Design and Build a Water Channel for a Fluid Dynamics Lab

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Abstract

Water channels are used for a variety of educational and research purposes including hydrodynamic and aerodynamic studies. The design, construction, and operation of such facilities involve numerous engineering challenges that make it a well-suited choice for an undergraduate capstone project whose emphasis is on multidisciplinary engineering capabilities, exposing to research, and learning and applying state-of-the-art methodologies. Since there was a need to build a water channel facility for the new Fluid Discovery Lab at Penn State University at Berks, a project was defined and presented to the Electro-Mechanical Engineering Technology (EMET) students as an option for their Senior Capstone Project courses (EMET 403 and EMET 440). The specific engineering focus of this project included the following: a) framing support structure and glass test section design, b) pump selection, c) flow conditioning to enable laminar freestream flow, d) controls with implementation, and e) filtration analysis. In fact, this project reinforced the goals of the degree program by providing problems that required knowledge in Electrical Engineering, Mechanical Engineering, and Controls Engineering. Students not only had to employ their engineering skills to design and implement, but also were confronted with time and budget as well as interacting with different vendors. In particular, students had to combine their knowledge in the field of Statics, Strength of Materials, Fluid Mechanics, PLC Programming, Instrumentation, Computer Aided Design (CAD), and Economics. The students found themselves to be fortunate to choose this project and they were very committed to its completion. However, the farther they got into the project, the more they realized it was a much larger task than they initially thought. During the design stage, it took a long time to create a structure in SolidWorks that would meet the project requirements, while staying within the budget. It also gave the team a new insight for what could be considered as a small scale project in an industrial environment. Verbal and technical communications along with an effective documentation were the key factors for the water channel construction in an efficient manner. The team put significant effort into providing a high quality facility that can be used for teaching and research purposes. While the design project worked well as a capstone project, the constructed water channel will be used as a valuable facility in both Mechanical Engineering and Electro-Mechanical Engineering Technology programs.

1. Introduction

Fluid Dynamics is an inseparable part of the Mechanical Engineering world and many universities include lab activities in the area of Fluid Dynamics in their curriculum. However, commonwealth campuses have very limited access to laboratory facilities where real life research experiences can take place. Previous studies such as Kubesh and Allie's have stated that the design and construction of a wind tunnel suitable has proved to be an economical addition to a course on fluid mechanics, since it provides valuable hands-on experience to complement theoretical coursework ^[1]. John and Matin also have reported that extensive engineering knowledge was acquired throughout the undergraduate study of shearing forces developed in the boundary layer ^[2]. This motivated the faculty at Penn State Berks to build a water channel through a capstone project for educational and research purposes. Water channels are sometimes used in place of wind tunnels to perform measurements because techniques like particle image velocimetry (PIV) are easier to implement in water. The water channel allows students to gain a better understanding of fluid flow studies through dye flow visualization and hands on

experiments. It also provides a facility for undergraduates and faculty to conduct research at Berks campus without being tied with governmental regulations and restrictions like other water tunnels at Penn State University at University Park. Moreover, K-12 students will have the opportunity to visit and learn about the beauty of fluid dynamics through colorful flow visualization, encouraging them to pursue STEM programs. The water channel for this study was designed based on the wind tunnels because there exists a significant body of knowledge describing the topology of the flow field and measurements of wind tunnels. Complementary information about wind tunnels, water channels, and other experimental facilities can be found in recommended literature ^[3-9]. The focus of this paper is on describing the design and construction of the circulating water channel facility at Penn State Berks and especially, the educational aspects of this project.

2. Water Channel Specifications and Design Process

The objective of this work was to engage undergraduate engineering students through a multi-disciplinary study to design a water channel for instructional purposes. The needs of a water channel facility for the Engineering programs at Penn State Berks were justified in Fall 2015. Subsequently, the students in the Fluid Mechanics course in Spring 2016 were asked to identify a water channel that is in use for Undergraduate Research or Teaching at other academic institutes and write a short report on that. The reports provided some information regarding the dimensions, required space, and potential teaching and research applications. The room reconstruction to house the water channel was performed in Spring and Summer of 2016. A selected group of four students in the Capstone Project Course (Summer and Fall 2016) provided a brief review that compared some possible designs of water channel facilities. They also visited three water channels in local institutes ^[10] prior to Summer 2016 and had the chance to see the advantages and disadvantages of different designs. Dr. Sabatino thoroughly explained the design process for a water channel and sounded it doable through a capstone project.

The designed water channel is 22 ft long and 7.5 ft high. A schematic of the channel is shown in Fig. 1. The inlet and end tank walls are fabricated from polyvinyl chloride (PVC). The framework is constructed of anodized extruded aluminum members from 80/20. The test section is constructed of low-lead ultra-clear float glass for excellent light transmission and has a cross section area of 30 in width and 24 in height. The project was heavily relied on Fluid Dynamics and Strength of Materials. Structural components including glass, PVC, and aluminum extrusion frames were verified for strength and safety. Other mechanical aspects included being able to keep the flow laminar in the contraction section, as well as test section. This laminar flow channel has a close-coupled centrifugal pump with a variable frequency drive (VFD) for control of the free-stream velocity up to 3.3 ft/s. The maximum Froude number for the 24 in depth water at maximum flow speed will be 0.42 which indicates the subcritical or tranquil flow ^[4]. The pump serves as the main drive of the entire system and dictates the flow speed and quality. The VFD is controlled by a user friendly programmable logic interface (HMI) on the control console. The PLC/HMI also controls a filtration loop electronically with a series of electronic components ranging from pressure transmitters to solenoid valves. All of these components need to work together in order to create a water channel with laminar flow.

Figure 1. (a) The SolidWorks model of the water channel indicating its main sections: 1) inlet tank, 2) contraction section, 3) test section, 4) end tank, and 5) pump; (b) The constructed water channel.

2.1. Framework Structure

The framework is constructed of anodized extruded aluminum members from 80/20 to give the channel a high degree of rigidity and stability. 80/20 profiles are easy to work with because students were able to assemble their design with simple hand tools, where no welding was required. T-slot profiles are modular, meaning they could make adjustments and reassemble very fast and modify their design along the process. Students imported the 80/20 drawings into the CAD design and calculated the beam deflections for different loads to modify their design.

2.2. Inlet and End Tanks

The inlet and end tank walls are fabricated from PVC. To attach the parts, the PVC sheets were heated with a specific PVC welding heat gun. As the sheet became semi-melted, a PVC welding rod was forced into the seam. The rod slowly melts down in between the sheets and then solidifies such that it essentially became part of the sheet. This helped to hold the sheets together besides waterproofing the joints and corners of the tank.

2.3. Flow Conditioning and Contraction Section

In order to achieve laminar flow in the test section, a flow distributor, flow straighteners, and contraction section was used based on the wind tunnel designs in previous literature ^[5-8]. The distributor is located at the bottom of the inlet tank which forces the flow to spread out over a series of holes. As the flow moves into the tee-shape pipe, it is forced left or right with each side having a number of holes facing downwards. These holes are spread out across the length of the inlet tank, causing the flow to be spread much more evenly.

The next components are the flow straighteners which eliminate large scale vorticities. Most of this is accomplished in a 2 in thick honeycomb screen with 1/4 in cell size which covers the entire flow region. It is a passage of ducts, laid along the axis of main stream to minimize the lateral velocity components caused by swirling motion in the flow at entry. The honeycomb eliminates large scale swirling motion. Following the honeycomb are three stainless steel wire screens with different mesh size which work to break down smaller scale swirling motion. The

screens set implies a huge pressure loss to the flow, reducing higher velocity axial components to an almost plane profile.

Another flow conditioning component downstream of the honeycomb and screens is a two-dimensional contraction which uses a sixth-order polynomial curve to increase the velocity 2:1 and reduce the remaining turbulence scales by accelerating the flow into the test section entrance. The geometry design of the contraction section is based on a controlled flow generation on its boundaries in order to maintain the flow attachment along the contraction walls and avoid flow separation ^[7,8]. This contraction accelerates the flow causing any small-scale vorticity which may remain in the flow to be stretched out. Due to the conservation of angular momentum the rotational speed increases, which in turn increase viscous forcing causing the vorticity to dissipate. This contraction feeds laminar flow directly into the test section where all of the experiments will be performed. In the present project, the contraction ratio is 2:1. Three curves were considered for the contraction section as shown in Fig. 2.

Figure 2. Three curves were considered for the contraction section and “Contraction 2” was selected for the present water channel.

Based on ANSYS simulation for these curve shapes (Fig. 3) and the design criteria (separation, boundary layer thickness, pressure loss) ^[11], “Contraction 2” was proved to result in the best flow in the test section and was selected in this water channel facility ^[12].

Figure 3. Isocontours of pressure coefficient for (a) Contraction 1, (b) Contraction 2, and (c) Contraction 3 profiles.

2.4. Test Section

Since the experiments will be conducted inside the test section, it is the most important element of an experimental channel. In fact, all other sections contribute to a good quality flow generation. An accurate control on flow properties, such as velocity profile, turbulence level, temperature, is essential for a successful experimentation. The test section of 30 in wide, 24 in deep and 10 ft long is constructed with low-lead ultra-clear float glass which has an excellent light transmission for flow visualization. The side walls and bottom walls are made of 5/8 in and 3/4 in thick glasses, respectively. Considering its length and cross-sectional area, this test section provides flexible working zone which can also be used as a towing tank. Regarding verification measurements, PIV experiments with high-quality results will be obtained to prove that the test section is ready to be employed for experiments.

2.5. Pump System

Water is circulated by a 7.5-hp close-coupled stainless steel centrifugal pump, as shown in Fig. 4, with a variable frequency drive (VFD) for control of the free-stream velocity up to 3.3 ft/s. The main pump delivers water to the inlet tank from an 8 in-diameter pipe. The pump is about 2200 lbm and can operate up to 4 ft³/s. All interconnecting pipes and fittings are made of non-corroding materials.

Figure 4. A 7.5-hp close-coupled stainless steel centrifugal pump selected for this water channel.

2.6. Filtration and Drain System

Regarding the filtration loop design, it was desired to implement electrical controllable valves to the loop instead of having all manual valves. There are four solenoid valves, three pressure sensors, one float sensor, together with an emergency manual valve for draining. When using the solenoid valves for draining, there are three different kinds of loops that the water could pass through: the first loop would bypass the filter and goes straight to the drain, second loop would have a solenoid valve after the filter to filter the water then goes straight to the drain, and the last solenoid valve would be after the filter that lets the water straight back into the end tank of the water channel. The final solenoid valve is used to fill the water channel. As of the pressure sensors, there is one on both sides of the filter to measure the differential pressure in order to determine the proper time for filter change. There is a pressure sensor right before the main

pump to measure the head pressure assuring that the main pump is safe. All these controls are wired to a PLC with a HMI display.

2.7. Control Console

The control console, as shown in Fig. 5, is a unique addition to this water channel which is easily accessible from a station next to the channel. The Filling Control screen is used to activate and deactivate water channel filling operations. A high level float switch will automatically shut off the filling activity and deliver the channel full alarm. The flow rate of the main pump can be controlled directly from the VFD or from this console. Moreover, the filtration and drainage methods can be selected from this console. Also located on the console there are the emergency stop button and the pump controls to adjust the flow rate.

Figure 5. The control console screens of the PLC for the water channel to control the (a) filling, (b) main pump, (c) filter pump, and (d) draining.

3. Lessons Learned

Once the four EMET students were identified for the project, they had to work together quickly and efficiently to achieve the goals. This included dividing the tasks based on each group member's strengths and weaknesses. Student 1 focused on the design including 80/20 framework, PVC, and glass. Student 2 focused on researching material selection such as the required glass thickness and the polymer selection for the tanks and contraction section. He also researched adhesive materials for sealing seams with the strength and integrity needed for the water channel. Student 3 focused on the filtration loop, finding a good match for the filter and filter pump based on the regulations for drainage flow rate. He also helped with the determination of fittings types used for connecting the pipes to the tanks. Student 4 helped with finding the correct pump for the water channel which was incorporated into a selection matrix. With his experience and knowledge, the team was able to quickly determine the pressure

transmitters and valves they needed in the system. He also chose the PLC and HMI based on the desired outcomes and input/output requirements.

The team's individual members focused on their tasks during the project narrowing the selections down based on the team discussions and feedback. Designing and researching individually and discussing them as a team proved to be very successful. The weekly meetings helped bring the individual ideas together and create a concrete path to move forward. The team personally requested quotes for all the items they needed. This did require effective communication between the team members and with the vendors prior to purchasing in order to prevent overlaps and confusion. As items were received, they were documented and verified based on their estimated costs. Parts were also verified as they came in and any corrective or machining process were planned and scheduled. Testing of certain processes such as PVC welding was also performed as well.

One of the initial challenges with this project was realizing and understanding the scope. The conceptual design had been created, but the exact dimensions and properties of some of the components were unknown until they arrived. Pieces such as the PVC base of the contraction section and the large pipe fittings were difficult to work with because of their sheer size. Other challenges came in the form of managing material procurement. Without good organization, there would have been no method to easily track all the parts coming in.

Another challenge the team faced was the lead time for the big items. The team also struggled with the customer service of some distributors that components were purchased from. It was hard to estimate the arrival time of the parts. On several occasions the parts were received with a two week delay and some of them were wrong orders.

Another challenging issue was the room remodeling for the water channel installation from the architectural, electrical, plumbing, HVAC, and safety aspects. The room was a regular classroom on the main floor of a new building which went under reconstruction to meet the requirements for the new laboratory. Moreover, in order to gain height in the room, a big trench was made on the floor to house the water channel and avoid flood on the main floor.

Throughout the course of this project, the team learned many important lessons. The first, biggest, and simplest lesson is the value of time. In the initial stages, the team was doing well with managing the time properly. Then they got behind because of their busy schedules as part-time students and working at the same time. The students eventually made the decision to change schedules around in order to accommodate the needs of the project. With such a large and ongoing bill of materials, parts were constantly coming in, and not often on time. This was difficult to deal and work with, but it was just a matter of being patient and working on other small things in the meantime.

Another lesson learned, was the importance of working as a team. This includes multiple aspects such as respecting other's opinions, coordinating time to work on the project, and general teamwork to physically move components and materials. By listening to each other, the students were able to get multiple perspectives on how to overcome obstacles when they arose. If schedules were not coordinated, there would have not been enough time to work to complete

large tasks. Most importantly, teamwork was pivotal when the parts needed to be moved. Without good teamwork, this project would never have been completed. Moreover, extensive engineering knowledge acquired throughout this undergraduate capstone project by students. Significant understanding of shearing forces developed in the boundary layer has been gained throughout this study.

One of the important learning outcomes of this project was to expose the students to design process of a real world fluid system with realistic design requirements and design constraints. Moreover, the students approached the problem in three phases to design the main components of the water channel: 1- conceptual design using SolidWorks, 2- assembly and construction, and 3- modification. They learned how to apply the fundamentals of Fluid Mechanics to design the flow conditioning section and Strength of Material for the framing structure. Furthermore, the student gained hands-on experience working with different engineering software such as MATLAB, SolidWorks, ANSYS, and Microsoft Office. They also learned how to manage time and budget for the entire project in spite of some deviations and modifications along the project.

4. Areas to Improve

Concerning verification measurements, high-quality PIV experiments will be conducted on flow characteristics such as velocity profile, turbulence profile, and boundary layer thickness to prove that the test section is ready to be employed for experiments ^[9]. Detailed tests need to be carried out in order to obtain refined velocity profiles to confirm the flow quality in the contraction and test section. Furthermore, velocity profiles should be measured in different locations through the section length and with different water levels to verify the flow quality along the channel is as desired. Subsequently, the flow quality can be improved by screen mesh density and corrections in the diffuser. The end tank will be also modified to avoid any flow reflection from the end wall.

Despite the students spent a lot of time and effort on this project and they were very committed to its completion, they were not able to finish the construction in time. It was originally expected that the project could not be finished in two semesters because it was a highly time-demanding and multi-disciplinary project. The students graduated in December 2016 and did not have a chance to see the final product, leak test the channel, work with the pump, or confirm the flow quality. Due to the lack of documentation by students, it was not feasible to transfer the project to another group of students. Therefore, the faculty members who had been involved in the design of the water channel decided to finish up the project with significant assistance of the Mechanical Lab supervisor in the machine shop. Appropriate documentation was concluded to be vital to transfer the knowledge of each project to the next generation of students. Machining and assembly of the flow distributor and the contraction section, final sealing, and final assemblies were performed after students graduated. For educational aspects, the students were invited to visit for the first filling process where numerous leaks found. They even mentioned that they were too disappointed to see those many leaks after all the time they put into sealing the tanks and pipes. However, they learned that not everything is going to work the way they expect and they should spend more time on the research phase and testing. After applying a more appropriate sealant for underwater applications, the water channel is now operational for teaching and research purposes.

5. Conclusions

Water channels are used for a variety of teaching and research purposes in the field of Fluid Dynamics. A circulating water channel is designed and constructed in the new Fluid Discovery Lab at Penn State University at Berks with the significant assistance of undergraduate students through a capstone project. This paper discussed the design and construction process of this new facility. The design procedures applied to find the geometry of important parameters of the channel were also described. The laminar flow channel has a close-coupled centrifugal pump with a variable frequency drive to control the free-stream velocity up to 3.3 ft/s. Low-lead ultra-clear float glass was used in the test section for excellent light transmission. Moreover, the challenges faced through this project were explained. Identifying good students, regular weekly discussion meetings, good assembly plans, and access to appropriate resources such as machine shop were the key factors for success in such a remarkable project. The Engineering programs at Penn State Berks place a heavy emphasis on undergraduate research and encourage students to learn state-of-the-art methodologies in practical design applications. The constructed water channel facility will be also used to support fundamental research studies, such as the study of unsteady boundary layers and coherent vortex structures, as well as more applied experiments in flapping flight. Some suggestions on the design to improve the flow quality in the test section of a water channel were also provided.

6. References

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