FloMov

Aeration Performance

Technology Evaluation Report

Introduction

Within the aquaculture industry, aeration and water circulation are among the most essential needs to maintaining the proper dynamics of a lake [1]. Both these processes assist in sustaining and prolonging the life of a body of water, while simultaneously improving the water quality, as well as the health and the production capacity of the farmed aquatic animal [2]. Water circulation is typically used to keep the water temperature consistent, reduce stratification, increase nutrient solubility, and reduce the buildup of organic substances at the bottom of the tank [3]. In contrast, aeration, which is the addition of oxygen into the water, is used to support the aquatic life within the system by providing adequate aerobic conditions [1]. Airlift pumps have been proven to be effective systems within this industry due to their ability to aerate and circulate water simultaneously.

An aerator's main function is to supply a pond with the proper concentration of dissolved oxygen in order to improve the energy efficiency of the oxygen transfer process [4]. A study testing the oxygen transfer within an airlift system concluded that if designed properly, an airlift pump can reach greater efficiencies for oxygen transfer than a diffused aeration system [5], eliminating the need for an added aeration device. Some important oxygen transfer parameters that are used to evaluate the oxygenation occurring in the system are the standard oxygen transfer rate (SOTR) and the standard aeration efficiency (SAE). The SOTR can be defined as the mass of oxygen that can be added to the body of water per unit time at standard conditions (20°C water, 0 mg/L initial DO concentration and 1 atm pressure in clean water) [4]. In comparison, the SAE is the SOTR per unit of power [4].

This study was conducted in order to evaluate the performance of FloNergia FloMov airlift pumps as aeration devices. The effects of injection mode, submergence ratio and pump size were assessed to better understand oxygenation capabilities of these airlift pumps.

Methodologies

FloMov Airlift Pumps

The main focus of these experiments are the FloMov dual injector airlift pumps provided by FloNergia © and depicted in Figure 1. This pump design consists of two injection geometries, an axial and a radial injector, as designed by Ahmed and Badr [6] in Figure 2. The radial inlet consists of a perforated tube of the same inner diameter as the riser pipe. The small holes are evenly distributed radially along the circumference of this component, each hole measuring 1.7 mm in diameter. The purpose of the radial inlet is to create a multitude of small bubbles which allows for a larger surface area for oxygen mass transfer to occur between the gas and liquid phases, therefore enhancing aeration. The axial injection geometry consists of a smaller diameter pipe within the pump that extends above the injection site. This design forces the injected air to hit the inner pipe, creating a shear force upwards along the wall. For the purpose of these experiments, the axial and the radial injection geometries were operated simultaneously as a dual injection and compared to a radial injection move for potential improvement in oxygenation. The FloMov pump sizes tested were the 1", 2", 4", 6" and 8" pumps.

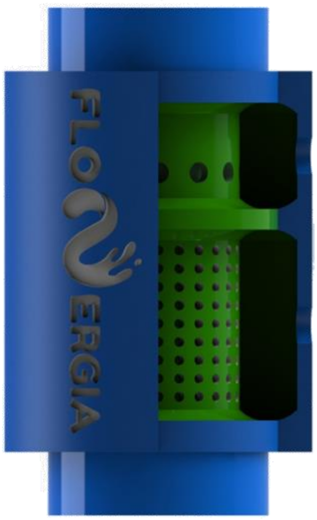


Figure 1: FloNergia FloMov dual injector airlift pump

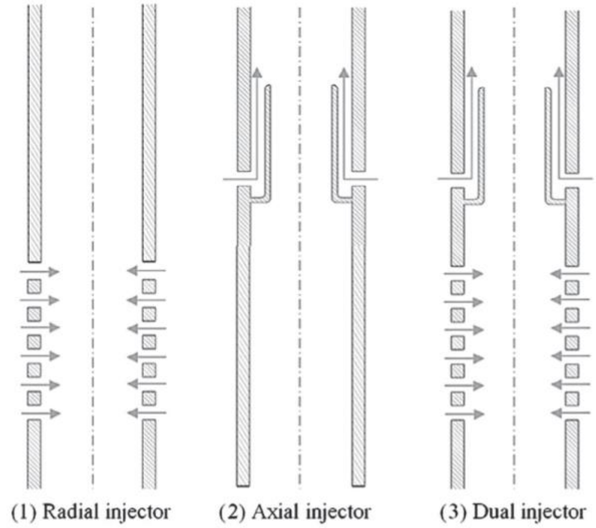


Figure 2: Inside look at the dual injector geometry of the airlift pump [6]

Experimental setup

The oxygen mass transfer experiments were conducted in a 47x37x45 tank with a capacity to hold up to 1249 L as seen in Figure 3. This enclosed system where the pump recirculated the water into the same tank provided ample mixing to avoid oxygen dead zones during testing. The FloMov pumps were attached to a structural frame that secured the pump to the tank and minimized movement and vibration during testing. The pumps were placed at a length of one diameter from the inlet of the pump to the bottom of the tank for proper operation and consistency during testing. In order to operate the airlift pump, a pneumatic system was used where the injected air was supplied through a regenerative blower. The supplied air passed through a relief valve, a pressure gauge and a check valve. The air flow rates of the axial and the radial injection geometries were controlled separately with the use of two rotameters reading up to 21 000 LPM and adjusted using control valves. From the rotameters, 1” tubing was used to supply the injected air to the injection ports of the FloMov pumps.

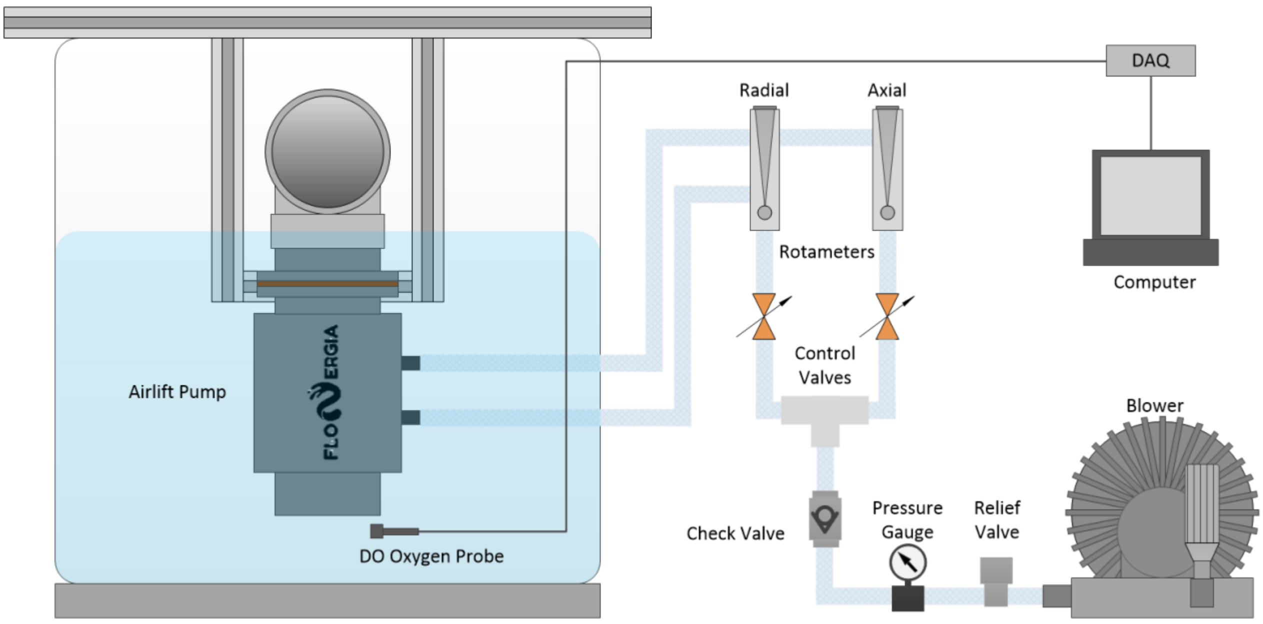


Figure 3: Schematic of the experimental setup

To measure the dissolved oxygen in these experiments, a galvanized dissolved oxygen probe was used. The probe works by allowing oxygen molecules to defuse through a membrane where they can be reduced when they reach the cathode. This produces a small voltage that increases as the oxygen increases. A circuit was designed using an embedded dissolved oxygen circuit in order to process the data recorded by the probe and record the findings through the LABVIEW interface. As stated on their data specification sheets, the uncertainty of both the probe and the embedded dissolved oxygen circuit were ± 0.05 mg/L [7], [8]. The dissolved oxygen probe was secured to the inlet of the pump as seen in Figure 3 to represent the time it would take to oxygenate the entire volume of water more accurately. This provides time for the pumped water at the surface to be thoroughly mixed all the way to the bottom of the tank where the dissolved oxygen probe is placed in order to better embody the oxygen transfer rate of the system. A second portable dissolved oxygen probe with repeatability of ± 0.05 mg/L [9] was attached at the inlet of the pump and used as a means to verify the recorded readings. This portable oxygen probe was also used as a means to record the temperature of the water before each trial with accuracy of ± 0.2 °C [9].

Testing Conditions

The water flow performance of FloNergia airlift pumps is highly dependent on several adjustable settings, namely, the airflow provided, axial to radial airflow ratio, and the submergence ratio. The performance of these pumps is also highly dependent on their inner pipe diameter, hence different size airlifts will pump at different rates. To account for all these variables, the experimental matrix provided in Table 1: Test conditions was used.

Table 1: Test conditions

Test Parameter	Variable Levels Tested						
Pipe Diameter (in)	1	2	4	6	8		
Submergence (%)	50	60	70	75	80	90	100
Injection Method	Dual	Radial					
Injection Ratios	0%A: 100%R	25% A: 75% R	50% A: 50% R	75% A: 25% R			
Total Airflow (LPM)	40 – 2100						

Each experimental test was run once, as earlier testing confirmed the lack of statistically significant difference between individual runs conducted at the same settings. An uncertainty calculation found a ± 5% uncertainty in both the SOTR and SAE calculations. Five different size pumps were used for these tests, each one being fitted into the tank separately as the experiments progressed. The submergence was adjusted by decreasing or increasing the water level in the silo as required. Before each trial, the water temperature was recorded and used to find the equivalent saturation point using a maximum dissolved oxygen concentration saturation table [10]. Each test commenced by de-oxygenating the water using injected nitrogen dispersed through two air stones placed the bottom of the tank. Once the dissolved oxygen readings were below 1 mg/L, the nitrogen was turned off and allowed to settle for a short period of time before continuing. Once settled, the airlift pump was turned on and left to oxygenate the water until reaching saturation.

Oxygenation Analysis

The measurement of oxygenation capabilities of aeration equipment can be difficult to standardize as the performance will be greatly affected by various properties of the water. Generally, such equipment will add lower amounts of oxygen into water that has higher temperatures or higher levels of already present oxygen. Despite this, the rate of oxygen transfer is often higher in warmer water. Furthermore, the continued addition of oxygen into water will increase the dissolved oxygen (DO) levels as desired but will also decrease the amount of potential oxygen that can be added.

To account for these factors, researchers and industry determine a standard oxygen transfer rate (*SOTR*) of their aeration equipment. This can be calculated using equations presented by Loyless and Malone [11] by first obtaining the transfer coefficient ($K_L a_T$), based on the amount of time (t) it takes for the equipment to raise a water body's DO level from 20 % of saturation (C_O) to 90 % of saturation (C_t), with the actual level of potential saturation (C_S) based on the water's temperature:

$$-\ln\left(\frac{C_S - C_t}{C_S - C_O}\right) = K_L\, a_T \times t$$

To account for different experiments potentially using different temperature water, the experimental transfer coefficient is then converted to the transfer coefficient that would be obtained with 20°C water ($K_L a_{20}$):

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

Finally, by applying the volume of the water body that was oxygenated with the equipment, a comparable SOTR value is determined:

$$SOTR = K_L a_{20} \times C_S \times V$$

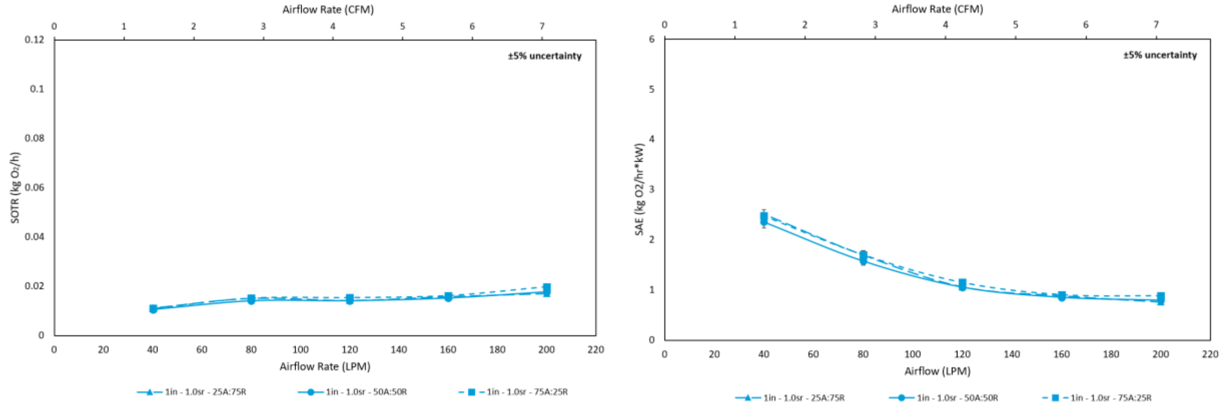
These factors impose important constraints on aeration testing that must be accounted for to obtain reliable results. Apart from the constant measurement of DO levels, these levels must be representative of the tested water body. This requires researchers to account for the water flow and mixing dynamics to assess if the readings are disregarding oxygen dead zones. For this reason, testing done in larger bodies of water will not be as reliable, and experiments in smaller controlled bodies of water are preferred. Conversely, it must also be considered that most aeration equipment relies on the mixing of atmospheric gas with water, resulting in a medium containing both fluids. For this reason, experimental design must also consider taking measurements in already treated water containing only dissolved gases with no air bubbles, as these would impact the DO readings.

Experiments measuring oxygen transfer must also be mindful of potential environmental impacts on the water that can skew the results. If the body of water will be subject to significant changes in temperature or atmospheric pressure, the rate of gas transfer will also be subject to change and will likely affect the calculated SOTR. Water can also contain various contaminants or organisms that can also affect the DO levels and may impact the outcome of the experiment. The potential for external influences on water DO levels is therefore highest in natural water bodies which would be unreliable locations for scientific testing of aeration equipment.

Results and Discussion

Effect of Injection Ratio

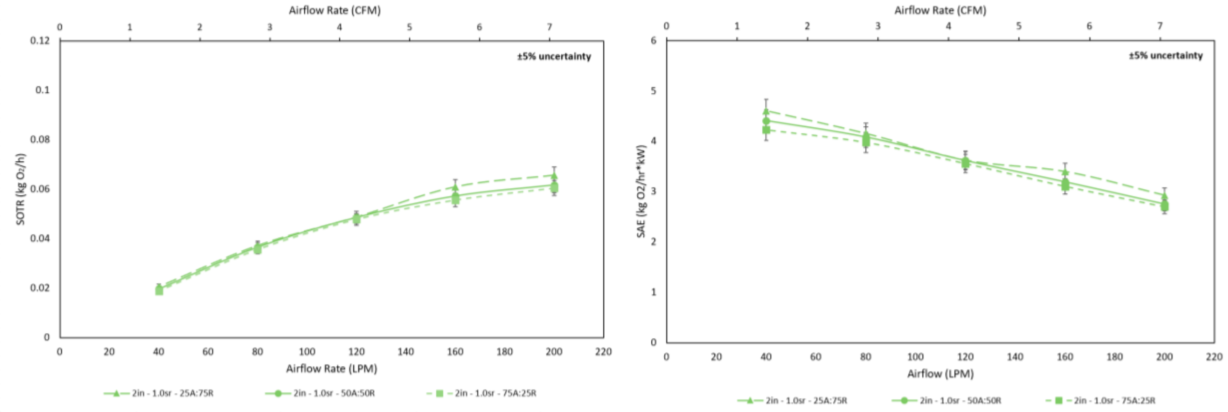
The effect of injection ratio between the axial and radial injectors were tested on the 1- and 2-inch pumps. A dual injection was utilized at injection ratios of 25% axial to 75% radial, 75% axial to 25% radial and 50% axial to 50% radial. These tests were performed at submergence ratios of 1.0, 0.75 and 0.5 for comparison. These results showed that a higher percentage of radial airflow resulted in greater oxygen transfer. This was expected due to a greater proportion of smaller bubbles resulting in a greater total surface area for mass transfer to occur. However, this relationship was most pronounced with increasing pipe diameter. The 1-inch airlift did not show a significant increase in SOTR or SAE with higher radial airflow in some instances [Figure 4, 6 and 8], however the 2-inch pump had a slightly more visible impact on the SOTR and SAE values as seen in Figure 5, 7 and 9. This may be due to higher void fractions in the airlift, where bubble coalescence may occur and negate the effects of producing smaller size air bubbles in smaller pump sizes. Therefore, smaller size pumps will need lower airflow rates to see an advantage of radial airflow over axial on oxygenation. The change in injection ratios did not seem to have and effect on submergence ratios, however this may change with larger pump sizes. Further testing would be required for additional analysis.



a) Standard oxygen transfer rate

b) Standard aeration efficiency

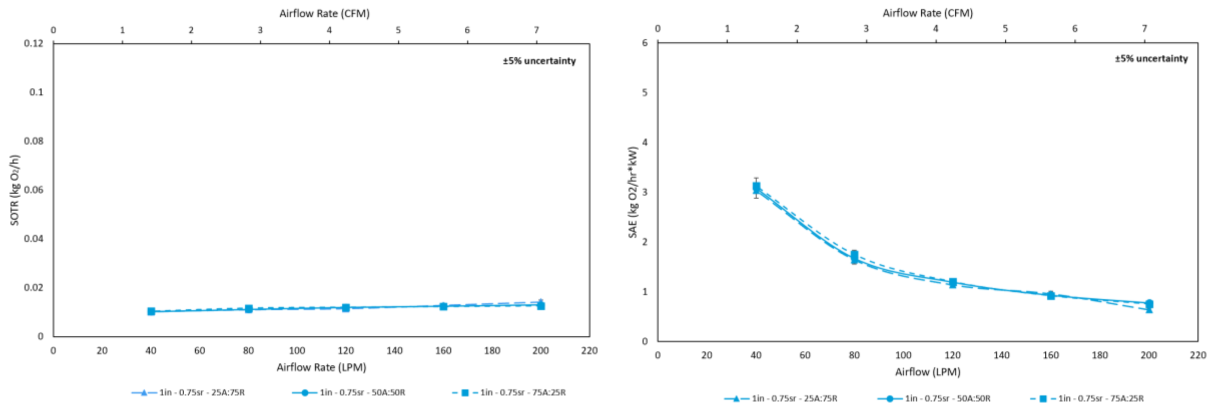
Figure 4: Effect of injection ratios on 1in pump at 1.0 sr



a) Standard oxygen transfer rate

b) Standard aeration efficiency

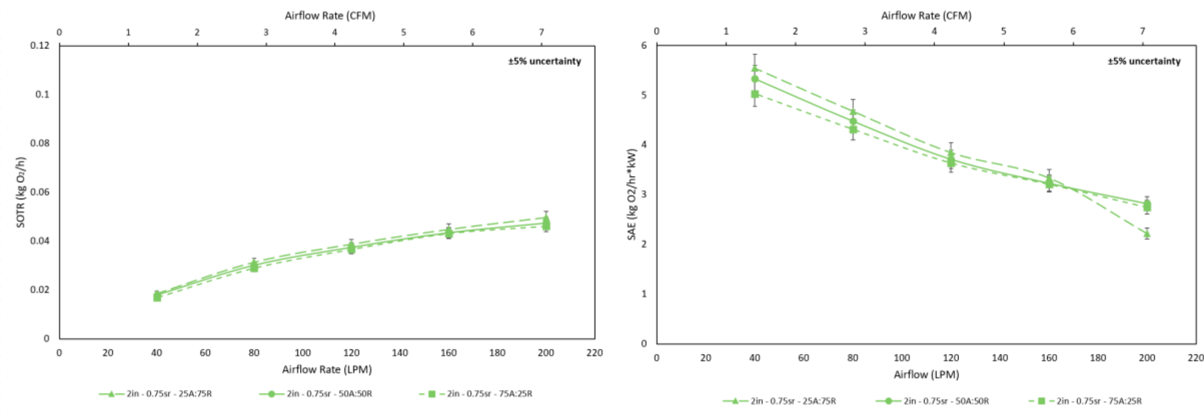
Figure 5: Effect of injection ratios on 2in pump at 1.0 sr



a) Standard oxygen transfer rate

b) Standard aeration efficiency

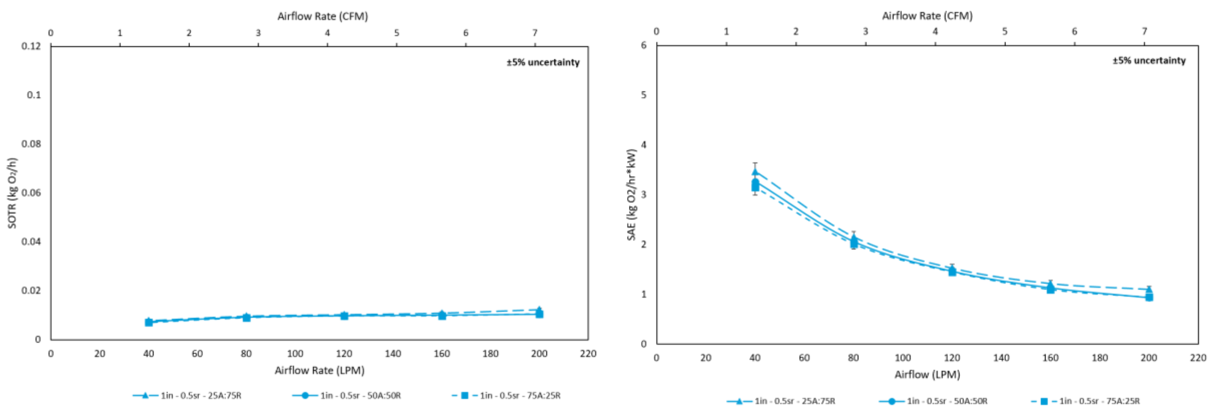
Figure 6: Effect of injection ratios on 1in pump at 0.75 sr



a) Standard oxygen transfer rate

b) Standard aeration efficiency

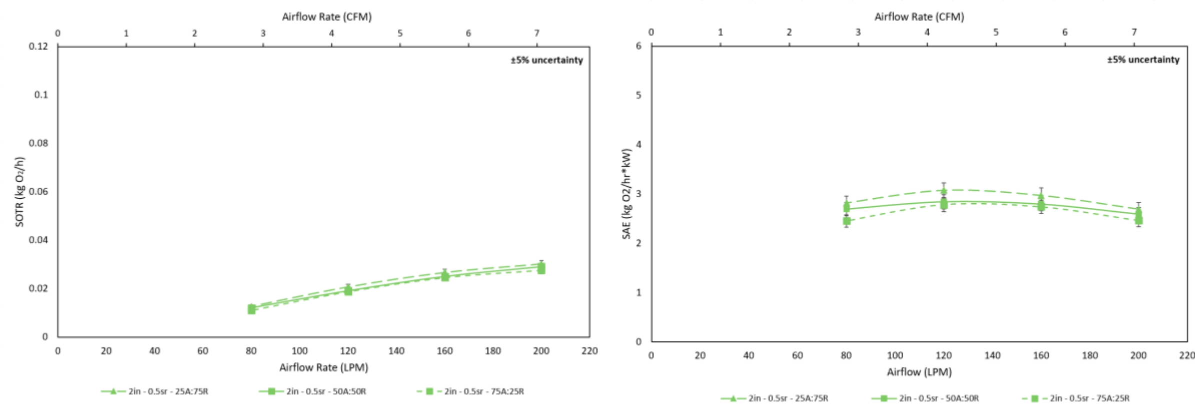
Figure 7: Effect of injection ratios on 2in pump at 0.75 sr



a) Standard oxygen transfer rate

b) Standard aeration efficiency

Figure 8: Effect of injection ratios on 1in pump at 0.5 sr



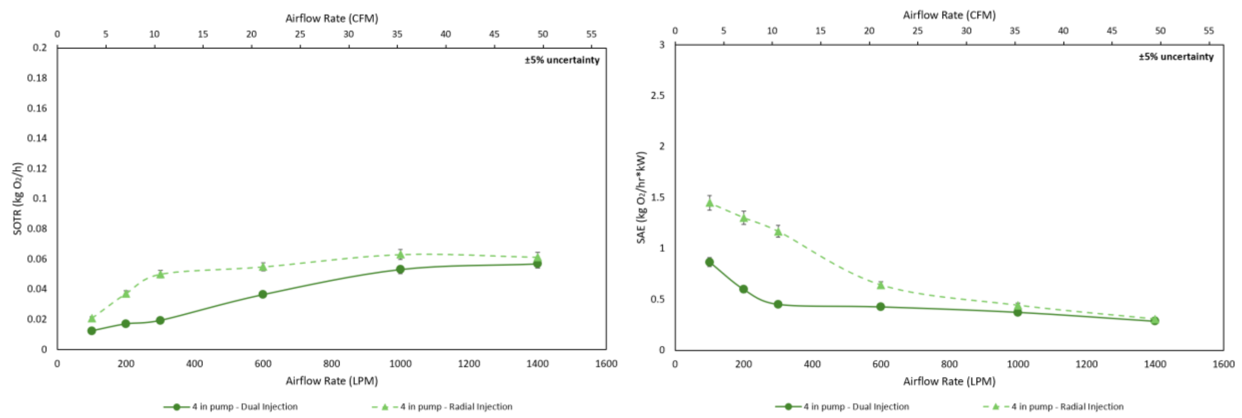
a) Standard oxygen transfer rate

b) Standard aeration efficiency

Figure 9: Effect of injection ratios on 2in pump at 0.5 sr

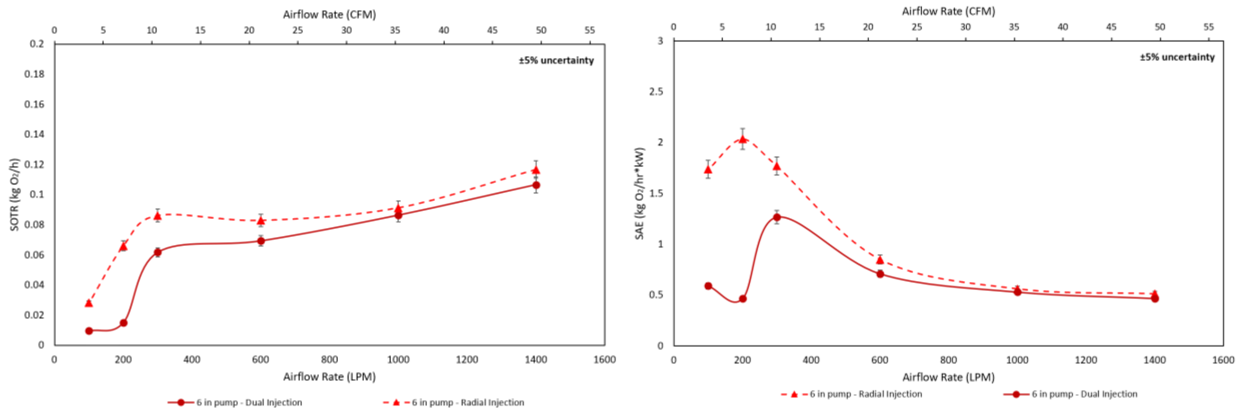
Effect of Injection Mode

From the previous section, it was found that a higher ratio of airflow in the radial injection during dual injection can improve the SOTR and SAE of the system. Therefore, further testing comparing the injection modes on the larger pump sizes of 4, 6 and 8-inch pumps were conducted at a consistent submergence ratio of 0.9. The injection modes tested were the dual injection at a 50% axial to 50% radial injection ratio versus a 100% radial injection. From Figure 10 Figure 12 below, there is a significant improvement in SOTR as well as SAE when utilizing a radial injector, especially at lower airflow rates. This can be due to bubble coalescence occurring at higher airflow rates which then decreases the positive effects of the radial injector. For the 4-and 6-inch pumps specifically, at airflow rates higher than 600LPM, the radial injector starts to provide oxygenation increasingly similar to the dual injector. Therefore, at higher airflow rates the radial effect is negated so the user may as well use higher axial contribution to obtain higher water flow, as no effect will be seen on oxygenation. Furthermore, at airflow rates below 400 LPM for all three pumps, a significant increase in SAE is depicted which further validates the use of a radial injector for lower airflow rate applications.



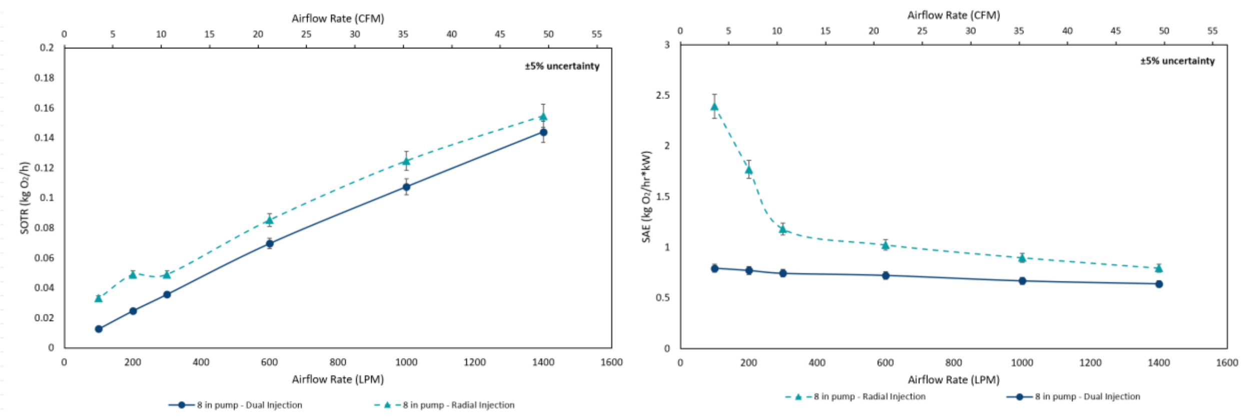
a) Standard oxygen transfer rate   *b) Standard aeration efficiency*

Figure 10: Dual versus Radial injection mode for 4in pump at 0.9 sr



a) Standard oxygen transfer rate *b) Standard aeration efficiency*

Figure 11: Dual versus Radial injection mode for 6in pump at 0.9 sr

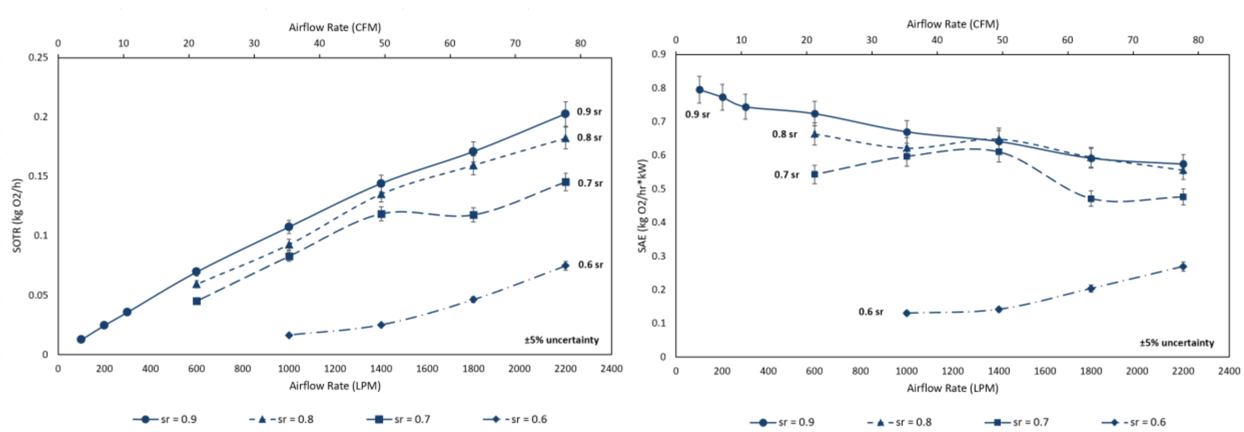


a) Standard oxygen transfer rate *b) Standard aeration efficiency*

Figure 12: Dual versus Radial injection mode for 8in pump at 0.9 sr

Effect of Submergence Ratio

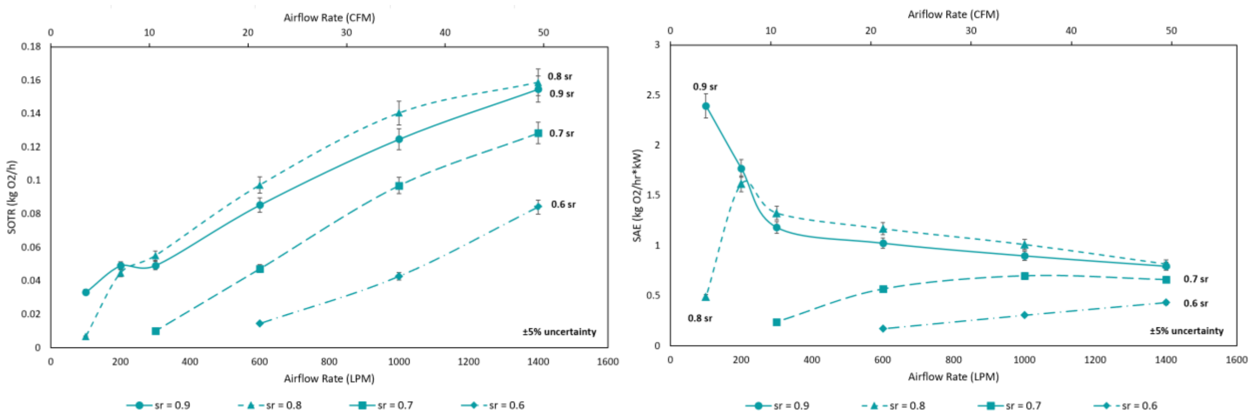
The effect of the submergence ratio on aeration was tested on the 8-inch pump for both the dual and radial injections. The submergence showed to also have a significant effect on SOTR, with higher submergences resulting in higher oxygen transfer rates. However, at some submergence settings there were no values obtained as there was either no water flow observed or just a trickle. This occurred for the 8-inch pump at any airflow below 300 LPM for 0.7 submergence, 600 LPM for 0.6 submergence and any airflow rate at submergences below 0.6. This demonstrates how during system design it is crucial to provide as much submergence for the airlift as possible to obtain the greatest performance and oxygenation results. It also demonstrates how when only low submergences are possible, lower diameter pumps are the most effective. Therefore, in systems that require high lifts but have low airflow outputs, such as small-scale aquaponics, the use of lower diameter airlifts is preferable.



a) Standard oxygen transfer rate *b) Standard aeration efficiency*

Figure 13: Effect of submergence ratio on the 8-inch pump for dual injection

Figure 13 depicts how the SOTR increases as the submergence ratio was increased, with similar results for the SAE values. Figure 14 plots the radial injection at the various submergence ratios and shows comparable results to the dual injection tests. However, the radial injection showed an improved SOTR for the 0.8 submergence specifically. This could possibly be due to the flow pattern changing at the highest submergence, causing the bubbles to coalesce and therefore begin to negate the effects of the radial injector in improving oxygenation.



a) Standard oxygen transfer rate　　　　*b) Standard aeration efficiency*

Figure 14: Effect of submergence ratio on the 8-inch pump for radial injection

Effect of Pump Size

The five pump sizes tested throughout this research can be compared to one another to determine the role pump size plays in aeration. It is important to note that in Figure 15 presented by FloNergia, each pump size has an airflow rate at which the pump provides its highest efficiency and another airflow rate for the highest performance. Table 2 below outlines the airflow rate for these conditions for each pump size in LPM. These flow rate limits can be used to better understand the range at which these airlift pumps will most likely be operated at in most applications. Due to limitations in blower capacity of this experimental setup, the full range for every pump size could not be tested.

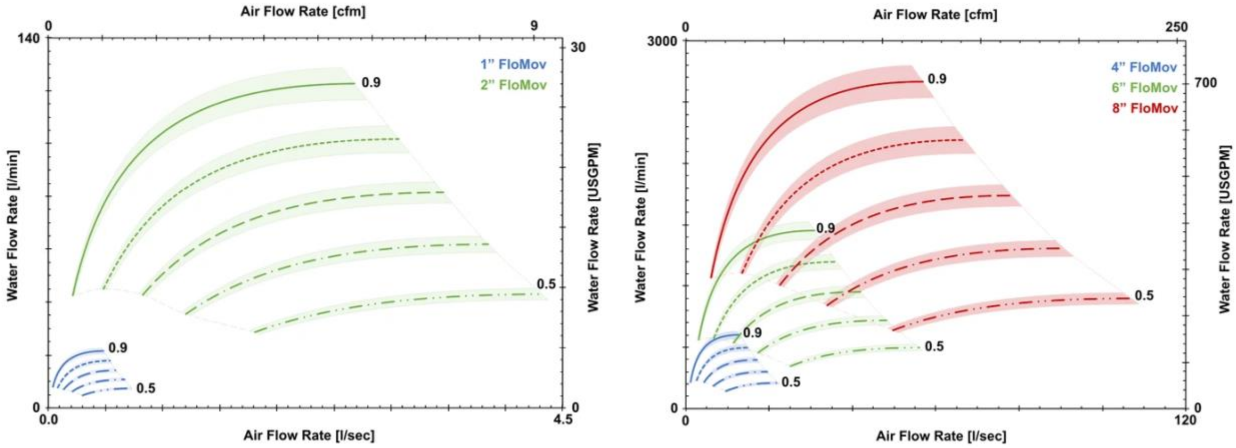


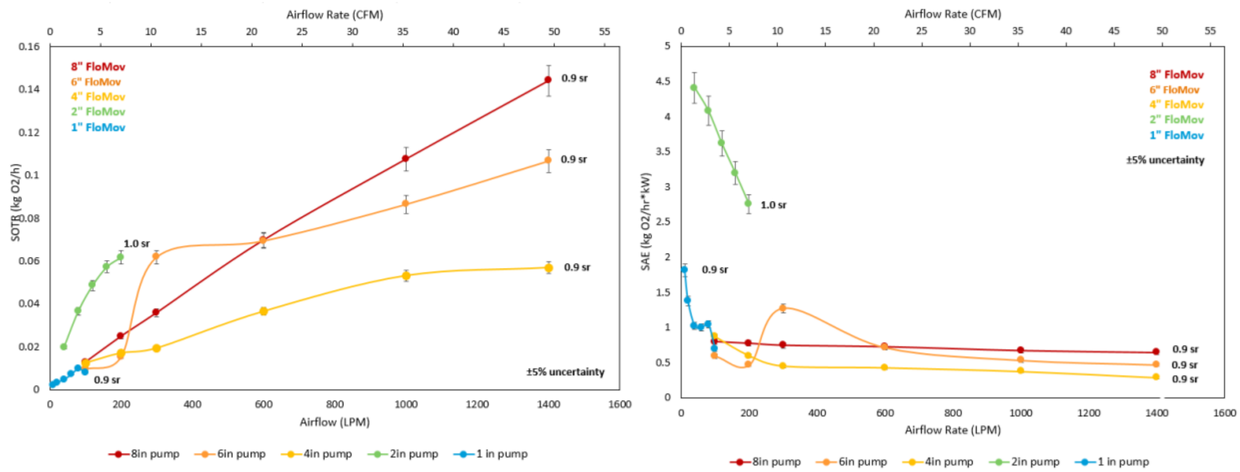
Figure 15: Performance data for FloNergia © FloMov airlift pumps

Table 2: Optimal airflow rates for each FloMov pump

	Pump Size				
	1”	2”	4”	6”	8”
Best Efficiency Airflow rate	3 LPM	14 LPM	71 LPM	255 LPM	396 LPM
Best Performance Airflow rate	31 LPM	161 LPM	765 LPM	1189 LPM	3398 LPM

When plotting the results of the experiments based on the airflow rates used, it can be observed that the pump pipe diameter plays a significant role on the SOTR. These results imply that increasing airflow rates 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. To observe a logarithmic pattern there would likely need to be more samples taken at higher airflows for the each of the pumps. However, as previously described, increasing the airflow rate past the best performance point in Figure 15 will plateau the performance results and reduce the efficiency of the pump. Therefore, it is important to make note of which parameters should be optimized between the pump performance, efficiency and oxygenation for a given application.

Figure 16 below depicts the SOTR and SAE graphs for all 5 pump sizes at a dual injection mode of 50% axial and 50% radial and the highest submergence ratios of 0.9 and 1.0. From this figure it can be seen that generally, the oxygen transfer rate tends to increase with pump size and similarly with the aeration efficiency. The 1- and 2-inch pumps seem to defer from the trend that the other three pumps present. This may be due to the experimental matrix not containing points where higher airflow rates reach the optimal O_2 transfer efficiency before plateauing or low enough airflow rates to correspond with the best performance range of the smaller pumps. In other words, to observe a logarithmic pattern there would likely need to be more samples taken at a wider range of airflow rates for the smaller pump sizes.



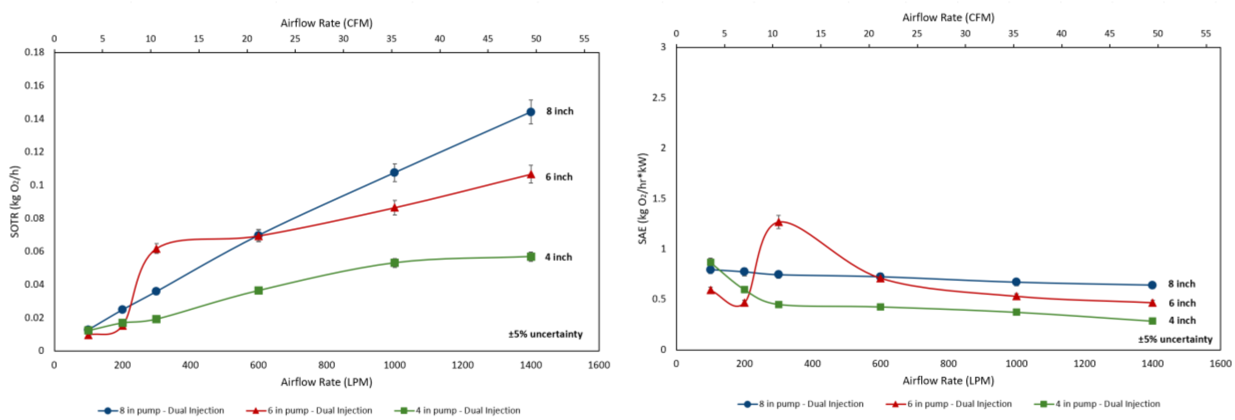
a) Standard oxygen transfer rate

b) Standard aeration efficiency

Figure 16: Effect of pump size on SOTR and SAE at high submergence ratios

Due to the significant jump in size between the 2 and the 4-inch pumps, the data for the larger pump diameters were presented in a separate graph, considering the larger sizes would likely have different applications. Figure 17 depicts the larger diameter pumps operating at a submergence ratio of 0.9 at a 50:50 dual injection mode. The SOTR graph clearly depicts a logarithmic trend that begins to form at the flow rates below 1400LPM. From this it can be predicted that with increased airflow rates passed 1400LPM, each pump will reach a maximum SOTR value then begin to plateau at the point where the high void fraction and large bubble sizes no longer provide any additional aeration to the system.

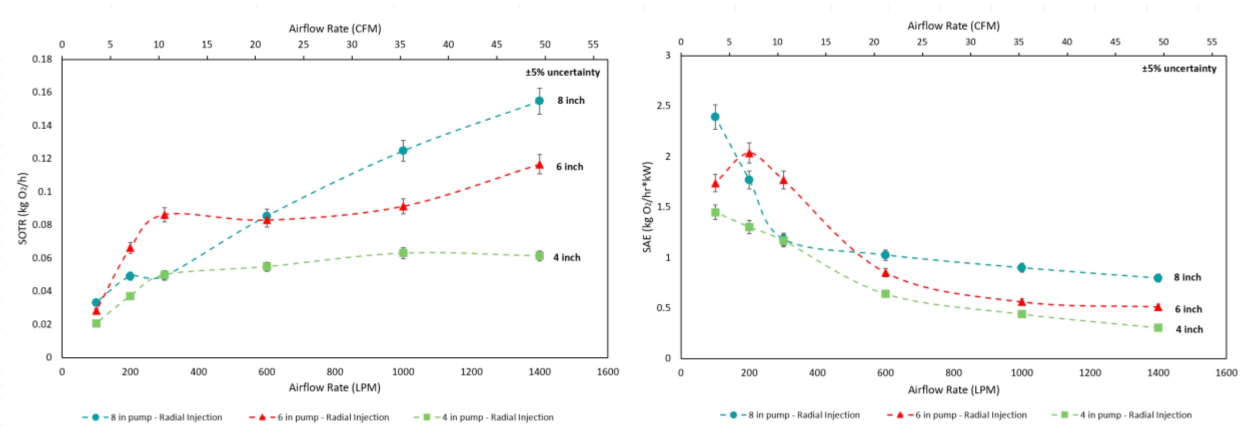
In Figure 17 b) the SAE depicts a trend where the efficiency is highest at the lower airflow rates, most likely when the bubble sizes are small enough to provide adequate and efficient oxygen mass transfer to the water, and then begins to decrease as the airflow rates are increased. It should be noted that for the larger pump sizes, lower airflow rates such as 300 LPM and below have very little amounts of water being pumped, therefore creating these conditions at which the aeration efficiency is improved.



a) Standard oxygen transfer rate *b) Standard aeration efficiency*

Figure 17: Effect of pump size on SOTR and SAE for the larger pump sizes at dual injection

Similarly, the SOTR and SAE was graphed for the radial injections for the larger pumps as seen in Figure 18. With the radial injector, higher SAE values are reached and show more of a clear trend upward as the airflow rate is decrease. The 6-inch pump even reaches its peak SAE value at a flow rate of 200LPM. This implies that each pump should reach a peak SAE value at lower airflow rates then the range tested in these experiments. Further experimentation at a wider range of airflow rates would be required to determine if peak SAE value increases as pump size increases. However, it can be concluded that SOTR increases with pump size and SAE at higher airflow rates also increase with pump size.



a) Standard oxygen transfer rate *b) Standard aeration efficiency*

Figure 18: Effect of pump size on SOTR and SAE for the larger pump sizes at radial injection

For the smaller pump sizes of 1 inch and 2-inch, additional testing is needed at a wider range of air flow rates better suited to these smaller pumps and their applications. An additional set of tests were conducted for the 1-inch pump seen in Figure 19 at a 50% - 50% dual injection and radial injection modes for a 0.9 submergence ratio. Limitations from the experimental setup only allowed flow rates between 10 LPM to 100 LPM to be tested. A second set of tests should be conducted in the future for the 2-inch pump at similar airflow rates for better comparison of the smaller pump sizes and a more complete set of data.

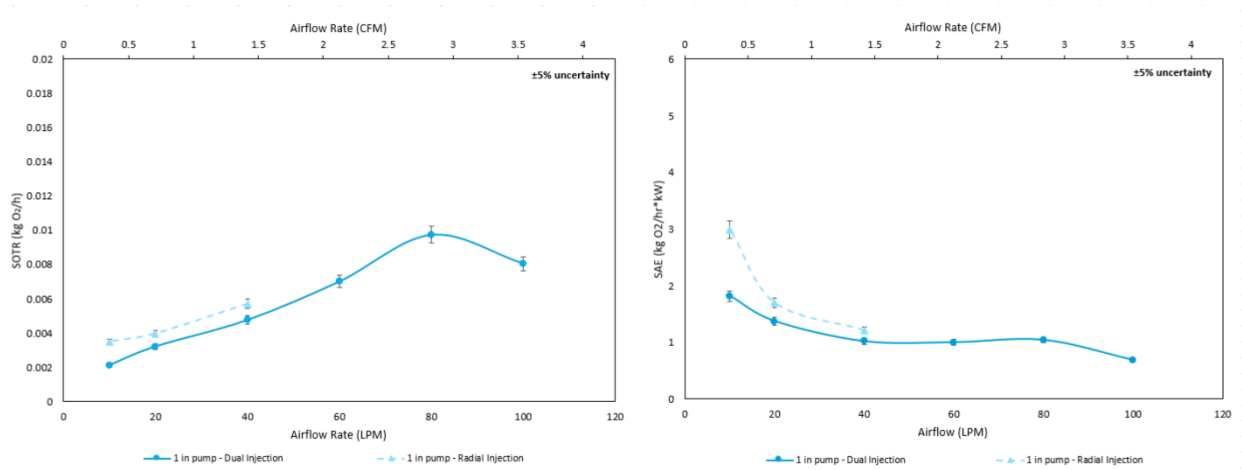


Figure 19: Additional 1 inch pump SOTR and SAE tests for smaller pump sizes

Complete Data Representation

The data collected throughout these experiments were presented in a clear manner that can be utilized by FloNergia to help their clients better understand the capabilities of the different FloMov airlift pumps and help them in selecting the appropriate pump for their specific oxygen mass transfer needs. The figures below were displayed in two separate graphs: for the larger pump sizes of 4, 6 and 8 inches, and for the smaller pumps of 1 and 2 inches. Figure 20 gives a more general range of standard oxygen transfer rates and aeration efficiencies using geometric shapes. These geometric shapes show the lower range of mass transfer at the bottom of each shape when the pump is operating at dual injection. The top line of the geometry indicates the maximum possible mass transfer using a radial injection mode. The figure depicts the airflow rates correlating the mass transfer data in both LPM and CFM. Overlapping between ranges for each pump can indicate that multiple pump sizes can provide similar oxygen transfer rates, depending on what is required for the intended application. Similarly, the data for the smaller pump sizes of 1 and 2 inches were presented in the same manner in Figure 21.

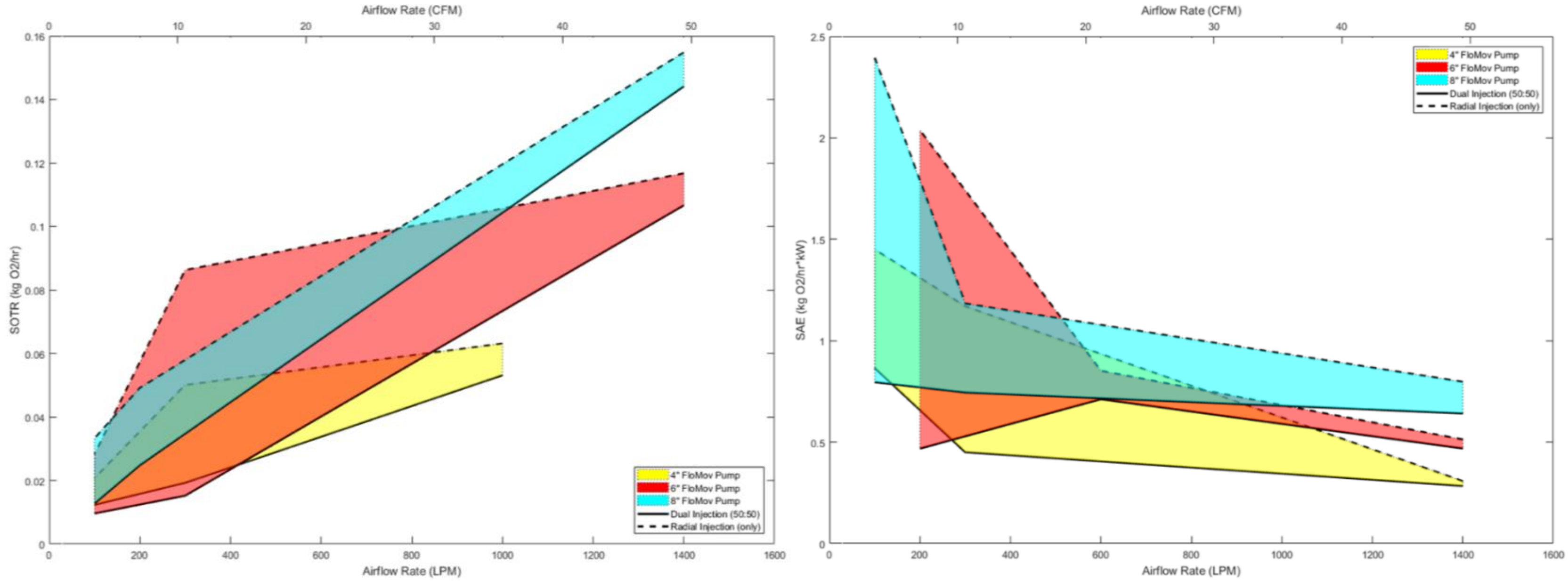


Figure 20: Oxygen mass transfer data representation for larger FloMov pump sizes of 4", 6" and 8"

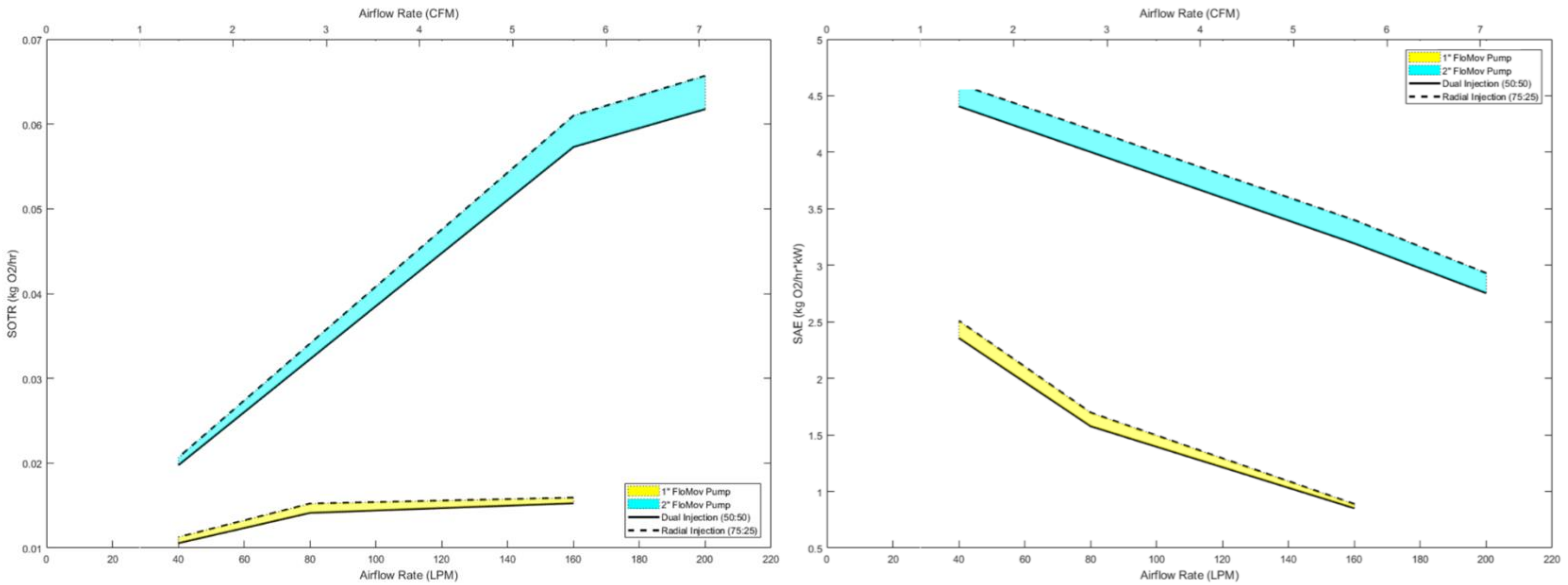


Figure 21: Oxygen mass transfer data representation for FloMov pump sizes of 1" and 2"

Conclusions

In this research, five FloMov airlift pumps were tested for their aeration capabilities under different airflow rates, injection modes, submergence ratios and pump diameters. It was found that larger airlift pump diameters and airflow rates will result in greater SOTR values. Such information could be beneficial for aqua culturists for planning system designs and fish biomass capacities. It was clear from the study that increasing submergence was necessary for obtaining optimum SOTR values, however, this may not always be feasible for production systems that require high performance or efficiency as well. Therefore, aquaculture systems will need to consider their design requirements and constraints, when choosing how to apply these dual-injection airlifts for oxygenation. Ideally, to obtain the greatest SOTR, the systems should use larger diameter pumps with high submergences and high airflows. Depending on their water flow requirements, they can also adjust to obtain higher radial airflow for increased oxygenation. However, in situations where the airlift is required to provide a high lift or will receive low airflow rates, smaller diameter airlifts will be more suited for oxygenation.

Aside from recirculation and oxygenation, future experiments should also focus on carbon dioxide stripping given that it is equally required in aquaculture systems. Build up of CO_2 in aquaculture typically results from the organisms within the system, mainly fish, but also bacterial populations [12]. Carbon dioxide in these systems can be a limiting factor for production and therefore it is important to keep levels maintained at the appropriate amounts [13]. There are currently no common accepted guidelines on safe levels of dissolved CO_2 within a system as sensitivity to CO_2 is species specific. However, a study by Colt [14] suggested that cold water fish have thresholds of 10-20 mg/L while warm water fish have thresholds of 20-40 mg/L. Given that airlift pumps can recirculate and deoxygenate in systems like these, they could also be used to strip CO_2 from the water. Studies such as Loyless and Malone [11] studied airlifts for this application and Moran [15] continued this work in 2010. However, there is still little research available on an airlift pump's efficiency in CO_2 stripping. Testing CO_2 stripping capabilities of FloMov pumps is presented in a separate report.

References

[1] G. L. Rogers, "Aeration and circulation for effective aquaculture pond management," *Aquac. Eng.*, vol. 8, no. 5, pp. 349–355, 1989, doi: 10.1016/0144-8609(89)90041-1.

[2] J. Szeliga, "Testing and modelling the oxygenation potential of a novel dual-injection airlift pump for aquaculture applications," The University of Guelph, 2018.

[3] N. C. Parker and M. A. Suttle, "Design of airlift pumps for water circulation and aeration in aquaculture," *Aquac. Eng.*, vol. 6, no. 2, pp. 97–110, 1987, doi: 10.1016/0144-8609(87)90008-2.

[4] A. Kumar, S. Moulick, and B. C. Mal, "Performance evaluation of propeller-aspirator-pump aerator," *Aquac. Eng.*, vol. 42, no. 2, pp. 70–74, 2010, doi: 10.1016/j.aquaeng.2009.12.001.

[5] D. J. Reinemann and M. B. Timmons, "Prediction of oxygen transfer and total dissolved gas pressure in airlift pumping," *Aquac. Eng.*, vol. 8, no. 1, pp. 29–46, 1989, doi: 10.1016/0144-8609(89)90019-8.

[6] W. H. Ahmed and H. M. Badr, "Dual-injection airlift pumps: An enhanced performance," *Part. Sci. Technol.*, vol. 30, no. 6, pp. 497–516, 2012, doi: 10.1080/02726351.2011.604396.

[7] "EZO-DO: Embedded Dissolved Oxygen Circuit," *Atlas Scientific LLC*, 2020. https://atlas-scientific.com/files/DO_EZO_Datasheet.pdf.

[8] "Dissolved Oxygen Probe," *Atlas Scientific LLC*, 2019. https://atlas-scientific.com/files/l-do-probe.pdf.

[9] "Handy Polaris 2: Portable Dissolved Oxygen Monitor with Datalogger," *partech*. https://www.partech.co.uk/product/handy-polaris-2-portable-dissolved-oxygen-monitor/.

[10] "Maximum dissolved oxygen concentration saturation table," *Lake Stewards of Maine - Maine Volunteer Lake Monitoring Program*. https://lakestewardsofmaine.org/wp-content/uploads/2014/01/Maximum-Dissolved-Oxygen-Concentration-Saturation-Table.pdf.

[11] J. C. Loyless and R. F. Malone, "Evaluation of air-lift pump capabilities for water delivery, aeration, and degasification for application to recirculating aquaculture systems," *Aquac. Eng.*,

vol. 18, no. 2, pp. 117–133, 1998, doi: 10.1016/s0144-8609(98)00025-9.

[12] P. V. Skov, "CO2 in aquaculture," *Fish Physiol.*, vol. 37, pp. 287–321, 2019, doi: 10.1016/bs.fp.2019.07.004.

[13] T. J. Pfeiffer, S. T. Summerfelt, and B. J. Watten, "Comparative performance of CO2 measuring methods: Marine aquaculture recirculation system application," *Aquac. Eng.*, vol. 44, no. 1, pp. 1–9, 2011, doi: 10.1016/j.aquaeng.2010.10.001.

[14] J. Colt, "Aquacultural production systems.," *J. Anim. Sci.*, vol. 69, no. 10, pp. 4183–4192, 1991, doi: 10.2527/1991.69104183x.

[15] D. Moran, "Carbon dioxide degassing in fresh and saline water. II: Degassing performance of an air-lift," *Aquac. Eng.*, vol. 43, no. 3, pp. 120–127, 2010, doi: 10.1016/j.aquaeng.2010.09.001.