Testing and Modelling the Oxygenation Potential of a Novel Dual-Injection Airlift Pump for Aquaculture Applications

by

Johnathan Szeliga

A Thesis
presented to
The University of Guelph

In partial fulfilment of requirements
for the degree of
Master of Science
in
Animal Biosciences

Guelph, Ontario, Canada

© « Johnathan Szeliga, December, 2018 »
ABSTRACT

TESTING AND MODELLING THE OXYGENATION POTENTIAL OF A NOVEL DUAL-INJECTION AIRLIFT PUMP FOR AQUACULTURE APPLICATIONS

Johnathan Szela
University of Guelph, 2018
Advisor(s):
Professor D.P. Bureau
Professor W.H. Ahmed

In aquaculture, dissolved oxygen (DO) content of the water is critical, requiring continuous water reoxygenation. The oxygen transfer efficiency of a novel dual injection airlift pump, with control of axial and radial modes of air injection, was examined and modeled in this thesis. Oxygen transfer was examined at different combinations of airflow rates, axial to radial airflow ratios, pump pipe diameters, and submergence levels. Each parameter significantly affected oxygen transfer (p<0.0001), with pump pipe diameter being most significant. Oxygen transfer was modeled for pumps of different pipe diameters. This oxygen transfer model was combined with a tilapia bioenergetics and oxygen requirement model to predict the DO level change of aquaculture systems stocked with tilapia and aerated with the novel airlifts at different settings. The results suggest this novel airlift design can effectively meet DO demands of fish raised in aquaculture and potentially reduce energy consumption compared to conventional oxygenation technology.
ACKNOWLEDGEMENTS

I would first like to thank my advisor Dr. Dominique P. Bureau for all the assistance and direction he provided me in the completion of my thesis. Despite a hectic schedule that required him to constantly be travelling around the world, he always managed to find the time to reply to my emails and answer any concerns or questions I had. Ever since my undergraduate years, Dr. Bureau has provided me several opportunities to take part in interesting projects that greatly expanded my experience and knowledge in fish nutrition. Thank you, Dom, for all the guidance and potential you provided so I can be a better person and professional.

I would also like to thank my co-advisor Dr. Wael H. Ahmed, for all his support in helping me understand the engineering of airlifts, of which I had little prior knowledge of. Thank you for the generous funding and many opportunities to go out in the field and apply developed skills to exciting new problems. Working with you and your airlift pump team was a truly enjoyable experience and I am so glad to have been a part of it. Thank you also to my final advisory committee member, Professor Rich Moccia, whose insights and attention to detail helped guide my thesis project to be clearer and more organized.

Thank you also to the members of the Fish Nutrition Research and Mechanical Engineering Laboratories for all the support you provided in helping me complete my thesis. Whether it was help with experimental system construction, LabVIEW setup, computer modelling, or just being someone to talk to, I am truly grateful for having such wonderful lab mates. I would also like to thank the Library Writing Services and the OAC
Statistical Support Services, whose boot camps and workshops helped improve my skills in writing and statistics, so I could finish my thesis in a timely manner.

Finally, I would like to thank my friends and family, whose love and encouragement provided the motivation I needed to overcome any issues I had to face. I especially wish to thank my wonderful parents, Wieslaw and Jolanta, whose emotional, financial, and moral support has always helped me pursue my academic and life goals.
# TABLE OF CONTENTS

Abstract ................................................................................................................................. ii
Acknowledgements ............................................................................................................... iii
Table of Contents .................................................................................................................. v
List of Tables ....................................................................................................................... viii
List of Figures ..................................................................................................................... ix
List of Symbols, Abbreviations or Nomenclature ................................................................. x
Declaration of work performed ........................................................................................... xii

Chapter 1: General Introduction ......................................................................................... 1
  1.1 Objective ....................................................................................................................... 5

Chapter 2: Literature Review ............................................................................................. 6
  2.1 Water Quality Parameters ......................................................................................... 7
      2.1.1 Dissolved Oxygen ............................................................................................... 7
      2.1.2 Carbon Dioxide ................................................................................................. 13
      2.1.3 Ammonia ........................................................................................................... 14
      2.1.4 Solid Wastes ....................................................................................................... 16
  2.2 Water Quality Management and Airlift Pump Potential ........................................... 18
      2.2.1 Water Flow and Exchange ............................................................................... 18
      2.2.2 Aeration and Oxygenation ............................................................................... 24
      2.2.3 Water Stratification Breakup ............................................................................ 28
      2.2.4 Degassing .......................................................................................................... 30
      2.2.5 Protein Skimming / Algal Removal .................................................................. 32
  2.3 Conclusion .................................................................................................................... 34
Chapter 3: Measuring Oxygen Transfer and Efficiency of the Dual-Injection Airlift Pump

3.1 Introduction .......................................................................................................................... 37
3.2 Materials and Methods ........................................................................................................ 39
  3.2.1 Experimental Setup ....................................................................................................... 39
  3.2.2 Data Collection and Analysis ......................................................................................... 46
3.3 Results .................................................................................................................................. 48
  3.3.1 Experimental Precision Test ......................................................................................... 48
  3.3.2 SOTR Analysis ............................................................................................................... 50
  3.3.3 SAE Analysis ................................................................................................................ 58
3.4 Discussion ............................................................................................................................. 59
  3.4.1 SOTR Analysis ............................................................................................................... 59
  3.4.2 SAE Analysis ................................................................................................................ 64
3.5 Conclusion ............................................................................................................................ 70

Chapter 4: Modelling Oxygen Transfer of Dual-Injection Airlifts for Aquaculture Production

4.1 Introduction .......................................................................................................................... 72
4.2 Model Inputs ........................................................................................................................ 74
  4.2.1 Fish Requirement of Oxygen ....................................................................................... 74
  4.2.2 Airlift Oxygen Transfer and Efficiency ......................................................................... 76
  4.2.3 System Oxygen Balance and Concentration ................................................................. 84
  4.2.4 Modelled Experimental Setup ..................................................................................... 84
4.3 Model Output ......................................................................................................................... 86
4.4 Discussion ............................................................................................................................. 88
4.5 Conclusion ............................................................................................................................ 91
LIST OF TABLES

Table 1: SOTR and SAE values for pond aeration devices (Boyd and Ahmad, 1987). . 26

Table 2: Visual representation of the variables tested by each of the 4 experimental parameters. Trials were run covering each possible combination of the 4 variables resulting in 135 different combinations of parameters. ................................................................. 44
LIST OF FIGURES

Figure 1: Primary components of an airlift.................................................................20

Figure 2: Submerged 4-inch and 2-inch pumps in the experimental tank setup. Front and side views of the 4 cm pump outside of the tank setup.............................................40

Figure 3: Experimental Rotameter Setup .....................................................................43

Figure 4: Schematic of the experimental setup .............................................................45

Figure 5: SAS generated boxplot for 4-inch pump at 100% submergence and 50:50 axial-radial air distribution with 3 replicates per airflow.........................................................49

Figure 6: Individual SOTR values for 1, 2, and 4-inch airlift pumps.............................53

Figure 7: Combined SOTR values for 1, 2, and 4-inch airlift pumps.............................54

Figure 8: Individual SAE values for 1, 2, and 4-inch airlift pumps...............................56

Figure 9: Combined SAE values for 1, 2, and 4-inch airlift pump..................................57

Figure 10: Comparison of observed SOTR values with those generated by a multiple regression model based on pipe size, submergence, total airflow and axial-radial contribution..................................................................................................................78

Figure 11: Regressions comparing observed and predicted SOTRs based on models that exclude one of the experimental test variables .........................................................80

Figure 12: Comparison of observed SOTR values with those generated by three multiple regression models based on submergence, total airflow and axial-radial contribution..........................................................................................................................82

Figure 13: Modelled changes in oxygen inputs, outputs and concentration in a potential feeding trial using dual-injection airlift pumps.................................................................87
LIST OF SYMBOLS, ABBREVIATIONS OR NOMENCLATURE

General Gas Exchange Terms:
DO – Dissolved oxygen
RAS – Recirculating aquaculture system
CO₂ – Carbon dioxide
O₂ – Oxygen
NH₃ - Ammonia
POM – Particulate organic matter
S – Submergence ratio
A – Axial contribution of airflow
R – Radial contribution of airflow

General Oxygen Transfer Calculation Variables:
SOTR – Standard oxygen transfer rate
AOTR – Actual oxygen transfer rate
SAE – Standard aeration efficiency
AAE – Actual aeration efficiency
K_LaT – Oxygen transfer coefficient at experimental temperature
K_La20 – Oxygen transfer coefficient at 20 °C
C₀ – Initial dissolved oxygen concentration
Cᵣ – Final dissolved oxygen concentration
Cₛ – Saturated dissolved oxygen concentration
t – Time required for water to reach oxygen saturation
T – Water temperature
V – Tank water volume
ρ – Water density
g – Gravitational force
Hₛ – Static head
Q_air – Airflow rate
\( \Delta O_2 \) – Oxygen concentration differential
ALQ – Airlift quantity used

**Biological Model Variables:**
d – Days of growth trial
\( BW_{\text{initial}} \) – Initial body weight of fish
\( BW_{\text{pred}} \) – Predicted body weight of fish
HE – Heat produced
TGC – Thermal growth coefficient
\( DE_{\text{req}} \) – Digestible energy required
\( DE_{\text{feed}} \) – Digestible energy of feed
RE – Recovered energy
HeE – Energy used for basal metabolism
HiE – Heat increment of feeding
UE + ZE – Urinary and branchial losses of energy
\( Q_{OX} \) – Fish oxycalorific coefficient
\( O_2, \text{fish} \) – Oxygen requirement of fish
\( O_2, \text{bio} \) – Oxygen requirement of biofilter
\( CP_{\text{feed}} \) – Crude protein content of feed
\( CP_{\text{fish}} \) – Crude protein content of fish
\( ADC_{CP} \) – Dietary digestibility coefficient of crude protein
DECLARATION OF WORK PERFORMED

This project was a collaboration between the Gryph Energy Laboratory, School of Engineering and the Fish Nutrition Research Laboratory, Dept. of Animal Biosciences.

All work reported in this thesis was performed by me, except for the following:

Manufacturing of the airlift pumps and support frames was performed by students working in Dr. Wael Ahmed’s Gryph Energy Lab, some of whom also assisted in the installation of the pump at the Fish Nutrition Research Laboratory, Dept. of Animal Biosciences, University of Guelph.

Installation of the LabVIEW program and connection of the Atlas D.O. probes used for measuring dissolved oxygen content in the experimental water tank was performed by Thariq Mohammed from the Gryph Energy Laboratory, School of Engineering, University of Guelph.
Chapter 1: General Introduction

Aquaculture is partially defined as the rearing of aquatic organisms under controlled conditions (Hannesson, 2003). Optimizing these conditions to ensure good health and high growth performance of the cultured species is a major concern of aquaculture operations. Key conditions that affect fish growth include the levels of certain dissolved gases such as oxygen (O$_2$), carbon dioxide (CO$_2$), and ammonia (NH$_3$) in the water. Like other animals, fish consume O$_2$ while producing CO$_2$ and NH$_3$ due to their metabolism (Ballestrazzi et al., 1994; Page et al., 2005). However, unlike terrestrial animals that have access to atmospheric gas of which 21% is O$_2$ (Boyd, 1998), fish need to respire the O$_2$ dissolved in the water (DO) which cannot saturate past 14.6 mg/L at our atmospheric conditions (Benson and Krause, 1984). Continuous O$_2$ consumption by the fish often results in a significant depletion of DO in its rearing environment, as well as the build-up of CO$_2$ and NH$_3$ concentrations that can reach toxic levels (Fivelstad et al., 1998; Solstorm et al., 2018).

Aeration equipment, such as paddle wheel aerators, aspirators, and air blowers or compressors connected to diffusers commonly known as “airstones”, can be used to mix atmospheric gas with the water, causing transfer of O$_2$ to the water while stripping out CO$_2$ (Boyd, 1998). The provision of new oxygenated water or recirculation of existing water through filters and water treatment infrastructure can remove or detoxify metabolic wastes and to some extent resupply DO (Ebeling and Timmons, 2012; Ruan et al., 2015). Oxygenation and water recirculation equipment is generally powered using electrical motors or diesel engines which results in additional energy and maintenance costs,
significantly increasing production cost for many fish farms (Roque d’Orbcastel et al., 2009). Implementing more energy efficient and robust tools that require less maintenance could therefore help decrease production costs of many aquaculture operations.

Airlift pumps have been used in aquaculture for decades (Mitchell and Kirby, 1976; Castro and Zielinski, 1980), and are considered a low cost and robust approach for pumping and recirculation. Airlift pumps are operated using air blowers or compressors that transport air through a tube underwater to the pump. The injected air displaces a significant amount of liquid as it rises back to the surface. Releasing the air in a vertical enclosing, such as a pipe, limits the trajectory of where the water may be displaced to (Reinemann and Timmons, 1989). Water removed from the enclosed space results in a decrease in pressure causing new water to enter the pipe. With sufficient and sustained airflow, a continuous pumping effect can be achieved, displacing a significant amount of water (Barrut et al., 2012b). Airlifts of various designs have been used for a variety of applications in aquaculture and other fields such as river dredging and ocean floor mineral mining (Khalil et al., 1999). Airlifts are generally considered more energy efficient than centrifugal water pumps, since moving a certain volume of air requires considerably less energy than moving the same volume of water and can thus offer significant energy savings (Reinemann and Timmons, 1989).

However, design and operational constraints can limit the effectiveness, versatility and efficiency of airlift pumps. For example, once the air bubbles reach the water surface the buoyancy forces are no longer causing them to displace water, hence the vertical height that the water can travel above the surface is highly limited (Reinemann and
Timmons, 1989). The diameter of the pipe can also cause constraints, since although larger cross section areas allow for more water to mix with the air, it also gives more room for the water to move laterally rather than vertically upward (Castro and Zielinski, 1980). The air flow volume and size of the air bubbles injected can also have a substantial role on the effectiveness of the pump (Barrut et al., 2012b). Larger volumes of air released into the airlift tube will generally provide greater water flows, but the amount of water displaced is not linearly related to the amount of air injected, so the energy efficiency decreases at higher air injection volumes (Loyless and Malone, 1998). Size of the injected air bubbles can also affect airlift pumping efficiency. The release of air through larger openings, can create larger bubbles known as “gas slugs” which will result in higher water flow rates compared to smaller bubbles (Reinemann and Timmons, 1989). The modification of air flow and bubble sizes can therefore result in different water flow volumes and patterns.

Since airlift pumps submerge air into the water column, this also provides gas transfer and thus can oxygenate water. However, the $O_2$ transfer efficiency of airlift pumps is generally considered relatively poor compared to other aeration equipment (Mitchell and Kirby, 1976; Boyd, 1998). The amount of surface area the submerged air has in contact with the water, and the time the bubbles have available to transfer gases across this surface area will impact the $O_2$ transfer efficiency. Conventional airlift pumps are generally designed to produce relatively large gas bubbles compared to those created by diffusers commonly used in aquaculture (Loyless and Malone, 1998), as these will increase the volume of water displacement. Bubble surface area is thus relatively small and time available for gas diffusion low due to the high pumping rate. Airlift pumps
producing smaller bubbles with a larger total air surface area, could improve the O$_2$ transfer efficiency but would result in lower water pumping performance.

Ahmed and Badr (2012) designed a novel airlift pump differing from conventional airlifts by having dual air injection compartments. One of the compartments is designed to produce larger air bubbles travelling axially, thus vertically up the pipe, while the other compartment produces smaller bubbles travelling radially, thus perpendicularly to the length of the pipe. This dual air injection design and control of bubble size has proven very valuable to improve efficiency and versatility of the airlift pump for pumping performance (Ahmed and Badr, 2012). This novel airlift design may also have improved O$_2$ transfer efficiency compared to conventional airlift pumps commonly used by aquaculture operations. The smaller air bubbles injected radially may more effectively contribute to gas transfer due to their higher total surface area and dispersion throughout the water column. Research on this novel airlift design has thus far only focused on water flow performance (Ahmed and Badr, 2012; Ahmed et al., 2016) and the O$_2$ transfer capacity has not been investigated. Several other characteristics of the novel airlift pump such as its submergence, pipe diameter, and airflow rate could also influence O$_2$ transfer performance and should be investigated (Reinemann and Timmons, 1989; Loyless and Malone, 1998). Contrasting O$_2$ transfer capacity of the novel airlift at different values of these setup conditions with the O$_2$ demand of aquaculture species cultivated under intensive conditions could help determine whether the novel airlift pump can meet O$_2$ requirements of aquaculture systems and at what setup conditions. Theoretical comparison of the energy efficiency of the novel airlift pump with conventional
oxygenation equipment, such as paddlewheels and diffusers, would help determine if the novel airlift pump would be a more energy efficient alternative for intensive aquaculture.

1.1 Objective

The first objective of this study was to examine and model the O$_2$ transfer rate and efficiency of a novel dual-injection airlift pump based on the following four design characteristics: submergence, inner pipe diameter, airflow rate, and axial to radial airflow contribution. This was investigated through a series of laboratory scale experiments which measured the change in dissolved O$_2$ level in a water tank depleted of DO.

The second objective of this study was to determine if the O$_2$ transfer potential of the novel airlift pump at different settings could effectively meet the theoretical O$_2$ requirements of fish reared under intensive aquaculture production conditions. This was determined by combining an existing bioenergetics model for tilapia that calculates O$_2$ requirement with a newly developed model for O$_2$ transfer of the novel airlift pump at different settings.
Chapter 2: Literature Review

Water quality management is a key issue in aquaculture. Several environmental parameters influence the growth performance of aquatic animals and maintaining these within an optimal range is crucial to ensure adequate health and welfare of the animals. Parameters such as dissolved oxygen (DO), ammonia (NH₃), carbon dioxide (CO₂), and total suspended solid (TSS) concentrations, as well as pH, salinity, and hardness are considered the most important (Tidwell, 2012). Like other animals, fish consume oxygen (O₂) to sustain their metabolism, while excreting CO₂ and NH₃ as a by-product of these processes (Ballestrazzi et al., 1994; Page et al., 2005). The continuous consumption of O₂ by fish in aquaculture often results in a significant depletion of DO in the rearing environment, coupled with a rise in CO₂ and NH₃ concentration that can reach toxic levels (Fivelstad et al., 1998; Solstorm et al., 2018).

In an aquaculture setting, the levels of these dissolved gases are highly dependent on the metabolic rates of the animals, and by extension on the biomass present (i.e. stocking density) which is determined by the number and weight of the individual animals. Water exchange rate, waste removal or conversion, and the replenishment of consumed DO are important processes in this regard. There are various approaches, tools, and equipment available to aquaculturists for carrying out these processes (Boyd, 1998). For some operations, such as those characterized by high stocking density (intensive aquaculture operations) or those using recirculating aquaculture system (RAS) technology, ensuring adequate water quality maintenance can be very costly and contribute significantly to production costs (Roque d’Orbcastel et al., 2009). This presents
the need for efficient, economical, and reliable approaches and equipment to maintain water quality, which in turn could also help decrease production costs for many aquaculture operations.

Airlift pumps have been used in aquaculture for decades (Mitchell and Kirby, 1976; Castro and Zielinski, 1980), and are considered an energy efficient and robust tool for water pumping and circulation, as well as the promotion of gas transfer. This chapter reviews some key water quality parameters along with the methods used to maintain them, highlighting the potential for airlift pumps to be used through this context in aquaculture.

### 2.1 Water Quality Parameters

#### 2.1.1 Dissolved Oxygen

DO is arguably the most important water quality parameter in aquaculture. The solubility of O$_2$ in water is highly limited and as a result DO concentrations are very low compared to ambient atmospheric O$_2$ levels. About 21% of our atmosphere consists of O$_2$, which will dissolve in water until it reaches saturation level (Boyd, 1998). The O$_2$ saturation level in water depends on several environmental factors such as, temperature, salinity, and barometric pressure.

According to Henry’s Law the dissolution of gases into water depends on the pressure exerted from their molecules in the atmosphere, so at higher barometric pressures more gas can saturate into the water (Henry, 1803). The effect of pressure on gas dissolution can also be extended to hydrostatic pressure, caused by water weight.
This means that if air is located deeper underwater, for example in bubble form, the additional weight of the water on the gas will result in more of the gas dissolving in water (Enns et al., 1965). This helps explain why the water underneath dams and waterfalls will at times be oversaturated in DO since the descending water exerts more pressure on the trapped gases (Lindroth, 1957).

O$_2$ saturation also decreases with higher salinity due to the dissociated components of the salt forming an electrolyte solution that will reduce gas presence through a function known as “salting out” (Lang and Zander, 1986). Salts that have a high degree of dissociation into their respective anions and cations will in turn attract nearby polar water molecules, reducing the potential of the water to attract atmospheric gases instead (Lang and Zander, 1986). However, the higher intermolecular forces seen in water at greater salinity will also increase the surface tension (Ruen-ngam et al., 2008). This means that air submerged underwater is exposed to greater internal forces that will result in smaller air bubbles, resulting in greater total surface area of the gas allowing for more O$_2$ transfer to take place (Ruen-ngam et al., 2008). Conversely, reductions in surface tension, as observed from the presence of lipids in the water, will result in more bubbles coalescence, decreasing surface area available for gas transfer (Guyon et al., 2001). Smaller bubble size is theorized to be the reason why O$_2$ transfer is similar between fresh and salt water despite salinity reducing the saturation level of DO (Barrut et al., 2012a).

O$_2$ saturation level decreases with increasing temperature due to the heat liberating effects of gas absorption into water (Chatterjee and Altwicker, 2008). The mechanics of this relationship can still be understood in the context of Le Chatelier's Principle, despite
the principle being largely supplanted by the more detailed Laws of Thermodynamics in modern research (Fernandez-Prini, 1982). The principle states that as a system in chemical equilibrium experiences stress, the system will react to absorb the stress (Fernandez-Prini, 1982). The solution of gaseous O₂ into water to result in DO and released heat in the water is a reversible reaction, so when the reaction is subject to additional heat from an external source it can react to this stress by releasing the additional heat energy through gaseous O₂. Due to this reaction, the DO concentration of water at full saturation typically decreases from 11.3 – 7.6 mg O₂/L as water temperature increases from 10 to 30 °C (Benson and Krause, 1984). The increasing temperature will influence the physical properties of the water as well, including a decreased surface tension (Vargaftik et al., 1983). Although a lower surface tension would generally indicate a lower gas transfer as well, increasing temperature results in higher gas transfer coefficients (Barrut et al., 2012a). The higher transfer coefficients may be associated with the lower viscosity observed in higher temperature water, which would reduce the resistance for gases to interact with the liquid, resulting in faster O₂ transfer into water at higher temperatures (Guo-Qing, 1995).

Temperature also affects water density, with a maximum density of 1000 kg/m³ observed at about 4 °C and decreasing density as the water progresses from 4 °C until it either freezes or boils (Weast, 1973). As denser water is heavier, it will sink to the bottom of a water body. This separation of water due to density will result in thermal stratification, often seen in lakes where heavier water at the bottom is colder while water closer to the surface is warmer and thus less dense (Cole, 1994). However, due to the densest water not being at 0 °C, when the lake surface water cools in the winter and melts in the spring,
it will at times reach 4 °C and will mix with the bottom layer of the water column (Cole, 1994). This breakup of stratification will result in mixing of nutrients such as O\textsubscript{2} throughout the water body. Surface water can contain higher DO due to atmospheric air interaction (Bryson and Suomi, 1952) and algal photosynthetic activity (del Giorgio and Peters, 1994), while deeper water can be depleted in DO due to sediment and decaying organic matter consumption of O\textsubscript{2} (Giga and Uchrin, 1990). The mixing therefore allows a more uniform DO profile in the water body. Water bodies that have constantly thermally stratified water layers will have disproportionate levels of DO which will limit available growing space for animals like fish (Cole, 1994).

In an aquaculture setting, the DO concentration is greatly influenced by the O\textsubscript{2} consumption of the animal and the rate at which DO is replenished in the rearing environment (Loyless and Malone, 1998). O\textsubscript{2} is consumed by animals as a result of cellular respiration based on oxidative phosphorylation (Nicholls and Ferguson, 2013). O\textsubscript{2} is the final electron acceptor in the electron transfer chain involved in the catabolism of organic nutrients (Nicholls and Ferguson, 2013). The reactions result in the consumption of O\textsubscript{2} and the final products are CO\textsubscript{2} and water (Nicholls and Ferguson, 2013).

O\textsubscript{2} consumption of animals can be predicted using a bioenergetics framework. Based on stoichiometry of cellular respiration, it is expected that fish will consume 1 g of O\textsubscript{2} per 13.6 kJ of heat production (HE) (Cho et al., 1982). Temperature has a very significant effect on the metabolic rate and growth potential of fish. The basal metabolism (HeE) of salmonid fish increases in a linear manner with increases in water temperature within an optimal non-stressful range (NRC, 2011). Growth potential and thus feed
requirement of the animals increases proportionally to an increase in temperature or sum of degree days (Dumas et al., 2007). The O₂ consumption of a 50 g rainbow trout fed to near-satiety kept at 15°C is estimated to be almost 0.5 g, which is nearly 3 times higher than the amount consumed at 5°C (Cho and Burau, 1998). The increased O₂ consumption of these animals combined with the lower O₂ solubility results in a greater potential for DO depletion as water temperature increases in an intensive aquaculture setting.

Processes such as the decomposition of organic matter by microorganisms (Hargreaves, 2003) and bacterial nitrification of NH₃ (Wimberly, 1990) also involve the consumption of O₂ which can deplete DO levels in water bodies, including those used in an aquaculture setting if organic matter accumulates. Outdoor water bodies, such as ponds, with high algal concentration can experience dramatic daily fluctuations of their DO due to net O₂ production by the algae through photosynthesis during the day and net O₂ consumption during nighttime when no photosynthesis occurs (Hargreaves, 2003). Nitrifying microbes are estimated to consume a total of 4.6 g of O₂ for the combined processes of converting 1 g of NH₃ to nitrite (NO₂⁻) and converting NO₂⁻ to nitrate (NO₃⁻) (Summerfelt and Sherrer, 2004), providing a significant source of DO depletion for systems relying on biofilters.

Due to the critical role of O₂ in animal metabolism, exposure to low DO levels (hypoxia) for even short periods of time can have dramatic impacts. Compared to other aquatic animals, fish are some of the most sensitive to hypoxic conditions, intolerant of lower DO concentrations and experiencing lethal effects in a shorter time after exposure
The full range of negative health effects experienced by fish from hypoxia include reduced appetite and growth (Buentello et al., 2000), higher susceptibility to disease (Pickering and Pottinger, 1989), and even death (Cooper and Washburn, 1949). The onset of these conditions generally takes place after the DO concentration has decreased past a level known as the $P_{\text{crit}}$, after which point the required $O_2$ consumption rate of the fish for maintaining standard metabolic activity can no longer be attained (Rogers et al., 2016). The $P_{\text{crit}}$ for fish can be highly variable, depending on genetic factors such as species type as well as environmental factors such as seasonal temperature acclimation, where some fish species will develop a lower $P_{\text{crit}}$ during warmer periods of the year to compensate for lower water DO levels (Ultsch et al., 1978). The adaptation of lower $P_{\text{crit}}$ in warmer environments might help explain the evolutionary pressure that resulted in the observed higher tolerance to low DO levels of warm water fishes such as tilapia compared to cold water fishes such as salmonids (Tidwell, 2012). For example, the warm water fish, Nile tilapia, can have a $P_{\text{crit}}$ in the range of 2.5 to 6.4 mg/L (Mamun et al., 2013), while the coldwater fish, Atlantic salmon, can have a $P_{\text{crit}}$ in the range of 3.7 to 5.2 mg/L (Remen et al., 2013). The variability in the range can be attributed to observations of fish immediately situated in water above normal temperatures, where due to the lower saturation of DO in water at higher temperatures, the $P_{\text{crit}}$ of a fish will generally increase (Ott et al., 1980). Some fish such as carp also possess adaptations for survival of hypoxic conditions through the regulation of metabolic enzyme pathways, where a controlled metabolic depression reduces aerobic metabolism while maintaining low lactate levels produced from anaerobic metabolism through ethanol production (Fagernes et al., 2017). However, despite the various survival strategies for
hypoxic conditions, feed intake and growth will still decrease in fish exposed to a low DO level environment. While hypoxic conditions are the main DO issue for fish, oversaturation of O\textsubscript{2} in water is also possible under specific conditions and is notably associated with gas bubble disease (Espmark et al., 2010). This condition is characterized by gas bubbles forming within the tissue of the animal, that will cause blocking of blood vessels, tissue damage, and potentially death (Bouck, 1980).

2.1.2 Carbon Dioxide

CO\textsubscript{2} can also be dissolved in water and is another important water quality criteria for good fish health. Although this gas makes up a small composition of our atmosphere at around 0.04% (IPCC, 2007), due to its higher solubility in water compared to O\textsubscript{2} (Lide, 1993), it will saturate to about 1.5 g/L in pure water at 25° C (Dodds et al., 1940). Nonetheless, CO\textsubscript{2}, like all gases, will follow the same principles of gas transfer as outlined in the description of DO (Chapter 2.1.1.), meaning it will saturate to greater concentrations at higher barometric pressures and lower salinities and temperatures (Loyless and Malone, 1998; Barrut et al., 2012a). Also, like other gases, if the content of CO\textsubscript{2} in the water rises above saturation, then it will naturally begin to degasify back into the atmosphere, which can be expediated through turbulence in the water.

CO\textsubscript{2} can naturally oversaturate in the water through biological processes such as fish metabolism, with 528 g of CO\textsubscript{2} produced for every 385 g of O\textsubscript{2} consumed (Loyless and Malone, 1998). The nitrification process of bacteria in RAS biofilters also produces CO\textsubscript{2}, with a ratio of 5.9 g of CO\textsubscript{2} for each 1 g of NH\textsubscript{3} that gets converted to NO\textsubscript{2}\textsuperscript{-} and then to NO\textsubscript{3}\textsuperscript{-} (Summerfelt and Sharrer, 2004).
Long term exposure to high CO₂ concentrations can induce negative effects on fish health. High environmental levels of CO₂ can affect fish by decreasing their blood pH (Wurts and Durborow, 1992), reducing cardiac pumping output (Lee et al., 2003), and inhibiting growth (Fivelstad et al., 1998). Most importantly, high concentrations of CO₂ can impact respiration by decreasing the affinity and carrying capacity of hemoglobin for O₂ through a phenomenon known as the Root effect (Root, 1931). Maintaining CO₂ levels below a toxic threshold is therefore crucial for preventing suffocation, the level of which will be dependent on the fish species with critical values of 60 mg/L for tilapia (Timmins and Ebeling, 2010), 30 mg/L for catfish (Tucker and Robinson, 1990), and 26 mg/L for Atlantic salmon (Fivelstad et al., 1998).

2.1.3 Ammonia

NH₃ is a significant by-product of amino acid metabolism of fish and is an important water quality parameter. The quantity of NH₃ in the atmosphere is relatively negligible, as it ranges in the parts per trillion to parts per billion (Gong et al., 2011), and so water saturation of NH₃ from atmospheric gas transfer is not considered an issue in aquaculture. Rather, the appearance of NH₃ in aquaculture systems overwhelmingly originates from amino acid catabolism of fish (Brunty et al., 1997). If the water pH decreases, a certain portion of NH₃ molecules will convert to the cation ammonium (NH₄⁺) (Martinelle and Haggstrom, 1993). The change from a neutral to positively charged molecule will impact some chemical properties of the NH₃ that will have important implications on fish health.

Due to the presence of a positive charge, the diffusion rate of NH₄⁺ across cell membranes is much lower compared to that of NH₃ (Knepper et al., 1989). Instead, NH₄⁺
is transported across cell membranes through transport proteins intended for the transport of other positive ions such as potassium, sodium and calcium (Kikeri et al., 1989). This can result in abnormal cellular function, particularly through the overactivation of NMDA receptors on nerve cells. This is believed to begin a cascade of reactions, where the overstimulated NMDA receptors permit high levels of calcium ions to accumulate in post-synaptic neurons, activating enzymes such as nitric oxide synthase, resulting in nitric oxide production that inhibits antioxidant enzymes (Kosenko et al., 1999). Therefore, high levels of NH$_3$/NH$_4^+$ buildup can result in oxidative stress from free radicals that could potentially cause neural cell damage and death (Randall and Tsui, 2002). High levels of internal NH$_4^+$ can also result in reduced feeding (Alderson, 1979), gill hyperplasia (Thurston et al., 1978) and the inhibition of enzymes involved in the tricarboxylic acid cycle (Cooper and Plum, 1987). The wide range of toxic effects experienced by fish at high NH$_3$/NH$_4^+$ levels illustrate the importance of monitoring this chemical for maintaining optimal fish health.

Toxicity levels of NH$_3$ like with other dissolved gases is dependent on the species, with freshwater fishes tolerating on average up to 2.79 mg NH$_3$/L (USEPA, 1984), while saltwater fishes tolerating on average up to 1.86 mg NH$_3$/L (USEPA, 1989). However, there are greater differences of NH$_3$ tolerance between species within either group, as both salinity and temperature are considered to only play minor roles on affecting toxicity (Ip et al., 2001). NH$_3$ toxicity is more affected by pH and water hardness, as higher pH (USEPA, 1998) and lower hardness (Randall and Wicks, 2000) will result in greater NH$_3$ toxicity. The removal of NH$_3$ can occur naturally through the metabolic processes of nitrogen fixing bacteria, first by converting NH$_3$ to NO$_2^-$, and then by converting NO$_2^-$ to 15
much less toxic $\text{NO}_3^-$, which itself will be converted to $\text{N}_2$ or consumed by plants (Stein and Klotz, 2016). Intensive aquaculture systems often integrate biofilters whose main function is the conversion of toxic $\text{NH}_3/\text{NH}_4^+$ into $\text{NO}_2^-$ and $\text{NO}_3^-$. 

2.1.4 Solid Wastes

TSS, largely originating from fecal matter egested by fish, can accumulate and is an important water quality criterion. The amount of fecal matter produced in fish culture is largely dependent on dietary composition. The digestibility of ingredients and the amount of feed provided are the main determining factors for fecal waste quantity (Cho and Bureau, 2002). Suspended organic matter is a potential substrate for pathogen development, which in salmonid culture can lead to gill stress and onset of disease (Wold et al., 2014). Suspended organic matter has been observed to promote the development of bacterial organisms, notably potential pathogens, such as *Renibacterium salmoninarum* (Balfry et al., 1996) and *Aeromonas hydrophila* (Leung et al., 1992), but can also serve as a vector for viruses, such as carp interstitial nephritis virus (Dishon et al., 2005), and for protozoan parasites, such as *Cryptosporidium molnari* n. sp. (Alvarez-Pellitero and Sitja-Bobadilla, 2002). Although various bacterial species have adapted to proliferate at different temperature ranges, bacterial culture will generally reproduce at the greatest rate at the top end of their optimum temperature range (Ratkowsky et al., 1982). This means that under higher water temperatures when the fish are feeding and therefore excreting fecal matter at a greater rate, the greater quantity of pathogenic growth medium with greater pathogenic proliferation will result in the fish being more susceptible to disease.
The importance of managing and limiting organic waste accumulation and suspension is increasingly recognized in intensive aquaculture. Solid waste can be effectively removed using mechanical filtration or sedimentation tanks (Cripps and Bergheim, 2000; Brambilla et al., 2008). However, the breakup and suspension of solid wastes makes them more difficult to remove and provides more surface area for pathogen growth (Wold et al., 2014). Effective fecal waste removal therefore depends on maintaining the cohesiveness of the excrements until it can be collected at a filtration or waste settling area. Maintaining fecal cohesiveness is largely dependent on the chemical adhesive properties of the feces, which can by improved with dietary binders (Brinker et al., 2005), and by reducing the forces generated from the water in terms of turbulent flows (Vittasalo et al., 1999). If these fecal pellets can then sink at a consistent rate, this will concentrate their mass to limit potential negative effects on the surrounding environment and provide an easier target for waste removal. The sinking rate of fecal waste is generally increased with fecal pellet size (Smayda, 1969) and density (Wong and Piedrahita, 2000) and decreased water turbulence (Viitasalo et al., 1999). However, aquaculture systems that require the transport of fecal material away from the fish in a horizontal manner may work more efficiently with floating feed that can nonetheless maintain cohesiveness and limit turbulence generated from water transportation (Unger et al., 2015). This will require a system design that can incorporate water flow mechanics to efficiently remove wastes and limit potential growing space for pathogen development.
2.2 Water Quality Management and Airlift Pump Potential

2.2.1 Water Flow and Exchange

Water flow is crucial to maintaining adequate water quality conditions, through replenishment of the system with clean water to ensure adequate removal of wastes, such as solid wastes, TSS, CO₂, and NH₃, while replenishing DO (Fivelstad and Binde, 1994) or ensuring water recirculation through treatment equipment. The amount of water flow required for sustaining cultured fish populations depends largely on chemical and biological considerations as discussed above. Water flow and exchange rates need to be adjusted as a function of water temperature, standing biomass, feeding activity of the animals and other factors (Fivelstad, 1988).

Water flow is achieved through various means. In intensive indoor aquaculture, rearing units may be fed by gravity which will require pumping and storing water at a certain height or alternatively directly pumping into the system. In either case, this is generally achieved using centrifugal motorized water pumps (Ebeling and Timmons, 2012), which are generally costly in terms of energy consumption.

It has been suggested that replacing conventional centrifugal pumps with airlifts can provide economic benefits to aquaculture operations, due to the better energy efficiency of the airlift pumps (Martins et al., 2010). These pumps have been used in fish culture for decades (Mitchell and Kirby, 1976; Moses and Colt, 2018), largely due to their simple design and potential for energy savings. The pumps have been used in other fields as well, notably river dredging and ocean floor mineral mining (Khalil et al., 1999). The higher
energy efficiency of airlift pumps compared to centrifugal pumps is a result of the movement of a certain volume of air requiring considerably less energy than moving the same volume of water (Reinemann and Timmons, 1989). However, relying on a lighter (less dense) substance to displace a heavier (denser) substance creates certain design and operational constraints, which reduces the effectiveness of airlift pumps limiting their applicability and energy efficiency. Overall, airlift pumps have lower water lift capabilities and more design constraints compared to centrifugal pumps.

The structure of an airlift pump consists of a vertically facing enclosing, generally a pipe, that is suspended in the water and supplied air to its underwater opening by an air blower or compressor (Figure 1). By releasing the air in a vertical enclosing, the trajectory of where the air may displace the water is limited, causing the water to be removed up out of the pump along with the rising air (Reinemann and Timmons, 1989). Water removed within the enclosed space causes a decrease in pressure causing new water to enter the pipe. With sufficient and sustained airflow, a continuous pumping effect can be achieved, and a significant amount of water can be pumped (Barrut et al., 2012b).
Figure 1: Simple schematic of typical airlift pump design.
The physical design of the airlift pump, specifically in terms of the pipe that air and water mixes and travels through will influence water flow performance of the pump. Manipulating these design parameters results in certain trade-offs, which need to be accounted for to increase the pumping efficiency for the given function of the pump. Most airlifts follow a consistent setup including a pipe which the water and gas travel up, and a fitting at the pipe outlet directing the water. Modifications to this design, like increasing the number of outlet holes to supply more tanks with water, are possible though will result in less total water flow due to friction loss (Castro and Zielinski, 1980). Increasing the distance of the outlet above the water surface might also be carried out if the water needs to be pumped to a higher location. However, once the air bubbles reach the water surface, the buoyancy forces no longer cause them to lift the water, hence the vertical height that the water can travel above the surface is highly limited (Reinemann and Timmons, 1989).

Thus, most design changes focus on keeping the same shape while using greater pipe diameters and submerged lengths where possible, as increasing these dimensions has been found to improve water flow (Castro and Zielinski, 1980; Parker and Suttle, 1987; Reinemann and Timmons, 1989). However, increasing the pipe diameter can cause constraints, since although larger cross section areas allow for more water to mix with the air, it also gives more room for the water to move laterally rather than be moved up vertically (Castro and Zielinski, 1980). The diameter to pipe length ratio will also affect the pumping performance of the airlift, with a ratio of 1:15 reported as being the optimal for maximum efficiency (Reinemann and Timmons, 1989). When the ratio is smaller than 1:15, air bubbles returning to the surface interact less with the water due to the 'slip' effect, decreasing the eventual water flow (Reinemann and Timmons, 1989). When the ratio is
higher than 1:15 then the loss in efficiency might be attributable to the greater water pressure at deeper air injection sites, requiring more power to submerge the gas to that depth (Reinemann and Timmons, 1989). Therefore, culturists should try to maintain the 1:15 diameter to pipe length ratio, while increasing the total size of the pump to the maximum possible for the best water flow performance.

Another major factor influencing airlift performance is the submergence ratio (Loyless and Malone, 1998), referring to the submergence distance over the combined length of the lift and submergence. At constant airflow rates, greater water flows are observed at greater submergence ratios, with the most efficient occurring when the airlift is completely underwater, thus having a ratio of 1:1 (Loyless and Malone, 1998). This can create some issues in design optimizations, as generally the purpose of the pump is to elevate the water to a new height, but the higher the pump needs to lift the water the lower the resulting water flow will be. The submergence ratio can also be increased by injecting the air deeper underwater, though this may create pressure issues resulting in the air blower not being able to submerge the air to the exit holes. In some cases, it might then be more pragmatic to use an air compressor to overcome the pressure (Barrut et al., 2012b), though this will generally be more energy demanding. Therefore, even selecting the location of the airlift in relation to the water column will have significant consequences on pump performance, as the height that the water needs to travel and whether an air blower or compressor is available will determine the resulting water flow.

Airlift pumping performance will also be influenced by the presence of certain solids within the water. Since the presence of salt causes a greater surface tension, resulting in
smaller bubbles (Barrut et al., 2012b), this means that pumps in marine environments will have lower water flows when set at similar settings to pumps in fresh water. Meanwhile, the presence of certain surfactants in the water, such as leached lipids from fish feed, would reduce the water surface tension, resulting in greater air bubbles coalescence and higher water flow rates (Barrut et al., 2012b).

The volume of air and size of the air bubbles injected can also have a substantial role on the pumping efficiency of the airlift (Loyless and Malone, 1998; Barrut et al., 2012a). Larger air volumes released in the airlift will generally provide greater water flows, but the amount of water displaced is not linearly related to the amount of air injected, so the energy efficiency decreases at higher air flow rates (Castro and Zielinski, 1980; Reinemann and Timmons, 1989; Loyless and Malone, 1998). The reason for the decreased efficiency at higher airflows is likely due to the aforementioned ‘slip’ effect (Reinemann and Timmons, 1989) though the actual point where the efficiency begins to drop will depend on the dimensions of each individual airlift in terms of pipe length and diameter (Parker and Suttle, 1987). The size of air bubble released plays a role in the pumping efficiency of airlift pumps. The release of air through larger openings will create larger bubbles, which if they occupy more than 25 % of the pipe volume will create flow patterns known as “gas slugs” that result in higher water flow rates compared to smaller bubbles (Reinemann and Timmons, 1989). Although air volume can be used to increase the air void fraction within the pipe and cause bubble coalescence, increasing the number of “gas slugs”, the released air bubble size will largely be static as a product of the hole size. The high presence of “gas slugs” can also substantially decrease the efficiency of
gas transfer (Reinemann and Timmons, 1989), therefore limiting the oxygenation performance of the airlift pump.

Ahmed and Badr (2012) designed a novel airlift pump differing from conventional airlifts by having dual air injection compartments, specifically for influencing the volume of certain bubble size types within the airlift. One compartment releases larger air bubbles in an axial manner so they can travel vertically up the pipe, while the other compartment releases smaller bubbles in a radial manner so they can mix perpendicularly and directly into the water. This dual air injection design and control of bubble size has proven very valuable to improve the efficiency and versatility of the airlift pump (Ahmed and Badr, 2012). The incorporation of two simultaneous modes of air injection at different proportions has allowed for further control of bubble flow patterns past bubbly and slug to include churn and annular patterns (Kassab et al., 2009), which will affect water pumping performance and the movement of small solids in three-phase flow (Kassab et al., 2007). Modification of air injection frequency to create pulsating patterns can further improve the water flow efficiency of the airlift pump, further reducing energy consumption costs (Ahmed et al., 2016). The incorporation of new state of the art airlift pump designs could contribute to improving the economic efficiency of aquaculture operations by reducing energy consumption while maintaining water flow rates required to maintain water quality.

2.2.2 Aeration and Oxygenation

A variety of approaches and equipment can be used by aquaculture operations to replenish DO levels. Aeration equipment, such as centrifugal pumps, pump sprayers, propeller-aspirator-pumps using the Venturi effect, paddle wheels, tractor-powered
aerators, and air blowers or compressors that diffuse air using airstones or perforated tubing can all be used to mix atmospheric gas with the water, causing $O_2$ transfer to the water (Boyd, 1998). Fish culture sites may alternatively inject pure $O_2$ opposed to atmospheric gas into their systems (Seginer and Mozes, 2012), as this method may better maintain DO levels compared to the use of atmospheric air.

Although each aeration method can use a slightly different mechanism for dissolving $O_2$ into the water, their effectiveness is universally measured in terms of standard oxygen transfer rate (SOTR) in kg $O_2$/hr and standard aeration efficiency (SAE) in kg $O_2$/kW-hr. Research comparing the various aeration methods in ponds seems to indicate that machines which cause more water turbulence, such as paddlewheels and propeller-aspirator-pumps, have higher SOTR and SAE values then systems which diffuse the air underwater (Boyd, 1998), despite requiring more electrical energy.

Boyd and Ahmad (1987), reported that paddlewheels are the most efficient at increasing DO at an average SAE of 2.2 kg $O_2$/kW-hr while diffused-air systems were the least efficient (Table 1). SAE comparisons of different diffused-air systems are limiting; however, the reported literature suggests that airlift pumps have lower SAEs compared to airstone based diffusers (Mitchell and Kirby, 1976; Loyless and Malone, 1998). Nonetheless, Boyd (1995) reports that a custom system combining diffused-air with an airlift pump could achieve a SAE of 6.37 kg $O_2$/kW-hr (Boyd, 1995).
Table 1: SOTR and SAE values for pond aeration devices (Boyd and Ahmad, 1987).

<table>
<thead>
<tr>
<th>Type of aerator</th>
<th>Number of aerators</th>
<th>Range of SOTR</th>
<th>SAE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Paddle wheel</td>
<td>24</td>
<td>2.5 – 23.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Propeller-aspirator-pump</td>
<td>11</td>
<td>0.1 – 24.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Vertical pump</td>
<td>15</td>
<td>0.3 – 10.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Pump sprayer</td>
<td>3</td>
<td>11.9 – 14.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Diffused-air</td>
<td>5</td>
<td>0.6 – 3.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>
It is important to note that there is great variability in the design and operation characteristics for each given type of oxygenation technology, which can have a significant impact on cost that may not be fully recognized through simply comparing SAE values. Costs allotted for equipment price and maintenance can affect the long term economic sustainability of a given oxygenation technology and should be accounted for. This can be observed when comparing effectiveness of aeration to supplying pure liquid O$_2$. The generation of liquid O$_2$ generally requires more expensive technology than that used for aeration, however it will provide a more efficient use of electrical energy for O$_2$ transfer (Seginer and Mozes, 2012). One case study found that incorporating the capital, maintenance, and energy costs for pure O$_2$ supply required $0.23 for supplying the O$_2$ requirements of an individual fish cultured in the study, while the cost of an airlift pump for the same amount of O$_2$ supply varied from $0.18 to $0.43 depending on temperature (Seginer and Mozes, 2012). The temperature dependence of the airlift pump was associated to lower performance at higher temperatures due to lower gas saturation levels, which did not affect the infusion of pure O$_2$ (Seginer and Mozes, 2012). Therefore, apart from the capital, operational, and maintenance costs of an oxygenation system, the versatility and compatibility with the aquatic system in question will greatly affect the efficiency of oxygenation.

However, despite potentially having lower SAE compared to other oxygenation equipment (Mitchell and Kirby, 1976; Boyd and Ahmad, 1987; Seginer and Mozes, 2012; Barrut et al., 2012a), the ability of airlift pumps to efficiently move and mix water may provide additional energy savings not provided by other forms of oxygenation equipment. The design of airlift pumps to improve their SAE while maintaining efficient water pumping
could provide great benefits for maintaining various water quality parameters in an aquaculture system.

The SAE of airlifts depends on the contact surface and contact time of the air with water and is affected by the design characteristics of the pump. For example, if the air is released lower in the water column, then the additional water pressure prevents the retainment of larger bubbles, creating smaller units and therefore increasing the gas surface area available for contact with the water (Reinemann and Timmons, 1989). Generating higher levels of airflow will increase SOTR simply due to a higher volume of air interacting with the water over a shorter time (Loyless and Malone, 1998). However, the resulting increased air velocity will reduce contact time between the air and water, so that less $O_2$ is diffused per unit of air used causing a decrease in the SAE (Loyless and Malone, 1998). Conventional airlift pumps are generally designed to release large gas bubbles (Loyless and Malone, 1998) since these result in greater volumes of water displacement. However, studies have found that using this design will provide only half the SAE that would be seen under similar conditions if the hose ending was simply fitted with an airstone diffuser (Loyless and Malone, 1998). The contact surface and time available for gas diffusion of conventional airlift designs is thus relatively low. Airlift pumps producing smaller bubbles with a larger total surface area could improve the $O_2$ transfer of such pumps.

**2.2.3 Water Stratification Breakup**

The breakup of thermocline gradients using technology such as airlifts could benefit fish production as it could increase the available growing space by distributing the DO
content more evenly through the water (Parker et al., 1984). Airlift pumps have been shown to be more effective to prevent thermal stratification in ponds compared to centrifugal pumps and motorized propellers (Szyper, 1996). However, the breakup of thermoclines decreases as the size of the water body increases and water is located further from the airlift (Szyper, 1996). This reduces the effectiveness at disrupting the thermoclines in larger bodies of water such as lakes and oceans. Using airlift pumps in large bodies of water would require the upwelling of great volumes of cold deep water (Leng et al., 2014), requiring extensive pipe infrastructure. Such an application could be carried out for providing colder, oxygenated water to cage sites.

In the same way that breaking up thermal stratification can prevent the negative effects of warmer water, airlifts can also help counter some negative effects of colder water. Aquaculture sites in locations where ice develops can experience issues due to damaged cages and the inability of farmers to reach their stock for feeding or harvest (McNaughton and Lee, 2010). Although some operations allow the freezing of the cages to occur (Fletcher et al., 1997) this is not the preferred husbandry method in other sites. Turbulence at the water surface can prevent ice from forming above the fish pens (McNaughton and Lee, 2010), so farms may employ motorized impellers to mix the water. These propellers do not provide any discernible function during warmer months, so replacing them with airlifts that can also upwell colder water in the warmer season might be more efficient. However, the economic benefits of using airlifts in cage operations to regulate water year-round still needs to be completed with a proper cost assessment to determine its practicality.
Apart from gas mass transfer and the disruption of thermoclines, airlifts can also improve water quality by preventing plant and nutrient stratification (Hargreaves, 2003). During the day, aquaculture ponds will experience DO increases due to photosynthetic activity of naturally growing algae (Tucker and Hargreaves, 2012). However, when the sun sets, and the photosynthetic activity of the plants ceases, some of the algae will then consume large amounts of O$_2$ due to decomposition, causing the DO level to drop at night. This decaying alga generally settles at the pond bottom, causing that portion of the pond to experience the greatest drops in DO (Hargreaves, 2003). If the O$_2$ gets depleted at the pond bottom, this may cause anaerobic decomposition of the algae, resulting in the production of chemicals such as volatile fatty acids and fermentation products, some of which may be toxic to fish (Hargreaves, 2003). By mixing the pond water, airlifts can distribute algae and DO in the water column more evenly, preventing potentially toxic effects on the fish from anaerobic algal decay.

### 2.2.4 Degassing

Apart from injecting O$_2$ into the water, airlifts can also be used to remove unwanted gases, such as dissolved CO$_2$. Assessing whether airlifts could successfully remove CO$_2$, first requires examination of the common techniques currently used for this function. Generally, these can be divided into two categories: methods which affect CO$_2$ level through pH control and methods which control CO$_2$ level through degassing (Summerfelt et al., 2000). Seeing as the main detrimental effect of CO$_2$ in the water is an increase in acidity, some culturists will simply increase the pH as opposed to manually removing the CO$_2$. This is often done through adding bases like hydroxides and carbonates, which in
turn will convert the CO₂ to bicarbonate (CO²⁻³) (Loyless and Malone, 1997). However, this is a finite solution as the fish will continue to excrete CO₂ over the course of production, requiring a constant addition of bases to convert CO₂ to CO²⁻³ (Hargreaves and Brunson). Otherwise, additional CO₂ could further decrease the pH and cause the stored CO²⁻³ to convert back to CO₂. This shows an advantage that degassing technology has over pH control, in that it removes the CO₂ itself, preventing buildup that could negatively impact the fish. Just as CO₂ can diffuse into the water to reach saturation, it can diffuse back into the atmosphere if the water is oversaturated and has enough contact with air, especially under higher temperatures and salinities (Barrut et al., 2012a). To maximize this exposure, surface water needs to undergo some degree of mixing and turbulence, which can be achieved using mechanisms like mixers, pumps, and surface aerators (Colt and Orwicz, 1991).

Airlift pumps can also provide degassing of CO₂, the efficiency of which has been studied (Loyless and Malone, 1998; Barrut et al., 2012a). The effects of airlift pump setup configurations on removal of CO₂ mirror the effects seen on the ability of the pump to transfer O₂ into the water, as similar gas transfer principles are in effect. For example, increasing the level of airflow that is being sent to the airlift will increase the amount of CO₂ being transferred from the water to the gas, although at a cost in efficiency (Loyless and Malone, 1998). Decreasing the size of the bubbles increases the amount of surface area available for gas diffusion to take place and leads to more CO₂ being removed from the water (Barrut et al., 2012a). Meanwhile higher lipid content, leached from feed or waste, can cause more bubble coagulation thus decreasing CO₂ removal efficiency (Barrut et al., 2012a).
However, since the function of the airlift is to increase the DO while removing CO₂, this will have some important implications in system setup. Since water at lower temperatures can be saturated more with dissolved gases, systems growing cold water species will hold more O₂ as well as CO₂. This would theoretically mean that fish in cold water systems are more likely to suffer from high CO₂ than from low DO. Meanwhile, warm water systems should contain lower dissolved levels of both gases, so the fish being cultured in them would be more likely to suffer from low DO opposed to high CO₂. Since airlifts perform oxygenation and CO₂ degassing simultaneously, the efficiency of both functions should improve with better gas transfer setups. However, there is some evidence indicating that increasing the number of airlift pumps while maintaining the same amount of total airflow will increase CO₂ degassing while having no effect on O₂ transfer (Loyless and Malone, 1998). The implication of this data indicates that aquaculture systems can increase CO₂ degassing efficiency by using more airlift pumps even without changing total airflow rates provided. However, apart from this one design characteristic, airlift pumps can generally be optimized for degassing using the same methodology as for optimizing oxygenation; meaning increasing the airflow and submergence while decreasing the bubble size.

### 2.2.5 Protein Skimming / Algal Removal

Solid particulates in the water can present issues for fish health and must be monitored to ensure optimal conditions for the livestock. Solid wastes excreted by the fish can provide a source for harmful bacterial development, and if not mitigated can cause disease in the fish (Wold et al., 2014). If the fecal matter begins disintegrating in the water
to pieces of a smaller size, it becomes referred to as particulate organic matter (POM) and may become more difficult to remove. Lake and ocean sites may also encounter algal blooms which, depending on the species of plant, can release toxic chemicals (Landsberg, 2002). Contact with these blooms can pose a serious threat to the cage aquaculture industry, being responsible for high fish mortalities and economic losses (Corrales and Maclean, 1995).

One method through which POM can be removed is through protein skimming, where water is aerated so that as the air bubbles rise to the surface they attach to protein particles and create a layer of foam at the surface of the water (Timmons, 1994). The foam can then be skimmed using a mechanical process separating the water from the concentrated waste at the surface (Timmons, 1994). Aerating the water using an airlift pump for the function of protein skimming has been shown to remove POM, albeit at different rates depending on the setup of the pump (Barrut et al., 2013). It was found that the highest rates of foam fractionation and efficiency were observed when releasing smaller bubbles, either by smaller air injection holes or lower airflow rates (Barrut et al., 2013). Therefore, like gas exchange, the best filtering efficiency of POM is achieved with smaller air bubbles.

Research into effective ways for mitigating algal blooms is limiting, though it has been suggested that airlifts could be used (Maclean, 1993). Although not tested with algal blooms, there has been research conducted on the ability of airlifts to harvest cultured algae (Barrut et al., 2012c), which in principle is performing the same function. The experimentation in question removed algae from the water at a reduced cost of 10 to 100
times compared to conventional technology, likely due to significantly lowered electrical energy cost of the airlift (Barrut et al., 2012c). The researchers also found that algae removal increased with lower airflow rates and smaller bubble size (Barrut et al., 2012c), mimicking the parameters needed to maximize foam fractionation efficiency (Barrut et al., 2013). Algae removal was found to be more efficient in salt water (Barrut et al., 2012c), meaning it would be more effective in marine aquaculture, where the algal bloom issue is most prevalent. Although a similar experiment would need to be carried out in the field to determine if it can be used for algae bloom repulsion, the potential benefit to oceanic cage culture if successful could be substantial.

The improvement of both waste removal functions by using small bubble flow patterns is interesting considering that past research on airlift performance has demonstrated higher pumping of solids using larger bubble size flows such as “gas slugs” (Kassab et al., 2007). The discrepancy in these findings may be related to the density of the solids being pumped. POM and algae generally floats in the water while the aforementioned study used limestone particles that were denser then the surrounding liquid (Kassab et al., 2007). This demonstrates how airlift performance in three-phase-flow will be dependent on the density of solids being pumped and must be considered to obtain optimal pumping efficiencies.

2.3 Conclusion

Maintenance of appropriate water conditions is crucial for the successful rearing of aquaculture species. Failure to do so can result in significant impacts on fish health
including poor growth performance and even mortality. Many water quality parameters are directly tied to the feeding quantity and regime employed by aquaculture sites, which must be incorporated into the general operational strategy to understand the water maintenance demands of the system. The metabolic demands of fish for DO and the excretion of their CO\textsubscript{2}, NH\textsubscript{3}, and fecal waste are dynamic and will be impacted by fish growth and environmental factors such as water temperature.

Whenever the water quality conditions cannot be sustained by the natural environment, the aquaculturist will need to accommodate for this by using various approaches, tools, and equipment available (Boyd, 1998). This can include the generation of water flow to transport new water to the fish while removing waste; enhancing gas transfer to resupply O\textsubscript{2} while removing CO\textsubscript{2}, mixing stagnant water to prevent stratification, and the removal of wastes such as POM and algae. Past research has shown that airlift pumps are to some degree capable of all these functions (Reinemann and Timmons, 1989; Szyper, 1996; Loyless and Malone, 1998; Barrut et al., 2012c; Barrut et al., 2013), and therefore have the potential to be effective water maintenance tools in aquaculture. The use of airlifts for performing several functions simultaneously can also reduce the need for using multiple water maintenance equipment, which can reduce electrical energy consumption and economic costs of the operation.

However, the performance of airlift pumps for various water maintenance functions is highly variable and depends greatly on specific design characteristics of the airlift. Increasing the size of the released air bubbles inside the airlift pipe, especially to create flow types such as “gas slugs”, has been shown to increase the pumping performance of
the airlift, benefiting in functions such as water transportation and destratification (Reinemann and Timmons; 1989; Syper, 1996). Meanwhile, reducing the released bubble size has been shown to be more beneficial for increasing gas transfer, as well as in functions requiring three phase flow of floating solids such as protein skimming or algae transportation (Loyless and Malone, 1998; Barrut et al., 2012c; Barrut et al., 2013).

Ahmed and Badr (2012) have designed a novel airlift pump that can release smaller or larger air bubbles to affect water flow patterns and performance. Thus far, research has only studied the water pumping performance of these novel airlifts (Ahmed and Badr, 2012; Ahmed et al., 2016). The effects that the novel design would have on gas transfer volume and efficiency still need to be quantified. The study of design characteristics effects on SOTR and SAE could help determine the applicability of this pump for oxygenation in aquaculture.
Chapter 3: Measuring Oxygen Transfer and Efficiency of the Dual-Injection Airlift Pump

3.1 Introduction

Ensuring appropriate water quality conditions in fish production systems is crucial for maintaining optimal fish growth and health. Dissolved oxygen (DO) level is arguably the most important water parameter for fish health and is routinely monitored in aquaculture practices. DO concentration decreases due to fish metabolism and must be resupplied, either with additional water containing sufficient DO levels or with equipment that will promote the dissolution of atmospheric O\textsubscript{2} into the water (Boyd, 1998). Aquaculture operations manage aeration and either water flow or exchange through two separate processes, which require multiple electrical or diesel fueled pieces of equipment, such as centrifugal pumps, aerators, air blowers or compressors, and others, resulting in additional operational costs for maintaining sufficient water quality (Boyd and Ahmad, 1987).

Airlift pumps offer an opportunity to move and oxygenate water in an energy efficient manner due to performing both functions at once. However, they generally have lower O\textsubscript{2} mass transfers and oxygenation efficiencies than other aeration devices (Mitchell and Kirby, 1976; Boyd and Ahmad, 1987). Airlift pump performance is also highly dependent on design characteristics, where airflow rate, submergence, cross-sectional diameter and bubble size will affect the rate of O\textsubscript{2} transfer (Reinemann and Timmons, 1989; Parker and Suttle, 1987; Loyless and Malone, 1998).
Ahmed and Badr (2012) have developed a novel dual-air injection airlift pump design intended for improving water quality by releasing different size air bubbles through one of two compartments. One compartment has larger holes for producing larger air bubbles that will travel axially and thus vertically up the airlift pipe. The other compartment has smaller holes for producing smaller air bubbles that travel radially and thus perpendicularly to the length of the pipe. This novel airlift pump design and control of bubble size has proven very valuable to improve efficiency and versatility of the pump for pumping performance (Ahmed and Badr, 2012). This novel airlift design may also have improved O₂ transfer efficiency compared to other airlift pumps currently used by aquaculture operations which generally produce larger air bubbles (Loyless and Malone, 1998). Releasing a volume of air in the form of multiple smaller air bubbles opposed to fewer larger air bubbles will increase the total available surface area for gas diffusion; therefore, air traveling through the radial compartment should theoretically provide greater O₂ transfers. However, research on the novel airlift pump design has thus far only focused on water flow performance (Ahmed and Badr, 2012; Ahmed et al., 2016) and their O₂ transfer efficiency remains to be examined.

The goal of this study was to examine the O₂ transfer efficiency of the novel airlift pump with different design and operation characteristics (pipe diameter, total air flow rate, ratio of radial to axial air flow rate, and submergence level).
3.2 Materials and Methods

3.2.1 Experimental Setup

A series of aquatic lab-bench trials was performed to test the $O_2$ transfer rates and efficiencies of the novel airlift pump. Three dual-injection airlift pumps of different diameters were manufactured by the Gryph Energy Laboratory (School of Engineering, University of Guelph) using polyvinyl chloride (PVC) resin and 3-D printers (Form 2, Formlabs Inc., Somerville, Massachusetts, USA) for the 1 and 2-inch diameter pumps, and using a mill with computer numerical control (MicroMill DSLS 3000, Microproto Systems, Chandler, Arizona, USA) on a schedule 40 PVC pipe to create the 4-inch diameter pump. The axial and radial holes were created in accordance with the patented design, under US patent US 8,596,989 B2. The pumps were brought to the Fish Nutrition Research Laboratory (Dept. of Animal Biosciences, University of Guelph) to carry out a series of bench tests to examine their oxygenation transfer rate and efficiency (Figure 2).

The aquatic bench set up consisted a circular tank (silo) that was 74 cm in diameter and 103 cm in height (Figure 2). The airlift pumps of different diameters were each in turn secured in the tank with a metal frame. The pumps remained stationary during the trial. The outflow water from the airlift pump projected into the middle of the tank. Adjustment for different submergence ratios was carried out by changing the water level in the tank, with 100% submergence having an injection depth of 69 cm. Air was supplied through a high pressure (55 PSI) airline originating from three rotary-screw air compressors located in the Central Utilities Plant of the University of Guelph.
Figure 2: Submerged 4 (a) and 2-inch (b) diameter pumps in the experimental tank setup. Front (c) and side (d) views of the 4-inch pump outside of the tank setup.
This air then travelled through a PVC manifold that led to six air rotameters (Figure 3). These rotameters had ranges of 0 to 10, 0 to 100 and 0 to 500 LPM. Three of the rotameters were fed to an airline going to the axial compartment of the pump while the other three led to the radial compartment. This rotameter setup allowed for easy control of airflow rate and axial-radial contribution of the air.

The tank was filled with raw well-water to a maximum volume of 380 L. New water was always first allowed to equilibrate to room temperature (23.5 ± 0.5 °C) before any trial runs. Before each trial run, a ceramic airstone connected to a nitrogen cylinder was used to dissolve N\textsubscript{2} gas into the water to remove O\textsubscript{2}, until DO level reached below 1 mg/L.

Three DO probes (Model # ENV-40-DO, Atlas Scientific, Long Island City, New York, USA) were placed in the tank and connected to an analog-to-digital converter which then relayed the data to be read using the LabVIEW program (National Instruments, Austin, Texas, USA) on a personal computer. One DO probe was located at the inlet of the airlift pump and the other at the outlet of the pump. The third probe was attached to the inner wall of the tank, located just behind the airlift, a location deemed likely to receive the least water circulation and in theory the area with the lowest DO level.

Each test run would commence once the tank DO level was below 1 mg/L and stable, which was checked using the DO probes. The LabVIEW program would then begin recording the DO readouts by the probes, and the rotameters were then adjusted
to the desired airflow rates for that test run. The probes would continue recording until the
DO level in the tank reached 8.5 mg/L, which is the DO saturation level at 23.5 °C.

This study was designed as a 3 (axial-radial airflow contribution) x 3 (submergence
ratio) x 3 (airlift pipe diameter) x 5 (total airflow rate) multifactorial experiment (Table 2).
The axial to radial airflow contribution ratios were 25:75, 50:50, and 75:25. The
submergence ratio percentages were 100, 75, and 50 %. The airlift pipe inner diameters
were 1, 2, and 4-inches. The total airflow rates were 40, 80, 120, 160, and 200 LPM.
Figure 3: Experimental Rotameter Setup
Table 2: Visual representation of the variables tested by each of the 4 experimental parameters. Trials were run covering each possible combination of the 4 variables resulting in 135 different combinations of parameters.

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>Variable Levels Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Diameter (inches)</td>
<td>1  2  4</td>
</tr>
<tr>
<td>Submergence (%)</td>
<td>100 75 50</td>
</tr>
<tr>
<td>Axial-Radial Airflow Ratio</td>
<td>25:75 50:50 75:25</td>
</tr>
<tr>
<td>Total Airflow (lpm)</td>
<td>40  80 120 160 200</td>
</tr>
</tbody>
</table>
Figure 4: Schematic of the experimental setup. Depicted is the 4-inch airlift pump at 100 % submergence (a). The DO in the tank is monitored using 3 probes which send constant input into a digital database using the LabVIEW program (b). An air compressor system (c) located outside the lab supplies the gas flow to two sets of rotameters, with each set then leading to a different injection point in the pump. Before each oxygenation run, the tank was deoxygenated using nitrogen gas stored in a tank (d) supplied through a ceramic air stone.
3.2.2 Data Collection and Analysis

Once the DO of the tank was below 1 mg/L, the nitrogen gas was turned off and after waiting a few minutes for the water to settle, a trial was commenced. Measurements were recorded from the beginning of each trial until all the probe readings had passed 8.5 mg/L, seeing as that is the O₂ saturation value for the tank’s water temperature of 23.5 °C. The first set of trials, consisting of the 4-inch pump at 100 % submergence was performed in replicates of 3 to assess the precision of the experiment’s design and data collection method. Once it was established that there was no significant difference in readings obtained from trials consisting of the same settings, the rest of the combinations in the experimental matrix could be performed. Over the course of the experiment it became clear that some of the intended settings did not provide ample water flow and so were omitted from having saturation trials performed. Specifically, the 2-inch pump at 50 % submergence for the 40 LPM airflow and the 4-inch pump at 50 % submergence for all airflows were omitted. The 1-inch pump provided sufficient water flow at all experimental settings and so all its data points were used in the ensuing analysis.

After the trials were completed, the O₂ transfer effectiveness was determined by calculating the SOTR, using the equations described by Loyless and Malone, 1998. First, the transfer coefficient \( (K_L a_T) \) was obtained based on the time \( (t) \) in seconds that it took for the DO level to rise from the initial \( (C_0) \) to the final \( (C_f) \) concentration:

\[
- \ln \left( \frac{C_S - C_f}{C_S - C_o} \right) = K_L a_T \times t
\]
As in the previously mentioned paper, the data range used extended from above 20% of the saturation ($C_S$) concentration to just below 90% of the $C_S$. Therefore, $C_t$ and $C_O$ were 7.65 and 1.7 mg/L respectively. This was to avoid data from the ends of the curve that could be a result of residual chemical effects or measurement error when approaching saturation point (Loyless and Malone, 1998). The calculated coefficient was then corrected to the standard reference temperature of 20°C ($K_L a_{20}$) at experimental temperature ($T$), by using an Arrhenius type relationship where the $\theta = 1.024$:

$$K_L a_T = K_L a_{20} \times 1.024^{(T-20)}$$

The adjusted coefficient was then used to determine the SOTR considering the dissolved saturated O$_2$ concentration at 20°C of 9.07 mg/L, and the tank water volume ($V$). The value was also converted from per minutes to per hours by multiplying by 60 and converted from milligrams to kilograms by multiplying by $10^{-3}$:

$$SOTR = K_L a_{20} \times 9.07 \times V \times 60 \times 10^{-3}$$

The SOTR values were then used to find the standard aeration efficiency (SAE), in kg O$_2$/h * kW, using the power consumption determined from the following equation:

$$Power = \frac{\rho \times g \times H_S \times Q_{air}}{1000}$$

Seeing as the air supply was provided by a system of air compressors that supported all air input throughout the university campus, determining the specific power used for providing the airflow in this experiment could not be obtained directly. Instead, the above equation was used to calculate power from a hypothetical ideal air blower or
compressor, incorporating the water density in kg/m$^3$ ($\rho$), gravitational force of 9.81 m/s$^2$ ($g$), static head in m ($H_s$), and airflow in m$^3$/s ($Q_{air}$). This would determine the power value in watts, and so to convert to kW the value was also divided by 1000. The SAE value was then obtained by simply dividing the SOTR value by the power usage:

$$SAE = \frac{SOTR}{Power}$$

All statistics used to then test for significant difference between the treatment factors were carried out using generalized linear models (GLM) with SAS 9.4.

### 3.3 Results

#### 3.3.1 Experimental Precision Test

There were 15 trials run with the 4-inch pump at 100% submergence and a 50:50 axial to radial distribution of the airflow. The difference between the runs was total airflow provided, which included 40, 80, 120, 160, and 200 LPM. The GLM generated for this data (Figure 5) in SAS indicated that there was no significant difference between replicates of a treatment ($p=0.3097$), while airflow did have a significant effect ($p<0.0001$).
Figure 5: SAS generated boxplot for 4-inch pump at 100% submergence at 50:50 axial-radial air distribution with 3 replicates per airflow.
3.3.2 SOTR Analysis

After the precision test confirmed the replicability of the experimental procedure, tests were conducted for the other settings of the experimental matrix without replicate. It became evident throughout the experiment that not only did the pump size have a significant effect on SOTR, but also on how the SOTR changed respective to the other setup parameters. To better exemplify these results, they have been presented individually for each pump size (Figure 6) and simultaneously for comparison between pumps (Figure 7). Statistical analysis was then carried out to measure the significance of each experimental setting on SOTR. When analyzing all the SOTR values together, it was noted that each variable was significantly relevant in affecting the resulting $O_2$ transfer ($p<0.0001$). The only test results that showed no significant difference between the trials were interactions of axial-radial contribution with either submergence ($p=0.9408$), size and submergence ($p=0.2973$) or airflow and submergence ($p=0.9956$).

Seeing as there was a different relationship in SOTR increase between the three pump sizes, there was a following statistical analysis carried out on the effect of each of the other setup parameters for each pump size. The results showed that once again the individual parameters of submergence, axial-radial contribution, and airflow rate had significant effects ($p<0.0001$) on the SOTR for the 2 and 4-inch pumps; however, axial-radial contribution did not have a significant effect on the 1-inch pump SOTR. The axial-radial contribution interaction with airflow rate also did not have significant effect for the 1-inch ($p=0.9095$) or 2-inch ($p=0.1446$) pumps. Meanwhile, the axial-radial contribution
interaction with submergence did not have a significant effect on the 2 (p=0.5458) or 4-inch (p=0.4291) pumps.
Figure 6: SOTR values for 1 (a), 2 (b), and 4 (c) inch airlift pumps. Data is further divided based on pump submergence (S) and the axial (A) to radial (R) ratios.
Full SOTR Data

Figure 7: All SOTR values obtained from experiment. Dotted lines denote lines of best fit for 1-inch pump data. Broken lines with dot intermissions denote lines of best fit for 2-inch pump data. Solid and simple broken lines denote lines of best fit for 4-inch pump data.
Figure 8: SAE values for 1 (a), 2 (b), and 4 (c) inch airlift pumps. Data is further divided based on pump submergence (S) and the axial (A) to radial (R) ratios.
Figure 9: All SAE values obtained from experiment. Dotted lines denote lines of best fit for 1-inch pump data. Broken lines with dot intermissions denote lines of best fit for 2-inch pump data. Solid and simple broken lines denote lines of best fit for 4-inch pump data.
3.3.3 SAE Analysis

Once all the SOTR values were obtained, they were then used to calculate the respective SAE values. These were then also plotted, first on an individual pump size basis (Figure 8) and then all together (Figure 9). Although the individual variables all had significant effects on aeration efficiency ($p<0.0001$), there were several interaction effects that did not show significant difference in the results. Like with the SOTR analysis, there was no statistical significance in the SAE response based on the submergence to axial-radial contribution interaction ($p=0.2075$), or to the interaction of submergence and axial-radial contribution with either pump size ($p=0.3838$) or airflow rate ($p=0.4726$). However, there was also no significant effect when looking at the interaction of axial-radial airflow contribution with total airflow ($p=0.0625$) or with the interaction of axial-radial contribution with total airflow and size ($p=0.6597$).

Interestingly, the analysis showed that contrary to the SOTR data, when analyzing solely the 1-inch pump, there was a significant difference from the axial-radial contribution on the SAE ($p=0.0322$). However, in conjunction with the SOTR analysis, there was no significant effect seen from the total airflow interaction with the axial-radial airflow contribution ($p=0.2998$). The mass transfer and efficiency analysis did show similar statistical results for the 2-inch pump, where there was no significant effect from the interaction of axial radial contribution with the submergence ($p=0.5244$) or the total airflow ($p=0.2578$). Similarly, the 4-inch pump analysis also showed no statistical significance on efficiency from the interaction effect of axial-radial contribution to submergence ($p=0.4408$) or total airflow ($p=0.5982$).
3.4 Discussion

3.4.1 SOTR Analysis

The current study quantified the effects of different experimental setups on the airlift pump’s O₂ transfer capabilities to indicate how they would influence the effectiveness of the pump for aeration. In general, increases in pump size, airflow rate, submergence and radial airflow contribution resulted in greater SOTR values as was predicted. However, it should be noted that these increases were not always linear and deserve more investigation to better understand how the pump would perform under various conditions encountered in different aquaculture systems.

Throughout the experiment, airflow rate was a statistically significant parameter for all pump sizes (p<0.0001), with higher airflow rates resulting in increased SOTR given all other factors were consistent. The only point at which an increase in airflow rate resulted in a decrease of SOTR was with the 1-inch pump at 100% submergence and a 25:75 axial-radial distribution going from 80 to 120 LPM. This discrepancy in the pattern may be related to pump size, as when visually examining the data (Figure 6), it can be observed that with increasing pump size the changes in airflow rate have a larger impact on SOTR. For example, the average differences in SOTR between the lowest and highest airflow rates for the 1, 2, and 4-inch pumps are increases of around 50, 200, and 800 %, respectively. Therefore, since the smallest pump had the smallest proportional increase in SOTR with increasing airflows, there was a higher probability of experimental error causing an observed drop in the upward pattern. The reason as to why larger pump size
causes greater increases in SOTR with higher airflow rates could be due to the pipe's void fraction. If a pump has a smaller cross-section, then a greater proportion of its pipe will be filled with gas compared to a pump with a larger pipe cross section at similar airflow rates. This higher void fraction will result in the air bubbles coalescing and taking on new flow patterns such as slug, churn, and annular (Mahrous and Matrawy, 2014). Such patterns will have lower bubble surface areas and thus be less efficient at gas transfer (Reinemann and Timmons, 1989). Thus, the experimental airflow rate range might have been at levels which produced coalesced air bubbles known as gas slugs or other low surface area flows in the 1-inch pump, resulting in lower \( O_2 \) transfer increases with higher airflow rates.

Another source of inconsistency in the data stems from the results comparing axial to radial contribution for the 1-inch airlift pump, which did not have a significant impact on the SOTR (\( p=0.099 \)). The data for the 2 and 4-inch pumps shows a consistent trend of higher SOTR values with greater radial airflow contributions, and the results do point to a significant impact of the bubble size on \( O_2 \) transfer (\( p<0.0001 \)). This is in accordance with the theory of the pump’s design where the higher axial contribution is intended to increase water flow while higher radial contribution should increase \( O_2 \) transfer due to greater bubble surface area available for gas transfer. The reason as to why this was not observed with the 1-inch data might be due to inconsistencies in flow pattern once the pump has passed a certain void fraction threshold as suggested with the airflow rate data interpretation. This can be inferred from the difference in high to low radial contribution effect on the 4 and 2-inch pump SOTRs, which on average had 37 and 4 % increases respectively when going from 25 to 75 % radial airflow contribution (Figure 6). These
numbers further support the idea that the pump size will affect flow pattern at similar
airflows, so that greater bubble coalescence occurs in smaller airlifts due to higher void
fraction, leading to less efficient O2 transfers. This would therefore negate the aeration
benefits of radial air injections once the void fraction has passed a certain level, creating
significant implications on system design. The data suggests that smaller size pumps will
need lower airflow rates to see an advantage of radial airflow over axial on oxygenation.
Meanwhile, at higher airflows the radial effect is negated so the user may as well just use
higher axial contribution to obtain higher water flow, as no effect will be seen on
oxygenation.

Throughout the study, higher submergence always had a positive effect on SOTR
increase, given that all other factors remained consistent. However, it should be
addressed that some points in the experimental matrix could not be obtained under
certain conditions. For example, when the 2-inch pump was set at 50% submergence,
the provision of total airflow at 40 LPM was unable to generate any consistent water flow
out of the airlift. This does however make sense when reviewing the curve for the pump’s
SOTR generated by the other 50% submergence data, as it predicts there to be no O2
transfer at 40 LPM (Figure 5b). Although air is still being released and providing gas
transfer to the water in the pipe, since it is not being pumped out of the airlift at that setting
the actual increase in DO would not be enough to justify such a setup. Meanwhile, the 4-
inch pump did not generate any results at 50% submergence, namely because either the
water could not be pumped out or it was at such an insignificant trickle as to not warrant
any further investigation. All these examples contrast with the 1-inch pump which
consistently showed results for all points in its data matrix regardless of how low the
submergence was. This might simply indicate the amount of airflow and submergence required for the 1-inch airlift to pump water out is at a lower threshold than for the 2 and 4-inch pumps. This relationship might also be a result of gas slugs which would form easier in a smaller cross section of pipe, and then aide in moving water. The creation of these larger bubble flows in the pump could provide an advantage for pumps with smaller pipe cross sections, since as was seen in the study (Figure 7) there were greater O₂ transfers for the 1-inch pump compared to the other two at lower airflow rates and submergences. Therefore, if an aquaculture system is limited by low airflow rates or needs to pump water to an elevated level as would be seen in recirculating or aquaponics system (Huguenin and Colt, 2002), then it might be more reasonable to implement small diameter airlift pumps for better oxygenation. This helps to illustrate how higher values for the four test variables do not always yield greater SOTR responses, and that they can influence each other to affect O₂ transfer.

When comparing how the different variables will interact with one another to affect SOTR, there is significant interaction (p<0.0001 – 0.0021) between all of them except for submergence with axial-radial injection (p=0.9408). This likely indicates that the depth or head of the pump will not change the capability of higher radial flows to provide more O₂ transfer even at lower submergence levels. This lack of significant interaction between submergence and axial-radial contribution is also seen when analyzing the data for solely the 4-inch (p=0.4291) and 2-inch (p=0.5458) pumps, but not for the 1-inch (p=0.0189). It should be noted though that the injected bubble size did not have a significant effect on the 1-inch pump data (p=0.099), hence its significant interaction with submergence may be simply a result of statistical artifact. However, the axial-radial injection also did not
have a significant interaction effect with airflow for both the 1 (p=0.9095) and 2-inch (p=0.1446) airlift pumps. This would again imply that the airflow rate would not significantly impact the axial to radial airflow ratio’s effect on O₂ transfer. It is then noteworthy to mention how there was a significant interaction between these two variables for the 4-inch pump data (p=0.0261), since as can be seen from the data the improvement in SOTR by higher radial airflow contributions is greater at higher airflow rates (Figure 6c). Although the reason as to why this pattern was observed for the largest pump and not the other two is unclear, it could be possible that it was simply due to the statistical analysis being based on less observations. For example, the data for the 2-inch pump SOTRs (Figure 6b) also appears visually to indicate higher O₂ transfer at high radial airflow contributions when at greater airflows rates, yet the analysis does not indicate this as a significant effect (p=0.1446). To resolve whether these results were simply due to experimental design, future research could examine a narrower experimental matrix for the 4-inch pump to avoid setups that will not yield results as was seen at 50 % submergence for this airlift size. Nonetheless, these analyses suggest that although there are significant interactions between the airlift setup variables on the resulting O₂ transfers, the exact relationship between the injected bubble size with the other parameters warrants further investigation.

The results and analyses of this study have shown that each of the test variables had a significant effect on pump performance, yet the greatest effect was likely due to pump size. The impact this variable had on SOTR is likely best realized when reviewing the lines of best fit that were used to illustrate the patterns of O₂ transfer observed in the experiment (Figure 7). As can be seen, when at constant axial-radial and submergence
settings, greater airflow rates will increase the SOTR of the 1, 2, and 4-inch pumps in a power-based, logarithmic and linear fashion respectively. These results most likely imply that increasing airflow will cause an overall logarithmic rate of SOTR increase, where eventually the higher airflow rates do not yield better O$_2$ transfers due to greater void fraction. The reason as to why this was not the best relationship for the 1 and 4-inch pump data may be due to the experimental matrix not containing points where higher airflow rates reach the optimal O$_2$ transfer efficiency before then plateauing SOTR with higher airflows. In other words, to observe a logarithmic pattern there would likely need to be more samples taken at higher airflows for the 4-inch pump, and at lower airflows for the 1-inch pump. This can have important implications on system design as it means the optimal aeration efficiency will be at different settings for each pump. For this reason, the pump efficiency also had to be calculated to determine how the airlift setups would impact energy usage for O$_2$ transfer.

### 3.4.2 SAE Analysis

Unlike SOTR which showed a nearly constant positive trend with increasing airflow, the SAE would mostly decline with higher airflows. This result makes sense considering that the efficiency is calculated in part based on airflow used, so higher airflow rates will require more electrical consumption thus decreasing the energy efficiency. Interestingly, although increased airflow rates always decreased aeration efficiency for the 1-inch pump so long as other design characteristics remained consistent (Figure 8a) this was not always observed for the 2 and 4-inch airlifts. For the 2-inch pump at 50 % submergence, the data shows better aeration efficiency when the airflow rate increases from 80 to 120
LPM (Figure 8b). Meanwhile, the SAE results for the 4-inch airlift show a similar trend of increasing aeration efficiency, either steeply for the 75 % submergence or gradually for the full submergence, with plateauing at the greater airflow rates (Figure 8c). The increasing SAE values with higher airflow rates at the beginning of some of the curves suggest more economical usage of the injected gas for O₂ transfer, possibly due to better mixing with the surrounding water. The points at which the SAE starts to decrease or plateau with greater airflow rate increases could be indicative of greater bubble coalescence and lower surface area for gas exchange. It should also be noted that as was seen with other variables, the different observed patterns in the data might also be a result of the experimental matrix chosen. This could be verified by conducting trials at lower airflow rates for the 1 and 2-inch pumps, to see if the SAE will eventually begin to decline with lower airflow rates. This could potentially create SAE curves more similar in shape to those for the 2-inch pump at 50 % submergence and the 4-inch at 75 % submergence, which show clear peaks in efficiency. If this were shown to be the case for the other settings, then the peak of each modelled curve would indicate the optimal design parameters for each pump to maximize aeration efficiency.

Unlike total airflow rate, the contribution of air to either axial or radial compartments does not affect the energy efficiency calculation. Therefore, the effects of injected bubble size did not have a different effect on aeration efficiency compared to that seen with the O₂ mass transfer. Namely, higher radial contributions of airflow provided higher SAEs for the 2 and 4-inch pumps, while there were inconsistent results for the 1-inch pump data. However, the energy calculation was affected by the submergence as it factors in the pump’s static head. When the injected air is subject to greater depths it requires to be
pumped at greater inlet pressures to account for having to counter the greater surrounding water pressure. So even though air entering an airlift at two different submergences may be doing so at similar airflow rates, to achieve the same airflow rate for the deeper injection the air blower needs to blow air at a greater pressure, requiring more electricity. The clearest demonstration of this effect on SAE can be observed with the 1-inch pump data (Figure 8a), where greater submergences resulted in lower aeration efficiencies. This contrasts with the effect submergence had on mass O₂ transfer, where deeper settings resulted in higher SOTR values. Therefore, despite greater submergence increasing the power consumption required by the blower, it might also provide greater O₂ transfers that could offset the power costs. Although these offsets were not seen with the 1-inch pump SAE data, it might help to explain some of the less clear patterns in submergence effect observed with the 2 and 4-inch pumps. For example, the greatest aeration efficiencies for the 2-inch airlift were observed at the 75 % submergence, followed by the 100 and then 50 % submergence. This indicates that the additional O₂ transfer observed by the 75 % submergence settings in comparison to those at 50 % submergence was enough to negate the negative effect of greater power consumption for deeper air injection, but the same cannot be said for the pump at 1.0 submergence in relation to 75 % submergence (Figure 8b). Interestingly, this relationship changes for the 4-inch pump depending on the total airflow used. At lower airflow rates there are greater SAEs observed at full submergence settings, but as the airflow rates get higher there is instead a greater efficiency observed for the 75 % submergence values (Figure 8c). This may be related to how for the 4-inch airlift there were much greater SOTRs seen at full submergence compared to 75 % at lower airflow rate. For example, when comparing the
values obtained using 40 LPM of air, the full submergence SOTRs are on average almost 170% greater, whereas at 200 LPM the full submergence values were only 30% greater compared to those obtained at 75% submergence. Thus, at lower airflows the additional electricity cost from greater submergence is much easier offset by higher SOTRs compared to higher airflow rates where the SOTR increase is much smaller. This analysis of this data could therefore be useful in system design to help predict when greater submergences can result in worse aeration efficiency despite providing higher O2 mass transfers.

Despite the SAE data showing a more complex relationship to the setup parameters then seen with SOTR, all the studied design variables showed a significant statistical effect on efficiency for all pumps (p<0.0001 – 0.0322). The lack of a significant interaction effect between axial-radial contribution and submergence that was observed with the SOTR analysis was once again displayed with SAE (p=0.1026). However, the efficiency analysis also showed that there was no significant interaction between axial-radial contribution and airflow rate on SAE (p=0.0625). This would therefore indicate that the benefit of greater radial airflow rate on aeration efficiency is not affected by level of airflow, though it is of interest as to why this lack of interaction was not seen with the SOTR data (p=0.0021). Upon closer inspection of the O2 transfer statistical analysis, it can be noted that as mentioned earlier there was no significant interaction between axial-radial contribution and airflow for the 1 (p=0.9095) and 2-inch (p=0.1446) airlifts, but there was for the 4-inch (p=0.0261), possibly affecting the results considering the data in its entirety.

As mentioned before in the SOTR analysis discussion, this significant interaction could
be a result of less sample points for the 4-inch pump which could increase the observed
effect of varying airflow rates on axial-radial contribution effects on SOTR.

Meanwhile, pipe diameter once again had a significant role in performance and
dictated how the other variables would affect SAE. There was a similar observation to
that of the SOTR data, in that at higher airflows and submergences larger pumps
performed better, while at lower airflows and submergences the smaller airlifts had higher
SAEs. As was suggested in the SOTR analysis, the varying pump diameters would have
different optimal power efficiencies based on size and settings, some of which can be
inferred from the curves displayed in the plot (Figure 9). Meanwhile, the other curves all
suggest that their highest efficiency will be observed at ranges lower than that of the
current experimental matrix, so using lower airflows and at times lower submergences.
This tendency for the highest efficiencies to be viewed towards the lower range of airflow
rate and sometimes submergence, can be problematic from an aquaculture system
design perspective; as greater airflow and submergence is often necessary for greater O₂
transfer. Therefore, the aquaculturist may need to at times sacrifice on energy efficiency
to ensure that there is enough O₂ mass transfer entering the fish’s rearing environment.
The other possible solution to such a dilemma could be to have several airlift pumps
optimized at high efficiency settings, so that when combined the lower O₂ transfers will
be able to together match the requirements of the fish being raised. However, the
capability to implement such a strategy will be based on other factors, such as available
space, airline infrastructure, and financial capital. Nonetheless, the pump pipe diameter
is still a significant design choice that will greatly affect the airlift’s aeration efficiency.
Apart from having to choose the size of airlift that would be most efficient for aeration at a specific range of settings, the aquaculturist would also need to decide whether such a dual-injection airlift is the most practical choice for their system. In a comparison of conventional aeration technology that is used for oxygenating catfish ponds, researchers observed a SAE range of 0.7 – 3.0 kg O₂ / hr * kW by these various tools (Boyd and Ahmad, 1987). The results from the current study indicate that the dual-injection airlift is more efficient, delivering over 5 kg O₂ / hr * kW under certain tested settings, and averaging 2.9 kg O₂ / hr * kW for all the conditions observed. However, it should be noted that these values were calculated assuming air blowers that are 100% efficient, which in the field will not be the case; so, the lower blower efficiency will also decrease airlift pump efficiency. Also, despite the conventional technologies mentioned being less energy efficient, they can generate much greater O₂ transfers to the ones observed from this study, ranging from 0.1 to 23.2 kg O₂ / hr (Boyd and Ahmad, 1987). Meanwhile, the highest transfer observed by the dual injection airlifts was 0.11 kg O₂ / hr, and the average for all the settings was 0.03 kg O₂ / hr. Although the plotted SOTR data indicates that at higher radial airflow contributions, total airflow rates, submergences and pipe diameters than those in the experimental matrix, the pumps will transfer more O₂ (Figure 6), some of these changes might then result in decreased power efficiency (Figure 8). For this reason, a practical usage of this technology for aquaculture might require the application of several airlifts, as they could all be functioning using a single air blower, while the sum of their combined performance could possibly generate sufficient O₂. Another factor that is being ignored in this analysis relates to the pump having the dual function of aeration and water flow. So apart from replacing less energy efficient aeration tools in a system,
the airlifts might also replace some centrifugal water pumps that would be used for water turnover or transportation. This would eliminate additional energy consuming technologies and provide more electricity to be used by blowers for more airlifts. Overall, the studied dual-injection airlifts when implemented correctly have a good potential to replace conventional technology being used in aquaculture by reducing electricity consumption while providing the necessary $O_2$ transfers.

### 3.5 Conclusion

The current study quantified the $O_2$ transfers and efficiencies of the dual-injection airlift pump, which by doing so illustrated the strengths and weaknesses that can be encountered based on system design settings. In general, larger pipe size diameters, greater airflow rates, higher radial airflow contributions and deeper submergences provided better $O_2$ transfers as is expected according to gas transfer physics (Reinemann and Timmons, 1989; Loyless and Malone, 1998; Barrut et al., 2012a). The data, especially for the 1-inch airlift pump, also suggests that greater airflow rates can eventually contribute to a larger void fraction which can increase bubble coalescence and therefore size in the pipe, possibly negating the positive effects of radial contribution on $O_2$ transfer. However, the possible presence of higher void fraction might also then generate more slug-like flow patterns which can increase water flow and overcome pumping issues encountered at low submergences. The issue of low submergences not providing ample water flow resulted in missing data within the experimental matrix. The results from the current study can indicate what the optimal operating ranges are for different airlifts to generate $O_2$ transfer results, which could help future studies in selecting
functional operating conditions to better map out the transfers at specific settings. Such research, along with some of the curves generated in the plots from the current study, can present the optimal aeration efficiencies from a power consumption perspective. Overall, higher airflow rates showed lower aeration efficiencies, possibly from greater bubble coalescence that would decrease available surface area for gas transfer. Higher submergence also showed lower efficiency at some settings, which along with the airflow rate data shows an opposing relationship on SOTR and SAE values. Users of these airlifts will therefore need to remember that increasing settings for higher O₂ transfers can lead to worse power efficiency, so the design choices of every system will need to reflect their individual requirements and constraints. The amount of O₂ required as well as available electricity to power air blowers or compressors will need to be considered before implementing an airlift. However, the efficiency values are comparable to those of tools being currently used for aeration (Boyd and Ahmad, 1987; Barrut et al., 2012a), and as such demonstrate potential to be successfully implemented in aquaculture. To obtain maximum savings on power from these pumps, the users may need to implement creative solutions in their designs, such as installing more airlifts to have higher efficiency at lower individual transfer rates and using them in place of any centrifugal water pumps to remove additional power uptakes. By taking note of how the different setup parameters will affect the O₂ transfers and efficiencies, airlift pumps could be successfully installed in aquaculture systems and save unnecessary electrical consumption for the user.
4.1 Introduction

A key component of maintaining optimum water quality in aquaculture sites is the monitoring and controlling of DO in the water. O$_2$ is an essential component for the metabolism of fish but can be easily depleted under intensive feeding conditions due to the low solubility of O$_2$ in water (Benson and Krause, 1984). Exposure to hypoxic conditions can have negative consequences on fish health, including death (Cooper and Washburn, 1949), so maintaining DO levels that can satisfy the metabolic demands of the fish is critical for maintaining their health. Some aquaculture operations can maintain appropriate DO levels through natural water currents that will continually and naturally supply the fish with new O$_2$ (Page et al., 2005). Operations that lack such currents will need to provide O$_2$ using available aeration and oxygenation technology. However, the use of such technology can provide additional operating costs, including maintenance and electrical energy costs. Aquaculturists therefore need to select the equipment that will provide the least amount of economic costs while maintaining the required DO levels.

Airlifts pumps are an efficient tool for providing water flow and mixing for aquaculture operations (Martins et al., 2010). Although these pumps can also provide O$_2$ transfer to the water, they are in general less efficient at this function compared to other forms of aeration equipment (Boyd and Ahmad, 1987). Ahmed and Badr (2012) have designed a novel dual-injection airlift pump which has high water flow efficiency, but also the potential
to provide SAEs comparable to that of other aeration equipment. The efficiency of this design is predicated on possessing two different modes of air injection. The axial mode of injection releases larger air bubbles directly vertically up the pump for greater water flows, while the radial mode of injection releases smaller bubbles horizontally into the pipe of the pump to provide better mixing and gas transfer. A series of lab-bench trials testing the \( O_2 \) transfers and efficiencies of the pumps at different settings indicate that the airlifts can efficiently oxygenate the water compared to other aeration equipment, but also that the level of each setting can greatly impact the oxygenation potential (Chapter 3). In general, higher \( O_2 \) transfers were observed when using greater pump pipe diameters, deeper submergences, higher airflow rates, and greater percentages of radial injection. The influence of all these factors on the \( O_2 \) transfer of the pump could be modelled to better represent the potential of the airlift for oxygenation in aquaculture.

The \( O_2 \) requirement of fish is directly related to their metabolic rate, which will increase at higher temperatures and with greater weights, activity levels and feed consumption rates of the animal (NRC, 2011). Finfish and shrimp consume an estimated 200 to 400 mg of \( O_2 \) per kg of body weight each hour (Boyd, 1990), and it has been estimated that around 220 g of \( O_2 \) are required for each kg of feed consumed (Huguenin and Colt, 1989). However, these values of \( O_2 \) requirement are also affected by feed composition and several other factors. It has been reported that the \( O_2 \) requirement of fish can be predicted with good accuracy using bioenergetics approaches, such as the Fish-PrFEQ framework (Cho, 1992; Cho and Bureau, 1998; Bureau et al., 2002; 2003).
Other biological processes also consume O$_2$ and can contribute to the depletion of DO in aquaculture systems. Bacterial conversion of the excreted ammonia (NH$_3$) waste into nitrite (NO$_2^-$) and nitrate (NO$_3^-$), results in about 4.6 g of O$_2$ consumed for each g of NH$_3$ (Wimberly, 1990). Decomposition of organic matter as can be observed in ponds with high algal concentration can also result in significant depletions of DO (Hargreaves, 2003). The different processes and their factors contributing to O$_2$ consumption in aquaculture systems are generally well defined and predictable, and so can be modeled.

Therefore, a modeling approach was used to integrate the effects of airlift pump design characteristics on O$_2$ transfer, along with the predicted O$_2$ requirement of fish to determine the suitability of the novel airlift pump in an aquaculture setting.

4.2 Model Inputs

4.2.1 Fish Requirement of Oxygen

A bioenergetics model based on the Fish-PrFEQ framework (Cho and Bureau, 1998; Bureau et al., 2003) and calibrated for Nile tilapia (Chowdhury et al., 2013) was used to predict O$_2$ requirement of Nile tilapia, one of the most important aquaculture species commonly reared in Canadian RAS (Watanabe et al., 2002). The model predicted growth of the animals based on growth potential and water temperature using the thermal growth coefficient (TGC), the initial fish body weight ($BW_{initial}$) and time interval in days ($d$) according to values determined by Chowdhury et al., (2013):

$$BW_{pred} = \left( BW_{initial}^{0.71} + \frac{TGC}{100} \times T \times d \right)^{0.71}$$
The digestible energy requirement ($DE_{req}$) of the fish was estimated based on expected energy retention (recovered energy, $RE$), basal metabolism ($HeE$), heat increment of feeding ($HiE$) and non-fecal energy losses ($UE+ZE$) of the animals based on the calibrations suggested by Chowdhury et al. (2013):

\[ RE = (BW_{pred} - BW_{initial}) \times 6.43 \]
\[ HeE = (-30.33 + (2.37 \times T)) \times BW_{pred}^{0.8} \]
\[ HiE = 0.45 \times (RE + HeE) \]
\[ UE + ZE = 0.043 \times (RE + HeE + HiE) \]
\[ DE_{req} = RE + HeE + HiE + UE + ZE \]
\[ Feed = \frac{DE_{req}}{DE_{diet}} \]

This model determined the theoretical feed requirement using ($DE_{req}$) and the digestible energy content of the feed ($DE_{diet}$). Based on this bioenergetics framework, theoretical O$_2$ requirement of the fish ($O_{2\cdot fish}$) can be determined based on expected heat production (HE) and the oxycalorific coefficient of 1 mg of O$_2$ per 13.64 kJ HE (Cho and Bureau, 1998; Chowdhury et al., 2013):

\[ HE = HeE + HiE \]
\[ O_{2\cdot fish} = \frac{HE}{Q_{ox}} \]
This calculation determined the O$_2$ consumption of fish based on their energy losses to heat and metabolism divided over the animal’s oxycalorific coefficient ($Q_{ox}$) of 13.64 kJ. O$_2$ requirement for converting excreted NH$_3$ into NO$_2^-$ and then NO$_3^-$ through aerobic bacterial processes ($O_{2\, bio}$) was also integrated within the model based on the following equation, which predicts NH$_3$ excretion of the fish:

$$O_{2\, bio} = \left(Feed \times CP_{feed} \times ADC_{CP} \right) - \left((BW_{pred} - BW_{initial}) \times CP_{fish}\right) \times 0.16 \times 4.6$$

The calculation first determines the digestible protein intake, obtained as the product of feed consumed ($Feed$), crude protein content of the feed ($CP_{feed}$), and the digestibility coefficient of the protein ($ADC_{CP}$). The digestible protein intake is then subtracted from the crude protein content retained from the diet, by obtaining the product of the total crude protein composition of the tilapia ($CP_{fish}$) with the change in fish weight during the growth period. To account for the catabolized protein mass that resulted in excreted NH$_3$, this value is then multiplied by 0.16 and is then multiplied by 4.6 to account for the mass in g of O$_2$ required for bacteria to convert NH$_3$ to NO$_2^-$ and then NO$_3^-$ (Summerfelt and Sherrer, 2004).

### 4.2.2 Airlift Oxygen Transfer and Efficiency

The data for the standard oxygen transfer rate (SOTR) of the airlift was derived from the experimental trials presented in Chapter 3. Originally these values were used to generate a multiple linear regression model using the SAS program, which encompassed all four of the test variables. However, despite producing a high $R^2$ of 0.98 when plotting the model results with actual data (Figure 10), several predicted values were still
significantly different from the model. For example, the experimental SOTR values for the 1-inch pump at 200 LPM airflow and 0.5 submergence were double of those predicted in the model. This prompted the need for a more accurate SOTR prediction method that would not create such great outliers. To resolve this issue, the model was segmented into smaller sub-models, each one pertaining to a value of a specific test variable. The best variable to choose for these sub-models was likely size, based on visual observations of the SOTR curves developed in the experimental chapter (Figure 7).
Figure 10: Comparison of observed SOTR values with those generated by a multiple regression model based on pipe size, submergence, total airflow and axial-radial contribution.
However, to confirm whether statistically this would be a reasonable solution, additional regression models were created, with each one excluding one of the experimental test variables effects (Figure 11). As can be seen from the $R^2$ values, the least accurate model was the one excluding variation in SOTR due to pump size. Therefore, since this variable was causing the greatest source of error, it was effectively eliminated by creating three separate models each pertaining to a different pipe diameter. This choice also makes the most sense from a functional point of view, due to this variable having the least amount of practical varieties. This is because an aquaculture system operator might utilize an infinite amount of different airflow rates, axial-radial ratios, and submergences all based on controlling airline valves or water levels in tanks. Meanwhile, there is only a finite range of common pipe diameters, with any variation to this dimension often requiring custom manufacturing which could be more expensive when compared to the common mass-produced sizes. Therefore, since most aquaculture system designs are likely to be constructed economically, they will prefer to use available pipe sizes. Due to all these reasons, there were three regression models created, one for each pipe diameter.
Figure 11: Regressions comparing observed and predicted SOTRs based on models that exclude one of the experimental test variables. The variables excluded from left to right are: size, submergence, axial-radial contribution, and total airflow rate. The associated adjusted $R^2$ values are from left to right: 0.78, 0.95, 0.99, and 0.82.
Although the combined results of all three models only slightly improves the fit of a line based on the observed and predicted values (Figure 12), the new models eliminate the presence of significant outliers. These regression models calculate the SOTR ($\hat{Y}$) using the following combination of linear, quadratic, and cross-product functions:

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1^2 + b_5X_2^2 + b_6X_3^2 + b_7X_1X_2 + b_8X_1X_3 + b_9X_2X_3$$

The variables used in the models are therefore the submergence ($X_1$), axial-radial contribution ($X_2$), and total airflow ($X_3$). To standardize the SOTR units with those already being used in the model, they are multiplied by 1000 to convert from kg O$_2$ to g O$_2$ and multiplied by 24 to convert from hours to days.
Figure 12: Comparison of observed SOTR values with those generated by three multiple regression models based on submergence, total airflow and axial-radial contribution.
To then incorporate how the pump would perform under theoretical conditions, the actual oxygen transfer rate (AOTR) had to be calculated using the following:

\[
AOTR = SOTR \times \left( \frac{C_S - C_t}{9.07} \right) \times 1.024^{(T - 20)}
\]

This transfer rate is determined by accounting for how the SOTR of an airlift would change considering the temperature (\(T\)) and current DO of the water (\(C_t\)). This is to account for the higher O\(_2\) transfer, but lower saturation point that occurs in warmer water (Loyless and Malone, 1998). The equation also needs to consider what the saturated DO concentration (\(C_S\)) would be at the actual temperature. The model then uses the AOTR value to determine the actual aeration efficiency in kg O\(_2\)/h * kW (AAE) using the following:

\[
AAE = \frac{AOTR \times 1000}{\rho \times g \times H_S \times Q_{air} \times 1000 \times 24}
\]

The power usage of a theoretically fully efficient air blower or compressor was calculated, assuming 100% of consumed power was used for air displacement with no energy losses. The equation incorporates the water density in kg/m\(^3\) (\(\rho\)), gravitational force in m/s\(^2\) (\(g\)), static head in m (\(H_S\)), and airflow in m\(^3\)/s (\(Q_{air}\)). The power calculation determines the value in wattage, so the value would need to be multiplied by 1000 for kW, but this gets cancelled by dividing by 1000 to convert from g to kg. The value is also divided by 24 to change from hours to days.
4.2.3 System Oxygen Balance and Concentration

The next part of the model determined the daily mass difference of O₂ in the system (ΔO₂) using the following equation:

\[ \Delta O₂ = (AOTR \times ALQ) - O₂_{fish} - O₂_{bio} \]

Here, the amount of O₂ consumed is determined by factoring the losses due to fish (O₂_{fish}) and biofilter (O₂_{bio}) respiration. Meanwhile, the injected O₂ is determined based on the AOTR and the number of airlifts running (ALQ). The number of airlifts running is determined with conditional IF functions, where if during the trial the concentration of O₂ drops below a predetermined critical level then the model will automatically ‘turn on’ another airlift to compensate for the lost DO. This is designed to indicate to the user how many airlifts at the designated airflow, size, submergence, and axial-radial settings will be required to maintain the desired minimum DO level throughout the length of the indicated production cycle. The temporal DO concentrations during the trial run are determined by considering the integral relationship of the previous day’s concentration, and the new one obtained from the O₂ mass difference (ΔO₂) divided over the volume of water.

4.2.4 Modelled Experimental Setup

To incorporate the model into real system designs, it was calibrated to match the conditions seen at a RAS in the University of Guelph’s Fish Nutrition Research Laboratory used for fish growth trials and incorporating the dual-air injection airlift pumps. The system consists of a single container that is partitioned into a settling area, biofilter, and sump;
which then provides water into two sets of a dozen fish tanks each, that then drains back
into the filter. One of the tank sets is provided water from a centrifugal motorized pump,
while its O₂ is replenished using air stones releasing air into each tank. The second set
of tanks has the water supplied using airlift pumps, with each pump being used to provide
water into two different tanks for a total of six airlifts used. The airflow supplied into these
airlifts is also used as a method to dissolve O₂ into the tanks.

Each tank has a water holding volume of 60 L at a regulated temperature between
26 to 28 °C for trials using Nile tilapia. The saturated DO level at the average of this
temperature range is 8 mg O₂/L. When starting feed trials, the system is first run without
fish for a few weeks so that a bacterial colony can develop in the biofilter giving plenty of
time for the water to saturate with DO. Therefore, the model water was also set at an
initial concentration of 8 mg O₂/L. The model simulation was set for 56 days as that is the
minimum length of a feeding trial conducted in the lab. The model fish were given the
same initial average weight as those currently in the lab at 83 g, which were distributed
at 10 fish a tank to not exceed the tank’s carrying capacity of the fish at the end of the
trial, given how much they would grow with the bioenergetics model. The crude protein
content of the feed was 30 % (Chowdhury et al., 2013), while the apparent digestibility
coefficient of the protein was at 0.9 and the $DE_{diet}$ was estimated at 13.9 kJ/g.

The airlift settings of the model were set to the same submergence, airflow rate, and
axial-radial airflow contribution observed in the laboratory system. The static head was at
0.4572 m in height, while the total submergence ratio was at 0.41. The total airflow rate
going to each airlift was 37 LPM while the axial-radial contribution ratio was 50:50. The
model was run starting with just one airlift to see if that would be enough to carry the tank’s biomass throughout the feeding trial.

4.3 Model Output

The output generated from the model indicated that one airlift would be sufficient to carry the biomass of the tank for the duration of the feeding trial, seeing as the dissolved concentration does not drop below the critical level of 5 mg/L (Figure 13a). It can be noted from the results that the amount of O₂ being provided by the airlift is nearly matching the sum of O₂ consumed by the fish and biofilter, but not exceeding it. The resulting DO concentration decline may seem counterintuitive as the SOTR value for the airlift at the model settings was 174.96 g O₂/day, which is well over the combined amount of O₂ being taken up by the fish and biofilter, estimated to only reach 43.4 g O₂/day at the end of the 56-day trial. However, when calculating the AOTR, the SOTR gets adjusted to account for the temperature and current DO concentration in the water. When the DO concentration is closer to saturation, the O₂ transfer coefficient of the airlift pump decreases, explaining the low AOTR at the beginning of the test run. Although the decreased DO concentration after the first day will result in a higher O₂ transfer coefficient of the airlift pump, at the modelled experimental settings the pump cannot fully compensate for the lost O₂, as the fish are continually eating and consuming greater amounts of O₂. If the model had begun at a lower DO concentration, the airlift pump at the current settings would have been transferring greater amounts of O₂, until the fish and bacterial demand was too great for the airlift to consistently maintain (Figure 13b)
Figure 13: Modelled changes in $O_2$ inputs, outputs and concentration in a potential feeding trial using dual-injection airlift pumps at starting DO concentration of 8.0 (a) or 7.0 (b) mg/L.
4.4 Discussion

The current model provides a prediction of the oxygenation capability of the novel dual-injection airlift pump for maintaining DO levels in an aquaculture setting. The model accomplishes this by combining the effects of certain design characteristics on the $O_2$ transfer of the airlift pump along with the estimated $O_2$ requirement for maintaining the metabolic function of Nile tilapia and the bacterial conversion of $NH_3$ to $NO_2^-$ and then $NO_3^-$. The resulting model output indicates that the novel airlift can maintain the DO levels required by the fish and bacteria for the modelled time-period. The output also indicates that due to the increased feeding rates of the tilapia over the course of the modelled run, the DO concentration will be continually declining, and likely eventually surpass the $P_{crit}$ of the fish. However, the equations required for generating this model are affected by several factors pertaining to system design and fish bioenergetics, therefore changing any of these values could greatly affect the model results.

Compared to the airlift pump settings that had been previously tested (Chapter 3), the pump setup in the Fish Nutrition Research Laboratory included design characteristics that would most likely result in lower $O_2$ transfers. The lab-bench trials were conducted using submergence percentages of 50 to 100 %, whereas the submergence in the model was at 0.41 submergence. The air flow rates used in the lab-bench trial ranged from 40 to 200 LPM, while the modelled airflow was set at 37 LPM. Although the modelled design characteristic values are only slightly lower below the tested range, they still constitute the lower range of $O_2$ transfer performance and oxygenation efficiency (Figure 7, 9). Small pipe diameters also reduce the oxygenation performance and efficiency, however, at the
modelled low airflow and submergence settings the 1-inch pump that was used would provide better \( \text{O}_2 \) transfers then the 2 and 4-inch pumps that had also been tested. Overall, the model output predicts that even at design characteristic values lower than those in the lab-bench experiment range, the novel airlift pumps can provide sufficient \( \text{O}_2 \) transfer for a fish feeding trial using RAS technology.

The effectiveness of the airlift pump will also depend on the target DO concentrations it needs to maintain considering the \( \text{O}_2 \) consumption by the fish and nitrogen fixing bacteria. Overall, the modelled respiration demands of the tilapia caused a continuous decline in DO concentration. However, the model did also predict the ability of the airlift pump to increase DO concentration levels at the beginning of a trial (Figure 13b), likely from a combination of low \( \text{O}_2 \) demand from smaller fish and a lower initial DO concentration that would result in a higher \( \text{O}_2 \) transfer coefficient. Therefore, at certain airlift pump settings it might be possible to maintain DO concentrations for longer periods of time, though this would require determining the fish biomass carrying capacity of an airlift when subject to certain design parameters. The fish biomass would increase based on the quantity, size, and expected growth rate of the fish, which would result in higher \( \text{O}_2 \) demands and therefore require higher \( \text{O}_2 \) transfer by the airlift pump.

It is also important to note some limitations that the predictions may contain when applying the model values to aquaculture systems. For example, the model assumes that all \( \text{O}_2 \) additions and depletions are taking place in one body of water, which contains both the fish and the airlift pump(s). However, many systems that circulate water will utilize additional containers for treating the water, including solid waste settling areas and \( \text{NH}_3 \).
treat biofilters. Therefore, the DO concentration at different components of such an integrated system can be different, which would then affect the O$_2$ transfer coefficient of the airlift pump. Given that the outlet to inlet water pathways can be interrupted with several intermediary components that can affect DO concentration, it might be useful to study the O$_2$ transfer that takes place directly in the airlift between the inlet to outlet water. However, measuring solely the difference between inlet and outlet DO would not be able to determine the SOTR that the airlift could provide to the water body, as it would not account for the effects of water flow. For example, if an airlift pump is circulating water through a tank at a higher rate, well-oxygenated water would pass through the inlet faster, decreasing the DO difference between the inlet and outlet water which could incorrectly suggest that the O$_2$ transfer is less efficient at that setting. Therefore, the measurements would also need to account for the water flow and diffusion rate within the tank to accurately predict SOTR. However, the SOTR could still be affected by other design parameters, such as how lift and submergence would affect the mixing of atmospheric air with the outflow water as it leaves the pump. For this reason, the SOTR values from the current study (Chapter 3) were obtained by simply tracking the inlet DO, as it would factor in all the mentioned effects that would be seen on the tank DO level at different airlift settings. However, if future studies or analyses could account for all these additional factors, then that would improve the application potential of the model in aquaculture systems with different water flow setups.
4.5 Conclusion

Overall, the current model can be used to predict the O₂ concentration change of aquaculture systems using the dual-injection airlift, albeit certain factors must be considered to determine the most accurate results. The design characteristics of the airlift in terms of axial to radial airflow distribution, pump pipe diameter, submergence percentage, and total airflow rate will all influence the capability of the airlift pump to oxygenate the water. However, the O₂ transfer coefficient will decrease in water approaching saturation, resulting in lower AOTR values. Certain qualities of the fish such as feeding rate, quantity and size will impact the decline of DO in the water, both for sustaining O₂ requirements of fish and nitrogen-fixing bacteria. The amount of digestible protein in the diet of the fish will also impact the amount of DO required for the nitrogen-fixing bacteria.

The model output suggests that the novel airlift pump design could maintain necessary DO levels required in aquaculture. However, the DO concentration would generally decrease over time due to the higher O₂ demands of the fish as they grow. Nonetheless, it is possible for airlifts to maintain required DO levels over longer time-periods though it will depend on available pump setup and O₂ consumption of the fish over time. Determining the setup requirements to maintain high and constant DO levels can help aquaculture systems plan their system design to ensure sufficient O₂ for fish metabolism.
Although this model can be a useful tool for determining whether certain airlift setups can generate enough O$_2$ transfer to meet the metabolic requirements of fish in an aquaculture system, further research should be carried out to increase the scope and accuracy of the predicted results. By integrating the O$_2$ transfer component with other pump effects such as water flow and diffusion, the model can predict additional water quality variables, resulting in a more useful tool for planning dual-injection airlift pump integration in aquaculture systems.
Chapter 5: General Conclusion

DO is a critical water quality component for maintaining optimum fish health due to its crucial role in the metabolism of animals. Aquaculture operations often employ high feeding rates to optimize fish growth, which can significantly deplete available DO. This prompts the need to use aeration technology, such as airlift pumps, to resupply the consumed O$_2$ content. Airlift pumps can be highly efficient for pumping water (Martins et al., 2010), but are often less efficient at oxygenation than other available technology (Mitchell and Kirby, 1976; Boyd and Ahmad, 1987). The development of a novel airlift pump design by Ahmed and Badr, 2012, which uses two modes of air injection, an axial mode for higher water flow, and a radial mode for higher gas transfer, may enable airlift pumps to be simultaneously efficient at water flow and oxygenation.

Three novel airlift pumps at different diameters were tested in a lab-bench experiment to record the effects of radial airflow contribution, pump pipe diameter, submergence depth, and total airflow rate on O$_2$ transfer and oxygenation efficiency. The results indicate that increased values for all the tested parameters mostly provided greater O$_2$ transfer (p<0.0001), and that interaction between the parameters also generally resulted in a significant effect on SOTR. However, increasing airflow rate and submergence depths requires greater electrical energy usage, which sometimes resulted in poorer SAE. Compared to standard aeration technology used in aquaculture, the airlift pumps at the experimental settings provided lower SOTR but higher SAE (Boyd and Ahmad, 1987). These results indicate the potential for the novel airlift pump to be an
efficient oxygenation tool for aquaculture operations and that the design parameters will have a great effect on gas transfer performance and efficiency.

The data obtained from this lab bench experiment was combined into a model that predicted the DO concentration in water based on the O₂ transfers provided by the airlift and the metabolic O₂ requirements of fish. The generated model output indicates that the novel airlift pump design can be used to maintain the DO levels required for fish metabolism in a setting such as a research fish feeding trial. However, the total metabolic O₂ requirements of fish will increase over the course of their life cycle. This highlights the need for the proper application of bioenergetic modelling to determine expected O₂ consumption over the course of a specific fish feeding cycle, to then provide airlift pumps capable of meeting the demands at all stages of the growth period.

By determining the effect of certain design characteristic parameters on the oxygenation performance of novel airlift pumps and incorporating the results with fish bioenergetic modelling to determine the pump applicability in aquaculture, the study completed both its intended objectives. The outcome of this research can be further assessed by conducting field trials to determine if any factors will greatly influence airlift performance that were not considered in the lab bench experiment and model. Recording DO of an aquaculture system being supplied O₂ by the novel airlift pumps is needed to determine the validity of the model. Testing the airlift pumps at existing fish growth operations that currently use other forms of oxygenation technology can also provide a direct comparison of energy efficiency between the two types of systems. Considering the other potential uses of airlift pumps for aquaculture, such as water transportation,
designing a system that can fully take advantage of the multiple functions of these tools could provide high improvements of energy efficiency compared to conventional aquaculture system designs. Further research on the water quality maintenance capability of the novel airlift pumps could therefore help determine the potential energy savings for aquaculture operations.
REFERENCES


Boyd, C.E. 1990. Water Quality in Ponds for Aquaculture, Alabama Agricultural Experiment Station, Auburn University, Alabama, pp. 482.


Boyd, C.E. and Ahmad, T. 1987. Evaluation of aerators for channel catfish farming, Bulletin 584, Alabama Agricultural Experiment Station, Auburn University, Alabama, pp. 52


disease in juvenile Atlantic salmon exposed to water supersaturated with oxygen.
Aquaculture. 306 (1-4): 198 – 204.

Fagernes, C.E., Stenslokken, K.-O., Rohr, A.K., Berenbrink, M., Ellefsen, S. and
Nilsson, G.E. 2017. Extreme anoxia tolerance in crucian carp and goldfish
through neofunctionalization of duplicated genes creating a new ethanol-
producing pyruvate decarboxylase pathway. Scientific Reports. 7 (7884).
doi:10.1038/s41598-017-07385-4

Fernandez-Prini, R. 1982. Le Chatelier’s Principle and the Prediction of the Effect of
Temperature on Solubilities. Journal of Chemical Education. 59 (7): 550 – 553.

Fivelstad, S. 1988. Waterflow Requirements for Salmonids in Single-pass and Semi-
closed Land-based Seawater and Freshwater Systems. Aquacultural
Engineering. 7: 183 – 200.

Fivelstad, S. and Binde, M. 1994. Effects of Reduced Waterflow (Increased Loading) in
Soft Water on Atlantic Salmon Smolts (Salmo salar L.) While Maintaining Oxygen
at Constant Level by Oxygenation of the Inlet Water. Aquacultural Engineering.

levels of carbon dioxide in seawater for Atlantic salmon postsmolts (Salmo salar):

Fletcher, G.L., Wroblewski, J.S., Hickey, M.M., Ming, B.B., Kao, H. and Goddard, S.V.
1997. Freezing resistance of caged Atlantic cod (Gadus morhua) during a
Newfoundland winter. Canadian Journal of Fisheries and Aquatic Sciences. 54:
94-98.

Giga, J.V. and Uchrin, C.G. 1990. Laboratory and in situ sediment oxygen demand
determinations for a passaic river (NJ) case study. Journal of Environmental

Atmospheric ammonia measurements in Houston, TX using an external-cavity


Hargreaves, J. and Brunson, M. 1996. Carbon Dioxide in Fish Ponds. Southern Regional Aquaculture Center Publication. No. 468


Randall, D.J. and Wicks, B.J. 2000. Fish: ammonia production, excretion and toxicity. Proceedings of the Fifth International Symposium on Fish Physiology, Toxicology
and Water Quality. 10 - 13 November 1998, City University of Hong Kong. p. 41 – 50.


diversity in marine recirculating aquaculture system (RAS) for Atlantic cod (Gadus morhua L.) production. Aquaculture. 422: 69-77.
