Low head oxygenator performance characterization for marine recirculating aquaculture systems

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ABSTRACT
This study evaluated the effect of temperature (20 and 25 °C), salinity (10, 15, and 20 ppt), and dissolved oxygen levels within low head oxygenator (LHO) outlet water on oxygen transfer efficiency (OTE) of LHOS for a planned marine recirculating aquaculture system (RAS). Test results indicated that OTE was generally greater at salinities of 10–15 ppt compared to OTE measured with freshwater and at 20 ppt salinity. Oxygen transfer efficiency in freshwater with LHO outlet oxygen saturation of 230% was only 58% compared to OTE in 10 ppt and 15 ppt salinity with an LHO outlet oxygen saturation of 230% of 79% and 72%, respectively. As expected, OTE declined as target dissolved oxygen levels in LHO outlet water increased from 150 to 230% saturation. Oxygen transfer efficiency at 15 ppt salinity and 150% dissolved oxygen saturation at the LHO outlet was 97%, while OTE dropped to 72% at 230% oxygen saturation. Increased OTE at higher salinities of 10–15 ppt was attributed to increased ionic strength of the water under saline conditions resulting in formation of smaller diameter bubbles, as opposed to larger bubbles formed in freshwater. However, at 20 ppt this effect may have caused the formation of small diameter bubbles with such a slow rise velocity that they were overcome by the water velocity leaving the bottom of the LHO and were carried out of the LHO, thereby reducing OTE. Improvements in performance for similarly-designed LHOS in intensive marine RAS can be realized by designing LHOS for lower hydraulic loading, taller fall height, and increased submergence.

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1. Introduction
The multi-stage low head oxygenator (LHO) is a patented device that consists of multiple spray or packed column segments that receive water in parallel but are connected serially for pure oxygen injection (Watten, 1989). Adjacent spray or packed column segments (contact chambers) often share a common wall in commercial LHOS. In operation, water is introduced into the column segments at the top of the LHO through an inlet head box with perforated plate. The water pools over the perforated plate to provide a gas seal at the top of the LHO. Water falls through the contact chambers and into a common receiving area. Pure oxygen is injected into the LHO at one end of the device into a single column segment. Off-gas from that column segment is directed to the adjacent column segment, and the off-gas from that column segment is then directed to the next adjacent column segment. Off-gas is serially contacted in this manner throughout all contact chambers and residual off-gas is vented from the LHO. The repeated contacting of the off-gas provides a high mean dissolved gas deficit for oxygen and nitrogen gas transfer (Watten, 1994).

LHOS are typically hydraulically loaded at 33.9–50.91 per second per square meter of plan area (50–75 gpm per ft 2) but may be loaded at higher rates (Watten, 1994; Vinci et al., 2004). The height of the contact chambers ranges from 0.3 to 1.0 m (0.984–3.28 ft). The performance of the LHO is affected by the contact chamber height, hydraulic loading, gas flow rate, influent dissolved gas concentrations, number of contact chambers, presence or absence of packing media in the chambers, and perforated plate orifice size (Watten, 1994; Davenport et al., 2001). Dwyer and Peterson (1993) and Wagner et al. (1995) have reported oxygen absorption efficiencies for LHO operation in freshwater fish hatcheries ranging from 65 to 91%, with a trend for decreasing oxygen absorption efficiency with increasing ratios of volumetric oxygen gas flow to water flow (G/L ratio). The reported G/L ratios ranged from 0.10 to 0.83% (Wagner et al., 1995).

Reliable data that characterizes oxygen transfer efficiency (OTE) across a LHO operated within a marine recirculating aquaculture system (RAS) is limited. Therefore, a series of trials were conducted.
to evaluate LHO performance at various salinities, water temperatures, and targets dissolved oxygen levels in the LHO outlet water for an existing LHO design. These trials were conducted to provide critical information for the optimal design and sizing of LHO’s to be incorporated within intensive marine RAS.

2. Materials and methods

2.1. Experimental recirculating aquaculture system

A 9.5 m$^3$ RAS at The Conservation Fund’s Freshwater Institute (Shepherdstown, WV, USA) was used for the trials (Fig. 1). The existing system process flow was re-configured to maximize the fall height from the LHO distribution plate to the water level inside the LHO sump and to optimize LHO submergence (Fig. 2). In the reconfigured process flow, recycle water was pumped from the pump sump through a fluidized sand biofilter and then cascaded through a force-ventilated carbon dioxide stripping column to a LHO distribution plate and through the LHO unit process where oxygen was added. Oxygenated water flowed by gravity from the LHO sump to the fish culture tank. The average recycle water flow for all trials was 413 l per minute (109 gpm). The majority of the water (approximately 90%) was directed through the fish tank’s bottom center drain and into the pump sump, and approximately 10% of the recycle water flowed through the fish tank’s side box drain into the pump sump. The solids settling unit, drum filter, and heat exchanger were bypassed during this study. Adjustments to the recycle loop reduced the normal system water volume to 6.5 m$^3$ for the trials. The experimental RAS was operated as a closed system with no makeup water addition. The LHO had eight equal “pie-shaped” contact chambers. The LHO was operated with an average fall height of 34.3 cm (13.5 in.) and an average hydraulic loading rate of 42.1 l per second per square meter (61.7 gpm per ft$^2$) (Fig. 3).

2.2. Experimental trials

The study considered a range of temperatures, salinities and target dissolved oxygen levels at the LHO outlet; experimental
conditions were tested in duplicate at a minimum, and triplicate when possible (Table 1). The conditions that were selected for testing were based on the range of anticipated operating conditions for a proposed sea bass production facility; however, no fish were present during the testing. The target salinity of the culture water at the proposed facility was expected to be 15 ppt, but could vary depending on fish performance and a cost/benefit analysis for creating saltwater.

The subsequent sections describe in detail the methods that were used to create and control these conditions.

2.2.1. Oxygen

Dissolved oxygen concentrations were measured at the LHO inlet and outlet using a Hach SC100 Universal Controller (Hach Company, Loveland, CO, USA) and integrated LDO probes (Hach Company). The LDO probes were calibrated weekly using a manufacturer recommended air saturation technique. Each day, prior to

| Water Salinity | Water Temperature | Target Oxygen Saturation | Number of Replicates |
|----------------|-------------------|--------------------------|----------------------|
| 0.2 ppt        | 25°C              | 150%                     | 2                    |
| 0.2 ppt        | 25°C              | 200%                     | 2                    |
| 0.2 ppt        | 25°C              | 230%                     | 2                    |
| 10 ppt         | 25°C              | 150%                     | 3                    |
| 10 ppt         | 25°C              | 200%                     | 3                    |
| 10 ppt         | 25°C              | 230%                     | 3                    |
| 15 ppt         | 20°C              | 150%                     | 3                    |
| 15 ppt         | 20°C              | 200%                     | 3                    |
| 15 ppt         | 20°C              | 230%                     | 3                    |
| 15 ppt         | 20°C              | 230%                     | 3                    |
| 15 ppt         | 20°C              | 150%                     | 3                    |
| 15 ppt         | 20°C              | 200%                     | 3                    |
| 15 ppt         | 20°C              | 230%                     | 3                    |
| 15 ppt         | 20°C              | 150%                     | 3                    |
| 15 ppt         | 20°C              | 200%                     | 3                    |
| 15 ppt         | 20°C              | 230%                     | 3                    |
| 20 ppt         | 25°C              | 150%                     | 3                    |
| 20 ppt         | 25°C              | 200%                     | 2                    |
| 20 ppt         | 25°C              | 230%                     | 2                    |
| 20 ppt         | 25°C              | 150%                     | 2                    |
| 20 ppt         | 25°C              | 200%                     | 2                    |
| 20 ppt         | 25°C              | 230%                     | 2                    |

Fig. 2. Schematic of recycle water flow during the experimental trials.
data collection, both LDO probes were located at the LHO inlet to validate the calibration for internal quality control. Calibration was considered valid if the difference in digital readout between probes was <0.05 mg/l. Gaseous oxygen was applied at rates to achieve the desired oxygen saturation conditions in the LHO outlet water. Oxygen gas flow to the LHO was monitored and controlled using an Aalborg mass flow meter (Model GFC371S, Aalborg Instruments & Controls, Inc., Orangeburg, NY, USA) to achieve the following target dissolved oxygen conditions in the water leaving the LHO: 150, 200 and 230% of saturation. Dissolved oxygen saturation levels were calculated according to Colt (1984) using dissolved oxygen, salinity, and temperature measurements. The mass flow meter was factory-calibrated for oxygen gas at standard conditions of 1 atmosphere and 21.1 °C. Real-time inlet and outlet oxygen concentrations were continuously logged to a computer (Fig. 4) located tank-side. When the inlet and outlet dissolved oxygen concentrations reached steady-state (as indicated by the trend lines; Fig. 4) data was collected for all relevant parameters. Steady state conditions were typically achieved after one hour.

2.2.2. Salinity
Red Sea Salt (Red Sea USA, Houston, TX, USA) was added and mixed within the experimental RAS to achieve the following target salinities: 10, 15, and 20 ppt. Salinity was measured using a YSI 30 Conductivity/Salinity/Temperature meter (Model 30/10 FT, YSI Inc., Yellow Springs, Ohio, USA), which was calibrated using recommended standard solutions prior to the study. Salinity was adjusted between trials by adding makeup water for dilution or by adding additional salt as required to increase salinity.

2.2.3. Water flow
Water flow was measured using a Panametrics Digital Flow DF868 Ultrasonic Liquid Flowmeter with Wetted Ultrasonic Flow Transducers (General Electric Co., Lewistown, PA, USA). Flow meter accuracy was specified by the manufacturer as ±0.5% of the measured flow rate. The recirculating water flow passing through the RAS, and in particular the LHO, was measured at a pipe run located just after the pumps and before the water entered the fluidized sand biofilter in order to achieve the required straight run of pipe before and after the transducers.

2.2.4. Water temperature
Water temperatures of 20 and 25 °C were targeted during the experimental trials in combination with various salinities and dissolved oxygen levels in the LHO outlet water. These water temperatures were atypical of those used for on-site fish culture; therefore, a series of resistance-type heaters were placed in the pump sump and the fish tank to achieve the necessary temperatures. The ambient temperature of the room was also increased as needed to increase water temperature.

2.2.5. Aeration
Significant aeration was required in order to return the dissolved oxygen concentration of the recycle water to near-saturation as it

![Schematic of experimental stacked CO2 stripper and LHO.](image)
was returned to the LHO. The average dissolved oxygen saturation level of recycle water returning to the LHO for all trials was 102.7\%. Aeration of the recycled water following oxygénation simulated oxygen consumption by the fish, which were not present during the experimental trials. Primary aeration took place in the culture tank using two air stones that diffused compressed air. Additional aeration was achieved by operating a centrifugal pump positioned in the culture tank to create a cascading flow and by optimizing the water depth in the pump sump for additional cascading and aeration. Final aeration took place in the force-ventilated carbon dioxide stripping column above the LHO. Room air was drawn through the carbon dioxide stripping column from bottom to top by a small blower, and then expelled from the room through a duct to the outside.

3. Results

Experimental data was used to determine oxygen mass transfer efficiency according to following calculation:

\[
O\text{TE} = \frac{\text{Mass of Oxygen Transferred into the Water}}{\text{Mass of Oxygen Applied to the LHO}}
\]

(1)

Where:

\[
\text{Mass of Oxygen Transferred into the Water} = \frac{\text{liters water}}{\text{minute}} \times \left( \frac{\text{mg Oxygen Out}}{\text{liter}} - \frac{\text{mg Oxygen In}}{\text{liter}} \right) \times \frac{\text{kg}}{10^9\text{mg}} \times \frac{1440 \text{ minutes}}{\text{day}}
\]

(2)

\[
\text{Mass of Oxygen Applied to the LHO} = \frac{\text{liters oxygen}}{\text{minute}} \times \frac{1.331 \text{ g}}{\text{liter oxygen}} \times \frac{\text{kg}}{1000\text{g}} \times \frac{1440 \text{ minutes}}{\text{day}}
\]

(3)

Oxygen transfer efficiency was calculated for each replicate and then averaged for the experimental condition tested. The tests were conducted without fish or feed, so the results are considered clean-water OTE. The results indicated that OTE peaked when the experimental RAS was operated with a salinity of 10 ppt (Fig. 5). Oxygen transfer efficiency was generally greater at salinities of 10–15 ppt compared to OTE measured within freshwater (0.2 ppt) and at 20 ppt salinity. The data taken at 25 °C is tabulated in Table 2.

Fig. 6 illustrates improved LHO performance when the system was operated at 10 ppt as compared to all other combinations of salinity and temperature that were evaluated. As expected, OTE declined as the LHO outlet dissolved oxygen level was increased from 150 to 230% saturation (Fig. 6). The complete data is tabulated in Table 3.

The experimental trials conducted were primarily focused on characterization of LHO performance at 25 °C to simulate the optimal water temperature planned for sea bream culture at the proposed facility. However, several trials were conducted to determine if a slight variation in water temperature would significantly impact LHO performance. LHO transfer efficiency was observed not to be different when the experimental RAS was operated at a salinity of 15 ppt at approximately 20 °C and 25 °C (Fig. 7).

4. Discussion

Low head oxygénation is an oxygénation supplementation process commonly utilized in intensive freshwater RAS operations. However, the process design for intensive marine RAS may require
Fig. 5. Average oxygen transfer efficiency at varying salinities and LHO outlet dissolved oxygen saturation levels. Data presented is for trials conducted at 25 °C.

Fig. 6. Average oxygen transfer efficiency at various salinities and LHO outlet dissolved oxygen for all experimental trials.

Table 2
Average oxygen transfer efficiency data for varying target salinities and target effluent dissolved oxygen saturation levels at 25 °C.

| Target Salinity | 150% Saturation | 200% Saturation | 230% Saturation |
|-----------------|------------------|------------------|------------------|
| 0.2 ppt         | 96.9             | 78.7             | 58.0             |
| 10 ppt          | 97.3             | 80.9             | 72.2             |
| 15 ppt          | 97.0             | 80.9             | 72.2             |
| 20 ppt          | 94.9             | 72.6             | 62.7             |

Table 3
Oxygen transfer efficiency data for varying target effluent dissolved oxygen saturation levels and varying temperature and salinity levels.

| DO Saturation | 15.6 ppt | 15.5 ppt | 20 ppt | 10.2 ppt | 0.2 ppt |
|---------------|----------|----------|--------|----------|---------|
| 24.4 °C       | 97.0     | 93.1     | 94.9   | 97.3     | 96.9    |
| 20.3 °C       | 80.9     | 78.9     | 72.6   | 88.1     | 78.7    |
| 24.8 °C       | 72.2     | 74.6     | 62.7   | 78.6     | 58.0    |
ciency in freshwater at 230% dissolved oxygenation saturation was only 58%, while OTE at 15 ppt salinity was 72%. This increase in OTE is attributed to an increase in interfacial area from the formation of smaller diameter bubbles in saltwater versus freshwater. Winkel et al. (2004) reported that bubble diameter decreases and interfacial area increases in increasingly saline waters due to increasing ionic strength. Winkel et al. (2004) tested freshwater and saltwater solutions of 9, 19, 33, and 38 ppt made with a similar artificial saltwater product to the one used in this study. Additionally, smaller diameter bubbles have a slower rise velocity, i.e., the terminal velocity at which they rise to the surface when formed below the surface (Kulkarni and Joshi, 2005). The different rise velocity is impacted by the velocity of water leaving the bottom of the LHO and can be both positive and negative to oxygen transfer. If the velocity of water leaving the LHO is slower, or the same as the rise velocity then the bubbles will remain within the LHO and transfer oxygen to the water. Conversely, if the velocity of water leaving the LHO is greater than the rise velocity then the bubbles will be carried out the bottom of the LHO and escape rather than transfer oxygen to the water. This carry-out effect may explain the lower OTE seen at the highest salinities after peaking at 10 ppt in this study. The highest salinities tested (20 ppt) may have caused the formation of bubbles with a too large rise velocity so that they were overcome by the water velocity leaving the bottom of the LHO and were carried out of the LHO. In this study, the hydraulic loading on the LHO was 42.11 per second per square meter (61.7 gpm per ft²), which corresponds to a water velocity of 4.2 cm/s (0.14 ft/s). A slight decrease in oxygen transfer performance may be expected at the higher hydraulic loadings of 50.91 per second per square meter (75 gpm per ft²; 5.1 cm/s, 0.17 ft/s) commonly used in LHO design due to this water velocity effect. However, the LHO drop height and submergence used in this study were sub-optimal and could be optimized by increasing both. The LHO drop height used in this study was approximately 34.3 cm (13.5 in.) and the LHO submergence was 56 cm (22 in.). More optimal LHO drop height and submergence are 61 cm (24 in.) and 91 cm (36 in.), respectively. A taller LHO drop height results in increased turbulence created by water impacting the pool below and increases the OTE. Deeper LHO submergence increases the period of time that gas bubbles remain in contact with the water, and increases the OTE.

5. Conclusions

Oxygen transfer efficiency of LHOs in intense marine recirculating aquaculture systems is affected by salinity and required dissolved oxygen at the LHO outlet. There may be an ideal salinity to optimize LHO performance, but performance is also affected by LHO drop height, submergence, and hydraulic loading. Increasing the required dissolved oxygen at the LHO outlet requires higher G/L ratios and results in lower OTE. However, OTE at required dissolved oxygen levels at the LHO outlet as high as 230% are not so low that it is not feasible to use a LHO, especially at the optimal salinity. Improvements in performance for similarly-designed LHOs in intensive marine RAS can be realized by designing LHOs for lower hydraulic loading, taller fall height, and increased submergence. Optimal performance would require a lower hydraulic loading rate than used in this study, likely 33.91 per second per square meter (50 gpm per ft²). Reduced hydraulic loading would result in lower water velocities exiting the LHO and would likely shift the OTE peak measured during this study at 10 ppt to occur at higher salinities. Additional testing is recommended to determine the effect of hydraulic loading on OTE in LHOs in marine RAS.

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