



## Water Tunnel Design: A Senior Capstone Project to Promote Hands-on Learning in Fluids

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# **Water Tunnel Design: A Senior Capstone Project to Promote Hands-on Learning in Fluids**

## **Abstract**

Mechanical Engineering courses in fluid mechanics typically provide robust instruction into theoretical concepts, while often providing physical examples through lab demonstrations. In order to supplement this instruction with more hands-on design experience in fluid mechanics while also introducing students to naval hydrodynamics research methods, a senior Capstone design project is proposed in which students design and build a portable, affordable, low-speed water tunnel. Upon completion, this water tunnel will be used as a tool for both classroom demonstrations and for research in fluid mechanics and naval hydrodynamics.

This project is currently being implemented in an ongoing two-semester senior design course with a group of six senior mechanical engineering students. Throughout this project, the group has surveyed industry experts, performed a market analysis to identify industry standards and competition, developed an array of design concepts, and utilized knowledge acquired in earlier coursework to analyze the function of this device. As these students have moved through the Detail Design phase, they have extended their knowledge beyond their prior coursework in order to utilize the modern engineering tools necessary to analyze and manufacture individual components. While building and testing their device throughout the second semester of the course, the students have become familiar with state-of-the-art fluids measurement techniques that the water tunnel will need to accommodate, such as Particle Image Velocimetry and the practical realities associated with creating a research project from inception.

When completed, this water tunnel will serve as a tool for classroom and laboratory demonstrations in undergraduate-level courses related to fluid mechanics, as well as a resource in performing undergraduate research on a small scale. One of the capabilities of this device will be interchangeable test section models. This will allow for a variety of applications to different course topics and research ideas. The portability of the device will allow for use in a typical classroom setting rather than requiring a separate laboratory space, which should facilitate more frequent use in demonstrations.

This paper provides an overview of the primary aims of this senior design project, detailing the ways in which this design experience provides a unique platform for students to further their knowledge of fluid mechanics and build interest in hydrodynamics research. It also addresses the usefulness of the final design product towards developing undergraduate-level laboratory and classroom demonstrations, as well as providing a means of encouraging undergraduate research. Impact on student learning outcomes are also discussed.

## **Introduction**

Senior capstone projects have long been incorporated into undergraduate engineering programs as a means to provide a hands-on design experience. These design projects typically act as the

culmination of the entire curriculum, where students must apply fundamental concepts learned in their prior coursework and incorporate them in a novel context while working as part of a team. This type of project engages students in a more active learning environment, focused on the integration of prior knowledge to solve a complex engineering problem [1]. This allows students to develop deeper understanding in specific fields, a skill that is necessary to develop expertise in engineering [2]. Students work together in teams, preparing them for the collaboration necessary in future employment. This also promotes cooperative learning, which has been shown to produce better learning outcomes [3].

Within fluids education, hands-on learning experiences are typically reserved for laboratory demonstrations using large, expensive, or inaccessible equipment. While valuable for giving students active and visible examples to help in developing their intuition, these laboratory demonstrations are typically characterized by pre-made devices and pre-determined outcomes. Undergraduate and graduate research often fosters open-ended, fluids-based design experiences. Experimental fluids research typically requires the design and construction of a flow testing facility, development and assembly of measurement systems, and collection and interpretation of data. These experiences speak to the open-ended, design-based nature that typical laboratory demonstrations do not possess.

Incorporating research into a classroom environment could provide the experiential learning that is often lacking in fluids education. Teaching and research are often viewed as being at odds for time, space, and money within a university context. Telenko et. al. [4] argue that creating synergies between research and design-based learning is mutually beneficial to faculty research and student learning.

Water tunnels have been utilized as a tool in hydraulic and naval research since the late 1800s [5], and their applications have grown to include research into areas as varied as drag reduction [6], flapping wings [7], fishlike swimming [8], sand dunes [9], and heart valves [10]. With the technological improvements associated with the advent of computers and improvement of camera technology, quantitative optical measurement techniques like particle image velocimetry (PIV) [11] have become the standard in fluid mechanics, and water tunnels are ideally suited for these techniques.

Using Reynolds number similarity, which characterizes the ratio of inertial forces to viscous forces, the flow field in any Newtonian fluid can be considered to behave in the same manner. Using this idea, the use of water tunnels is also common practice in studying aerodynamics [12], which provides certain benefits over wind tunnels. In order to achieve the same level of turbulence, a water tunnel can use a considerably lower flow speed than a wind tunnel. This allows for improved visualization of the flow, making it an ideal demonstration tool. When utilizing optical measurement techniques, tracer particles must be injected into the flow and should be small enough and neutrally buoyant enough to faithfully follow the flow, conditions that are more easily met in water than air. This means that experiments on the same flow phenomenon can be performed more easily and inexpensively in a water tunnel than in a wind tunnel. Still, the flow similarity between them means that the techniques used in each remain the same.

The senior capstone project discussed herein has two main goals: to provide a hands-on, design-based experience within fluid mechanics that integrates research into the classroom, and to create a functional water tunnel that can be used in both classroom demonstrations and in small-scale research in an integrated way.

### **Course Structure**

Senior design projects at The Citadel are created as part of a two-semester senior capstone course sequence in which design projects are a mix of faculty-sponsored projects from multiple departments on campus and projects fostered through industry partnerships with local companies. During the end of their junior year, students are presented with project ideas and have the opportunity to propose their own, after which each student ranks the projects according to preference. The faculty determines team assignments based on estimated necessary team size, funding availability, and this preference sheet.

The first semester of this course focuses on design, while the focus of the second semester is building and testing a fully functional prototype. Students begin the course with assignments relating to the project concept, technical requirements, and constraints in which each team meets with a faculty advisor or client to determine the scope of the project and required deliverables. Following this, each team performs a literature review and market analysis in which they perform a patent search and determine market competition for their project, perform a literature review in order to find resources outside of the classroom that will aid in the engineering design process, and distribute surveys to determine critical customer requirements. After the project concept and target market is fully conceived, students are tasked with creating preliminary concepts in which they generate hand sketches or 3D models of different design permutations for major subsystems. Following this, each team performs a functional decomposition, engineering analysis, and unit cost analysis in order to determine the criteria by which their preliminary designs will be compared. Using these criteria, each team selects a final design concept, generates a detailed final design, and creates a bill of materials to be ordered over the break between semesters. Upon design completion, each team generates a final design report as well as a final design presentation that is delivered to a group of students and Mechanical Engineering faculty.

At the beginning of the second semester, each team is tasked with identifying a short-, medium-, and long-term milestone in the development of the design prototypes. Throughout the semester, each student design team presents their prototype at these pre-defined milestones, demonstrating functionality of various subsystems as they are constructed. After nine weeks, students begin transitioning from the construction phase into the testing of their prototypes, developing a plan of experimentation to test the feasibility and performance of the critical customer requirements set forth at the beginning of the course sequence. This experimental data is then compared with theoretical predictions generated as a part of the engineering analysis during the design phase. At the end of the semester, each team presents their final prototype and comparative engineering analysis to a group of students and Mechanical Engineering faculty.

## **Project Definition and Market Analysis**

The water tunnel design project is currently in progress by a team of six senior mechanical engineering students at The Citadel. At the beginning of the senior capstone course sequence, these students were given project requirements by their faculty client which included the following criteria:

- Entire apparatus should be mounted on a board/plate/etc. for easy transport
- Entire apparatus should fit within a 3 ft x 3 ft x 2 ft volume or less
- Test section should be at least 1 ft long with a cross sectional area 3 in wide and 8 in high (water level will never be higher than 6 inch high, extra 2 inch height to prevent spillage)
- Water speed must be variable from 0 m/s up to 0.5 m/s in the test section
- A flow straightener should be installed upstream of test section to reduce turbulence
- 3D printed parts should be mountable in test section with no leakage from test section
- Test section must be constructed from clear material for flow visualization

This team was also given a general budget constraint of \$300 to \$500 for all materials and outside labor, but were tasked with developing their own budget through the engineering design process.

Through the process of performing a literature review and market analysis, the students discussed the project with multiple faculty members as well as industry experts in water tunnel design. The team found that water and wind tunnels are hard to come by in most small labs. Water tunnels are typically fairly large in size, taking up most of the space in a traditional classroom setting. Smaller scale test tunnels are difficult to find; most distributors deal solely in industrial and commercial tunnels designed for product testing and experimentation. As such, universities, high schools, and other educational institutions often lack the means to obtain a water tunnel, where research money must be spent wisely and lab space is a finite resource. The result is a severe lack of practical application and understanding, key for grasping the abstract concepts and tendencies of chaotic water and air flows. Water tunnels offer the foundational practical knowledge that companies are looking for. Motor vehicle and airplane manufacturers use air and wind tunnels regularly in their product analysis. It should be expected that students, their future employees, have some form of exposure to their methods of testing and analysis. Of particular interest to students at The Citadel is the steady rise of science and engineering that comes with the continued expansion of automotive and aerospace companies in the Charleston area. Institutions of higher learning must seek to match rises in the occupational field in order to prepare their students for their eventual careers. This product will offer institutions an affordable option that still produces practical test results.

## **Functional Decomposition and Preliminary Design**

Once the scope and objective of the project was clearly defined, the students began the design process by creating a functional decomposition. This allows the product function to be understood before the form is fully realized, leading to more creative ideation when preliminary

design concepts are generated. The functional decomposition of the water tunnel is shown in Figure 1, which breaks the device into functions rather than components.

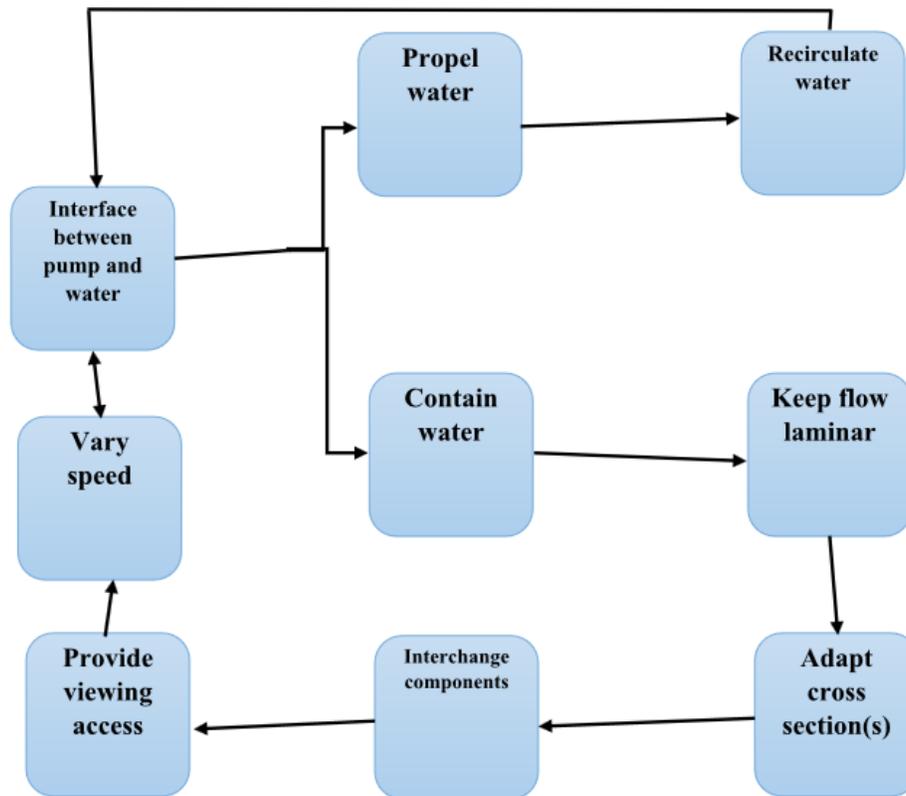


Figure 1: Functional Block Diagram

Using this diagram, the students began to generate preliminary design concepts in order to identify the critical design decisions and the overall form of the product. The original design, shown in Figure 2, included basic features of the design: a pump to drive the flow, a PVC pipe loop to recirculate water, a rectangular test section to provide optical access, a flow control mechanism to vary the speed, and a nozzle/diffuser to adapt the cross section. In addition to the overall form of the device, a number of design decisions became clear using these methods.

The first design alternatives centered around the most expensive and critical component: the pump. Pumps take a number of different forms, with the most common pumps of the necessary size and speed range falling into the categories of end-suction pumps (common among pool pumps) and submersible pumps (common among sump pumps). While end-suction pumps have a completely enclosed inlet and outlet for the water to flow, submersible pumps sit fully submerged in a fluid. Submersible pumps are typically cheaper, but the plumbing configuration required for this application is somewhat more complex. The second design alternative for the pump was whether to purchase a variable speed pump, which controls the flow speed electrically, or to utilize a fixed speed pump in conjunction with a flow control valve to vary the flow speed. While variable speed pumps are more expensive than their fixed speed counterparts,

flow control valves typically produce very large pressure drops so that the flow can be accurately adjusted, necessitating the use of a larger pump.

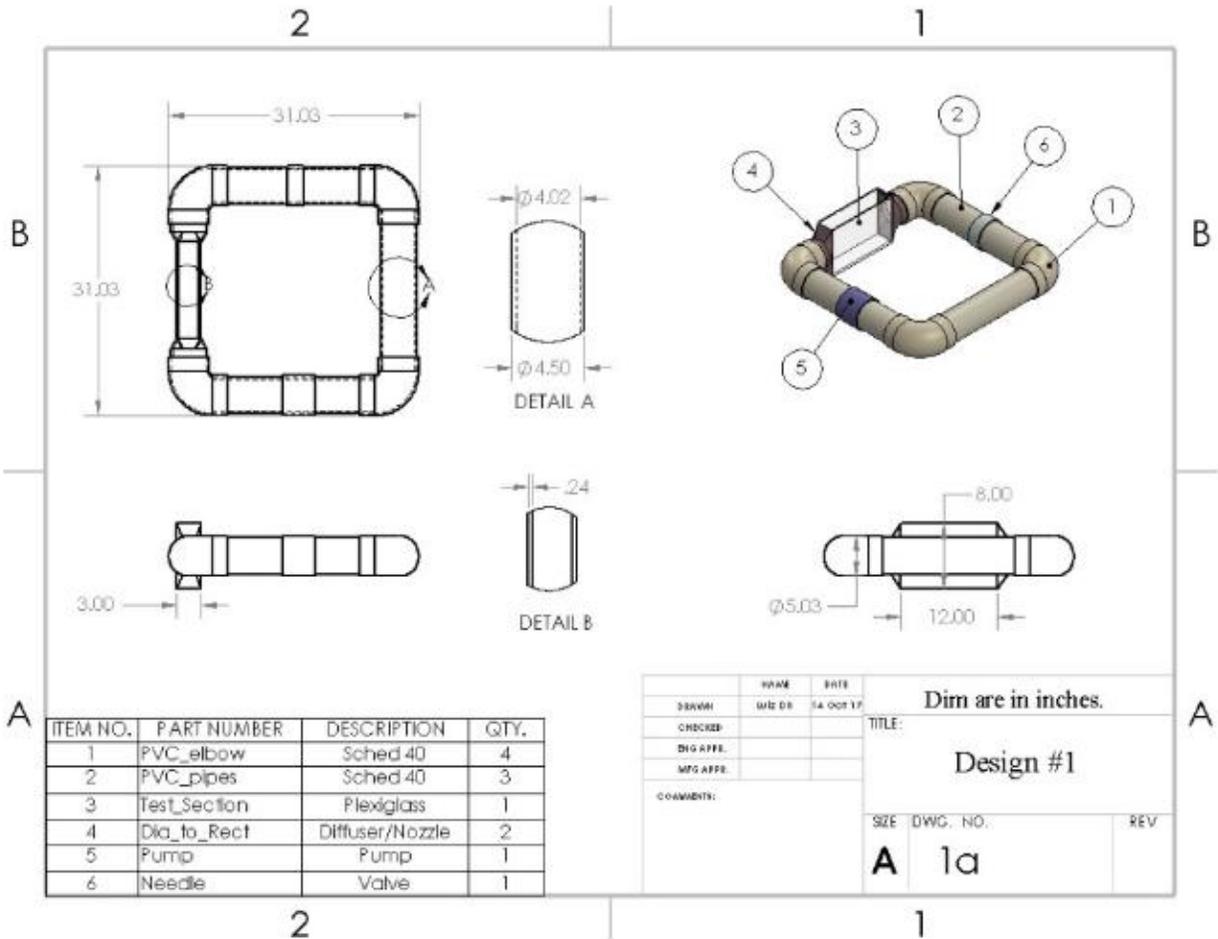


Figure 2: Preliminary Design Concept of the Water Tunnel

The next design alternatives dealt with the straightening the flow to reduce free-stream turbulence in the test section. While screens are sometimes used in wind tunnels, honeycombs are often more effective at reducing turbulence in water tunnels [13]. The first design idea for creating a honeycomb was to bundle straws together. As they pack together, they form a hexagonal pattern with small gaps in between. The alternative to this was to 3D print a honeycomb pattern using nylon or ABS plastic. While 3D printing gives more customization to the size and shape of the honeycomb, the small wall thickness of the straws means that they block less of the flow and give a smaller pressure drop. Other considerations touched on the length of honeycomb, its placement in the loop, and the manufacturability and durability of the final product.

The final set of design considerations dealt with the mounting structure for the water tunnel. In the preliminary design shown above in Figure 2, the diffuser is symmetric about a horizontal plane, which is ideal for reducing its expansion angle and delaying flow separation. However,

this creates the issue of the test section extending below the bottom surface of the PVC pipe and if the test section sits on a mounting plate, the pipe is left suspended in the air, leaving it susceptible to damage. One solution to this problem is to create legs to support the PVC, as shown in Figure 3, which is a fairly simple solution, but not preferred due to its lack of stability. The second idea, shown in Figure 4, is to create an asymmetric diffuser, which only extends up from the bottom surface of the PVC loop. This allows the entire bottom surface of the water tunnel to sit on one plane so that it can all be secured to one surface. The downside of this idea is that the diffuser angle is greater in one direction, which could affect the flow in the test section.

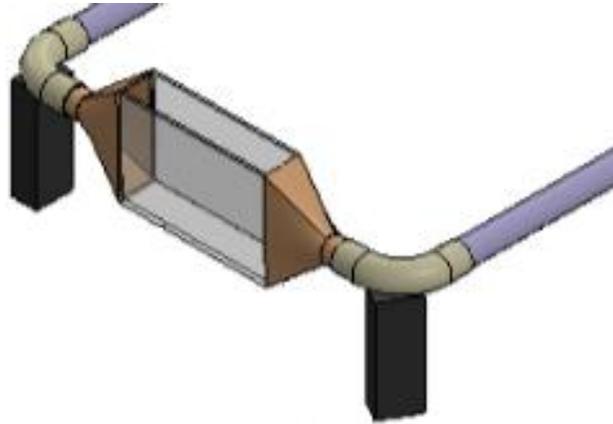


Figure 3: Preliminary concept for creating a mounting structure

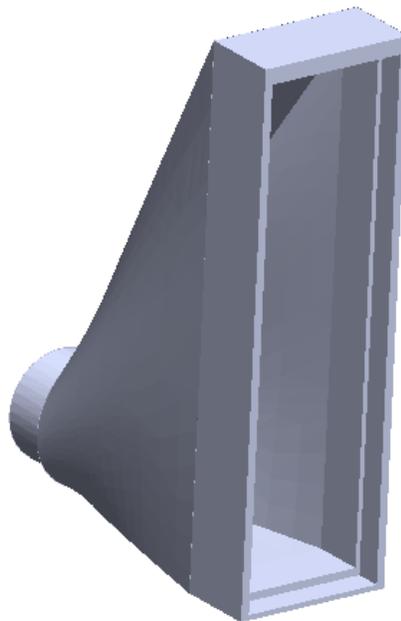


Figure 4: Asymmetric diffuser design concept that allows the PVC to sit on the same plane as the bottom of the test section

After analyzing each of these design alternatives, the senior design team determined that the design should include a submersible variable speed pump, 3D printed honeycomb to be placed after the diffuser, and an asymmetric diffuser, as shown in Figure 5. Using this final design, the team performed an engineering analysis using Bernoulli's Equation with head loss in order to determine the necessary flow rate and pressure output of the pump. From this, they generated a bill of materials, included below as Figure 6, with an estimated cost of \$418, considerably less than the cost of commercially available water tunnels.

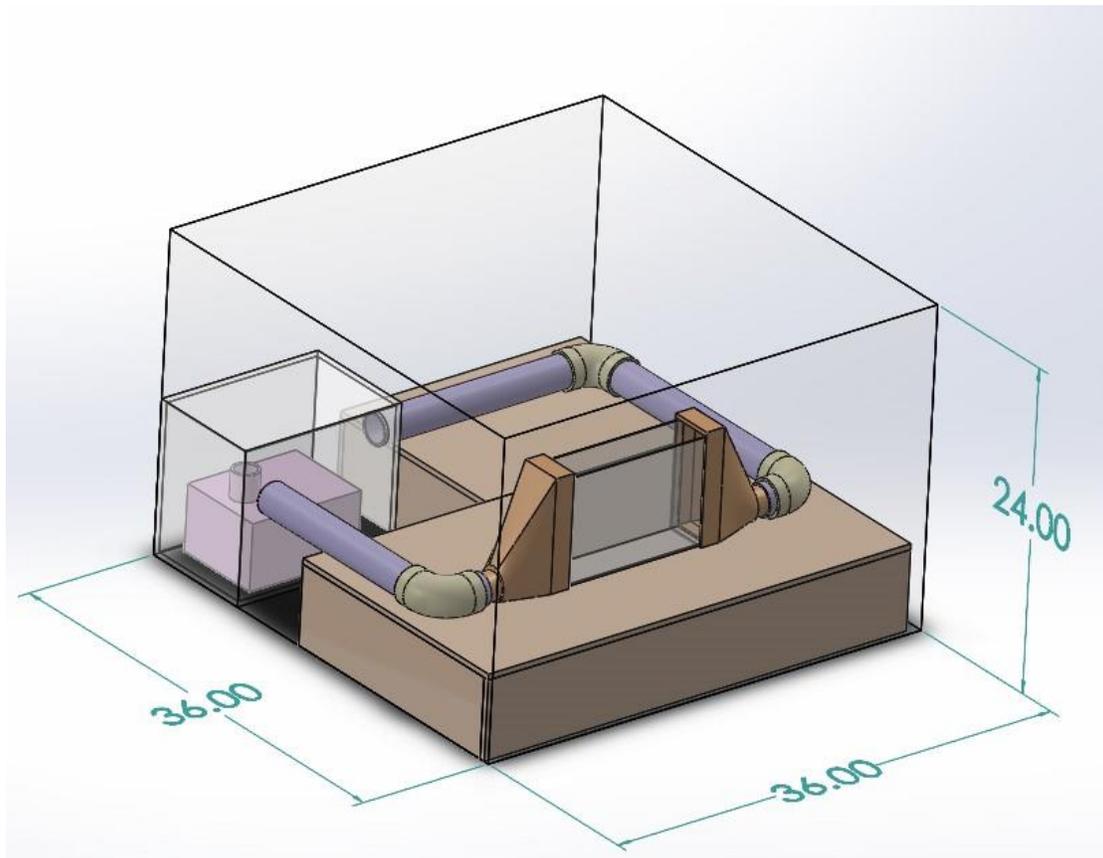


Figure 5: Final design concept

Item Discription	Item #/ Part #/ Serial #	Qty	Cost per Item	Subtotal	Unit Cost Analysis
1.5 in. x 10 ft. 280-PSI Schedule 40 PVC DWV Plain End Pipe	Model # 531137	1	8.31	8.31	8.31
1.5 in. Schedule 40 PVC 90-Degree Elbow	Model # C406-020	4	2.70	10.80	2.7
3" X 4" X 4" SDR 35 PVC SOLVENT WELD DOWNSPOUT ADAPTER	SKU 6513	2	3.94	13.43	6.72
4 in. x 2 in. PVC DWV Hub x Hub Reducing Coupling	Model # C4801HD42	2	6.47	12.94	6.47
16 oz Heavy Duty Gray PVC Cement	Model # 311213	1	10.72	10.72	10.72
Optix 36in. X 48in. X .093 in. Acrylic Sheet	Model # MC-09	1	42.98	42.98	3.58
Made in USA - 1 Ft. Long, 1/8 Inch Diameter, Nylon 6/6 Plastic Rod	#63393292	1	0.47	12.07	12.07
#1-72 x 1/4 in. Phillips Pan-Head Machine Screw (50-Pack)	Internet #204775290	1	5.46	7.46	0.55
Little Giant 509204 95N-CIA-RF Submersible Effluent Pump	Model # 95N-CIA-RF	1	225.26	225.26	225.26
Flow Straightener (3-D printed)	N/A	1	N/A	N/A	2.05
3D Printed Support for Pipes	N/A	3	19.98	59.94	59.94
Plastic Box for Pump Submersion DC1813-15 18 x 13 x 15	T9F270281GY	1	14.50	14.50	14.5
			Total	418.41	352.87

Figure 6: Final design concept bill of materials

## Prototype Generation and Preliminary Testing

At the completion of the first semester, each design team in the course placed orders for major components based on their final designs so that those parts could be shipped over the winter break. During the second semester of the course, the student design team was tasked with generating a prototype based on their paper design. To accomplish this task and demonstrate progress throughout the semester, each team established short-, medium-, and long-term milestones that correspond to the completion of subsystems of their design. At each of these milestones, the team demonstrated specific functionality of their prototype in front of the class, while discussing design challenges and updates to their build timeline.

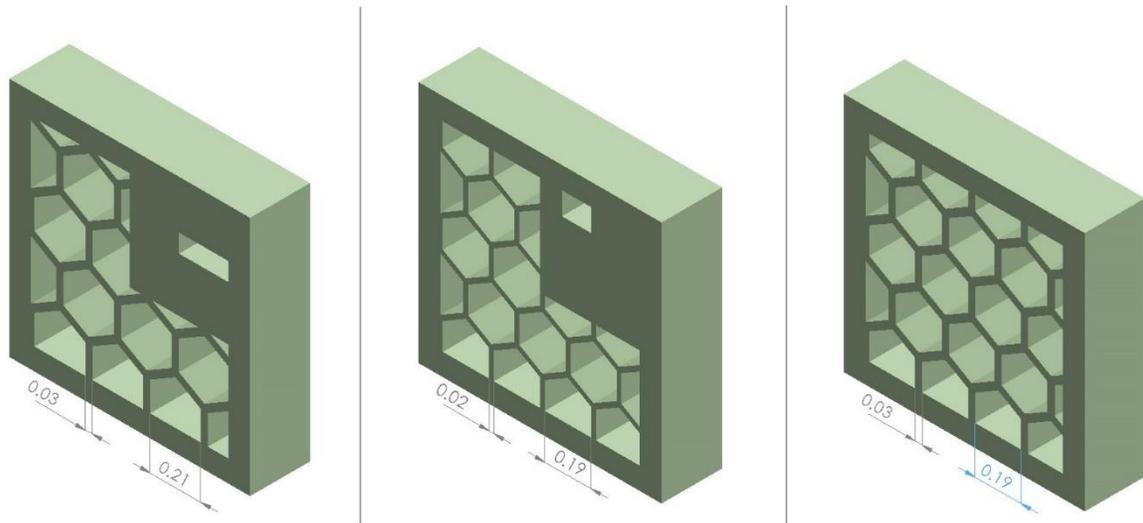
The first milestone for the water tunnel design team was to cut all of the PVC pipe necessary for the plumbing of the water tunnel and dry-fit the pump into its reservoir. The deadline for this milestone was week 3 of the semester in order to get students kick-started in their build process. Because the pump is submersible, it must sit in a reservoir from which it draws water, as shown in Figure 7. This reservoir must remain filled to an acceptable level as the pump operates so that air is not pulled through the pump and eventually transported through the test section. Because of this, the team decided to set the reservoir lower than the flow loop, which was built on a raised platform.



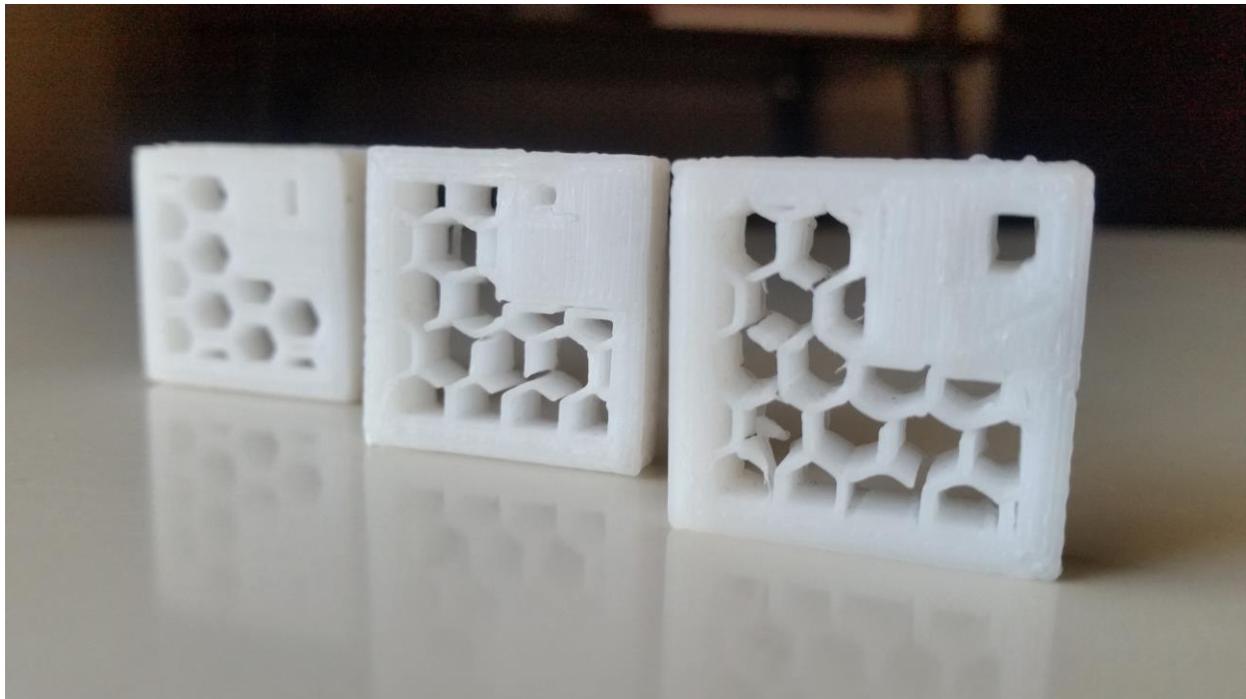
Figure 7: Submersible pump dry-fitted in reservoir

The second milestone was to build the test section, which included cutting acrylic pieces for the walls of the test section viewing area, manufacturing the diffuser, nozzle, and flow straightener, and assembling these components. This completion deadline was week 6 of the semester, giving the students ample time to 3D print multiple iterations of components. Many of the design issues for this milestone arose from print tolerances of the 3D printer available to the students. Initial

prints of the flow straightener resulted in disconnected sections of honeycomb, most likely due to the honeycomb wall thickness not being equal to an integer multiple of the extrusion thickness of the 3D printer nozzle. In order to test various design iterations, multiple smaller models were created with varied parameters so that multiple parts could be printed at once and compared, as shown in Figure 8. Once an acceptable configuration was found, the students printed a full scale version to fit inside the diffuser, as shown in Figure 9, and assembled the test section.



(a)



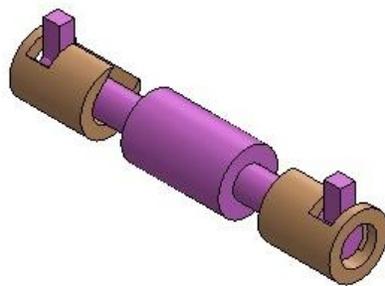
(b)

Figure 8: Multiple iterations of honeycomb design shown as (a) 3D models and (b) printed parts



Figure 9: 3D printed diffuser with honeycomb insert

The third milestone, which occurred during week 11 of the semester, came after the final assembly of the main structure of the water tunnel and included the mounting method for interchangeable test pieces into the test section. The initial design of this mounting method is shown in Figure 10a and is made up of three pieces. In this design, a stationary mounting bracket would have been glued onto each wall and each interchangeable 3D printed test piece would include notches to snap into each end of the mounting bracket. As the design team developed a prototype for this initial design, they realized that increased flexibility in the mounting height of the test piece would be beneficial to future applications in the classroom, and supports that are fixed to one wall location reduces this flexibility. The students decided to change the design to that depicted in Figure 10b, which utilizes powerful magnets on either side of the clear test section wall to keep the test piece fixed in place. Because the magnets are not permanently fixed to the wall, this allows the user to mount the test piece at any vertical or streamwise position in the test section.



(a)



(b)

Figure 10: Method for interchanging test pieces in (a) design phase and (b) final configuration

With the completion of these individual subsystems, constructing the final prototype was a simple matter of assembling them into a working device, shown in Figure 11. After completion of the construction phase, the students began testing the functionality of the water tunnel to determine how well their design met the customer requirements set forth in the design phase. To provide a proof of concept, the primary requirement that the students tested was the desired flow speed in the test section. To accomplish this, the students utilized elements of Particle Tracking Velocimetry (PTV), in which they introduced particles into the water tunnel, recorded movies of the flow, and tracked the path of individual particles frame-by-frame. An example image from their analysis is shown in Figure 12. Using this method, the students recorded video, correlated pixel spacing to real-world coordinates using a ruler placed in the frame, and determined the distance traveled by a particle between frames, which corresponds to a known amount of time. Using this method, the students determined that the average flow speed reached 0.262 m/s at a medium pump flow rate setting. Measurement of higher flow rates was rendered impossible due to the limited frame rate of the available recording devices.



Figure 11: Completed final prototype

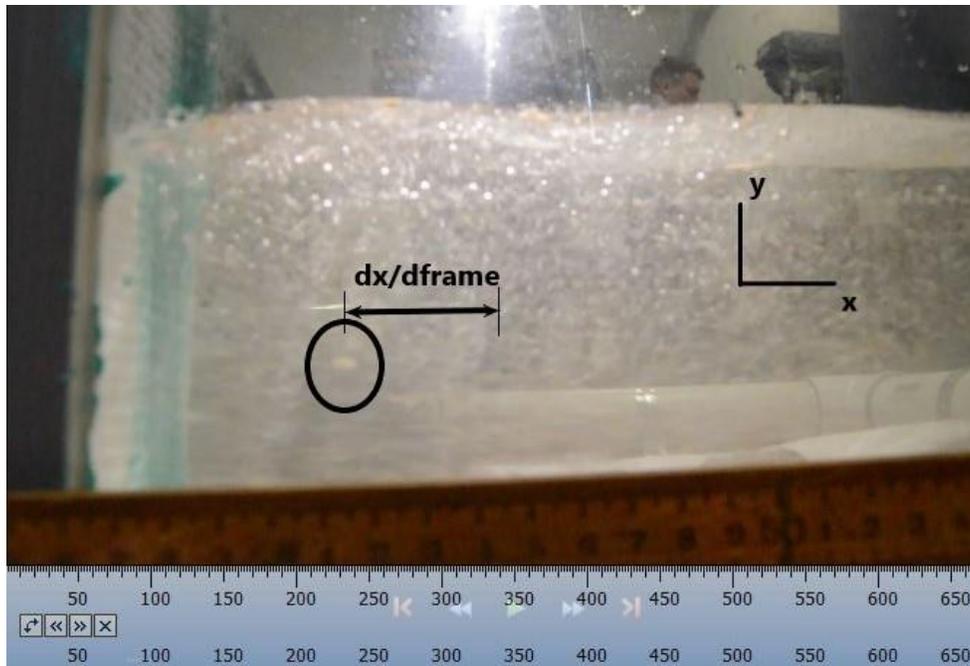


Figure 12: Sample image from flow testing of the water tunnel

### Learning Outcomes and Future Considerations

The development of this water tunnel prototype up to this point has resulted in a unique design experience within the mechanical engineering curriculum, demonstrated by the wide range of ABET student outcomes addressed throughout this project. The project definition assignment tasks students with formulating an engineering problem definition given a range of requirements and constraints, which involves ABET Criterion 3 [14], Student Outcome (c), an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability. The following assignment, in which students perform a market analysis and literature review speak to Student Outcome (h), the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.

The functional decomposition and preliminary design assignments tasks students with identifying the necessary function of the device as well as applying engineering principles to formulate solutions. This addresses Student Outcome (e), an ability to identify, formulate, and solve engineering problems.

Throughout the second semester of the course, the students worked to construct and test their design, learning practical realities and methods of manufacturing. Once construction was complete, the students began to integrate this product into research activities by measuring the flow field generated in the test section, which both tested their engineering analysis as well as characterized the water tunnel for future experiments. In doing this, these students learned about state of the art optical measurement techniques like PIV and PTV, giving them access to knowledge and training of methods used in industry through experiences not typically available to undergraduate students in their coursework. These experiences are reflective of Student

Outcome (k), an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Each semester of the course culminates in the students formulating design documentation as well as presenting their final designs and prototypes to a large group of students and faculty, addressing Student Outcome (g), an ability to communicate effectively. Throughout the entire design, prototyping, and testing process, students need to function effectively as members of a team, which feeds into Student Outcome (d), an ability to function on multidisciplinary teams.

Once completed, this water tunnel will become a valuable tool for use in research and fluids demos. As a demonstration tool, the optical access in the test section will permit viewing of a given flow field from all directions. Interchangeable models will allow for use of the tunnel in demonstrations on a variety of topics, and will allow students to design and 3D print their own models to perpetuate this hands-on design experience in fluids to students in future years. This feeds directly into Student Outcome (b), an ability to design and conduct experiments, as well as to analyze and interpret data. If students are required to learn and use PIV processing software, this activity could also be tied into Student Outcome (i), a recognition of the need for, and an ability to engage in life-long learning. Several other student outcomes could easily be included if desired.

As a research tool, the water tunnel will provide an easy-to-operate and versatile tool for studying fully submerged models. Its open surface will also allow for the study of free surface flows. In particular, when turbulence interacts with the free surface, the resulting disturbances can be so mild so as not to create any noticeable effect on the free surface, or so disruptive as to break up the free surface leading to air entrainment and droplet production [15]. This wide range of available demonstrations will allow students to utilize this tool in diverse demonstration and design activities throughout their fluids education, fostering their engagement and intuition with fluid mechanics.

## **Conclusions**

This paper describes a senior capstone project in which students design and build a classroom-scale water tunnel. The goals of this project are twofold: to provide students with a hands-on, design-based experience in fluid mechanics, and to create a small-scale water tunnel to be utilized in classroom demonstrations and faculty research. This water tunnel project is currently in progress as part of a two-semester senior capstone course at The Citadel. In the second semester of this capstone course sequence, students manufactured this water tunnel and were exposed to undergraduate research using state-of-the-art measurement techniques to characterize the tunnel. To this point, it has provided a unique design experience, addressing many of the ABET student outcomes, and has provided an active learning experience designed to engage students in fluid mechanics. This combination of faculty research and student learning provides mutual benefit to all those involved including the sharing of time, effort, and funds across both areas.

Once completed, this water tunnel will be utilized in a wide variety of interactive and design-based fluids demonstrations and activities in the classroom. This will continue to provide

interactive fluids educational experiences that will allow students to develop intuition and deep understanding of fluid mechanics. Future work will involve the characterization of the flow generated in the test section, testing of a variety of test pieces, and the development of fluids laboratory demonstrations and exercises around this water tunnel.

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