Using Ultrasonic Flowmeters in Integral PWR Instrumentation

Department of Nuclear Engineering
The University of Tennessee

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Senior Design Final Report

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Abstract

The objective of this design project is to determine the viability of ultrasonic instrumentation for non-circular geometries that would be encountered in the measurement of primary coolant flow rate in an integral modular nuclear reactor, specifically, in the downcomer region. Currently, integral pressurized water reactors do not have a reliable method of determining the primary coolant flow rate, which is crucial for safety and operation.

The project has successfully established that ultrasonic instrumentation can work for monitoring flow rate for a non-circular geometry. This is accomplished using a carbon steel test section that is modeled to simulate the downcomer of an integral reactor. The ultrasonic flow meter is compared to a control flow meter, which for this project is a turbine flow meter. The ultrasonic flow meter is determined to be within statistical uncertainty of the turbine flow meter, verifying that the ultrasonic instrumentation can be used on geometries that might be encountered in integral modular reactors, such as small modular reactors.

The deliverables of this project include a fully functional flow loop located on the University of Tennessee's Knoxville campus, in Pasqua engineering building; data from multiple experimental runs, and several Python and MATLAB scripts.

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Acknowledgments

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Special thanks to Matt Lish for his assistance with this project and advising.

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Special thanks to Dr. Jamie Coble for purchasing the turbine flow meter, and for advising on the EUReCA poster presentation.

Special thanks to Greg Meinweiser for his advice regarding thermocouples and temperature correlation analysis.

Special thanks to Dane De Wet for his assistance with LabVIEW data acquisition.

This project was showcased in an undergraduate research exhibition, EUReCA, at the University of Tennessee, Knoxville.

Objectives

The goal of this design project is to determine whether ultrasonic instrumentation can be used to measure the flow rate of primary coolant in integral nuclear reactors. The motivation for this research comes from the piping space and penetration restrictions imposed by small modular reactors (SMRs) and pool-type integral reactors. Primary coolant flow rate measurements are important and mandatory during accident or transient reactor operation to ensure safety. The current implementation of instrumentation of reactors uses primarily differential pressure transmitters to measure coolant flow rates. These meters, while reliable and accurate, are intrusive methods, and are somewhat bulky compared to ultrasonic meters. The benefits of ultrasonic meters are that they are non-intrusive and they are very accurate compared to most meters. Ultrasonic meters are mounted on the outside of process flow conduits, and cause no interference with the flow of liquid. Ultrasonic meters can have an accuracy of 1%, which is better than venturi tubes (1-2%), and can be used for liquids that venturi tubes are not suitable [1,7].

Ultrasonic flow meters are currently used for water, sewage, and food industry piping with circular cross-sections. This project addresses whether or not ultrasonic instrumentation can also be used in flow channels with non-circular cross-sections. Measured flows are compared to measurements using a turbine flow meter. An inferential approach was also attempted using thermocouples and signal cross correlation [8].

Background

Ultrasonic flow meters use two transducers mounted on the exterior of the process flow channel. These transducers emit and receive high-frequency acoustic pulses. The transducers are mounted on the same side of the channel and both downstream and upstream reflection transit times are measured. Acoustic pulses travel through the channel wall and fluid, reflect off the opposite inner channel wall, and then travel back through the fluid and original wall. Pulses are sent in both the upstream and downstream directions. By measuring the difference in the transit time of these upstream and downstream pulses, the two times of flight, and by knowing the geometry of the pipe and transducers, the fluid flow rate can be estimated.

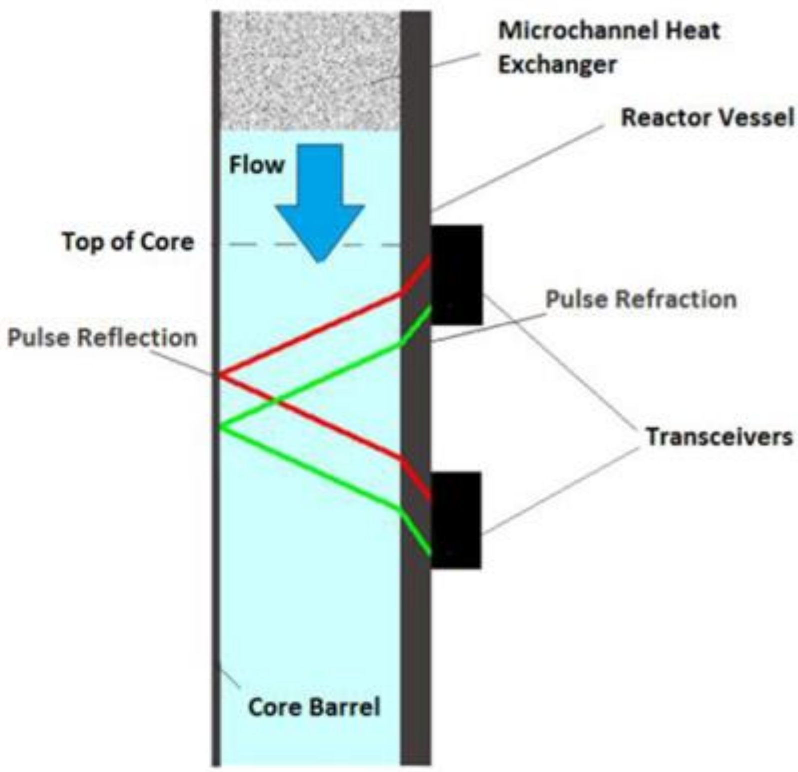

Figure 1: Schematic of ultrasonic instrumentation theory of operation

The flow velocity is given by Equation (1). Then, knowing the channel cross sectional area and the density of the liquid, the mass flow rate can be calculated.

$$V_{flow} = \frac{L * \Delta t}{2\sin(\varphi)\, t_{up} t_{down}} \tag{1}$$

L: path length of acoustic wave in the coolant
φ: angle of the reflected wave to the normal axis
Δt : t_{up} - t_{down}

Temperature correlation analysis

Velocity of a fluid can be measured by two thermocouples placed a small distance apart in the fluid using cross correlation techniques. Given two signals, $x(t)$ and $y(t)$, over a time domain from zero to T, the cross correlation gives the similarity between the two signals as function of lag time τ.

$$R_{xy}(\tau) = \frac{1}{T}\int_0^T x(t)y(t+\tau)dt$$

The thermocouple signals can be assumed to be related by a transport delay time D, and a measurement noise $n(t)$.

$$y(t) = c * x(t+D) + n(t)$$

If the noise function is assumed to be independent of x(t) the cross correlation between x(t) and y(t) is given by

$$R_{xy} = \frac{1}{T}\int_0^T x(t)x(t-D+\tau)dt = R_{xx}(\tau - D)$$

This correlation coefficient has a maximum at a lag time, $\boldsymbol{D}$. Thus, by calculating the cross correlation between two thermocouple signals, the lag time at which the cross correlation has a maximum, gives an estimate of the transport delay time D. If the thermocouples are placed a distance L apart, the average velocity V of the fluid is estimated by

$V = L/D$.

Methods

The ultrasonic flowmeter is evaluated using two methods. The first is a comparison with a flowmeter with known properties. For this experiment, a turbine flowmeter is selected for its low cost, robustness, ease of installation, ease of operation, and adequately low uncertainty of 3%. The second method is transit time estimate using cross correlation between temperature sensor signals. Thermocouples were selected to measure temperature because of their low cost.

The temperature correlation analysis is performed using 2-3 thermocouples and looking for correlation in the signals to estimate the velocity. This correlation analysis is done using MATLAB and LabVIEW.

The project uses a flow channel with a rectangular cross-section to approximate a small slice of the annular down-comer region typically found in SMR vessels where flow measurements are required to ensure safe operation. This approximation allows for easier fabrication and installation and results in a negligible difference in cross-sectional area for a thin slice with width of a few inches. This approximation should not affect the capability of the ultrasonic flowmeter according to its theory of operation. To clarify, the small change in shape of the flow channel should not affect how the acoustic pulses traverse the channel and reflect off the opposite interior wall.

The ultrasonic flow meter that was purchased is a GE AT 600, which is capable of less than one percent uncertainty, and can report upstream and downstream acoustic pulse traverse times as well as velocity. The GE AT 600 does provide digital output; however, due to issues with obtaining the required GE software, the control panel of the device was used to manually log the data. Unfortunately, manual data collection is not quite as accurate as digital data collection. The issues with the GE software are discussed later in this report.

The actual test section was fabricated in the John D. Tickle Engineering Building's machine shop. The test section uses a rectangular design, with a sloping top and bottom, due to spacing and vectoring. The flow loop is constructed in the basement of the Pasqua Nuclear Engineering Building. There are photographs available in appendix B of the full test section and flow loop. The first test section design had a funnel-shaped top to minimize disruption to the flow, but because the ceiling height is too low to allow for this funnel-shaped cap, the section was redesigned to have water enter at the side, and depart from the side. The test section is shown in

Figure 2. The flow loop was constructed using PVC piping, a Bell and Gossett 7.5 horsepower pump, and the test section, which was made of carbon steel. The test section was made vertically, in a rectangular piping configuration, with the outlet of the pump going up, to the right, through the test section, and out the bottom of the test section directly to the pump.

The test section, as well as the pump, variable frequency drive (VFD), and piping, were mounted using wall and floor mounts. The VFD is a 60 Hz variable frequency drive that is used to vary the speed of the pump. Because the wall near the VFD is a radiological source safe, the VFD was mounted independently on the ground to prevent interfering with the vault shielding or requiring approval from the university's radiation safety office.

The ultrasonic flow meter is mounted to the wall, in the middle of the flow loop. The ultrasonic transducers were first installed on the piping, to compare them directly to the turbine flow meter, and then to the test section. This is to ensure that the ultrasonic flow meter and turbine flow meter roughly agree with each other for the piping, before even attempting to use the ultrasonic flow meter on the test section. The data are then catalogued and analyzed; results are given in the results section of this report.

Description of the Flow Loop

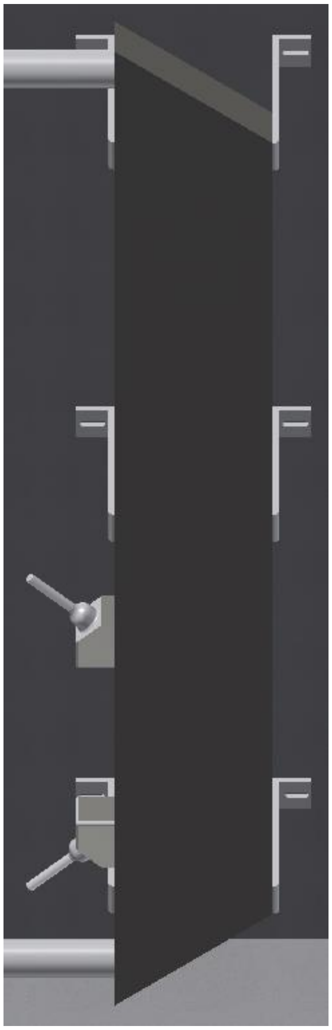

Figure 2: CAD drawing of the test section, mounting hardware, and connecting pipes, with ultrasonic transducers installed.

The design of the loop was begun by evaluating the possible cross section and size of the test section to simulate the down-comer region of integral modular reactors. There was consideration for the size of the test section, since there was limited space for the test section in the basement of Pasqua engineering building. For simplicity, a 12” by 3” rectangular cross section was chosen due to ease of construction and minimal difference from an actual slice of the reactor’s down-comer region. Calculations were performed to determine the flow rates and Reynolds number through the test section to aid in the design selection. The design of the test section, including hand and CAD drawings, were given to the machine shop in John D. Tickle Engineering Building for construction. The test section was mounted to the wall with six brackets, and it contained an inlet and an outlet pipe. The test section is where the meaningful flow measurements took place to determine applicability to non-circular geometries. The two transducers from the ultrasonic flow meter were mounted at a pre-calculated distance apart to maximize the strength of the received acoustic pulses. A signal was reflected off of the right side of the test section at an angle at which it would be received by the other transducer. The transducers were mounted using a coupling gel and wire bands that were not included in the CAD drawing for ease of visualization. Each transducer also has a signal cable coming out of the long end that is not pictured in the CAD drawing.

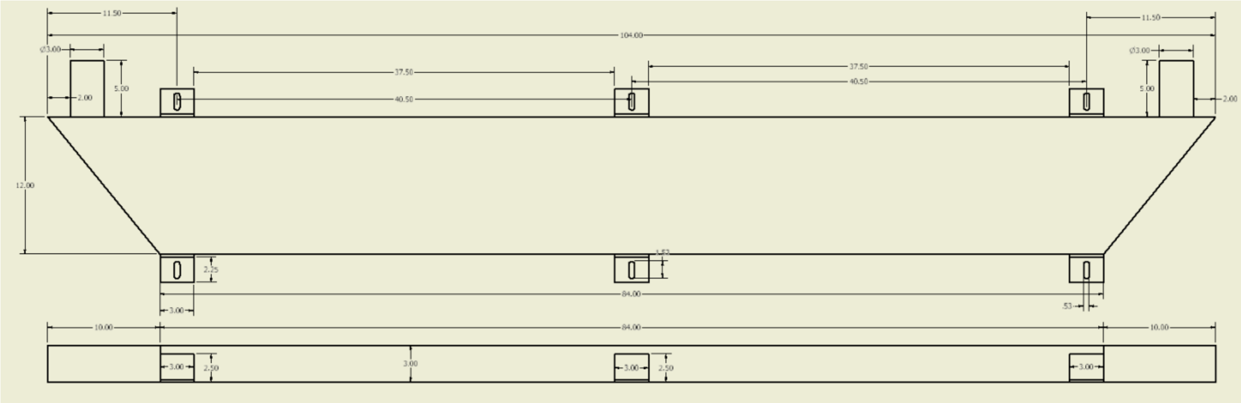

Figure 3: Figure showing schematic with dimensions in inches of steel test section

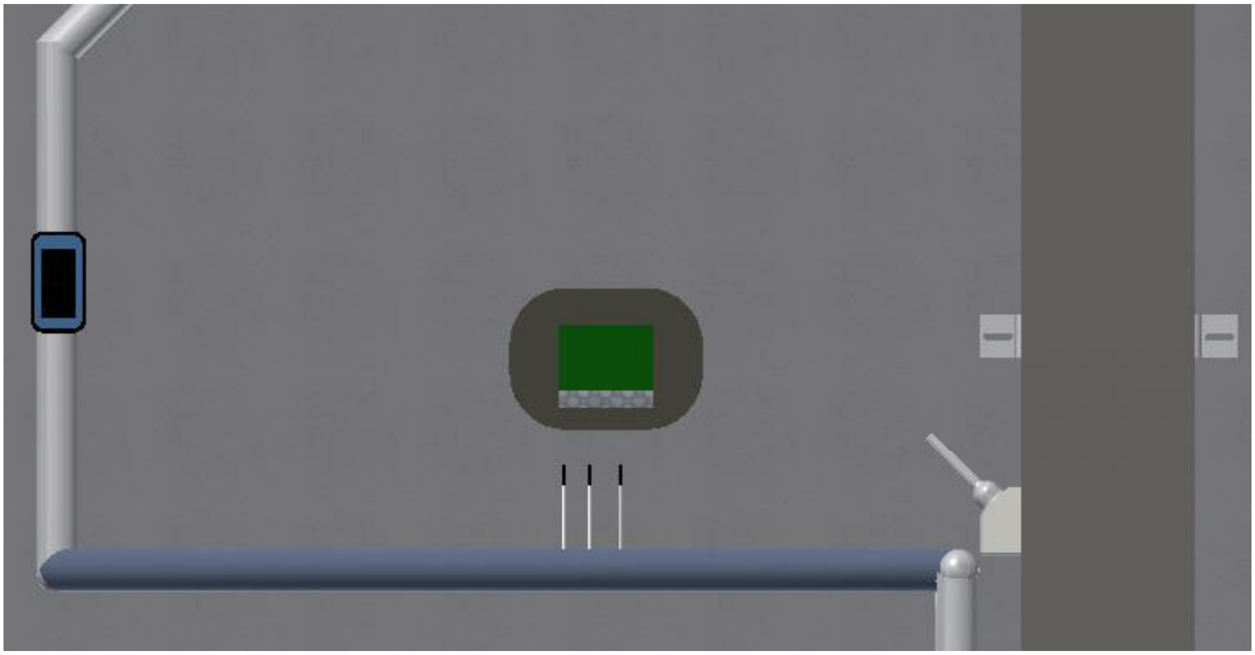

Figure 4: CAD drawing of the ultrasonic flowmeter, turbine flowmeter, and thermocouple installation

The measurement portion of the flow loop is pictured in Figure 3. The turbine flow meter is shown on the far left, connected to the PVC piping. This was used as a ground truth calibration for the ultrasonic flowmeter, which is in the middle of Figure 3. The ultrasonic flow meter is wired to the transducer, depicted on the right of Figure 3 with the test section. The blue pipe represents transparent PVC that was used to visually observe the flow. This allowed us to see if bubble reduction was needed when running the loop. The three pin-like appendages coming out of the blue pipe are thermocouples. The thermocouples were used to collect data for temperature correlation. There is also a pressure gauge for safety near the thermocouples that is not pictured.

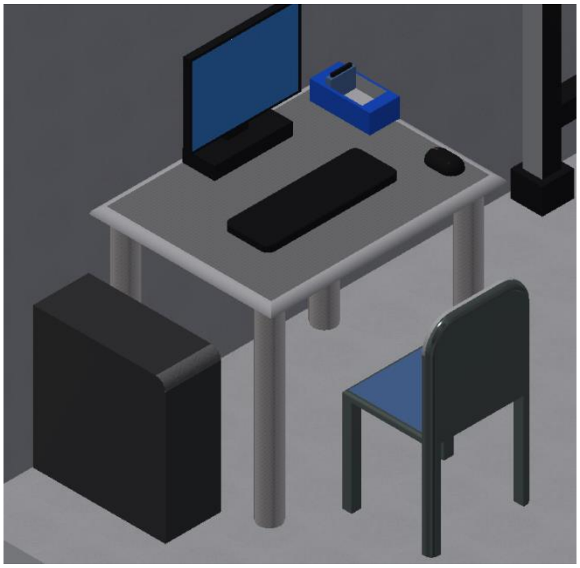

Figure 5 : CAD drawing of the computer and data acquisition modules used to collect data

The variable frequency drive (VFD), the pump, the thermocouples, and the turbine flowmeter are pictured in Figure 6. The pump outlet rejects water to the long system of piping that will be pictured later. The variable frequency drive allowed people to change the pump frequency or speed. The VFD allows for running the pump at different flow rates. The pump inlet comes from the test section of the flow loop after a reading has been made by the transducers.

The computer station and data acquisition modules are shown in Figure 4. The DAQ modules acquired data from the thermocouples using LabVIEW. These data were used for cross-correlation analyses.

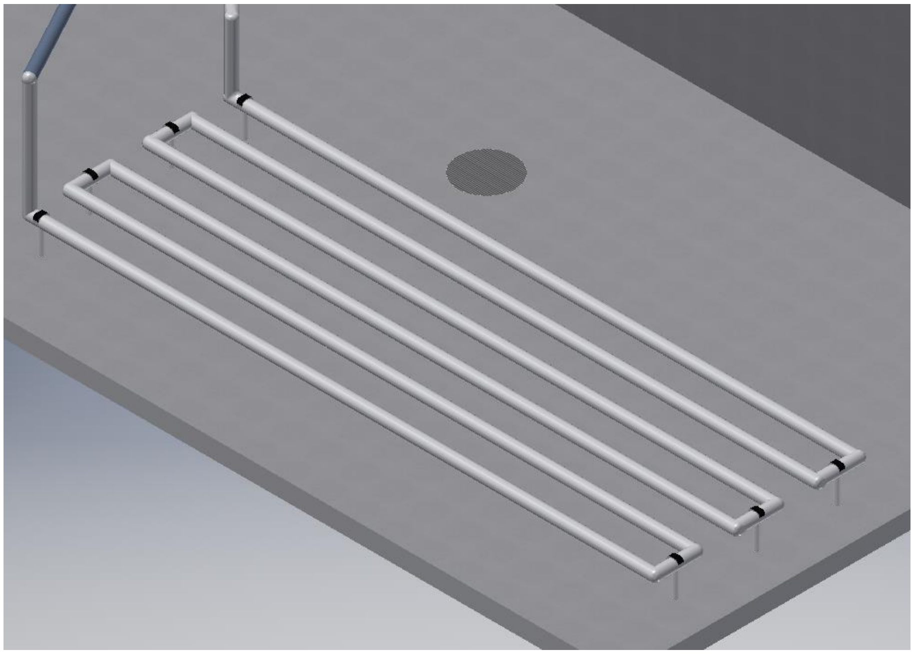

Figure 6: Additional lengths of PVC pipe used to condition the flow

Figure 5 represents long sections of PVC piping that were added later in the design to condition the flow. The flow was found to contain a large amount of dissolved gas that was dissociated from the water due to the low pressure at the pump inlet. This long section allowed most of the gaseous bubbles time to be reabsorbed before the water reached the meters and affected their ability to produce accurate readings. The piping in this section of the loop is at different elevations to remove air pockets that might get trapped at the top of piping. This elevation change is not pictured in the figure.

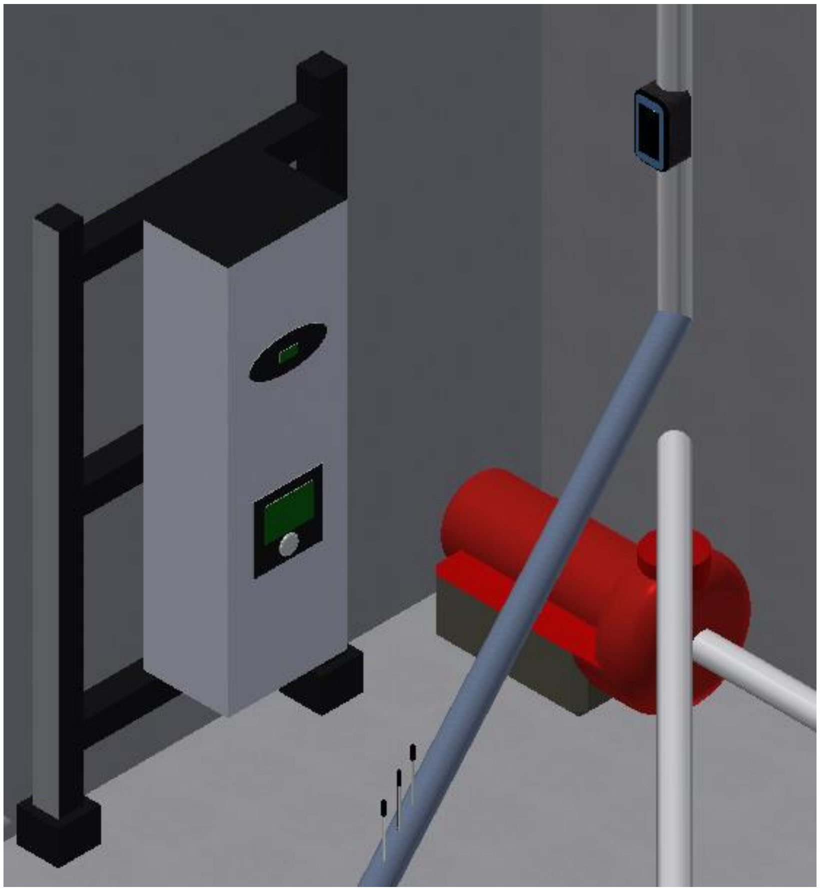

Figure 7: CAD drawing of the pump and variable frequency drive (VFD). The thermocouples, turbine flowmeter, and clear section of pipe are also shown.

The final loop design is pictured in Figure 7. There are several pieces that have been left off due to their non-integral status. Several relief valves are contained within the loop that allow for pressure relief as well as flushing the loop of any air pockets that could hamper data acquisition efforts. The electrical systems for the loop and building have also been left off of this representation. The CAD drawings of the loop were developed using Autodesk Inventor software.

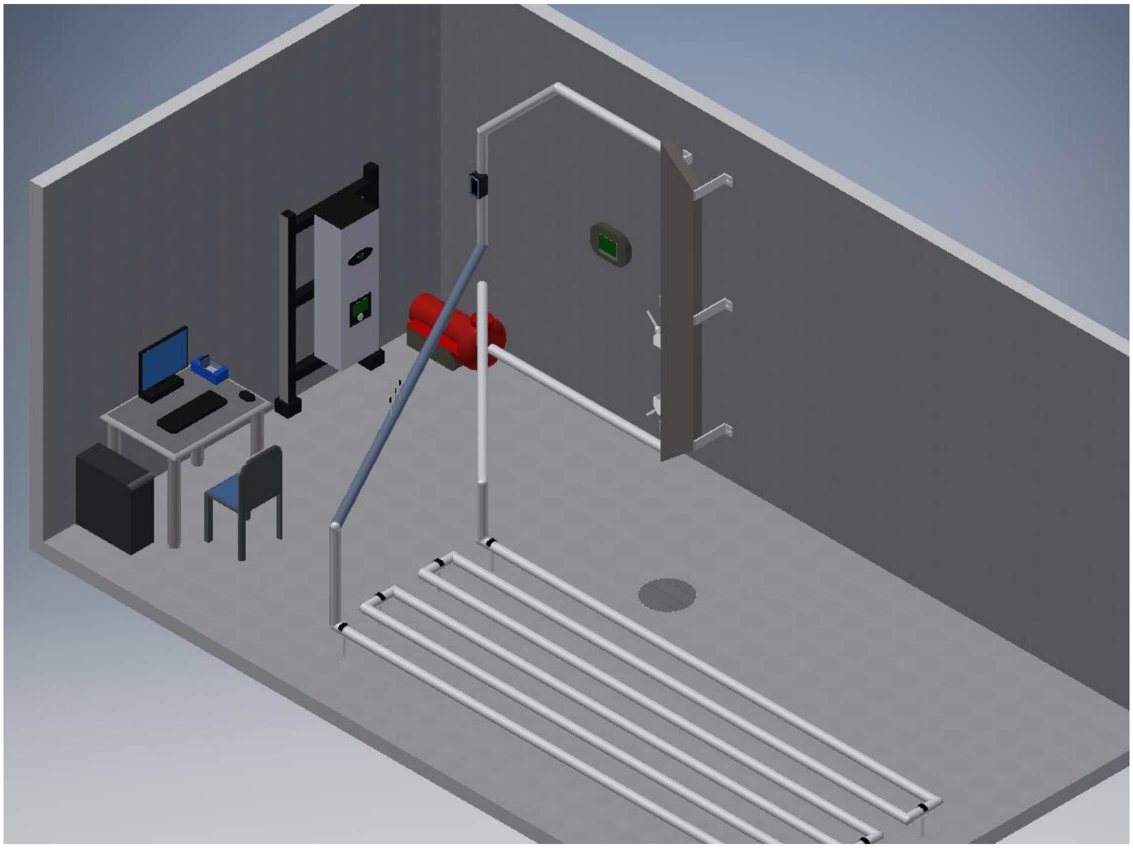

Figure 8: CAD drawing showing the entire flow loop experiment

The flow loop was constructed using PVC pipe and fittings to complete the loop connecting the test section and the pump. The PVC was cut to size and secured together with the fittings using PVC primer and cement. Initially, the loop had some leakage issues from the couplings attached to the test section that were solved using some hand-made rubber gaskets. Because the initial loop design was much smaller than the final design, there was a problem collecting good data from the ultrasonic flow meter. This is believed to be due to air bubbles (gases coming out of solution) in the loop. Without having a clear section of PVC to see into, Dr. Arthur Ruggles assisted in using an ultrasound scanner to monitor the flow profiles throughout the loop and look for bubbles, many of which were found. It is also possible that there was inadequate venting of the loop, but this is unknown due to not having a pressure gage or a clear section. At this point, it was decided to add the additional length of piping to allow for extended loop transit time allowing for gas to be reabsorbed into water after leaving the pump. Also, a clear section of piping and a pressure gage were installed which greatly enhanced the ability to monitor and adequately vent/operate the loop.

Procedure

To operate the loop it is first filled with water using the hose connection between the pump and test section. There are three other hose connections that are used as vents during the filling process. An additional vent is located on the pump to release the air out of the pump during filling. The clear section of the piping and the pressure gauge were monitored during the filling and venting. After the initial filling, the pump was turned on with the VFD set at 15 Hz to circulate any entrapped air to the top of the loop where it could then be vented. The final result of the venting and filling would be an air free loop pressurized to 5-10 psig. The pump can be varied from 15 Hz to 60 Hz to give the desired flow rates for data collection.

First, both the ultrasonic flowmeter and the turbine flowmeter were installed on the three-inch PVC piping. Data were collected at pump frequencies of 15, 25, 35, 45, 55, and 60 Hz. When changing the pump frequency, the flow in the loop is given time to change and stabilize before data collection occurs. Twenty-five readings separated by 15 seconds were taken from each meter at each pump frequency. Also, thermocouple data were recorded at a 1000 Hz sampling frequency for fifteen seconds for each of the flowmeter readings. Next, the ultrasonic flowmeter was installed on the test section, and the data collection process was repeated.

After the data collection was completed, the flow loop was drained to minimize the amount of rusting of the test section. Hoses were connected to the two low point hose connections allowing the loop to be drained to a storm drain.

The ultrasonic flowmeter gives data as a velocity. To calculate the volumetric flow rate, the velocity is multiplied by the cross-sectional area of the flow channel.

The test section was bowed outward during pressure and leak testing, which changed its dimensions. The original cross-sectional shape of the inside of the test section was a 3 inch wide by 12 inch long rectangle. The bulge outward along the long sides of the rectangle caused it to resemble an irregular hexagon where the ultrasonic meter was installed. The 12 inch inner length shortened to 11.75 inches. The 3 inch width remained the same at both ends, but the width in the middle increased to 4 inches. Approximating the shape of the bulged section as a hexagon, the inner cross-sectional area changed from 36 square inches to 41.125 square inches, a 14.2% increase. This increase was factored into the volumetric flow rate calculations.

The flowmeter measurements have both an inherent machine uncertainty as specified by their manufacturers, and a measurement uncertainty affecting their accuracy. The machine uncertainties for the ultrasonic flowmeter and the turbine flowmeter are 1% and 3%, respectively [1,5]. The measurement uncertainty is taken to be the standard deviation of a set of measurements at a constant pump frequency. The total uncertainty for each averaged set of measurements is calculated by taking the square root of the sum of the squares of these two uncertainties. The total uncertainty was calculated using the formula

$$\sigma_{total} = \sqrt{(p\mu)^2 + \frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N-1}}$$

where x_i is the value of each measurement, N is the number of measurements, μ is the mean, and p is the machine relative uncertainty (0.01 for the ultrasonic meter and 0.03 for the turbine meter) [6].

To perform cross-correlation analysis on the thermocouple voltage data, the data are loaded into MATLAB software and scaled to have a mean of zero and a standard deviation of one. The data are then digitally filtered using a low pass filter with a passband frequency of 0.001 Hz, a stopband frequency of 50 Hz, a passband ripple of 1 dB, a stopband attenuation of 60 dB, and a sample rate of 1000 Hz. The cross-correlation coefficient of the z-scored and filtered voltage data from two thermocouples is calculated for lag times up to 0.5 seconds, or 500 data points.

Team Member Contributions

Michael Cooper: Team leader, weekly reports, final report, flow loop design, flow loop construction, software, Python, LabVIEW, MATLAB, scheduling, analysis of results, research, parts ordering, flow meter operation and selection, selection of thermocouples

Shawn Tyler: Flow loop construction, flow loop design, parts ordering, electrical wiring, pump and VFD set up, consulting, final report

Matt Buttrey: Flow loop construction, flow loop design (recommended rectangular geometry approximation, which made test section very basic to construct), secondary flow meter selection, final report

Jason Rizk: Software, flow meter operation, flow meter selection, LabVIEW, MATLAB, Python, data analysis, thermocouple data correlation, final report

Kendall Minor: Software, flow meter operation, flow meter selection, LabVIEW, data analysis, CAD, final report

Results

Data were acquired through manual logging of the ultrasonic flow meter's display panel, and then Python was used to analyze the data. The data were plotted and are listed in Table 2.

The overall results are very promising, as the data from the ultrasonic and turbine flow meters are within 8% of each other, and their difference is within the propagated uncertainty of the measurements.

Table 1: This table shows the costs of the parts which were used in the construction of the flow loop

Parts and Equipment List:

Test section+C23A29A1:D25	$750
The Bell and Gossett 7.5 HP	$4,700
Pump mounting plate	$0
GE AT 600 ultrasonic flow meter	$3,200
Turbine flow meter	$560
Masonry drill bit and anchor kits/screws	$18
90 ft of 3" PVC pipe	$270
5 ft of 2" PVC pipe	$10
4 ft of 3" clear PVC pipe	$70
1 3" to 2" PVC pipe reducer	$10
7 3" female unthreaded unions	$175
2 Inside Connectors, Male Unthreaded Pipe Ends	$40
1 2" Thick-wall PVC unthreaded pipe fittings and flanges	$10
1 3" Thick-wall PVC unthreaded pipe fittings and flanges	$16
2 3" 45° elbows, female unthreaded socket ends	$14
16 3" 90° elbows, female unthreaded socket ends	$112
2 2" socket weld ball valves	$60
1 3" socket weld ball valve	$90
2 8oz can PVC pipe cement primer	$12
2 16 can PVC pipe cement	$18
4 3" to 2" Inline reducing tees, Female unthreaded socket ends	$34
40' slotted strut channel	$140
20 ¼ 20 nuts and bolts	$10
20 washers and lock washers	$5
4 compressor feet and spacers	$0
Floor mounting equipment (clamps, rods, etc.)	$250
4 hose connections	$30
Variable Frequency Drive	$2,000
Modbus USB adapter	$5

Total **$12,609**

Table 2: Averaged Flowmeter Data for Each Pump Frequency

Pump Frequency (Hz)	Ultrasonic Flowrate (m^3/sec) X 10^{-3}	Turbine Flowrate (m3/sec) X 10^{-3}	Percent Error (%)
UFM on PVC Pipe:			
15	4.49 ± 0.05	4.38 ± 0.07	2.4 ± 1.9
25	7.74 ± 0.08	7.45 ± 0.09	3.9 ± 1.7
35	10.99 ± 0.11	10.56 ± 0.12	4.1 ± 1.6
45	14.30 ± 0.15	13.73 ± 0.15	4.2 ± 1.6
55	18.08 ± 0.22	16.89 ± 0.21	7.0 ± 1.9
60	19.81 ± 0.27	18.43 ± 0.20	7.5 ± 1.9
UFM on Test Section:			
15	4.86 ± 0.34	4.43 ± 0.06	9.8 ± 7.9
25	8.13 ± 0.56	7.48 ± 0.10	8.7 ± 7.6
35	11.74 ± 0.73	10.58 ± 0.13	10.9 ± 7.1
45	14.48 ± 0.82	13.78 ± 0.16	5.1 ± 6.1
55	18.32 ± 0.99	16.96 ± 0.19	8.0 ± 6.0
60	19.43 ± 1.17	18.53 ± 0.20	4.9 ± 6.4

This table shows the average results from each of the experimental runs for different VFD settings, with their associated propagated uncertainty.

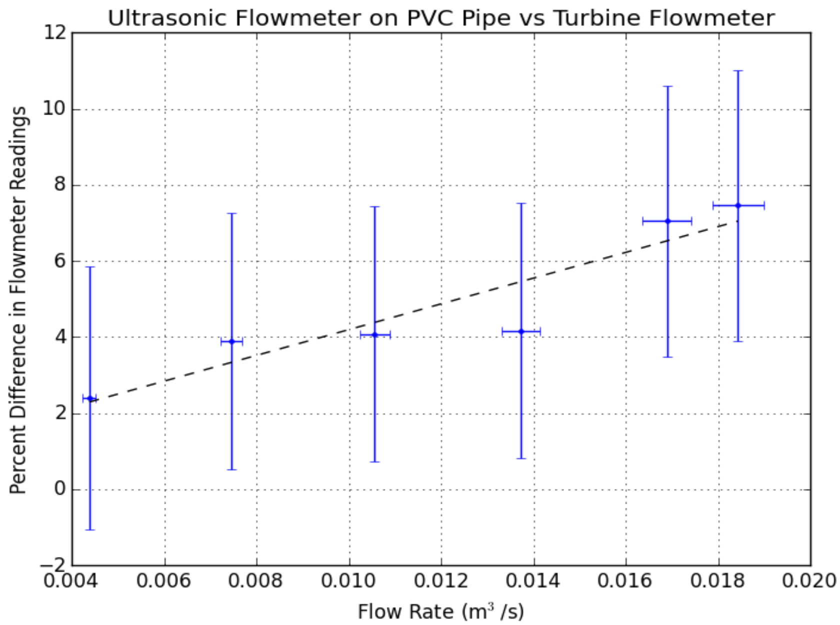

Figure 9: Percent difference in the ultrasonic flowmeter measurements and turbine flowmeter measurements as a function of flow rate when the ultrasonic flowmeter is installed on the PVC pipe. The difference increases as flowrate increases

$$\% \, Difference = 313.2 * \ (Flow\ rate\ in\ m^3/s) \ + 0.9021 \qquad R^2 = 0.872$$

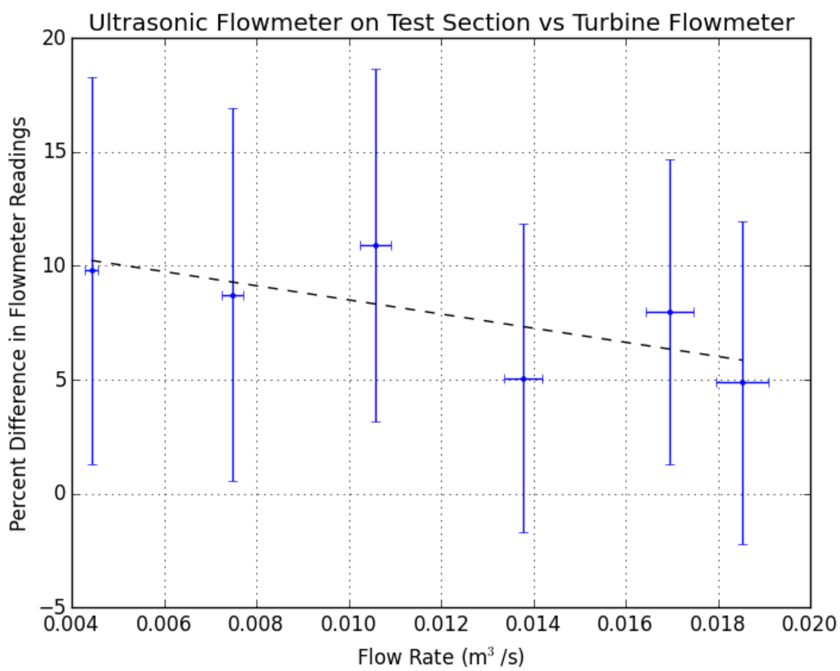

Figure 10: Percent difference in the ultrasonic flowmeter measurements and turbine flowmeter measurements as a function of flow rate when the ultrasonic flowmeter is installed on the test section. The difference lightly decreases as flowrate increases.

$$\% \, Difference = -310.5 * (Flow\ rate\ in\ m^3/s) + 11.61 \qquad R^2 = 0.4764$$

The ultrasonic flowmeter installed on the PVC pipe provides slightly higher measurements than the turbine flowmeter. The difference in the meter readings averages 4.8% over the flow velocities measured, and this difference tends to increase with higher flow velocities.

The ultrasonic flowmeter installed on the test section also provides slightly higher measurements than the turbine flowmeter. The difference in these meter readings averages 7.9% and approximately tends to decrease with higher flow velocities.

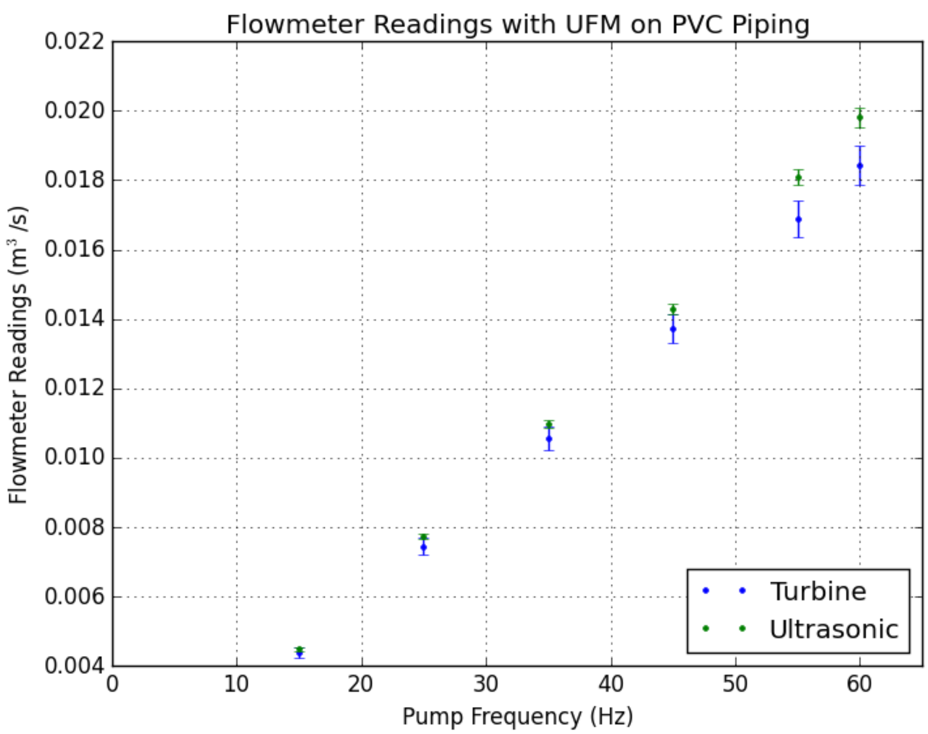

Figure 11: The averaged flowmeter readings at each pump frequency with the ultrasonic flowmeter installed on the PVC piping. The ultrasonic meter reads an average of 4.8% higher than the turbine meter.

Because the ultrasonic meter gives higher readings on the PVC pipe than the turbine flowmeter, it is not surprising that the ultrasonic meter would also give higher readings when installed on the test section. The average error when the ultrasonic flow meter is installed on the test section is only 3% higher than the error when installed on the PVC pipe.

The ultrasonic flowmeter readings on both the PVC pipe and the test section in Figure 12 below agree within the margin of measurement error.

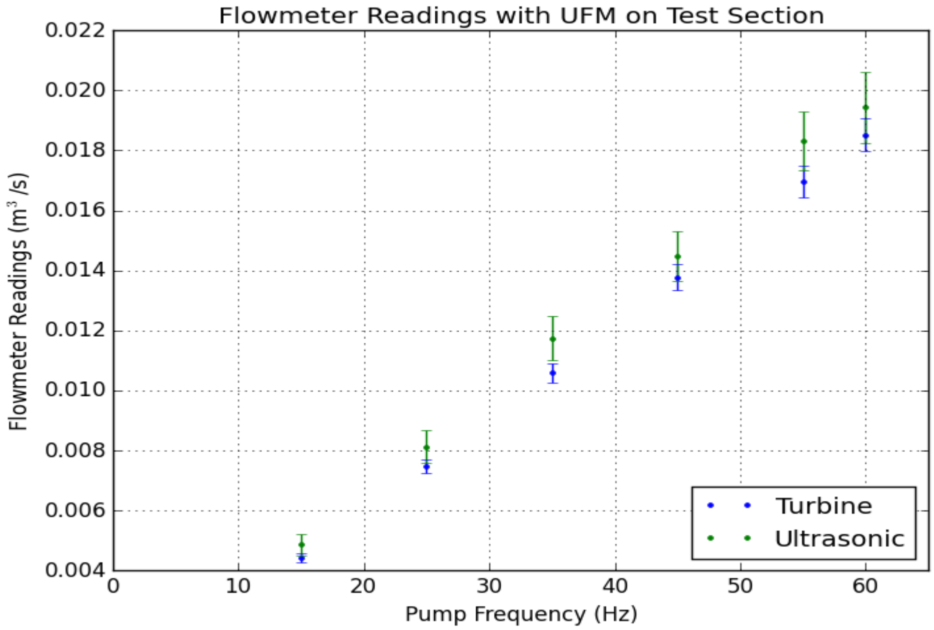

Figure 12: The averaged flowmeter readings at each pump frequency with the ultrasonic flowmeter installed on the test section. The ultrasonic meter reads an average of 4.8% higher than the turbine meter.

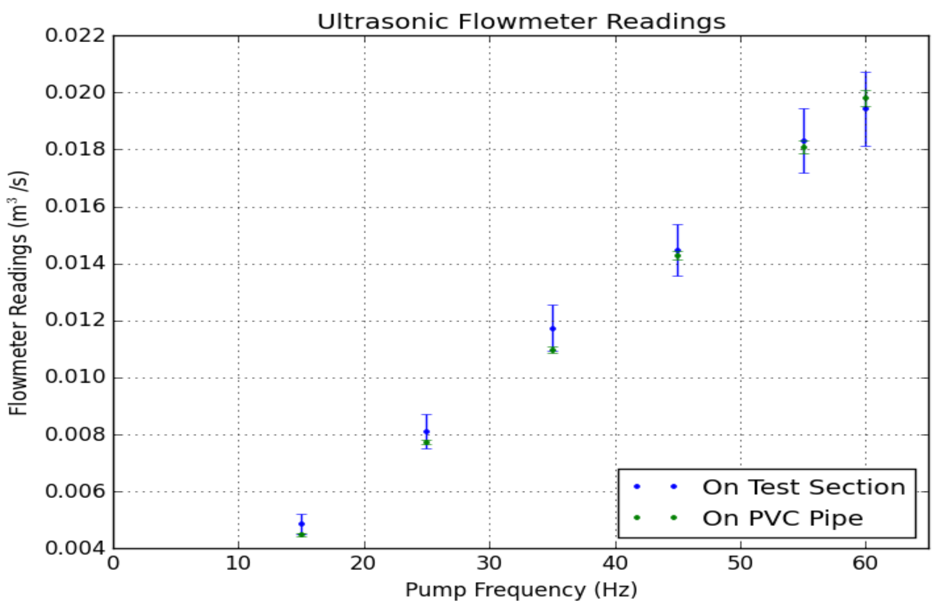

Figure 13: The average ultrasonic flowmeter readings for each pump frequency with both the ultrasonic meter installed on the PVC pipe and on the test section. The fact that the measurements are within the margin of error from each other indicates that the flowmeter is accurate when installed on the test section.

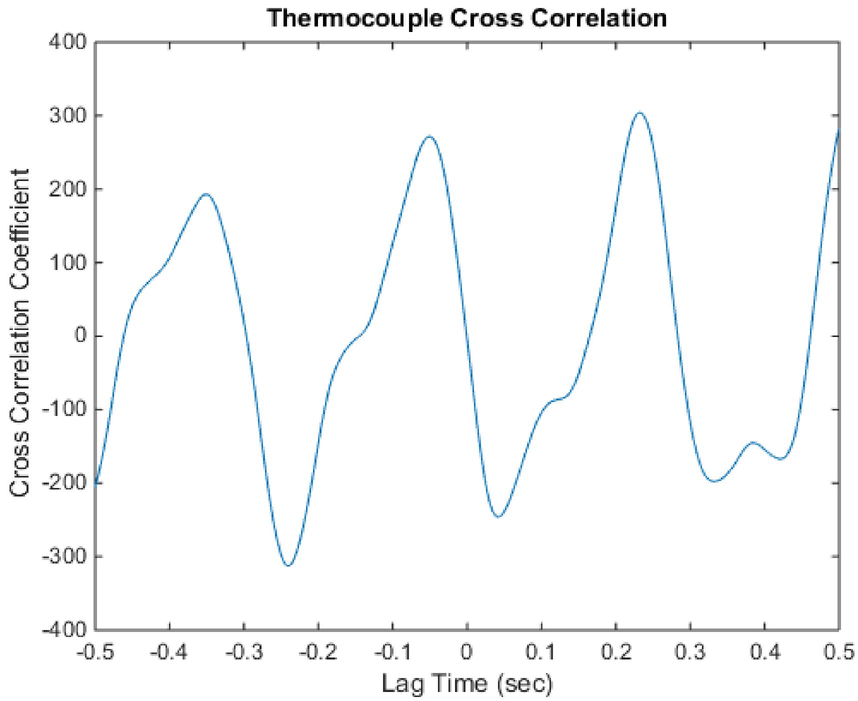

Figure 14: Thermocouple cross correlation as a function of lag time. The periodicity suggests that any visible correlation between thermocouples is due to signal properties and does not give the transport delay information necessary to calculate flowrate.

The cross correlation coefficient between two thermocouples exhibits an oscillatory behavior. There is consistently about a 0.25 second period (±10%) between thermocouple cross correlation coefficient peaks no matter the speed of the flow or the distance between thermocouples (6 or 12 inches). The result suggests that the observable correlation between thermocouples is intrinsic to the experiment and the signal property, and is not related to transport delay. Therefore, the thermocouple setup and data acquisition method cannot be used to find flow velocity as is.

Summary

The project started with a theoretical possibility of using ultrasonic pulses through water, in a non-standard channel area, to measure primary flow rate in an integral pressurized water reactor (iPWR). This is a crucial task, as the primary flow rate is an important safety and diagnostics tool for iPWRs, and as of the date of this report there is no valid and proven way to make this measurement. Ultrasonic instrumentation provides this possibility.

The project team successfully built a steel test section representing a reactor vessel and a flow loop that consisted of over 25 meters of PVC piping, which was a mix of schedule 80 and 40, depending on the thickness required for the sections of piping. A 7.5 HP B&G pump, which outputs a flow rate of approximately 300 GPM at full power, is used with a VFD to provide varying flow rates. The ultrasonic transducers were mounted on the PVC piping to check their performance compared to a secondary turbine flow meter. After confirmation, the ultrasonic transducers were mounted onto the steel test section, and 150 data points were manually taken, which consisted of 6 runs of 25 data points each. Each run corresponded to a VFD setting, with the settings being 15, 25, 35, 45, 55, and 60 Hz. The VFD settings are indicative of flow rates, with 15 Hz being around 70 GPM, and 60 Hz being around 300 GPM.

The results of the ultrasonic flow meter's performance compared to the turbine flow meter on the piping indicates that the ultrasonic is working correctly on the test section, within the uncertainty surrounding the project environmental conditions. The ultrasonic flow meter's data are within 5% of the turbine flow meter data, which is actually within the error bar range of the two meters. This is interesting, especially because the rusting on the inside of the steel test section is likely a cause of error for the ultrasonic, because the ultrasonic flow meter interface requires that the wall thickness of the flow channel be specified, and the rusting makes this thickness subject to error. Another cause of error is that one of the students on the team inadvertently bowed the test section while pressure testing the section. These two sources of error are very likely responsible for some of the discrepancy between the ultrasonic and turbine flow meters.

The deliverables that are the result of this project are a fully functioning flow loop, flow rate data from 6 experimental runs, a CAD model of the flow loop (pictorial, not for fluid flow analysis), and graphs showing the performance of the ultrasonic flow meter compared to the turbine flow meter. There are also some data regarding temperature correlation analysis; however, these are not usable.

Conclusions

The design and the experiments verify that ultrasonic instrumentation can be used to measure flow rate in channels with non-circular cross-sections with high fidelity. The ultrasonic flowmeter showed only a small error in measurements on the rectangular section when compared to a conventional turbine flow meter on a circular section. While the error between the turbine flowmeter and the ultrasonic flowmeter on the test section is nearly 8%, 5% of this error is likely due to calibration when considering the error between the turbine meter and the ultrasonic meter on the same PVC pipe. The ultrasonic meter data on the test section is only an average of 3.5% higher than the ultrasonic meter data on the PVC pipe. This evidence strongly indicates that the ultrasonic flowmeter can accurately measure flowrate in a flow channel with a non-circular cross-section in addition to a circular cross-section as known prior to this experimentation.

The thermocouple data showed no correlation that could ultimately be used to calculate flowrate. Whatever correlation that might be observed was hidden by the signal properties of the thermocouples.

Future Work to Improve the Design

One of the largest project-defining problems encountered was the inability to successfully get the workstation computer to interface with the GE Ultrasonic Flowmeter. The team was under the impression at the time of the flowmeter's purchase that GE software would be provided so that the digital data from the flowmeter could be successfully retrieved. The software did not come with the flowmeter as originally thought, and in reality it cost a few hundred dollars that the project could not spare. The flowmeter installation tech provided a light version of the software that was used for purely viewing data. This software did not allow for data manipulation in the ways that were needed as defined in the project goals. This led to a search for alternative methods to send flowmeter data to the computer.

Another effort to receive data from the flowmeter hinged on serial communications using MODBUS. After some investigation, it was determined that the ultrasonic flowmeter did in fact have optional MODBUS capabilities installed. After several attempts to connect the meter to a PC using its MODBUS capabilities, it was concluded that the data could not be digitally retrieved with purchasing the expensive GE software.

The ultrasonic flow meter on an average is within 5% of the turbine flow meter's flow rates, verified across 150 measurements. The ultrasonic flow meter originally was having issues reading the flow rate through the test section, but, after the third iteration of the loop was built and the gas bubbles in the fluid were allowed to reabsorb in the fluid, the ultrasonic now reads from the test section without any difficulty. The turbine was calibrated to be within 3% of the ultrasonic, when both are installed on piping. There is some dismay about the ultrasonic instrumentation data acquisition not being digitalized. The GE software that was provided was likely only a partial piece of software and includes a log viewer, but not a log creator. The Modbus options for data acquisition were discussed; however, the software that would potentially work for Modbus was not acquired until early April.

For future work, it is recommended that the test section be replaced with a stainless steel section. The design project test section was made of carbon steel due to budget limitations.

The temperature correlation analysis did not yield much in the way of results, and the results that it did provide were unreliable and, in most cases, incorrect. This is likely because the thermocouples used were made with 3/16 inch thick Inconel sheath, and thus increasing the response time of the thermocouples. Another likely cause is interference in the signal that could be solved by using shielded thermocouple wires. It was also suspected that there was insufficient temperature fluctuation in the measurements for effective cross correlation analysis.

Future work includes digitizing the data acquisition and making the experiment take place in a more controlled environment, using stainless steel for the test section, and utilizing a larger space for the flow loop. It is known that the GE software should work, if it were purchased; however, it is somewhat expensive for a senior design project. The next step that is recommended is to get the Modbus data acquisition working. To do this, Modbus integration software would need to be used (a USB adapter has been purchased, but the software hasn't been integrated). A new test section made of stainless steel would need to be constructed.

The project is ready for a major corporation to spend some time formally evaluating the possibility of using ultrasonic instrumentation for integral modular reactor primary flow rate measurements.

References

[1] "AquaTrans AT600 Ultrasonic Liquid Flow Meter." GE Measurement & Control. General Electric, 27 Jan. 2015. Web. 13 Apr. 2016.

[2] General Electric. AT600 User's Manual. N.p.: General Electric, 2014. Print.

[3] Upadhyaya, Belle R. "Reflection Transit Time Flow Meter Using Ultrasonic Transducers for Primary Coolant Flow Measurement in Integral Reactors." Nuclear System Design: NE 471. University of Tennessee, Knoxville, TN. 31 Aug. 2015. Lecture.

[4] Upadhyaya, Belle R. Estimation of Transit Time Using Cross Correlation and Cross Power Spectrum Methods. Tech. N.p.: n.p., n.d. Print.

[5] "McMaster-Carr." McMaster-Carr. N.p., n.d. Web. 15 Apr. 2016

[6] Tsoulfanidis, Nicholas. Measurement and Detection of Radiation. 3rd ed. N.p.: CRC, 2010. Print.

[7] Signal, Primary Flow. The Factors That Impact Venturi Meter Accuracy(n.d.): n. pag. Venturi_Flowmeter_Accuracty. Web. 27 Apr. 2016.

[8] "Ultrasonic Flowmeter Technology." Flowmeters.com. N.p., n.d. Web. 27 Apr. 2016.

Appendix A

Python code used to create plots:

```
import matplotlib
import matplotlib.pyplot as plt
import numpy as np
from pylab import *

ultsn,trbn = np.loadtxt('pvc.txt',usecols=(3,4), skiprows=0, unpack=True)
#ultsn,trbn = np.loadtxt('section.txt',usecols=(3,4), skiprows=0, unpack=True)

TB = []
errTB = []
Ul = []
errUl = []
Diff = []
errPdiff = []
for i in range(0,6):
	TB.append(sum(trbn[i*25:(i+1)*25])/25)
	errTB.append(np.sqrt(np.sum(np.square([.03*TB[i],np.sqrt(sum(np.square(np.subt
ract(TB[i],trbn[i*25:(i+1)*25])))/24)]))))
	Ul.append(sum(ultsn[i*25:(i+1)*25])/25)
	errUl.append(np.sqrt(np.sum(np.square([.01*Ul[i],np.sqrt(sum(np.square(np.subtr
act(Ul[i],ultsn[i*25:(i+1)*25])))/24)]))))
	Diff = 100*np.divide(np.subtract(Ul,TB),TB)
	errPDiff =
100*np.divide(np.sqrt(np.square(errUl)+np.square(np.divide(np.multiply(errTB,Ul),TB))),
TB)
x = [15,25,35,45,55,60]

m,b = polyfit(TB,Diff, 1)

plt.errorbar(TB,Diff,xerr=errTB,yerr=errPDiff,ls=' ', marker='.')
plt.plot(TB,np.add(np.multiply(m,TB),b),'--k')
#plt.title('Ultrasonic Flowmeter on Test Section vs Turbine Flowmeter')
plt.title('Ultrasonic Flowmeter on PVC Pipe vs Turbine Flowmeter')
plt.xlabel('Flow Rate (m$^3$/s)')
plt.ylabel('Percent Difference in Flowmeter Readings')
plt.grid()
plt.show()

#################################################################

ultsn,trbn = np.loadtxt('section.txt',usecols=(3,4), skiprows=0, unpack=True)
```

```
#ultsn,trbn = np.loadtxt('pvc.txt',usecols=(3,4), skiprows=0, unpack=True)

TB = []
errTB = []
Ul = []
errUl = []
for i in range(0,6):
	TB.append(sum(trbn[i*25:(i+1)*25])/25)
	errTB.append(np.sqrt(np.sum(np.square([.03*TB[i],np.sqrt(sum(np.square(np.subt
ract(TB[i],trbn[i*25:(i+1)*25])))/24)]))))
	Ul.append(sum(ultsn[i*25:(i+1)*25])/25)
	errUl.append(np.sqrt(np.sum(np.square([.01*Ul[i],np.sqrt(sum(np.square(np.subtr
act(Ul[i],ultsn[i*25:(i+1)*25])))/24)]))))
x = [15,25,35,45,55,60]
plt.errorbar(x,TB,yerr=errTB,ls=' ',marker='.')
plt.errorbar(x,Ul,yerr=errUl,ls=' ',marker='.')
plt.title('Flowmeter Readings with UFM on Test Section')
#plt.title('Flowmeter Readings with UFM on PVC Piping')
plt.xlabel('Pump Frequency (Hz)')
plt.ylabel('Flowmeter Readings (m$^3$/s)')
plt.legend(['Turbine','Ultrasonic'],loc=4)
plt.xlim(0,65)
plt.grid()
plt.show()

##############################################################

Usec,Upvc = np.loadtxt('ultdata.txt',usecols=(0,1), skiprows=0, unpack=True)

US = []
errUS = []
UP = []
errUP = []
for i in range(0,6):
	US.append(sum(Usec[i*25:(i+1)*25])/25)
	errUS.append(np.sqrt(np.sum(np.square([.03*US[i],np.sqrt(sum(np.square(np.subt
ract(US[i],Usec[i*25:(i+1)*25])))/24)]))))
	UP.append(sum(Upvc[i*25:(i+1)*25])/25)
	errUP.append(np.sqrt(np.sum(np.square([.01*UP[i],np.sqrt(sum(np.square(np.subt
ract(UP[i],Upvc[i*25:(i+1)*25])))/24)]))))
x = [15,25,35,45,55,60]
plt.errorbar(x,US,yerr=errUS,ls=' ',marker='.')
plt.errorbar(x,UP,yerr=errUP,ls=' ',marker='.')
plt.title('Ultrasonic Flowmeter Readings')
plt.xlabel('Pump Frequency (Hz)')
plt.ylabel('Flowmeter Readings (m$^3$/s)')
```

```
plt.legend(['On Test Section','On PVC Pipe'],loc=4)
plt.xlim(0,65)
plt.grid()
plt.show()
```

MatLAB script used to perform thermocouple correlation:

```
clear all
fileid = fopen('SD_TC_OUT_1.txt','r');
A = transpose(fscanf(fileid,'%f',[7 inf]));
fclose(fileid);

x = zscore(A(:,5));
y = zscore(A(:,7));

hpFilt = designfilt('lowpassfir', 'PassbandFrequency', .001,
'StopbandFrequency', ...
    50, 'PassbandRipple', 1, 'StopbandAttenuation', 60, 'SampleRate', 1000);
fx = filter(hpFilt,x);
fy = filter(hpFilt,y);

[r,lags] = xcorr(fx,fy,500);

time = lags.*.001; % sec
plot(time,r)
xlabel('Lag Time (sec)')
ylabel('Cross Correlation Coefficient')
title('Thermocouple Cross Correlation')
```

Appendix B

Pictures of flow loop

Figure 15: Picture of the steel test section of the flow loop, meant to simulate downcomer of an integral reactor

Figure 16: Picture of computer station with DAQ modules on right of desk

Figure 17: Picture of extra length of piping to stabilize flow and recombine bubbles in flow

Figure 18: Picture of variable frequency drive

Figure 19: Picture of AT 600 ultrasonic flow meter

Figure 20: Picture of ultrasonic transducers mounted on test section. Coupling grease is placed between transducers and steel.