Flow Velocity Characterization in an Experimental Flume

Undergraduate Honors Thesis

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By

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Abstract

Only seventeen percent of the United States' energy generation in 2017 came from renewable sources, and hydroelectric power makes up a about forty percent of this. Hydroelectric power has large potential for growth, as new technologies develop. In particular, low-head dams and weirs across the country provide potential sources to harness more energy. Unfortunately, a lot of existing weirs have large economic and environmental impacts, and there has been little work done to improve the infrastructure and design of weirs themselves. In order to best analyze the effects of dams and weirs in a laboratory environment, experimental flumes can be used to simulate open channel flow of rivers and streams. The purpose of this research is to provide an understanding and process to characterize flow velocities in an experimental flume.

Reviews of literature were used to guide purchasing decisions on equipment viable to suit the needs of the laboratory. Methods have included obtaining a slotted weir design and characterizing flow through and around the weir with yarn. In addition to this, a pitot tube and Hach FH950 electromagnetic sensor have been used to compare flow velocities in the open channel flume. Each measurement device was tested at varying flow velocities by altering the cross-sectional area of the flow and keeping the flow rate constant.

To this point, flow characterized through the weir has behaved as expected, with increased flow velocity through the slot of the weir. The results of experiments characterizing flow in an open channel can be adapted to measure velocities through a modular slotted weir design to guide future weir construction projects to be used in conjunction with turbines to produce hydroelectric power. Therefore, it is important to develop a functioning measurement system and process in order to aid in future research, investigations, and educational projects involving experimental flumes.

Acknowledgements

My gratitude is extended to the many people who have helped aid in the completion of my Undergraduate Research Thesis work. Thank you to Dr. Belloni for advising and guiding me through the Undergraduate Research experience. Special thanks for Dr. Sritharan and his colleagues at Central State University for allowing me to use their facility in order to conduct my study. To Mr. Chris Carter for helping aid in the design and fabrication of the traverse and mounting system of a variety of measurement methods. To Mr. Paul Kling, Fred Williams, and kWRiver for providing motivation behind the work and providing contact with Mr. Cody Fleece and Stantec who graciously lent their equipment. Finally, to all those peers and friends who helped support and motivate me along the way.

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Nomenclature

Acronyms

ADV	Acoustic Doppler Velocimetry
PIV	Particle Image Velocimetry

Symbols

A_c	Cross Sectional Area of the Flume (m^2)
g	Gravitational Acceleration (m/s^2)
h	Depth of pitot tube measurement (m)
P	Total gauge pressure
Q	Flow Rate (m^3/s)
Re	Reynolds Number
R_h	Hydraulic Radius (m)
V	Point Velocity (m/s)
V_{avg}	Average velocity of flow (m/s)
V_{error}	V_{meas} with an added 5 Pa error
V_{max}	Maximum Velocity (m)
V_{meas}	Measured Velocity Average
y	Height of Measurement from Bottom of Fluid (m)
δ	Height of Boundary Layer (m)
Δh	Difference in height of orifice meter monometer (m)
ν	Kinematic Viscosity (m^2/s)
ρ	Density of water (kg/m^3)

Chapter 1: Introduction

The following introduction introduces the motivation for this research study. The study's objectives and an outline of what is to come in the rest of the thesis conclude the section.

1.1 Need for Low-Head Hydropower

The U.S. Energy Information Administration reported that in the year 2017, only seventeen percent of energy generation came from renewable sources. Seven percent came from specifically hydroelectric sources (EIA.gov, 2018). With growing energy demands every year, new means of generating energy from renewable sources have become a driving force in the economy. Many companies are seeking ways to develop new technologies to harness the energy flowing through the world around them.

1.2 Current Approach

1.2.1 Hydropower

The majority of hydropower is produced by large hydroelectric plants. These plants have implemented massive dams which drastically change the flow of the river. In turn, such structures impact the wildlife and landscape around them. Due to the large hydraulic head, the distance between upstream and downstream water surface levels, the majority of the energy produced by such sites are a result of harnessing the gravitational potential energy of the large mass of water. These structures direct the majority of flow directly into turbines within the structures.

1.2.2 Low-Head Dams and Weirs

In addition to the large dams that people are used to seeing, there are around 75,000 low head dams or weirs in the United States. These structures have a head of no more than 15 feet and are generally used to help control and shape the river or stream they are placed in (kWRiver, 2019). As opposed to large dams, these structures generally direct all of the water over the top of the structure. Because of these differences in design there is a smaller amount of potential energy to be harnessed from the flow, but rather the kinetic energy would be the driving source of energy when paired with a turbine. Figure 1 below shows an example of a low head weir as identified by kWRiver.

Figure 1: Low-Head Weir Site (kWRiver, 2019)

1.3 Proposed Improved Weir Design

Due to most of the current low-head weirs in the United States being designed for river control rather than energy production, kWRiver was considering implementing an improved modern modular weir design to be paired with hydro turbines. They have developed a cross flow turbine that intakes the water cresting over existing weirs but would also like to investigate implementing a slot through the cross section of the weir to act as a nozzle into the downstream turbines. The rationale is that the slot would increase the velocity of the water entering the turbine, therefore resulting in a higher input of kinetic energy. To analyze how viable the slotted weir design may be, testing must be done to see the distribution of energy through the slot compared to that of the water cresting the structure or tunneling beneath it.

1.4 Objectives

To increase the energy production of clean and renewable energies, many new technologies are being developed which need to be tested and understood. Specifically, within hydropower, many technologies in use have not been updated for decades. There is a large potential for implementing small scale hydropower turbines around the United States with existing weirs. In addition, there is room for improvement in weir designs to specifically be paired with a turbine. To understand how the fluid passes through and around such structures, it was necessary to develop a reliable lab environment to understand the movement and velocity of the fluid.

In order to better understand the testing environment for developing new weir designs, the purpose of this research was to design a measurement system to characterize flow velocities within an experimental tilting glass flume.

This purpose was to be achieved by first selecting appropriate equipment to record the flow velocity after determining what equipment characteristics were necessary. Following this, the design and implementation of a traverse system to allow precise and rigid equipment positioning on the flume was required to run testing. Finally, tests were to be run to characterize the flow in the flume while comparing and validating the equipment used.

1.5 Thesis Outline

The rest of this thesis contains five chapters. Chapter 2 discusses the background theory necessary to discuss open channel turbulent flow, while motivating the slotted weir investigation. Next, Chapter 3 explains the choice of measurement equipment and corresponding design and development of the traverse system created to hold the equipment for testing. Once the equipment and traverse system were finalized, Chapter 4 explains the experimental setup and procedure used to record flow velocities within the flume and the results of such testing. This section will compare measurement systems, mention potential errors or limitations in the experiment, and provide the data recorded. Finally, Chapter 5 will conclude the findings of experimentation for measuring fluid velocity in an experimental tilting glass flume.

Chapter 2: Theory

While discussing fluid velocity characterization, it was important to understand the effects of open channel flow in rivers and streams. Additionally, the effects of flow over a weir or through a nozzle needed to be understood to predict flow velocities around a structure placed within the flow.

2.1 Open Channel Flow

The flume environment being considered acts as open channel flow. This means that the surface of the water is open to the atmosphere, while the sides and bottom of the flow are constrained. In this case, the glass walls and concrete floor of the flume were considered to be smooth. In general, open channel flow is considered to have a representative average velocity when measured at 40% of the height, or 60% of the depth of the flow (Sritharan, 2013). In addition to this, the boundary of the flow experiences the no slip condition and has no velocity when in contact with the walls of the channel. Figure 2 shows lines of constant velocity, showing that the general form of the velocity of the flow is fastest in the middle away from the walls, though the surface has a slowing effect from the contact with surrounding stationary air.

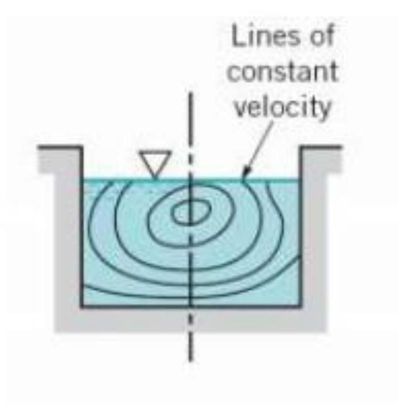

Figure 2: Lines of Constant Velocity in Open Channel Flow (Munson 2012)

For the sake of the experiments in this study, the flow was considered to be turbulent, as the Reynolds number was always above 12,500 for the open channel flow. Because of this, the open channel would have a boundary layer that was fully developed for the channel. The Reynolds number for the flow can be calculated using Equation 1 shown below.

$$Re = \frac{V_{avg} R_h}{\nu} \tag{1}$$

In this equation, the Reynolds number is a dimensionless number used to determine if a flow is laminar or turbulent. In general, if the Reynolds number is less than 500 for open channel flow, it is laminar, and over 12,500 is turbulent. V_{avg} is the average velocity of the flow, R_h is the hydraulic radius of the flow, and ν is the kinematic viscosity of the flow (Munson, 2012).

Because of the flow being turbulent, the flow velocity profile for a smooth boundary can be approximated using the following power law in Equation 2.

$$\frac{V}{V_{max}} = \left(\frac{y}{\delta}\right)^{\frac{1}{7}} \tag{2}$$

This means that V (m/s) is a function of y, the height of the measurement in meters, δ the height of the boundary layer (m), and the maximum velocity. Due to the flow being fully developed turbulent flow, δ is the total depth of flow (Chanson, 2004).

Chapter 3: Experimental Setup

The experimental setup will detail the facilities and equipment used to perform testing within the glass flume. It will also discuss the equipment selected for characterizing the flow in detail.

3.1 Experimental Tilted Glass Flume

The Armfield Tilting Glass Flume S6 was used to perform this study on flow characterization. The flume in the laboratory at Central State University can be seen below in Figure 3. The body of this flume was 30 cm wide and 45 cm tall. It had glass walls and a concrete floor.

Figure 3: Armfield Experimental Tilting Glass Flume at Central State University (Sherping, 2019)

This flume allowed for continuous recirculation of water. The user was able to determine the flow rate of the water moving through the flume, the slope or tilt of the structure, and the depth of the water. The flow rate was controlled by opening a valve by the pump which drove the continuous movement of the water. Downstream of this valve, an orifice pressure meter and manometer system were used to determine the flow rate. This will be later discussed in Chapter 3. The depth of the water was controlled by using the flume's wave generator. The structure included a wooden board in the downstream sink of the structure that could be raised up to provide an obstruction in the flow. The height of this board and the flow rate were used to control the height of the flow.

3.2 Slotted Weir Design

The design of the slotted weir proposed by kWRiver was important to consider when determining how to obtain flow velocities. The structure, shown below in Figure 4 shows the slotted weir design as modeled in computer aided design software.

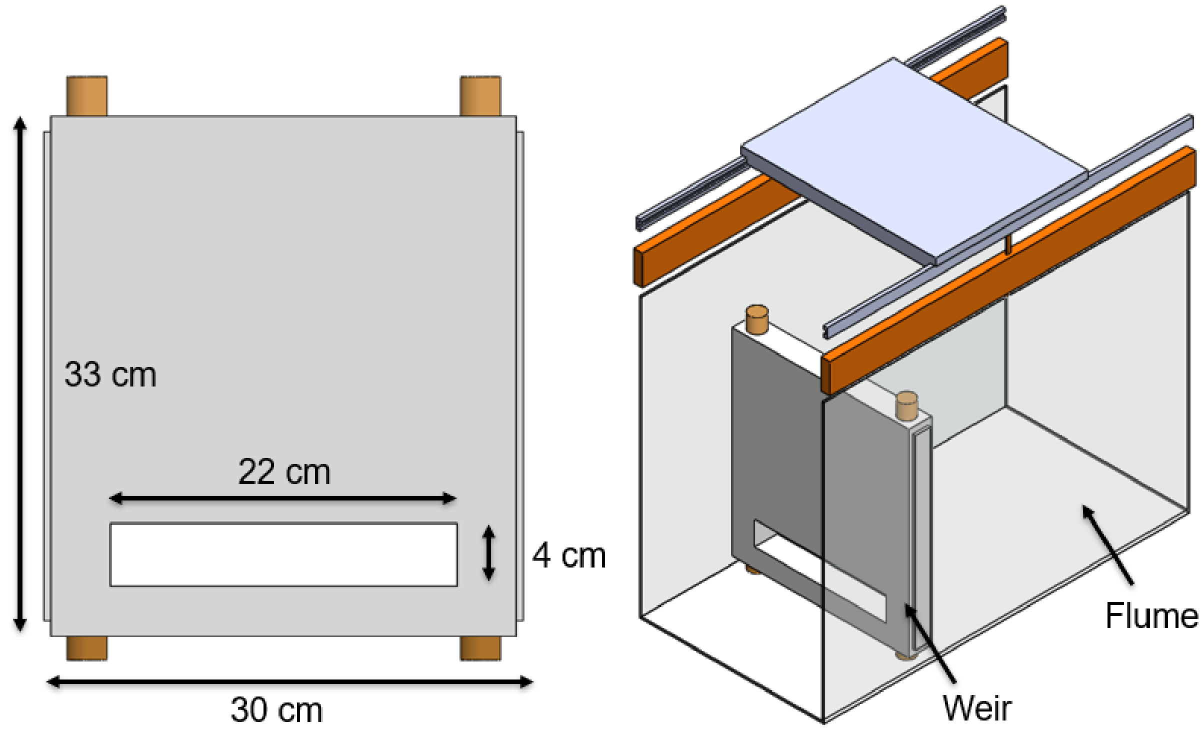

Figure 4: Proposed Slotted Weird Designed by kWRiver

This design constrained the measurement devices in a few ways. First and foremost, the measurement devices needed to be able to capture varying flow velocities in the bottom slot of the weir, designed to let sediment pass under the structure. Additionally, the geometry of the slotted weir controls to velocities expected from further measurements. The whole range of velocities needed to be captured. Finally, this slotted weir design required relatively noninvasive measurement techniques, as obstructions in the flow would alter how the water moved around the structure.

3.3 Flow Characterization

The Armfield S6 tilting glass flume housed in Central State's C. J. McLin International Center for Water Resources Management needed some additional equipment to perform tests.

Measurement equipment was needed to perform tests and analyses on varying weir designs. In order to accurately model and predict turbine behavior, velocity profiles were needed to design for harnessing increased kinetic energy. The focus was on harnessing the fastest velocities for turbine input, though flow characterization showing the boundary layer effects of the flume were also of concern. These profiles could play an especially large role in designing for minimizing environmental impacts of a weir.

Many flow characterization techniques were considered for use in the open channel flume. Decision qualifiers included the ability to read flow velocities parallel to the bulk flow accurately and reliably, while being in the financial scope of the laboratory's recourses. Increased precision and small disturbances to the flow were considered as parameters to finalize decision making on which equipment to invest in. The following sections outline the various measurement techniques considered.

3.3.1 Yarn Visualization

The cheapest and easiest flow characterization method was to use yarn visualization on the weir design or channel walls. By taping or tying pieces of yarn to the weir or surrounding structures, qualitative data could be gathered on the direction and relative velocity of the flow at given points. This method lacked the ability to give quantitative data but proved useful in confirming the general shape of the flow profile through and around a model weir. In addition, the yarn provided a very low invasion in the flow due to its flexibility allowing the yarn to follow the existing flow streamlines. This process cost less than 10 dollars.

3.3.2 Pitot Tube and Monometer

Pitot tubes and manometers were a known laboratory measurement system which had been studied in great length. The pitot tube when placed in the flow of water acted to record the total pressure at an inlet hole. By closing off the back side of the tube and allowing water to flow into the tube, the air that had been in the tube previously becomes pressurized to the total pressure of the tube. This pressure both includes a hydrostatic and kinetic component. Some pitot tubes have static ports that allow researchers to quickly determine how much of the total pressure if static or kinetic pressure. The pitot tube considered was the Dwyer Series 160 Stainless Steel Pitot Tube Model 160-36. This pitot tube, seen below in Figure 5, was intended for use in air ducts and other gas analysis. This tube was selected as it could capture the full range of velocities which were possible to obtain around the flume.

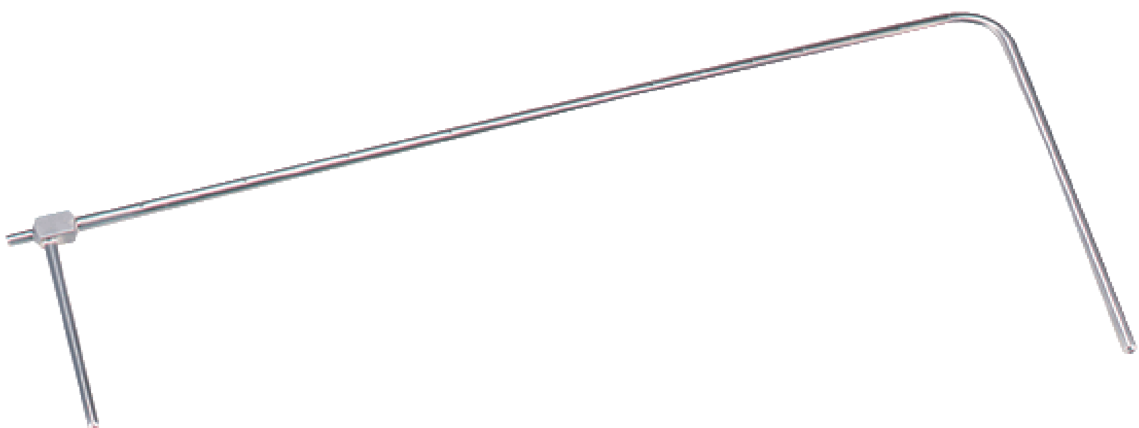

Figure 5: Dwyer Pitot Tube Model 160-36 ASME Standard (Dwyer)

The pitot tube allowed for calculations of one-dimensional flow velocities only. Given that the relative flow velocities that would enter a hypothetical turbine were of the most concern, this one-dimensional flow measurement would suffice. The pitot tube had a relatively small profile in the water, meaning it was not very invasive. This was ideal when considered for use alongside the slotted weir.

The pitot tube itself was used in conjunction with a manometer. The Dwyer 477AV Handheld Digital Manometer was used to record the pressure of the tube. This handheld device utilized two ports connected to the pitot tube with rubber tubing. These ports had piezo pressure sensors to record the pressure at any given time. The device would subtract the pressures at each port, giving the pressure differential experienced between two reference points. The handheld manometer can be seen below in Figure 6.

Figure 6: Dwyer Handheld Manometer Series 477AV (Dwyer)

Finally, the pitot tube and manometer setup was considered affordable, as the two devices together cost a few hundred dollars.

3.3.3 Propeller Velocimeter

The pigmy propeller current meter was considered for use due to its availability at Central State University. The pigmy propeller current meter utilizes a series of conical shapes mounted on a spinning wheel. When placed in a moving fluid, the conical shapes catch the velocity and begin to spin. By determining the rotational velocity, the one-dimensional velocity of the fluid can be estimated by multiplying by the radius at which the cones sit. This system neglects losses from the rotation and creates a large obstruction and additional turbulence in the flow. An image of a pigmy current meter can be seen below in Figure 7.

Figure 7: Pigmy Current Meter Example (Humboldt)

3.3.4 Electromagnetic Velocimetry (Hach FH950)

The Hach FH950 velocity meter was designed for wading in rivers and streams. There is little documentation to its use in similar experimental flumes. The device is intended to be mounted on a wading pole to hold it oriented within the flow. The sensor itself uses a magnetic field, which when placed in flowing water creates a voltage proportional to the fluid's velocity. This voltage is sensed by electrodes embedded in the sensor and are analyzed in the device's microcontroller to output flow velocity. Due to its intended use in streams, it has a somewhat large profile that can obstruct flow, though it is stationary. These attributes made the sensor moderately invasive. Figure 8 below depicts the Hach FH950 sensor head which attaches to a wading pole and the accompanying handheld readout.

Figure 8: Hach FH950 Sensor and Handheld Readout (Hach)

This velocity meter was able to record one-dimensional flows ranging up to 3.3 m/s. Its ability to easily mount to wading pole helped to ease the setup required. Additionally, this piece of equipment was able to be lent for use with no cost, making it affordable and attainable.

3.3.5 Acoustic Doppler Velocimetry (ADV)

Acoustic doppler velocimetry utilizes the doppler effect to calculate fluid velocity. As shown in Figure 9 from SonTek below, the device transmits a signal which then hits the measured volume and bounces a signal back to the receivers.

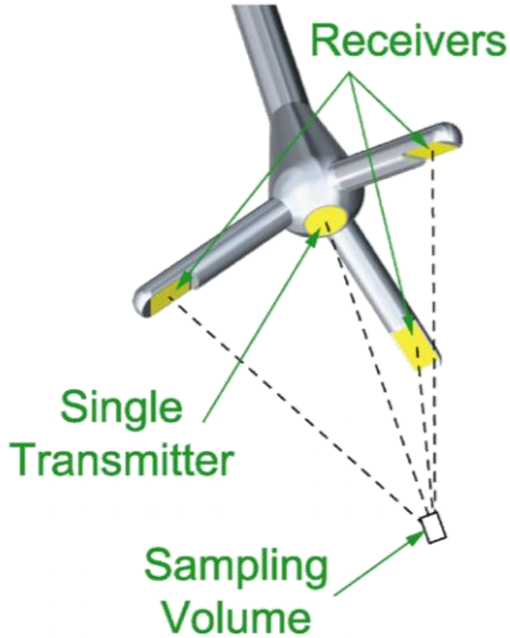

Figure 9: ADV Probe Image (Velasco, 2019)

The device can determine the three-dimensional velocity of the sampling volume from the transmitted and received frequency and speed of sound in the medium. By analyzing the results from the different probes, a three-dimensional velocity vector can be calculated. The ADV system is not an intrusive measurement system because it records the velocity of the fluid away from the probe itself. Its ability to get point velocities from a distance were considered ideal for calculating the flow around the weir geometry. This type of technology has a cost of over $10,000 which exceeded the budget for flow characterization equipment.

3.3.6 Particle Image Velocimetry (PIV)

Particle image velocimetry consists of an extensive setup to produce a map of flow velocities. This method is noninvasive as the equipment sits outside of the flow itself. The system works by shining a laser sheet through the flow. Florescent particles are then placed in the flow. As these particles go through the laser sheet, a camera records their motion. From here, software can produce a map of the flow velocities over a given cross sectional area. Such systems exist for tracking either two-dimensional or three-dimensional flow. For the slotted weir considerations, two-dimensions were more than necessary. Figure 10 below shows a schematic produced by Armfield showing the setup of the PIV equipment for mapping flow velocities over a cross sectional area. Such systems are often over $20,000, which exceeded the available budget for such equipment.

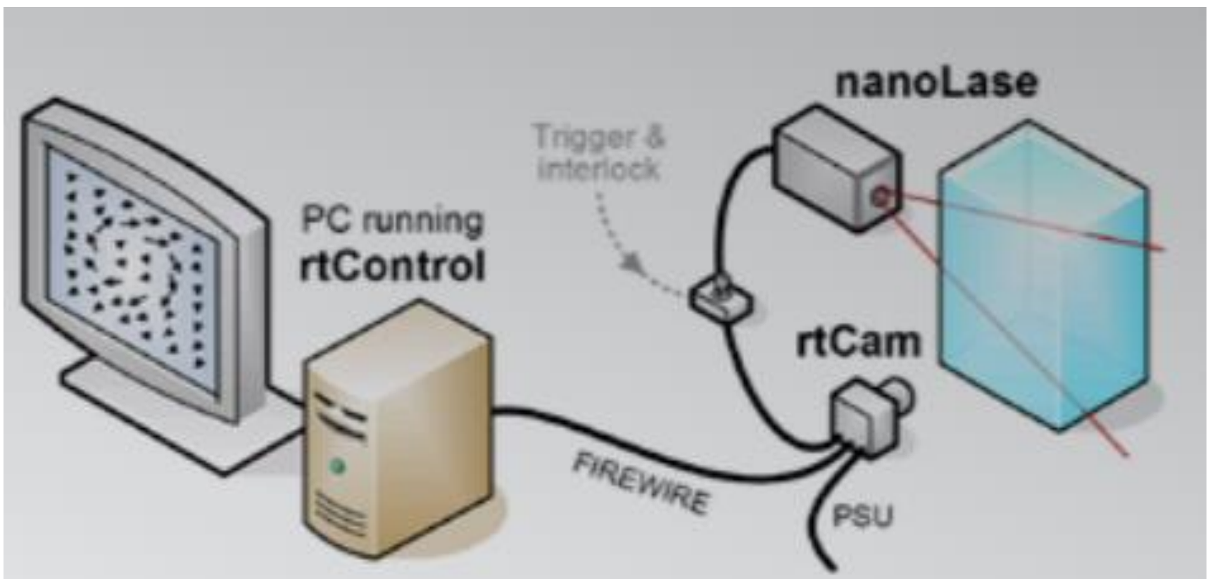

Figure 10: PIV Schematic of Setup and Equipment (Armfield, 2015)

3.3.7 Flow Characterization Summary

In order to compare the devices considered, Table 1 below was constructed based on five qualities desired for the devices to be implemented into testing. Each quality was weighted from 1 to 5 based on importance. Affordability was weighted to be the most important, because it determined whether it was realistic to acquire the equipment. Following that, invasivity was considered as the testing flume environment required point velocities in small cross-sectional areas. It was important to not introduce large amounts of blockage or extra turbulence in the flow. Next, the measurement device needed to have a fine enough resolution to differentiate changes in the flow of a few centimeters per second in order to accurately determine the behavior of the flow. Following this, the range of velocities able to be measured were important as the device needed to measure slow velocities upstream of the structure while also capturing accelerated velocities that could occur through the slot of the weir. Finally, whether the device captured one to three-dimensional flow velocities were considered. The flow in the bulk flow direction was what was most important, though additional information on the flow velocity was preferred.

Table 1: Equipment Comparison Based on Performance Requirements

	Velocity Dimensions	Affordability	Invasivity	Measurement Resolution	Measurement Range	Total
Weight	1	5	4	3	2	
Yarn	0	10	10	1	10	22.6
Pitot Tube	3	9	7	5	7	21
Propeller	3	4	1	3	10	11.2
ADV	9	2	8	7	8	17.6
Hach FH950	3	10	5	6	7	21
PIV	9	0	10	7	10	18

To better visualize the table shown, Figure 11 shows a graphical representation comparing the devices.

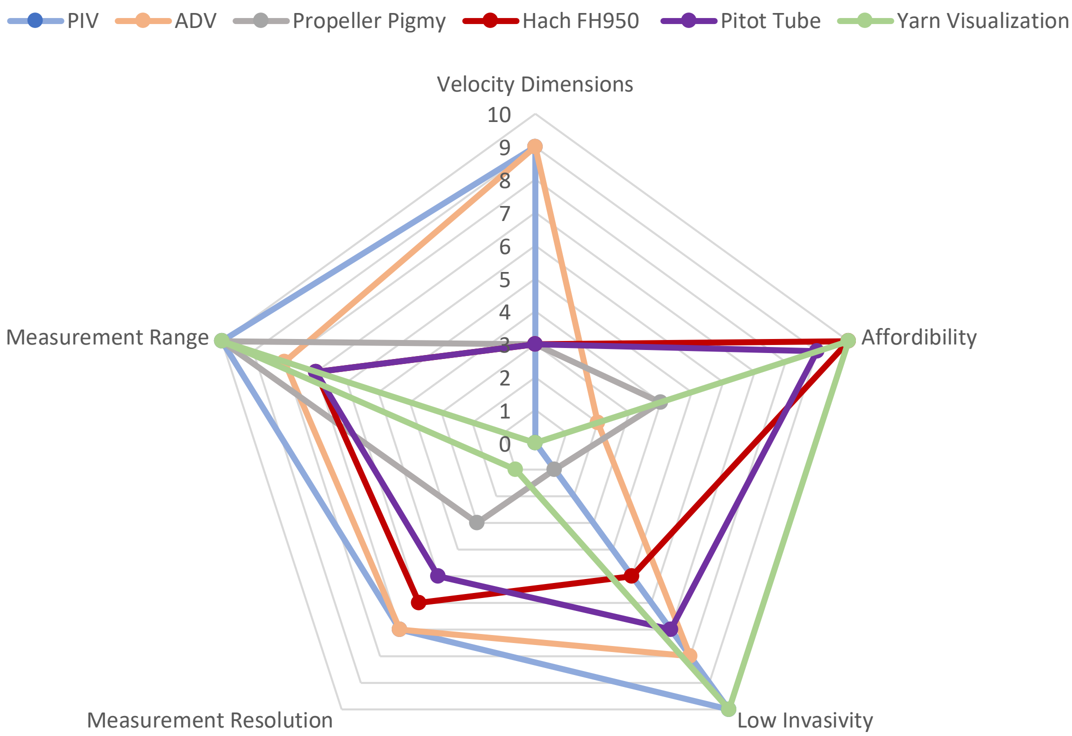

Figure 11: Radar Chart Comparing Measurement Devices Considered to Characterize Flow

The table and figure above show that the PIV and ADV system were the most ideal pieces of equipment for characterizing the flow but were not affordable. Due to their affordability, the Hach FH950 and Pitot tube were determined to be the best option for device purchase. These devices performed well overall and had limited weaknesses. In addition to those quantitative measurement devices, it was also decided that yarn visualization would be implemented as a first step due to its low cost.

3.4 Traverse Design

3.4.1 Design Considerations

In order to reliably perform testing, it was important to ensure repeatable positioning for both the pitot tube and the Hach meter. This required forming a method to be able to position the equipment in all three traverse directions. In addition, the system had to mount each piece of equipment in a rigid state with the equipment being held in the correct orientation despite the force of the fluid pushing against the device itself.

For the sake of time, cost, and ease of manufacturability, it was decided to modify existing brackets that were designed to hold depth gages for the flume. The existing brackets, depicted below in Figure 12, were aluminum blocks that spanned the width of the flume and had a set screw to hold them in place which is circled in red. These brackets were able to move the length of the flume parallel to the flow. Along one of the tracks which the brackets was a position scale as shown in the second image of Figure 12. This allowed the user to already reliably locate themselves in the direction parallel to the flow.

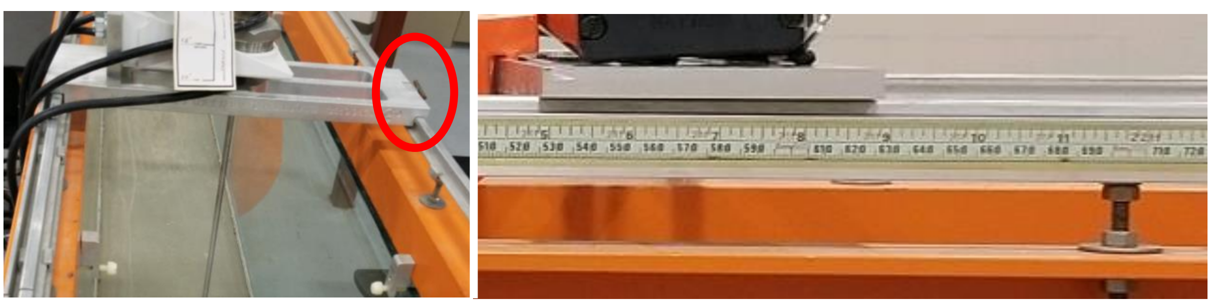

Figure 12: Traverse System Pre-existing Mounting Bracket Front and Side View

In order to best utilize the traverse system, the design needed to be able to be applied to both the pitot tube device and the wading pole that held the Hach meter. While the existing bracket was able to position the devices in the direction parallel to the flow, systems were still required in order to position within the cross-sectional area of the flume.

3.4.2 Implemented Design

In order to allow for movement in the horizontal direction, slots were milled into an aluminum bracket along its length. These slots acted like a track, which a mount could slide along. A simple set screw would be able to hold the mount in place along the track.

The final positioning required was to be able to adjust the depth of the devices. The Hach FH950 was specifically designed to be used in conjunction with a wading pole. Because of this, its position was able to be controlled by the wading pole so long as the pole was constrained. The pitot tube did not have a method to mount in any way and required a scale to be drawn on the tube itself.

In order to draw the measurement scale on the wading pole, the Hach meter was placed in the lowest position possible off the bottom of the flume. The middle of the sensor was measured to be 2.5 cm off the bottom surface, and therefore the position of "2.5" was marker on the wading pole as the position shown in Figure 13. From here, the rest of the scale was drawn using a tape measure down the rod in order to position higher heights. Lining up the measurement with the surface indicated by the red arrow ensures that the middle of the sensor is that high above the floor of the flume.

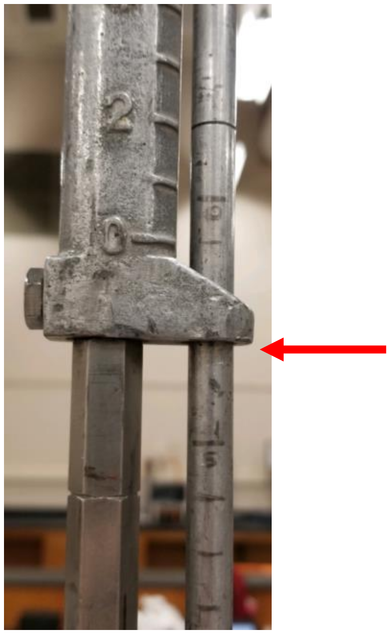

Figure 13: Wading Pole Scale Positioning with Sensor 2.5 cm Above Floor

Similar to the Hach meter height positioning, the pitot tube was placed in the lowest position possible off the bottom of the flume. The middle of the sensor was measured to be 0.4 cm off the bottom surface, and therefore the position of “0.4” was marker on the wading pole as the position shown in Figure 14. From here, the rest of the scale was drawn using a tape measure down the rod in order to position higher heights. Lining up the measurement with the surface indicated by the red arrow ensures that the middle of the sensor is that high above the floor of the flume.

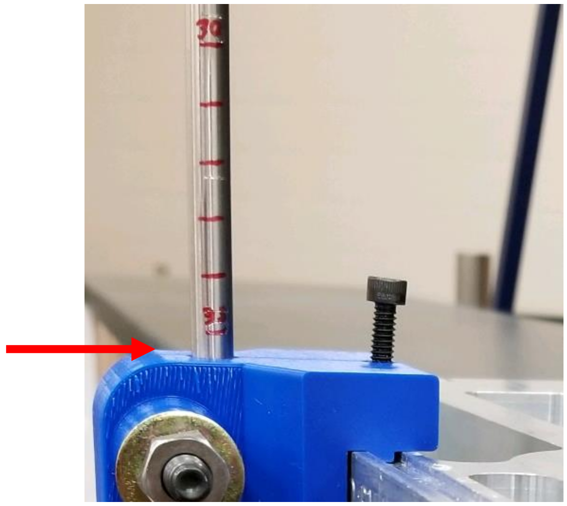

Figure 14: Pitot Tube Scale Positioning with Device 36 Centimeters Above Floor

Once positioned, the cylindrical sleeve of the mounting piece constrained the measurement devices and held them rigid despite the force of the drag from the water. This constraint was able to hold the pitot tube and Hach meter from rotating about a mounted pivot point. Additionally, one layer of duct tape was placed within the cylindrical sleeve allowing a small amount of compliance. This ensured that the pressure applied from the mount onto the measurement devices was more consistent. The tape gave some additional padding to account for imperfections in the manufacturing process of the mount and devices alike. This also helped protect the device from being deformed from an overtightened mount. This was especially important for the pitot tube, where collapsing the tube could lead to different pressure build up. Figure 15 below shows the Hach meter and pitot tube mounts.

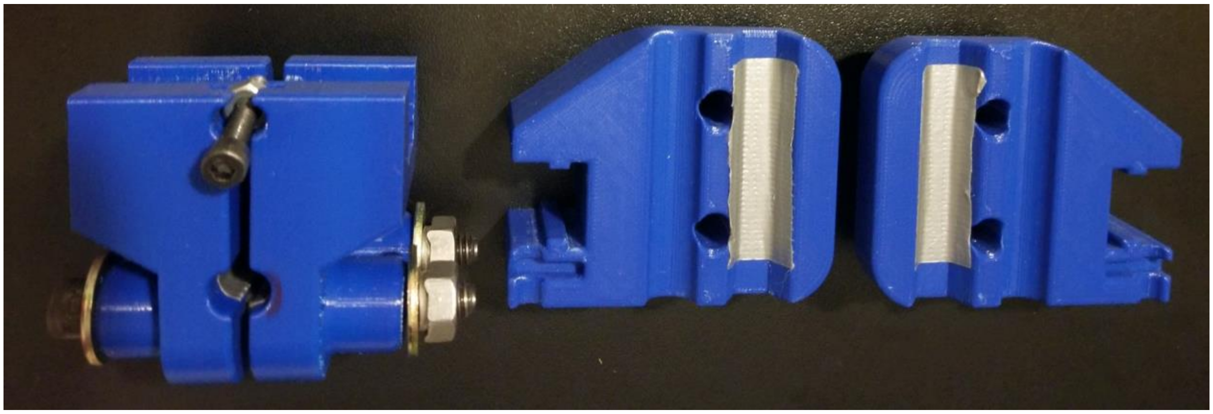

Figure 15: Wading Pole and Pitot Tube Mounts for Traverse System

Shown on the left side of the image is the assembled pitot tube mount. The pitot tube was held within the cylinder lined with duct tape as shown. The parts on the right made up the mount for the wading pole. This mount was constructed similarly to the pitot tube mount.

Chapter 4: Experimental Procedure

4.1 Yarn Visualization

While the Hach meter and pitot tube were able to get quantifiable data on flow velocity, some initial understanding of flow through a slotted weir was desired. In order to get a basic understanding of how the flow of fluid went around and through the structure, yarn was taped or tied to critical positions downstream of the weir to see the general direction and relative speed of flow. This qualitative measure was used to provide guidance for identifying areas of greater interest for future studies.

Figure 16 below depicts the setup for the positioning of the weir and yarn from a downstream and side view.

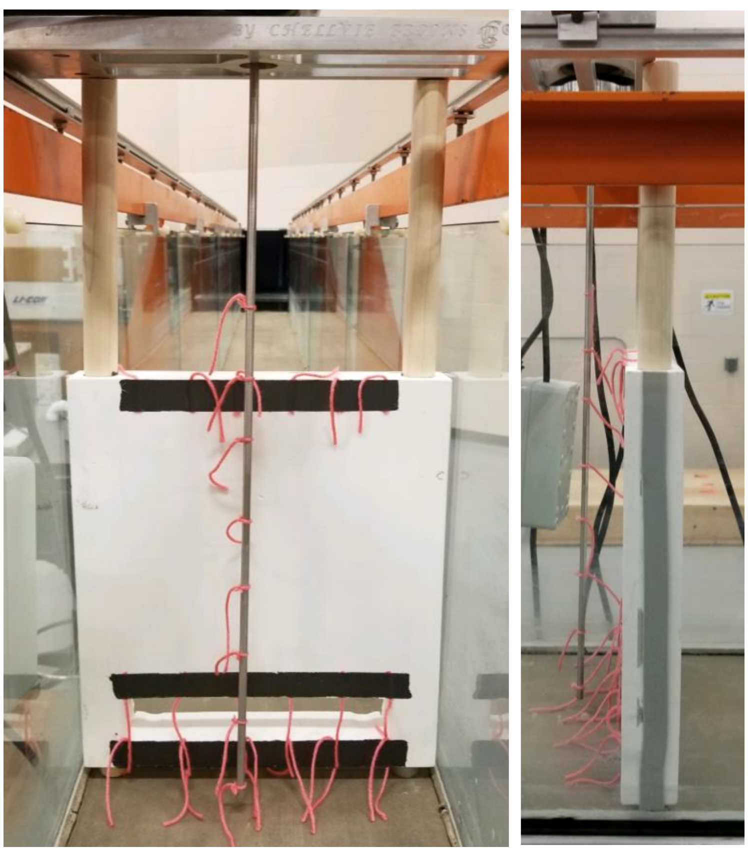

Figure 16: Yarn Visualization Experimental Setup

4.2 Orifice Flow Predictions

The Armfield flume had an orifice meter which measured the pressure difference across an orifice downstream of the pump. This orifice was attached to a manometer mounted to the side of the flume. The orifice meter and manometer looked as shown below in Figure 17.

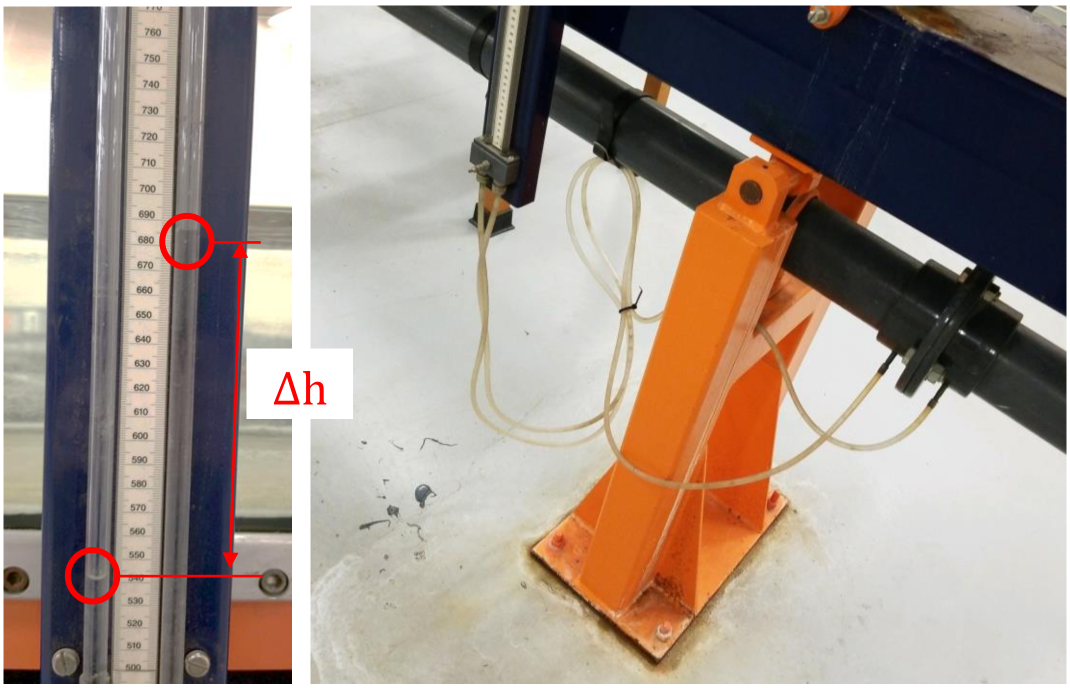

Figure 17: Orifice Flow Meter and Monometer

Based on orifice calculations given from Dr. Sritharan's report from Central State University, the flowrate from the flume could be calculated from Equation 3 below (Sritharan, 2013).

$$Q = 0.01267 * \Delta h^{\frac{1}{2}} \quad (3)$$

In Equation 3, Q (m^3/s) is given as the flow rate and Δh (m) is the change in water height in the manometer. Given the flow rate from equation one, the average velocity of the flow could then be calculated from Equation 4 below.

$$V_{avg} = \frac{Q}{A_c} \tag{4}$$

This equation could be used to determine the average velocity of the flow from the flow rate and cross-sectional area of the flume. To determine the cross-sectional area, the 0.3 width of the flume was multiplied by the water surface level height. As discussed in the open channel flow section, this average velocity should compare to the velocity at 40% of the height of the flow from the bottom surface in the measured data when measured in the middle of the open channel walls.

For further testing of the Hach meter and pitot tube, the Δh value of the orifice meter was kept at a constant 0.150m difference. This height corresponded to a flowrate of 0.0155 m^3/s used for all measurements within the flume. This flowrate was used as it was large enough to provide a wide range of average velocities to be measured by the other equipment. To achieve varying velocities with the constant flowrate, the wave generator in the back of the flume was raised to produce three different water height levels. The three heights of flow were 0.090 m, 0.178 m, and 0.273 m which led to expected average velocities of 0.574, 0.290, and 0.189 m/s respectively. The heights were recorded by using a measurement scale mounted to the outside of the flume as shown below in Figure 18.

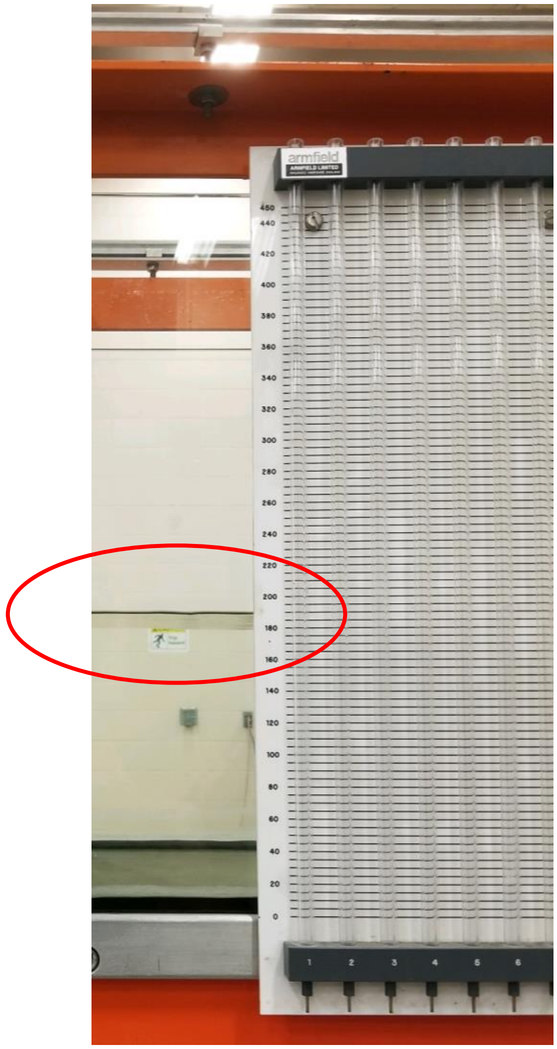

Figure 18: Flow Height Measurement Scale Mounted to Side of Flume

4.3 Hach Meter Testing

The Hach meter flow velocity testing took place by mounting the sensor on the wading pole and securing the wading pole in the developed traverse mount. The mount was placed in the middle of the flume horizontally across the cross section of the flow. The setup of the equipment was as shown below in Figure 19. This set up required the wading pole, wading pole mount, electromagnetic sensor, Hach FH950 handheld device, the flume and accompanying traverse system.

Figure 19: Hach Meter Testing Set Up for Fluid Velocity Characterization

To record velocity measurements with the Hach meter, the meter was set to record flow velocity in cm/s. The handheld display provided a graph over a ten second interval of the flow velocity. The display would then show the average over the ten second measurement period. For each trial, the device was recording for three intervals of ten seconds, and these velocity measurements were averaged. An example of the handheld readout display can be seen in Figure 20 below.

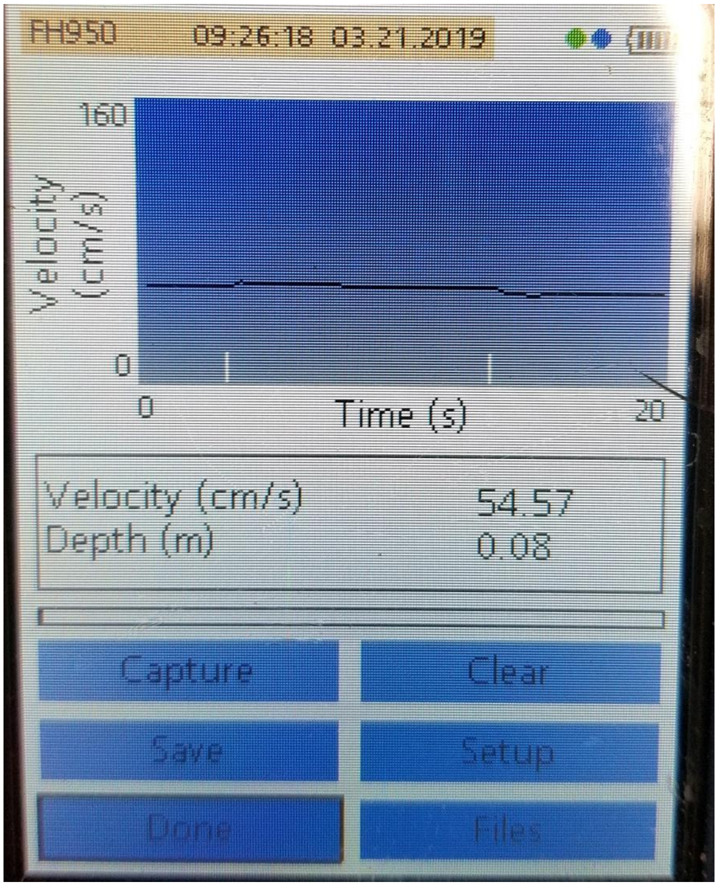

Figure 20: Hach FH950 Handheld Display of Velocity Measurement

As the Hach meter was tested for the three average velocities listed in the previous section, ranges of heights were recorded for each average velocity. The fastest velocity, and the lowest water surface level height had five measurement heights. The lowest height that the Hach meter could record was 2.5 cm from the surface of the flume due to the meter and wading pole geometries. The highest measurement that could be accurately recorded was one cm below the surface, as the meter would begin to crest the surface of the water higher than that. The height measurements taken were first 2.5 cm, 3.0 cm, 4.0 cm, and then increased by 2.0 cm until the height was no closer than 1 cm from the surface of the water. The increased resolution at the bottom of the water level was intended to capture any boundary layer effects of the flow.

After recording the necessary data from the Hach meter at each of the corresponding depths, calculating the average velocity using the orifice meter from Equation 3, and the theoretical turbulent boundary profile from Equation 2, Figure 21 was used to compare the results for each average velocity.

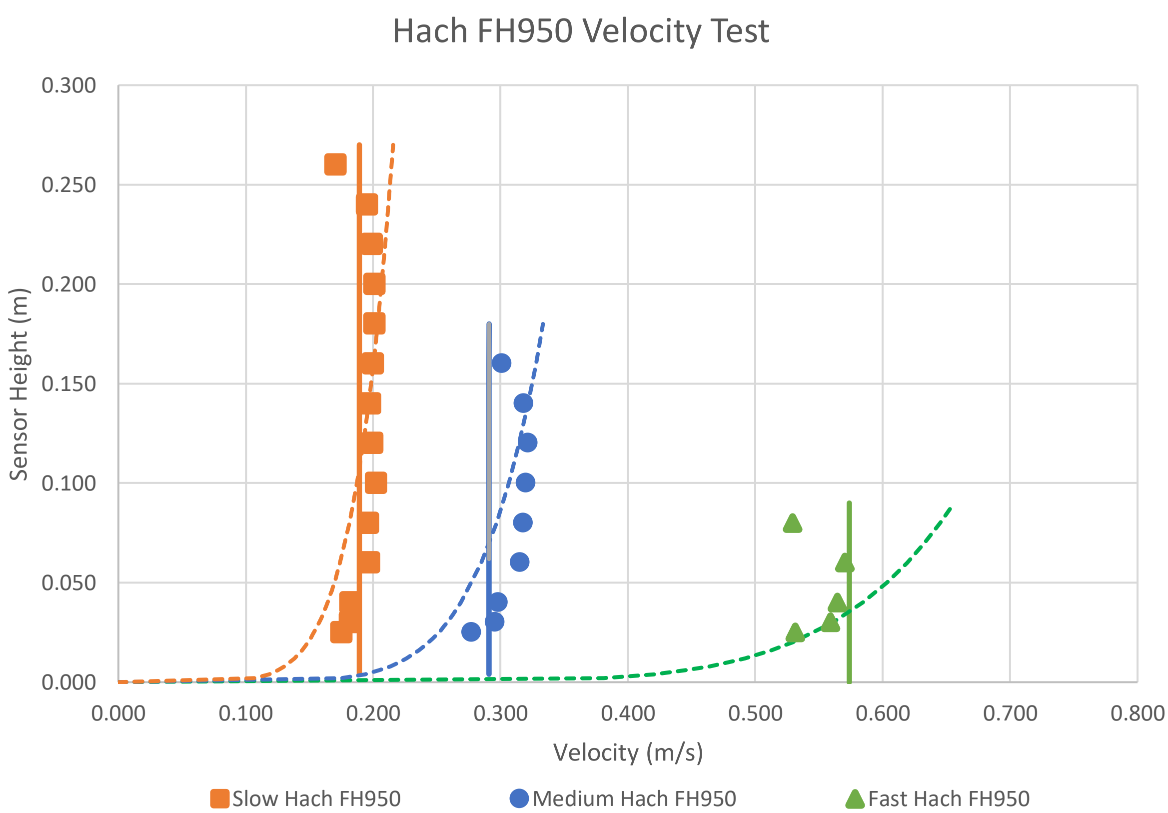

Figure 21: Hach Meter Testing Results Compared to Theoretical Estimates

The discrete points in the plot represent measured data points, while the solid vertical lines are representative of the calculated expected averaged velocity from the orifice meter. Finally, the dotted curves represent the estimated velocity profile from the power law assumption.

4.4 Pitot Tube Testing

Testing for flow velocities with the pitot tube was done in a similar manner to that of the Hach meter. The pitot tube was mounted in the same position as the Hach meter but had additional resolution at the bottom and top of the flow due to its small profile. The pitot tube was tested for the same flow rate and velocities as the Hach meter. The pitot tube set up can be seen in Figure 22. The equipment necessary to run the testing was the Dwyer 160-36 pitot tube, Dwyer 477AV handheld digital manometer, rubber connector tubing, pitot tube mount, flume, and accompanying traverse system.

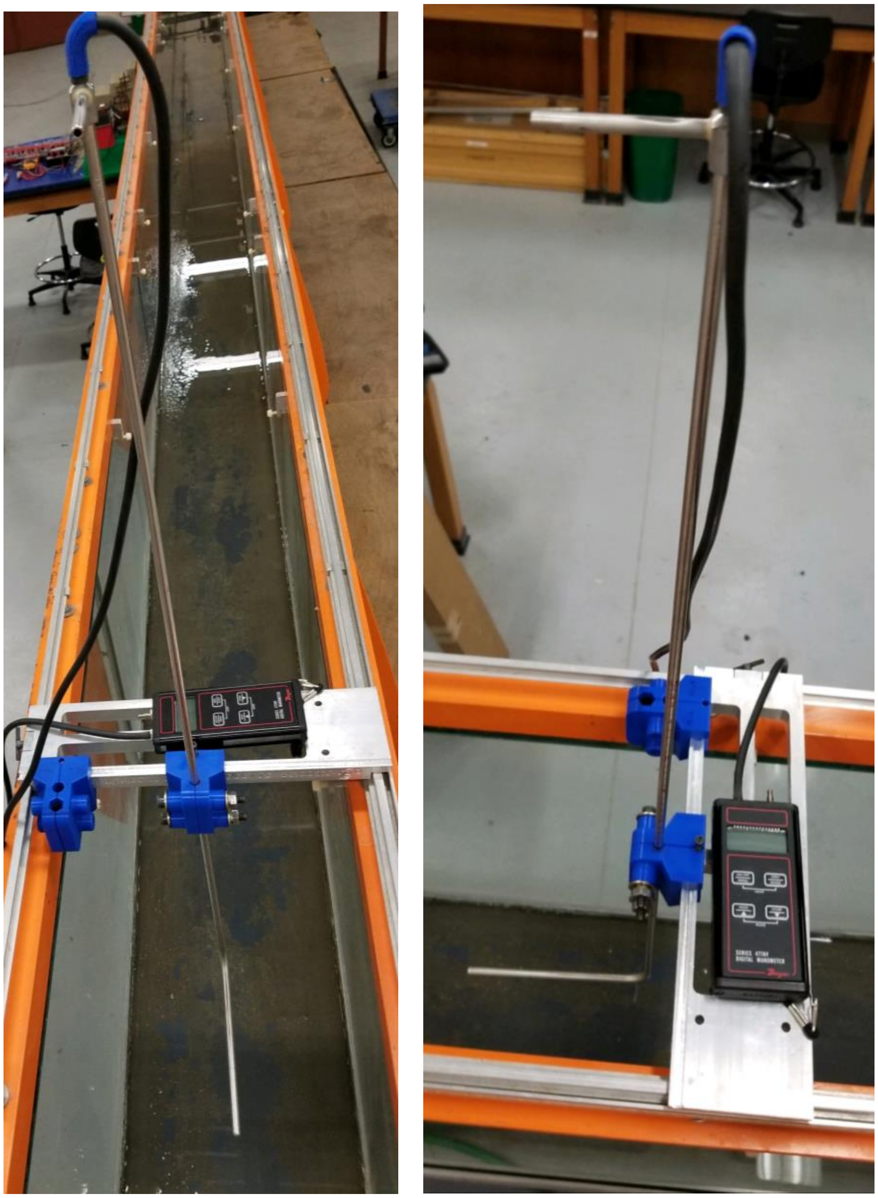

Figure 22: Pitot Tube Flow Velocity Measurement Set Up

The pitot tube measurements were taken similarly to the Hach meter in that for each height tested within the flow, measurements were taken for thirty seconds. The 477AV handheld manometer constantly read out pressure values real time. Measurements were taken at 10 seconds, 20 seconds, and 30 seconds and then averaged to find the pressure measurement for that height.

The manometer output was the total gauge pressure of the water at the given depth. This was achieved by connecting the positive pressure port on the manometer to the total output of the pitot tube and leaving the negative pressure port on the manometer open to the atmosphere. Because of this, to calculate the velocity the hydrostatic pressure needed to be subtracted from the total pressure and then the velocity could be calculated from the kinetic pressure. The total gauge pressure equation was given as shown in Equation 5 derived from Bernoulli's equation.

$$P = \frac{\rho V^2}{2} + \rho g h \tag{5}$$

This is given where P is the total pressure in Pascals, ρ is the density of water assumed to be 1000 kg/m^3, g is gravitational acceleration assumed to be 9.81 m/s^2, h is the water depth of the measurement in meters, and V is the point velocity in m/s. Having rearranged Equation 3 to solve for the velocity, Equation 6 was used to calculate the velocities directly from the other inputted variables.

$$V = \sqrt{\frac{2(P - \rho g h)}{\rho}} \tag{6}$$

These measured velocities were then plotted against the same orifice meter average velocity and theoretical power law curve as seen in the Hach meter results. Figure 23 shows the pitot tube results compared to the expected theoretical values.

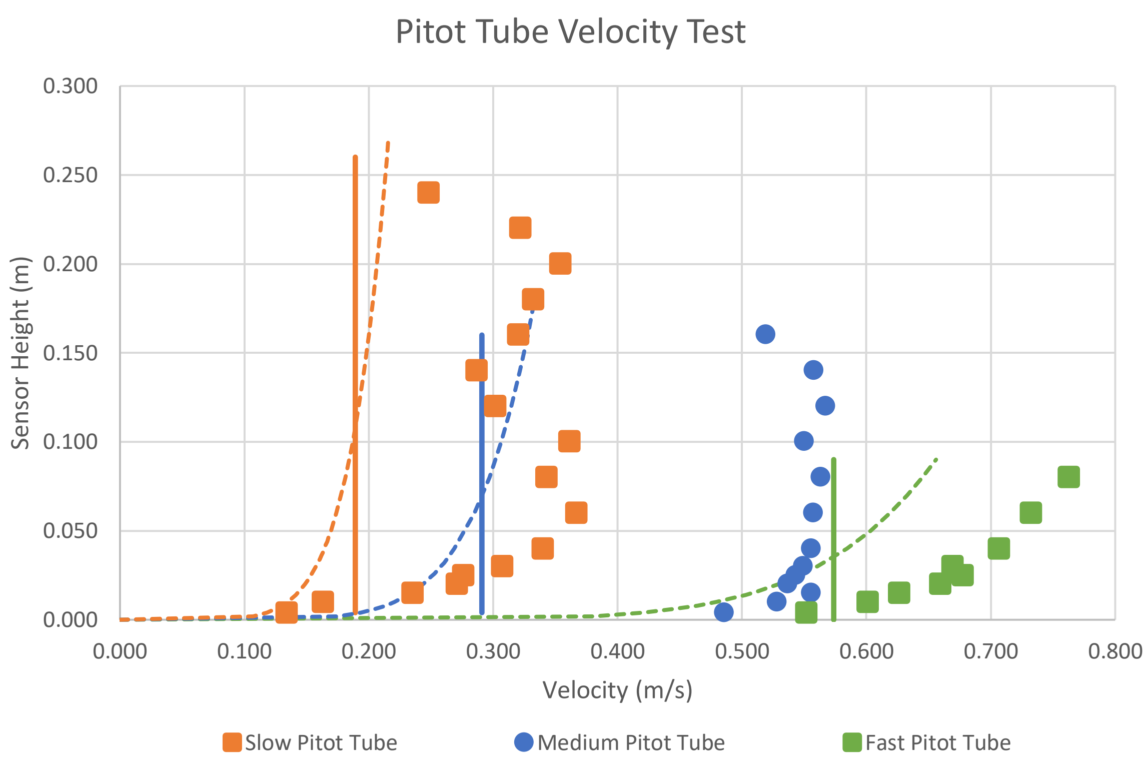

Figure 23: Pitot Tube Testing Results Compared to Theoretical Estimates

As the plot shows, the pitot tube measured results trended to be much higher than the expected theoretical values.

4.4.1 Purging the Pitot Tube

One hypothesis for the discrepancy seen in the pitot tube data was that there were pockets of air and water building up within the tube. As these pockets moved and settled in the tube, the pressure would vary. In order to attempt to solve this problem, several attempts were made to purge the pitot tube with air before the trials took place.

The pitot tube was purged with the aid of a standard bicycle pump. Air was pumped through the tube, clearing it of any excess water trapped inside. This had the desired effect of clearing out excess water that had been trapped in the small tube. Unfortunately, the results of testing still showed higher velocities than expected. For the final tests of the pitot tube, the tube was purged before each flow velocity, but once the tube was submerged, it remained submerged for that average flow velocity while measurements were taken at different heights. This was done to attempt to capture the correct shape of the velocity profile, and to not introduce any additional random error from starting conditions within each trial.

4.4.2 Error Analysis

As the digital handheld manometer readings were inconsistent, an error analysis was performed to determine how much error was influenced by calculations. The average range of measurements between the three data points at each height was about 5 Pa. This means that of the three measurements, the difference in the maximum data point and minimum data point were about 5 Pa on average. Because of this, 5 Pa was added to the average pressure of two cases to see the impact it would have on the resulting velocity measurement. In the best-case scenario of the fastest flow, and shallowest depth the velocity was increased by 0.85 percent or 0.0065 m/s. This was assumed to be the best case because the kinetic portion of the pressure is the highest at the shallowest depth and fastest velocity as indicated by Equation 3. On the other hand, the worst-case scenario of the slowest and deepest measurement had a percent difference of 15.87 percent or 0.0282 m/s. The percent difference formula used was Equation 7, shown below.

$$\% \, Difference = \frac{V_{meas} - V_{error}}{(V_{meas} + V_{error})/2} \tag{7}$$

These fluctuations in measurement do not account for the systematic error of the pitot tube consistently reading high velocities, though it may contribute to some of the random error in the shape of the velocity curves for the pitot tube.

4.5 Discussion

From the results of the Hach meter and pitot tube testing, the trends indicate that the Hach meter performed well in the flume environment despite its intended use in streams and rivers. This meter's velocity profiles matched closely to the expected shapes and average velocities based on previous studies and the orifice meter calculations. The main limitations of this meter for use in the flume was the meter's large size. The fastest velocity and lowest water surface level showed the Hach meter recording velocities lower than expected. This could be due to the meter's size acting as an obstruction in the flow in which the narrow channel of water would have to change direction to go around. This effect would be less noticeable for larger cross sections of flow. These size concerns become relevant int terms of measuring flow around the slotted weir design of kWRiver. This device would not be able to accurately record velocities coming from under the structure and its size would make it difficult to record point velocities near the slot itself. This device could be used with the slotted weir to get an idea for the average velocity coming through the slot but would not be useful in mapping out a velocity field of separate points.

The pitot tube measurements overall displayed a trend higher than the expected average velocities. The error analysis showed that a relatively low amount of the error could be attributed to measurement error compounded by pressure calculations, especially at high velocities and shallow measured depths.

Chapter 5: Conclusion

To determine the effectiveness of a slotted weir design produced by kWRiver, this research focused on characterizing flow velocity in an experimental tilted glass flume. The objectives were to mount the slotted weir, select suitable measurement equipment, design and implement a traverse system, characterize flow in the empty flume, and characterize flow around the slotted weir design. This research contributed an understanding of the effectiveness and limitations of various velocity measurement devices in the experimental flume environment. Additionally, it contributed a working traverse framework for mounting and positioning measurement equipment. This traverse system could be used and altered to hold other devices in the future of differing geometries.

5.1 Future Work

The future of this research lies within understanding the limitations of the pitot tube measurements. To better understand the limitations of the pitot tube and digital manometer set up, experiments could be run with a physical manometer water column to compare the results of the handheld piezo pressure sensor system. Additionally, varying the size of the pitot tube to have a larger inlet diameter could reduce fluid effects inside the tube. This could reduce the theorized pockets of air and water building up within the tube by allowing more movement of the water within the tube as there would be a larger volume to move away from the walls of the tube.

With the working pitot system, the flow upstream, downstream, and through the slotted weir should be characterized to determine the effects on the percentage of useable kinetic energy for turbine production. Additionally, the use of a porous plate within the slot to simulate a turbine’s obstruction to the flow should be tested. The porosity of the plate could vary to simulate varying turbine designs and should be mounted to the weir itself. This testing should all be performed with an increased tailwater depth created by varying the wave generator to the desired height. This tailwater depth should consider realistic river conditions.

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