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Project OASIS: Optimizing Aquaponic Systems to Improve Sustainability


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Honors Thesis for Mechanical Engineering

Project OASIS: Optimizing Aquaponic Systems to Improve Sustainability

Sid Nigam, Mechanical Engineering

Paige Balcom, Mechanical Engineering

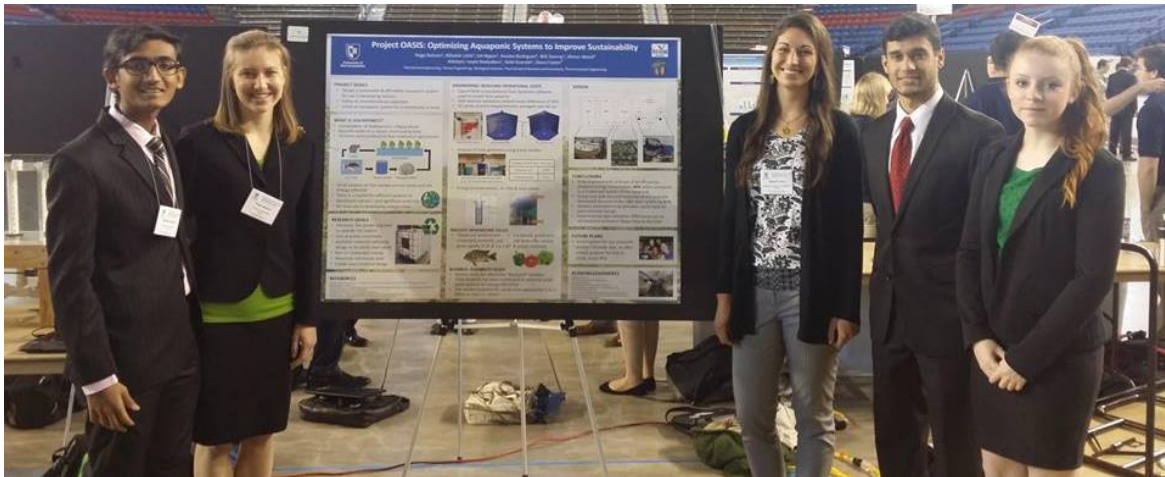
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Andrew Ogden, Biological Sciences

Diane Foster, Mechanical & Ocean Engineering



ABSTRACT

Started in Fall 2015, Project OASIS (Optimizing Aquaponic Systems to Improve Sustainability) is an interdisciplinary capstone project with the goal of designing a sustainable and affordable small-scale aquaponic system for use in developing nations to tackle the problems of malnutrition and food insecurity. Aquaponics is a symbiotic relationship between fish and vegetables growing together in a recirculating system. The project's goals were to minimize energy consumption and construction costs while using universally available materials. The computational fluid dynamics (CFD) software OpenFOAM was used to create transient and steady-state models of fish tanks to visualize velocity profiles, streamlines, and particle movement. CFD and small scale experiments showed vertical manifolds were more efficient than horizontal inlets. The components' layout was analyzed to minimize head losses and airlifts were used instead of traditional water pumps. Full-scale research and traditional systems were constructed for side-by-side comparison of biological and energy factors. Flow improvements and use of air-lift pumps dropped energy consumption 40% when compared to a traditional system of the same size. Using local and recycled materials where possible decreased the cost of the UNH pilot system by 27%.

The team also partnered with Forjando Alas, a non-profit in Uvita, Costa Rica. During a January 2016 assessment trip, four members spent a week gathering data and building relationships with the community to develop a user-centered design. Project OASIS also successfully competed in two entrepreneurship competitions this year.

ACKNOWLEDGEMENTS

This project was also completed by Allison Wood, Will Taveras, and Mikalah Little for their non-honors senior capstone projects and research purposes. Without them, the project would not have been possible.

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INTRODUCTION

“Hunger kills more people every year than malaria, tuberculosis, and AIDS combined. Approximately 805 million people suffer from chronic hunger.” [1] One child dies every five seconds from hunger-related causes. [2] Every day, people around the world struggle to access nutritious food in their local communities. In developing nations, poverty is often widespread and food availability may depend directly on weather, politics, and other variables.

Traditional farming methods of food production have geographic limitations, creating the need for a large distribution network to ship food to grocery stores, where it can be accessed by consumers. This network is very susceptible to disruption by weather conditions, infrastructure outages, commodity fluctuations, and the demands of consumers. Food producers across the globe have identified aquaponic technology as a viable supplement for traditional farming techniques in the future. Resultantly, most aquaponics research has been focused on commercial-scale production that would generally be subjected to the same distribution, logistic, and capital difficulties facing the traditional agricultural market. Small-scale systems currently on the market are often custom-made or do-it-yourself systems, and tend to be energy inefficient and too expensive for the families and schools who would likely purchase them. Little research has been done from an engineering standpoint to optimize small-scale aquaponic systems for energy and cost efficiency.

The vision of Project OASIS (Optimizing Aquaponic Systems to Improve Sustainability) is to develop a low cost, easily maintainable aquaponic system that runs on renewable energy and could provide families or groups of up to 10 with fresh vegetables and protein from growing fish. We will be able to accomplish this by using state-of-the-art engineering tools to create innovative designs that decrease energy consumption. These systems would have applications in areas where traditional farming methods would not be effective; indoors, outdoors, in a wide range of climates and ambient conditions, and with or without a stable electrical grid. These systems could be used year round, in places around the globe.

For our first system, we are working in the town of Uvita, Costa Rica. The goal for the first system is to provide Forjando Alas (an afterschool program for at-risk youth from ages 5-11)

with a user centered design of a family sized aquaponic system. In order to achieve these goals, we plan to conduct surveys to get the user input into our design process.

Our main research goals were to increase energy efficiency and decrease cost. Lower energy use gives us the opportunity to consider renewable energy. One of the major changes we made was choosing to use a recycled International Bulk Container as a fish tank because of its universal availability and low cost. This is not typical of a conventional system, where cylindrical tanks are used. Another goal was to maximize nutritional yield by providing a variety of crops.

TEAM MEMBERS

The Project OASIS team was carefully assembled in order to utilize an interdisciplinary approach drawing strengths from different majors. Each team member carries a unique background and skillset which has contributed to our success this year.

Paige Balcom, Mechanical Engineering

- Roles: OpenFOAM flow modeling, renewable energy studies
- Qualifications:
 - Background in aquaponic systems and their potential for use in developing nations
 - Former President of UNH's Engineers Without Borders (Experience organizing international humanitarian projects)

Mikalsh Little, Sustainable Agriculture & Food Systems

- Roles: Balance nutrient cycle, maximize nutritional yield
- Qualifications:
 - Background in sustainable farming practices
 - Knowledge of nutrient requirements for different plant species

Sid Nigam, Mechanical Engineering

- Roles: OpenFOAM flow modeling, International Communications
- Qualifications:
 - International Affairs dual major

Will Taveras, Mechanical Engineering

- Roles: Fluid mechanics, energy use considerations, renewable energy studies, fundraising
- Qualifications:
 - Minor in Economics
 - Internship working with solar technology

Allison Wood, Environmental Engineering

- Roles: wastewater design, fluid mechanics, grant writing
- Qualifications:
 - Former Vice-President of UNH's Engineers Without Borders (Experience with international humanitarian work & applying for major grants to support international projects)

BACKGROUND

Aquaponics is the fusion of aquaculture (growing fish) and hydroponics (growing plants without soil) that is more effective than either independent process. Aquaponics is a form of biomimicry, in which humans emulate the natural systems observed on Earth to solve anthropogenic problems. It is a symbiotic relationship because the fish waste provides the nutrients for the plants to grow while the plants and bacteria clean the water for the fish to survive. It is similar to houseplants being used as aquarium filtration. Figure 1 shows a schematic of the aquaponics process. In modern aquaponics, the fish are grown in one tank, the vegetables are grown in another, and water is pumped between them. The radial settler removes the solid fish waste from the water, and the bacteria in the biological filter converts the waste's toxic ammonia to nitrite and then plant-accessible nitrate. The problem is that systems for purchase are very expensive or backyard systems are constructed by hobbyists and are not energy efficient. So there is a need and a market for small-scale, energy efficient aquaponics in both developed and developing nations.

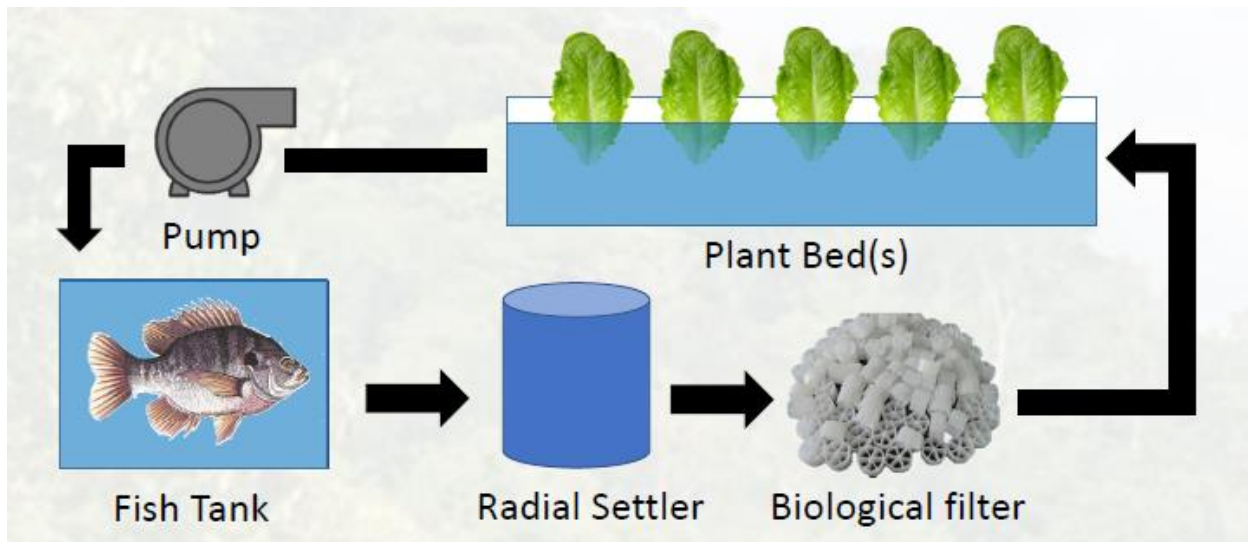


Figure 1: Diagram of Modern Aquaponics

Water is arguably our most valuable resource, but 70% of the world's freshwater is already being used [3]--90% of it for agriculture. [4] Of the water used in agricultural irrigation annually, a small portion is actually utilized by crops. The excess water, contaminated with fertilizers, herbicides, or pesticides, drains from fields into water bodies, causing degradation. In an aquaponic system, water is recirculated from plants to fish in a closed loop, so no excess water is wasted into the environment. This diminishes the opportunity for environmental pollution and

decreases water usage considerably. Aquaponic systems provide an inorganic medium in which crops can thrive due to lack of competition. There is no opportunity for weeds to develop in the system, because the only organic matter is introduced into the system by the operator. Pest pressure is limited, and integrated pest management practices are an option if pressure becomes an issue.

Aquaponic produce is entirely organic (and thus can be sold for a higher price) and high-value cash crops can be grown in areas where conventional farming can only produce grains. Plus, the fish provide a protein source, which is often lacking in many developing nations. Aquaponics is also less labor intensive than conventional farming [5] and is ideal for drought-prone and water-scarce regions because it recirculates water. Aquaponics is also resistant to weather changes. Tilapia is the most commonly grown fish because it is hardy, tasty, and quick growing, but Pangasius can grow even faster and survive more extreme conditions than tilapia. [6] Blue gill, koi, goldfish, [7] and catfish can also be used. [8]

Aside from the initial capital investment, the only inputs to the system are power for the pump (which can be diesel, electric, or solar generated), water lost from evaporation, and food for the fish. Fish food can be supplemented by growing some of it in the aquaponic system. Lettuce, duckweed, sprouts, and worms have been used. [9]

There are three main types of aquaponics designs: raft, Nutrient Film Technique (NFT), and media-filled beds. Figure 2 shows the raft design where the plants are placed in floating rafts, and the roots dangle in the nutrient-rich water. In the Nutrient Film Technique plants are placed in long, narrow channels, and a thin stream of continuously flowing water passes through. The system can also be oriented vertically to reduce the amount of required space. This configuration works well indoors with artificial lighting, but it is not as effective outdoors because not all the plants receive full sunlight. Figure 3 illustrates the media-filled bed system where the container is filled with gravel, perlite, or another medium to support the plant. While the raft systems are limited to leafy vegetables, media beds can support fruiting plants, such as peppers and tomatoes.



Figure 2: Aquaponics Raft System



Figure 3: Aquaponics Media Bed System

Rice-fish cultures in Southeast Asia date back to 25-265 AD, [10] and the Aztecs grew plants in floating rafts on a lake in 1000 AD. [11] Modern aquaponics is an emerging industry that began in the 1980s and 1990s, [11] and it has huge potential—it is six times more productive than conventional farming methods, [12] uses 75% less energy than mechanized agriculture, and consumes 80-90% less water. [13] While a few universities are conducting aquaponics research and several commercial ventures exist, it is by far most popular among hobbyists and backyard enthusiasts. There are an estimated 3,000 to 5,000 of such systems in the U.S., and Australia

boasts over 5,000. Aquaponics is also popular in schools—an estimated 1,000 systems are used in the U.S. to teach science and business principles. Universities are starting to offer classes in aquaponics and some 12 U.S. commercial organizations offer training classes. There are also several online forums with over 5,000 members each. [14] The International Aquaponics Society was started in 2013 to provide information about aquaponics, guide the industry, and host conferences. The Aquaponics Association was founded in 2011 and is more focused on education and outreach. [15]

PROJECT

Project OASIS (Optimizing Aquaponic Systems to Improve Sustainability) was created in summer 2015 as a senior capstone project by two mechanical engineering students, Paige Balcom and Sid Nigam. Paige and Sid have known since they were freshmen they wanted to incorporate humanitarian work in developing countries into their senior design project. This year, Project OASIS is proudly the first international capstone effort in the mechanical engineering department. The project was also inspired by past involvement with the group Engineers/Students without Borders; all members have been active in the group over the last few years, traveling to Uganda, Peru, and serving as Engineers/Students without Borders officers. The primary goal of Project OASIS is to develop a low-cost, highly energy efficient aquaponic system design, followed by building the system for a community in need of fresh, local food. Aquaponics is the intersection of aquaculture; raising fish with hydroponics and growing plants in water instead of soil. The over-arching goal of the project is to establish a system design easily replicable in similar climates for use in communities with various needs across the globe. The modular design will enable the system to be scaled and built in various sizes. This non-traditional capstone effort has attracted students from engineering, biology, sustainable agriculture, and the business school forming a dynamic team. The group's collaborative work has already yielded a first place win in the undergraduate research conference, a third place win in the 2015 NH Social Venture Innovation Challenge, and fundraised over \$30,000.

Project Goals

The project goals are as follows:

- Design a sustainable & affordable aquaponic system for use in developing nations

- Decrease the power required to operate the system
- Run on renewable energy
- Maximize nutritional yield
- Utilize an interdisciplinary approach
- Install an aquaponic system for a community in need
 - Use recycled, universally available materials (allowing design to be easily replicated)
 - Create user-centered design

Category	Specific Goals	Completion Date
System Design	Complete Preliminary Design	December 2015
Prototype Construction	Begin Prototype Construction	January 2016
	Complete Prototype Construction	February 2016
Research	Begin Testing w/ Prototype	February 2016
	Complete Testing w/ Prototype	April 2016
Travel	Assessment Trip	January 2016
	Implementation Trip	June 2016

Figure 4: Project Timeline

PROJECT SUMMARY

OpenFOAM

We learned OpenFOAM computational fluid dynamics (CFD) software to study the flow of the water in the fish tanks because our rectangular IBC totes are different than the cylindrical tanks used in traditional aquaponics. Our goal was to have a uniform distribution of dissolved oxygen and remove the fish effluent as quickly as possible while inputting minimum energy. OpenFOAM is an open source software and highly regarded as one of the best CFD programs available. Currently, computational fluid dynamics research for aquaponics application has only been done at Cornell on a commercial scale. We are the first team to conduct CFD based research on aquaponics for small scale aquaponic systems.

We started with modeling a small-scale experimental fish tank so it was easier to validate the model with experimental results. The model was scaled down from the full size system using Reynold's number scaling. Both horizontal and vertical manifold inlets were modeled.

Since OpenFOAM is a Linux-based software, Ubuntu was first installed and then OpenFOAM. A series of tutorials provided by Dr. Ivaylo Nedyalkov were completed to gain a basic understanding of the software. Similar to any fluids problem, the geometry, initial conditions, and boundary conditions must be defined. Additionally, an appropriate solver must be chosen to identify equations and find a solution specifically related to the given task.

Geometry

The OpenFOAM geometry is based on vertices, blocks, and faces. It can be created in a blockMeshDict file where all shapes are defined in the code or through snappyHexMesh, which can import geometry files. When using blockMeshDict, first, the coordinates of each point are programmed, then eight vertices are connected in a block, and finally, the sides of each block are defined as faces. There are many different types of faces, such as wall and empty. Each block is discretized into a specified number of cells with a user-defined grading. The geometry represents solely the water inside the experimental tank, which is an 11x11x10 inch cube for the small scale model. The tank's inlet velocity was defined one inch from the top corner of one side and the outlet was defined one inch from the bottom in the center of the bottom face. Both the inlet and outlet were modeled as one inch circles to simplify the geometry. Additionally, OpenFOAM cannot work in 2D—everything must be defined as 3D.

Several methods of creating the geometry were tried. The vertices were created in a separate program called Gmsh as shown in Figure 5, but it was difficult to import the vertices into OpenFOAM. Next, blockMeshDict, which is an inbuilt geometry creator for OpenFOAM was used, but the geometry proved too complex as shown in Figure 6. Finally, the geometry was created in SolidWorks and exported as a .stl file and snappyHexMesh was used to read in the file. Figure 7 shows the final rendering of the solidworks stl file with the breakdown of the mesh size. The stl file breaks down the geometry into triangles and their coordinates are saved in a text file. Once saved as stl, we had to edit the file and define patches. There are 3 patches - inlet, outlet, and wall. The inlet and outlet are self-explanatory but the wall is the part defined for the

boundary through which there is no transfer of mass. Figure 8 shows the breakdown of a vertical manifold inlet into the triangles.

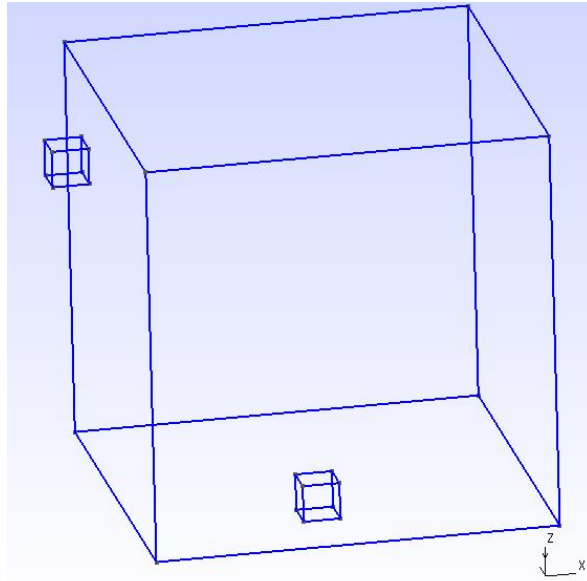


Figure 5: Gmsh to Generate Mesh

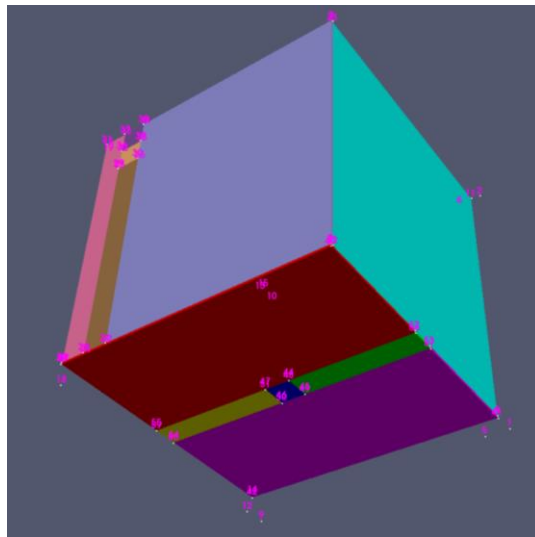


Figure 6: blockMeshDict to Create Mesh

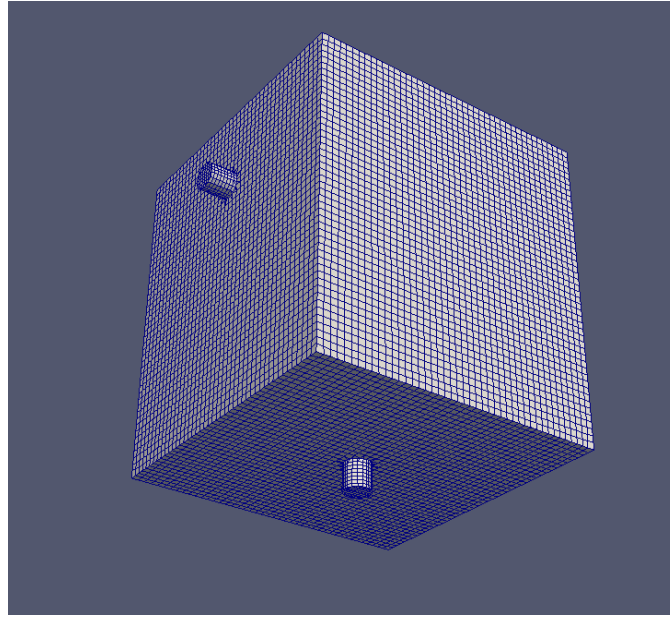


Figure 7: Final Solidworks Imported .stl Files to Define Geometry

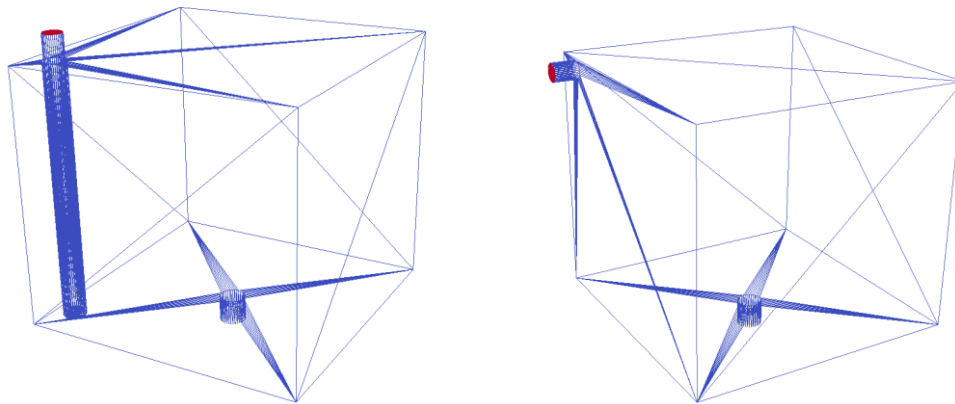


Figure 8: Breakdown of Geometry into Triangles - Vertical Manifold (left) and Horizontal (right)

Solvers

In order to create a numerical model, OpenFOAM allows users to apply different solvers for the system. The solvers we used were *simpleFoam* and *pisoFoam*. These solvers allowed us to create transient and steady-state solutions of our flow in the tanks.

The way *simpleFoam* works is that it uses a guess and correct procedure to solve for the pressure and velocity in the flow [16]. Figure 9 shows the SIMPLE algorithm (Semi-Implicit Method of Pressure Linked Equations). The parameters used in Figure 9 are defined in Table 1.

Table 1: Parameters in the *simpleFoam* Algorithm

Parameter	Description
p	Estimated pressure field
u, v	Velocity components
ϕ	Transport equation variables like k and ω

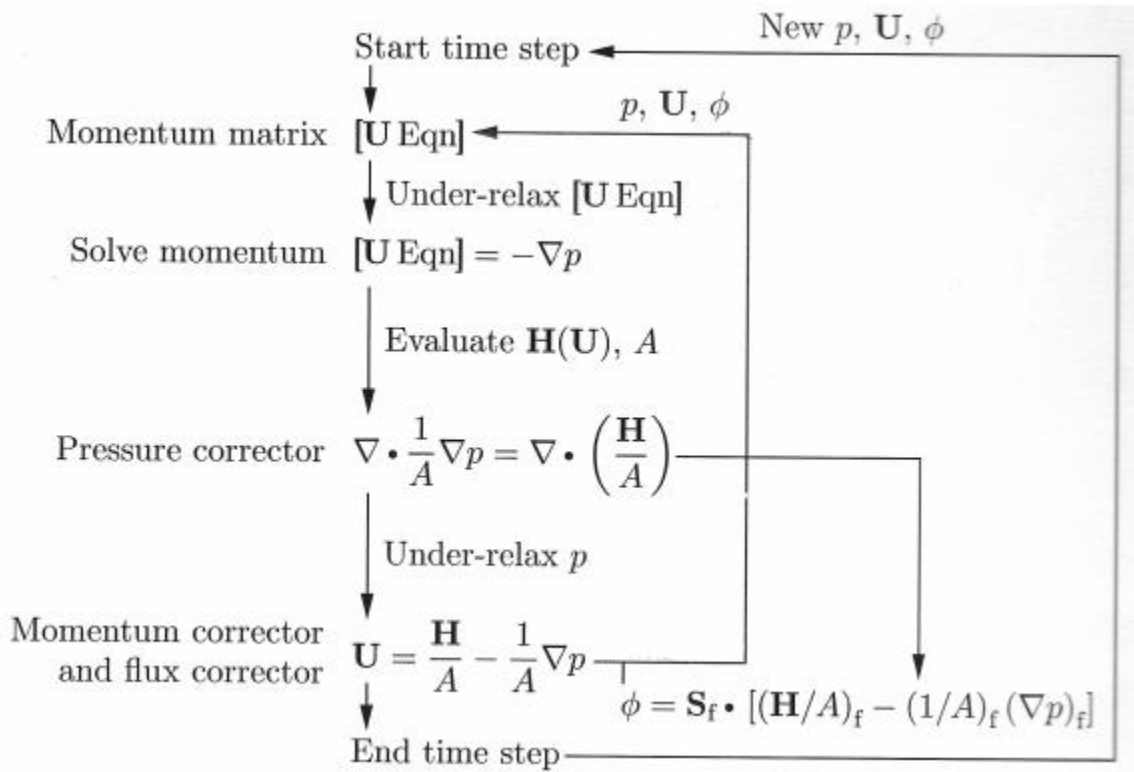


Figure 9: *simpleFoam* Algorithm

The terminal window was used to call the commands to generate the mesh and run the solver. Finally, the solution as shown in Figure 10 was viewed in paraView by calling paraFoam. The

geometry can be rotated; cut into sections; and viewed as a surface, wiremesh, or other types of transparencies. The velocity and pressure fields can also be viewed throughout the geometry and the scales adjusted.

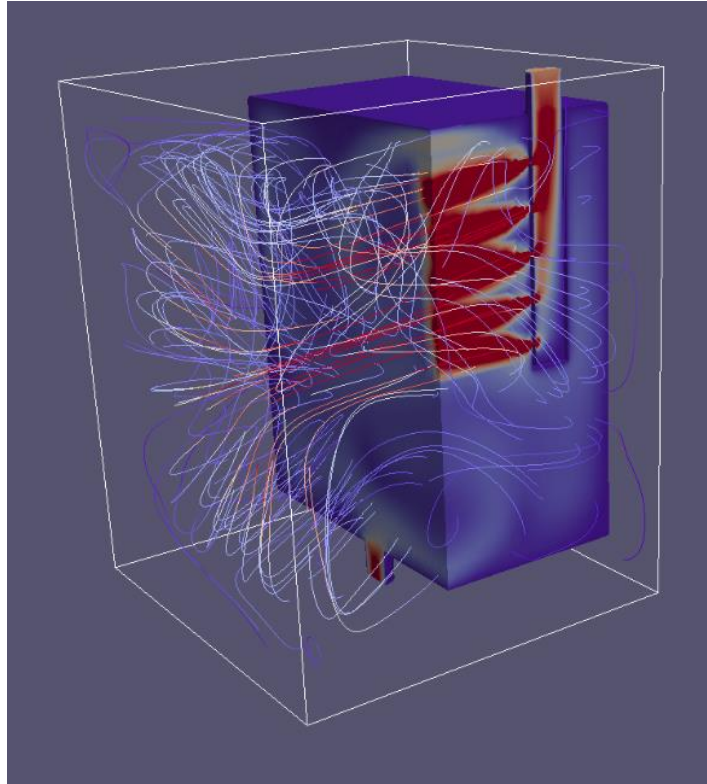


Figure 10: ParaView to View the Solution

The initial and boundary conditions had to be analyzed and set for each patch using OpenFOAM. We defined three patches - inlet, outlet, and wall. There are several different types of initial and boundary conditions that can be prescribed for all the parameters such as velocity and pressure. Table 2 gives the initial and boundary conditions for the different patches.

Table 2: Initial and Boundary Conditions for Parameters

Parameter	Inlet		Outlet		Wall	
Condition	Initial	Boundary	Initial	Boundary	Initial	Boundary
U (velocity)	(0 0 -0.12) (0.12 0 0)*	fixedValue	(0 0 0)	zeroGradient	(0 0 0)	fixedValue
p (pressure)	0	zeroGradient	0	fixedValue	0	zeroGradient

* = Horizontal Inlet

Once the geometry was defined, the boundary and initial conditions were examined. The initial conditions of the velocity of the walls were defined as fixedvalue with uniform (0 0 0) velocity. The inlet velocity was also fixedValue but had an x-component of 0.12 m/s. The value of the outlet velocity was not set—the software solved for it based on the internal field. The boundary was defined as zeroGradient. For the pressures, the wall boundary condition was zeroGradient. The inlet and outlet were defined as uniformValue fixed 0 pressure. The initial conditions were dependent on the solver used.

Eulerian v. Lagrangian

For transient models, both Eulerian and Lagrangian solvers were tried. Lagrangian models provide the capability of particle tracking because the solver follows a single particle's path through time. Conversely, Eulerian models look at a fixed point in space and monitor the flow of the particles past that point. Originally, we wanted to track the path of individual water molecules through the tank, but after some time working on Lagrangian solvers, we realized an Eulerian model would be sufficient to validate our OpenFOAM results with our experiment. Therefore, Eulerian models were used for the majority of the project. Plus, paraFoam has some limited but built-in particle injection capabilities, so we were still able to visualize the movement of zero-density particles with Eulerian models.

Mesh Sensitivity

Since OpenFOAM breaks the geometry down into discretized blocks and converges to a solution using mathematical approximations, the size of the mesh blocks is very important and can greatly influence the results. Smaller mesh sizes yield more accurate results but greatly increase computation time. Thus, a mesh must be found that balances accuracy with computational run time.

Simulations were run at many different mesh sizes for both horizontal and vertical manifold inlet geometries. To assess the impact of different mesh sizes, velocity line plots in the x, y, and z directions intersecting at the center of the cube were examined. The white lines in Figure 11 shows the lines over which the velocities were measured.

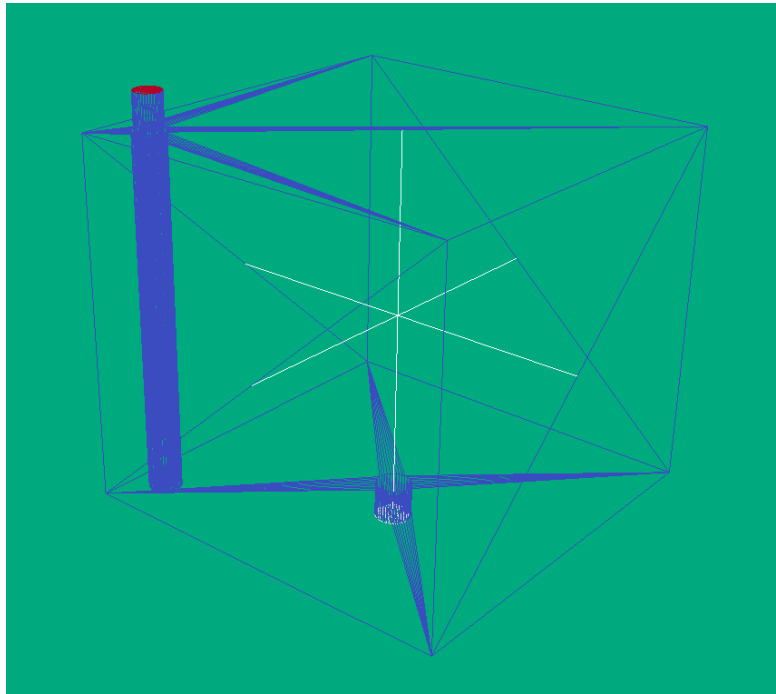


Figure 11: Lines of Velocity Measurement for Mesh Sensitivity Analysis

Using a probe in paraView, the velocities were sampled for each of the mesh sizes and plotted against each other. The x-line velocity plots are shown in Figures 12 and 13 and the y-line and z-line plots are included in Appendix B.

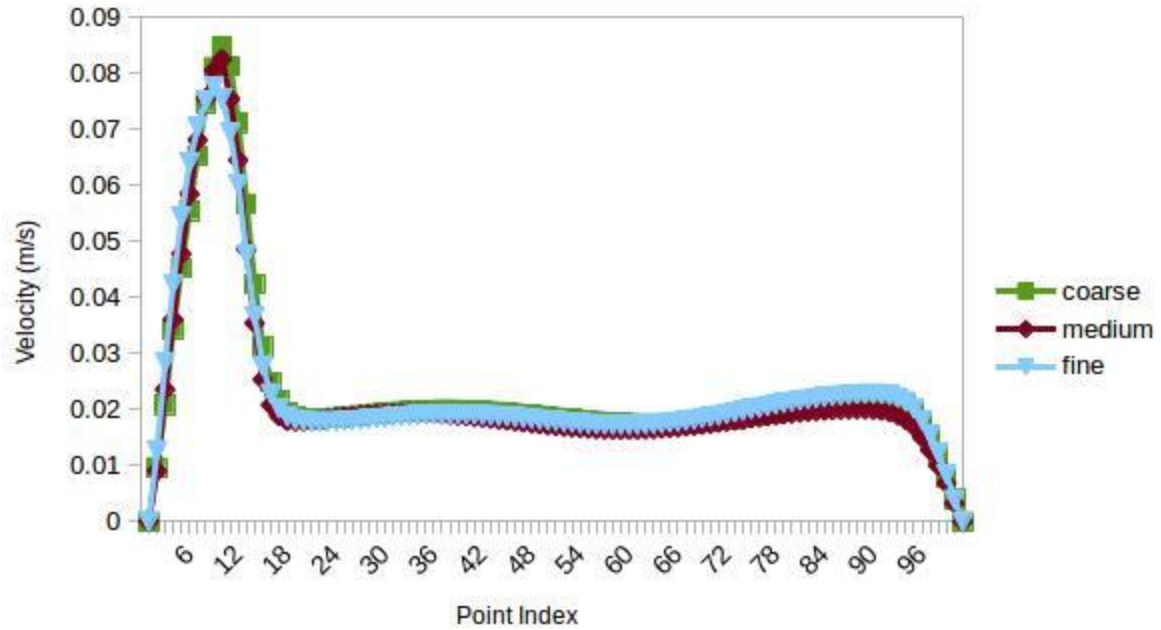


Figure 12: Mesh Sensitivity Results (in x-direction) for Vertical Manifold

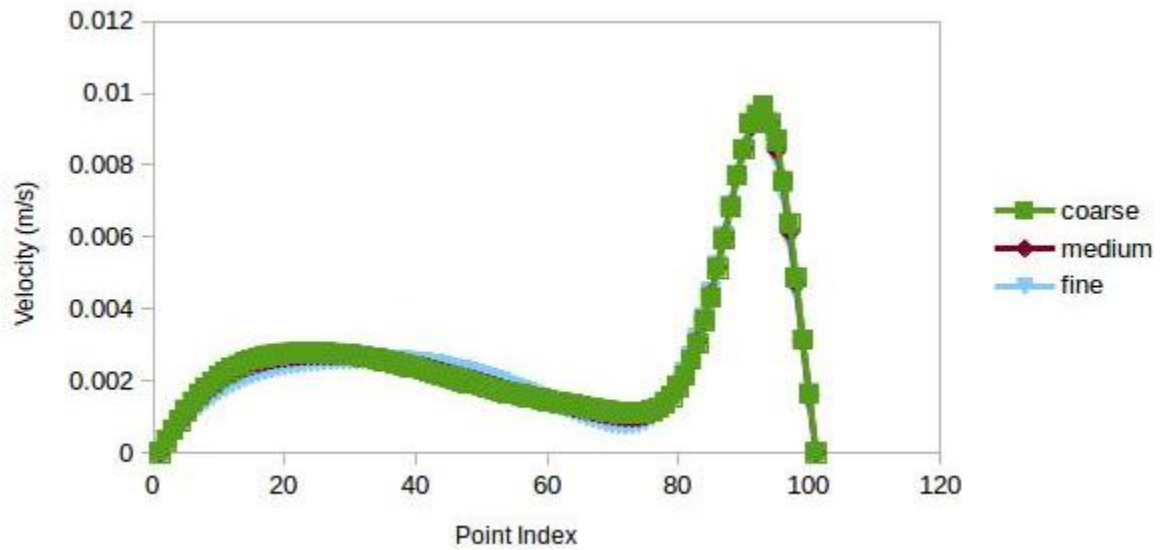


Figure 13: Mesh Sensitivity Results (in x-direction) for Horizontal Inlet

Eventually, the velocities reach the same values regardless of decreasing mesh size. If the mesh is made too small, the results can actually be worse. Therefore, the largest mesh which gave the same velocity results as smaller meshes was used. For the horizontal inlet, a mesh of (84 77 77) was used, and a mesh of (100 100 100) was used for the vertical manifold design.

Experimental Validation

To compare our OpenFOAM computational results to the real world, we constructed an experiment with the same geometry as the OpenFOAM vertical manifold model and used a Vectrino Acoustic Doppler Velocimeter (ADV) to measure the velocity at points in the tank. The experimental setup is shown in Figure 14 and the Vectrino datasheet can be found in Appendix C. Using a probe in paraView, we were able to get the velocity at those same points in OpenFOAM. We measured the velocity at 11 points throughout the tank as shown in Figure 15. With the ADV sensor, we collected data at each point for 60 seconds and averaged each time series to get a more accurate velocity measurement. The ADV sensor measured the velocity 5 centimeters below the probe.



Figure 14: ADV Sensor Setup

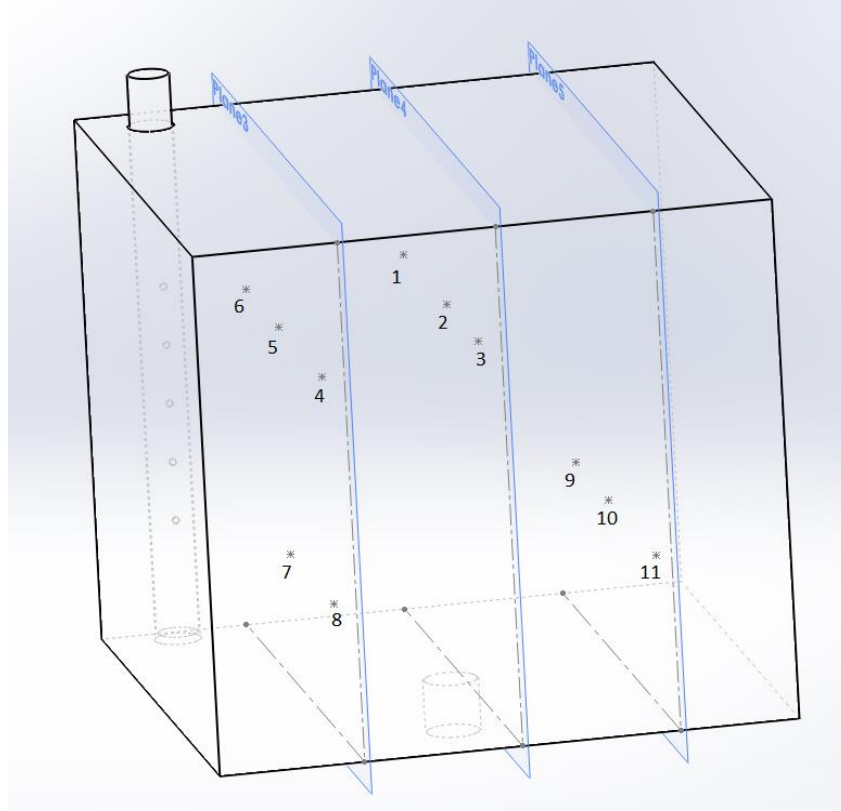


Figure 15: Schematic of ADV Sampling Points

Point 8 was considered an outlier because its placement in line with the tail of the inlet jet experienced high degrees of turbulence, so it was difficult to get an accurate velocity reading. The mean difference for the remaining 10 points between the experimental and OpenFOAM velocities was 34%. The largest differences occurred close to the inlet, but other points had smaller differences, even down to 6% where there was less turbulence. Table shows the differences at each point.

Table 3: Velocity Differences Between Computational and Experimental Results

Point	OpenFOAM Velocity (m/s)	Experiment Velocity (m/s)	% Difference
1	2.10E-02	3.32E-02	36.98
2	1.47E-02	1.57E-02	6.02
3	1.46E-02	3.14E-02	53.69
4	2.34E-02	4.71E-02	50.26
5	1.85E-02	1.68E-02	9.93
6	2.16E-02	1.73E-02	24.82
7	9.00E-03	1.75E-02	48.52
8	2.88E-02	1.75E-02	64.72
9	1.52E-02	1.89E-02	19.69
10	1.96E-02	3.14E-02	37.58
11	2.80E-02	3.44E-02	18.70
Mean*			33.72

*excluding point 8

The results could be improved by accounting for more turbulence near the inlet in the OpenFOAM model and taking more ADV point measurements in the turbulent areas of the experimental tank.

Final Solution

ParaView is the OpenFOAM post-processing tool that allows users to visualize their results and collect data. We were able to create velocity profiles of the tank in 2D and 3D and streamlines that showed the paths of the water molecules and their velocities along those paths. We also used

probes to sample the velocities at points and along lines in the tank. With the transient models, we were able to watch the development of the flow by looking at simulations of the velocity profiles and streamlines through time. We were also able to inject zero-density particles and watch them travel along the streamlines through time. The following figures showcase some of these capabilities.

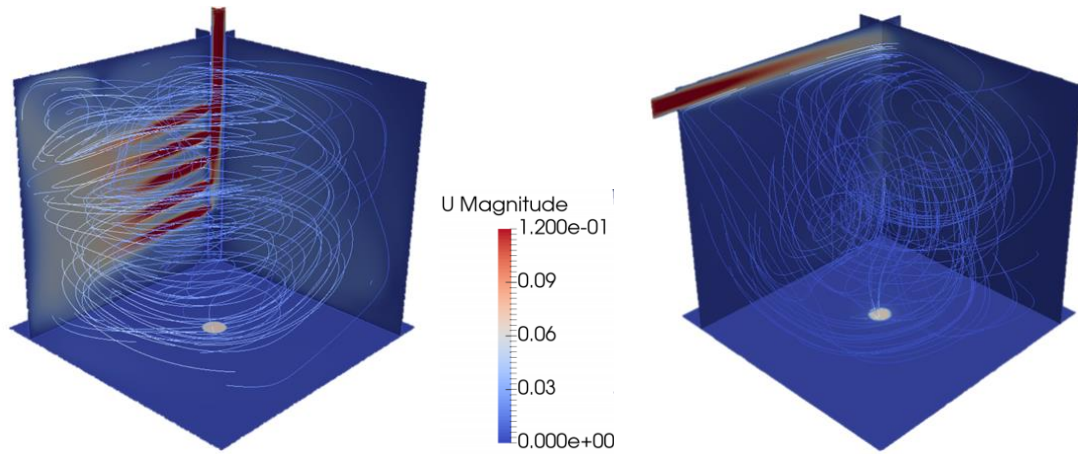


Figure 16: Streamlines in Vertical Manifold (left) and Horizontal (right) at Steady State

As evident from Figure 16, the flow in the vertical manifold is more uniform and cylindrical thereby reducing the energy required to create the flow necessary for proper spreading of dissolved oxygen and fast removal of fish effluent.

Experiments

Dye tracer studies were conducted using a horizontal inlet and vertical manifold with 5 orifices (9/64 inches in diameter) to evaluate inlet geometries with respect to tank mixing. Two cubic acrylic tanks were constructed to hold 28 liters of water. During experiments a liquid volume of 19.4 L and a flow rate of 1.32 L/min were used. A fully developed flow was established before each tracer test, which took approximately ten minutes. During each test 1 mL of dye was injected into each tank and samples were taken every minute until minute 25, then samples were taken every two minutes until minute 60. Relative absorbancies of each sample were obtained using a spectrophotometer.

Instead of integrating this data with a best fit function, Equation 1 [17] was used to find the mean retention time of the dye:

$$\bar{t} = \frac{\int_0^{\infty} Ct \, dt}{\int_0^{\infty} C \, dt} \approx \frac{\sum \bar{C}t\Delta t}{\sum \bar{C}\Delta t} \quad (1)$$

The second portion of this equation is a common method of estimating the area under a curve, commonly known as the trapezoid rule. Using this equation, the average retention time of the dye was calculated to be 35.28 and 31.21 mins, for the horizontal and vertical setups respectively. The hydraulic retention time (HRT), or amount of time it should take for the tank volume to be replaced based on the flow rate, was 14.64 min. In this experiment, it was visually determined that the vertical manifold was far more efficient at mixing the dye as shown in Figure 17, and according to the average retention time, was also more efficient at removing waste from the experimental tank.



Figure 17: Concentration Experiment

Based on the water flowrate and the high diffusion coefficient of the tracer dye, it can be assumed that both dispersion and advection transport processes were affecting dye concentrations throughout the tank. For this reason, the dye tracer study yielded high average retention times compared to the HRT, because dispersion was occurring constantly during the experiment. Thus, the replacement of water in the tank did not directly reflect the efficiency of the removal of “waste” from the tank, but rather served as a relative representation of which tank was most efficient at moving particles from the inlet to the outlet. In the aquaponic system, particles will have relatively low dispersion rates compared to the tracer dye, therefore, in order

to validate retention times calculated in OpenFOAM a different tracer would have needed to be selected for experimental validation. The team decided instead to investigate velocities within the tank using the vertical manifold setup.

Three dimensional velocity measurements were taken in order to characterize the flow and to validate the computational models that were constructed using OpenFOAM. These tests were conducted on the small scale acrylic tanks from the dye tracer studies. The velocity tests were conducted only on the vertical manifold inlet set up for this tank, because it was determined to have flow that was more difficult to be characterized, with more visually noticeable turbulence and vertical flow. Between the two inlets, the vertical manifold is the more useful case to study because dye tests showed it to be more effective at solids removal. However, it was also the worst case for validation with turbulent flow.

In order to validate and characterize the flow, the velocity was tested at a group of 11 sample points. These samples were taken using an Acoustic Doppler Velocimeter, or an ADV sensor. We used a single point Vectrino II fixed probe sensor by NortekUSA. ADV works by measuring the Doppler shift of the particles at a single point. The probe contains a transmitter and three receivers. The transmitter sends out pulses in the water at 10 MHz one pulse at a time and ‘listens’ for the reflection. The Doppler shift is estimated from a measured phase shift between two consecutive signals. The Doppler relationship is governed by equation 2 below:

$$\Delta f = \frac{2f}{c} V_{rel} \quad (2)$$

The x, y, z velocity coordinates were exported as a ‘.vna’ file and imported into MATLAB for manipulation. The 60 second time-averaged values were compared to the model values which were found to differ by less than 6% for less turbulent points and up to 34% for more turbulent points (these results omit one data point for reasons discussed in the OpenFOAM Experimental Validation section). These results were enough for a general validation of the model so that more analyses can be run computationally before constructing full-scale physical experiments.

Fluid Mechanics

The principles of fluid mechanics were used to decrease the power required to pump water through the system. By evaluating headlosses throughout the PVC Pipe, our team was able to adjust the plant beds to allow gravity flow from the fish tanks all the way back to the sump. Headlosses were calculated based on Schedule 40 1 ¼ in. diameter pipe, using standard minor loss coefficients.

$$\text{Pipe Headloss} = f \frac{L V^2}{D 2g} \quad (3)$$

$$\text{Component Headloss} = K \frac{V^2}{2g} \quad (4)$$

Table 4: System Headlosses

HEADLOSSES (ft)	ft	inches
Fish Tank to Mech. Filter	0.10	1.23
Filter to Airlift (Gravel Bed)	0.29	3.42
Gravel Bed to Raft 1	0.29	3.42
Raft 1 to Raft 2	0.29	3.42
Raft 2 to Sump	0.57	6.82
Total	1.53	18.32

Airlift pumps were used to reduce power demands to operate the system. This was evaluated in an effort to minimize the costs involved in circulating the water to remove waste and transfer nutrients.

In an airlift, instead of mechanical components pushing water as in a traditional water pump, air used to move the water up a column as shown in Figure 18. A stream of air is inserted into the bottom of a column of water in a pipe, and as the air rises due to the effects of buoyancy, it carries with it a flow of water as water gets trapped between the bubbles.

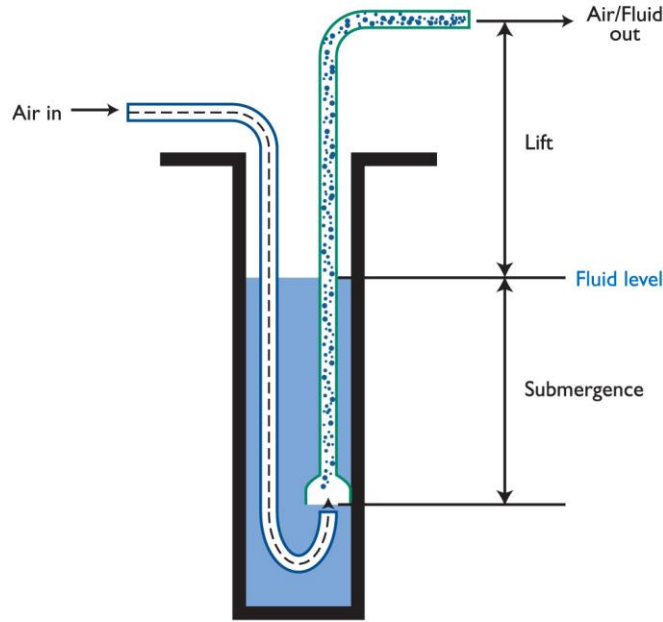


Figure 18: Diagram of Airlift

This flow can occur in vertical piping in three more commonly characterized regimes: slug flow, bubbly flow, or bubbly slug flow. Slug flow involves large bubbles of air that fill the cross sectional area of the pipe pushing larger volumes of water that are trapped in between. Bubbly flow consists of much smaller bubbles of air and smaller volumes of water that travel together through the pipe. Bubbly slug flow is somewhere in between the other two regimes. The major characteristics that govern the flow of water in the air lift are the air to water ratio and the submergence to lift ratio. The air to water ratio is simply a volumetric ratio of the air and water in the pipe. In this case higher ratios tend to result in higher overall water flows, but the relationship also depends on the pipe diameter and subsequently the cross sectional area. The submergence to lift ratio measures how much of the water column that the air is being injected into is underwater with no flow, or the static height that is also in the tank, and the lift, or the height that the water is lifted above the static surface. For submergence to lift ratios, the ideal ratio is less known, but best water flows tend to occur between ratios of 3:1 and 4:1. Our research system is currently operating at the top of this range with a 4:1 ratio, but the study of the air lift flows in this system has been identified as a topic for further study in the coming years.

Biological Considerations

The goal of this part of the project was to maximize the nutritional yield of our system. After evaluating current small-scale systems, it was decided that a combination of raft and gravel plant beds would be used to grow a variety of crops, as opposed to many traditional systems which only grow lettuce. Production of vegetables like tomatoes, peppers, and lettuce provide nutritious options to people in areas that would otherwise depend on expensive imported vegetables, or go without. At the location of our first system, Uvita, Costa Rica, soil pH is around 5, far too acidic for propagation of most vegetable crops. Aquaponics does not depend on local soil conditions because the inorganic nature of the system allows for control of pH.

Tilapia were chosen as the fish species because they are resilient, globally available. With a feed conversion ratio of 1.6-1.8, they utilize feed more efficiently than other potential species. [18] Tilapia fertilize the plants in the system while growing to a harvestable size, eventually providing a protein source. The fish are extremely resilient and can survive in low oxygen levels, high ammonia levels, temperatures ranging from 60-80 degrees (F), and pH from 7-8. These conditions are achievable in both New Hampshire and Costa Rica, so our prototype could be tested at the University.

The first 30-45 days are crucial to the success of the system. Within that timeframe ammonia from fish waste attracts naturally occurring bacteria which begins the breakdown of ammonia to nitrite. Nitrite then is converted into nitrate, which is readily available to plants. If conditions (temperature, salinity, pH, ammonia levels) in the system aren't within proper operating limits, the nutrient cycling will not occur and the system will not function. Daily readings of system conditions will provide insight as to when and if cycling has begun. The only input into the system includes pellet fish food.

Energy Considerations

One goal was to power the system using renewable energy to improve the project's sustainability, lower operating costs, and introduce the people of Uvita to renewable power sources. After a site assessment, solar power was determined to be the best source of renewable energy.

Although Costa Rica ran the first 285 days of 2015 on 100% renewable energy, solar power accounts for less than 0.1% of the national installed capacity (approximately 2 MW) [19]. As shown in Figure 19, Costa Rica has large potential for solar power with global horizontal irradiation (GHI) values from 1700 to 2100 W/m²/year since it is located near the equator. [19]

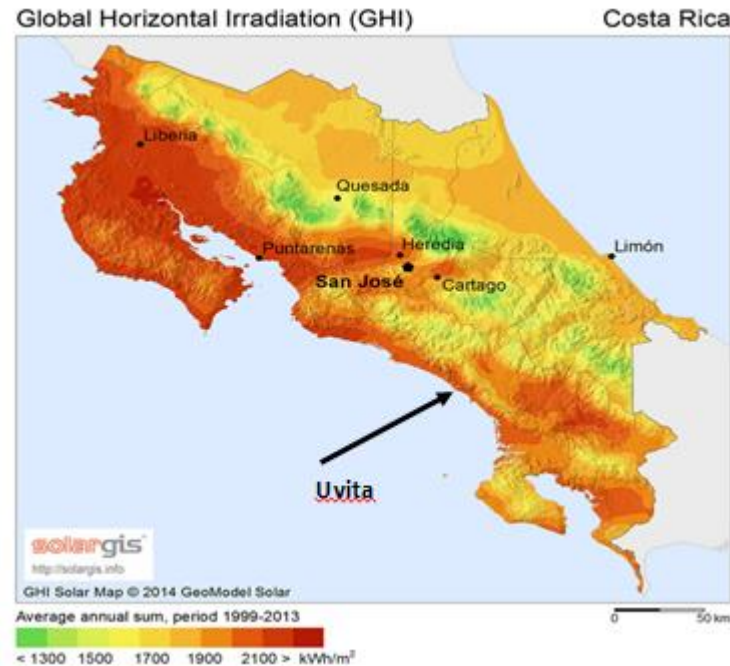


Figure 19: Global Horizontal Irradiation Map of Costa Rica [20]

Queries were made about solar power in Uvita, and the team talked with Ricardo, an agent at the local hardware store called Iguana Ferreteria. He had one solar panel available and could order other sizes from larger stores in the nearby city of San Isidro and have them delivered. Marine or car batteries sold in downtown Uvita shops could be used to store the excess solar power generated during the day and used at night. Other parts, such as an inverter and roof rack, are also available. Aside from at luxury hotels for tourists far up in the mountains, Uvita does not have any solar panels, so installing a system at Forjando Alas could introduce the people to solar power and encourage them to use it in their own homes.

The only power needs for the aquaponic system are the pump to circulate the water. Since our aquaponic system design decreases the overall energy needs of the system, solar power is feasible. The air pump requires 322 W, but for an added safety factor, 400 W was used for all calculations. It needs to run continuously, so 3,500 kWh are required per year. The National

Renewable Energy Laboratory (NREL) online PVWatts Calculator was used to determine the necessary size of solar panel. Figure 20 shows one input panel of the calculator. Although the online tool did not have weather data for Costa Rica, the closest site was Rivas, Nicaragua whose longitude differed by only 2.3°. Plus, the GHI values differed by 2.4%, so Rivas solar resource data was deemed acceptable for Uvita.

The screenshot displays the NREL PVWatts Calculator interface, specifically the 'SYSTEM INFO' tab. The top navigation bar includes 'My Location' (set to 'rivas, nicaragua'), 'HELP', 'FEEDBACK', and a dropdown for 'ALL NREL SOLAR TOOLS'. The main content area is divided into three sections: 'RESOURCE DATA', 'SYSTEM INFO' (active), and 'RESULTS'. The 'SYSTEM INFO' section contains a 'Go to resource data' button on the left and a 'Go to PVWatts results' button on the right. The central area is titled 'SYSTEM INFO' and includes the instruction 'Modify the inputs below to run the simulation.' Below this are six input fields, each with an information icon: 'DC System Size (kW)' (2.6), 'Module Type' (Standard), 'Array Type' (Fixed (roof mount)), 'System Losses (%)' (14), 'Tilt (deg)' (15.4), and 'Azimuth (deg)' (120). A 'RESTORE DEFAULTS' button is located at the top right of the input area. To the right of the input fields is a 'Draw Your System' section with the text 'Click below to customize your system on a map. (optional)' and a map interface showing a solar panel layout on a roof.

Figure 20: NREL PVWatts Calculator

Next, the system info was inputted. Based on the Forjando Alas roof measurements the team took, the roof angle was calculated to be 15.4°. The azimuthal angle was also calculated to be 120°, and a DC to AC size ratio of 1.2 and an inverter efficiency of 96% were used. The results showed that to get 3,500 kWh per year, a 2.6 kW panel is needed. The panel would cover approximately 16.25 square meters (22% of the roof).

Business Feasibility Study

A business feasibility study was conducted in order to test the feasibility of the design to penetrate the U.S. market as a potential fundraising effort and commercialization model. The project made it to the semi-final round of the Holloway competition, one of five teams in the track to do so out of 80 entrants to the competition. This was a great validation of our efforts to

improving life across the globe. The team also won 3rd place in the NH Social Venture Innovation Challenge in Fall 2015.

Traditional farming methods of food production have geographic limitations, creating the need for a large distribution network to ship food to grocery stores, where it can be accessed by consumers. This network is very susceptible to disruption by weather conditions, infrastructure outages, commodity fluctuations, and the demands of consumers. Food producers across the globe have identified aquaponic technology as the leading viable supplement for traditional farming techniques that will lead the new era of food production for the future. Aquaponics requires no soil and alleviates the headaches of weeds, soil pests or pathogens. Additionally, there is no labor required for tilling, cultivating, fertilizer spreading, compost shredding, manure spreading, plowing cover crops in, or irrigating.

To date, most aquaponics research has been focused on commercial-scale production that would generally be subjected to the same distribution, logistic, and capital difficulties facing the traditional agricultural market. Small-scale systems currently on the market are often custom-made or do-it-yourself systems, and tend to be energy inefficient and too expensive for families and schools who would likely purchase them. Little research has been done from an engineering standpoint to optimize small-scale aquaponic systems for energy and cost efficiency.

The vision of Project OASIS is to develop a low cost, easily maintainable aquaponic system that runs on renewable energy and could provide families or groups of up to 10 with fresh organic vegetables and protein from growing fish in any climate/geographic setting. These systems would have applications in areas where traditional farming methods would not be effective. Project OASIS' design could be used year round; indoors, outdoors, in a wide range of climates and ambient conditions, and with or without a stable electrical grid at the ease of monthly maintenance and services.

Project OASIS is initially targeting three customer segments, home-gardeners, farmers' market shoppers, and health enthusiasts interested in accessible, local, fresh, organic produce without having to garden themselves. From Spring 2008 - Spring 2015, an average of 10.46 million

shoppers visited Whole Foods daily. 70-72% of entire purchases were for fresh fruits and fresh vegetables. Capturing 3% (313,800 buyers) of the total addressable market of shoppers who frequent Whole Foods, Project OASIS has a total addressable market of \$1.6 billion (313,800 * \$5,000 - price of cheapest Project OASIS system). The business model will generate revenues from the initial sale of a system (\$5,000 for the small size and \$10,000 for the medium size) for the buyer option or interested customers have the option to lease a system for \$100 or \$200 per month.

Currently those with an interest in owning their own aquaponics system either pay thousands of dollars for the plans on how to build their own or pay thousands of dollars for a small inefficient and ineffective system. Three of our main competitors are Backyard Aquaponics, Grove Labs, and Portable Farms. Backyard Aquaponics has a wide variety of systems that cost from approximately \$1,000 to \$10,000, but are just components and parts. Grove Labs sells a fish tank sized system retailing at \$4,500, and Portable Farms sells the plans for a system with part of the necessary components for close to \$3,000. Our system is the first at its scale to be analyzed from an engineering perspective, in order to improve efficiencies. The Project OASIS design will fill a need for customers who are searching for a more energy efficient, productive, cost- effective system and who already pay for inferior products because they are so passionate.

We are exploring a couple different business models for our system. The first would be selling directly to consumers with full costs upfront, this is the structure most common in the market today. Alternatively we would lease the system for monthly payments and a maintenance contract if we find there is interest from the consumer. We plan on marketing at farmers' markets, on online message boards, in gardening magazines, and via social media to reach our intended audience.

The barriers and challenges associated with entering and competing within Project OASIS's initial target market is the perceived convenience of shopping at a grocery store/farmers market versus harvesting food in your own backyard. Typically, aquaponic systems seem like a burden for enthusiasts who are interested in learning more about the technology involved in aquaponics but realize the learning curve to operate and/or build a system, fit to a consumer's direct needs

and desires for the produce they would like to grow, is too time intensive. Additionally, many home-growers not only enjoy the taste of fresh food grown in their backyards but also the process and activities involved in growing food (the process of “getting dirty”). Project OASIS is solving several pain points; the first is the steep learning curve involved in operating aquaponic systems. The engineering behind this system is specifically designed for simplicity and also will be installed for every user. The maintenance that comes with the sale of the system (\$250 per month) is set up to take care of the concerns addressing the *need* to understand how the technology works, a Project OASIS sales rep will take care of the “boring” aspects of the aquaponic systems, allowing consumers to fully enjoy the picking and eating aspect. Once this is taken care of, the convenience factor will then multiply, as customers will begin to realize how much *easier* it is to approach one’s aquaponic system and just pick the fruits and vegetables steps from the kitchen.

User-Centered Design

Project OASIS is proudly the first international capstone effort in the mechanical engineering department. In fall of 2015 Project OASIS connected with Professor Andrew Ogden of UNH’s Sustainable Agriculture and Food Systems Department, who put the team in touch with our international partner, Forjando Alas (Forging Wings), located in Uvita, Costa Rica.

With the generous support of the UNH Emeriti Council, four members of Project OASIS were able to travel to Uvita, Costa Rica from Dec 31st 2015 through January 8th 2016 for a week of data gathering and relationship-building with the community. Team leaders Paige and Sid were joined by Will Taveras and Allison Wood. The goal of the trip was to gather information about the project site, locate locally available materials, and foster relationships with community volunteers who will be critical to the project’s success. In order to create a user-centered design, community input and ideas were vital throughout the whole process.

Some of the tasks the team accomplished while in Costa Rica included determining the site location at Forjando Alas, taking various measurements (such as roof height for solar panel installation), pricing system components at a local hardware store, taking water samples from the river that runs behind the center, visiting a nearby tilapia farm to learn about local aquaculture

practices, volunteering at the center and interacting with children there, administering local surveys regarding income and vegetable consumption, signing a partnership agreement with Forjando Alas director Ericka and volunteer Natalia, and making plans for gathering community volunteers to help with the June installation. This trip did not require many materials; however the team did locally print some surveys to leave at the center. The June 2016 implementation trip will require more planning and materials such as tools in order to construct the system.

One of the most important components of the trip was talking with the volunteers who will be maintaining this system; this will aid the team in creating a feasible maintenance plan which will in turn help make the project sustainable. Following this trip, Project OASIS is confident in the location choice for the aquaponic system, and is looking forward to continuing to work with Forjando Alas toward implementation in June.

At UNH, our team has worked closely with Dr. Todd Guerdat to construct two full-scale systems at the MacFarlane greenhouses. One system is a traditional small-scale design, consisting of three floating raft beds which grow lettuce, and are run in parallel (water from the fish tanks is divided evenly among all three beds, and then returns to the fish). The other system is our research system, which is roughly the same size as the tradition system, allowing for side-by-side comparison. Our research system design as shown in Figure 21 incorporates recycled materials, efficient water pumps, and a combination gravel grow bed that functions as a biological filter.



Figure 21: UNH Research System Design

For the fish tank, we used two 250 gallon IBC (International Bulk Container) totes with vertical manifold inlet designs. Large solids from the fish tanks are removed via a radial flow settler, which uses gravity settling. Water containing soluble nutrients then flows through the three plant beds in series, as opposed to the traditional system which runs in parallel. This cuts down the length of pipe in the system, decreasing headloss. As mentioned, the gravel plant bed also serves as a biological filter to convert nitrogen to a form usable for the plants, cutting out the necessity of a separate, expensive biofilter.

Overall, flow improvements and use of air-lift pumps dropped energy consumption 40% when compared to the traditional system (of the same size). Using local and recycled materials where possible decreased the cost of the UNH pilot system by 27%.

The team also partnered with Forjando Alas, a non-profit in Uvita, Costa Rica. During a January 2016 assessment trip, four members spent a week gathering data and building relationships with the community to develop a user-centered design. It was determined that IBC totes are available in the area at a much lower cost than cylindrical tanks, and will be a viable option for fish tanks. Gravel that has been thoroughly washed and cleaned will serve as the medium in the media beds and foam insulation will serve as a raft in the other bed. Since the sun in Costa Rica is extremely strong, the system will be shaded with the thin mesh commonly used in many Costa Rican homes. Water will be pumped through the system using airlifts which will be powered by a solar panel. The whole system will be built of local Costa Rican materials, therefore broken parts may be easily replaced. Most parts are available in Uvita hardware stores, but IBC totes and solar panels must be ordered in advance and delivered from the nearby town of San Isidro. Tilapia may be purchased in Uvita, and the fish food is available at a pet store in town, but may be bought in bulk in San Isidro. Construction tools, such as drills, saws, shovels, and machetes, will be provided by Forjando Alas and their volunteers. An aquaponic system requires very little maintenance; the fish need to be fed daily and sized and sorted periodically, and the mechanical filter should be cleaned once a month.

Project Finances

Table 5: Current Funds

CURRENT FUNDS		
Source	Purpose	Amount
Ocean Department	Ocean Engineering Funding	\$2,000.00
ME Department	Mechanical Engineering Funding	\$200.00
ME Department	NHJES Conference Attendance Award	\$200.00
SVIC	3rd place, NH Social Venture Innovation Challenge	\$2,000.00
ECSISI	Student International Service Grant	\$10,000.00
ME Department	Outreach Award - IAB and Admitted Students Day	\$400.00
ME Department	Tech 757 - Student Project Award	\$50.00
Rosenberg	Student Project Award	\$5,000.00
URC	First place prize, Ocean Engineering Research	\$500.00
Holloway	Bud Albin Semi-Finals 3rd Place	\$500.00
Entrepreneurship Cer	Summer Seed Grant	\$7,000.00
ME Department	Outreach Award - Mini Admitted Students Day	\$200.00
ECSISI	Student International Service Grant	\$3,500.00
TOTAL		\$31,550.00

Table 6: Current Budget

CURRENT BUDGET		
Category/Description	Item	Cost per Item
Research Equipment and Materials for UNH Research Prototype	Square polytank 24x24x36	\$411.76
	Round polytank 21x36	\$278.00
	Bubble bead filter	\$1,331.00
	Sequence circulation pump	\$1,100.00
	Sequence circulation pump - backup	\$550.00
	Bulkhead fitting - 1.5" - Slip x Thd	\$198.60
	Bulkhead fitting - 2" - slip x Thd	\$293.30
	Uniseal - 2"	\$53.76
	6" airstones with 1/2" barbs	\$121.50
	Strainer pot/basket	\$96.72
	Swetwater liner - 25x50	\$996.90
	Air diffuser bumpers	\$9.84
	Poly tank 60" x 30"	\$998.00
	Sensaphone monitoring devices	\$800.00
	Miscellaneous research supplies	\$50.00
Subtotal		\$7,289.38
Costa Rica System	Materials (Tanks, piping, etc.)	\$4,268.00
	Startup fish	\$315.00
	Plant seedlings	\$125.00
	Misc. (Power, heating, etc.)	\$100.00
Subtotal		\$4,808.00
January Travel	Flights, Room and Board, Transportation, Other	\$3,743.48
June Travel	Flights, Room and Board, Transportation, Other (Larger team, longer trip duration)	\$4,000.00
Summer Research	Room and Board, Other	\$7,000.00
Subtotal		\$14,743.48
TOTAL		\$26,840.86
SURPLUS:		\$4,709.14

RESULTS AND DISCUSSION

The goal of the project was to design a sustainable and affordable aquaponic system, and make plans to actually build such a system for a community in need. Using materials that are readily available in developing communities across the globe, the team was able to create a replicable design, and by incorporating recycled materials was able to decrease the capital cost of the system by 27% when compared to a traditional system of the same size. By using computational

fluid dynamics software, the team has identified a valid system setup incorporating unique rectangular tanks. Evaluating flow through these tanks and throughout the system has decreased the power consumption by 40%. After assessing power usage in the UNH prototype system and using field data from the project site in Costa Rica, it was determined that a 2.6 kW solar panel with surface area of 16.25 m² (approximately 22% of the roof) will suffice to operate the system, validating the idea that this size aquaponic system can be run using renewable energy in places where access to electricity is limited.

The prototype system is still under evaluation; however, once the system is cycling regularly the nutritional yield will be compared to that of the traditional setup to quantify any differences. Provided that nutrients cycle through the system properly, the peppers and tomatoes in combination with the lettuce are expected to far exceed the nutrient yield of the lettuce alone being produced in the traditional setup.

By utilizing an interdisciplinary approach, the team has been able to work efficiently to research, fundraise, plan, and publicize the project in a short amount of time. Over two semesters, the team raised over \$30,000. Through these efforts, the team was able to perform an assessment trip in January and is ready to return to the project site over the summer to install the system. By working with the community from an engineering, economics and biological perspective, the team was able to gather data to create a user-centered design that will provide the community with the nutrition they need and that they will feel confident operating and maintaining.

NEXT STEPS

Project OASIS is currently working toward finalizing the design of the aquaponic system, including using computational fluid dynamics software to model different flow patterns and study energy efficiency. The team recently finished constructing full-scale research and traditional aquaponics systems located in UNH's McFarlane Research Greenhouses. Four different species of lettuce are growing and tomatoes and peppers have started fruiting as well. In anticipation of the Tilapia being added to the system, a nursery is being constructed. Project OASIS' system has been constructed alongside a traditional aquaponic system, allowing for a side-by-side performance comparison. So far, both systems are going through the initial nutrient

cycling phase. Over the summer and as part of next year's senior project, an extensive biological comparison will be conducted to study the performance of the research aquaponic system in comparison to the traditional system. Project OASIS also plans to travel to Uvita in June to build the system, involving both the children at the center and community volunteers. We have also recruited four mechanical engineers, one electrical engineer, and one marine biology student to continue the project next year.

CONCLUSION

In its first established year, Project OASIS has proven to be a valuable undertaking in interdisciplinary education. Though the project is housed in the Departments of Mechanical & Ocean Engineering, it has already grown to incorporate students from the College of Life Sciences and Agriculture and the Peter T. Paul School of Business and Economics. Together this team has worked as a combined force to fundraise over \$30,000, start an international humanitarian project, build two full scale prototype systems in the UNH MacFarlane Greenhouses, participate in two campus-wide entrepreneurship competitions, and participate in outreach events for prospective students, admitted students, the UNH Mechanical Engineering Industrial Advisory Board, the UNH Board of Trustees, and will present at an UNH Alumni Networking Alumni Reception in New York City later in May. The team is looking forward to advising next year's group of students and is excited to see where they will take Project OASIS in the future.

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APPENDIX A

All of our code is housed on GitHub. The different branches have code for the various steady state and transient models and horizontal inlet and vertical manifold geometries. Feel free to peruse our code at: <https://github.com/pbnh/unh-aquaponics>

APPENDIX B

The following Appendix shows the y-line and z-line OpenFOAM Mesh Sensitivity plots.

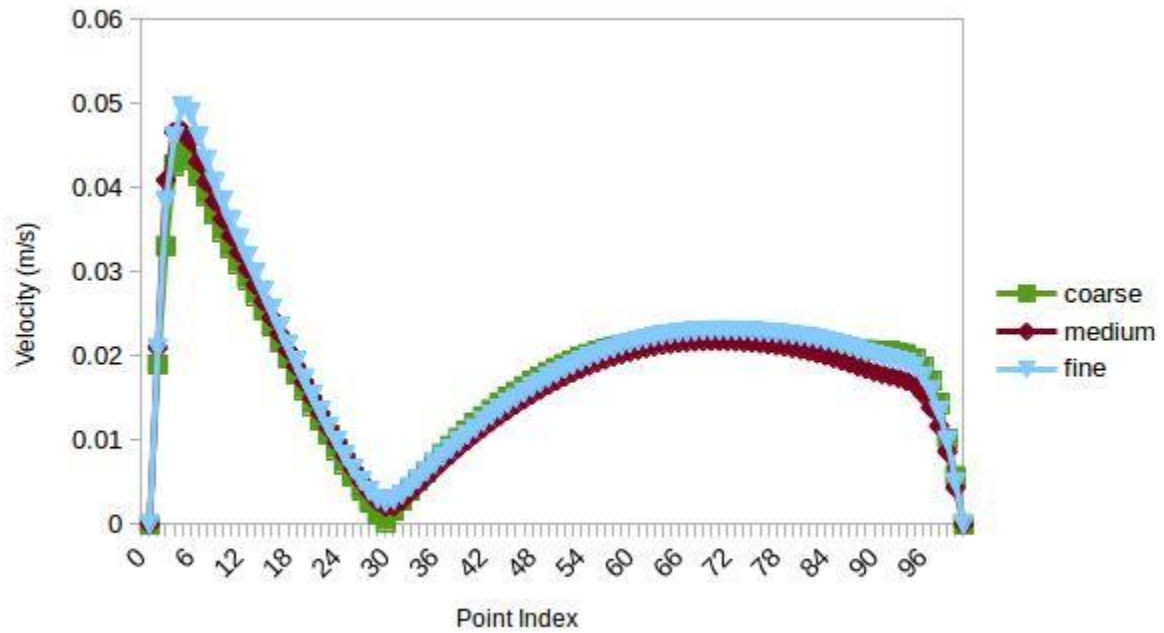


Figure 22: Mesh Sensitivity Results (in x-direction) for Vertical Manifold

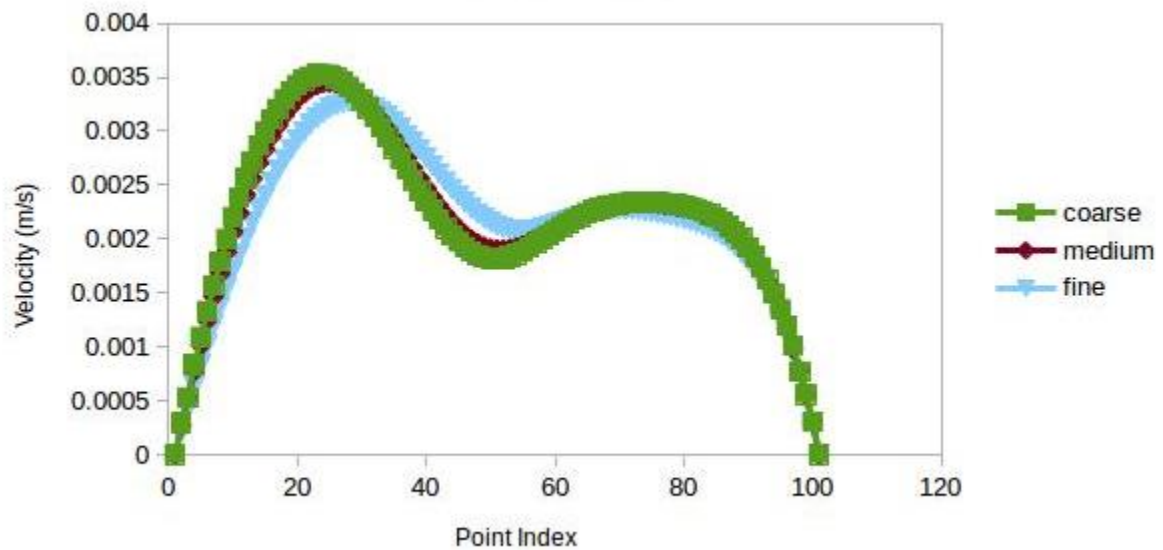


Figure 23: Mesh Sensitivity Results (in y-direction) for Horizontal Inlet

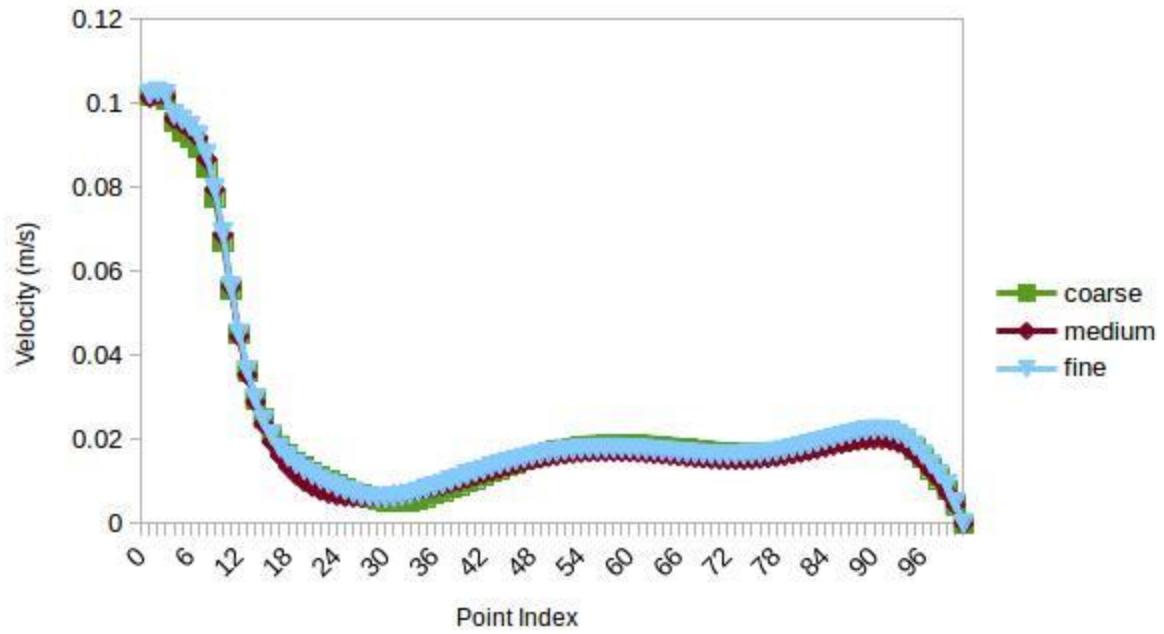


Figure 24: Mesh Sensitivity Results (in z-direction) for Vertical Manifold

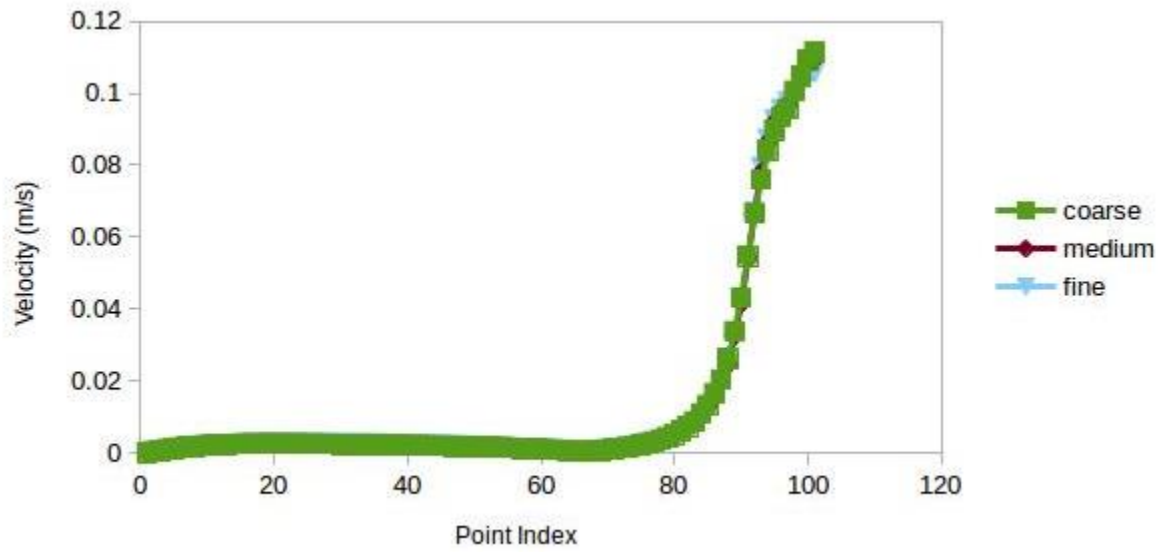


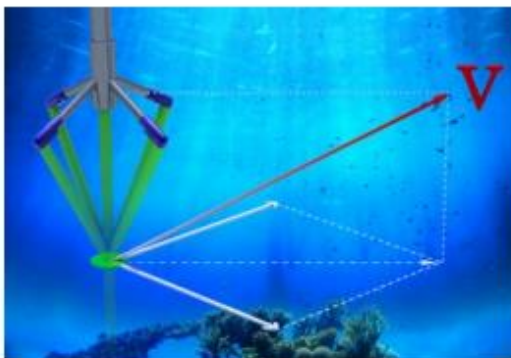
Figure 25: Mesh Sensitivity Results (in z-direction) for Horizontal Inlet

APPENDIX C

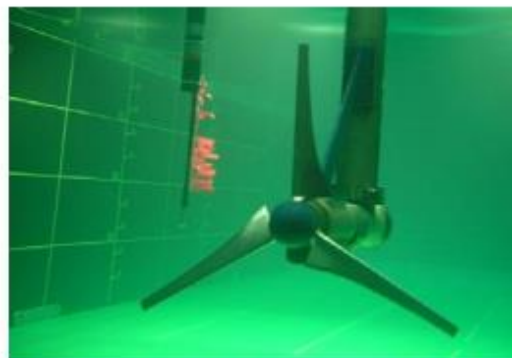
The Vectrino is a high-resolution acoustic velocimeter used to measure 3D water velocity in a wide variety of applications from the laboratory to the ocean in order to study rapid velocity fluctuations. The basis measurement technology is coherent Doppler processing, which is characterized by accurate data with no appreciable zero offset.

Vectrino

3D water velocity sensor
Lab Probe



The acoustic sensor has one transmit transducer and four receive transducers. The sampling volume is located away from the sensor to provide undisturbed measurements. Acoustic Doppler Velocimeters work by sending out a short acoustic pulse from the transmit element. When the pulse travels through the focus point for the receiver beams, the echo is recorded in each of the acoustic receiver elements. The echo is then processed to find the Doppler



shift, the scaling is adjusted with the measured speed of sound in the liquid (hence the temperature measurement), and the velocity vector is recorded or transmitted to a PC at a rapid rate. The Vectrino Lab Probe is used in a variety of laboratory applications for example in hydraulic laboratories to measure turbulence and 3D velocities in flumes and physical models.

CURRENT AND WAVE MEASUREMENTS IN THE OCEAN, LAKE AND LABORATORY



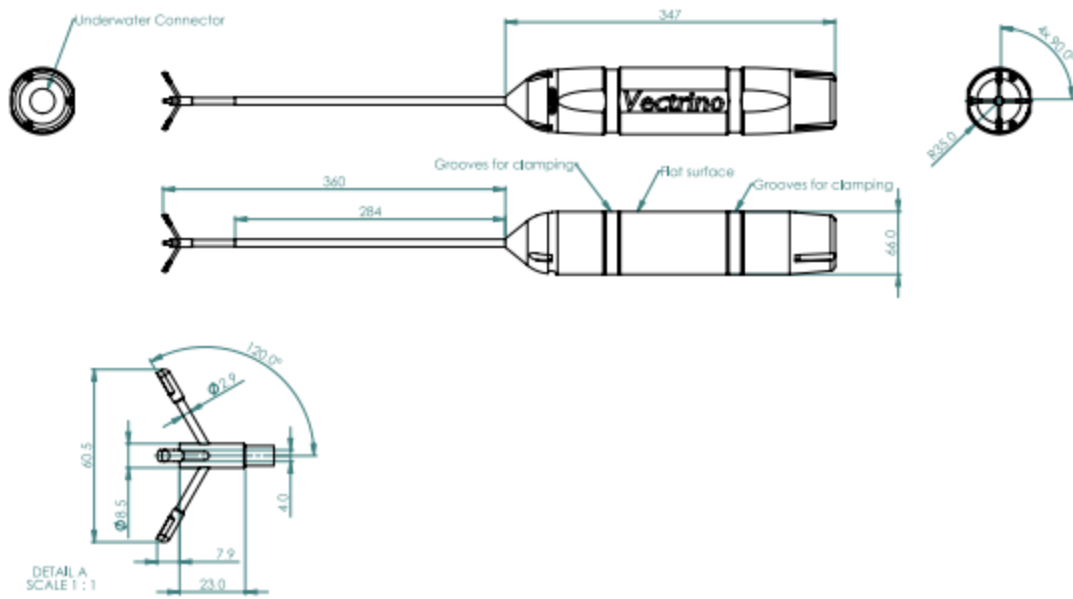
Nortek AS
Vangkrøken 2
1351 Rød, Norway
Tel: +47 6717 4500
Fax: +47 6713 6770
E-mail: inquiry@nortek.no



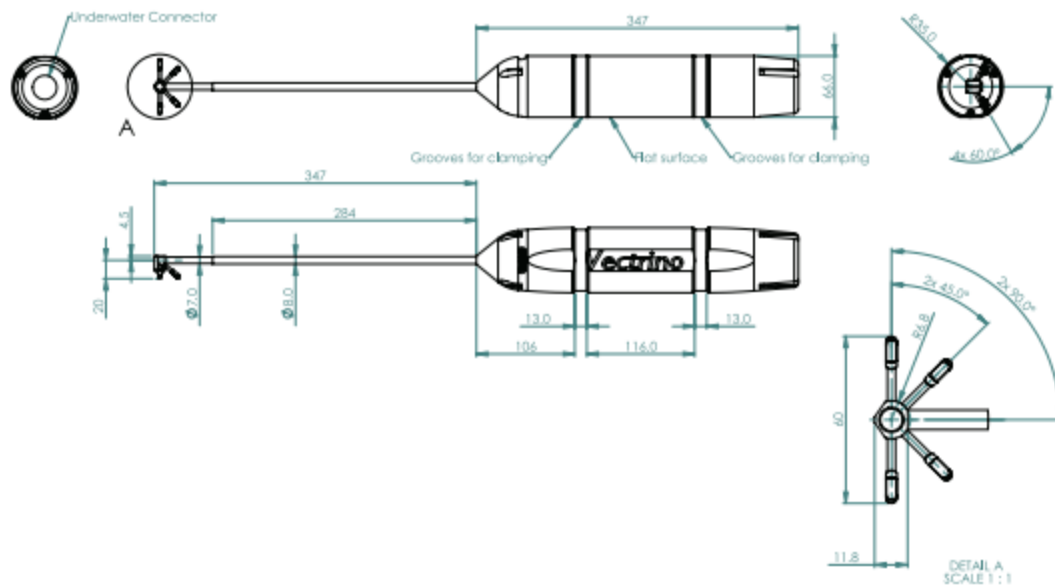
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True innovation makes a difference

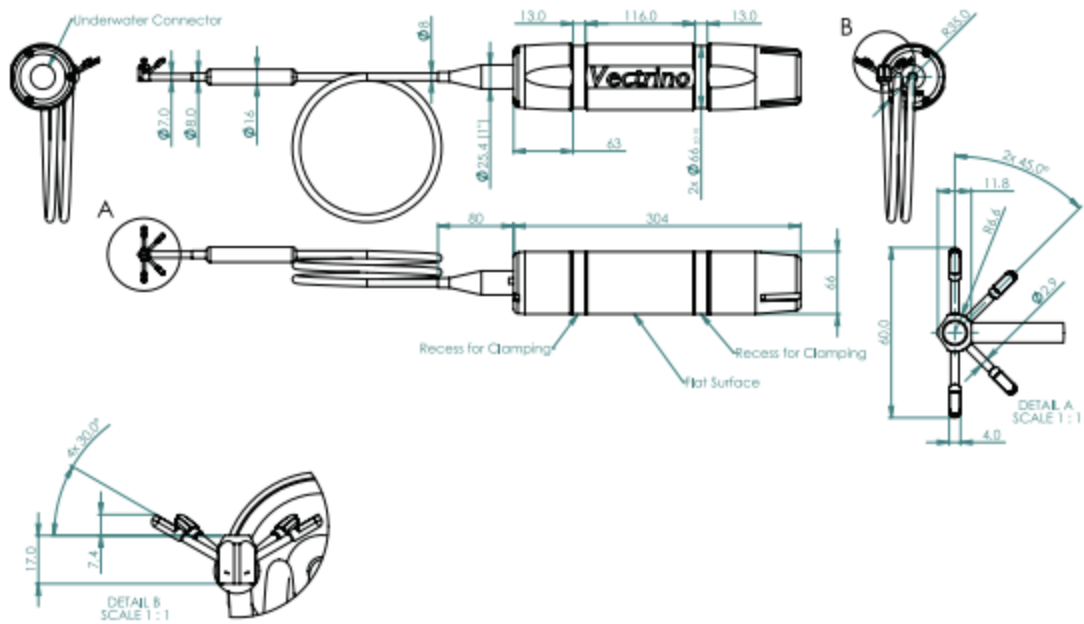
Vectrino 3D Downlooking, fixed stem



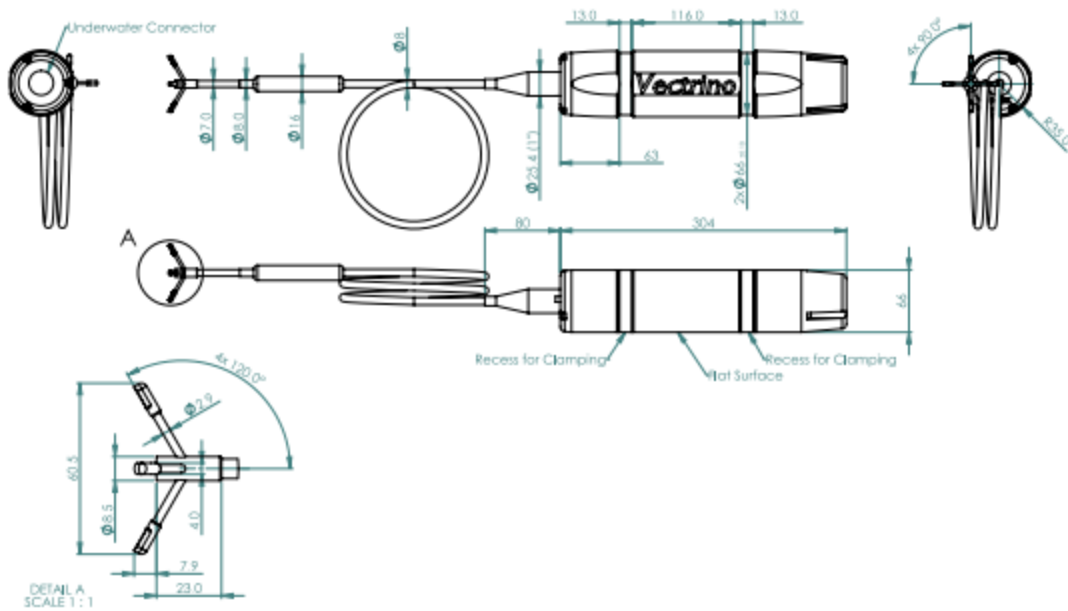
Vectrino 2D-3D Sidelooking, fixed stem



Vetrino 2D-3D Sideloooking, Cable Probe



Vetrino Downlooking, Cable Probe



All dimensions in mm.

Technical Specifications