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VALIDATION AND VERIFICATION FIELD TRIALS OF AIR DIFFUSER SYSTEMS FOR UPWELLING APPLICATIONS

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ABSTRACT

As a consequence of climate change, the ocean surface temperature is rising. Warmer water has low dissolved oxygen, which can adversely affect the health of fish and their survival rates in aquaculture operations. Upwelling is a process in which deeper, colder water is lifted to the surface providing thermal mixing and circulation of oxygen-rich water. This paper discusses the design and execution of field trials to validate the performance of CanadianPond air diffuser upwelling systems for use in the aquaculture industry. Field trials were carried out at The Launch, an ocean innovation hub owned by the Marine Institute, in Holyrood Bay, NL, Canada. The upwelling systems were deployed at 20 m water depth and tested with 10 to 100 Standard Cubic Feet per Minute (SCFM) air flow rates. An electromagnetic current meter was used to measure the vertical and horizontal velocities generated by the upwelling systems at various locations underwater. Water depth-temperature profiles and dissolved oxygen levels were also measured prior to and during the trials. A Computational Fluid Dynamics (CFD) model was developed in parallel to assess the upwelling performance in different conditions and scales. The study concluded that localized upwelling was possible using the air diffusers tested, with effectiveness varying based on the applied air flow rate.

Keywords: Aquaculture, upwelling, air diffuser, field trial

1. INTRODUCTION

Climate change and associated surface water temperature change can be a significant challenge for the marine aquaculture industry worldwide. The success of marine aquaculture depends heavily on maintaining favorable conditions for fish health, including temperature, dissolved oxygen, pH and nutrient levels in the water. During summer months, the increase in surface water temperature may cause metabolic distress and asphyxia, resulting in mass mortality of fish. In this work, upwelling using air bubbles is tested as a means of controlling water temperature and thus creating a more favorable microenvironment within the cage. Upwelling is a process in which deeper, colder water is lifted to the surface providing thermal mixing and circulation of oxygen-rich water. An illustration of an upwelling system installed in a typical aquaculture cage is shown in Figure 1.

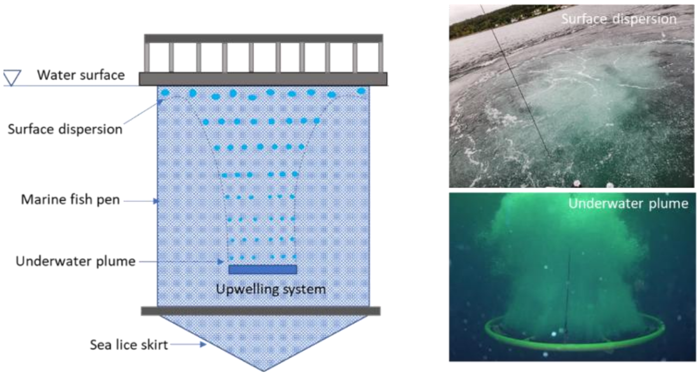


FIGURE 1: UPWELLING SYSTEM IN OPERATION

SalmoAir® and OctoAir-60, developed by CanadianPond are two commercial solutions to induce upwelling of a large volume of water to improve seawater quality within cage for creating optimum conditions for fish growth. The upwelling system consists of a diffuser ring, which is capable of generating upwelling and movement of water to the surface (Figure 2).

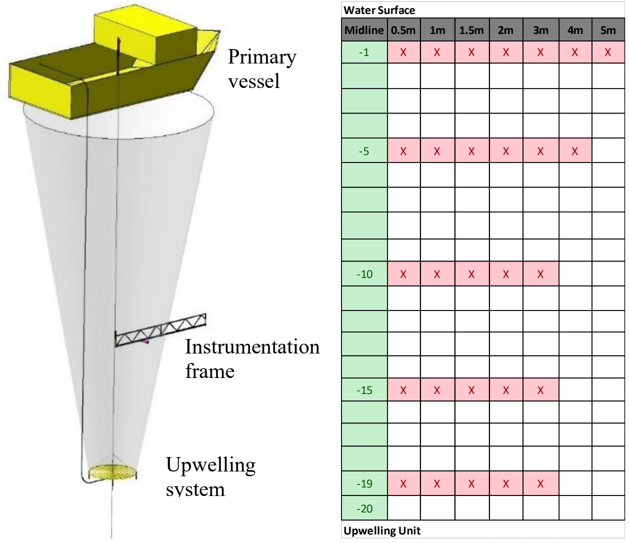
FIGURE 2: CANADIANPOND UPWELLING SYSTEMS (SALMOAIR® (LEFT) AND OCTOAIR-60 (RIGHT))

2. BACKGROUND

Summer mortality of caged fish is a major problem that affects production at commercial farms [1]. The water column thermal stratification in summer may be caused by coastal warming, wind, current, and wave actions [2]. As long as the surface water is in motion, it reduces still water conditions within the cage. However, in between tidal cycles and low-wind, there is a potential for still water condition within cages for an extended period of time. This warm water at surface would have low dissolved oxygen, causing stress and asphyxia in fish. Also, fish may try to swim down towards the lower thermoclines to secure more favorable health conditions. This clustering could potentially increase the chances for asphyxia or stress related issues to fish. When replenished with bottom cold water by the upwelling system the dissolved oxygen levels increase. However, it was clear that the technology should be the subject of future research with an assessment of different air flow rates and designs related to each geographic site of interest and targeted species as a countermeasure for global warming and rising surface water temperature [1]. Artificial upwelling elevates nutrient rich bottom water to surface, which promotes food sources for fisheries and aquaculture [3].

3. METHODOLOGY

The tests were completed at The Launch facility, an ocean innovation hub owned by the Marine Institute, in Holyrood Bay, NL, Canada. C-CORE contracted a 35 ft vessel (see primary vessel in Figure 3) with sufficient deck space to conduct the field trial. The vessel was anchored in-place where water depth was greater than 30 m (~100 ft) for the duration of the 2-week field trial program and a fast rescue craft (FRC) was used to commute people and light equipment to and from the primary vessel. The primary vessel was equipped with a crane that was used to deploy the diffuser over the side of the vessel and lower it to a depth of 20 m. A 6 m long instrumentation frame was designed and fabricated, and was used to lower and raise sensors to various depths and distances from the center of the plume. The primary measurements included the vertical and horizontal water velocity and temperature as a function of depth and horizontal distance from the center of the plume (see schematic of sampling locations in Figure 3, right). The Dissolved Oxygen (DO) level and water temperature were measured using a DO sensor, and a temperature data logger, respectively. During testing, the instrumentation frame was lowered to depths 1, 5, 10, 15 and 19 m below surface for a duration of 5 minutes at each location to measure the velocities and temperature at these depths. Once a vertical drop was completed at the center of the plume, the sensor was moved horizontally at 0.5, 1, 1.5, 2, 3, 4 and 5 m increments away from the center of the plume to map the vertical and horizontal velocities generated by the diffusers as shown in Figure 3.



Water Surface

Midline	0.5m	1m	1.5m	2m	3m	4m	5m
-1	X	X	X	X	X	X	X
-5	X	X	X	X	X	X	
-10	X	X	X	X	X		
-15	X	X	X	X	X		
-19	X	X	X	X	X		
-20							

Upwelling Unit

FIGURE 3: TEST SCHEMATIC (LEFT) AND SAMPLING LOCATIONS (RIGHT)

In this study, the upwelling rate is defined as the volume of water uplifted by the air diffuser per unit time. The upwelling rates are estimated using the vertical velocity and area of plume at a certain water depth (e.g., 1, 5, 10, 15, 19 m below surface). That is, the vertical velocity for each horizontal distance measurement from center at a given depth, and the annulus area that corresponded to that velocity were combined in the calculations using the Equation 1 to 4. Thus, for each distance, the area of ring and velocity are calculated as follows:

$$A_i = \pi(R_{i+1} + R_i)(R_{i+1} - R_i), and\ A_{tot} = \sum (A_i) \tag{1}$$

$$V_i = \frac{(V_{i+1}+V_i)}{2}, and\ V_{tot} = \sum (V_i) \tag{2}$$

$$Q_i = A_i \times V_i, and\ Q_{tot} = \sum (Q_i) \tag{3}$$

$$\text{Also, } Q_{tot} = A_{tot} \times V_{tot} \tag{4}$$

where, $i = 0.5, 1, 1.5, 2, 3, 4, 5\ m$, horizontal distance from the plume center, Q_i is the vertical flow (i.e., upwelling) rate at the horizontal distance i, A_i is the area of annulus corresponding to V_i, V_i is the associated vertical velocity, Q_{tot} is the upwelling rate at each depth (i.e., 1, 5, 10, 15, 19 m below surface). To smooth the transition between measurements, a linear interpolation was carried out here between the vertical velocity values for each horizontal position. Once the vertical flow rates are estimated at each depth, these values are summed up to get an average upwelling rate for the diffuser, using Equation 5,

$$Q_{avg} = mean\ (Q_{tot}) \qquad (5)$$

where, Q_{avg} is the average upwelling rate, considering all depths (i.e., 1, 5, 10, 15 and 19 m) in m^3/s.

Computational Fluid Dynamics (CFD) was used to model the upwelling process in seawater using SalmoAir® and OctoAir-60 diffusers. The commercial CFD package STAR-CCM+, a Siemens product, was utilized to perform the simulations and post-process the results. The CFD model was initially used as a qualitative tool to optimize the planning and design of field trials, and later was validated against the measurements from the field trials. The validated model can then be used to model the use of the air diffusers in future field installations.

4. TEST PLANNING AND DESIGN

The Launch facility is equipped with a wharf, jib crane and a small marina as shown in Figure 4. The project team mobilized light equipment and sensors from the wharf to the anchored vessel on a daily basis using the FRC. The test site was located approximately 555 m from the wharf (coordinates 47° 23' 60" N, 53° 7' 53" W) at 30 m water depth.

FIGURE 4: THE LAUNCH FACILITY, WHARF AND CRANE

The vessel chosen for the field trial was the MV Dalton Redeemer (Figure 5, left), which is a 35 ft (10.7 m) open vessel. The deck space was sufficient for housing all test equipment including compressor, air diffuser and manifold. The Dalton Redeemer was equipped with a crane to deploy the air diffuser over the side of the vessel and lower it to a depth of 20 m. An FRC, shown in Figure 5 (right), was used to commute people and light equipment and sensors from the wharf to the anchored vessel. Its length was 20 ft (6.1 m) and has a rated capacity of 6 people.

FIGURE 5: DALTON REDEEMER (LEFT) AND FRC (RIGHT)

Two upwelling systems supplied by CanadianPond, known as SalmoAir® and OctoAir-60 were tested during the trials. SalmoAir® is designed specifically for aquaculture aeration, mixing and upwelling applications and features a smooth surface without sharp angles protecting salmon from scale damages, injuries and other accidents (Figure 6). The OctoAir-60 is a high-performance industrial diffuser designed for aeration, mixing, upwelling and deicing (Figure 7). In both these diffusers, Bubble Tubing® was arranged in spiral form, technical specifications of each diffuser are shown in Table 1.

FIGURE 6: SALMOAIR® READY FOR DEPLOYMENT

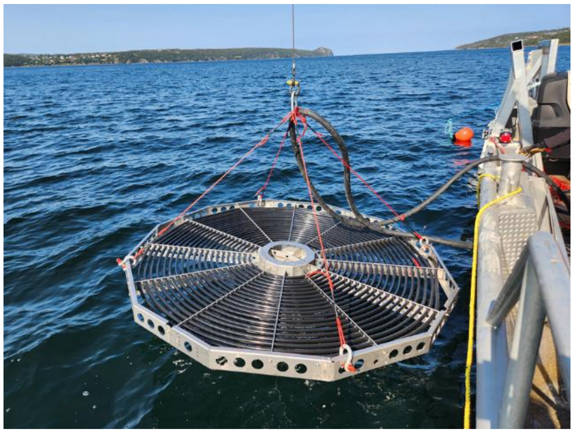


FIGURE 7: OCTOAIR-60 READY FOR DEPLOYMENT

TABLE 1: UPWELLING SYSTEM SPECIFICATIONS

Parameter	SalmoAir®	OctoAir-60
Tubing diameter in inch (mm)	¾ (21)	¾ (21)
Tubing length in ft (m)	100 (30)	300 (90)
Diffuser diameter in inch (m)	70 (1.78)	96 (2.44)
Weight in lbs (kg)	100 (45)	315 (143)
Frame material	Stainless steel	
Lifting bridle height in ft (m)	4.9 (1.5)	4.9 (1.5)

A Doosan C185 diesel powered compressor was used to supply air to the upwelling systems. Compressor specifications are given in Table 2, and a picture of compressor and manifold onboard Redeemer is shown in Figure 8. Two flow control valves, 4 pressure gauges and 2 air flow meters (one with 50 SCFM (Standard cubic feet per minute, 1.42 m³/min) and another with 250 SCFM (7.08 m³/min) capacity) were used to control and measure the inlet pressures and airflow rates.

TABLE 2: COMPRESSOR SPECIFICATIONS

Parameter	Specifications
Actual delivery in SCFM (m³/min)	185 (5.2)
Rated pressure (psig)	100
Pressure range (psig)	80 - 100
Weight, lbs (kg)	2,359 (1,070)
Length, in (m)	137.4 (3.490)
Width, in (m)	68.5 (1.740)
Height, in (m)	67.5 (1.715)
Fuel tank capacity (L) and run time	130.6 at 12.6 hours

FIGURE 8: COMPRESSOR (LEFT) AND MANIFOLD (RIGHT)

The following three sensors were used during the trial: electromagnetic current meter (ECM), temperature and depth data logger, and DO sensor. For measuring the vertical and horizontal velocities generated by the upwelling systems, a MIDAS ECM (having an accuracy of +/- (1% of reading + 0.005 m/s and a resolution of 0.001 m/s) from Valeport (Figure 9), was attached to instrumentation frame and deployed.

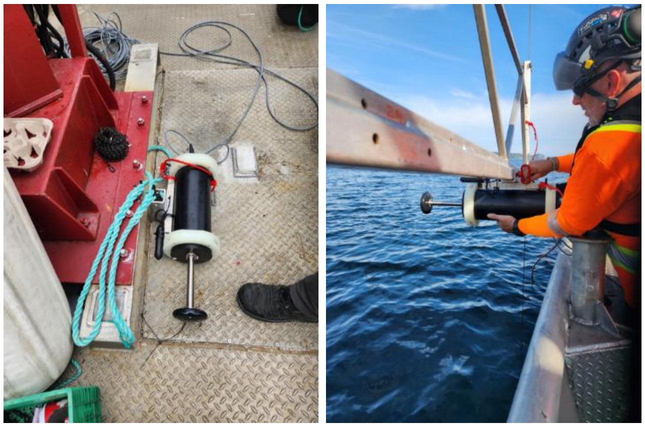


FIGURE 9: ECM SENSOR (LEFT) AND ON FRAME (RIGHT)

For measuring temperature across depth, the HOBO U20L-02 Logger (with an accuracy of +/- 0.44°C from 0 to 50°C, see Figure 10) from Hoskin Scientific was deployed. The temperature measurement would help provide thermocline information for the effective location of air diffusers.

FIGURE 10: WATER LEVEL AND TEMPERATURE LOGGER

For measuring DO levels within and outside the air plume, a Polaris C Oximeter from Oxyguard (with an accuracy +/- 1%) was deployed (Figure 11). The amount of DO is a good indicator of water quality.

FIGURE 11: DISSOLVED OXYGEN SENSOR

An instrumentation frame (Figure 12) was designed and fabricated to mount the ECM and temperature sensors and lower in a grid pattern within and outside the plume. The frame was 6 m long and was attached to the crane cable through two pulleys.

FIGURE 12: INSTRUMENTATION FRAME

The following test parameters were varied during testing.

- Airflow rate through the diffuser as per Table 3
- Water depth: 1, 5, 10, 15, and 19 m below surface
- Horizontal distance: 0.5, 1, 1.5, 2, 3, 4, and 5 m

TABLE 3: AIR FLOW RATE VARIATIONS

CanadianPond upwelling systems	Air flow rate in SCFM (m^3/min)		
	Low	Medium	High
SalmoAir®	10 (0.28)	20 (0.57)	30 (0.85)
OctoAir-60	30 (0.85)	60 (1.70)	100 (2.83)

5. TRIAL PROCEDURE

Shakedown tests were conducted initially to ensure that the required water depth, temperature profile and airflow rates are achievable, as well as, to ensure that all sensors are working and acquiring the targeted data as designed. The following step-wise procedure was followed during testing:

- Connected the air diffuser to manifold and tested that it was functional on the deck of the vessel. Made sure that there were no air leaks from connections.
- Air diffuser was lifted off deck using the onboard crane and lowered to position (i.e., 20 m below water surface) using the vessel crane.
- The ECM and temperature data logger was attached to the instrumentation frame at desired locations and secured ECM data cable to avoid snagging. Go pro camera was attached to the frame facing the ECM.
- Instrumentation frame was attached to the crane cable at one end through a pulley and lowered to position manually using two ropes attached at either ends.
- Instrumentation frame was deployed over the side of the vessel by hand with two field personnel and lowered to the required depth using two ropes (one on either end). Markers were added to the rope at 1 m, 5 m, 10 m, 15 m and 19 m to provide indication for how much each line should be paid out as the instrumentation arm is lowered. Ropes were tied off to vessel rail to keep its position when instrumentation arm reached required depth. That was the beginning of a test.
- Collected required data (i.e., vertical and horizontal currents and temperature) at defined water depths. The frame was kept at least 5 minutes at each location to obtain the stabilized current and temperature data.
- After data collection, recovered the frame to the deck using attached ropes. Repositioned the sensors to cover the horizontal distances (i.e., 0.5 m, 1 m, 1.5 m, 2 m, 3 m, 4 m and 5 m) and repeated the tests lowering the instrumentation frame to the required depths.
- Once the test was over, the diffuser was brought aboard the vessel using crane.
- The DO sensor was lowered to 2 m depth keeping the monitor in hand, before testing to monitor the baseline, and during testing to monitor the DO level changes. The DO levels were measured at the plume center, as well as at 3 m and 6 m away from the plume center.

6. COMPUTATIONAL FLUID DYNAMICS MODELING

A CFD model was developed to quantify the upwelling process in seawater using SalmoAir® and OctoAir-60 diffusers. The physical process of interest was lifting the colder (and denser) water from underneath the thermocline towards the water surface due to the upward flow induced by the rising air bubbles. The multi-phase (water and air) fluid flow dynamics were captured by solving the governing equations (Reynolds Averaged Navier-Stokes) for a three-dimensional meshed representation of a defined volume of water body around the air diffuser. A mesh sensitivity study was completed at first to ensure that the results were independent of the mesh size and distribution. The multiphase mixture model was then utilized to simulate the flow pattern and thermal field. The mixture model accounts for the average performance of the flow system, and captures the turbulent flow behavior.

The CFD set up is shown in Figure 13. The current direction is from left to right. The computational domain covers a 60 m by 60 m area of water and has a 30 m depth. The diffuser is placed at the depth of 20 m and is located towards the inflow (left) in order to allow for complete capturing of the plume behavior when there is a strong current tilting the plume. The diffuser is modeled as a cylinder with the same dimensions as SalmoAir® or OctoAir-60. The upper and lower sides of the cylinder is interfaced with the domain so water can transfer from one to another. A mass source term is defined in the diffuser (cylinder) area to introduce the air phase in the model. The air bubbles then start rising due to their small densities, and transfer their upward momentum to water, leading water towards the surface. Also, the density of air-water mixture is low due to the presence of large volume of low-density air bubbles and hence the cold-water particles tend to move upward due to buoyancy force acting upon them.

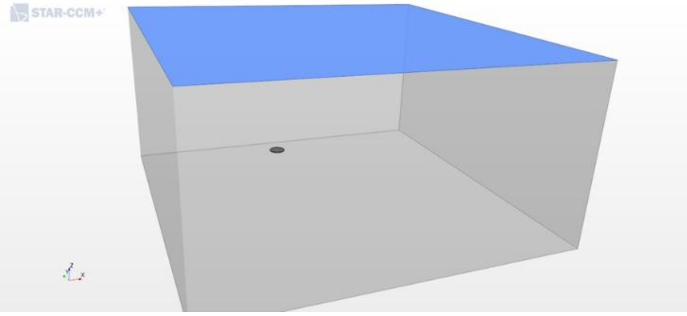


FIGURE 13: COMPUTATIONAL DOMAIN USED FOR CFD

The results such as vertical component of water velocity and temperature were monitored over several areas such as various depths within the plume (e.g., 1, 5, 10, 15 and 19 m below surface), as well as vertical lines starting from the plume center at 0, 0.5, 1, 1.5, 2, 3, 4, and 5 m horizontal distances from the plume center. These areas are shown in Figure 14. Table 4 presents the fluid properties used in the CFD models.

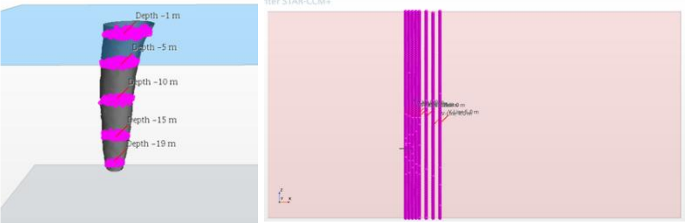


FIGURE 14: DATA MONITORING LOCATIONS

TABLE 4: FLUID PROPERTIES

Type of fluid	Fluid density (kg/m^3)	Dynamic viscosity (Pa.s)	Specific heat (J/kg.K)	Thermal conductivity (W/m.k)
Water	See below	141 e^{-5}	4003.0	0.600
Air	1.216	1.785 e^{-5}	1003.6	0.026

The water density was set at a constant value of 1026 kg/m^3 in the hydrodynamics only models. The following polynomial function was programmed in the model for the models with heat transfer included (see Equation 6). This polynomial function was derived from a more extended function presented by Lewis and Perkin (1981), which includes dependency on temperature and salinity. From field trials, the salinity of water was confirmed to be around 0.035 kg/kg and stayed relatively constant throughout the trials.

$$\rho_{water} = (-5 \times 10^{-8})T^4 + (2 \times 10^{-5})T^3 + (-5.6 \times 10^{-3})T^2 + (-4.97 \times 10^{-2})T + 1028 \qquad (6)$$

7. RESULTS AND DISCUSSION

Prior to testing each diffuser, the following baseline parameters were measured and recorded:

- Temperature profile across water depth; and
- Baseline dissolved oxygen level in water.

Once the installation and shakedown tests were completed, the test parameters were varied by lowering the instrumentation frame to the desired test location. During each test, the following test parameters were pre-set:

- Airflow rate through the air diffuser;
- ECM and temperature sensor depth; and
- Horizontal distance from the plume center.

During testing, the following data were recorded:

- Vertical and horizontal velocities;
- Temperature at each test location;
- DO within the plume (i.e., 0 m and 3 m from center) and outside the plume (i.e., at 6 m from center); and
- Test pictures and videos.

7.1 Vertical Velocity

As a sample case, the average vertical velocities measured with SalmoAir® and OctoAir-60 at 30 and 100 CFMs are shown in Table 5 and 6, respectively. It can be seen that the vertical velocity increases as the bubbles rise to surface and the peak is observed to be at 5 m below surface (0.43 m/s for SalmoAir® and 0.62 m/s for OctoAir-60), after which the velocity begins to slow as the energy is converted to horizontal velocity near the surface. Also, it is worth noting that the velocity decreases as the sensor moves horizontally away from the plume center.

TABLE 5: VERTICAL VELOCITY BY SALMOAIR®

Average velocity (m/s) generated by SalmoAir® at 30 CFM							
Depth	0m	0.5m	1m	1.5m	2m	3m	4m
-1 m	0.35	0.27	0.20	0.17	0.27	0.19	0.08
-5 m	0.43	0.36	0.27	0.16	0.15	0.13	0.10
-10 m	0.40	0.36	0.25	0.19	0.13	0.10	
-15 m	0.40	0.35	0.16	0.16	0.06	0.06	
-19 m	0.27	0.13	0.05	0.08	0.07	0.05	

TABLE 6: VERTICAL VELOCITY BY OCTOAIR-60

Average velocity (m/s) generated by OctoAir-60 at 100 CFM								
Depth	0m	0.5m	1m	1.5m	2m	3m	4m	5m
-1 m	0.43	0.44	0.43	0.35	0.32	0.26	0.14	0.08
-5 m	0.62	0.60	0.53	0.44	0.35	0.23	0.11	0.05
-10 m	0.62	0.58	0.46	0.28	0.17	0.08		
-15 m	0.62	0.52	0.19	0.05	0.03	0.04		
-19 m	0.40	0.22	0.03	0.03	0.03	0.04		

7.2 Vertical Velocity vs. Air Flow Rate

The vertical velocity vs. air flow rate comparison plot for SalmoAir® is presented in Figure 15. This is a sample plot and is developed by using the measured vertical velocities at the plume center. Similar plots for 0.5 m, 1.0 m, 1.5 m and 2 m horizontal distances from plume center can be plotted as well. From this plot, it is evident that the higher air flow rates produced better vertical velocity, with 30 CFM being the highest. That is, a moderate air flow rate of 30 CFM or 0.3 CFM/ft (i.e., 30 CFM over 100 ft tubing) is an efficient option for maximizing vertical flow.

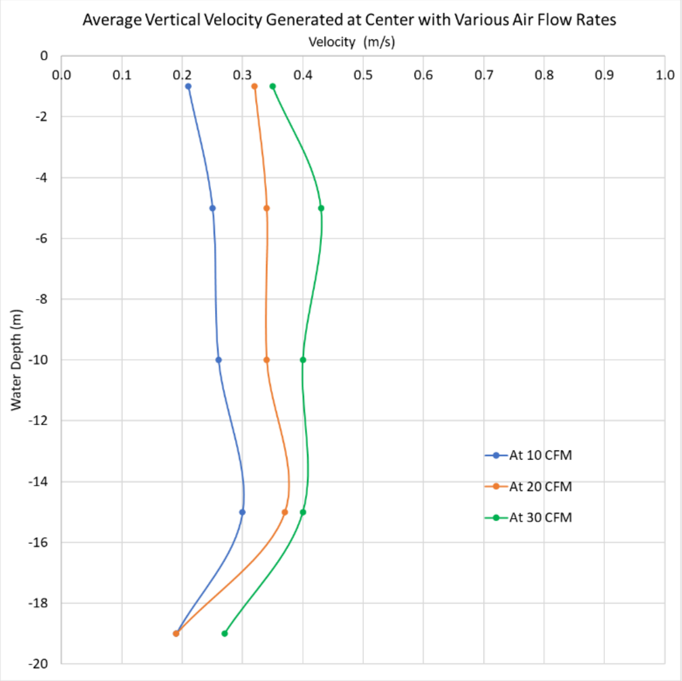


FIGURE 15: VERTICAL VELOCITY CURVES BY SALMOAIR®

A sample plot of vertical velocity at the plume center for OctoAir-60 with various air flow rates is presented in Figure 16. Similar to SalmoAir®, higher air flow rates produced better vertical velocities for this diffuser as well.

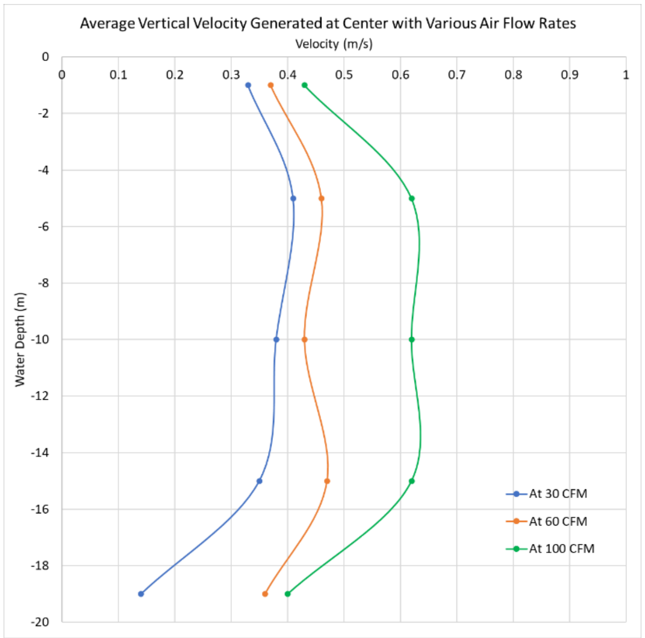


FIGURE 16: VERTICAL VELOCITY CURVES BY OCTOAIR-60

7.3 Vertical Velocity as Function of Horizontal Distance

SalmoAir® results at 30 CFM are plotted as a function of horizontal distance from the plume center in Figure 17. It is evident from this figure that the highest velocity is observed at the plume center and the velocity decreased as the sensor moved horizontally away from the plume center.

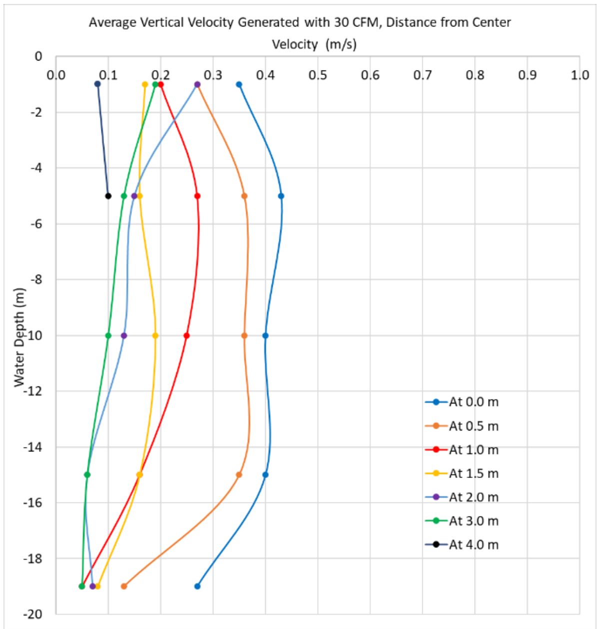


FIGURE 17: VERTICAL VELOCITY CURVES BY SALMOAIR®

As a sample, the OctoAir-60 test results at 100 CFM are plotted as a function of horizontal distance from the plume center in Figure 18. It is evident from this figure that the highest velocity is observed at the plume center. Also, the measured velocity was found to decrease as the sensor moved away from the center towards outer edge of the plume.

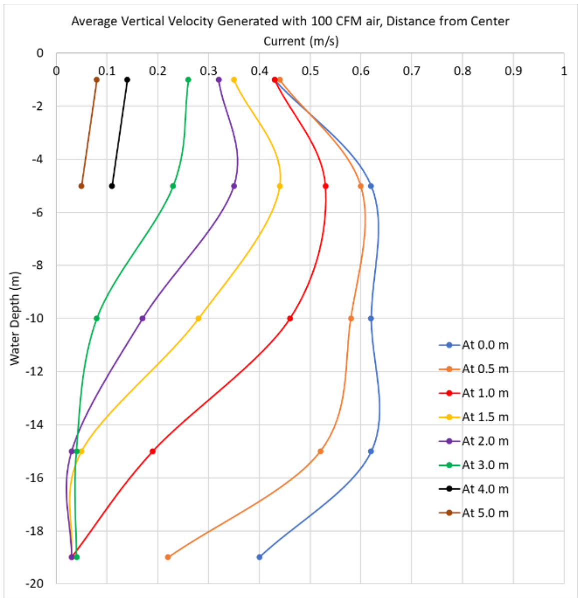


FIGURE 18: VERTICAL VELOCITY CURVES BY OCTOAIR-60

7.4 Horizontal Velocity

The average horizontal velocity comparison at plume center and 3 m distance for SalmoAir® is shown in Figure 19. A similar result was observed for OctoAir-60 as well. At the plume center, the measured horizontal velocity was less than 0.1 m/s for both SalmoAir® and OctoAir-60. At 3 m horizontal distance, the measured horizontal velocity has increased slightly to 0.19 m/s.

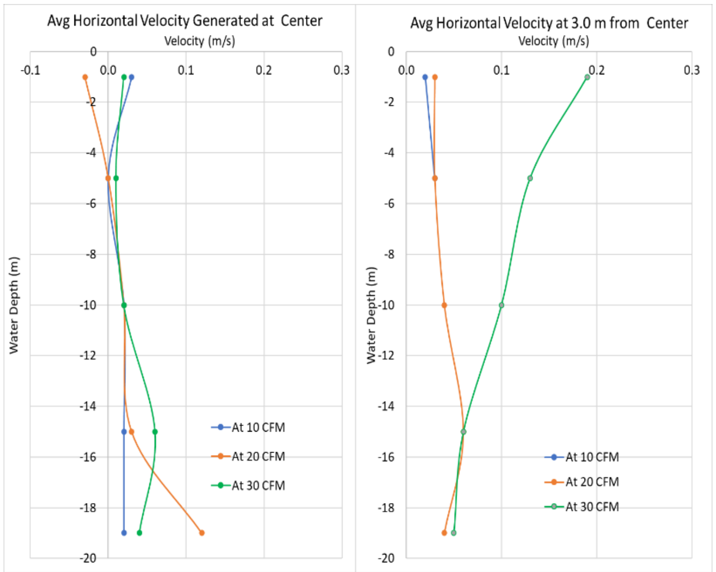


FIGURE 19: HORIZONTAL VELOCITY DATA BY SALMOAIR®

At all other tested locations, the horizontal velocity was observed to be insignificant (i.e., less than 0.1 m/s). The data collection was limited to a depth of 1 m below surface. Actual surface velocity would likely be higher than that measured at 1 m depth.

7.5 Upwelling Rates

The estimated upwelling rates at measured depths for SalmoAir® at 30 CFM are shown in Figure 20 as a sample case. From this figure, it is evident that the vertical flow rate is increasing as the plume rises towards the surface as the plume diameter increases. The ambient noise in the vertical velocities (i.e., <0.05 m/s) is excluded from these calculations.

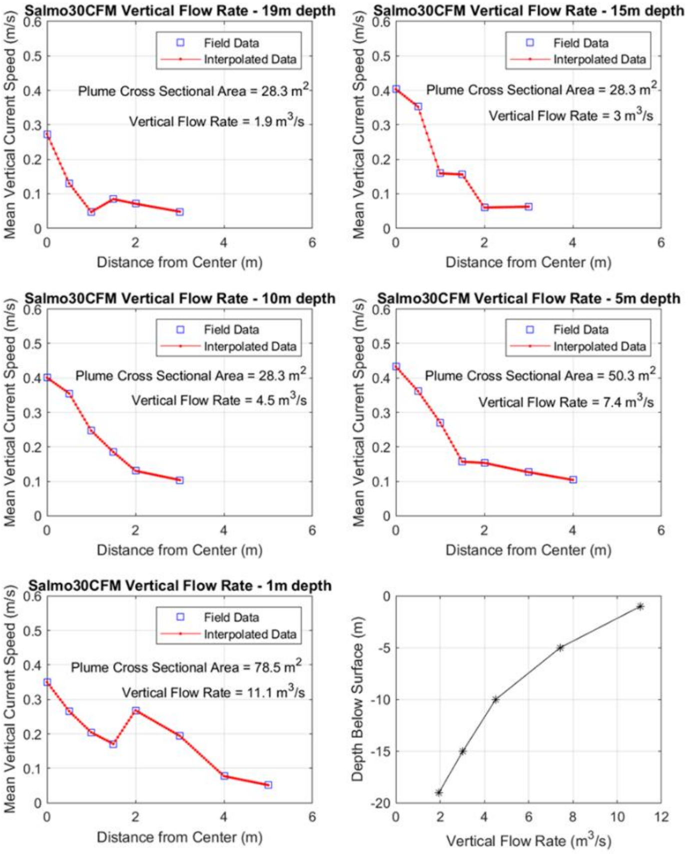


FIGURE 20: UPWELLING RATE FOR SALMOAIR® AT 30 CFM

7.6 SalmoAir® vs. OctoAir-60 Comparison

Estimated average upwelling rates of SalmoAir® and OctoAir-60 are compared in Table 7 and illustrated graphically in Figure 21 for SalmoAir® and Figure 22 for OctoAir-60. From this Table, it is evident that the 30 CFM air flow rate provides highest upwelling rate for SalmoAir® and 100 CFM air flow rate provides the highest upwelling rate for OctoAir-60.

It is observed that the upwelling rate increases with increasing air flow rates at the tested air flow rates for SalmoAir® and OctoAir-60. Also, it is better to use two SalmoAir® at 30 CFM instead of one OctoAir-60 at 60 CFM to achieve high upwelling rates. This level of upwelling rate (i.e., greater than 20,000 m^3/h) means the exchange of a large volume of water from the bottom to surface to break the still water conditions within fish cage during summer.

TABLE 7: UPWELLING RATE COMPARISON

Water depth (m)		SalmoAir® rate (m^3/s) at			OctoAir-60 rate (m^3/s) at		
		10 CFM	20 CFM	30 CFM	30 CFM	60 CFM	100 CFM
-1		1.36	3.95	11.05	5.02	12.43	19.38
-5		1.64	3.57	7.43	2.26	10.98	16.12
-10		1.43	4.97	4.51	1.94	7.93	6.25
-15		0.77	3.22	3.03	0.63	4.77	1.66
-19		0.35	0.35	1.95	0.16	2.85	0.48
Mean	m^3/s	1.11	3.21	5.60	2.00	7.80	8.80
	m^3/h	4,001	11,560	20,138	7,214	28,051	31,593

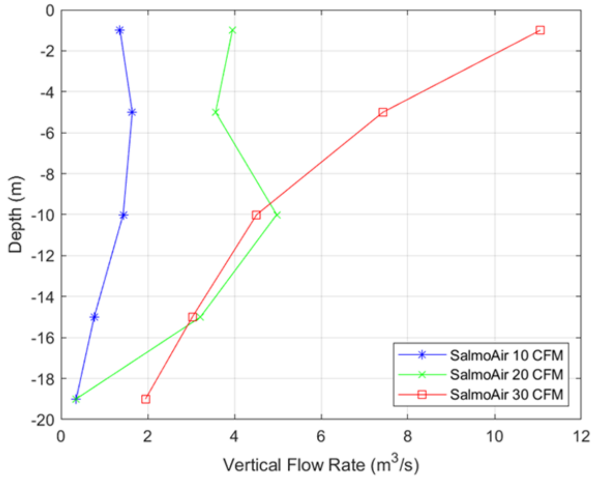


FIGURE 21: UPWELLING RATE FOR SALMOAIR®

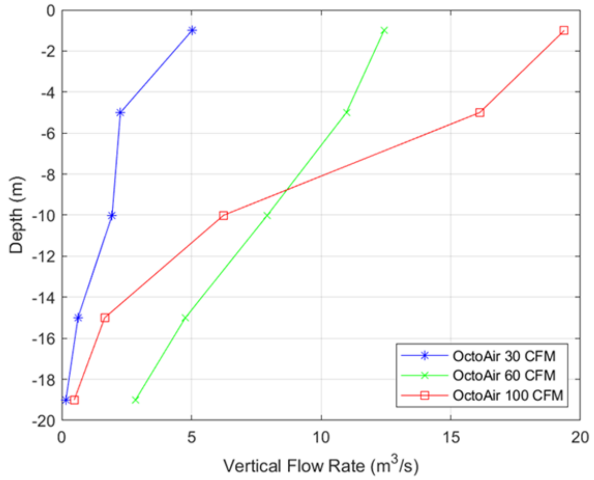


FIGURE 22: UPWELLING RATE FOR OCTOAIR-60

7.7 Temperature

To ensure that the temperature data logger is stabilized during measurement (i.e., keeping 5 minutes at each test location) a temperature stability analysis was carried out. Sample result of the analysis for SalmoAir® at 10 CFM test case with sensor located at 19 m depth and at 0.5 m horizontal distance from the plume center is shown in Figure 23. Given that the temperature vs time plot is fairly flat (especially at the end of the 5 minutes period), it is evident that 5 minutes is sufficient time for the sensor to obtain the stabilized temperature data.

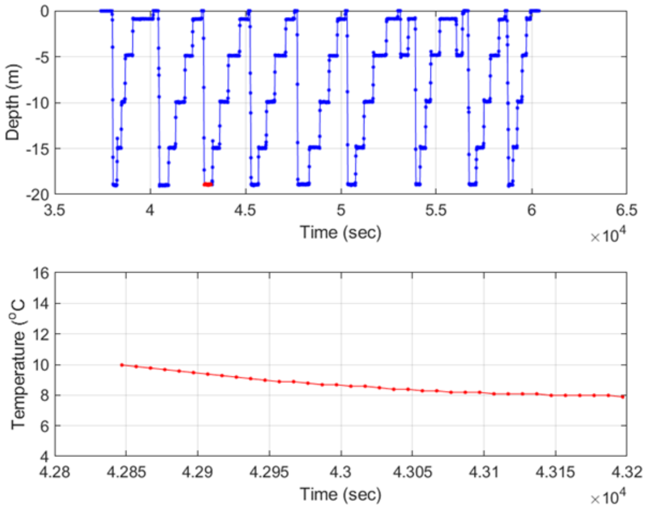


FIGURE 23: TEMPERATURE DATA STABILITY CHECK

The baseline temperature – depth profile (i.e., prior to turning on upwelling systems) measured on September 18th (before SalmoAir® test) is shown in Figure 24. The temperature sensor is kept approximately 3 minutes at 1 m depth interval during the September 18th drop to 30 m water depth. The near bottom temperature was 2-3°C, whereas at the diffuser location (20 m depth) the measured temperature was 7°C, 16°C at 5 m and 21°C at 1 m below surface, which means that the ocean water is well stratified and the water gets colder as the sensor goes deeper. The upwelling can thus be well quantified by measuring the thermal profile across depth during testing.

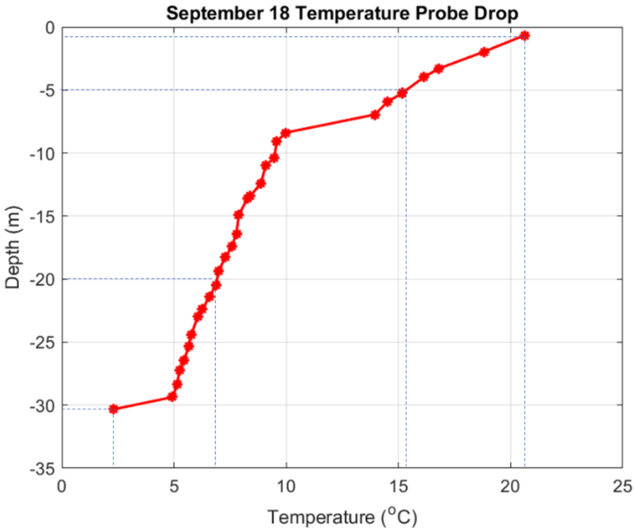


FIGURE 24: BASELINE TEMP-DEPTH PROFILE

During testing, the temperature sensor was attached to the ECM, so that the location specific temperature was measured and quantified. Figure 25 presents a sample temperature measured during SalmoAir® test with 30 CFM air flow rate along with the baseline temperature measured on September 18 (i.e., dotted line). In this plot, the sensor horizontal distance variation from 0 to 3 m is illustrated. If no upwelling system in operation, the baseline profile will be preserved with distinct thermoclines. With the introduction of upwelling by air diffuser, the thermoclines get disrupted as the plume tends to mix the water particles during its upward journey from 20 m to surface modifying temperature differentials.

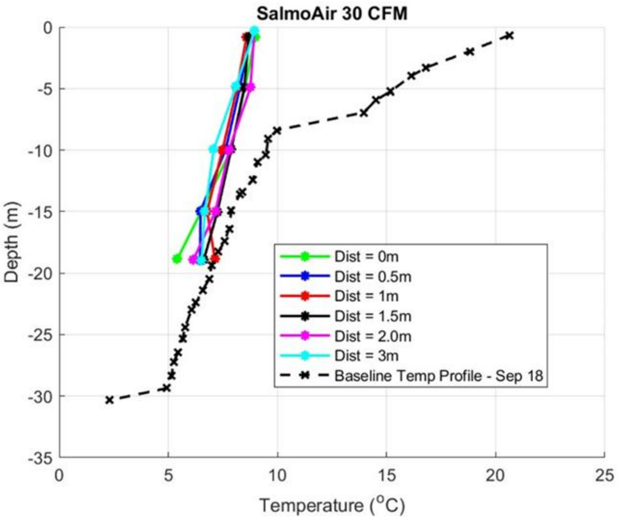


FIGURE 25: SALMOAIR® TEST RESULT AT 30 CFM AIR

7.8 Dissolved Oxygen

The average DO measured using 10, 20 and 30 CFMs are shown in Figure 26 for SalmoAir®. It was observed that the DO level increased at the plume center and it was found to decrease as the sensor moved away horizontally from the center to 3 m and 6 m away. This may be due to upwelling of deeper, colder water to surface, and mixing with surface warm water as it moves away from the plume center. Cold water has higher DO levels. Similarly, the temperature decreased at the plume center and increased as the sensor moved away from the plume center towards the edge (Figure 27). This also indicates that the cold-water upwelling is happening due to air diffuser operation, resulting in reduced temperature within the plume.

It is interesting to note that the DO level increased to highest level (i.e., 13.3 mg/L) with 20 CFM air flow rate while testing SalmoAir®, and correspondingly the lowest temperature (i.e., 9.1°C) was observed at 20 CFM air. The minimal increase in the measured DO levels due to tested ranges of air flow rates (i.e., 10, 20 and 30 CFMs) indicates that the increase in DO levels may be predominantly due to the cold water (having higher DO levels) upwelling rather than diffuser-induced aeration.

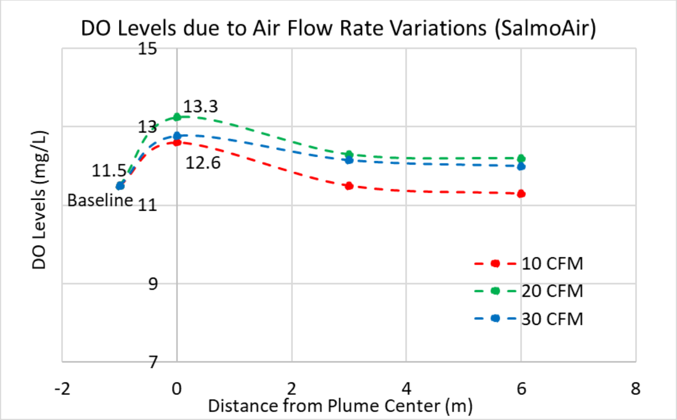


FIGURE 26: SALMOAIR® DO WITH AIRFLOW RATES

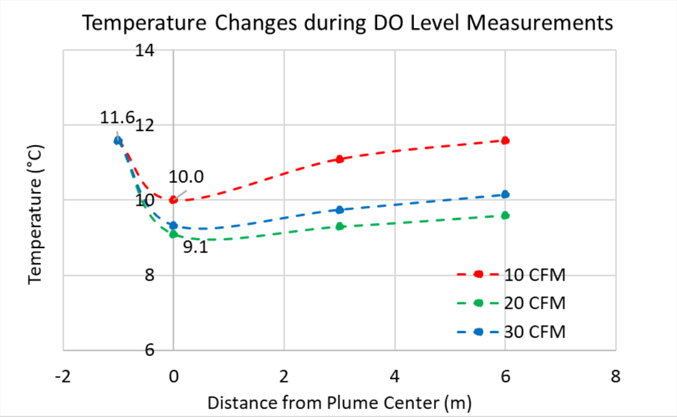


FIGURE 27: SALMOAIR® TEMP WITH AIRFLOW RATES

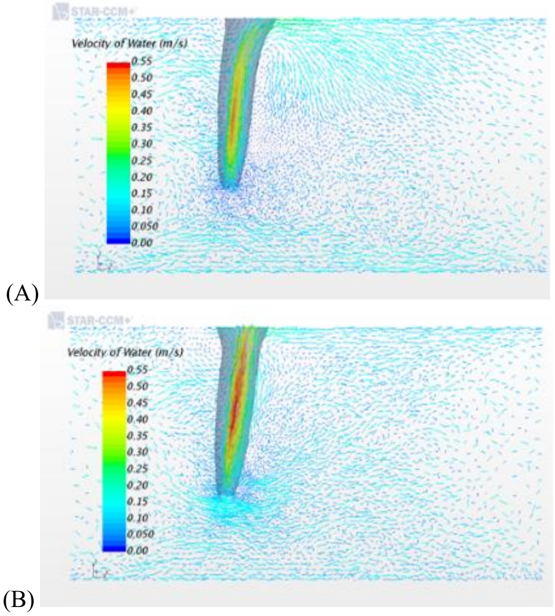
7.9 CFD Modeling

The initial simulations covered a range of test parameters such as the type of air diffuser (i.e., SalmoAir® and OctoAir-60), air flow rates from 7 to 100 CFM, and water current as a uniform profile from 0.01 to 0.075 m/s. In the postprocessing, several parameters were looked at including plume diameter and angle, as well as vertical velocities within the plume. Table 8 provides a summary of these models and the main simulation outcomes.

TABLE 8: MODEL CASES AND RESULTS SUMMARY

Air diffuser type	Air flow rate	Ocean current	Plume dia at surface	Plume dist frm center	Max vert vel
	(CFM)	(m/s)	(m)	(m)	(m/s)
SalmoAir®	7	0.075	3.6	2.0	0.40
SalmoAir®	14	0.075	6.5	2.0	0.55
SalmoAir®	21	0.075	8.0	2.0	0.65
OctoAir-60	20	0.075	7.4	2.5	0.60
OctoAir-60	60	0.010	11.5	0.0	1.00
OctoAir-60	100	0.075	13.5	2.5	1.20

The initial models were completed as a pure hydrodynamic model, and then the heat transfer was added to the model to provide an opportunity to directly compare the effects of thermocline and water density as a function of temperature on the velocity and temperature fields. Figure 28 compares the plume profile and water flow patterns of SalmoAir® at 14 CFM air flow rate and 0.075 m/s current with and without thermal effects. It was observed that the upwelled cold water has the tendency to sink back to the water column due to its heavier density than the warm water at the surface. The upwelling process is a relatively short process with the time magnitude of a few minutes which is not sufficient for the upwelled cold water to exchange thermal energy with the surface water and reach an equilibrium. The phenomenon of cold water sinking into the water column is expected to scale with the temperature difference between the water layers. Closer the temperatures, lower will be the density difference and the "cold" water should stay close to the surface for a longer period.



(A)

(B)

FIGURE 28: PLUME PROFILE AND WATER FLOW PATTERN WITH (A) AND WITHOUT (B) HEAT TRANSFER

Most of the field trial measurements were performed when the plume was fairly vertical, suggesting that the current was not significant such as during tide reversal process. As such, a small current of 0.01 m/s was applied to all the validation models. The baseline temperature profile measured on Sep. 18 (Figure 24). was applied as initial condition to all SalmoAir® validation cases.

The water temperature on the vertical lines (see Figure 14) and average vertical water velocity within the plume were compared to the field trial measurements. Figure 29 presents the velocity and temperature contours for a sample case (i.e., SalmoAir® at 30 CFM airflow rate). Figure 30 presents the comparisons of the average vertical velocity and temperature between CFD and field trials for the abovesaid test case. Overall good agreement was observed in the graphs suggesting the validity of the CFD modeling. The tested and validated CFD model can be used as a predictive tool in the future fish farm installation projects to optimize the design, equipment selection, diffuser arrangement, and energy conservation. For such applications, the model needs project specific data such as local currents including tidal effect, water depth, thermocline information, and water properties.

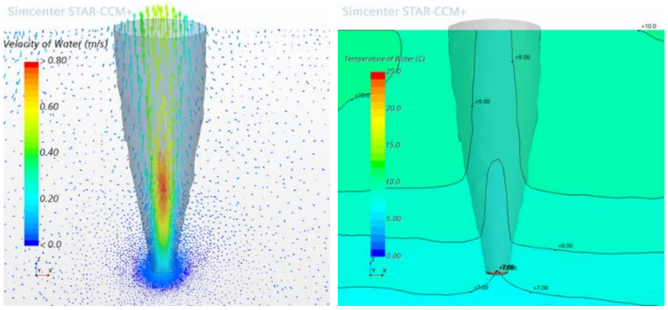


FIGURE 29: VELOCITY FIELD, TEMPERATURE CONTOURS

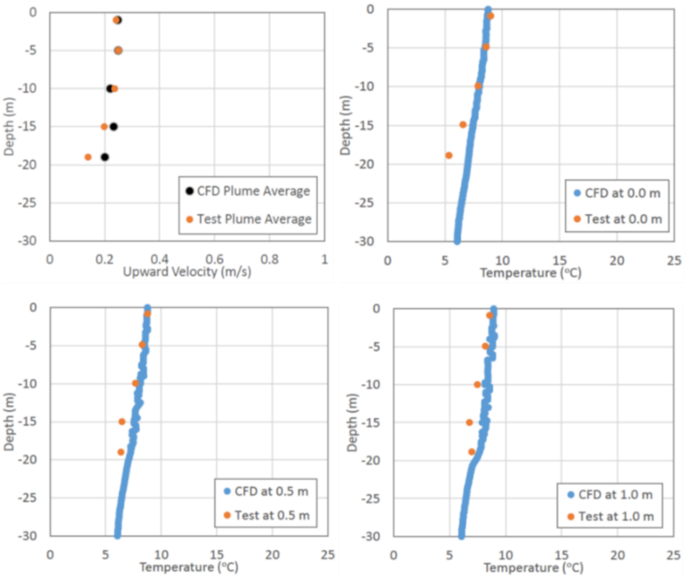


FIGURE 30: VERTICAL VELOCITY AND TEMPERATURE PROFILE COMPARISONS BETWEEN CFD AND FIELD TRIAL

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Through field trial and CFD modeling, this study estimated the performance of CanadianPond upwelling systems. Major conclusions from this study are presented below.

Upwelling Rate

- The upwelling rates are found to increase with air flow rates passing through the diffuser, i.e., 30 CFM air flow rate produced the highest upwelling rate for SalmoAir® (20,138 m^3/hr) and 100 CFM air produced the highest upwelling rate for OctoAir-60 (31,593 m^3/hr).
- While comparing the performance of diffusers at the same air flow rate (for e.g., at 30 CFM), the performance of SalmoAir® (20,138 m^3/hr) was much better than that of the OctoAir-60 (7,214 m^3/hr).
- Depending on the site conditions and cage size, this study provides a basis for selecting the number and type of diffusers required for adequate upwelling in the cage.

Vertical Velocity

- The cold water appears to be lifted to the surface by the following two processes:
    - Kinetic energy - the exiting air bubbles cause an upward momentum by imparting kinetic energy to the surrounding water particles; and
    - Density change - the presence of air bubbles in water reduces the density of air-water mixture, causing the buoyancy force overtaking gravity leading to an upward motion.
- The vertical velocity increases as the air bubbles move towards the surface, before slowing near surface as the energy is translated to horizontal velocity, with the peak vertical velocity being observed at 5 m below surface.
- The highest value of average vertical velocity measured was 0.43 m/s for SalmoAir® with 30 CFM air, and 0.62 m/s for OctoAir-60 with 100 CFM air flow rate.
- The highest vertical velocities were observed at the plume center. The vertical velocity decreased as the sensor moved horizontally away from the center.

Horizontal Velocity

- The measured horizontal velocity was insignificant (< 0.1 m/s) for both SalmoAir® and OctoAir-60 at the plume center. At 3 m horizontal distance, the measured horizontal velocity was increased to 0.19 m/s at a depth of 1 m below surface. The horizontal velocity measured was insignificant at depths measured below 1 m. Furthermore, the horizontal velocity close to surface (i.e., from mean sea level to 1 m below surface) was not measured, which is a limitation of the study.

Temperature

- Prior to starting tests, the ocean water was well stratified with 21°C at 1 m below, 16°C at 5 m below, 7°C at 20 m below (at diffuser location) and 2 - 3°C near seabed. During testing, the temperature 1 m below surface modified from 21°C initially to 7-9°C demonstrating the system performance.
- The temperature is found to decrease at the plume center and it was found to increase as the sensor moved away horizontally from the center. This indicates that the cold-water upwelling is happening due to the diffuser operation, resulting in reduced temperature within the plume.

Dissolved Oxygen

- The DO level was found to increase at the plume center and found to decrease as the sensor moved horizontally from the plume center to 3 m and 6 m away, respectively. This is due to upwelling of deeper, colder water to surface within the plume, and mixing with surface warm water as the sensor moved away from the plume center. The cold water has higher DO levels.
- The DO level increased to highest level (i.e., 13.3 mg/L) with 20 CFM air flow rate for SalmoAir®, and correspondingly the lowest temperature (i.e., 9.1°C) was also observed at 20 CFM air. The minimal increase in the measured DO levels due to tested ranges of air flow rates for SalmoAir® and OctoAir-60 indicates that the slight increase in DO levels may be predominantly due to cold water (having higher DO levels) upwelling.

CFD Modeling

- The developed CFD model showed an overall good agreement with the water temperature and average vertical velocity measured within and outside the plume during the field trial measurements.
- The validated CFD model can be used as a predictive tool for future projects requiring upwelling to optimize the design, equipment selection, diffuser arrangement and energy conservation. For such applications, the CFD model needs project specific data such as currents, depth, thermocline information, and water properties.

8.2 Recommendations

- The present study has shown that upwelling and temperature control is possible using CanadianPond upwelling systems, however integration with the cage, operational logistics, and the effects on the fish are unknown. Future studies could be conducted within a fish cage as a pilot project to study the effect of air bubbles on fish, temperature/thermocline, and DO and the resulting expected impact on fish health.
- The optimal location (i.e., inside vs. outside) and depth (i.e., within or below) for upwelling system installation with respect to the cage is not well studied in this project. Therefore, a future study including CFD modeling can help resolve these challenges.
- This study didn't cover the energy requirements for upwelling projects, therefore, a future study to assess the energy requirements and potential green sources (i.e., electrical/solar/wind) of energy to operate these diffusers should be considered.
- Development of a real-time monitoring decision support system to automatically turn on and off the air diffuser based on the in-cage temperature and DO level measurement is recommended.

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