based on these sparse design criteria, the laboratory-scale system was designed and constructed; however, it was later recognized that this laboratory-scale prototype would not meet the required design standard needed for optimum aeration performance of a Speece Cone (Table 6). For example, the Speece Cone used in these experiments failed to generate adequate velocities at the top of the cone. The diameter of the inlet and outlet ports were identical (e.g., 6.35 cm ID); hence, the maximum inlet velocity (i.e., 70 cm·s^{-1}) was only 23% of the recommended design velocity (i.e., 305 cm·s^{-1}). Consequently, the two-phase bubble swarm could never properly develop inside the cone, but remained as a gas pocket at the top of the cone, such that the inlet water dropped through; this resulted in a drastically reduced bubble surface area to water ratio. Therefore, all of the performance measures from this prototype Speece Cone are much lower than would be expected with the recommended inlet velocity of 305 cm·s^{-1}. Despite this flaw, the system was still capable of oxygen transfer efficiencies of about 61% (Table 4) under low gas flow rates; this is still higher than any full-lift design hypolimnetic aerator operating on air (Lorenzen and Fast 1977).

The cross-sectional velocity at the base of the cone was adequate to allow gas–water separation; however, an excessive amount of bubbles were observed leaving the system at higher gas-flow and water-flow rates. Therefore, it was recognized afterwards that the height of the cone was insufficient to allow physical separation of the three cone functions. Mass wasting of oxygen bubbles contributed to the relatively low SAE performance of this cone, as the energy used to generate and compress the oxygen and pump the water was wasted by the escaping bubbles. The residence time at the highest flow rates was about 40% greater than recommended design specifications (14 versus 10 s); however, as the bubble swarm failed to develop, it was not possible in this phase of the research to determine if a 14 s residence time would be adequate.

The explanation for the precipitous decline in SOTE at low oxygen flow rates (i.e., < 1 L·min^{-1}) and inlet–discharge velocities > 50 cm·s^{-1} (Ashley 2002) is due to purging of the gas pocket in the Speece Cone; this forced the oxygen bubbles out the discharge port, thus collapsing the partial DBCA effect and triggering the precipitous decline in SOTE (as well as K_La_{20}, SOTR, and SAE). At oxygen flow rates > 1 L·min^{-1}, there was sufficient positive buoyancy

Table 4. Adjusted least squares means, treatment, and interaction effects for various pressure swing adsorption oxygen flow rates with the Speece Cone without the 60 and 70 $cm \cdot s^{-1}$ water discharge velocities.

	Adjusted least squares means (± SE shown in parentheses)				
Treatment, oxygen flow rate ($L \cdot min^{-1}$)	K_La_{20} (h^{-1})[a]	SOTR (g $O_2 \cdot h^{-1}$)[a]	SAE (g $O_2 \cdot kW \cdot h^{-1}$)[a]	SOTE (%)[a]	*n*
1	4.4 (0.09)	47.9 (0.94)	55.9 (0.92)	61.1 (0.69)	16
2	6.6 (0.09)	71.7 (0.94)	75.1 (0.92)	45.6 (0.69)	16
3	7.7 (0.09)	84.2 (0.94)	80.0 (0.92)	35.8 (0.69)	16

Note: SE, standard error; SOTR, standard oxygen transfer rate; SAE, standard aeration efficiency; SOTE, standard oxygen transfer efficiency; *n*, sample size.

[a]Interaction, yes; O_2 flow effect and discharge velocity effect, significant at $\alpha = 0.05$.

Table 5. K_La_{20}, standard oxygen transfer rate (SOTR), standard aeration efficiency(SAE), and standard oxygen transfer efficiency (SOTE) mean values for Speece Cone hypolimnetic aerator operating on air at 3 $L \cdot min^{-1}$ and 50 $cm \cdot s^{-1}$ compared with pressure swing adsorption oxygen at 3 $L \cdot min^{-1}$ and 50 $cm \cdot s^{-1}$.

	Mean values (± SE shown in parentheses)				
Treatment	K_La_{20} (h^{-1})	SOTR (g $O_2 \cdot h^{-1}$)	SAE (g $O_2 \cdot kW \cdot h^{-1}$)	SOTE (%)	*n*
3 $L \cdot min^{-1}$ air at 50 $cm \cdot s^{-1}$	1.2 (0.01)	13.4 (0.04)	16.9 (0.05)	24.5 (0.08)	3
3 $L \cdot min^{-1}$ PSA O_2 at 50 $cm \cdot s^{-1}$	8.7 (0.20)	94.6 (0.94)	86.9 (0.92)	40.1 (0.69)	16

Note: SE, standard error; *n*, sample size.

Table 6. Comparison of experimental Speece Cone inlet water velocities and oxygen water ratios with design specifications.

Inlet water velocity ($cm \cdot s^{-1}$)	Water flow ($L \cdot min^{-1}$)	Hydraulic residence time (s)	Oxygen flow ($L \cdot min^{-1}$)	Base cross-sectional velocity ($cm \cdot s^{-1}$)	O_2 to water ratio (%)
20	38	51	1 to 3	0.7	2.6–7.9
30	57	34	1 to 3	1.0	1.8–5.3
40	76	25	1 to 3	1.4	1.3–3.9
50	95	20	1 to 3	1.7	1.1–3.2
60	114	17	1 to 3	2.1	0.9–2.6
70	133	14	1 to 3	2.4	0.8–2.3
305[a]	—	10[b]	—	≤30.5[a]	—

[a]Recommended design velocity.

[b]Recommended design residence time.

inside the Speece Cone from the additional oxygen bubbles, such that discharge velocities > 50 $cm \cdot s^{-1}$ were not able to purge all of the bubbles. Operationally, this would present a problem, as the mass wasting of bubbles could destratify a thermally stratified lake or reservoir. For this reason, full-size Speece Cones must have sufficient contact time and bubble collector hoods located downstream of the main cone outlet port to collect any residual bubbles and vent them to the surface through a discharge pipe (to avoid unintentional destratification). In theory, a properly designed Speece Cone should not discharge any excess bubbles, as all of the pure oxygen gas delivered to the cone should be dissolved into the water. In practice, however, it has been noticed that occasional releases of small bubbles are emitted from the discharge port. This is likely a result of a minor imbalance between the delivered oxygen to water ratio, fluctuations in line voltage influencing the capacity of the main circulating pump or slight variations in oxygen purity from the oxygen generators. As a precaution, a bubble harvester is usually included in the design to prevent any residual bubbles from causing localized destratification.

The single test of the Speece Cone on air in this research program was curiosity-motivated research. The intent was simply to see what type of performance was possible on air, with a system designed to operate on oxygen. As shown in Table 5, the results of the air test were lower than any recorded on PSA oxygen for K_La_{20}, SOTR, SAE, and SOTE. The SAE performance on air was very low, as the higher energy cost required to operate the water pump penalized this energy-related unit of measure. In practice, a Speece Cone should not be operated on air, as this would forfeit the higher performance available with oxygen. There would also be concerns about nitrogen supersaturation causing fish mortalities, particularly in salmonids (Rucker 1972).

The next logical step in this on-going research program was to build a pilot-scale Speece Cone (this work has been underway for the past 12 months or so), with as close to the correct inlet and outlet velocities, hydraulic residence time, and physical dimensions as possible, such that a bubble swarm could be generated. The gas to water ratio could then be varied to determine the optimum ratio and to explore the sensitivity of this remaining design element. Once this experimental data is collected and analyzed, it can be properly compared with the predictive model of McGinnis and Little (1998) and will allow a comparison with other types of hypolimnetic aeration designs.

Conclusions

Based on a preliminary assessment of a laboratory-scale Speece Cone hypolimnetic aerator, the following conclusions can be put forth at this time:

(1) Inlet velocities of 70 $cm \cdot s^{-1}$ were insufficient to a generate two-phase bubble swarm, and resulted in oxygen transfer efficiencies that were less than reported in full-scale field installations.
(2) Purging of the gas pocket in a Speece Cone will result in a precipitous decline in oxygen transfer performance.
(3) Speece Cone designs require the simultaneous establishment of three distinct gas-transfer functions (energized inflows, two-phase bubble swarms, and bubble–water separation) to provide highly efficient oxygen transfer.
(4) Speece Cones should not be operated on air, as the energy costs required to circulate the water though the cone result in low oxygen transfer rates per unit energy input.
(5) The standard oxygen-transfer efficiency of a prototype Speece Cone, operating on oxygen, was higher than any reported full-lift hypolimnetic aerators operating on air.

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References

APHA. 1980. Standard methods for the examination of water and wastewater. 15th ed. American Public Health Association, Washington, D.C.

ASCE. 1992. Measurement of oxygen transfer in clean water. ANSI/SSCE 2–91, 2nd ed. American Society of Civil Engineers, New York.

Ashley, K.I. 1985. Hypolimnetic aeration: practical design and application. Water Research, **19**(6): 735–740. doi:10.1016/0043-1354(85)90120-4.

Ashley, K.I. 2002. Comparative analysis of oxygen transfer in full lift and downflow bubble contact hypolimnetic aerators. Ph.D. thesis, Civil Engineering Department, The University of British Columbia, Vancouver, B.C.

Beak. 1977. State of the art review: Aeration. Beak Consultants Ltd., Montréal, Que. CPAR Project Report 542–1.

Boyd, C.E. 1986. A method for testing aerators for fish tanks. The Progressive Fish-Culturist, **48**(1): 68–70. doi:10.1577/1548-8640(1986)48<68:AMFTAF>2.0.CO;2.

Boyd, C.E., and Watten, B.J. 1989. Aeration systems in aquaculture. Reviews in Aquatic Sciences, **1**(3): 425–472.

Colt, J. 1984. Computation of dissolved gas concentrations in water as functions of temperature, salinity and pressure. Special Publication No. 14. American Fisheries Society, Bethesda, Md.

Cook, G.D., Welch, E.B., Peterson, S.A., and Nichols, S.A. 2005. Restoration and management of lakes and reservoirs, 3rd ed. CRC Press, New York.

Doke, J.L., Funk, W.H., Jull, S.T.J., and Moore, B.C. 1995. Habitat availability and benthic invertebrate population changes following alum treatment and hypolimnetic oxygenation in Newman Lake, Washington. Journal of Freshwater Biology, **10**: 87–102.

Dunst, R.C., Born, S.M., Smith, S.A., Nichols, S.A., Peterson, J.O., Knauer, D.R., Serns, S.L., Winter, D.R., amd Wirth, T.L. 1974. Survey of lake rehabilitation techniques and experiences. Technical Bulletin No. 75. Wisconsin Department of Natural Resources, Madison, Wis.

HDR Engineering. 2004. San Joaquin River dissolved aeration project. Draft engineering feasibility report, July 2004. HDR Engineering, Folsom, Calif.

Lind, O.T. 1979. Handbook of common methods in limnology. 2nd ed. C.V. Mosby, St. Louis, Mo.

Lorenzen, M., and Fast, A.W. 1977. A guide to aeration/circulation techniques for lake management. U.S. Environmental Protection Agency 600/3–77–004. Tetra Tech. Inc., Lafayette, Ind.

McGinnis, D.F., and Little, J.C. 1998. Bubble dynamics and oxygen transfer in a speece cone. Water Science and Technology, **37**(2): 285–292. doi:10.1016/S0273-1223(98)00035-3.

Point Four Systems. 1997. PT4 users manual for UBC Civil Engineering Department. Point Four Systems, Inc., Richmond, B.C.

Rucker, R. 1972. Gas bubble disease of salmonids: a critical review. Technical Paper 58. U.S. Fish and Wildlife Service, Washington, D.C.

Speece, R.E. 1971. Hypolimnion aeration. Journal - American Water Works Association, **63**(1): 6–9.

Speece, R.E., Nirmalakhandan, N., and Tchobanoglous, G. 1990. Commercial oxygen use in water-quality management. Water Environment and Technology, **2**(7): 54–61.

Taggart, C.T., and McQueen, D.J. 1982. A model for the design of hypolimnetic aerators. Water Research, **16**(6): 949–956. doi:10.1016/0043-1354(82)90028-8.

Thomas, J.A., Funk, W.H., Moore, B.C., and Budd, W.W. 1994. Short term changes in Newman Lake following hypolimnetic aeration with the Speece Cone. Lake and Reservoir Management, **9**: 111–113.

Wilkinson, L., and Coward, M. 2000. Linear models II: analysis of variance. *In* SYSTAT 10, Statistics 1. Chapter 15. SPSS Inc., Chicago, Ill.

List of symbols

BP	barometric pressure (mm Hg)
C_1	dissolved oxygen concentration at time t_1 ($mg \cdot L^{-1}$)
C_2	dissolved oxygen concentration at time t_2 ($mg \cdot L^{-1}$)
C_s*	dissolved oxygen air-solubility value ($mg \cdot L^{-1}$) for the ambient barometric pressure, temperature and vapor pressure of water
C_s*_{760}	dissolved oxygen air-solubility value ($mg \cdot L^{-1}$) for the barometric pressure equal to 760.0 mm Hg and ambient temperature
C_{s20}	dissolved oxygen concentration in water ($mg \cdot L^{-1}$) at 20 °C and for the barometric pressure of 760.0 mm Hg
e	compressor efficiency (= 0.80 in adiabatic compression formula)
ID	inside diameter (cm)
k	unit (1.395) for air (and oxygen) in adiabatic compression formula
K_La	overall oxygen transfer coefficient (h^{-1})
K_La_{20}	oxygen transfer coefficient at 20 °C (h^{-1})

K_La_T oxygen transfer coefficient at temperature T °C (h^{-1})
n constant [= (k-1)/k = 0.283 for air (and oxygen) in adiabatic compression formula]
p_1 absolute inlet pressure before compression (bar)
p_2 absolute inlet pressure after compression (bar)
P_{H2O} vapor pressure of water for the ambient temperature (mm Hg)
P_w power input (kW)
r^2 correlation coefficient
R engineering gas constant for air (= 8.314 kJ/k·mol·K)
SAE standard aeration efficiency (g O_2 kW·h^{-1})
SOTE standard oxygen transfer efficiency (%)
SOTR standard oxygen transfer rate (g O_2 h^{-1})
t_1 time at point 1 on the semi-logarithmic plot (h)
t_2 time at point 2 on the semi-logarithmic plot (h)
T test water temperature
T_1 absolute inlet temperature before compression (K)
V volume of the liquid (m^3)
w weight of air flow (kg·s^{-1}) (i.e., 1.2927 g·L^{-1})
W_{O2} mass flow rate of oxygen in the gas flow stream (g O_2 h^{-1})
Winkler 1, Winkler 2 oxygen concentration in mg·L^{-1} of Winkler tests 1 and 2, respectively
x Variac voltage control unit setting
y energy consumption of the Speece Cone main pump (kW)
α statistical level of significance
θ Arrhenius temperature correction coefficient (= 1.024)