I, Scott A Mindel, hereby submit this original work as part of the requirements for the degree of Master of Science in Aerospace Engineering.

It is entitled:
Design of Experimental Facility to Simulate Pulsating Flow Through a Blockage

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Committee chair: Ephraim Gutmark, PhD, DSc
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Design of Experimental Facility to Simulate
Pulsating Flow Through a Blockage

A thesis submitted to the
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**Abstract**

In order to investigate the feasibility of noninvasively detecting blockages in pipelines, experimental research was by designing a facility at the University of Cincinnati to carry out the work. The goal of the work is to ultimately design a facility that can noninvasively detect blockages in arteries, while being able to simultaneously taking flow visualization and pressure measurements. The research primarily dealt with understanding the capabilities of the facility, as well as taking wall pressure and microphone measurements, as well as flow visualization, in order to study the effects of blockages, pulsation frequencies, and pressure head on flow through the pipeline, in hopes of understanding how to improve the facility in the future to achieve the goal of the facility.

The main experimental studies performed on the facility deal with steady flow, which simulates the diastole part of the cardiac cycle, and pulsating flow. These measurements of the steady flow resulted in determining that as the blockage size increases, as well the flow velocity, the pressure drop across the blockage increases. It was also determined that the spectra can be collapsed by the Strouhal number, a non-dimensional parameter based on the blockage, or in case of the largest blockage, the effective blockage, properties. Another way to try and collapse the blockages is to study blockages that have similar flow properties, such as Re or flow rate. It was determined that the most comparable flows come from having both the similar flow properties. For pulsating flows, it was concluded that due to the fact the pressure wave generated from rotating wheel is downstream of the blockage, the wave moves in the opposite direction of the flow, which causes the fundamental pulsation amplitude to be higher downstream of the blockage due to wave energy being reflected back towards the source.
Flow visualization was shown to be an invaluable tool to help visually verify many of the results from the steady and pulsating flow results. Many of the results, such as the fact that the largest blockage (96%) has different fluid dynamic properties than the smaller blockages were confirmed from flow visualization. Flow visualization also helps determine the length of a jet that forms downstream of a blockage. It was shown that as in previous studies as the severity of the blockage increases, the jet length decreases. Also, for pulsating flows, the higher the pulsating frequency, the shorter the jet length is due to the decreased amount of time the flow has to travel before the subsequent pressure wave. Microphone measurements were also investigated however due to the transmission loss through the pipe, no conclusive results could be found. Finally, recommendations for future work to improve the current facility were discussed.
Acknowledgements

I would like to first thank my advisor, Dr. Ephraim Gutmark for allowing me to work on this project. The idea to develop a facility that would be able to simulate and detect blockages in a pipe was his idea and he allowed me to pursue the development and implementation of the design. Without his guidance and suggestions, the results and understanding of how the facility behaves would have never been achieved.

Next, I give thanks to the other members of my committee Dr. Shaaban Abdallah and Dr. Jeffrey Kastner. I have had the pleasure of being a teaching assistant for Dr. Abdallah and his guidance through my graduate education was greatly appreciated. I cannot thank Dr. Kastner enough for the countless hours he put in throughout all stages of the project, from conception of the facility to final product. I could not have achieved the level of success on this study without his guidance.

Without the help of Russ DiMicco, who ran the GDPL, and senior research associate Curt Fox, who both provided me with great insights into the development of experimental facilities, I would not have been able to come up with the quality of facility I was able to design. I would also like to acknowledge Doug Hurd, who runs the college machine shop. Since I had to machine most of the parts that went into the facility, his knowledge and expertise was the only reason that I was able to machine precision materials for my facility.

I would like to thank my fellow lab mates in the GDPL, especially Dan Cuppoletti, who taught me how to acquire data for my experiments, as well as Nick Heeb who was able to help me through my MATLAB issues.

Finally, I dedicate this thesis to my parents and aunt who have always been there for me.
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<th>Definition</th>
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<tr>
<td>GDPL</td>
<td>Gas Dynamics and Propulsion Lab</td>
</tr>
<tr>
<td>CAD</td>
<td>Coronary Artery Disease</td>
</tr>
<tr>
<td>QRS</td>
<td>Ventricle Repolarization Wave</td>
</tr>
<tr>
<td>AR</td>
<td>Autoregressive</td>
</tr>
<tr>
<td>ARMA</td>
<td>Autoregressive Moving Average</td>
</tr>
<tr>
<td>ALE</td>
<td>Adaptive Line Enhancer</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>SPL</td>
<td>Sound Pressure Level</td>
</tr>
<tr>
<td>dB</td>
<td>Decibals</td>
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<tr>
<td>p</td>
<td>Pressure</td>
</tr>
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<td>g</td>
<td>Gravitational Constant</td>
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<td>Height</td>
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<td>U</td>
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<td>Density</td>
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<td>Width</td>
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<td>Volumetric Flow Rate</td>
</tr>
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<td>Area of Circular Drain</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>fₛ</td>
<td>Vortex Shedding Frequency</td>
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<td>ω</td>
<td>Angular Frequency</td>
</tr>
<tr>
<td>HR</td>
<td>Heart Rate</td>
</tr>
</tbody>
</table>
St  =  Strouhal Number
µ   =  Dynamic Viscosity
FRD =  Frequency Response Domain
h   =  Head Oscillation from Steady State Response
a   =  Speed of Sound
HT  =  Head Tank
BT  =  Baffle Tank
RWT =  Rotating Wheel Tank
RT  =  Reservoir tank
PVC =  Polyvinel Chloride
PIV =  Particle Image Velocimetry
NPT =  National Pipe Thread
S40 =  Schedule 40 Piping
ID  =  Inner Diameter
OD  =  Outer Diameter
E   =  Expansion Wave
C   =  Compression Wave
d   =  Blockage Diameter (alternative)
D   =  Diameter
β   =  Diameter Ratio (Dβ/D)
ΔP  =  Differential Pressure
CD  =  Discharge Coefficient
K₁  =  Inertial Quasi-Steady Term
K₂  =  Quasi-Steady Discharge Coefficient Term
qₙf =  Flow Rate Constant Based on Pulsation Frequency
FPS = Frames Per Second

$N_w$ = Wormersley Number

**Subscripts**

atm = Atmospheric

1 = Initial Position/Length

2 = Final Position/Length

p = Previous Time Step

loss = Volume Lost

s = Time Step

max = Maximum

th = Fundamental

b = Blockage

e = Effective
1. Introduction

1.1. Coronary Artery Disease

1.1.1. Coronary Artery Disease Background

Coronary artery disease (CAD) is the leading causes of death in the United States. In 2006 alone, 631,636 people died of CAD, causing 26% of the deaths in the United States that year<sup>1</sup>. CAD is not only an epidemic that costs hundreds of thousands of lives each year in the United States, but a great financial burden as well. It is anticipated that in 2010, accounting for the cost of medications, other health care services, and loss in productivity, CAD will account for $316.4 billion<sup>2</sup>. While many die from this disease each year, approximately 13 million people have CAD in the United States alone. Unfortunately, for over 300,000 Americans, the first symptom of CAD is their sudden death, due to a stroke, heart attack, or heart failure<sup>3</sup>. Early detection of this disease could save millions of dollars a year, as well as thousands of lives. However, the only procedure that can accurately detect CAD is angioplasty, which is a risky, invasive procedure<sup>4</sup>. While angioplasty has become an easier procedure over time, there is always an inherent risk with any surgery, and the procedure requires hospitalization afterwards. The need for an easy, safe, and simple non-invasive test that would be able to detect CAD as it is developing in the patient is paramount in order to determine if anyone with risk factors, not only patients with symptoms, have CAD.

Over the past 30 years, a non-invasive technique has been developed to be used not only as a screening tool, but to evaluate the condition of the arteries after corrective surgery, such as angioplasty. This technique involves detecting sounds associated from turbulent blow flood through the partially blocked arteries. This occurs since CAD affects the body by making arterial
walls thicker and harder. This is largely due to plaque deposition from substances such as fat, cholesterol, and calcium, among others, the arteries become narrow. The blood flow becomes restricted in this scenario and the heart is deprived of oxygen. The deprivation of oxygen to the heart is what can lead to chest pain, heart attack, heart failure, or other problems. Shown below in Figure 1.1 is depicts the difference between a normal and diseased artery looks like. It can be clearly seen that in the diseased artery, the path of the blood flow has been diverted by the plaque buildup.

**Figure 1.1: Comparison of Normal and Diseased Artery**

1.1.2. Progression of CAD

As CAD progresses, a patient's artery goes through massive changes that will ultimately lead to a heart attack or heart failure from a fully blocked, or ruptured, artery. It is important to understand how the artery becomes blocked as the disease progresses so that it can be properly
modeled in the experimental setup. Although intuitively obvious, shown below in Figure 1.2 is a normal artery. It can be seen that the coronary artery has a geometry and cross section very similar to a normal pipe. This is the reason the experimental model utilizes pipes for a basic model of a coronary artery.

![Figure 1.2: Normal Coronary Artery](image)

As all humans age, fatty substances such as cholesterol and triglycerides, as well as lipids, become deposited on the inner layer arterial wall as what are termed fatty streaks. These streaks form randomly along arterial walls and are not significant enough to produce any obstructions or symptoms. While the presence of fatty streaks does not necessarily mean one has or one will develop CAD, it is a feature that is present in the arterial walls of a patient with CAD. As shown in Figure 1.3 below, the fatty streaks can build up anywhere along the arterial walls. These streaks can have various thicknesses and lengths but are insignificant compared with the blood flow through the coronary artery.
Over time, patients with CAD will have increased fatty streak development, which can become so significant that atheroma forms. Atheroma is the buildup of a fatty layer that is significant enough to constrict and change the blood flow through the coronary artery. When atheroma starts sticking into the inner lining of an artery, the condition is known as atherosclerosis. It has been estimated that about 1/3rd of adults living in the United States has some form of atherosclerosis\(^6\). The development of the fatty layer on the arterial inner wall can be seen below in Figure 1.4. While this small blockage is not large enough to cause heart attack or heart failure, unless a significant clot forms, it starts to put an extra stress on the heart. Over time, this stresses and weakens the heart, leaving it more susceptible to heart failure or attack, especially as the disease progresses.

\[\text{Figure 1.3: Fatty Streak Buildup}^6\]

\[\text{Figure 1.4: Newly Formed Atherosclerosis in a Small Blockage}^6\]
When atherosclerosis keeps developing, fibers start growing and weaving into and around the atheroma. This causes the fluid, fatty blockage to harden and form what is known as plaque. As plaque develops in the partially obstructed artery a medium sized blockage forms. When the blockage is around 50% blocked, the decrease in blood flow is significant enough to deprive the heart of oxygen and other nutrients during times of need, such as exercise or stress. During this time, the improper balance of oxygen delivered to the heart can cause chest discomfort and pain, also known as angina pectoris. As long as the plaque grows slowly enough and remains stationary, heart failure and heart attack will not occur even with the patient’s pain and discomfort. This type of angina pectoris is known as stable angina since the patient can live relatively unaffected by the blockage. Plaque has a significantly different look than the fatty layer buildup and this is evident by examining Figure 1.5 below. It is at this stage and beyond that if a patient has angioplasty, the procedure will attempt to remove the fatty buildup and plaque from the coronary artery. It will be seen later that in some studies, pre and post angioplasty measurements are taken to study the improvement of the patient’s sound spectrum from the surgery.

![Figure 1.5: Plaque Buildup in a Moderate Blockage](image)

As plaque develops and builds up over time, it starts growing within the inner layer of the arterial wall, forming a large blockage. When this happens, the arterial wall can slightly crack, or
rupture. Though not significant enough to rupture the entire blood vessel, it is enough of a crack to cause plasma to start to form clots around it in order to seal the crack up. However, as the clot gets into the arterial wall, it constricts the flow even further, causing an even larger blockage. When this happens, the blood flow to the heart is significantly reduced and the deprivation of oxygen is so severe that prolonged and severe chest pain will occur, which is known as unstable angina. As long as the clot does not completely block the artery channel, the patient might not develop a heart attack if proper treatment is provided. This particular condition that has just been described can be seen visually below in Figure 1.6.

![Figure 1.6: Large Blockage with Ruptured Plaque](image)

Most of the time however, the clot continues to grow until it completely fills the final opening in the cross section of the artery. This completely cuts off the blood flow to the part of the heart that the artery supplies. The deprivation of oxygen is which causes the patient to suffer a heart attack. During the attack, the heart muscle that is deprived of oxygen starts becoming permanently damaged and unless the patient receives immediate treatment in a hospital, the damage to the heart will become too much for the patient to handle and this is what leads to death from heart attack. A diagram of a completely blocked artery is shown below in Figure 1.7.
The stages of CAD that have been shown can take decades to develop, or once plaque starts building up in arteries, they can develop within hours to progress to a clot\(^6\) as seen in Figure 1.6 and Figure 1.7. Either way, if left untreated and the patient gets to a fully blocked artery and suffers a heart attack, the patient could die or be severely disabled from the event. As stated previously, since angioplasty is the only current procedure that can determine how blocked a coronary artery is, only patients that have significantly progressed CAD will receive the procedure if they are exhibiting symptoms. Since most people are completely unaware they have CAD until they suddenly die of heart failure or a heart attack\(^3\), a non-invasive technique would allow for anyone, regardless of symptoms, to be screened for CAD. As mentioned before, early detection of CAD can be the difference between a lifetime of pain and possibly sudden death, and living without fear of sudden heart attack or failure.

### 1.2. Non-Invasive Models of CAD

In development since the 1980’s, the non-invasive CAD detection technique involves being able to predict blockages in arteries by the unique acoustic signatures produced by the turbulent flow through the partially blocked artery. Blockages in the carotid arteries in the neck can be detected using stethoscopes. These sounds produced by the blockages are called bruits. However, in the coronary arteries, sound detection is not so simple. The reason for this is because there are
many other noise sources than just the turbulent flow through the blocked artery. The biggest other noise source is the one produced by the valves although there is also the issue of the sound traveling through the chest cavity to the microphone. This leads to a large signal-to-noise problem, which means that the noise dominates the signal signature that is trying to be measured. This means that digital signal processing algorithms must be utilized in order to filter and amplify the sound produced by the blockage.

Shown below in Figure 1.8 is a diagram of how a non-invasive CAD detection system works. The microphone takes the raw pressure data which is then amplified. A QRS detector, which is able to determine when ventricle repolarization occurs, goes into which ever signal processing algorithm is being used, which culminates in the output and display of the conditioned signal. Ventricle repolarization is just the reflection of an electrical wave which triggers the contraction of the heartbeat.

![Figure 1.8: Block Diagram of CAD Detection Device](image)

This is important since the diastolic window, which is the time after the heart valves open and close until the next heartbeat, in which the valves will open and close again, is the optimal time to use the signal processing methods to obtain the acoustic signature. During the time
indicated by the diastolic window, the blood flow through the coronary artery is maximum, which allows for the most turbulent flow through any blockages. This means that this time period has the greatest chance to capture any acoustic anomalies created from the blockage, since the faster the blood is flowing, the louder any source is likely to be. Luckily, since this is the time period between heart beats, the biggest noise component, the opening and close of the heart valves, is not present in the flow\(^3\). While the experimental test facility with simulate both the heart sounds and the diastolic window, the signal will be processed from the diastolic window. Shown below in Figure 1.9 are ten different cardiac outputs from a patient. The heart sounds are captured with the QRS detector so that it is easy to capture the diastolic window for signal processing. The heart sounds will be simulated by the spinning wheel component of the test facility, while the time in between pulses will yield the diastolic window.

![Figure 1.9: Pressure Readings from Various Cardiac Outputs\(^3\)](image-url)
It is important to note that the flow in the diastolic window is essentially steady since the window occurs between the second heart sound of one cardiac cycle and the first heart sound of the next cycle. It will be shown in the experimental design, that four main pulsation frequencies are being studied. These frequencies correlate to different BPM (beats per minute) and are 0 Hz (steady flow), \( \frac{1}{2} \text{ Hz (30 BPM)} \), 1 Hz (60 BPM), and 2 Hz (120 BPM). While the frequencies besides the steady flow all correspond to various conditions of the human cardiac cycle, the 0 Hz case most closely correlates to the diastolic window and is including in the studies for this very reason.

1.2.1. Non-Invasive CAD Detection Studies in Human Subjects

There have been multiple studies that involve using the non-invasive CAD detection technique as described previously on human subjects. Usually, each different study utilizes a unique signal processing technique in order to obtain signatures for the normal and diseased subjects. The researcher then used a certain level, which is different in each study, as a baseline whether a patient had CAD or not. The reason for doing this is that not only are the signatures of a patient averaged 20-30 times to get an average frequency response, but many different patients were used in each study. It will be shown that each person has a unique signature, even if they have the exact same blockage as another patient. Even normal patients have spectrum unique to the individual.

One of the first studies of this nature was conducted in 1983 by Semmlow et al.\(^8\). The authors postulated that arterial narrowing of at least 25% could cause turbulence that could be detected. Stenosis, or hardening of the artery, from plaque buildup as mentioned previously, can produce sharply localized murmurs. As previously mentioned, since diastole yields minimum background noise and maximum turbulent coronary sounds and thus a 300 ms time window after diastole
was used to get the maximum amount of useable data in which a coronary sound could be detected. The power spectrum was calculated from the diastolic window.

For the signal processing techniques used in this study, the spectra were between 3.3 – 300 Hz. While the lower bound was determined from the averaging window, the upper bound was said to be determined empirically from analyzing the data. In this study, 100 cardiac cycles were used per patient and averaged to yield the power spectra. The single microphone was placed over the heart, near the fourth intercostals space as shown below in Figure 1.11, while patients held their breath as 8-10 cycles were taken, in order to inhibit respiratory sounds, until the 100 cycles was reached. Twelve confirmed diseased and normal patients were tested. The patients were considered to have CAD if they had a 40-90% blockage in at least one of the left coronary artery or circumflex. Power spectra for two healthy and two diseased patients are shown below in Figure 1.10.

\[\text{Figure 1.10: Normalized Spectra of Healthy (a and b) and Diseased (c and d) Patients}^{8}\]
Figure 1.10 clearly shows that different patients, whether diseased or healthy, have different spectra. It should be noted that the magnitude of the spectra has been normalized. For instance, patient $a$ has a maximum of $140 \frac{\text{dyn}}{\text{cm}^2}$, which is 14 Pa, while maxima of 64, 60, and 78 $\frac{\text{dy}}{\text{cm}^2}$ for patients $b$, $c$, and $d$, respectively$^8$. It can be seen that even though patients $a$ and $b$ are both healthy, they have very different spectra. Although the maximum pressure for patient $b$ is about half of that of patient $a$, the slight secondary peak around 90 Hz is present, although patient $b$ has additional high frequency components. This could be due to a slight blockage of perhaps 25 – 35%, although it is not clear from the study. What is clear, however, is that most patients that are diseased have the majority of the area under the spectra in the higher frequency domain. This was the basis behind the authors reasoning that a patient with CAD had over 50% of the spectra above 90 Hz. Shown below in Table 1.1 are the results from each patient in the study. By using the 90 Hz frequency as the cutoff, the study correctly diagnosed all but one of the healthy patients and all but one of the diseased patients.

<table>
<thead>
<tr>
<th>SUBJECT NUMBER</th>
<th>POWER SPECTRAL ENERGY ABOVE 90 Hz</th>
<th>DISEASED</th>
<th>NORMAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>LCA/LAD 60%</td>
<td>38</td>
<td>38.18</td>
</tr>
<tr>
<td>27</td>
<td>CIR 40%</td>
<td>64</td>
<td>22.34</td>
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<tr>
<td>20</td>
<td>LCA 50%</td>
<td>38</td>
<td>37.56</td>
</tr>
<tr>
<td>25</td>
<td>LCA/LAD 50% CIR 70%</td>
<td>38</td>
<td>38.38</td>
</tr>
<tr>
<td>24</td>
<td>LCA/LAD 60%</td>
<td>33</td>
<td>32.26</td>
</tr>
<tr>
<td>14</td>
<td>LCA 60%</td>
<td>37</td>
<td>40.78</td>
</tr>
<tr>
<td>16</td>
<td>LCA/LAD 60%</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>45.66</td>
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<tr>
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<td>LCA 50%</td>
<td>20</td>
<td>48.68</td>
</tr>
<tr>
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<td>RCA 50%</td>
<td>04</td>
<td>49.74</td>
</tr>
<tr>
<td>17</td>
<td>LCA/LAD 50%</td>
<td>03</td>
<td>61.33</td>
</tr>
</tbody>
</table>

Table 1.1: Power Spectra Results$^8$
However, the authors mention that there is no direct correlation between blockage and power spectra output. This could be due to the fact that locations of the blockage strongly influence the power spectra. Since only a single microphone was used in this study, there is no way to determine the location of the blockage. In future studies that Semmlow and others conducted, besides using different patients, different aliasing techniques were utilized, such as autoregressive (AR)\textsuperscript{10,11,12}, autoregressive moving average (ARMA)\textsuperscript{9,11,12}, adaptive line enhancer (ALE)\textsuperscript{11,12}, and minimum-norm (eigenvector)\textsuperscript{12}. While each spectral method yielded similar results, they each had different criteria for whether a patient was diseased or normal. Shown below in Table 1.2 is a comprehensive summary of the various medical studies reviewed. Significant information, such as the subjects, frequency range of interest, and the resulting findings are presented. As the studies progressed, researchers found a common thread; an increase for diseased patients in the frequency range between 400-800 Hz\textsuperscript{9,11,12}. Shown below in Figure 1.12 are results using all four signal processing methods mentioned above.

![Figure 1.11: Location of Microphone in Human Studies\textsuperscript{52}](image-url)
All four of the signal processing methods shown above in Figure 1.12 utilize the same abnormal and normal patient for comparison. It is interesting to note that in every method shown there are two main peaks regardless if the patient is diseased or normal. The first peak, which is also the largest one, is around 200 Hz, while another peak occurs at around 1000 Hz. The authors suggest that the low frequency peak may be attributed to flow fluctuations, aortic pumping, or ventricle filling that has been shaped by high-pass filter effects. The high frequency peak could be caused by design resonance frequency of the transducer. While the minimum-norm spectrum technique performed the best, it can clearly be seen in every method, with the exception of the ALE (FFT Spectrum), that the main difference between a normal and abnormal patient is an increase in spectra amplitude between 200-800 Hz.
Table 1.2: Summary of Medical Studies

While the studies shown above have yielded some interesting conclusions on the acoustic signatures produced from partial blockages in coronary arteries, there have not been significant developments in noninvasive acoustic CAD detection methods recently. One of the major problems with these studies is the only used one microphone. Many of the studies\(^8,9,12\) recognize that there are issues with microphone placement affecting results, but none of these studies attempt to use a microphone array. This also could be a reason that the studies failed to correlate the amount of blockage with the amount of spectra above a certain frequency. An array of microphones should be able to pinpoint the location of the blockage since the spectra will be highest nearest to the source of the noise. The studies also mention the inability to capture blockages greater than 95\(^%\)\(^9,12\) due to the quiet, low flow. A method using stress testing will be
investigated in this study to determine if the differences between the patient’s normal and stress test spectra can provide additional insight into detecting large blockages.

1.2.2. Experimental Studies of Obstructions in Pipes

Blockages in pipelines, no matter how big or small, can greatly affect their performance. For this reason, there have been numerous studies in trying to predict blockages in pipelines using non-invasive techniques. These numerical and experimental studies provide a greater insight into modeling the test section than in human studies not only because their is use of human patients, but it is blockages in a pipeline which the experimental setup is simulating. Also, many processing techniques have been integrated into the studies, which could provide great insight on how to analyze the data recorded to predict the blockages in the pipe. Finally, it is important to note that experimental models of CAD provide benefits over human studies not only because the blockage size and location can be fixed, but also due to the fact that results are much more repeatable.

1.2.2.1. Experimental Studies of Leaking Pipes

Most studies that experimentally predict blockages or leaks in pipelines utilize transfer matrices in order to solve for the blockage size and location. One such study was performed by Lee et al.\textsuperscript{13} in which a technique called frequency domain analysis is performed to detect leaks in pipelines. The basic concept is that a transfer function can be solved which relates the frequency spectra of an input and output signal, based on an excitation. For the Lee et al. study, this is achieved by an oscillating valve as seen below in Figure 1.13. The flow is heading from left to right due to the difference in head from $H_1$ to $H_2$. In fact, using a pressure head to generate flow has been utilized for the experimental facility that was created to study different blockages pipes.
When the flow passes through the leak and due to the oscillating valve, there is a difference in the input and output signals. This difference can be analyzed to determine the location by using a frequency response domain (FRD) technique. By using this technique, it has been shown that the magnitude of the peak response changes due to location along the pipeline. The two factors that impact the FRD the most are the measurement location and a leakage in the pipeline. The fact that the measurements change due to location is something that is being utilized in the design. The Lee et al. study shows through previous studies that previous studies have proven this and this particular study proves this by the analysis shown in Figure 1.14.

It can be easily seen that while the fluctuation in $h$, the head oscillation compared to the steady state response, is constant at the end of the pipe (2000 m), at a point near the middle of the pipe (742 m) the response is completely different. This is due to not only to the different location, but also differs from the frequency of the oscillation. The frequency of the oscillating valve matters since this changes the mode of the pipe. This leads to different head fluctuations at the same position, besides from the source of the oscillation. The reason for this is that the harmonic peaks at the source have stronger signals which yield a high signal to noise ratio, minimizing any difference due to oscillation frequency. Although this method is not utilized to predict blockage location in the current experimental setup that will be described later, it could
possibly be used in future studies since the spinning wheel design, that will be shown later, could act as the oscillatory valve.

![Figure 1.14: Response of Harmonic Frequencies at Various Measurement Positions](image)

**Figure 1.14: Response of Harmonic Frequencies at Various Measurement Positions**

As previously mentioned, the presence of a leak leads to a different $h$ response. Lee et al.\textsuperscript{13} discovered, as well as others mentioned in the study, that a leakage in the system changes the response since some of the pressure head response is absorbed by the leakage. This causes changes at some of the ratio of the oscillation frequency to the fundamental angular frequency of the pipe, given by the Equation 1.1 shown below

$$\omega_{th} = \frac{a \pi}{2L}$$  \hspace{1cm} (1.1)

where $a$ is the speed of sound, in the case of air $343 \text{ m/s}$ and in the case of water $1482 \text{ m/s}^{17}$, and $L$ is the length of the pipe. Shown below in Figure 1.15 is the effect a leaking pipe has on the pressure head response. It is evident that some modes, such as when $a = 2L$ yields little to no difference, but other modes lead to significant fluctuating head loss. While the experimental design uses blockages instead of leaks, the principle, such as the obstruction affecting the response is similar.
1.2.2.2. Experimental Studies of Blockages in Pipeline

A more current study by Lee et al.\textsuperscript{14} deals with a blockage in pipelines and its design has many similarities with experimental design that has been built for the study. Essentially, the only difference between the Lee et al. study, shown in Figure 1.16, is that the experimental design has a tank above to keep the head constant and the spinning wheel in the downstream tank that simulates pulsating flow, where the Lee et al. study uses a side discharge valve to generate perturbations needed to produce a transient response. Using the FRD technique discussed previously, the head response magnitude $h$ is calculated once more.

![Graph showing pressure head response for normal and leaking pipe](image)

Figure 1.15: Pressure Head Response for Normal and Leaking Pipe\textsuperscript{13}

![Diagram of pipeline blockage experimental setup](image)

Figure 1.16: Pipeline Blockage Experimental Setup\textsuperscript{14}
As was seen previously Lee et al.\textsuperscript{13}, having an unobstructed pipeline yields a sinusoidal response, with harmonic peaks correlate to the fundamental frequency of the system as defined by equation 1.1. The impact on the FRD from the blockages from the study\textsuperscript{14} is similar to Figure 1.15 and is shown below in Figure 1.17. The interesting result from the more current Lee et al. study is the fact that a sinusoidal pressure head perturbation change for the blockage compared to the normal pipeline exists. By solving the FRD matrix and performing FFT on the inverted peak magnitudes, the frequency, phase, and amplitude of the perturbations is calculated. The authors then detail an equation that uses these inputs to predict not only blockage location, but size as well. While the frequency and phase help determine the blockage location, the amplitude of the oscillation solves for the blockage size.

Figure 1.17: Pressure Head Response for Normal and Blocked Pipelines\textsuperscript{14}

Multiple blockages have been studied using this technique with similar ability to predict the location and size of the blockage. It should be stated that although the authors found more error in blockage size in the multiple blockages study, it was still small (1.1\% compared to the 0.5\% for single blockage). The authors note however, that in real systems there are some things that
need to be taken into consideration. Like the current experimental design, the authors use inline orifice plates as blockages. Since change in geometry is an important factor in changing the pressure head fluctuations, this will most certainly change the results slightly. Also, the analysis done in this study was assuming frictionless pipes which is an incorrect assumption.

While the FRD technique seems fitting to use for the present study, it should be noted that the lengths of the pipes were on the orders of kilometers in the Lee et al. study, while it will be shown that the pipes in the experimental design are not even half a meter between the blockages. One of the assumptions the authors state in the Lee et al. study is the fact that the pipes much be extremely larger than the blockage for this method to work. However, these studies give insight into how taking pressure and microphone readings will yield similar results.

### 1.2.2.3. Orifice Plate Effects

Orifice plates are a good way to simulate blockages in pipes since they offer the advantage of being able to study multiple blockages by just removing the orifice plate and fitting two pipe flanges as shown below in Figure 1.18. In this study, performed by Qing et al., wall pressure fluctuations due to orifice plates were studied. Besides the fact that wall pressure will be studied in the current study, another important part of the Qing et al. study is the evolution of their experimental design, which has influenced the experimental design of this project.

![Orifice Plate Blockage Setup](image)

**Figure 1.18: Orifice Plate Blockage Setup**
Initially, the authors had a setup in which a recirculation pump was in the same room as the orifice plate and measurement system. Unfortunately, the pump noise completely dominated initial readings as can be seen in Figure 1.19. While the first few pipe modes are present when the pipe is hit with a hammer, the most notable peak, which is clearly not a sub-harmonic of the fundamental pipe mode. This disturbance is produced by the pulse of pressure that the pump uses to circulate the flow. The authors go through the process on how they calculate the frequency of the pump pulsation to be 245 Hz and since the highest peak is at 244.14 Hz, it is a good assumption that this peak and the frequency of the pump pulsation are one in the same.

In order to observe just the pipe modes in the undisturbed flow, the pump noise needed to be minimized. This was achieved by adding an additional water tank to absorb acoustic waves after the pump, as well as another water tank after the test section in order to prevent backward propagating waves from affecting the test section. The improved setup, as well as the resulting undisturbed FFT results, which show only the pipe modes, is shown in Figure 1.20 and Figure 1.21 respectively. Without the pump pressure pulsation waves affecting the results, only the pipe modes are present when the pipe is excited by getting struck by a hammer. This is an important discovery that is the main reason for the head tank feeding the baffle tank in the current
experimental design, which will be shown in more detail later. This allows for experiments to be run without the pump being on, which would dominate the results as shown by the Lee et al. study. There are other similarities such as the baffle tank and the pulsating tank acting similar to the water block tanks, which will be described in greater detail in the experimental design.

Figure 1.20: Improved Experimental Setup

With the errors in the facility minimized, the authors of this study test various orifice plate diameters and study the effect of measuring wall pressure at various points, in the case of the Lee et al. study, eight measurement locations as can be seen above in Figure 1.20 from transducers as shown in Figure 1.18. Upon examining the results, a clear trend presents itself; as the location from the orifice plate (blockage) increases, the pressure amplitude decreases, as seen in Figure 1.22. This is one of the reasons this study plans on being able to locate blockages by...
using an array of pressure and microphone measurements. It is also fairly intuitive that the farther away you are from a source, the less vibration and noise the system will have.

![Wall Pressure Fluctuations at Various Locations](image)

Figure 1.22: Wall Pressure Fluctuations at Various Locations

### 1.2.2.4. Experimental Models of CAD

While the experimental facilities shown previously helped make great strides in the design of the facility, it is also critical to look at studies that specifically modeled CAD. One such study was performed by Borisyuk. The study investigated measuring pressure on the surface of a pipe, which could either be rigid or flexible depending on if supports were placed on it. The point of the study was to study pressure downstream of a blockage and investigate what happens to the spectra as blockage size is varied. A schematic of the test section is shown in Figure 1.23. It is important to note that region I is the flow separation region, region II is the flow re-attachment region, while region III is the flow redevelopment region. The other important part of Figure 1.23 is that the label ‘3’ points to the pressure transducer location.

The important results of the study can be summarized in Figure 1.24. First off, it shows that the amplitude of the FFT spectra is increased when blockage is increased. This will be shown to be the same in results from the experimental facility that was designed (besides for the
96% blockage which will be shown to have different fluid flow dynamics), as well as the fact that the peak amplitude has a higher frequency when the blockage size is increased. Similar to the results of the facility, there is a distinct roll off to the floor level. These frequencies will be shown to be much higher than the results obtained from the facility although it will be shown that transducer mounting is the most likely culprit of this deviation.

![Figure 1.23: Test Section Simulating CAD](image1)

Shown below in Figure 1.25 is a typical setup for a facility that models CAD. There is a tank upstream of the blockage which provides a constant pressure head (velocity) to the test section. At some point in the test section there is a blockage, which is usually a nozzle, but in

![Figure 1.24: FFT Spectral Results of CAD Model](image2)
some studies, such as the Borisuk\textsuperscript{53} study shown previously, a sharp edged orifice plate is utilized. For the studies that investigate pulsating flow, a pulsating valve or pump is used downstream of the blockage. Finally, most systems recalculate the water, so a pump is used to achieve this goal.

![Figure 1.25: Typical CAD Model Setup](image)

1.2.2.5. Computational Models of CAD

Another effective way to model CAD is to use computational models. It is much easier to specify accurate geometries and flow properties, such as viscosity and density. Also, multiple solvers can be compared in order to show which type of flow models best fits the flow properties of blood flow through blockages in arteries. One such study was performed by Ghalichi\textsuperscript{54} who investigated not only the effects of blockage and how it pertains to the recirculation zone, but comparing a low-Re turbulence solver to a typical laminar model. This makes sense because blood flow is laminar normally, but turbulence can develop at blockages over 25\% as was stated previously.

The models used by Ghalichi were of non-concentric geometry, which has been shown to be a more accurate description of coronary artery blockages. The viscosity was given as .035 cm\textsuperscript{2}/s, while the density was specified at 1.06 kg/m\textsuperscript{3}. Homogenous, incompressible flow was
assumed, as well as steady flow. Although not studying the effect of pulsating flow, the study was essentially investigating the diastole, in which studies on human subjects have been shown to use for analysis. Shown in Figure 1.26 are the results comparing the length of recirculation zone of different blockages to different models as well as experimental results. It can be seen that the Wilcox low-Re turbulence solver outperforms the laminar model for both the 50% and 75% stenosis.

While the laminar model works well for Re less than 400, it quickly diverges from the low-Re turbulence model which more accurately follows the trends from experimental results. It makes sense that the low-Re turbulence model works better because the blockages studied are above 25% so even though they are still at low Re, they exhibit turbulent flow properties. The effect of blockage on the length of the recirculation zone can be specifically seen in Figure 1.27. Similar to the designed experimental facility, as the blockage increases so does the recirculation zone.

![Figure 1.26: Recirculation Zone Length Comparison](image)

*Figure 1.26: Recirculation Zone Length Comparison*
1.3. Coronary Artery Properties

It is important to understand the flow properties in coronary arteries if a facility is to be built to simulate blood flow through an artery. The most important difference between water flowing through a pipe and blood flowing through arteries is the fact that the latter is a non-Newtonian fluid (besides in blood flow through the aorta). While Newtonian fluids have a shear rate that is proportional to shear stress, non-Newtonian fluids, such as blood have different properties. For blood flow, which is a shear thinning fluid, the apparent viscosity decreases with increased stress\textsuperscript{55}. This means that while blood flow is relatively stagnant, such as in flow through an artery with severe stenosis, the viscosity of blood will be even higher than average viscosity which will be given later. The increased viscosity will make it even harder for the blood to start flowing again as compared with water flowing in a pipe with a similar blockage.

Other fluid properties of blood besides the non-Newtonian flow are much different than the water that is being used in the test facility, so properties such as the density $\rho$ and viscosity $\mu$ must be compared. Also, it is useful to know the diameter of the arteries, as well as the maximum flow velocity for various artery types so that Re can be calculated and simulated through the test setup to achieve a dynamically similar flow. Elad et al.\textsuperscript{16} states that blood has a
constant mass density of 1.05 g/cm$^3$, which is slightly higher than the density water, which is 0.998 g/cm$^3$, at room temperature water of 20$^\circ$C\textsuperscript{17} which will be used during the testing. The Elad et al.\textsuperscript{16} paper also states that the viscosity of blood is .04 poise, which is four times the viscosity of water at 20$^\circ$C\textsuperscript{17}.

The maximum velocity of the blood flow through a particular artery is important since this velocity is a vital part in calculating Re. Since the study will be looking at the maximum velocity for reasons described earlier in Semmlow\textsuperscript{3}, Figure 1.28 shows the maximum velocities of various arteries. Although it can be seen that the maximum velocity for the aorta and large coronary arteries are about 60 cm/s, which yields a Re of approximately 4000, which has been shown to be correct for an aorta from a review by Ku\textsuperscript{18}. However, the same review also shows that in a previous study, for significant stenoses, as seen in Figure 1.29, the maximum velocity is around 100 cm/s, which yields a Re of 6825 for the properties mentioned previously. Since blockages from coronary stenoses are being considered for this study, this maximum velocity will be used for the aorta calculations. In a study conducted by Cox et al., it was determined that the velocity of blood flow for patients with stenoses increased to up to 150 cm/s\textsuperscript{57}. Finally, the physical properties such as the diameter of the aorta and main arteries will lead to velocity calculations needed to simulate similar Re conditions for the test section. For the aorta, the diameter is 2.54 cm, or about one inch, while for a main coronary artery it is .8 cm\textsuperscript{19}.  


Figure 1.28: Velocity and Pressure for Different Arteries

Figure 1.29: Velocity Waveforms of the Aorta for 0% (a), 33% (b), and 66% (c) Stenosis
It should be noted that for the facility design, the pipe walls incorrectly simulate flow through a blood vessel since it has been shown numerous times, such as Elad et al.\textsuperscript{16} that show the cross section of the artery changing in volume as the blood flows through the artery. The pressure of the pulsation affects the arterial walls since the arteries are flexible. An idealized deformation of the arterial wall due to the blood flow passing through the artery can be seen below in Figure 1.30. Since the clear acrylic tubing is being used for the test section, the walls will not have this kind of deformation. However, since this setup is just an idealized and simplified version of an actually artery, this is an acceptable material to simulate the artery.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure130.png}
\caption{Coronary Artery Wall Deformation\textsuperscript{16}}
\end{figure}
2. Facility Design

2.1. Objectives

While designing the facility, a few key objectives were kept in mind in order to design a facility that would be to study flow through blockages in a pipe effectively. First, the facility should be designed in order to simulate flow through arterial blockages. While this does not necessarily mean that a completely accurate model of stenosis be studied, a distinct quantifiable blockage should be used in conducting the study. The facility should also be able to study the impact of blockage size while varying the flow velocity. This is important because as previously mentioned, as the blockage size increases, so the velocity that travels through the constricted area. Since blood flow is not steady, the facility should be able to simulate both steady and pulsating flow to be able to study not only the diastole (steady) but investigate the effect of pulsating flow on the blockages at various velocities. Finally, in order to quantify the results, surface pressure measurements as well as flow visualization should be used to study the various types of flow through the different blockages that will be investigated at multiple pressure heads.
2.2. Facility Overview

![Figure 2.1: Experimental Setup](image)

Figure 2.1: Experimental Setup

Shown above in Figure 2.1 is the proposed experimental setup. The design utilizes a head tank (HT), the top most tank, which supplies the baffle tank (BT), directly under the HT, with a constant pressure head. The BT is in-line with the rotating wheel tank (RWT), on the right, which allows for straight flow from the HT, through the test section (clear pipe with black blockage section in the middle), and into RWT. Overflow water from the RWT flows down into the reservoir tank (RT). Currently, there is no pump; however, if the facility ever needs recirculation, the pump will only be used after an experiment is conducted in order to refill the HT. The pump will be to the left of the RT and pump up to the HT. The BT will be filled with water to a specific height to achieve a desired velocity. In order to keep the height of the BT constant, a control ball valve, shown below in Figure 2.2, will be opened to a specified amount for each case, allowing the mass flow of water exiting the BT to be compensated by an equal mass flow of water entering the BT through the control valve. The process in which the velocity is calculated for various BT heights will be discussed later in greater detail.
For an actual experiment, the water will flow through the test section and fill the tube before testing. This is so that when the ball valve, seen aft of the clear tube in Figure 2.1, is opened the test can begin immediately. If the tube was not pre-filled, the experiment would need to be delayed until the tube fills, which for the larger blockages can take several minutes. After the experiment is finished, the valve, as well as the control valve in Figure 2.2, is closed. The water in the RT can be drained, or if a pump is added, pumped back up to the HT. As mentioned previously, if recirculation of the fluid is required, such as if a substance like cornstarch is added to simulate blood viscosity, one benefit of running the experiment like this is that the pump noise does not affect the experiment since it is only used after the experiment is finished. Another advantage is that the flow experiences no bends on its way to and through the test section, minimizing separated flow around elbows during the experiment. Another benefit is that if a velocity sweep is desired, the velocity will be constantly decreasing if the control valve is left closed as prescribed below in Equation 2.2.
2.3. Velocity Calculation

The flow is draining from the BT to the RWT via difference in height from the water level of the BT to the entrance of the RWT where the bulkhead is located in Figure 2.1. This allows for gravity to do the work to create the velocity needed to flow through the test section. To calculate the velocity, Bernoulli’s equation is utilized shown below in Equation 2.1 are calculations utilizing Bernoulli’s equation

\[
p_{\text{atm}}/\rho + g z_1 + \frac{U_1^2}{2} = p_{\text{atm}}/\rho + g z_2 + \frac{U_2^2}{2}
\]  

(2.1)

Since \(U_1\) and \(h_2\) are 0, once \(p_{\text{atm}}/\rho\) cancels out, \(U_2\) can be solved by the following equation

\[U_1 = \sqrt{2g\Delta z}
\]  

(2.2)

Table 2.1: Water Tank Spec Sheet

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<th>Company</th>
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<th>Fittings</th>
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</table>

Shown above in Table 2.1 are the various tanks that were looked into. As described previously, the experiment begins when the valve aft of the test section is opened, allowing the flow to go past the test section and into the RWT. Since the velocity out of the BT is solely dependent upon the difference in height between the water level in the BT and the entrance of the RWT, as seen in Equation 2.2, a longer, wider tank is seen to be the best choice for the HT. This is because the tank will tank longer to change the height due to the increase in the length.
and width. This allows for HT to control the height of the BT for a longer time. Also, if a velocity sweep is required and the control valve from the HT to the BT is closed, the change in velocity to be decreased, which will allow for a longer velocity sweep experiment to be conducted.

2.4. Tank Design

Four American Tank Company 20 gallon tanks were chosen for the reasons mentioned above. Also, a tank cover was purchased in order to host the HT directly on top of the BT. While the dimensions of the tank are shown in Table 2.1, the usable dimensions of the tank are 23.75” x 17.75” x 11.75”. As seen in the models, various sized bulkhead fittings in the tanks. This is to allow the appropriate sized piping to fit into the tank. After holes were drilled in the tanks, the bulkhead fittings are then screwed into the tanks in order to accommodate the incoming pipe.

2.4.1. Baffle Design

It was noticed early on when the facility was first assembled that there was a great deal of sloshing in what was soon to be named the BT when the valve was opened between the HT and BT to provide constant pressure head during the experiments. It was determined after some literature review that the best way to minimize sloshing would be to design baffles into the system. Detailed below is the result of this research and the reasoning behind the baffle design.

As previously stated, the addition of baffles into the BT is to minimize the sloshing that happens when water is flowing from the HT to the BT and through the BT to the RWT during the experiment. There are three baffles, two upper baffles and one lower baffle. The explanation of the upper baffles, which are eight inches long, and lower baffles, which are 3.75 inches long, will be provided shortly. The width of the baffle, one inch, was chosen due to approximate a rule
of thumb that states baffle width should be $1/12$ of the tank length, which in this case is 17.75 inches$^{20}$. Since one and a half inch material was not readily available for purchase, one inch polypropylene was selected. The heights of the baffles were calculated after reviewing Younes et al.$^{21}$, which showed to maximize the hydrodynamic dampening ratio in tanks with baffles, two upper mounted baffles with a lower mounted baffle in the center is ideal.

It will be shown later that the BT will be filled to 11” for the maximum velocity case and is why the lower baffle is 3.375” high. This is because the study showed that the lower baffle should come close to one third the maximum height level of the water. The study also showed that the ratio of the height of the water to the height of the upper baffles should be around $\frac{3}{4}$. Using the maximum head height of 11 inches as a guide, eight inches was chosen to accommodate for the smaller heads as well. The paper also stressed having all baffles equally spaced, which is why the distance between the walls and the baffles is 4.4375”.

2.4.2. Tank Selection

2.4.2.1. Benefits of Laboratory Tanks

It should be noted that while the design called for the purchase of the four American Tank Company tanks, there are already two tanks available in the lab. The test setup could flow from either the large, clear tank that is in the oil rig facility, the giant plastic tank that was used in the oil rig tests, or the American Tank Company tanks. Also, both tanks already in the lab could be utilized. The benefit of using available tanks is that no additional tanks need to be purchased. Another benefit of using these larger tanks is that a full HT will take longer to drain while it keeps the BT head level constant.
Another obvious benefit of using tanks that are already in the lab is the cost savings from not having to purchase these tanks or fittings. Since the American Tank Company tanks do not come with any openings or fittings, not only will the entrance and exit holes need to be drilled, but the bulkhead fitting would have to be purchased and installed into the system, adding cost and complexity to the design.

2.4.2.2. Drawbacks of Laboratory Tanks

While there are some positives to using the current tanks in the lab there are numerous drawbacks as well. The tanks are not clean and thus particulates could be introduced to the flow, affecting the results. This could be fixed by thoroughly cleaning the tanks before the experiments, but it still might not completely solve the problem. Also, while the tanks already have fittings and openings that would have to be fabricated for the purchased tanks, they are not in ideal locations to run the experiments. For example, in the large clear tank, the flow would exit from the bottom of the tank. This would mean that in order to use those fittings, there would have to be an additional bend in the pipe; something that the design in Figure 2.1 was made to prevent. Also, the piping has been glued together so it would be difficult to remove the current piping system. In the end, a new hole, plus fittings would most likely need to be fabricated in order to use the tank. The same goes for the giant plastic tank; there are two outlets that could be used, however one is connected to the giant pump and the other one is near ground level. The ground level piping cannot be used since the flow would enter the bottom of the tank and not the top as designed.

Other drawbacks include the pipe diameters for both of the tanks currently in the lab are two inches and not the one inch that the test section is designed for and that, especially in the case of the giant plastic tank, the tanks are immobile. As seen in Figure 2.1, the facility is on a
mobile cart. The drawback of having immobile tanks is that if the test facility needs to be moved to a different location, such as the anechoic chamber for proper acoustic testing, it is not possible to do so. Although difficult, the large clear tank could be moved if necessary since it is on wheels. Another drawback of the available lab tanks are the pump systems themselves. The way the pumps are setup is not beneficial for the compact test section design shown above. The pumps in both cases would require many bends in the pipe to pump the flow from the fill tank back to the control tank. Having the purchased tanks would allow for a simplified setup, as well as being able to use the smaller pump that is already in the lab. This would allow for a reduction in noise if it is determined later that the pump needs to be on during certain tests.

2.4.2.3. Tank Recommendation

After weighing the benefits and drawbacks of using the existing tanks in the lab, it is determined that the American Tank Company tanks should be purchased for the experimental setup. First off, they are relatively cheap to purchase, cost just around $270 for all four tanks, as shown in Table 2.1. Not only will these tanks be clean and particulate free, but they allow for a versatile setup that can be moved depending on where the testing needs to be conducted. Since it has been determined that it is unlikely that the pre-existing openings can be used, the benefit of already having the holes and fittings for the openings is negated. Even if they could be used, two inch diameter pipe is required instead of the one inch diameter that the design has been made for.

2.5. Test Section Design

Figure 2.3: Fabricated Test Section
For visualization purposes, it was decided that the test section, in which the blockage would be located, should be clear. With clear glass, it is possible to do many different types of visualization such as thymol blue or injecting the flow with dye, coupled with using a camera to capture any unsteadiness in the flow from pulsation. If the glass is optically clear, a laser sheet can be shined through it and more advanced visualization such as particle image velocimetry (PIV) can be utilized. Currently, only unsteadiness in the flow due to the various pulsating frequencies from the rotating wheel section is being considered. While this will be described more in greater detail, using a camera will allow for the capture and calculation of pressure waves originating from the rotating wheel blocking the outlet pipe in the RWT.

Fortunately, a suitable test section was already available from the Voice Consortium Lab, at the University of Cincinnati, from a previous project. Shown above in Figure 2.3 is the test section modified to fit into the test facility shown in Figure 2.1. It should be noted that it was modified from its original configuration, initially meant to connect to ¾” NPT tube. However, since the point of the current study is to determine blockages in pipes, it was deemed that having a ¾” to one inch area change before and after the test section would contaminate the results. To minimize area change, 1.318 inch diameter holes were drilled into the ends of the tube, where the ¾” NPT threads originally were, to allow for the insertion of schedule 40 (S40) PVC one inch piping, which has an outside diameter (OD) of 1.315”\(^2\). Once the piping was bonded with the Plexiglas tubing with PVC cement, a permanent connection was made. Since the inner diameter (ID) of the Plexiglas tube 1.015” and the ID of S40 PVC piping is approximately 1.029”, the connection allows for minimum area change.

As seen in Figure 2.3, there are many ports for pressure transducers. When the transducers are not in use, brass fittings are screwed in to prevent water leaking through the port
holes. The locations for the pressure port holes can be seen in the Appendix. It should be noted that both halves of the test section are exactly the same. These port holes create a slight problem, which can be seen below in Figure 2.4. Cavitation caused by the port holes can clearly be seen from the displacement of water in the vicinity of the top port hole. This is due to the sound pressure amplitude from the capped off port hole overcoming the hydrostatic pressure in the water\textsuperscript{23}. Fortunately, it was found that to get rid of the cavitation effects, one must loosen the plug while the aft valve is closed and the pressure of the water is greater than that of the air and pushes the air out of the tube.

![Figure 2.4: Cavitation Effect in Pipeline](image)

In the middle of the test section in between the two flanges at the end of the test section halves is where the fabricated blockage section is placed. Each end of the test section half has a groove for an O-Ring, although currently, only one of the halves has an O-Ring that fits into the groove as seen in Figure 2.5. To seal the other half, an O-Ring is placed around the appropriate side of the blockage section to create the waterproof seal needed to prevent leaks on the other side of the flange. Figure 2.1 shows the two white test section supports that keep the test section from sagging and causing additional, unnecessary, stresses and height changes through the test
section. These support sections are machined from Polypropylene and the dimensions can be found in the Appendix.

![Figure 2.5: Flange End of Test Section Half](image)

### 2.6. Fabricated Blockage

#### 2.6.1. Blockage Construction

The test section from the Voice Consortium Lab also came with five different blockage section attachments. Four of the machined orifice plates that are used for blockage sections are shown below in Figure 2.6. From left to right are the large (96% area) blockage, medium (65% area) blockage, small (30% area) blockage, and 0% blockage. The fifth blockage is left fully blocked, as a “blank”, and may become an offset of whichever case yields the most interesting results in order to study the effects of location of the blockage. This is due to the fact that blockages are usually not concentric⁶, as the three current blockages are. The dimensions for each blockage can be seen in the Appendix under the appropriate percentage of area blocked.
The orifice plates are made from aluminum and were originally machined by Blue Chip Tool Company.

2.7. Blockage Theory

Since human subject studies such as Akay et al.\textsuperscript{12} noticed the inability to detect fully and nearly blocked arteries, the large, 96\% blocked area should be particularly important to study. The reason that nearly blocked arteries cause detection difficulties is because when the artery is almost fully blocked the flow is so constricted, the blockage acts like a diffusion nozzle and is very quiet. This can also been seen in a study conducted by Martinuzzi et al.\textsuperscript{24}. Adewumi et al.\textsuperscript{25} discusses the theoretical effects that an orifice blockage has on a pipeline system and the theoretical model is shown in Figure 2.7. In this case, E stands for an expansion wave, while C designates a compression wave. The lower case letters are allocated to show boundaries.

As mentioned earlier in Lee et al.\textsuperscript{13,14}, pipelines without blockages exhibit a constant behavior. In the case of the Lee et al. studies, there is a fluctuating valve driving the transient response. The resulting head fluctuation for the unblocked cases creates a constant amplitude and phase sinusoidal response. In the Adewumi et al.\textsuperscript{25} study, flow through the blockages themselves drive the pressure changes. So in the case of an unblocked pipe, neglecting friction, there is no change in pressure from the inlet to the outlet. It is not until blockages are introduced to a system
with no forced excitation that there are pressure fluctuations introduced to the system, caused by the expansion and compression waves.

As the water flows through the pipe and approaches the blockage, the Adewumi et al. study discusses a compression wave $C_1$ is generated and propagates towards the blockage due to the constriction. This causes a pressure buildup as the kinetic energy of the water is converted to potential energy. There is a subsequent compression wave that reflects towards the inlet at the boundary of the blockage. This is represented as $C_2$ and the pressure increase can be seen below in Figure 2.8. The more the pipe is blocked, the more of a pressure increase is recorded. Some of the compression wave is reflected off of the blockage from $C_2$ and is represented as $C_3$, accelerating the flow through the blockage due to the pressure head created from $C_3$. This increases the kinetic energy and volumetric flow rate through the blockage. When the front of the wave gets to the end of the blockage, the compression wave continues towards the outlet as represented by $C_4$. This process continues several more times with the same type of response which form the additional compression and expansion waves shown in Figure 2.7.

![Figure 2.7: Theoretical Blockage](image)
Since the experimental setup is similar to the Adewumi et al.\textsuperscript{25} study, this method not only shows the validity of using this type of orifice blockage in the current study, but also shows that using pressure transducers at multiple locations, including the inlet, could be used to verify the presence of a blockage and calculate the amount and location of the blockage.

### 2.8. Piping Dimension

The test section from the Vocal Consortium Lab, offers other advantages besides the visual and availability advantages described previously. As previously mentioned, the diameter of the aorta is 2.60 cm\textsuperscript{19}, or 1.023 in, which is almost identical to the ID of the test section which, as can be seen in the Appendix, is 1.015 in. Although not the .8 cm, or .315 in diameter of the main arteries, which are usually studied, this design allows for effects of the largest blood vessel to be modeled to scale, while the main arteries being modeled at around a three to one scale. Also, it would have been difficult to make the test section close to the diameter of the main artery since piping and fittings are not made in that diameter.
The length of the test section is also appropriate from a turbulent standpoint. As seen in the Appendix, each half of the test section is 15 in, for a total length of 30.125 in, when the blockage section is attached. According to computational work done by Latzko\textsuperscript{26}, the minimum entrance length for fully developed turbulent flow is given by Equation 2.3.

\[ L = 0.693Re^{\frac{1}{4}}D \]  

(2.3)

Since the maximum pressure head that will be seen in the BT is four inches, the Reynolds number can be calculated from Equation 2.4 shown below

\[ Re = \frac{\rho UD}{\mu} \]  

(2.4)

to be equal to approximately 35,790. This means that according to Equation 2.3, the minimum entry length for fully developed flow is about 8 ¾ in, which is more than satisfied by the test section.

While the facility ensures fully developed turbulent flow, it is unable to fully develop laminar flow. This is important because under normal conditions, blood flow is laminar\textsuperscript{27}. It is only when velocities become extreme, like in intense exercise, or due to blockages, that the flow becomes turbulent. According to computations by Asao, Iwanami, and Mori\textsuperscript{26}, the minimum entrance length for fully developed laminar flow is defined as

\[ L = 0.06ReD \]  

(2.5)

Using Equation 2.5 yields a minimum entrance length of 138 for a Re of 2300, which is when the flow starts transitioning to laminar, and about 75 for a Re of 1260, which is calculated from typical flow through the main arteries, using the properties of blood\textsuperscript{28}. It is unreasonable to
achieve this entry length with the amount of material and space that would be required to achieve fully developed laminar flow. In order to obtain the proper length, the diameter of the test section would have to be reduced to 1/8th of an inch. This would provide not only fabrication issues with the test section connecting the rest of the facility, but blockage fabrication and wall pressure measurements obstacles as well. The one inch pipe allows for not only an easily built, but reasonably sufficient test section.

2.9. Pulsating Flow Design

2.9.1. Rotating Wheel

In order to create a pulsating flow facility, a rotating wheel controlled by a stepper motor has been utilized as seen in Figure 2.9. A drawing of the wheel itself is shown in the Appendix. There are four machined 1.25” diameter holes spaced 90 degrees apart, with a ¼” diameter hole in the middle of the wheel which will allow the aluminum shaft, as seen in Figure 2.9 to be fastened to the wheel with a screw. The shaft was fabricated in the machine shop with dimensions that can be found in the Appendix. The multiple holes allows the wheel to rotate at a low speed, which will be shown later to be a maximum of 60 RPM, and allows for an easy fabrication of the wheel in the machine shop as specified above. It is interesting to note the difference between the diameters of the holes, 1.25 inches, and the ID of the S40 PVC pipe, approximately one inch. This will allow for a 21% duty cycle for the normal condition (60 BPM), which has been shown to be 20-30% in dogs in Butchler et al.29. The diameter of the wheel is 8” to allow enough spacing between the holes and the edge of the wheel. Also, the width of the wheel is .236”, or 6 mm.
Also seen above in Figure 2.9 is the housing that keeps the rotating wheel from spinning off axis. It is made out of one inch thick polypropylene. It is fixed together with two ¼ inch bolts then snugly fit into the one inch PVC piping that allows the water exiting the test section to enter the RWT. It is then fastened to with ¼” bolts to the stepper motor housing which will be discussed in the next section. Schematics of the rotating wheel housing can be seen in the Appendix. It should be noted that due to an excess of friction from the tight clearance from the original housing and the rotating wheel, the clearance has been slightly increased to allow the stepper motor to function properly.

2.9.2. Stepper Motor

Since the wheel will be rotating, it must be controlled by a stepper motor whose shaft will spin the wheel to the required speed. Shown in the Appendix is the schematic of the stepper motor being chosen and whose specifications are given in Table 2.2. The reason this particular stepper motor is being chosen is because is a unipolar stepper motor and will provide sufficient
torque to rotate the wheel at the required speeds. An aluminum shaft has been fabricated in the machine shop and while the diagram of the shaft can be seen in the Appendix, the shaft can be seen in use above in Figure 2.9.

<table>
<thead>
<tr>
<th>Stepper Motors</th>
<th>Company</th>
<th>Product</th>
<th>Deg/Step</th>
<th>Diameter</th>
<th>Price $</th>
<th>Shaft Length</th>
<th>Dimensions (mm)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oriental Motors</td>
<td>PK 266-02A</td>
<td>1.8</td>
<td>1/4”</td>
<td>$79.00</td>
<td>3/4”</td>
<td>56x56x42</td>
<td>Unipolar Stepper Motor</td>
</tr>
<tr>
<td></td>
<td>Trossen Robotics</td>
<td>M-200-ROB-09238</td>
<td>1.8</td>
<td>1/4”</td>
<td>$14.95</td>
<td>3/4”</td>
<td>42X42X34</td>
<td>Bipolar Stepper Motor</td>
</tr>
<tr>
<td></td>
<td>Parallax 27964</td>
<td>3.6</td>
<td>1/4”</td>
<td>1/4”</td>
<td>$15.99</td>
<td>3/4”</td>
<td>57X43X23</td>
<td>Unipolar Stepper Motor</td>
</tr>
</tbody>
</table>

Table 2.2: Stepper Motors Spec Sheet

Before the stepper motor can be attached to the rod and the rod attached to the wheel, a bracket will need to be placed and screwed into the proper place as seen in the Appendix. It will be screwed together than placed flush with the one inch PVC pipe in which water flows out of from the test section. It is only after this wedge is placed on properly before the stepper motor assembly can be fashioned into place, securing the stepper motor and the rotating wheel in the RWT. In order to assemble the stepper motor, shaft, and rotating wheel correctly, there are several steps that must be followed. The procedure to assemble this system together will be detailed in the experimental setup section.

First, the aluminum shaft and the rotating wheel are fastened together with two shear pins and a ¼” bolt. This then allows for the rotating wheel with shaft to be placed in between the wedge, making sure that one of the holes in concentric with the hole in the wedge. Next, a long Plexiglas piece, which holds the stepper motor in place in the RWT, is placed into the system. The machined piece is shown in the Appendix and has four small screw holes for the stepper motor, as well as three ¼” holes to fasten the rotating wheel wedge to the Plexiglas piece. The two unthreaded holes on each end are to fasten the Plexiglas piece to the Plexiglas side walls also.
shown in the Appendix, while the threaded holes allow for minor rotations in the piece that will level the stepper motor to the rotating wheel. After that, the stepper motor is placed into the shaft, with the flat edge of the stepper motor shaft placed flush with the set screw hole that is on the widget. The set screw then fastens the stepper motor with the shaft and the rotating wheel. Once the stepper motor is attached to the shaft, the four five mm screws can be fastened to the Plexiglas piece in order to keep the stepper motor from shifting during use. Finally, all five 1/4”-20 screws are fastened to the stepper motor sidewalls and wedge. At this time, the ¼”-20 screws that can adjust the level of the Plexiglas piece can be adjusted if necessary. The stepper motor is now ready to be hooked up to a stepper motor controller, which will send power to the stepper motor at the appropriate time in order to rotate the wheel at different frequencies.

2.9.3. **Stepper Motor Hookup**

Another benefit of the Oriental stepper motor is that it came with a sufficient length of wiring that allows the connector to overhang from the RWT. This allows for an easy connection to the stepper motor controller, which not only provides power to the stepper motor, but connects it to the computer that will control its movements. Another benefit of the overhang is that the chance of the wires to fall into the RWT is greatly diminished. A more detailed description of how the stepper motor is controlled by the computer and the process to set this up is detailed later in the experimental setup section.

2.10. **Draining Tank Theory**

As was mentioned above, the velocity and height of the system are coupled together and were analyzed to help facilitate the design of the system. If one considers the height system above the drain given by the following equation:
\[ z(t) = \frac{v(t)}{lw} \] (2.6)

Where \( V \) is the volume of the tank, \( l \) is the length, and \( w \) is the width. As previously mentioned, this allows for the calculation of \( U(t) \) as given by Equation 2.2. The volume of the tank is given by:

\[ V(t) = V(t_p) - V_{loss}(t_p) \] (2.7)

The subscripts \( p \) and \( loss \) stand for previous and for the volume lost which is yielded from:

\[ V_{loss}(t) = Q(t) * t_s \] (2.8)

In which the subscript \( s \) means time step and the volumetric flow rate is found using:

\[ Q(t) = A_0 * U(t) \] (2.9)

Where \( A_0 \) is the area of the circular drain which is given by \( \pi d^2/4 \). One thing to note is when the flow is pulsating, it is fluctuating not only because of the wheel but because of the backflow that occurs with a blocked flow (as when the rotating wheel passes the test section exit without a hole) and the new \( U(t) \) is given by the following equation:

\[ U(t) = \sqrt{2gA_z} * \cos^2(\omega t) \] (2.10)

The frequency, \( \omega \), depends on the heart rate (HR) that is being simulated. For a normal HR, \( \omega = 1 \text{ hz}, \) or 60 BPM. Two other conditions are being considered as well. These are for a stressed HR of 120 BPM, \( \omega = 2 \text{ hz}, \) and a minimum condition of 30 BPM, \( \omega = \frac{1}{2} \text{ hz}. \) The minimum HR of 30 BPM is based on heart rates of elite athletes. The reason that multiple heart rates are being considered is since most people do not have heart attack during normal
conditions. If the blockage is measured at different heart rates, it could give insight onto how the blockage affects the blood flow to cause problem at higher heart rates.

It is important to note that when the facility was first designed, the concept of the HT was not incorporated into the design. So while this draining theory is still very applicable for the HT, the fact that the HT controls the head at a constant throughout the test makes the height, velocity, and Reynolds number decay studies that were first looked at unnecessary. However, in theory, if the volumetric flow rate is known due to the blockage, from the velocity and area of the constricted blockage, as well as the area of the HT valve that is opened at various positions, a precise valve placement for each head and blockage case can be calculated. This method would be more accurate than the trial and error method that was used to determine valve position at various heads and blockages as seen in Table 2.3. The markings on the left side of Table 2.3 correspond to the most vertical marking (closest to being fully open) to the most horizontal marking (almost fully closed). The Black, Red, and Blue markings correspond the appropriately colored marking used. The first part of the ‘Type’ case is the blockage, with the next part being the correct amount that the BT should be filled up in inches. Finally, if there is an additional marking it signifies which pulsation frequency should be used for the case. The colors of the cases correspond to the amount of blockage, which will be the same colors used in the results.
Table 2.3: Valve Positions for Various Test Conditions

2.11. Expected Reynolds Numbers

Due to the fact that the piping has an ID of 1” and that the viscosity of blood is much higher than water, the Re of blood flow through various parts of the circulatory system cannot be realistically achieved. By examining Table 2.4 below, it is clear to see that the required head height cannot be met accurately since even to match the Re of the Aorta, the head height would be .0037 inches. It should be noted that the two in head matches the maximum velocity of the aorta and the 1 in head is similar to the maximum velocity of a main artery (60 cm/s). In fact, the 4 in case (141 cm/s) is very similar to the maximum velocities seen by Clark\textsuperscript{38} in Figure 2.10, justifying the 4 inch pressure head case. In the same study, Clark examined Re of around 15,730 for the pulsating cases, much higher than is experienced in the normal blood flow. In fact, a previous study by Clark\textsuperscript{39}, the Re in from the onset of rapid ventricular ejection is in excess of 30,000 during pulsations. Additionally, in a study by Abdallah\textsuperscript{40}, pulsating values of Re ranged
from 5,000 to 50,000. These studies justify the Re that are around or above 30,000, such as the four inch 0% and 30% blockages, and the three inch 0% case, which is shown in Table 2.4.

Some interesting cases to note are the large blockage at four inch head and the medium blockage at one inch head are within five percent of the Re of the unblocked aorta. Since both of these cases have the same expected Re, they should also provide some insight on how blockage effects flow with the same Re. The Re of the small blockage for the aorta is also within ten percent of the large blockage and three inch head, as well as the two inch head. These cases could provide insight on how the flow behaves in the aorta for unblocked and small blockages. Coupled with the fact that the four, two and one inch heads match, or approximate maximum

Figure 2.10: Pressure and Velocity Time Traces of Various Positions of a Stenosed Artery\textsuperscript{38}
velocities seen in a healthy and diseased circulatory system, the test matrix dealing with the different pressure heads and blockages is justified.

Other interesting cases include the cases highlighted in cyan, as these have similar Re and as stated previously should give a greater understanding of how the blockage affects flows with dynamic similarity. The cases highlighted in red (two inch 30% and one in 0%), as well as the four in 65% and one in 30%, and the four in 30% and two in 0% cases have the same expected flow rate. These cases will be imperative to study because they will enrich the insight of how blockages affect the same amount of fluid moving through the test section in a given time.

<table>
<thead>
<tr>
<th>Head</th>
<th>Blockage</th>
<th>Velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 in</td>
<td>0%</td>
<td>35790</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>29974</td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>14316</td>
</tr>
<tr>
<td></td>
<td>96%</td>
<td>7158</td>
</tr>
<tr>
<td>3 in</td>
<td>0%</td>
<td>30995</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>25958</td>
</tr>
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<td>12398</td>
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<tr>
<td></td>
<td>96%</td>
<td>6198</td>
</tr>
<tr>
<td>2 in</td>
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<td>25307</td>
</tr>
<tr>
<td></td>
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</tr>
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<td></td>
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<td>10123</td>
</tr>
<tr>
<td></td>
<td>96%</td>
<td>5061</td>
</tr>
<tr>
<td>1 in</td>
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<tr>
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<td>7158</td>
</tr>
<tr>
<td></td>
<td>96%</td>
<td>3579</td>
</tr>
<tr>
<td>Aorta (3.7 mil)</td>
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<td>6844</td>
</tr>
<tr>
<td></td>
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<td>5732</td>
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<td></td>
<td>65%</td>
<td>2738</td>
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<td></td>
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<td>1369</td>
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<tr>
<td>Artery (127 μin)</td>
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<tr>
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<td>1061</td>
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<td>507</td>
</tr>
<tr>
<td></td>
<td>96%</td>
<td>253</td>
</tr>
<tr>
<td>Artery Branch (10 μin)</td>
<td>0%</td>
<td>355</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>297</td>
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<td></td>
<td>65%</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>96%</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 2.4: Expected Reynolds Numbers

2.12. Flow Visualization

Flow visualization is an extremely important tool that is being utilized to study how the flow behaves at various blockages and pulsation frequencies. Wall pressure measurements can only give so much information; just because the pressure can be accounted for across the test section still does not mean that important features such as vortices can be predicted, or seen from the pressure measurements. Flow visualization can yield those answers and much more. This is why a valve is located on both sides of the blockage section as seen in Figure 2.1. This will allow the system to be easily disconnected and new sections, which can include a DP-15 low pressure
sensor for wall pressure and pressure drop across the blockage, or a wire that can inject dye, or Thymol Blue, into the flow.

Another flow visualization technique that was considered is Laser Doppler Velocimetry (LDV). This could be a good alternative to using dye, Thymol Blue, and Particle Image Velocimetry (PIV), which is also being considered. The advantage LDV has over Thymol Blue is the fact that velocity can be quantitatively calculated and not qualitatively shown. LDV has an advantage over PIV for a couple of reasons. First off, you do not need to shine a sheet of laser light, but only a point. Also, you can get a time resolution that is not achievable in PIV. Since there is already a LDV setup down in the Oil Rig (where the design is proposed to being built in), it is an ideal alternative to other flow visualization methods. For the moment, injecting dye into the flow is being utilized since it is the easiest to setup and has been found to be sufficient enough to visualize the flow. Although inherently qualitative, by importing the images into MATLAB, they can be quantitatively analyzed.
3. Experimental Setup

3.1. Facility Setup

As seen in Figure 2.1, the complete facility is made up of four main tanks and many different components. If the facility is broken down in order to move or store it and later needs to be reassembled for testing, there is a certain order that components should be assembled in order to get the facility back up to testing condition.

The most important piece of equipment needed to keep the facility in the same operating condition as before is to use the iron cart that can not only move the entire facility, but allows tests to operate with all the current fittings and piping that has been used in the previous testing. The initial testing has occurred in the room with the oil rig facility, so it would be ideal to return the cart to the original location. Once in the room, one must get the short side of the cart parallel and a foot in front of the large white tanks to the right of the oil rig, with the long side about a foot from the oil rig. The cart should be placed so that valve from the RT will drain into the drain, as seen below in Figure 3.1.

![Figure 3.1: Valve Positioning to Drain](image-url)
With the cart in position, the tanks can start to be placed. Even though the process of setting up the tanks will be described tank by tank, the BT, RWT, and RT can be placed in position before any of the other components are mounted in the tanks. Having these tanks in the proper position beforehand should in fact make the process of setting up the tanks easier.

### 3.1.1. Reservoir Tank Assembly

In order to keep the RWT piping connected to the RT piping when the union is placed between the sections, the RT needs to be raised about one inch from the lower level of the iron cart. This has been done with two long sections of half inch thick wood, but anything that will give the RT one inch of height and support the tank will suffice. The RT should be approximately in the center of the cart with the long side in line with the long side of the cart. The tank is in position as long as the hole on the long side is facing the drain.

Next, an unmodified ½” bulkhead should be placed on the side closest to where the BT will be placed. The bulkhead should be tightened so that the long side that has the threading is on the outside of the tank. Next, if not already done, apply Teflon and thread the ½” NPT to barb connection to the bulkhead. This allows ½” clear, flexible hose to be placed on the barb fitting, which is then sealed with a hose clamp. Although unnecessary in its current state, the original idea was to circulate the water after a section of testing with a pump. This idea has not been implemented since it is easier and quieter to just drain excess water from the facility and refill the HT when needed.

To connect the valve to the RT, another unmodified ½” bulkhead, that has the piping seen in Figure 3.1, should be secured into the sidewall and tightened until the end of the pipe is
pointing towards the drain. This allows the union that will connect the drainage valve with the piping together. The union should be tightened such that the end of the pipe coming off from the valve is directed towards the main drain in the oil rig room. Finally, an unmodified $\frac{1}{2}''$ bulkhead with a little less than a foot straight section, as seen below in Figure 3.2, will allow for the RWT to successful union with the RT. Figure 3.2 also shows the approximate distance the cart should be from the large white tank.

![RT and RWT Connection](image)

**Figure 3.2: RT and RWT Connection**

### 3.1.2. Baffle Tank Setup

The tank should be placed with the short side in line with the long side of the cart, similar to the RWT which can be seen above in Figure 3.2. The tank should also have a 7” overhang off the left side of the tank, which will allow sufficient room for the test section to fit in. Since the majority of the tank is still supported by the cart, this will not cause the tank to tip or fall even if
the BT is empty and the HT is filled. As with the RT, the BT should be centered on the cart as much as possible with the hole that is at 8” on the outside and the hole that is at 6” from the bottom on the inside of the facility.

After the tank is in place, the shortest of the three baffles should be placed into the tank as close to midway through the tank as possible. This will make it easier when the Plexiglas sidewalls are placed in. To make sure the sidewalls are placed in on the correct side, make sure that the filleted edges are going to the bottom of the tank and conform to the side of the tank you are placing them in. Once both sidewalls are in, the two identical upper baffles can be placed in, which will help support the whole system once they are in.

Next, the 1” bulkhead that has the ¾” ball valve should be placed in the hole that is on the outside of the facility. It should be tightened such that the ball valve is facing straight upwards. This will allow for a successful union with the HT. Another 1” bulkhead, which has a 1” ball valve attached to it, should be placed on the inside hole of the BT. The bulkhead should be tightened to allow the valve handle to be facing upwards, allowing for the easiest access during testing. Finally, an unaltered ½” bulkhead with a short tube and elbow, as seen below in Figure 3.3 should be fastened into the bottom of the tank, allowing for water to be drained out of the BT.
Figure 3.3: BT Drain Setup

Since all of the necessary components of the BT have been placed inside, the lid can now be placed on top of the tank. Although not completely necessary, ½” bolts should be placed in the holes that have been drilled into the lid. This allows for easier positioning of the HT when it is placed on top of the HT. Finally, the union that contains the ½” ball valve and the long ½” PVC piping can be fastened to the end coming from the BT such that the spout is facing down into the RT. This allows the HT to drain into the RT without any unnecessary spills.

3.1.3. Head Tank Setup

With the lid on the BT, the HT can now be incorporated into the facility. The tank should be placed on top of the BT lid in between the bolts with the hole on the sidewall facing the drain. This allows for a ¾” bulkhead to be placed on the hole outside of the facility. When fastened so the pipe faces downward, the union can successfully connect the HT to the BT. Next, an unaltered ½” bulkhead should be fastened so that the NPT side is facing the outside of the tank.
This allows the hose to be fastened into the tank when experiments are run. The hose should have Teflon on it and to get the best fit, it should be tightened in with pliers. Even with doing this, there is a slight drip, so a bucket should be placed under the connection to catch the dripping water.

### 3.1.4. Rotating Wheel Tank Setup

The RWT could be the second tank setup instead of the last, but since it is the most difficult, time consuming, and requires tweaking to be completely setup, it is presented as the final tank to setup. To begin, the tank should be placed similar in fashion to the BT, but with 5” of overhang from the aft end of the cart, as seen above in Figure 3.2. Once the tank is on the cart, the sidewalls can be placed inside just like they were in the BT. As the bulkheads could be placed in before the sidewalls; the order can be changed if desired.

The unmodified 1” bulkhead with a small piece of pipe attached to it should be tightened on the front of the RWT facing the BT and HT. Later, the aft valve will be connected to this pipe with a union. Next, an unmodified ½” bulkhead should be attached to the opposite wall, with the NPT side on the outside of the tank. With this bulkhead on, the ½” NPT adapter should be screwed in so that the long section of pipe that will connect the RWT to the RT with the ½” union that is on the end of the piping. Once the RWT and RT piping is aligned, the union can be secured. The RWT drain bulkhead, which is unmodified and ½”, can be placed so the NPT side is sticking out of the bottom of the tank. This allows for the ½” adapter that has the piping and drain valve so be secured so that the spout is over the RT as seen in Figure 3.2.

With all the bulkheads securely on, the inner workings of the RWT can be assembled. To start, screw in the 1” adapter that has multiple elbows on it so the end of the pipe is facing
straight up when fastened. After that, the polypropylene base and stepper motor holder support should be screwed together. Diagrams of these pieces can be seen in the Appendix, but they are the only completely white machined parts. Once these pieces are together, they can be fit snugly into the open end of the pipe by putting the bottom hole of the base into the piping and pushing down while rotating the piece back and forth. When the piece seems in place, try and align it parallel to the long sides of the tank.

With the base in place, the assembly of the rotating wheel can begin. First, the aluminum shaft and the rotating wheel are fastened together with two shear pins and a ¼” bolt. This allows for the rotating wheel with shaft to be placed in between the wedge, making sure that one of the holes in concentric with the hole in the wedge. Next, a long Plexiglas piece, which holds the stepper motor in place in the RWT, is placed into the system. The holder is slightly oversized, to allow a snug fit, so it may take some finessing to get both sides of the holder on the bottom edge of the slots. To secure the stepper motor holder with the rest of the system, place a washer and ¼”-20 bolt on the center hole on each side. Screw one side in about halfway to secure the one side. Once this is complete, the other side can be fastened in by having one person push the stepper motor holder towards the side that is already screwed in while pushing the tank sidewall in the opposite direction. This will move the center hole in line with the center hole in the Plexiglas sidewall so the screw can be fastened in. Once both sides are secure, put washers on three ¼”-20 bolts for the connection of the stepper motor holder and its polypropylene support. The bolts should be screwed in order to align the stepper motor holder with its support.

The machined piece is shown in the Appendix and has four small screw holes for the stepper motor, as well as three ¼” holes to fasten the rotating wheel wedge to the Plexiglas piece. The two unthreaded holes on each end are to fasten the Plexiglas piece to the Plexiglas side walls
also shown in the Appendix, while the threaded holes allow for minor rotations in the piece that will level the stepper motor to the rotating wheel. After that, the stepper motor is placed into the shaft, with the flat edge of the stepper motor shaft placed flush with the set screw hole that is on the widget. The set screw then fastens the stepper motor with the shaft and the rotating wheel. Once the stepper motor is attached to the shaft, the four five mm screws can be fastened to the Plexiglas piece in order to keep the stepper motor from shifting during use. Finally, all five 1/4”-20 screws are fastened to the stepper motor sidewalls and wedge. At this time, the ¼”-20 screws that can adjust the level of the Plexiglas piece can be adjusted if necessary. The Vexta PK 266-02A stepper motor is now ready to be hooked up to a stepper motor controller, which will send power to the stepper motor at the appropriate time in order to rotate the wheel at different frequencies. Finally, put a bolt on each aft most side of the two Plexiglas slots; this will allow for fine tune adjustment when getting the wheel rotating with the stepper motor controller. The RWT should look like Figure 2.9 and Figure 3.2 once everything is in place.

3.1.5. Test Section Setup

With all four tanks assembled and connected, the only thing left to setup before a test can be run is the test section. First, supports for the test section need to be placed properly so that the test section does not sag. The supports can be seen in Figure 2.1 and to position them correctly, put one 9 ¾” aft of the BT and 7 ¾” fore of the RWT. The aft test section (the section with the 1” ball valve as part of the section) should be attached with the RWT using the union such that handle of the valve is upward and is as parallel with the sides of the cart as possible. To attach the fore test section half, take the test section half seen in Figure 2.5 and insert one of the four blockages, as seen in Figure 2.6. On the other side of the blockage, wrap an O-ring around the outside of the blockage section.
After this is done, align the holes of the test section half with the ones on the blockage and insert the blockage/test section into the aft test section half. Next, insert the four bolts with washers into the blockage/test section half and turn until it is aligned with the fore test section half. At that point the bolt will slide through the holes. A washer and nut can then be placed on the end of each bolt and then should be tightened. This will seal the two test sections together and then the fore test section can be joined with the BT with the union. While putting the test section together with the 0% blockage, great care must be taken in not only putting the O-ring on, but sliding the blockage/test section into the aft test section and its subsequent removal for a new blockage. The reason is due to the very thin amount of aluminum that is left on the blockage piece so the piece is inherently frail.

3.2. Experimental Test Setup

Once the facility is setup and ready to go experiments can successfully be run. There are many different experiments that can be done with this facility; pressure change, pressure, microphone, and flow visualize are the ones that have been considered during this testing. While there are different procedures that need to be followed when running the different types of experiments, there are several things that need to be done no matter what kind of experiment is being conducted.

3.2.1. Equipment Needed

There are several important devices needed to insure that all the experiments can be properly conducted. A computer that has LabView capabilities as well as a DAQ board is necessary not only to take and store pressure and microphone data, but also runs the software that controls the stepper motor. A simple DAQ system, such as a NI BNC-2110 will suffice. After it is connected to the computer, a Validyne CD-23 display will not only display data as it
receives it from the Validyne DP-15 pressure transducer that is used to take the pressure and change of pressure measurements, but also can output it to the DAQ board then subsequently the computer. For the current LabView VI’s, the CD-23 output should go to AI-0. AI-1 should be devoted for the B&K NEXUS Signal Conditioner. The signal conditioner input comes from the microphone, with the output going to AI-1. Finally, the Velmex Stepper Motor Controller is used to control the Vexta PK266-02A stepper motor. It must be connected to the computer in order to speak with the COSMOS software which controls the motor.

3.2.2. Stepper Motor Calibration

In order to make sure the stepper motor is able rotate the wheel sufficiently for testing, a few steps must be undertaken. Once the facility has been adjusted to allow the stepper motor to work effectively, there should be no need to do anything but fine tune adjustments to keep the motor functioning correctly. Once the Velmex Stepper Controller is powered up and connected to the computer via a RS-232 cable, make sure the computer that is being used has COSMOS software. The version that was used in the results presented in this paper utilized version 3.1.6. If the software is not on the current computer, it is free and available to download on the Velmex site. The first time the program is run, the software needs to calibrate a few settings. Before starting the COSMOS software, make sure the power is turned onto the control box.

When the software starts up, a setup wizard will pop up on the screen. If this does not happen, or if you want to change or verify settings, go to File -> Run Wizard. The wizard first asks what the Limit 1 Setting should be. Make sure to choose [None], otherwise the software will be looking for something that is not there and the stepper motor will not function. Next, it will ask the user to choose a motor that the software has specifications on. Since a Vexta PK266-03, which is almost identical to the PK 266-02A that is being used, is preconfigured, the user should
choose this motor. It will then ask if a second motor is being used, which it is not. In future cases, there could possibly be two motors and if this is the case then the user would just go through the motor selection as just previously done. Regardless of whether or not there is a second motor, the next prompt asks for the Motor 2 Limit, which is [None] like the first motor. The final two things the wizard asks about are if there is a joystick or thumbwheel being used, both of which should be answered, no.

With the software setup correctly, it is time to test the stepper motor out to see if the bolts need to be tightened or loosened. In order to test this, as well as to run any experiment with a pulsation frequency, the user needs to go to Tools -> Quick Move -> Relative Move. A screen will then popup asking for the number of steps the motor should spin for, the number of steps per second the motor should rotate at, and if the stepper motor should move in the positive or negative direction. The most important thing to remember is to always rotate the wheel in the negative direction. The positive direction will not work, most likely due to the fact the wheel is probably not entirely parallel to the groove it is fit into. To test out the fit of the bolts, choose 1000 steps at 100 steps per second. If the wheel rotates without any problems, then the RWT is ready for testing.

More likely than not, however, there will be too much friction, which will cause the wheel to either not rotate, or jog a little before rotating. This could be from either too tight of a fit or too loose of a fit. In order to fix this problem, bolts may either need to be tightened or loosened, depending on how they were first setup. The best idea is to first tighten the bolts that are on the slots of the sidewalls. Slowly tighten and run again to see if it helps, if not try loosening them. If this does not fix the problem, get it is good as possible then move onto the four bolts fastening the stepper motor to the stepper motor holder. Repeat the same process and if
necessary try the three bolts securing the stepper motor holder to the stepper motor holder support. Eventually, the wheel will spin without stopping and after the cycles are complete, the hole of the acrylic wheel will be over the end of the pipe. Once this occurs, the stepper motor is calibrated and ready to go for testing.

3.2.3. Conducting Pressure Difference Measurements

Since the first experiments that were conducted with this facility were the pressure drop across the blockage at various positions, this will also be the first experimental setup described. Subsequent experiments are similar in many aspects, so only the deviations from the setup and conducting the experiments will be detailed.

Once the facility is ready to go, as seen in Figure 2.1, the first step that must be undertaken is to unscrew a fore port and an aft port that will be used for the experiment. Next, two ½” fittings that have tube connections at the end of them should be inserted into the port locations being tested. These pieces can be seen below in Figure 3.4; in this case, the far fore port and the medium aft port are being used. It should be noted that Teflon should always be put on the threads of the port fittings to ensure a tight, waterproof seal. Next, if not already done so, connect the ¼” fittings to the Validyne DP-15 pressure transducer. This allows for the tube connections seen in Figure 3.4. It is very important to note that for these tests, as well as the single port pressure measurements, the pressure on the fore side of the blockage goes to the (+) pressure transducer port and the aft side goes to the (-). This is because there is a pressure drop across the blockage, so the higher pressure will be preceding the blockage.

With the connections setup, the facility can now be filled. By letting water flow from the HT to the BT, through the test section, and into the RWT, the water level in the RWT will rise
until the 7” level is reached. Great care, especially in the 96% blockage case, should be taken to make sure that the BT does not overfill while this process occurs, since the flow area and thus the flow rate, are greatly reduced compared to the lower blockages. When the RWT is filled sufficiently, close the 1” aft ball valve and get the BT to the head level that the first experiment will be conducted at. When this is done, take off one of the tubes going to the pressure transducer. Making sure you have a bucket, hold the tube over the bucket and let water bleed into the line. When all the air pockets are out of the line, attach it back to the tube fitting. Repeat with the other tube and both lines will be filled and ready to go with testing.

It is now time to turn on the CD-23 to see what the voltage output of the pressure transducer is. Since there is no flow in the facility and the aft valve is closed, the pressure before and after the blockage is equalized. This means that the reading should be zero. However, if this value is off, just turn the dial on the zero gauge to zero the system. Once the pressure readout is zeroed, testing is ready to commence. If LabView is not already open, make sure that ‘Acquire Pressure.vi’ is open and ready for use. It is important to check the settings on the front panel of the vi to make sure they match what case the experiment is going to test. The important parameters are fore pressure port, aft pressure port, pressure head, and pulsation frequency. If a tube length study is being conducted, then that parameter should be checked as well, although a good rule of thumb is to always leave it as ‘Short’ if not.

Finally, everything is setup in order to run an experiment. Before the first experiment is conducted, make sure there is ample water in the HT, at least to the 4” level. This will be crucial in running as many experiments as possible without stopping. Another piece of advice is to have an idea of where the valve that controls the flow of HT to BT needs to be for a series of three or four tests (such as if a certain pressure head is being tested for the four different pulsation
frequencies), so that one test can flow right into another as quickly as possible. At first, this should not be attempted, but the more familiarity with conducting the experiments one has, the easier it will be to do this. The chart that has all the appropriate valve positions depending on the blockage and head should be on the HT, but if not, use Table 2.3 to find the correct position.

If the steady case (0 Hz) is being run, then all that is needed to be done is to open the aft valve, adjust the HT/BT valve appropriately, and hit the run button. As the program is reading in the data, make sure to monitor the head level in the BT and adjust the HT/BT valve if necessary. For the pulsation cases, the correct steps per second and total number of steps must be put into the COSMOS relative move screen. Values that were used for the initial experiments will be provided in the results section to use as a guide. Once those are put in, hit the negative button so the wheel will start rotating. Then open the aft valve and turn the HT/BT valve to the right position. After that, hit the run button on the front panel of the Acquire Pressure.vi program and monitor just like the steady case.

![Figure 3.4: Pressure Change Setup](image)
3.2.4. Conducting Single Port Pressure Measurements

Although, for the most part, the single port measurement is the same as the pressure difference measurement, there are a couple of distinct differences. First off, as see in below in Figure 3.5, there is obviously only the one pressure port going to the test section, but also the other port being placed in a water bottle. The reason for this is because the signal will saturate unless both the positive and negative sides are in contact with water. Therefore, while the one line is bled from the pressure port, the other line is bled from the filled water bottle. Great care should be made to make sure that the line that is going to the pressure port is on the correct side (positive if fore and negative if aft). The only other significant difference in testing to make sure “No” is selected for the side that has the line going to the water, since no pressure measurement is being taken from that side of the blockage. Also, for the current testing, instead of having a clear, flexible tube go from the pressure port to the pressure transducer, a short, rigid tube connects the two. This is to take dampening due to losses in the flexible tube out of the results and this will be shown to be true later. A picture of the pressure transducer and the new fitting can be seen in Figure 3.6.

![Figure 3.5: Single Port Pressure Measurement Setup](image-url)
3.2.5. Conducting Microphone Measurements

Microphone measurements are another very important measurement. Although currently there are a few problems with taking accurate measurements in the current setup, the process of conducting the experiment should be the same when these issues have been addressed. Since getting a noise clean and clear noise signature is paramount in these experiments, there are two considerations that need to be made with the RT. First, since noise from water dripping from the RT to the drain would add unwanted noise, the valve on the outside of the RT should be closed. Along the same lines, the before any microphone measurements are taken, the water level in the RT should be above the level of the bulkhead so that when water flows from the RWT to the RT, there is no excess noise from the water entering the tank.

The most important thing to do when running microphone experiments is the setup of the microphone and test section. A seen below in Figure 3.7, there is a Teflon barrier over the opening of the port hole. It acts as a diaphragm, letting the pressure wave affect its position. The
Teflon has been wrapped with tape to keep the water tight seal around the port hole. Although the microphone was originally perpendicularly to the Teflon as shown in Figure 3.7, but was changed to be directly over the Teflon barrier. This can be seen in Figure 3.8 and allows for the direct noise from the diaphragm to get to the microphone.

![Figure 3.7: Original Microphone Setup](image)

With the microphone setup, the tests are, for the most part, similar to those of the wall pressure measurements. However, there are a couple main differences between conducting the experiments. The most distinct is the fact that a different LabView program, ‘Acquire Mic.vi’ is utilized. The main difference in this program is the ability to add a Background case. The reason that a background is needed is to have the ability to see what the differences are from the actual flow, since the background noise is removed. When conducting an experiment at a certain pulsation frequency (even 0 Hz), a background is taken with no flow and the wheel spinning at
the frequency in question by switching the Background to [Yes]. Once that has been done, switch the Background to [off] and conduct the experiments as normal.

![Figure 3.8: Current Microphone Setup](image)

3.2.6. Conducting Flow Visualization

Setup for the flow visualization is paramount in obtaining a good quality video. Although there has been in evolution in how the flow visualization has been conducted, the most recent setup will be discussed. A more thorough investigation of flow visualization will be presented later. The first thing that should be done is to setup the test section for dye injection. To do this, screw in a ½” fitting that has a small hole at the top into the far fore position. Next, insert an injector tube, which is just a surface static pressure tube, into the opening in the hole. With a pair of needle nose pliers, bend the end of the tube that is in the test section to a right angle such that
it is as close to the centerline of the pipe as possible. With this achieved, wrap the fitting and tube with Teflon to seal the connection. An easy check to make sure the tubing is aligned is to look directly over the test section to see if the tube is vertically in line and to look directly at the side to see if it is horizontally aligned. A properly aligned injector tube can be seen in Figure 3.9.

![Figure 3.9: Aligned Flow Visualization Setup](image)

With the injection system ready to go, the next step is preparing the facility for flow visualization. To achieve this, make sure there is a black canopy that goes from the computer setup to the oil rig top base. This prevents direct light from shining on the facility causing glaring, but allows for enough light to get in to visualize the flow properly. The next step is to take the white board in the middle of the iron cart, as seen above in Figure 3.5 and to move it slightly towards the oil rig. The purpose of this is so the tripod that will hold the camera to be placed in the bottom part of the iron cart. This allows for the camera to take video without zooming in, which would degrade the quality of the film. With the tripod in place, screw the camera into the tripod and position it such that you can see the injector as well as all the ports aft of the blockage. Using the tripod, tilt the camera so that it is approximately 45 degrees offset pointing towards the setup. This will allow the video captured to be similar to Figure 3.9.
With the test section setup, the actual experiment is ready to be conducted. While filling up the test section with water, make sure to take the cap off of which ever color is being used for flow visualization (either blue or red) and insert a 1/8” clear, flexible tube into the dye container and tape up the container as best as possible. This will help prevent spills that could get the setup and person conducting the experiment stained with food coloring. Suction the tube to bleed dye into the line and attach it to the top of the injector tubing. It is important to make sure that after this is done, to raise the dye container to the appropriate height to balance the pressure so that the dye does not go into the test section and the water does not flow into the dye container. A picture of the current setup can be seen in Figure 4.8.

Finally, the facility is ready for flow visualization. Before testing begins, take a background photo for each blockage tested. Since the setup is taken apart for each new blockage, this ensures that the position for each set of testing will be accurate. This allows for, among other things, velocity of the flow to be calculated and position of the dye to be tracked. With the background taken, start the flow of water into the facility and the stepper motor (if necessary). The dye is now ready to be injecting and this can be done by raising the container and placing it on the lid of the BT. Make sure that the dye container is being held since it would tip over without assistance. Once the stream of dye starts going through the test section for a few seconds, turn the camera on, for about 15 seconds, in order to get enough footage for analysis. When testing is done and the blockages are going to be changed, make sure to take the flexible tubing of the injector tube and wedge the container in one of the circular holes on the iron cart, taping the tube to the RWT. This will prevent the dye from draining out of the container between testing.
3.2.7. Changing Experimental Parameters

Two important parameters that change throughout testing that have not been discussed are details on how to change out blockages, as well as changing head heights for the tests. To change the blockages, the first thing that should be done is to drain the test section of water. The section is sufficiently drained when the water levels on the BT and the RWT are below their respective bulkheads. Special consideration should be taken when the largest blockage (96%) is being drained. This is because the test section will not completely drain even when the appropriate levels are reached. To get the excess water out of the system, take the union off of both sides of the test section and slowly lift the section up, allowing it to be dumped into the HT. Once this is achieved, the section can be placed back into position with just the union of the aft side being put back on.

Regardless of which blockage is being changed out, with the union off on the fore side, unscrew the four bolts that are holding the two test sections and the blockage section together. With the bolts off, grab the fore test section and blockage sections and slide them off from the aft test section. Remove the blockage section and take the O-ring off. Put the O-ring on the side that is going to be placed on the aft test section, sliding the other side into the fore section of the pipe. Now the same procedure can be followed as when putting the test section together.

Adjusting the head heights is almost trivial and can be done two different ways. When running tests at multiple height levels, one should start at the highest height and work down. When done with testing at one height, tank can be drained to the next height that will be tested by either opening the drain valve on the BT, letting the water flow through the facility, or a combination of both. If the head level needs to be raised, this can be done by simply closing the aft test section valve and allowing water to flow from the HT to the BT.
4. Results

4.1. Experimental Setup Studies

During the course of conducting experiments, there were areas that it was thought there could be an improvement made to the experimental setup. All three of these areas were investigated and the results of these efforts will be detailed below. The three areas that were investigated were tube length on pressure differential and single port measurements, using a high-pass filter to try and amplify the floor level, and the improvement in flow visualization setup. As well as studying the changes in the setup, it is important to quantify the repeatability of experimental results.

4.1.1. Effect of Tube Length

Initially, the two pieces of flexible tubing that connect the pressure transducer to the wall pressure port was much larger than it currently is, as seen above in Figure 3.4. A comparison of the lengths of the original long tube and current short tube can be seen below in Figure 4.1. When the long tube is straightened out it is approximately 25”, with the smaller tube being about half the length. There were two limiting factors on the length of the tube. The first was that there still needed to be enough length to connect the tubes from the pressure port to the pressure transducer. The second was the fact that one of the pressure port connections (the longer tube in Figure 4.1), can only accommodate 1/16th inch tubing, while the other pressure port connector, as well as the pressure transducer, has fittings for 1/8th inch tubing. This means a brass adapter, shown below on the long tube, has to be included, which further lengthens the tube.
In order to show the benefits of shortening the tube length, pressure differential experiments at one through four inches of head were conducted for the large (96%) blockage for the three pulsation frequencies (1/2, 1, and 2 Hz). As it is seen in Figure 4.2, the trends for the pressure differential and single port measurements at four inch head clearly show the benefits of the shorter tube. It is clear that the long tube misses out on the amplitude of different harmonics. The reason that the longer tube does not capture the complete spectra is due to the dampening that occurs as the pressure travels through the port through the tube to the transducer. The more tube length there is the more dampening that occurs, especially with pulsation frequencies, since the pressure wave will not fully reach the transducer if the tube length is too long. Ideally, the tubing should be as short as possible, if not flush mounted, to eliminate these effects. It should be noted that while the frequency shifts from approximately 60 Hz for the pressure differential measurements to 50 Hz for the single port measurement. This frequency shift could be due to either interaction between the far upstream (fore) and medium downstream (aft) ports, or just continued improvement from shortening the tube length.
4.1.2. Repeatability

Before any additional analysis will be discussed, it is important to determine if the results are repeatable or not. This is not only important because it helps verify the accuracy of the results, but also important because of cavitation effects which have been previously seen in Figure 2.4. Although cavitation does not allow it to occur, it primarily only occurs sometimes after the test section is filled for medium and larger blockages, it something that could have detrimental effects on future results. For each ‘Run’ as seen below in Figure 4.3, the test section was filled up and subsequently drained for the next test. The first two cases did not have any cavitation while the third case had some that could not be removed from the test section. It is clear to see, besides an approximate five dB and frequency shift of about two Hz for the second
run of case two, the spectra are very similar. This shows that the repeatability of the experiments can be trusted and that while there is inherently some experimental error, the cavitation does not have to be the culprit as it was not in this study.

Figure 4.3: Repeatability Study for 4 in 65% Blockage

4.1.3. Effect of Filters

It is easy to notice from Figure 4.3 that there is a clear and distinct roll off after the vortex shedding frequency down to the noise floor, which around -140 dB and 200 Hz for the steady case and -120 dB and 500 Hz for the pulsating cases. Since some medical studies such as seen in Figure 1.12 show significant pressure amplitudes in frequencies above 100 Hz, a Stanford SR650 Dual Channel Filter was used to filter the results with a high-pass filter so that the higher frequencies could be amplified in hopes of improving the high frequency results. If successful, there should be additional high frequency effects because by filtering out the low frequency
effects, the amplitude difference for the signal will be much lower and amplifying the signal from the original ceiling should be possible.

![Figure 4.4: Comparison of Various Filtering Techniques](image)

Shown above in Figure 4.4 is the comparison of several different filters, as well as shortening the distance between the pressure port and transducer as seen in Figure 3.6. It should be noted that these results are normalized. For example, the 20 Hz DC 20 dB out means that a 20 Hz high-pass filter was applied to the measurements and was amplified by 20 dB after the signal was read in by the signal conditioner. To compare with the unfiltered results to see if there are any new higher frequency effects obtained from filtering out the low frequency amplitudes, the FFT was subtracted by 20 dB (and 40 dB for the 20 Hz DC 20 dB In & Out case). However, it is clear to see from Figure 4.4 that there are no significant effects from the filtering since the spectra essentially lay on top of each other. This means either there are no high frequency effects in the flow or improvements the pressure transducers themselves (better quality, better mounting, etc...) must occur to realize any of the possible high frequency effects of the flow.

### 4.1.4. Improvement of Flow Visualization Setup

Shown previously in Figure 3.9 is a still from the current flow visualization setup at four inches of head for 0% blockage, with the current full setup shown below in Figure 4.8. However,
there were many steps taken in order to get a better quality picture and this process will be discussed below. The first improvement from the basic facility that occurred was to add a black background and tape it to the Oil Rig support system. The reason this was done was to give a constant background, especially since the tube is transparent. Had the black backdrop not been implemented, the various parts of the Oil Rig would have been seen during flow visualization, which would hinder the ability to track the dye as it is flowing through the test section. Seen below in Figure 4.5 is a frame from the original setup.

![Figure 4.5: Original Flow Visualization Setup](image)

There are a couple of things to notice with this original setup. First off, there is a lot of glare from the ambient light in the lab. This makes viewing the images difficult because they are distorted. Also, the black background does not allow for uniform color along the test section. It is clear to see different shades of black and grey and this also distorts the clarity of the images. Originally, blue dye was used to seed the flow, however after viewing multiple videos at multiple blockages, the red dye was deemed best for video quality. A comparison between two still shots from a steady flow with 0% blockage is shown below in Figure 4.6. It was decided that to improve the setup, a white background would be used, which would help the dye to be recognized easier during the videos and analysis.
Figure 4.6: Dye Color Comparison

The addition of the white backdrop to aid in the improvement of flow visualization can be examined in the current setup in Figure 4.8. Another improvement to the setup is the fact that the black cover that drapes from the top of the oil rig to the DAQ computer (not shown). This cover allowed most of the direct ambient light to be blocked from test section. Black side panels were initially added as well, but they blocked off too much ambient lighting which made the flow visualization images to dark to distinguish significant differences from frame to frame. The result of adding the white backdrop and cover to the flow visualization setup can be seen in Figure 4.7. The quality of the picture is vastly improved from Figure 4.5 and Figure 4.6.
4.2. Microphone Measurements

The ultimate goal of this facility is to be able to use an array of microphones to be able to pinpoint the location and even the amount of blockage based on the acoustic signature. The method of beam forming has been detailed in many studies such as Smith et al.\textsuperscript{44} show how microphone arrays can be utilized for noise source location. For the initial investigation into microphones, a single microphone was placed just aft of the blockage as shown previously in Figure 3.8. A Teflon barrier was used to act as a diaphragm, which allowed the pressure waves to travel through to the microphone but prevent the water from leaving the test section. During the pulsations, it was very easy to see the fundamental frequency cause the Teflon to pulse up and down. Unfortunately, as shown below in Figure 4.9, the effect of pressure head and pulsation frequency had no effect on the spectra. There was no significant change from the background and no change even when the sampling frequency was varied from 2.5 – 10 kHz. This means that
the microphone did not pick up any signature from the blockage. Most likely, this is due to transmission loss through the test section.

Since the OD of the acrylic tubing is two inches and the ID is approximately one inch, which means that there is a half inch thick section of acrylic tubing in between the inner and outer walls. Due to this wall thickness, there is a certain amount of transmission loss associated with the propagation of the acoustic pressure wave from the inside of the pipe to the outside. There are several ways to calculated transmission loss through a material. One method, described by Yahya\textsuperscript{45}, puts a known noise source inside the tube, with a microphone a certain location from the source. Next, a microphone would be placed equidistant outside the tube and an analytical solution can be found from the pressure measurements.
As mentioned previously in Section 2.5, this test section was received from the Vocal Consortium Lab at UC and was designed primarily for compressed air flowing through the tube. The noise from the air blowing through the system would be much louder than the background noise of the lab. This means that even if the microphone could not detect any difference in spectra from blockage, it would at least detect a significant difference from the background noise. Since the flow through the pipe is very quiet, the microphone cannot pick up the difference from the background and the flow. Ideally, the test section would have been designed differently and this topic will be discussed later. Fortunately enough, the wall pressure measurements have sufficed enough to obtain many significant and important results as seen in previous sections. So while this is a definite area to look into, the investigation into the use of microphones will help aid in the future improvement of the facility.

### 4.3. Effect of Steady Flow

#### 4.3.1. Mean Pressure Profile Along Test Section

There is a great deal of theoretical work that has already been done on predicting pressure profiles through an orifice plate\(^{36}\). While this will be discussed in greater detail later, a pressure profile across a pipeline with an orifice plate can be seen below in Figure 4.11 along with results obtained experimentally. The single port measurements are taken at each fore and aft port and these figures tell two main things about steady flow through the blockages in the test sections.

The first is that all the blockages match up well with the theory. All the blockages have some sort of a pressure rise before the blockage and a distinct pressure drop across the blockage. In the larger blockages, particularly for the small (30%) and medium (65%), there is a distinct pressure recovery zone, as seen in the theoretical pressure profile. A possible reason that there is
only a slight pressure recovery for the large (96%) blockage is because the length of the jet flowing through the blockage is longer as the blockage size increases. The pressure cannot fully recover until the jet ends and because of the vena contracta, which as mentioned previously, is the point of smallest constriction of the flow. After this distance the jet can expand and the turbulence mixes into the pipe flow, allowing some of the pressure to recover. While this point will be discussed in greater detail in the analysis of the flow visualization, the basic premise is that the far aft port is not far enough away from the blockage to pick up the full pressure recovery since the jet size is largest for this blockage.

The other phenomenon that is explained from these figures is the nature of the pressure drop through the blockage. While, for the most part, the pressure fore of the blockage is around .02 psi, the pressure drop increases as the blockage increases. For no blockage, the pressure drops to about -.04 psi, while the small blockage drops roughly averages to be about the same, the pressure recovery can be seen, so the maximum pressure drop is actually about -.06 psi. For the medium blockage, there is a maximum pressure drop to -.1 psi with a slight pressure recovery, due to the fact that the jet length has been increased compared to the small blockage. Finally, in the large blockage, there is a maximum pressure drop of -.14 psi, with only a very slight pressure recovery, since the largest length jet is in the 96% blockage and the pressure has not started its recovery by the far aft port position. By this postulation, if there were farther aft ports available, a pressure recovery zone would be seen.

The slight rise in the pressure profile shown in Figure 4.10 before the blockage is due to the separation in the flow due to the frontward facing step that the flow sees as it approaches the blockage. As the flow exits the blockage, the flow sees a backwards facing step and there is separation once again. Until the flow finally reattaches downstream of the blockage, there will be
unsteadiness in the flow, which can be seen in many studies such as Ting and Prakash\textsuperscript{58}, and is shown below in Figure 4.12. This is something that occurs in turbulent flow, which occurs in flow through pipes in Re above 4000\textsuperscript{32} and causes even what is being considered steady flow in this study to behave like unsteady flow, since all the flows have a Re greater than 4000 as shown in Table 4.1.

![Theoretical Pressure Loss Recovery for Orifice Plate](image1)

**Figure 4.10: Theoretical Pressure Loss Recovery for Orifice Plate\textsuperscript{36}**

![Steady Pressure Profile Across Various Blockages](image2)

**Figure 4.11: Steady Pressure Profile Across Various Blockages**
4.3.2. Theoretical Pressure Drop

The most important result that is gained from taking $\Delta P$ measurements is to study the pressure drop across the blockage. These help quantify the overall pressure drop from the far upstream (fore) port to the medium downstream (aft) port. In order to ensure that the facility is working as designed, the experimental measurements should match up to the theoretical calculation of pressure drop across an orifice plate. The basic principle for flow across an orifice begins with Bernoulli’s equation, as seen in Eq. 2.1. Since the flow through the pipe is horizontal, there is no change in height, which reduces Eq. 2.1 to
\[
\frac{p_1}{\rho} + \frac{U_1^2}{2} = \frac{p_2}{\rho} + \frac{U_2^2}{2} \tag{4.1}
\]

Using the volumetric flow rate relationship that \( Q = U_i A_i \), the definition of area that \( A = \pi D^2/4 \), substituting into Eq. 4.1, and rearranging the equation to solve for the pressure drop across the two distances yields

\[
\frac{2(p_1 - p_2)}{\rho} = \frac{16Q}{\pi^2} \left( \frac{1}{D_2^4} - \frac{1}{D_1^4} \right) \tag{4.2}
\]

After taking the square root of Eq. 4.2 and rearranging the terms, along with some algebraic manipulations, when solving for the flow rate, the equation becomes

\[
Q = \frac{C_D A_2}{\sqrt{1 - \left( \frac{D_2}{D_1} \right)^4}} \sqrt{\frac{2(p_1 - p_2)}{\rho}} \tag{4.3}
\]

The reason that Eq. 4.3 has been solved for flow rate is because there is a discharge coefficient \( (C_D) \) that is associated with flow through an orifice plate\(^\text{30}\). It has to do with the area of the orifice plate and for orifice plates is typically around \( .64 \text{\(^\text{31}\)} \). Although the reasons for this will be explained shortly, the equation to calculate the \( C_D \) for a particular blockage is given from ISO standards\(^\text{30}\) as

\[
C_D = .5961 + .0261\beta^2 - .216\beta^8 + .000521 \left( \frac{10^6\beta}{Re_D} \right)^.7 + \\
\left( .0188 + .0063 \left( \frac{19000\beta}{Re_D} \right)^8 \right) \left( \frac{10^6}{Re_D} \right)^3 \beta^{3.5} + .043 \left( 1 - .11 \left( \frac{19000\beta}{Re_D} \right)^8 \right) \frac{\beta^4}{1 - \beta^4} - \\
.031 \frac{2M}{1-\beta} - .8 \left( \frac{2M}{1-\beta} \right)^{1.1} \beta^{1.3} + .011(.75 - \beta)(2.8 - \frac{D_2}{.0254}) \tag{4.4}
\]

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Where β is the ratio of the orifice diameter to the pipe diameter (D₂/D₁) and M is a constant based on the placement of the taps, which will also be explained in more detail shortly. Since the ΔP measurements were taken at the far fore and medium aft ports, as seen previously in Figure 3.4, the port setup closely resembles the D & D/2 tap configuration where M = .47. The D & D/2 configuration can be seen below in Figure 4.13. Since, as shown in the Appendix, these ports are 3.375” (far fore) and 2.125” (medium aft) from the orifice plate, they most resemble the D & D/2 configuration.

![Figure 4.13: D & D/2 Pressure Tap Configuration](image)

As previously mentioned, there are a few reasons for the C_D; the flow area at the location of the aft pressure tap is unknown due to the vena contracta (location where the flow is most constricted), frictional effects play a significant role in the flow, and the location of the pressure taps effects the differential pressure reading. The reason that pressure tap location affects the differential pressure is because even though there is a permanent pressure loss due to the constriction (orifice plate in this case), there is a period just aft of the blockage when the pressure loss is greatest, due to the constriction. As the flow travels aft of the constriction, some of the pressure loss is recovered as the flow begins to fill the unconstructed tube as it travels downstream.
4.3.3. Comparison of ΔP to Theory

4.3.3.1. Downstream (Aft) Port Position Effect on Pressure Drop

While pressure differential measurements are always taken from the far fore port as can be seen in Figure 3.4, pressure differential measurements were taken from all three aft ports. This helps show the pressure drop profile as some of the pressure that is lost traveling through the orifice plate is recovered as it travels aft of the blockage. A typical orifice plate pressure profile can be seen above in Figure 4.10. Experiments were conducted for all four blockages and the results of these experiments can be seen in Figure 4.14. It is clear to see that the pressure recovers, especially for the medium (65%) and large (96%) blockages, as the pressure drop declines as the ports go from close (1st) to far (3rd) aft positions. Since there is hardly any pressure drop across the blockage for no (0%) and small (30%) blockages, there is no discernable difference for these blockages.

Figure 4.14: Port Comparison for Pressure Drop for Various Blockages
4.3.3.2. Pressure Drop Comparison

By rearranging Eq. 4.3 to solve for the pressure differential \((p_1 - p_2)\) for a particular head, since the velocity and area, and thus the flow rate, for each blockage are derived from Eq. 2.1, the experimentally obtained pressure differentials can be compared to the theoretical values. This equation then becomes

\[
\Delta P = \frac{\rho}{2} \left( \frac{Q \sqrt{1 - \beta^4}}{C_D A_2} \right)^2
\]

(4.5)

Shown below in Figure 4.15 is the comparison between the experimental and theoretical pressure differentials due to the blockages and pressure heads that were tested. It should be noted that the pressure drop is taken from the far aft port, which is the right most port as seen above in Figure 3.9. The reason this port is chosen is due to the fact that the farthest aft position from the blockage allow for the fullest pressure recovery, as seen in Figure 4.10. Results are fairly promising, as the theoretical values match very well with the experimental data, within +/- 4 to 12% besides an anomaly for the small blockage (30%) at four inches of head, as well the entire unblocked (0%) case. However, the error for this blockage is easily accounted for.
Figure 4.15: Comparison of Experimental Steady Pressure Differential to Theory

For the unblocked case, where there should theoretically be no pressure drop, there is a small (at its maximum, approximately .01 psi pressure drop), that can be attributed to the fact that even though the orifice plate was machined to have no area change, there is undoubtedly tiny changes in area from the pipe through the orifice plate, and back to the pipe. This, along with the calcification that occurs on the 0% and 30% blockages, can attribute for the appearance of a small blockage in the experimental data. Calcification occurs over time when aluminum is subjected to non-distilled (hard) water for a long period of time. Calcification can be seen not only on the blockages in question, as seen below in Figure 4.16, but as well as the aluminum shaft that rotates the disk in the RWT. The reason that the larger blockages do not exhibit this is due to the fact that the blockages were anodized black by the company that fabricated them (Blue Chip Tool) to prevent corrosion and were left unaltered.
The most important thing to be learned from the above results is that as pressure head and blockage size increase, so does the pressure drop across a blockage. This is important because as the stenosis increases, so does the velocity through the stenosis, compounding the effect. As a patient with CAD has increased severity of the stenosis, the pressure drop across the stenosis with rise significantly. This will cause the heart to work much harder as it needs to increase the pressure in order to make up for the pressure lost across the blockage. Over time, this could degrade the heart and lead to failure.

4.3.4. Collapsing Steady Results

4.3.4.1. Strouhal Number

It is useful to understand how to collapse the results based on either the pipe or blockage properties. By calculating the Strouhal number shown below in Equation 4.6, which is a dimensionless parameter based on the relation between length scale and velocity of a flow, this can be achieved. A Strouhal number of interest is .21. This is because in turbulent pipe flow, the Strouhal number has validated from wind tunnel experiments by Prandtl. It should be noted
that in this study, the St was maximum at this value for blockages in piping, similar to blockages in arteries.

\[ St = \frac{f_l}{U} \quad (4.6) \]

To show the effect of using St to collapse the data, which will be based on the blockage properties, it is important to note that this molds Equation 4.6 into the following equation

\[ St_Db = \frac{f_{Db}}{U_b} \quad (4.7) \]

![Figure 4.17: Collapsing Blockages Using StDb](image)

By utilizing Equation 4.7, this helps collapse all the blockages but the 96% as shown in Figure 4.17. The dashed line in the $St_{Db}$ figure is for a St of .21, which appears to approximate the collapsing of the blockages. It can be clearly seen from the frames of the flow visualization in Figure 4.18 that distinct differences in the fluid dynamic properties are evident from lower blockages (in this study up to 65%) to the largest blockage (96%). It was determined since this higher blockage acts the most like a jet, that perhaps the size of effective blockage, which is given by the following equation is applicable

\[ D_e = \sqrt{\frac{4A_e}{\pi}} \quad (4.8) \]
Where $A_e$ is the effective area which is given by

$$A_e = \frac{\pi}{4} (D^2 - D_b^2)$$ (4.9)

By using Equation 4.8 as the length scale in Equation 4.7, the 96% does indeed collapse with the rest of the blockages as shown in Figure 4.19. This confirms the suspicion that for patients with severe CAD, different flow properties can occur in their blood flow.

![Figure 4.18: Snapshots of 65% and 96% Blockages](image)

![Figure 4.19: Collapsing Blockages Based on Effective Blockage for the 96% Blockage](image)

Interestingly enough, study by Cassanova\textsuperscript{41} shown in Figure 4.20 compares reasonably well with not only the FFT spectra in Figure 4.17. The spectra in the Cassanova study seem to have peaks around 5 – 20 Hz, based on the blockage, then roll off after the peak to the sound...
floor, which is exactly what is occurring in Figure 4.17. The FFT spectra in Figure 4.17 shows that as the blockages increase, the peak frequency in the energy spectra also increases. In the Cassanova study, the 50% stenosis has a peak around 5-7 Hz, while the 75% stenosis yields a blockage of around 10-20 Hz.

![Figure 4.20: Steady Flow Energy Spectra for Multiple Blockages](image)

4.3.4.2. Similar Flow Properties

Another way to collapse the data besides using a St normalization is to look at flows with similar flow properties such as Re and volumetric flow rates. The two tables shown below for the four pressure heads and four blockages illustrate the similarities in flow properties seen during the experiments. For the Re seen in Table 4.1, there are four sets of cases that have similar Re. These cases are 4 in 30% & 3 in 0%, 3 in 30% & 2 in 0%, 4 in 65% & 1 in 30%, and 4 in 96% & 1 in 65%. The three cases that have similar volumetric flow rates as detailed in Table 4.2 are 4 in 30% & 2 in 0%, 2 in 30% & 1 in 0%, and 4 in 65% & 1 in 30%. It is important to note that the final case described has both similar Re and volumetric flow rate. It is very important to understand that the cases with similar volumetric flow rate will have the same pressure
difference across the blockage. Equation 4.3 shows that the volumetric flow rate is a function of the pressure difference and this shows that both parameters are linked together. Therefore these flows with similar flow rate should be similar since they have similar pressure drop across the blockage.

<table>
<thead>
<tr>
<th>Reynolds Number for Various Pressure Heads and Blockages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head</strong></td>
</tr>
<tr>
<td>4 in</td>
</tr>
<tr>
<td>3 in</td>
</tr>
<tr>
<td>2 in</td>
</tr>
<tr>
<td>1 in</td>
</tr>
</tbody>
</table>

**Table 4.1: Re Number Test Matrix**

<table>
<thead>
<tr>
<th>Volumetric Rate (L/s) for Various Pressure Heads and Blockages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head</strong></td>
</tr>
<tr>
<td>4 in</td>
</tr>
<tr>
<td>3 in</td>
</tr>
<tr>
<td>2 in</td>
</tr>
<tr>
<td>1 in</td>
</tr>
</tbody>
</table>

**Table 4.2: Volumetric Flow Rate Test Matrix**

4.3.4.2.1. **Similar Reynolds Number**

There are three cases that only have similar Re and they are shown below in Figure 4.21 through Figure 4.23. These cases have dynamic similarity which means that the ratio of the inertial forces and the viscous forces of each case are similar. It does not necessarily mean that the volume flowing through the test section for a given amount of time is the same. The first case, which is a four inch pressure head at 30% and three inch pressure head at 0% blockage
yields a low frequency amplitude similarity until around 20 Hz where the becomes an amplitude difference of approximately 20 dB.

The next case being presented is three inches of pressure head at 30% blockage and two inches of pressure head at 0% blockage. Similar to the previous case for similar Re, the pressure amplitude deviates 20 dB at around 20 Hz, but only for about 20 Hz as compared to 100 Hz as seen in Figure 4.26. So far, only the 30% and 0% blockages have been looked at. Next, the 96% and 65% blockage will be examined, which will lead to greater insight on how similar flow properties such as Re are affected by blockage since the 0% and 30% cases are nearly identical, as seen previously in Figure 4.15.

![Figure 4.21: 30% 4 in and 0% 3 in Re Comparison](image)
Figure 4.22: 30% 3 in and 0% 2 in Re Comparison

The final case that involves only flows with similar Re is presented in Figure 4.23 shown below. The effect of dynamic similarity can be shown most distinctly in the steady flow case. Not only do both blockages show similar lower frequency amplitudes, but the deviation that occurs around 20 Hz is only about 10 dB and by 30 Hz and on, the flows exhibit the same energy spectra. This helps confirm that flows with similar Re can be used to collapse blockages and pressure heads. This also means that for patients with CAD, an issue with being able to determine whether or a patient has a higher blockage may be difficult. This is because as the blockage size increases, so does the velocity passing through the blockage.
These properties are confirmed from visual inspection of Figure 4.24, since in the far aft (downstream) region, the flow is completely mixed in both the 65% and 96% blockages. This is because of the decreased jet size from these larger blockages, which will be examined in greater detail later.

**Figure 4.24: Flow Visualization Comparison of 1 in 65% & 4 in 96%**

4.3.4.2.2. **Similar Volumetric Flow Rate**

The two cases that have only similar flow rates are shown below in Figure 4.25 and Figure 4.26. With the flow rates being similar, these cases exhibit nearly identical constant flow rate during the experiment. This allows for the effect of pressure head and blockage to be seen
with a similar amount of volume moving through the system. The first case being examined, seen in Figure 4.25 is the four inch pressure head at 30% blockage and two inch pressure head at 0% blockage. There are a couple of interesting things to note from this case. The 30% blockage exhibits slightly higher pressure amplitude around 20 Hz. After this point, the values are nearly identical. This, along with similar results seen in Figure 4.26 for two inch pressure head at 30% blockage and one inch pressure head at 0% blockage, lead to the conclusion that for similar flow rates, steady flow pressure amplitudes are dependent on pressure head in lower frequencies.

Figure 4.25: 30% 4 in and 0% 2 in Flow Rate Comparison
4.3.4.2.3. Similar Reynolds Number and Volumetric Flow Rate

The four inch pressure head at 65% blockage and one inch head at 30% blockage comparison is unique in the fact that it has not only similar flow rate but similar Re as well. This means that these two cases essentially have the same flow properties; the same amount of volume is flowing through the test section for each test and each test also has the same ratio of the inertial forces to viscous forces, or dynamic similarity. These two facts lead the steady case comparison to be the most similar of any of the other cases. The pressure amplitudes are very similar throughout the whole spectra.
To make sure that this is something only unique to the case that has similar flow rate and Re, on the left portion of Figure 4.27 shows four inch pressure head for both the 65% and 30% blockages. While the amplitudes above 20 Hz are similar, there is a distinct offset of 10-20 dB in the lower frequency spectra. This helps confirm that this effect is indeed from similar flow rate and Re. Using cases with these similarities is the best way to collapse the blockages. Shown below in Figure 4.28 is a comparison of flows with similar flow rate and Re. It can be clearly seen that the flow not only behaves similarly as shown in Figure 4.27, but appears the same visually.

![Flow Visualization Comparison of 1 in 30% & 4 in 65%](image)

**Figure 4.28: Flow Visualization Comparison of 1 in 30% & 4 in 65%**

### 4.4. Effects of Pulsating Flow

#### 4.4.1. Differences Between Steady and Pulsing Flow

As mentioned previously in Section 2.9, the flow can be pulsed by commanding the Vexta PK266-02A stepper motor to spin for a prescribed number of steps as well as specifying the steps per second speed that the motor will rotate at. Specifically, the pulsating frequencies that were examined in this study are ½ Hz, 1 Hz, and 2 Hz pulsations. The effect of the pulsating flow can then be compared to steady flow in order to learn about the effects of a pulsating flow for the four different pressure heads and blockages being examined in the study. Shown below in Figure 4.29 is a pressure time trace history as well as a FFT spectrum comparing steady flow to 1
Hz pulsations for 65% blockage at the far aft (downstream) port. It is interesting to note that the maximum pressure reaches the steady pressure and this finding will be explained shortly.

![Figure 4.29: Pressure & Spectra Comparison for Steady & 1 Hz Flow for 65% Far Aft Port](image)

The differences between steady and pulsating flow, especially pertaining to the pressure time traces seen in Figure 4.29 can be attributed to the Womersley number. This dimensionless parameter relates the frequency of pulsation to the viscosity of the medium that the pulsations are going through and is given by the following equation:

\[ N_w = D \frac{\sqrt{\omega}}{v} \]  

(4.10)

Where \( \omega \) is \( 2\pi f \) and \( f \) is the frequency of the pulsating wave. For the aorta, this value is around 15 for normal blood flow\(^{56}\), this value decreases as the diameter reduces for arteries to around 4.4 for small arteries. The facility experiences \( N_w \) of approximately 14.2, 20.1, and 28.2 for pulsations of \( 1/2 \) Hz, 1 Hz, and 2 Hz, respectively.

The interesting thing about the values of \( N_w \) for the facility is that since they all are above a value of 10, the velocity will be 90 degrees out of phase with the pressure profile\(^ {56} \). This means that when the pressure is at its maxima, the velocity will be at the minima and vice versa. This property also shows while the diastolic window is the preferred time to analyze pressure data in
human subjects since the diastole is the region that has the least pressure in the cardiac cycle. While the differences between steady and pulsating flow are understood for the pressure time histories, it is also important to understand the differences between the two types of flow for the FFT spectra.

By examining the FFT spectra of Figure 4.29, the differences between steady and pulsating flow are quite obvious. There are strong peaks at the fundamental pulsation tone. For the case of the 1 Hz pulsations, these occur every 1 Hz until around 30 Hz. The initial tone is the highest while subsequent harmonics decrease in amplitude and appear to follow the trends of the steady flow. At around 50 Hz there is a broadband peak that is not there for the steady flow. This is something that occurs for all pressure heads and all blockages. In order to clearly show this phenomenon, two extremes of pressure head and blockage are seen in Figure 4.30. On the left, the 0% blockage is shown with one inch head.

This result shows that even in unblocked flow through a pipe, for this facility, these tones are present. The right side of Figure 4.30 shows four inch pressure head for 96% blockage. Since the same trends are seen for both extremes; a broadband tone at 25 Hz for ½ Hz pulsations with tonal peaks at 50, 75, and 100 Hz. For the 1 and 2 Hz pulsations, broadband peaks at 50 Hz are seen. Since this phenomenon occurs no matter what the blockage or velocity is through the system, it is clearly brought on from the facility rather than an effect from a parameter. It is unclear at the present, but presumed that a pipe mode of the facility which is excited by pressure waves reflecting off of the ends of the facility is the cause of this phenomenon.
To summarize the differences between steady and pulsating flow, it is clear that the pulsing frequency has the highest amplitude, in particular the fundamental pulsating tone as seen in many of the figures such as Figure 4.30. The harmonics of the pulsing frequency are present for all of the three pulsating frequencies that are being studied. The overall trend and roll off occurs around 20 Hz as in the steady flow and subharmonics can be seen for the 2 Hz pulsations as shown in Figure 4.31. These subharmonics for the 2 Hz pulsations occur every ½ Hz. It is possible that these subharmonics exist for ½ Hz and 2 Hz but because of the sampling parameters there is not enough resolution to resolve these subharmonics. 16,384 points are used in the FFT with a sampling frequency of 4,096 Hz. This means that the resolution is .25 Hz, which yields eight points per pulsation frequency for the 2 Hz case, but only 4 and 2 for the 1 Hz and ½ Hz cases, respectively. The reason that this number of points is being used is to obtain resolution for not only the pulsating frequencies, but for the higher frequency effects as well.
Figure 4.31: Frequency Comparison at Far Aft Port for 4 in 65%

Figure 4.32 is important because it not only shows that all three pulsating frequencies line up as the pressure rises (and subsequently velocity decreases as the hole emptying to the RWT is blocked), but that these cycles, when normalized, appear to be extremely similar. This explains why the 1 and 2 Hz pulsations appear to have almost identical effects, but the preference of the $\frac{1}{2}$ Hz pulsations to have the most broadband energy at 25 Hz (the other pulsating cases have a slight broadband peak at this frequency as well, but at a lower amplitude than the 50 Hz frequency) is not as clear. It is possible that the duty cycle of the pulsations plays a role, since as the length of time that the flow is effectively steady; this could have a profound effect on how the broadband energy is distributed. Finally, Figure 4.33 visually shows the comparison between steady and pulsating flow. It is interesting to note that for each case, there is a clear jet that is formed downstream (aft) of the blockage. It appears that as the pulsating frequency increases (top left is 0 Hz, top right is $\frac{1}{2}$ Hz, 1 Hz is bottom left, and 2 Hz is bottom right), the length of the jet decreases. This seems to be true for all blockages and will be investigated further later.
4.4.2. Effect of Fundamental Pulsating Tone

Before any additional analysis as is performed, it is essential to study the fundamental pressure amplitudes. This allows for an important result regarding the direction of the pressure wave compared to the flow direction. The fundamental pulsation amplitude was found by simply finding the amplitude at the specific pulsation frequency (1/2 Hz, 1 Hz, and 2 Hz) as seen below in Figure 4.34. The fundamental frequency is labeled and gives a visual representation of how these pressure amplitudes were obtained.
Figure 4.34: Fundamental Amplitude Determination for 4 in 96%

No matter what the frequency under consideration, there should be a pressure drop across the blockage. This would mean that amplitude of these frequencies should drop across the blockage as well. In order to examine whether this phenomenon occurs as expected the pressure amplitudes for the various frequencies at four inches of pressure head are plotted against the axial position along the blockage, as can be seen with the specific dimensions in the Appendix. Figure 4.35 through Figure 4.37 shown below detail these amplitudes for all four blockages, allowing for a detailed analysis of the four various pulsation frequencies and blockages that were examined.

Figure 4.35: Pressure Amplitude Blockage Comparison for \( \frac{1}{2} \) Hz Pulsations
There are a few things to note about the above figures, as not only the pulsation frequencies change, but the blockages as well. First off, for the most part, the fundamental pressure amplitudes follow a similar trend as they travel across the pipeline. For each individual blockage, the fundamental tone amplitude stays about the same no matter what the pulsation frequency. This makes sense because pressure wave that comes from the rotating wheel blocking the flow should be exactly the same strength, no matter what the amplitude. The only difference is the frequency in which the wave propagates down the pipe, which is why the fundamental frequencies occur at the particular pulsation frequency that the experiment was conducted at.
4.4.2.1. Blockage and Pressure Head Effect on Fundamental Pulsating Tone

It is clear from Figure 4.35 through Figure 4.37 that as the blockage in the pipeline increases, there is more of a pressure amplitude rise across the blockage for both the fundamental and vortex shedding frequencies. This is contrary to what is expected, as there should be a pressure drop across the blockage. The pressure profile should appear something like Figure 4.10, where there is a slight rise before the orifice, followed by a region of pressure drop then partial pressure recovery. One thing that is important to note with this is that in Figure 4.10, the profile is showing the actual pressure and not the amplitudes of particular phenomenon in the flow. While the actual average pressure across the six ports will be looked into shortly, there is an explanation for why there is a pressure rise across the blockage, especially with an increase in blockage. The reason for this, which has been briefly mentioned previously, is due to the fact that the pressure wave from the pulsations is actually acting in the opposite direction of the flow. A diagram showing this occurring can be seen below in Figure 4.38.

![Flow and Pressure Wave Directions Relative to the Test Section](image_url)

**Figure 4.38: Flow and Pressure Wave Directions Relative to the Test Section**
For this to occur, the fundamental amplitude should actually be highest aft of the blockage with the pressure drop occurring through the blockage opposite of the flow, as shown above. If one examines the pressure profile relative to the direction of the pulsation pressure wave, the pressure drop across the blockage in that frame is interpreted as a pressure rise across the blockage relative to the flow direction.

What happens is that since the pressure pulsation wave is generated downstream (aft) of the blockage, the high energy pulsation wave propagates towards the upstream (fore) side. When the wave encounters a blockage, there is impedance that is caused by the blockage. Since the total wave energy is the sum of the energy that is allowed to pass through a medium and the energy of the wave reflected, most of the energy (for lower blockages) passes through the blockage, while some energy is reflected back towards the source. It is important to note that as the blockage size increases, so does the impedance and this will be confirmed later. This is an important result because this means as the stenosis increases in patients with CAD, the amount of pressure pulse reflected back to the source increases, which may have some harmful effects on the heart.

Experimental proof of this is shown below in Figure 4.39 where the all the aft positions have relatively the same amplitude for the fundamental tone. The change occurs at the various fore positions, where there is a small, but clear pressure drop for the three smaller blockages, with a distinct pressure drop increasing as the pulsation frequency decreases. In order to calculate these values, the amplitudes of close fore (upstream) and close aft (downstream) were compared as seen in Figure 4.34. It also shows visually how there is a distinct change fore and aft of the blockage from the significant 96% blockage. This change visually will be shown in the fundamental pressure amplitudes shown below. The values of these pressure drops can be confirmed by looking at Figure 4.40. It can also be seen from this figure that similar to steady
flow, as the pressure head increases, so does the pressure rise across the blockage (for steady flow it was the pressure drop across the blockage). This is also confirmed by examining the effect of pressure head directly for all pulsation frequencies seen in Figure 4.41. It is shown that regardless of pulsation frequency, there is a trend that the 96% blockage has a significant pressure rise while the other blockages do not have significant pressure rises. Although, as was seen in pressure drop for steady flow in Figure 4.15, as the pressure head increases, so does the pressure rise.

Figure 4.39: Blockage Effects for All 6 Ports at Various Pulsation Frequencies
Figure 4.40: Pressure Rise Across Blockage at Various Pressure Heads

Figure 4.41: Head Comparison of Pressure Rise Across Blockage for Pulsation Frequencies
Two things can be concluded from the results above. First, it shows that the pressure wave travels in the opposite direction of the flow which causes the direction pressure drop of the pressure amplitudes to occur going from aft of the blockage to fore of the blockage with respect to the flow direction. This means that the facility in its current state acts more like a vein than an artery, simulating the flow traveling into the heart instead of out of the heart. Later, there will be a discussion on how to flip the facility in order for the pressure and flow directions to match like they do in arteries. The second thing these results confirm is that the blockage does play a significant role is pressure drop across the blockage as expect and that as the pulsation frequency increases, for the most part, the pressure drop across the blockage decreases. While this can be related back to the human body, since this would mean part of the wave energy is reflected back to the heart, it should be noted that since the arteries and the aorta have curvature to them, these effects, which were shown to be small to begin with, will be reduced even greater so their effect will be minimized.

**4.4.2.2. Similar Flow Effects**

Another way to verify that for pulsating flow the pressure head is the only significant factor in collapsing the blockages, since the fundamental pulsing amplitude for the downstream (aft) ports, in particularly the far downstream port, is the same regardless of pulsation frequency. For steady flow, it was shown that the case with similar Re and volumetric flow rate, as confirmed in Table 4.1 and Table 4.2, was the best way to collapse different blockages. So in order to show that this is not the case with the pulsating flow, each pulsating frequency is compared in a similar fashion as the steady flow.

The 4 in 65% & 1 in 30% case, which has the similar flow properties, is compared with the 4 in 65% & 4 in 30%. The spectral results of this study can be seen in Figure 4.42 through
Figure 4.44, while these properties can be confirmed visually in Figure 4.45 through Figure 4.47. While the cases with similar flow properties have distinct fundamental tone and harmonic amplitude differences in the spectra, which can be seen in the flow visualization by smooth vortices that are formed downstream of the blockage for the 1 in head (bottom) as compared to the intense mixing and unrecognizable vortices in the 4 in head, the cases with similar head have similar amplitudes in the spectra. This is seen in the flow visualization because at the far downstream ports, although there is slightly more mixing for the medium blockage (top left), similar intensity flow seems to be passing by the medium and small blockage (top right). These results confirm that for pulsating flow, head is the most important factor in the flow.
Figure 4.44: Head Comparison for Similar Flow Properties at 2 Hz for the Far Aft Port

Figure 4.45: Flow Visualization Comparison for 1/2 Hz for Similar Flow Properties

Figure 4.46: Flow Visualization Comparison for 1 Hz for Similar Flow Properties
Figure 4.47: Flow Visualization Comparison for 2 Hz for Similar Flow Properties

4.4.3. Jet Length Comparisons

As was mentioned previously, while inspecting the flow visualization, it appeared that a jet was formed downstream (aft) of the blockage. This prompted an investigation of the subject in order to compare to previous results. As flow goes through a blockage, such as an orifice plate, the flow constricts into a jet and it increases out of the blockage due to the change in area it experiences according to Bernoulli’s Equation (2.1). A study by Roach and Stockley\textsuperscript{43} investigate the effects that the geometry (amount of blockage) influences the flow after the stenosis. Shown below in Figure 4.48 is a schematic of a jet forming through a blockage in a pipe. Zone A is the region that the jet protrudes out from the end of the blockage, while Zone B is the area after Zone A which still exhibits turbulent flow. The entire test section in the Roach and Stockley experiment since a $300 < \text{Re} < 700$ was utilized. It is important to note that since the Re in this facility are only turbulent, it is proposed that the jet length is the only zone that is of interest since the flow never becomes or was laminar to begin with.
Although all the experiments conducted with the facility have turbulent flow, as seen in Table 2.4, the basic result that was found in the Roach and Stockley study was that as the amount of blockage increases, the length of the jet decreases\textsuperscript{43}. Results from that study can be seen in Figure 4.50 where they are compared to the experimental results obtained from the facility. The values were obtained from video frames of the flow visualization. Since the camera that was used to take the videos shoots at 25 frames per second (FPS), a MATLAB code was written to examine every fifth frame, or every .2 seconds. The pixels were converted to inches since the geometry of the test section is known. The jet length was then determined by examining the figures. A sample figure, used to determine the jet length, is seen in Figure 4.49. By examining the figure, you can see that the jet travels approximately two inches before it starts dispersing into the rest of the tube. There is a clear recirculation zone seen above and below the jet, where there is no dye due to the jet flow.
Figure 4.50 shows the most comparable results from the Roach study with steady flow at four inch pressure head experimental results. The reason that the four inch head is shown even though it yields the highest Re (even the one inch head cases are at minimum 5 times higher than the highest Re in the Roach study), they yield results most comparable to the Roach study. An important note that should be considered throughout these results is the fact that if a case had a jet length that exceeded the range of the camera (an X/D value of 4.25 inches), then the data will not be shown because the actual length is not known and actually larger because of the window size of the flow visualization (see Figure 4.49). Another point to note is that the L/D normalization comparing the axial length of the blockage to the diameter of the pipe is .625 for the experiments, compared to the .105 and 2.1 values investigated by Roach\textsuperscript{43}.  

**Figure 4.49: Sample Frame Used to Calculate Jet Length**
It is almost important to know that when comparing the results shown in Figure 4.50 what the significance of each line is in the Roach figures. The bottom line indicates the length of the jet, which is Zone A of Figure 4.48, while the top line corresponds to the length of the turbulence region in the flow, which is indicated by Zone B in the same figure\textsuperscript{43}. Although a trend line for the experimental values would be at a lower slope than in the Roach results, there are two important things to note. First, as mentioned previously, the highest value of $X/D$ is in fact larger, but unknown, due to the length of the visualization window. Also, as shown in Figure 4.51, the Roach study found that as the Re increased, the $X/D$ distance decreased. Even though this should mean that there should be no jet length for the high Re seen in the facility, it is plausible that the jet length would go away as the flow transitions to turbulent flow. Once the flow becomes turbulent, it is possible that the jet length comes back and will decrease as the Re increases just as it did in the laminar region. This makes sense because there are clearly distinct jets present in the flow visualization. While this helps explains the lower values there is also another difference in the results, this dealing with the shape of the curve.
While examining Figure 4.50, it should be seen that the trend, especially considering the value at $d/D = 1$ should be much higher, is not a straight line as seen in the lower lines of the Roach study, which indicate the length of the jet. While most of the deviation could be explained in experimental error by looking at the error bars in the Roach study, there is also another distinct possibility. The Roach study only looked at $Re$ from 300 to 700\textsuperscript{43}, while all of the values obtained from the experiments are turbulent and have a $Re$ of at least 3500 (and over 7000 for the four inch head). This means that it is possible for the trend of the experimental values to appear more like the upper line, which represents the turbulent length, or Zone B of Figure 4.48. This would also make sense because the $L/D$ from the facility is 0.625 which is in between the two $L/D$ values used in the Roach study. While the short blockage length has a decrease in turbulent length, the longer one has a slight increase followed by a sharp increase as the blockage size relative to the pipe diameter decreases, which is similar to how the experimental results behave.

![Figure 4.51: Reynolds Number Comparison\textsuperscript{43}](image)

Since pulsating flow experiments were conducted, in addition to steady flow, which was only done in the study by Roach, these results were examined to study the effect of pulsating frequency on jet length. Shown below in Figure 4.52 is a compilation of these results. Generally
speaking, as the pulsation frequency increases, the length of the jet decreases. For the most part, the two Hz pulsations yield significantly shorter jets than their counterparts. This is due to the fact that the jet cannot travel as far during a short pulsation, only allowing the jet to travel for $\frac{1}{2}$ of a second before the next pressure wave stops the flow. This time between pulses is the main reason that the length of the jet decreases as pulsation frequency increases. For the unblocked flow, it was very difficult to determine how far the jet travels (since in 0% blockage it is not really a jet, just mainly pipe flow). There is a slight effect of head, which can be seen by examining Figure 4.52 or in the steady flow head comparison shown in Figure 4.53. Both show that for the most part, regardless of blockage, increased head slightly increases jet length.

Figure 4.52: Frequency Comparison of Normalized Distance vs. Blockage
Figure 4.53: Head Comparison for Steady Flow
5. Conclusions and Future Work

The design, implementation, and results from the experimental facility have yielded not only valuable insights into flow through a blockage in a pipe, but show much promise in the future for a more complete understanding and modeling of a stenosis in an artery. The designed facility simulates flow through arterial blockages using a 1” pipe, which is similar to the diameter of the aorta. The impact of three different blockages, including unblocked pipe flow, can be studied at four different velocities (pressure heads). The smallest blockage (30%), simulates a blockage in which turbulence can just start to be detected in the flow. The 65% blockage simulates a medium sized blockage, where although the heart works harder to overcome the pressure drop across the blockage, which is experimentally shown in Figure 4.14, it does not necessarily have to result in heart failure. The largest stenosis is simulated by a 96% blockage which larger than 75%, which requires angioplasty to insert a stent in order to reduced the degree of stenosis in the patient. Since it is also above 95%, it is interesting to study because many studies found a blockage higher than that to be difficult to diagnose in the human subject studies.

The velocities range from approximately 70 cm/s, which is close to the maximum velocity in normal coronary arteries (60 cm/s), up to 141 cm/s which is close to the maximum observed velocity in a patient with severe arterial stenosis (150 cm/s). The facility also successfully simulates steady flow, which is similar to the analysis that was performed on human subjects by examining the diastolic window, as well as pulsating flow. The facility simulates three pulsating frequencies, ½ Hz, 1 Hz, and 2 Hz. The ½ Hz pulsations correspond to 30 BPM which is the resting heart rate of elite athletes and other presumably healthy people. 1 Hz pulsations simulate a heart rate of 60 BPM which is the average resting heart rate. Finally, 2 Hz pulsations simulate 120 BPM which is a heart rate of someone that is under stress and more likely to have a heart
attack if the blockages in their arteries clot up. These pulsating frequencies are simulated by a rotating wheel that is controlled by a computer.

The facility allows for the study of flow through blockages in the pipe line by utilizing surface pressure measurements, as well as flow visualization. Some of the main results from these studies are that the pressure drop across the blockage increases not only with pressure head (velocity), but blockage size as well as was shown in Figure 4.14 and Figure 4.15. This is an important result because as the size of the patients’ stenosis (blockage) increases, the velocity of the blood flow through the blockage increases as well. Since both of these effects increase the pressure drop across the blockage, they compound on each other creating even more of a pressure drop. This means that the higher the blockage gets the more chance of heart attack or failure because of this effect. This effect also helps explain another important result from the experimental studies; the fact that the 96% blockage has different fluid flow dynamic properties than the smaller blockages. This was seen visually in Figure 4.18 as well as shown in the study of collapsing the blockages at the far downstream (aft) port as seen in Figure 4.17. While the smaller blockages could be collapsed by a St based on the blockage properties, the diameter that is used to collapse the 96% blockage is the effective blockage size as described in Equation 4.8.

Another important result from the studies conducted on the facility is that the pulsation frequency is the most dominant feature in the dynamic pressure spectrum. It was quickly discovered that because the pressure pulsation wave is generated downstream of the blockage in the RWT, the fundamental pulsation amplitude actually rises across the blockage going from upstream to downstream in the flow direction as detailed in Figure 4.35 through Figure 4.37. The reason for this is shown visually in Figure 4.38, which shows the effect that the blockage has on the pressure wave. As the full energy of the pressure wave encounters a blockage, most of the
energy in the smaller blockages passes through to the upstream side of the test section. However, some of the wave energy, or most of the wave energy in the case of the 96% blockage, gets reflected back towards the RWT. Even for the smaller blockages the trend remains the same; as the blockage size increases, so does the impedance at the blockage, which results in a larger reflection of the pressure wave. This subsequently decreases the fundamental amplitude across the blockage from downstream to upstream.

This result is important because it shows that as a person progresses in their development of CAD, not only does the heart have to work harder because the pressure is increasingly dropping across the blockage due to the increase and blockage and flow velocity, but more of the pressure wave is being reflected towards the heart. Although it can only be speculated from this study, there could be negative effects on the heart from having the pressure wave being reflected back towards it. While the results obtained from the study of the experimental facility have shown insights into what happens in patients with CAD, there can be improvements made to the facility. The perspective developments improve the results and allow for more in depth studies on blood flow through blockages in arteries. These recommendations are detailed in the next few sections.

5.1. Test Section Redesign

As discussed in Section 4.2, while results that verified the feasibility to measure pressure changes during steady and pulsating flow through a pipe with pressure transducers, there was an issue in trying to get microphone measurements to achieve the same results. It was proposed that the low noise from the pipe flow coupled with the transmission loss through the acrylic tube was the main factor in the microphone results. In order to improve the ability to capture the acoustic signature through a microphone array, there are a couple of improvements that should be made from the original Vocal Consortium Lab’s design. First, the test section should be designed that
even if pressure transducers will be utilized in the acquisition of pressure, that the thickness of the acrylic tube should be significantly less than the $\frac{1}{2}''$ that the test section currently is. This will reduce the effect of the transmission loss through the pipes.

Another improvement that could be made is the inclusion of pressure relief holes just aft of the blockage. This is important because as seen in many of the flow visualization frames, especially ones with the medium or large blockage such as in Figure 4.18, there are some effects of cavitation that cannot be accounted for. This is because of the increased stagnation region for these blockages due to the smaller jet size. Since the air is forced out of the tube either by the flow of water pushing it out or by opening one of the port holes to bleed the air out, air trapped just aft of the blockage before the close aft pressure port cannot be relieved. While this does not affect the results any more than experimental error might, as shown previously in Figure 4.3, the quality of the flow visualization is vastly improved with the removal of any and all cavitation from the test section.

Once the pressure wave is being generated upstream of the blockage (which will be detailed shortly), a great improvement to the facility would to be add bifurcation to the test section. Since blockages are found primarily in arteries and not the aorta, it begs to reason that the flow separation caused from bifurcating arteries is not only a reason that blockages form in arteries but causes the noise seen in many of the subject studies such as the spectra seen previously in Figure 1.10.

Additionally, a significant improvement could be made if at least part, if not all, of the test section was made with Kevlar® panels or cloth. The reason that this would improve the test section is due to the fact that Kevlar® allows for little to no transmission loss through the surface
while allowing flow to pass by it unobstructed. This technique was investigated by Jaeger\textsuperscript{46} with very favorable results as seen in Figure 5.1, with a thin amount of Kevlar\textsuperscript{®} preventing significant noise attenuation up to 25 kHz, which is more than enough for the spectra experienced in this facility. Utilizing Kevlar\textsuperscript{®} for this application was successfully integrated into a wind tunnel at Virginia Tech\textsuperscript{47}. If the entire test section is not made out of Kevlar\textsuperscript{®} there is a possibility of issues stemming from integration the Kevlar\textsuperscript{®} panel into the rest of the test section. Also, there could be issues with the interaction with water, since the Virginia Tech test panels were only used in air. However, utilizing Kevlar\textsuperscript{®} or some material that helps attenuate noise loss through the material will play a vital role in producing the most accurate results possible.

![Figure 5.1: Kevlar Noise Attenuation\textsuperscript{46}](image)

Finally, when designing a new test section, specific properties of the test section and the water flowing through it could be modified for more ideal simulations of blood flow through a stenosed artery. First, the Re could be matched more accurately to those in main arteries if a couple of steps were taken. Since the viscosity of blood is four times higher than water\textsuperscript{16}, the Re could be reduced significantly if corn starch is added to the water, since that increases the viscosity of water\textsuperscript{48}. If corn starch is utilized to increase viscosity, it is recommended that a pump be purchased to recalculate the flow in order to conserve the amount of corn starch that is needed.
to conduct experiments. Some pumps that were initially investigated in the original design can be seen in the Appendix. Something to consider when adding corn starch to water is that while corn starch does create a non-Newtonian fluid, it is a shear thickening fluid, meaning that the apparent viscosity increases with stress. This is different than the properties of blood, which is a shear thinning fluid, meaning that the apparent viscosity decreases with stress.

Another method of reducing the Re is to decrease the diameter of the test section, which is something that can be considering if a new test section is being designed. While the current test section simulates the Aorta, the diameter of a main artery is around .8 cm \(^{19}\). Even if the new pipe diameter is only \(\frac{1}{2}"\) diameter, it will cut the Re in half. While this will reduced the diameter, great consideration should be made because reducing the pipe diameter will reduce the boundary layer and could change the flow properties even more significantly than reducing the Re. Finally, if pressure transducers will be used to capture wall pressure measurements, there should be more port holes along the test section, especially at farther fore and aft ports as there are currently, to allow for a more accurate pressure profile to be compared to the theoretical pressure profile across an orifice plate as seen in Figure 4.10.

Another area of the test section that can be improved is study the effect of different blockage shapes, besides the concentric blockages that are currently only being studied. In fact, it has been shown in previous studies\(^ {59}\) that even just changing the blockage shape from concentric to eccentric changes the flow through a bifurcating artery and this can be seen in Figure 5.2. Additionally, blockages that have various radii of curvature, such as the ones that were computationally modeled by Ghalichi\(^ {54}\), would be of great value to study. Not only for their direct comparison to the study, but for the fact that there are secondary flows that are formed by these blockages, as well as stream-wise vortices\(^ {54}\). By modeling these stenoses more accurately,
there could be not only a greater understanding of what happens in actual blockages in human arteries, but unique pressure spectra could occur for the various blockages.

Figure 5.2: Shear Stress Magnitude Comparison for Differently Shaped Blockages

5.2. Changing Pulsating Flow Properties

5.2.1. Pulsating Pressure Wave Direction

While the lack of microphone measurements was a significant problem ran into during the implementation of the facility, it became clear that in order to properly simulate the condition of pulsating flow across a blockage, a couple of changes need to be made. The first change that should be made is changing the direction of the pulsation pressure wave so that it is in the same direction as the flow. This was discussed previously and visually shown in Figure 4.38.

Currently, the facility is more accurately simulating pulsating flow through a vein instead of an artery as intended. It resembles a vein rather an artery because in a vein, the blood is flowing to the heart but is stopped temporarily the venous valves closing, which is simulated by the
pressure wave traveling in the opposite direction of the flow. The pressure wave not in the same
direction as the flow led to an incorrect rise of pressure amplitude across the blockage, from BT
to HT as seen in Figure 4.40. Although correct due to the direction of the pulsation pressure
wave, changing the direction will help yield more accurate results for the simulation of
blockages in arteries. Thought was put into coming up with a couple of designs that would allow
the pressure wave to travel in the same direction as the flow and these proposed ideas will be
presented below. It should be noted that at any time if there is any question of what parts are
being discussed, to look up the specific drawing in the Appendix.

5.2.1.1. Modifying RWT

The first proposed idea involves modifying the RWT to raise the level that it currently is
at from seven to 11 inches. This will allow the flow of water to change from BT to RWT to
RWT to BT, making the flow and pressure wave directions the same. The BT would drain into
the RT during the experiments and make the baffles on the BT as well as the entire HT obsolete.
This is because the level of the RWT would be kept constant from flow entering the RWT from a
hose, as well as any excess water being drained by the pipe that currently keeps the RWT at
seven inches.

In order to change the facility using this idea, the Plexiglas stepper motor support panels
that go on either side of the RWT must be flipped over so that the slots machined for the stepper
motor support can be raised four inches to accommodate for the increase in height. The panels
will need to be sanded correctly so that they can be placed in the flipped configuration on the
opposite side that they were originally intended for. The ½” drainage pipe that allows flow to go
from the RWT to the RT during the test if excess head builds up must be increased by four
inches as well. This can be achieved by using a ½” PVC union and attaching it to the current
setup. This will allow for an easy change between setups since the excess four inch pipe will be attached to the other side of the union and only put together when needed to flip the facility.

Another part of the RWT that needs to be modified in order to achieve this new setup is to raise the one inch piping that transports the flow through the aft side of the test section into the RWT four inches to accommodate for the new height. A similar technique must be implemented as before with the ½” piping. However, the additional step of creating an additional base that houses the rotating wheel and the end of the one inch pipe. This additional base needs to be fabricated since the addition of the union will add to the diameter of the original one inch piping. While this is not an issue when the setup has been modified, if for any reason the facility would need to go back to its original configuration, the new base would all for the larger diameter of the one inch pipe with the end of the union attached to it to fit on the base.

The benefit of utilizing this method over the other proposed methods is that it changes the least amount of things from one setup to another and can be fabricated and setup in the least amount of time. Some drawbacks of the system are that some of the parts of the old setup (baffles and HT) would be obsolete, as well as the need to secure a hose to the RWT without damaging the stepper motor. Additionally, the drainage valve that drains the BT into the RT would probably have to be marked up similar to the valve connecting the HT to the BT in order to keep the BT to the appropriate height for experiments.

5.2.1.2. Placing HT on RWT

The second proposed setup is a slight modification from the first setup. After completing the fabrication and implementation for the first proposed redesign, changes would be made to the RWT to allow the HT to be placed onto the RWT. A ¾” bulkhead and unthreaded ball valve
would need to be purchased that would allow for a connection between the HT and RWT similar to the connection for the HT to the BT in the current setup. In order to help prevent the sloshing of the water entering the RWT from the BT, an upper slot could be machined into the stepper motor support side panels that would accommodate an upper baffle. While it would not have the same effectiveness as the three baffles on the BT, it would still help reduce sloshing and allow clean flow into the test section. After the bulkhead was put in at eight inches on the far aft side of the RWT, the lid that is currently on top of the BT can be placed on the RWT so that the HT can rest upon it. Once the connections are secured, the head can be controlled by the flow from the HT to the RWT instead of simply a hose.

Some benefits of this design compared to the first design is that with the baffle, it should be easier to prevent the stepper motor from getting wet. Great care will need to be taken to make sure that the RWT does not get overfilled much past the level of the ½” drain from the RWT to the RT to prevent ruining the stepper motor. Using the HT to control the head should be much easier than using the hose because the valve connecting the HT to the RWT can be adjusted with much less effort. This setup also uses the HT instead of wasting it as the first redesign does. Some of the cons of this setup are that it will take slightly longer in the machine shop to manufacture the slots and the additional baffle, as well as the extra materials needed to fabricate all of the additional parts that this setup requires. The setup also requires more preparation and setup time to switch pressure wave directions.

5.2.1.3. Redesign of BT

In the third and final proposed pressure wave direction redesign, an additional tank and cover are purchased in order to make a modified BT that will change the direction of the pressure wave, as well as other improvements. The basic idea of this proposed setup is to make another
RWT setup in another tank and use the newly designed tank in place of the BT. Items besides the extra tank and cover that would need to be purchased or acquired are an additional one inch bulkhead, one inch piping and elbows, Plexiglas for stepper motor support side panels and the stepper motor holder itself, aluminum rod for the shaft, polypropylene for the rotating wheel housing, an acrylic disk to act as the rotating wheel, and an additional stepper motor. The bulkheads for the connection to the HT and the drain to the RT could be purchased or used from the BT as seen fit.

Obviously, this proposed setup requires a lot more money for the purchase of the additional items, much more time in the machine shop, as well as much more time to implement the system. Also, even if the additional slots for one upper baffle before the rotating wheel is implemented, it is not the most ideal setup to reduce sloshing from the HT to the new RWT. However, there are many significant advantages from choosing this idea to change the direction of the pressure wave. Once fabricated and implemented, it will be very easy to switch between the old and new setups. With the new setup the ability to pulse the flow in either direction (to simulate an artery with the new RWT and simulate a vein with the original RWT). Both rotating wheels could be used at the same time as well which leaves the possibilities to study different variations of pulsating flow through a blockage almost endless. This is also the only setup that changes nothing with the original RWT. While taking the most significant time and monetary cost out of the proposed ideas, the benefits from the fabrication of an additional RWT greatly outweigh the benefits of the other proposals and it is recommended that this idea be implemented.

5.2.2. Modifying Pulsation Cycles of Rotating Wheel

Another change to the current facility that can lead to simulating the flow through the blockage more accurately to actual blood flow through stenoses in arteries is to try and recreate
the pressure time traces of heart beats more accurately. In its current setup, the rotating wheel simulates one of the two heart sounds by pulsing at four equal intervals as the wheel rotates. While this creates pressure time traces as seen before in Figure 4.29, ideally, pressure traces such as Figure 1.9 and Figure 5.3 will be more accurately matched. This will allow for the most similar type of flow going through the blockage to be analyzed.

Some changes that will need to be investigated greater in order to achieve a more accurate pressure trace are to change the spacing and shape of the holes in the rotating wheel. Changing the spacing to leave more time in between pulses while putting two holes close to each other could simulate the S1 and S2 heart sounds as shown in Figure 1.9. Also, it is possible the changing the shape of the holes from circles to ellipses, or perhaps other shapes could help mold the pressure time traces to become more realistic and this will help simulate pulsating flow through a blockage in an artery more accurately.

![Figure 5.3: Pulmonary Artery Pressure Time Trace](image)

5.2.3. Mounting the Facility

Currently, the facility is mounted on an iron cart that was in the lab, as shown in Figure 2.1. While the current placement of the facility in the Oil Rig room was fine for the duration of the experiments, due to upcoming projects that will be taking place in the room, the facility will have to be moved; most likely to the Large Scale Turbine Cascade Facility room. It is recommended
that the move to the different room would be a good time to look into changing how the facility is mounted together.

A major improvement that could be made is the addition of a flow meter that could be controlled from the HT to the BT (or new RWT if the flow direction is inline with the pressure wave). This would ensure constant head being held during the entire experiment, which is a slight issue currently (the BT just must be constantly monitored to make sure the flow is not coming in too fast or too slow, changing the head height). In order to implement this change, the HT must be raised above the BT / new RWT in order to allow enough length in order to place a flow meter into the system. This means that the HT will need to be rested on a higher platform, be it a shelf or some other method.

5.3. Improving Measurement Techniques

While improving the test section and the facility will have great effects on improving the results, another area that must not be passed over is the improvement of the measurement techniques. Currently, the experiments are conducting with whatever pressure transducers, etc… can be found in the Gas Dynamics and Propulsion laboratory at UC. If the quality of the pressure transducers and certain techniques are improved, such as the microphone measurement and flow visualization, the quality of the results will improve even more and many more additional studies could be conducted. Also, in order to get quantitative flow measurements, a hotwire or previously discussed PIV should be utilized to obtain velocities at various points upstream and downstream of the blockage.
5.3.1. Pressure Transducers

The pressure transducer being utilized for the experiments is a single Validyne DP-15 pressure differential transducer. As shown in previous results such as Figure 4.29, there is a distinct roll off after about 20-30 Hz to the sound floor. High-Pass filters were utilized in hopes of amplifying the higher frequency spectra with no success as shown in Section 4.1.3. As concluded in the filter analysis, the need for a better pressure transducer that would be able to pick up the higher frequency response of the FFT spectra should be investigated.

Ideally, the transducer would be a wet-wet pressure differential transducer that can be mounted flush into the test section and can handle upwards of .2 PSI, corresponding to 5.5 inches of water, which is about 1.5 inches more of pressure head that it should be exposed too. This will improve results because the less distance between the wall and pressure transducer, the better the results are, as shown previously in Figure 4.1. The high frequency response of the transducer will be the most important factor, as that is the main issue with the current transducer. Finally, if at all possible, multiple transducers should be purchased that would allow for multiple ports to take measurements simultaneously will not only improved repeatability, but significantly reduce the number of experiments that need to be conducted. This will allow for more thorough pressure head, pulsation frequency, and blockage studies to be conducted.

5.3.2. Microphone Measurement Improvement

As discussed and shown in Section 3.2.5, only a single microphone was placed directly over the close aft port in hopes of obtaining an acoustic signature different that the background. However, due to problems discussed in Section 4.2, the resulting spectra could not be distinguished between background and experimental tests, as shown in Figure 4.9. While improvements in the test section should greatly improve the ability to take the acoustic signature
of flow traveling across the blockage, in order to more accurately pinpoint blockage severity and location, an array of microphones should be implemented.

This will improve on previous medical studies\textsuperscript{8-12}, which only utilized one microphone placed near the subjects’ heart. A study by Rabinkin et al\textsuperscript{51} details the proper placement of a microphone array that yields the maximum ability to detect a noise source location. While a linear array of microphones placed along the test section should yield results that will help determine the source location (orifice) and hopefully severity of blockage, utilizes the techniques proposed by Rabinkin et al could yield even more accurate results, so it is recommended that the technique be implemented and compared to a simple linear microphone array.

\textbf{5.3.3. Flow Visualization Improvements}

While flow visualization in its current state was sufficient enough to compare the length of the jet coming from the blockage to previous studies\textsuperscript{43}, as well as determine the effects of blockage, pressure head, and pulsation frequency visually, improvements on the technique could lead to invaluable insights into the flow of water through a blockage. Some of these changes, such as having a pressure relief hole just aft of the blockage, have been addressed in the test section recommendations.

However, simple steps, such as using a high speed camera (which will be able to capture the vortices forming and shedding for all blockage), taking more care in setting up the flow visualization to ensure that the camera and test section are aligned perpendicularly to each other, and using a ruler in the videos to have a more accurate pixel conversion will allow for more precise locations of the center of the blockage and jet location. Also, if pressure port holes are slightly larger than the current $1/32^{nd}$ inch (just under .8 mm), a larger tube can be placed in them.
that can let flow out at multiple points vertically, allowing for multiple streamlines to be studied. Also, it is recommended that a study being conducted in the quality of flow visualization as the injection tube is placed closer to the orifice plate. This may prevent spreading of the dye until aft of the blockage, making some of the cases, especially ones with higher pressure head to have more clarity in that part of the test section.
References


Appendix
Appendix A: Drawings
## Appendix B: Additional Tables

### Centrifugal Pumps

<table>
<thead>
<tr>
<th>Company</th>
<th>Product</th>
<th>Flowrate (GPH)</th>
<th>Fittings</th>
<th>Price $</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cole-Palmer</td>
<td>EW-72021-23</td>
<td>Max of 28</td>
<td>1&quot;</td>
<td>$245</td>
<td></td>
</tr>
<tr>
<td>Dayton</td>
<td>AT 120</td>
<td>Min of 30</td>
<td>3/4&quot;</td>
<td>$218</td>
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<tr>
<td></td>
<td>2HNN2</td>
<td>Min of 20</td>
<td>1/2&quot; &amp; 1/4&quot;</td>
<td>$49.45</td>
<td></td>
</tr>
<tr>
<td>Little Giant</td>
<td>PES-70</td>
<td>Min of 25</td>
<td>3/8&quot; or 1/2&quot;</td>
<td>$30.70</td>
<td></td>
</tr>
</tbody>
</table>

Table B.1: Potential Pumps