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Hydraulic Average of Multiple Tap Sets to Improve Performance of Venturi Flowmeters With Upstream Disturbance

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HYDRAULIC AVERAGE OF MULTIPLE TAP SETS TO IMPROVE PERFORMANCE OF VENTURI FLOWMETERS WITH UPSTREAM DISTURBANCE

by

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ABSTRACT

HYDRAULIC AVERAGE OF MULTIPLE TAP SETS TO IMPROVE PERFORMANCE OF VENTURI FLOWMETERS WITH UPSTREAM DISTURBANCE

by

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In water distribution systems it has become increasingly important to accurately measure the flow rate. Venturi flowmeters have been used for many years to accurately measure the flow rate in pressurized piped systems. The simplicity and consistency of the Venturi flowmeter is why it has been used in many different applications. The ideal condition for a Venturi flowmeter to function properly is for a uniform flow profile to enter the flowmeter. This is achieved by installing sufficient straight pipe length that is the same diameter as the inlet of the flowmeter. Due to site installation constraints it may not be possible to install enough straight upstream pipe to establish a fully-developed uniform flow profile. For operational purposes, valves and other pipe-fittings are often

installed close to the inlet of the flowmeter which causes the flow profile to become distorted which may potentially lead to inaccurate measurements.

The pressure profile inside the flowmeter becomes distorted or non-uniform when a flow disturbance is present. A disturbed flow causes the differential pressure measurements at various locations in the meter to differ depending on the orientation of the tap set. Localized acceleration at the location of individual tap sets may lead to a high range of error in the measurement. To better understand the degree of uncertainty, multiple tap sets were used in this study to create a hydraulic average and simulated a more uniform pressure profile within the flowmeter. The uncertainty in the flow rate measurement was significantly decreased by the use of multiple tap sets to measure differential pressure when a flow disturbance is present upstream of a Venturi flowmeter.

(74 pages)

PUBLIC ABSTRACT

HYDRAULIC AVERAGE OF MULTIPLE TAP SETS TO IMPROVE PERFORMANCE OF VENTURI FLOWMETERS WITH UPSTREAM DISTURBANCE

Taylor B. Stauffer

Venturi flowmeters have been used to measure flow in piped systems for over 100 years (Finnemore & Franzini, 2006). There has been much research on the performance of Venturi flowmeters and for that reason they have become popular flowmeters used in various municipal and industrial applications. Venturi flowmeters can be calibrated in a laboratory setting to find their performance characteristics. In order for the flowmeter to achieve optimum performance, the flowmeter should be installed with sufficient length of straight pipe immediately upstream of the flowmeter. Often Venturi flowmeters that are not installed in ideal conditions produce errors and uncertainty is introduced to the flow measurement. This study used multiple tap sets on Venturi flowmeters in order to reduce error and uncertainty when a Venturi flowmeter is installed in non-ideal conditions. The multiple taps sets were used to measure an average of the hydraulic pressure within the flowmeter.

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I need to thank my wife Katie Stauffer for motivating me to complete my thesis research and to succeed in school for 4 years. It would not have been possible for me to achieve my goals without her by my side and for planning fun activities for when I was not studying.

Taylor B. Stauffer

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NOTATION

C_d = discharge coefficient

D_f = flowing diameter of meter inlet

d_f = flowing diameter of meter throat

g = dimensional conversion constant

Fa = thermal expansion coefficient

ΔP = pressure differential

Q = mass flow rate

Y = gas expansion factor

β = beta ration

ρ = density of fluid

$y+$ = wall y+ value

y = distance from boundary

ν = kinematic viscosity

υ_τ = shear velocity

τ_ω = wall shear stress

$P.E.$ = percent error

psi = pounds per square inch

ft/s = feet per second

Ci = discharge coefficient for *i* tap set

iD = distance upstream of meter measured in *i* diameters

CHAPTER I

INTRODUCTION

Venturi Flowmeter Overview

Venturi flowmeters have been used for over 100 years to measure the flow rate in pressurized piped systems (Finnemore & Franzini, 2006). Named after Giovani B. Venturi who developed the relationship between differential pressure and flow rate. The Venturi flowmeter consists of a constricted throat section which causes an increase in the flow velocity and a decrease in the static pressure, followed by a diverging section allowing for pressure recovery (Finnemore & Franzini, 2006). The application of the Bernoulli principal can calculate the flow rate by knowing the geometry of the flowmeter and the difference of the piezometric head between the inlet section and the throat section.

The Venturi flowmeter is popular in industry because of the simplicity of the design and the accuracy and consistency in measuring the flow rate. A Venturi meter can be used for the measurement of liquids and gases. Advances in manufacturing and continual research have resulted in the Venturi flowmeter becoming a very dependable and accurate flowmeter when properly installed. In the industry it is often seen that flowmeters may be installed in non-ideal conditions; resulting in undeveloped, non-uniform flow into the meters There is a need for research to be performed to determine

how Venturi and other meters perform in the non-ideal conditions. While much work is yet to be done on all meter types, this study will focus on Venturi meters.

The Venturi flowmeter functions best when the flow conditions entering the meter are uniform. This is accomplished by installing sufficient length of pipe upstream of the flowmeter that is the same inside diameter as the inlet of the flowmeter. Typically, Venturi meter manufactures recommend that over 20 diameters of straight pipe be installed upstream of the flowmeter. Often a Venturi will be installed downstream of a pipe fitting such as an elbow, valve, reducer, or tee. Because of physical size or operation constraints the meter is installed with less than the required upstream straight pipe length. When the Venturi flowmeter is installed behind a pipe fitting, a disturbance to the flow profile is created resulting in localized acceleration near the pressure taps. The localized acceleration of the flow rate affects the pressure readings at the taps which lead to error in accurately measuring the flow rate.

A discharge coefficient is applied to the Venturi meter which accounts for the small amount of head loss that occurs within the flowmeter. A Venturi flowmeter can be calibrated in a laboratory to find a more precise value for the discharge coefficient. The discharge coefficient C_d is calculated using equation 1 where Q is the mass flow rate, D_f is the flowing diameter of the of the meter inlet section in, d_f is the flowing diameter of the throat section, g is the dimensional conversion constant, ΔP is the pressure differential from the inlet section to the throat section at the specified tap set or arrangement, ρ_f is the flowing density of the fluid, and Y is the gas expansion factor for gasses or 1 for liquids. (ASME, 2005)

$$C_{d=}\frac{Q}{Y\frac{\Pi}{4}{d_f}^2\sqrt{\frac{2g}{1-\left[\left(\frac{d_f}{D_f}\right)^4\right]}}*\sqrt{\Delta P*\rho_f}}$$

Equation 1. Discharge Coefficient

As seen in equation 1 the flow rate and the discharge coefficient are directly proportional, meaning if the discharge coefficient is incorrect by 5% then the flow rate measurement will error by 5%. For this purpose the determination of the discharge coefficient is of high importance for accurate flow rate measurements.

The differential pressure is measured across the inlet section and at the throat sections. It is typical for flowmeter manufactures to design one or two tap sets for differential pressure measurements. The tap sets can be measured individually and the measurements numerically averaged. The tap sets can be manifolded to create a hydraulic average of multiple tap sets. The study investigated the performance of a Venturi flowmeter with several additional pressure tap sets used to create a hydraulic average as shown in Figure 1.

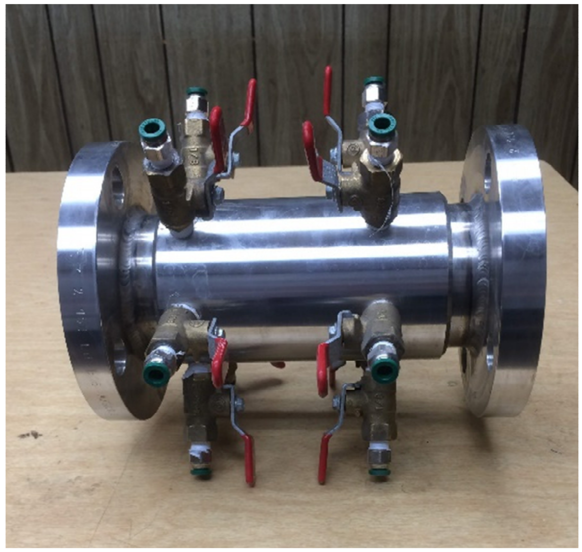

Figure 1. 2-inch Venturi with six tap sets

Computational Fluid Dynamics Overview

Computational fluid dynamics (CFD) is a testing method, which uses a numerical solver to analyze and solve problems involving the flow of fluids. CFD can be used as a tool that can simulate nearly anything that can be constructed in digital space. Recent research has proven quantitatively that CFD can be used to predict the performance of differential producing flowmeters (Sharp, 2016, Hollingshead, 2011). Using CFD testing methods in research can greatly reduce the expenses that are associated with using physical laboratory testing methods – especially when meters are installed in difficult piping configurations. Although CFD cannot and will not replace the need for physical testing, the two testing methods can be coupled together to gather conclusive data to evaluate flow metering installations. Both physical and numerical data were gathered in this research.

Objectives

The purpose of this research was to test the hypothesis that by installing several tap sets (ranging from two to six) on a Venturi flowmeter the performance of the meter would be more consistent and decrease the error of the discharge coefficient and consequently the error of the flow measurement. The project objectives were as follows:

1) Design a 2-inch classical Venturi flowmeter with six taps oriented around the circumference of the inlet section and the throat section.
2) Use the flowmeter to gather physical data of the individual tap sets, hydraulic average of all tap sets, and numeric average for different scenarios of upstream flow disturbances.
3) Run CFD simulations similar to the physical testing on the 2-inch Venturi to validate the CFD testing methods. Create CFD simulations to gather data for a wide range of pipe diameters, Reynolds numbers, and flow disturbance types.
4) Prove quantitatively that performance of Venturi flowmeters can be more accurate and consistent in non-ideal circumstances when using the hydraulic average of multiple tap sets.

CHAPTER II

LITERATURE REVIEW

A substantial amount of effort has been focused on a review of published literature related to the performance of Venturi flowmeters with a disturbed flow present. There has been a considerable amount of research performed to improve the performance of Venturi flowmeters in recent years. Presented in the literature review are the published works that have been found to have a related topic to the purpose of this research. Although there are multiple works found in published literature which are related to the work presented in this research, the purpose of this research is more unique than the others works found in several different aspects. Other research focused on the percent error caused by a flow disturbance at different locations upstream and how moving the disturbance further upstream would decrease the error. This research focused on if the flow disturbance location could not change then how measuring the differential pressure differently could improve results.

Other Differential Pressure Flowmeters

Morrison (Morrison et al. 1993) authored a paper that discussed the relationship of the fluid velocity profile as it entered the flowmeter and the performance of the flowmeter. In Morrison's research, an orifice plate was used and the focus was on finding

the percent change in discharge coefficient caused by a change in the fluid velocity profile. The baseline represented physical data of an approach velocity profile that is obtained after 100 diameters of straight pipe. Numerical solutions were found using a CFD solver. Variations in the velocity profile were created in CFD and simulations were ran to see how the disturbed flow affected the differential pressure across the orifice plate and consequently the calculation of the discharge coefficient. It was found that the ability of CFD to predict the discharge coefficient was influenced by the Reynolds number and the beta ratio (the ratio of the orifice diameter divided by the pipe inside diameter). Using the CFD solver, the predicted change in discharge coefficient caused by the change in velocity profile varied by two percent. Morrison found that CFD can accurately predict the overall flow field characteristics when compared to a laser Doppler anemometer measurement which was used in the research to take measurements of the velocity profile (Morrison et al. 1993).

Others have conducted research on the performance of differential pressure flowmeters using CFD. (Hollingshead, 2011) investigated the effect of very small Reynolds numbers on differential pressure type flowmeters. The research collected data on differential pressure flowmeters ranging in size from six inch to twelve inch in diameter. Physical testing took place in a laboratory to characterize the performance of the flowmeters at small Reynolds numbers. Numerical testing was performed using a CFD solver software to provide discharge coefficients for smaller Reynolds numbers that the laboratory did not have to the capacity to reach. It was proven CFD is able to match closely with laboratory testing. The purpose of the Hollingshead's research was to

provide discharge coefficients for the tested types of flowmeters for when the flow is at small Reynolds numbers however he also included a full Reynold number range.

Venturi Meters with Flow Disturbances

Other research has been performed on certain types of flow disturbance upstream of Venturi flowmeters (Bradford et at., 2006). Bradford investigated how Venturi flowmeters perform downstream of an elbow. Classical Venturi flowmeters were categorized according to the beta ratio and were installed at short lengths downstream of elbows. Different angles of elbows were included in the testing. Physical calibrations of the different test set-ups were performed and the discharge coefficients found were compared to the baseline discharge coefficients. The published relative uncertainties of each meter were gathered and compared to the actual deviation caused by elbow upstream. If the actual deviation was larger than the published relative uncertainty then it was determined that the elbow needed to be installed further upstream. It was found that for most of the tested meters the actual deviation was lower than the published relative uncertainty. The actual deviation for the meters with larger beta ratios were more likely to exceed the relative uncertainty.

The accuracy of Venturi flowmeters installed downstream of a pipe wall offset has been researched (Sharp 2016). Sharp used physical and numerical testing to determine the distance required to install a Venturi so that there is no effect on the flowmeter performance caused by the abrupt change in pipe diameter. Different types of Venturi meters and different beta ratios were tested for effects of different sizes of offsets and distance the offset was from the inlet of the flowmeter. The results of the study were

able to provide engineers with information about one type of flow disturbance and how it effects the performance of Venturi flowmeters. It was proven with the data that CFD can be an accurate tool to predict the effect of flow disturbances on the flow measuring capabilities and the distance required upstream of the meter so that the pipe offset has not effect.

There has been a considerable amount of research on Venturi flowmeters and how they are affected by various upstream flow disturbances. The research that has been discussed in the literature review provides important information to understand the performance of Venturi flowmeters for a variety of different installations. CFD has played an important part in research of differential pressure flowmeter by providing images of the velocity profile with the flowmeter. CFD has allowed for testing to be conducted for an unlimited amount of installations, pipe sizes, and flow rates. For these reasons Venturi flowmeters have become more reliable and used often in municipal and industrial applications.

The research topic of multiple tap sets used to create a hydraulic average of the pressure profile is unique to the other research discussed in the literature review. The research discussed in the literature review is related to the thesis topic in that the focus is on reducing error of differential pressure flowmeters when installed in specific non-ideal conditions. The thesis topic is unique because it is focused on the use of multiple tap sets in situations where a non-uniform pressure profile is present. The results of the research will be beneficial to the flowmeter users and manufactures of Venturi flowmeters because

it will demonstrate a method that can be used to decrease error for flowmeter installations with high uncertainty.

CHAPTER III

EXPERIMENTAL METHODS

Physical Modeling Methods

The testing for this research was performed at the Utah Water Research Laboratory (UWRL) in Logan, Utah. High precision instrumentation was used to measure flow rate and differential pressures. The UWRL has the capabilities to set-up test lines for a wide range of pipe diameters, from 0.25-inch diameter up to 72-inch diameter. A 2-inch diameter Venturi flowmeter was designed and manufactured to be tested in the laboratory. A 14-inch diameter Venturi flowmeter was provided by a flowmeter manufacturer and was tested in a set-up similar to the field set-up with severe upstream flow disturbances. Because of the extreme cost associated with manufacturing multiple sizes of flowmeters and test set-ups, CFD was used to simulate testing of several additional sizes.

The testing of the 2-inch Venturi was performed on a circulating flow pumped system. A traceable gravimetric system was used to measure the flow rate which was then compared to the flow rate measured by the Venturi flowmeter. High precision and traceable pressure transmitters were used to measure the differential pressure between the upstream section pressure taps and the throat section pressure taps.

Uncertainty exists in all physical measurements and can affect the results of any result dependent on those physical measurements. Uncertainty is comprised of systematic uncertainty and random uncertainty. Systematic uncertainty is an error in the measurement which causes a bias from the true value, random errors originates fromvariations in a physical measurement. Both types of uncertainty exist in every measurement which for this research included: temperature which influences the unit weight, acceleration of gravity, pressure, weight, flow meters used to measure the flow, multimeters used to measure voltage output.

The 2-inch diameter Venturi flowmeter was designed to the standards established by the American Society of Mechanical Engineers (ASME) in the Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi (ASME, 2004). To follow the standards established by the ASME, the design focused on the angle of the convergent and divergent sections, the lengths of the throat and upstream section, the location of the tap sets, the surface finish and the truncation of the divergent section. Special attention was put on the technique of manufacturing the tap sets to ensure that, at the tap location, the inside wall was smooth and free of any burrs. Having any type of burr near the tap set location can drastically change the performance ability of a flowmeter. The flowmeter was manufactured as a machined convergent section and follows the characteristic standards established by the ASME for Venturi tubes. The type of manufacturing was chosen to be a machined convergent type, ASME recommends this type for pipe diameters ranging from two inches to ten inches (Figure 2).

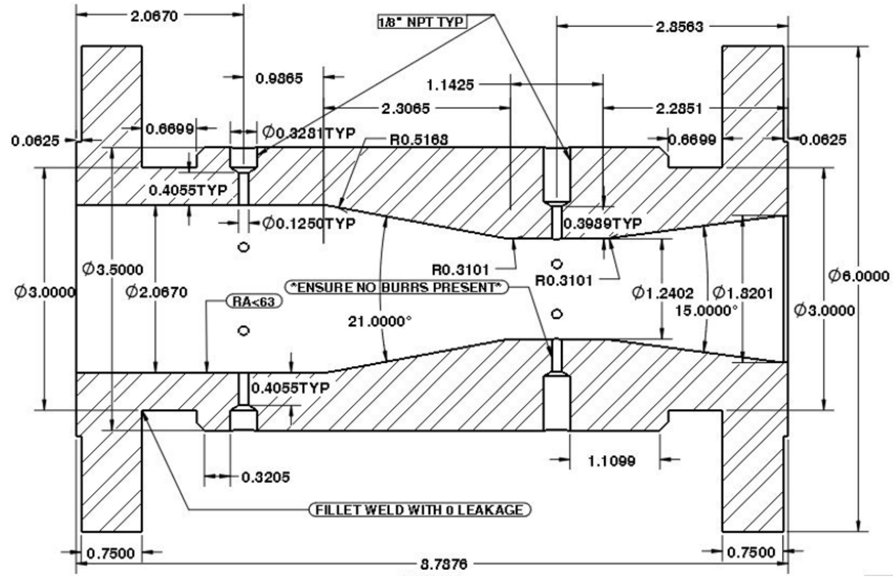

Figure 2. Design of two-inch Venturi following ASME standards

The beta ratio is defined as the diameter of the throat section divided by the diameter of the inlet section of the meter shown in equation 2. A beta ratio of 0.60 was chosen for the physical testing of the 2-inch Venturi because it is a common beta ratio used in industry. Typical beta ratios can be between 0.50 and 0.70 and it can be expected that as the beta ratio decreased then the discharge coefficient of each individual tap set would vary more for conditions with a disturbed flow profile. A complete study on the effect of different beta ratios was not completed but it would be possible to use CFD on other beta ratios to assess the influence of more pressure taps.

$$\beta = \frac{\text{Diameter of Throat}}{\text{Diameter of Inlet}}$$

Equation 2. Beta Ratio

The design of the 2-inch diameter flowmeter was such that six tap sets were installed around the circumference of the pipe wall in 60-degree intervals. Six taps were manufactured for the upstream section and six taps for the throat section. The purpose of the six tap sets was to measure the static pressure at different locations on the pipe wall. Each tap was installed with an isolation valve so that the tap sets could measure the static pressure individually and averaged hydraulically.

Tubing of consistent lengths was connected from each tap to a common plenum, one plenum for the tap sets of the upstream section of the flowmeter and one plenum for the taps of the throat section. The plenum is a means of collecting the static pressure of the individual taps and also creating a hydraulic average without having the individual taps interfere with the pressure of another tap at a different location. The plenum enabled an average pressure of several taps and was then connected, with similar tubing, to the high performance pressure transmitters. The pressure transmitters measured the difference in static pressure between the taps at the upstream section to the taps at the throat section. Figure 3 shows a typical installation of the 2-inch Venturi showing the tap sets connected to the plenum.

Each tap set was given a numerical value of 1-6 so that the results could be shown graphically. The individual taps located at the inlet of the meter were numerically paired

with a tap with the same circumferential location at the throat. Tap set 1 was located 30 degrees clock-wise off the top-center of the meter and the sequential 2-6 taps were spaced 60 degrees apart counter clock-wise. Figure 34 in Appendix C shows a diagram of the assigned numbering of the tap sets. The orientation of the valve and elbow is important because it will affect the individual tap sets differently. Figures 35 and 36 in Appendix C show how the butterfly valves and elbows upstream of the meter were oriented with respect to the tap set location.

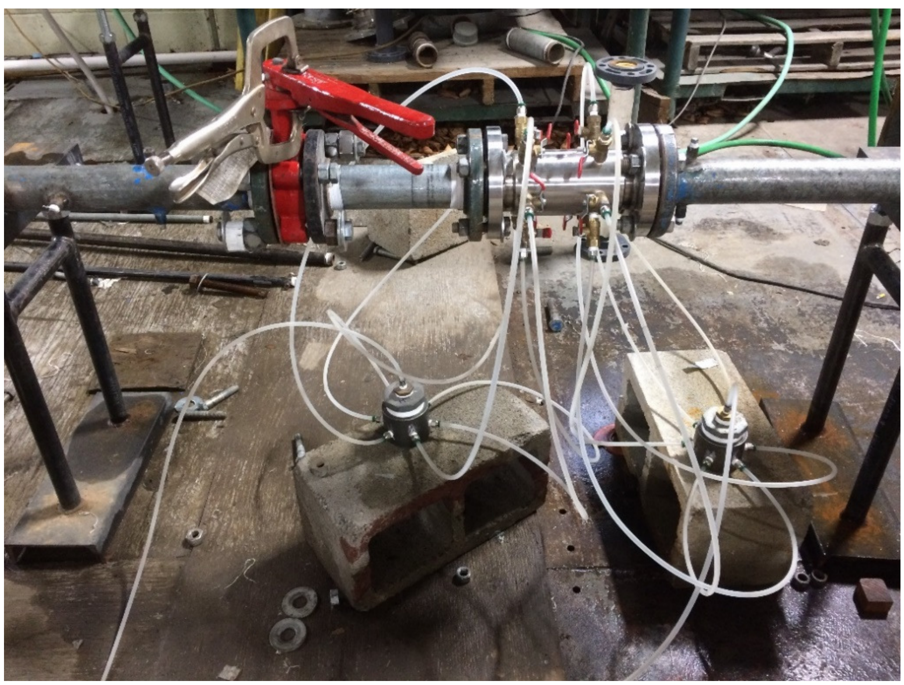

Figure 3. Typical installation of 2-inch Venturi with upstream disturbance

The physical testing continued with a 14-inch diameter Venturi flowmeter which was provided by Primary Flow Signal, a flowmeter manufacturer. There was concern

about the performance of the flowmeter because of the severe pipe set-up where the meter was installed. Figure 4 shows how the testing in the laboratory simulated the field installation. Upstream of the 14-inch flowmeter consists of two 20-inch supply lines which converge, a sudden contraction from 20-inch diameter to 14-inch diameter, a full open butterfly that was close coupled to the inlet of the flowmeter, and a throttling plug valve and short radius elbow downstream of the flowmeter. The close proximity of the stated flow disturbances created a concern of a disturbed flow existing within the flowmeter.

The method used in testing was to calibrate the flowmeter over a range of inlet Reynolds number for different pipe set-ups. The flowmeter was manufactured with two tap sets on the horizontal plane on opposite sides of the pipe wall. The performance of each tap set was calibrated individually and then the tap sets were connected so that a hydraulic average of the tap sets could be measured. Since the laboratory calibration of the 14-inch flowmeter was performed with the similar pipe set up as the actually field installation, there is high certainty in the flowmeter's accuracy.

An uncertainty analysis was completed for this research to demonstrate the extents of the uncertainty of the provided results. When the Reynolds numbers were with in the range of 50,000 and 260,000 then the uncertainty was less than 0.80% of the discharge coefficient. The flow rates with very low Reynolds numbers , in the range of 25,000 to 50,000, had uncertainty less than 1.25%.

All the measurements in the study were measured with high precision instrumentation to reduce the amount of experimental uncertainty as much as possible. If

the measurements are used to calculate another value, then the uncertainty of all measured propagate through the calculations and into the result. The limits of uncertainty in the measurements propagate into the calculation of the discharge coefficient and the uncertainty of the meter calibration becomes a function of the uncertainty limits of the instrumentation used to make the measurements.

Figure 4. Setup for calibration of 14-inch Venturi flowmeter

The experimental methods were focused on physical laboratory testing and CFD numerical modeling testing. The physical testing of the 2-inch and 14-inch Venturi flowmeters provides results and understanding for the specific set-up and diameter. Because it is not reasonable to design and build physical test set-ups for every possible type of flow disturbance and pipe diameter, CFD simulations were created to expand the extent of the project to a larger range of pipe sizes and different disturbance types. CFD

has the capability of testing a range of Reynolds numbers that are extremely difficult to test in a laboratory.

Numerical Modeling Methods

It is important to show that the results obtained from the CFD models can represent the actual performance of a physical models. To validate the numerical methods used in STAR-CCM+, numerical models were created to replicate the physical models of the 2-inch and 14-inch Venturi meters. The exact dimensions were either measured or obtained from the manufacture and recreated in STAR CCM+. The research is not interested in using CFD to match the exact discharge coefficient of the CFD testing to the physical testing, rather it is interested in finding the percent change caused by an upstream flow disturbance in the physical model and if the numerical model sees the same percent change for the same flow disturbance. While CFD is highly accurate, meter fabrication results in slight differences that are not properly simulated in CFD models. However, CFD has shown excellent agreement with laboratory obtained discharge coefficients.

Creating an accurate mesh of the meter and associated piping including any disturbances is key to obtain accurate results. In all the simulations a polyhedral mesher and a prism layer mesher were used to create the volume mesh of the flow area. The base size of the cells, the number of prism layers, and the thickness of the prism layers were adjusted for the different simulations so that the most accurate results could be obtained.

Star CCM+ includes three options for near wall treatments which are high y+ wall treatment, low y+ wall treatment, and all y+ wall treatment. The all y+ wall treatment was chosen to be used in all simulations of the study because it is the most general approach and should be used most of the time unless circumstances require a high y+ or a low y+ (Field, 2017).

The wall y+ is the dimensionless wall distance of the boundary layer. The y+ value is calculated using equation 3 and equation 4 where y is distance from the boundary layer, υ_τ is the shear velocity, and ν is the kinematic viscosity. Equation 3 can be used to calculate υ_τ where τ_ω is the wall shear stress and ρ is the density.

$$y^+ = \frac{y * u_\tau}{\nu}$$

Equation 3. Wall y+ value

$$u_\tau = \sqrt{\frac{\tau_\omega}{\rho}}$$

Equation 4. Shear velocity

The run times of the simulations are drastically increased when more cells are in the volume mesh. The beginning steps in running a simulation is to perform a mesh dependency analysis which is used to observe how increasing the number of cells would change the result. The mesh dependency analysis or grid convergence index (Celik et at. 2008) created 3 meshes with each new mesh increasing the number of cells by 1.4 times

more than the previous mesh. The discharge coefficient was found for the three meshes were compared to the other meshes. The numerical uncertainty can be found by the procedure by using the method outlined by Celik. When it was found that the result did not change with a change in the volume mesh, then the mesh values were used for the testing.

The solution for the motion of the incompressible fluid is governed by the Reynold-averaged Navier-Stokes equations (RANS). The continuity equation, the momentum equations, and select equations for turbulence properties are solved. The continuity, momentum, and energy equations in integral form are indirectly and simultaneously solved by means of discrete approximations which are converted into algebraic equations which can be solved on a computer (Peric et al, 2015).

The computer used to run all CFD simulations was a Supermicro X10DAi with the following specifications: 64.0 gigabyte of Random-Access Memory (RAM), Intel Xeon 20 core dual processor, and Microsoft Windows 10 Pro operating system. The numerical models were created and tested on the STAR-CCM+ software version 11.02.010 by CD-adapco - Siemens. STAR-CCM+ is a double precision solver.

CHAPTER IV

RESULTS

Discharge Coefficient Calibrations

The discharge coefficient is calculated by knowing the geometry of the flowmeter, the flow rate, fluid properties, and the differential pressure. The flow rate is directly proportional to the discharge coefficient so any percent error in the discharge coefficient should cause a similar percent error in the flow rate. Following the calibration testing methods of the flowmeter, which were described in Chapter III, the results provided a trend line for the discharge coefficients over the range of the Reynolds numbers, which was tested. To visually display how the resulting discharge coefficients varied for each of the different tap sets, plots were created and several calibration results are shown in Figures 5-8. For each of the test simulations, which were performed in the laboratory, a plot was created to compare the discharge coefficient of the disturbed flow to the baseline flow. Plots of the additional test setups are shown in Appendix A. The plots show that when a flow disturbance is present the measurement of the discharge coefficient varies substantially based on the location of the tap sets that measure differential pressure.

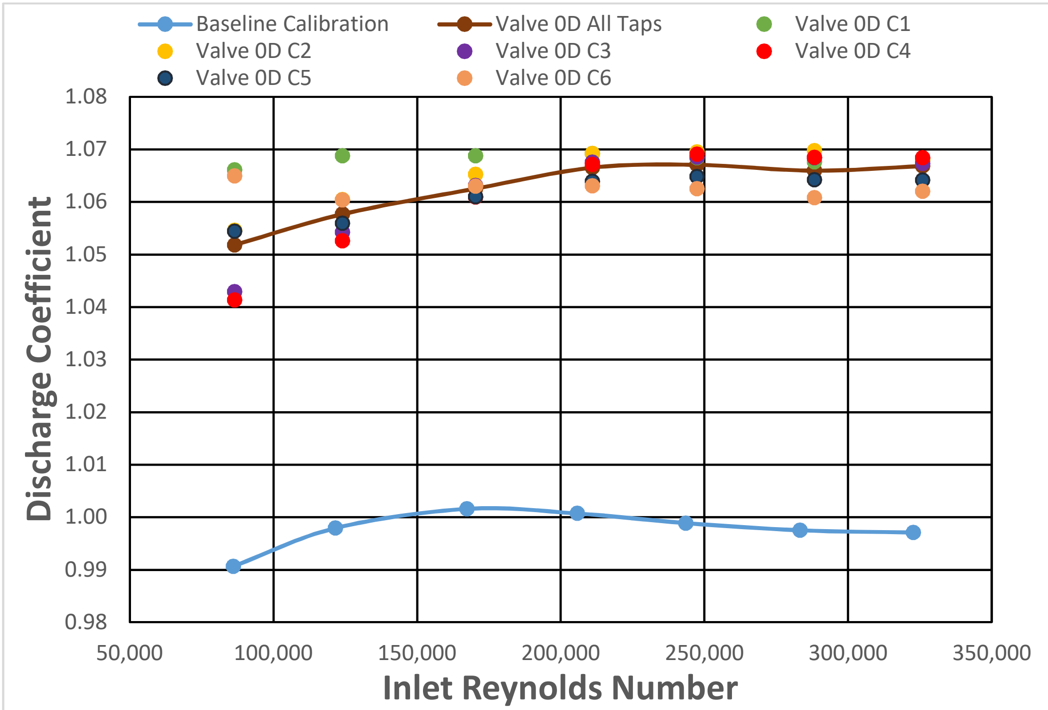

Figure 5. Calibration of 2-inch Venturi with butterfly valve 0D upstream

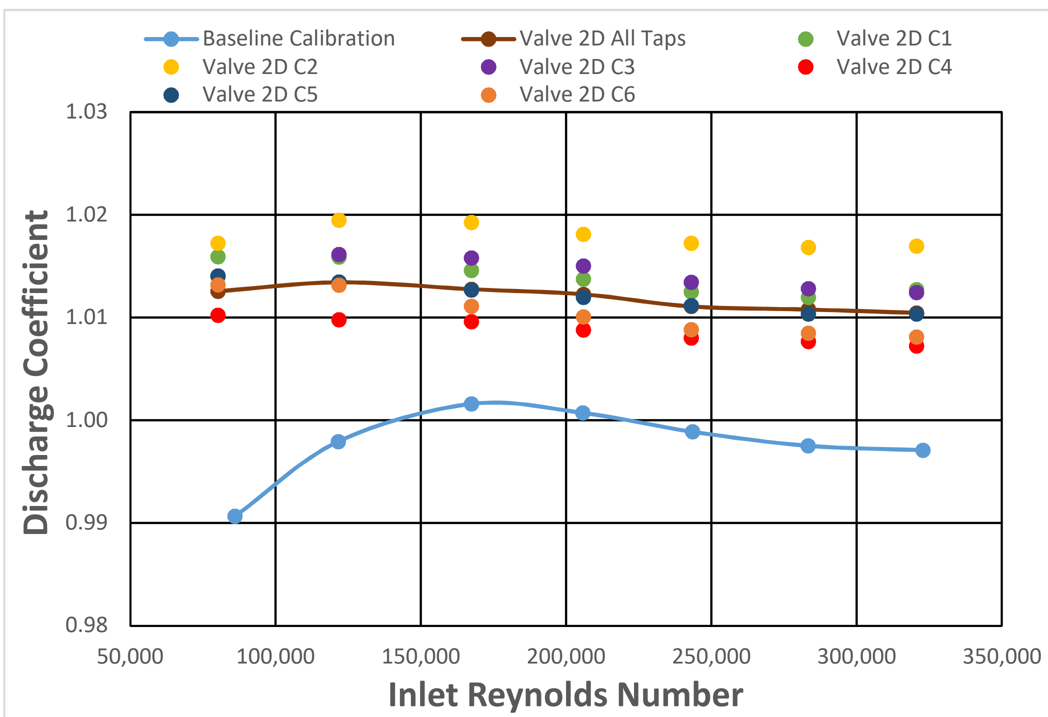

Figure 6. Calibration of 2-inch Venturi with butterfly valve 2D upstream

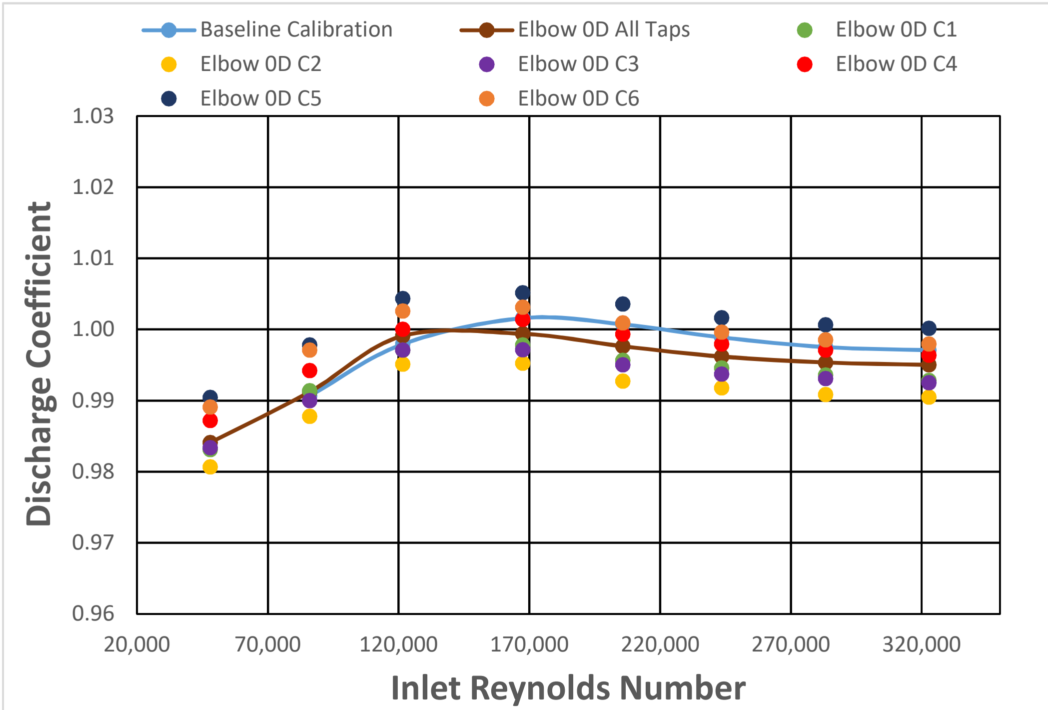

Figure 7. Calibration of 2-inch Venturi with elbow 0 diameters upstream

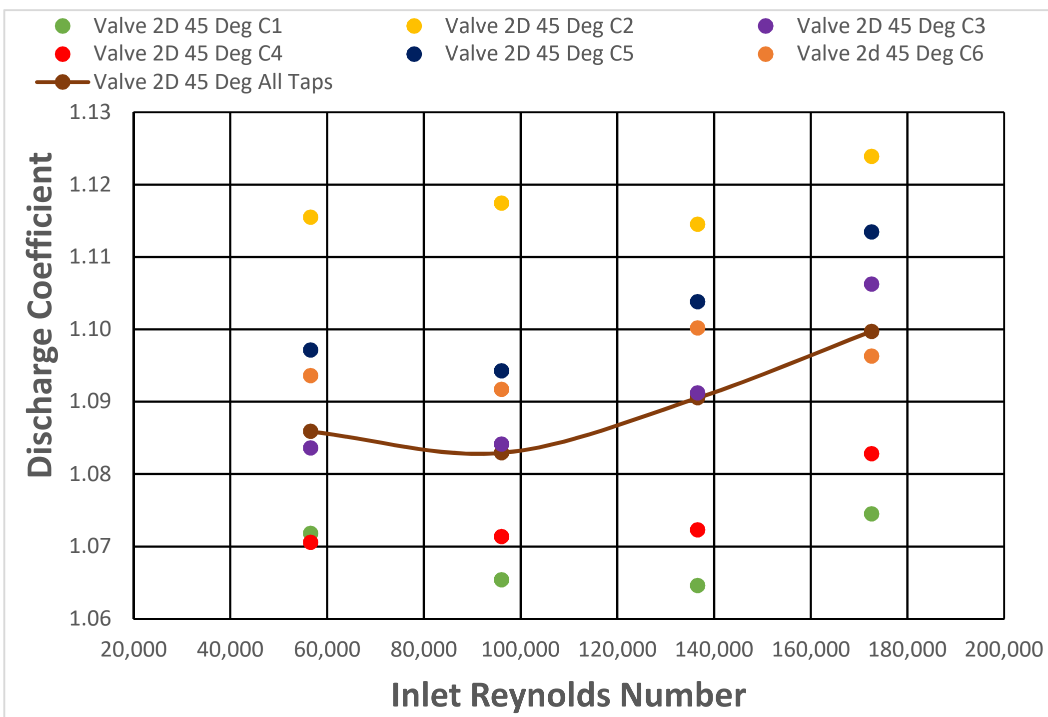

Figure 8. Calibration of Venturi with 45 deg butterfly valve 2D upstream

A non-uniform pressure profile and localized acceleration near the pressure taps is a consequence of a flow disturbance at a close location to the inlet of the flowmeter. The discharge coefficient of each individual tap set was compared to the other individual tap sets and the baseline calibration. The plots in Figures 5-8 show large variations between the performance-characteristics of each individual tap set caused by the flow disturbances. Based on orientation of the tap set, the discharge coefficient can vary by up to 4.8% from the baseline calibration results (Table 1). The calibration of the hydraulic average of all tap sets consistently resulted as an average value in the spread of the discharge coefficients of the individual tap sets as would be expected. The uncertainty of the discharge coefficient for individual tap sets was up to 3.5% but by using the hydraulic average the error can be reduced by half.

Table 1. Percent deviation of individual taps for butterfly valve 45 deg 2D

Inlet Reynold Number	Tap Set 1 Percent Deviation	Tap Set 2 Percent Deviation	Tap Set 3 Percent Deviation	Tap Set 4 Percent Deviation	Tap Set 5 Percent Deviation	Tap Set 6 Percent Deviation
56,554	4.07%	4.02%	2.94%	4.19%	2.42%	2.10%
96,063	4.88%	4.66%	3.07%	4.30%	2.64%	2.41%
136,613	4.69%	4.48%	2.44%	3.94%	3.55%	3.24%
172,536	4.60%	4.39%	2.87%	3.80%	3.50%	2.52%

Average	3.57%
Standard Deviation	0.87%

The flow rate can be accurately measured even when a flow disturbance causes a non-uniform flow profile by applying an accurate discharge coefficient found by performing a laboratory calibration. The calibration of the individual tap sets showed that based on the circumferential location of the tap, the calibration can vary by a significant percentage. Figures 9-12 are plots of the percent error of the flow rate measured by the Venturi meter compared to the actually flow rate measured by the gravimetric system. The performance of each individual tap set is plotted to visualize how the measured flow rate varies.

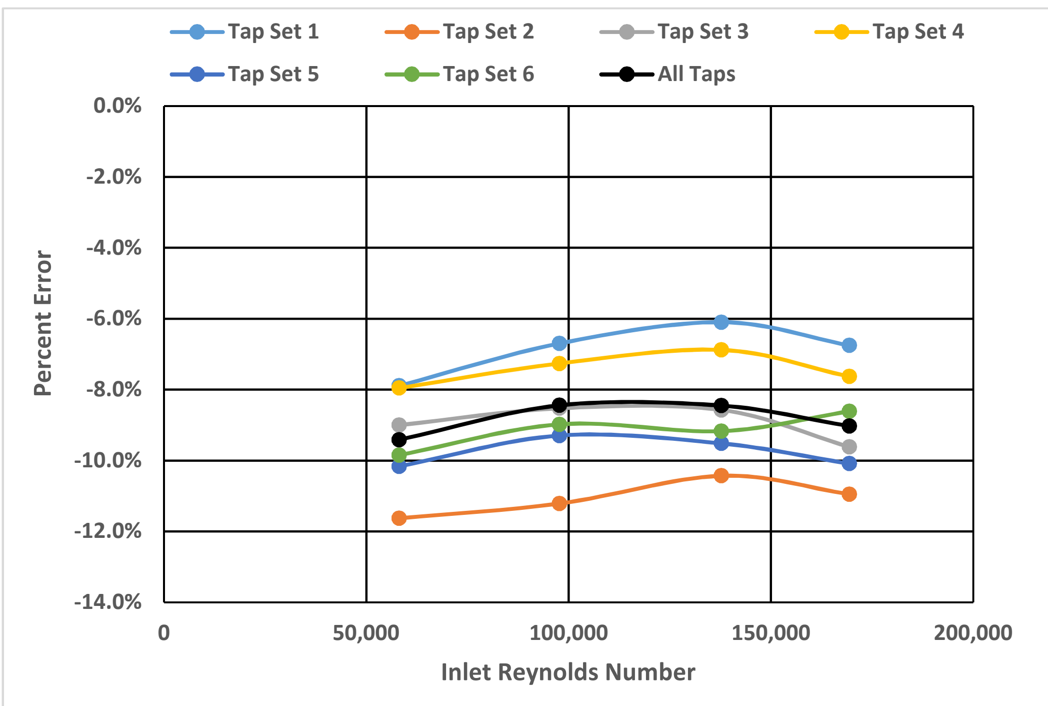

Figure 9. Measured vs actual flow rate with 45 deg butterfly valve 2D

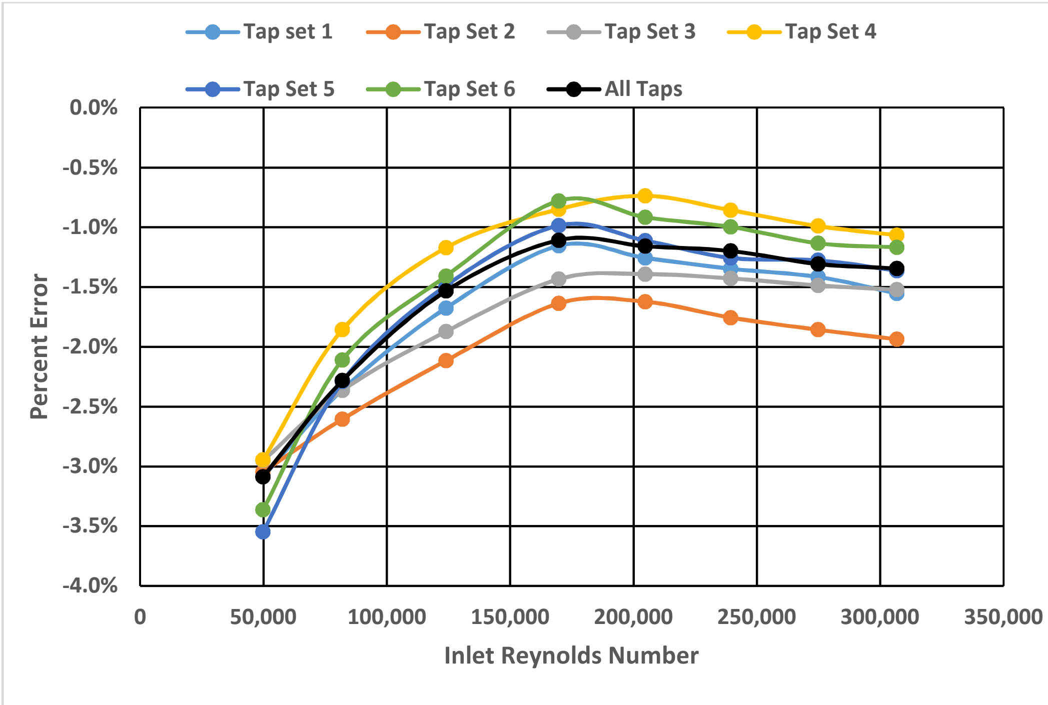

Figure 10. Measured vs actual flow rate with butterfly valve at 2D

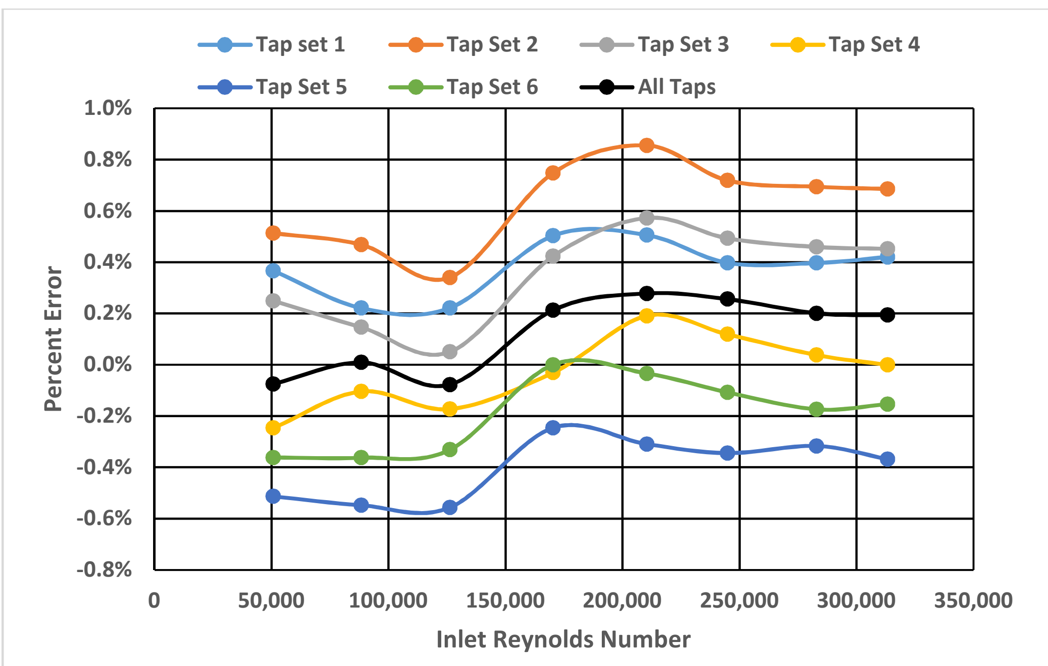

Figure 11. Measured vs actual flow with elbow 0 diameters upstream

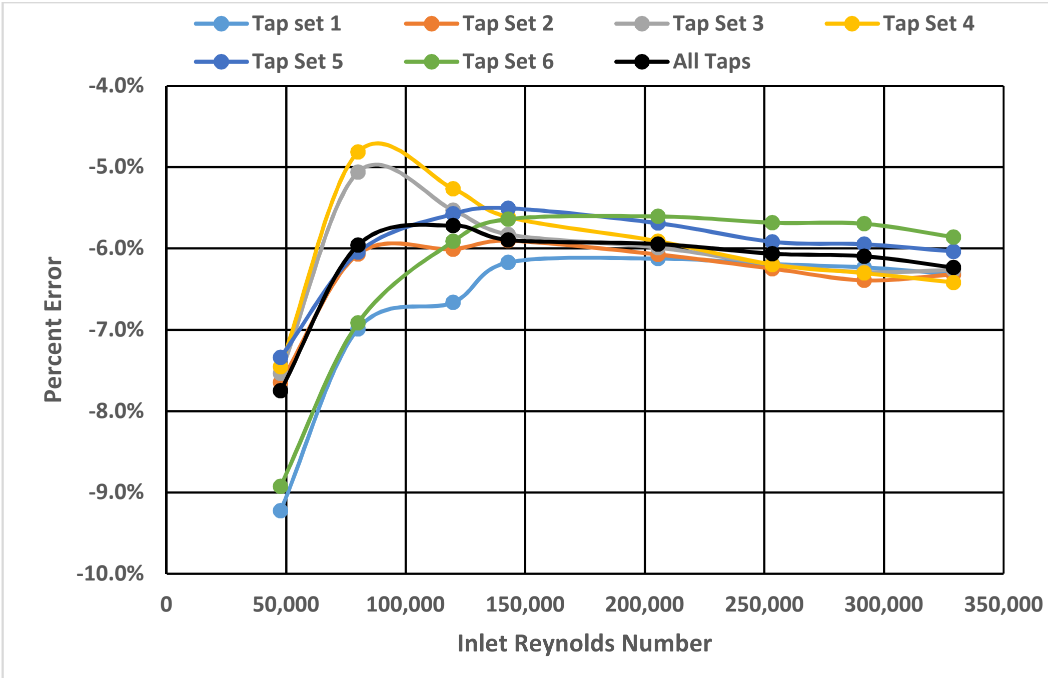

Figure 12. Measured vs actual flow rate with butterfly valve at 0D

Equation 5 was used to calculate the flow rate of the Venturi flowmeter. Q is the volumetric flow rate, Fa is the thermal expansion coefficient, C_d is the discharge coefficient, d_f is the flowing diameter of the throat section, D_f is the flowing diameter of the inlet section, g is the gravitational constant, and ΔP is the differential pressure in units of length between the inlet section throat section taps at specified tap set.

$$Q = FaC_d \frac{\Pi}{4} {d_f}^2 \sqrt{\frac{2g\Delta P}{1 - \frac{{d_f}^4}{D_f}}}$$

Equation 5. Calculated flow rate

The results of the testing consistently illustrated that when an upstream flow disturbance is installed near the inlet of the flowmeter then there can be a substantial error in the measured flow rate. The percent error in the measured flow rate compared to the flow rate measured as baseline conditions can vary by 1% to 4% based on the circumferential location of the tap set. Using all of the tap sets to create the hydraulic average of the differential pressure resulted in the trend line of the percent error in flow rate was consistently in the median for the range of values shown in the plots.

CFD Results

The CFD testing results provided information on the effect of the flow disturbance on the pressure distribution. Several different meter sizes were constructed in digital space and tested in CFD simulations. The laboratory flow range was extended, by performing CFD simulations at flow rates that are not obtainable in the laboratory. Numerous CFD simulations were created which replicated the laboratory test set-up of the 2-inch Venturi meter. The data of the laboratory testing and from the CFD simulation testing were compared to determine if the testing methods of CFD accurately predict the effect of upstream disturbances on the performance characteristics of the Venturi meter.

The performance characteristic data from the baseline test were compared to the data from the tests with the flow disturbance present and the percent error caused by the disturbance was calculated. The testing methods of the CFD simulations can be proven accurate if the average percent error from the CFD baseline simulation is similar to the

average percent error from the baseline of the comparable test set-up in the laboratory testing. The percent error from baseline was calculated by using equation 6 and an average value was created over the range of flow rates. Where P.E. is the percent error, $C_{d\ test}$ is the calculated discharge coefficient with a flow disturbance, and $C_{d\ baseline}$ is the calculated discharge with no flow disturbance. The comparable data of the physical and numerical testing is in table 2. There exists a good agreement between the average percent error from baseline for the physical testing and the numerical test.

$$P.E. = \frac{C_{d\ test} - C_{d\ baseline}}{C_{d\ baseline}} * 100$$

Equation 6. Percent Error

The numerical uncertainty of the numerical simulations was estimated using a grid convergence method by Celik (Celik et al. 2008). The numerical uncertainty was found for several of the simulations and since similar methods were used for all simulations, it is assumed that the uncertainty found applies to all the simulations. The numerical uncertainty for the all the CFD testing was found to be smaller than 0.5%.

Table 2. Average Percent Error of baseline data obtained numerically or physically

Meter Size *inches*	Flow Disturbance Type	Beta Ratio of Meter	Physical or Numerical Data	Distance From Disturbance to Meter Inlet *Pipe Diameters*	Average Percent Error from Baseline *%*
2	Butterfly Valve Full Open	0.60	Numerical	0	6.33
2	Butterfly Valve Full Open	0.60	Physical	0	6.50
2	Butterfly Valve Full Open	0.60	Numerical	2	0.30
2	Butterfly Valve Full Open	0.60	Physical	2	1.42
2	Butterfly Valve Full Open	0.60	Numerical	4	-0.09
2	Butterfly Valve Full Open	0.60	Physical	4	-0.21
2	Butterfly Valve 45 degree Open	0.60	Numerical	4	-0.30
2	Butterfly Valve 45 degree Open	0.60	Physical	4	-0.04
2	Short Radius elbow	0.60	Numerical	0	-0.09
2	Short Radius elbow	0.60	Physical	0	-0.15
2	Short Radius elbow	0.60	Numerical	4	-0.26
2	Short Radius elbow	0.60	Physical	4	-0.34
12	Butterfly Valve Full Open	0.60	Numerical	0	1.12
12	Butterfly Valve Full Open	0.60	Numerical	2	0.45
14	Combined Flow and Butterfly	0.56	Numerical	2	-0.57
14	Combined Flow and Butterfly	0.56	Physical	2	-0.55

The numerical testing provided visual images of the flow characteristics within the flowmeter such as the pressure profile, velocity profile, streamlines, and turbulent energy. The information obtained from the visual images demonstrates how the differential pressure varies for each tap set due to the flow disturbance. In Figure 13 are cross-sectional views of the 2-inch Venturi meter. The figures represent the pressure distribution at the location of the inlet taps (subfigures A and C) and the throat taps (subfigures B and D). When no flow obstruction is present the pressure profile is uniform through the cross sections as shown in subfigures C and D. A full open butterfly valve

was installed zero diameters upstream of the meter in subfigures A and B and it is observed that the pressure distributions is inconsistent and has higher and lower pressure spread throughout the cross section.

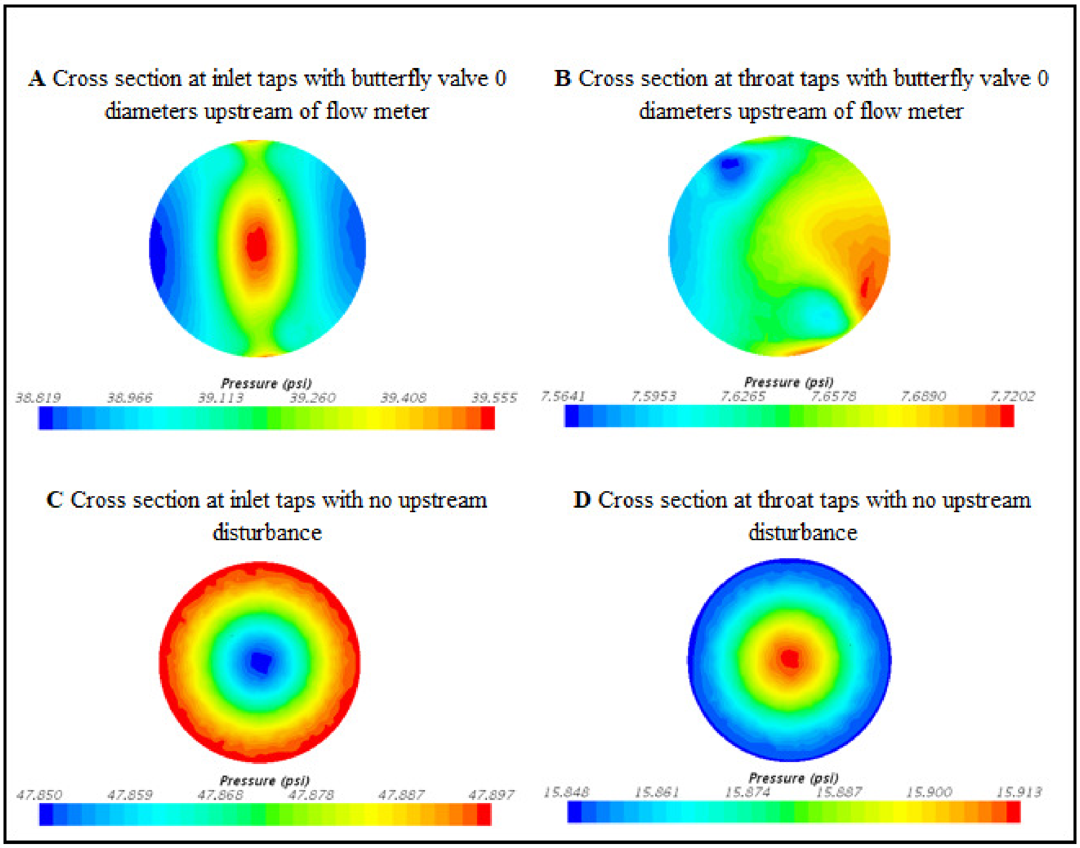

Figure 13. Pressure profiles of non-uniform disturbed flow and uniform flow

Significant differences in the flow measurement will occur depending on where on the cross section the differential pressure is being measured. The pressure profile will vary with changes in the flow rate and inconsistencies in the differential pressure will lead to errors in the flow measurement. The visual images from the CFD simulations demonstrate how measuring a hydraulic average of several pressure taps will provide a

consistent average of the high and low pressures throughout the cross section, resulting in a more consistent discharge coefficient and less variation in the flow measurement.

A plane section which runs the length of the test section was created to visualize the effect of the flow disturbance on the flow behavior throughout the test section. The flow disturbance introduces localized acceleration and areas of flow separation. Highly turbulent and unpredictable flow propagates through the system and disturbs the flowmeters performance. The disturbed flow is visualized in the velocity profile of a 12-inch diameter Venturi meter with a butterfly valve opened to 45 degrees and located four diameter lengths upstream in figure 14. A pressure profile of the same test set up is in figure 15. The localized acceleration caused by the valve increases the local velocities. Due to the relationship of pressure and velocity from Bernoulli's equations the increase in localized velocities decreases the localized pressure (Finnemore & Franzini, 2006). A non-uniform pressure profile becomes introduced into the flowmeter. Additional figures showing the results of the CFD test set ups of the velocity and pressure profiles are shown in Appendix B.

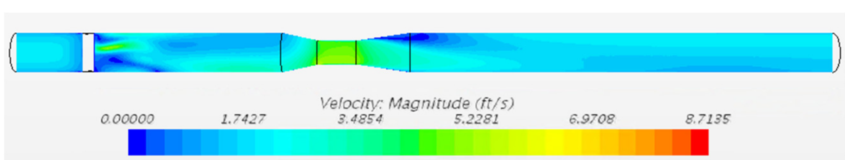

Figure 14. Velocity profile of Venturi with butterfly valve 45 degrees open

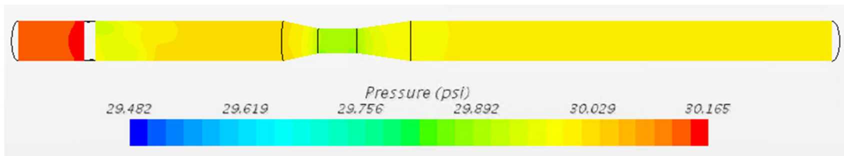

Figure 15. Pressure profile of Venturi with butterfly valve 45 degrees open

Effects of Distance Upstream of Flow Disturbance

The effect of the flow disturbance is magnified the closer the disturbance is to the inlet of the meter. When the flow disturbance is installed further upstream so that there is more length of straight pipe section upstream, then the flow profile can return to a uniform profile. Manufacturers typically set required upstream straight pipes distances so that a pipe-fitting does not affect the flowmeters performance. That distance is typically between 10-20 diameters. A plot of the testing results (Figure 16) showed that percent difference in discharge coefficient is largest when the flow disturbance is zero diameters upstream of the inlet as expected. When a butterfly valve is installed farther upstream than four diameters the percent difference in discharge coefficient is less than 0.5% and approaches 0% as the distance increases. When possible any pipe-fitting should be installed upstream at the manufacturer's recommendations or greater. When is it not possible to meet the manufacturer's recommendations, then it should be expected to make an adjustment to the discharge coefficient which is best accomplished by performing a laboratory calibration.

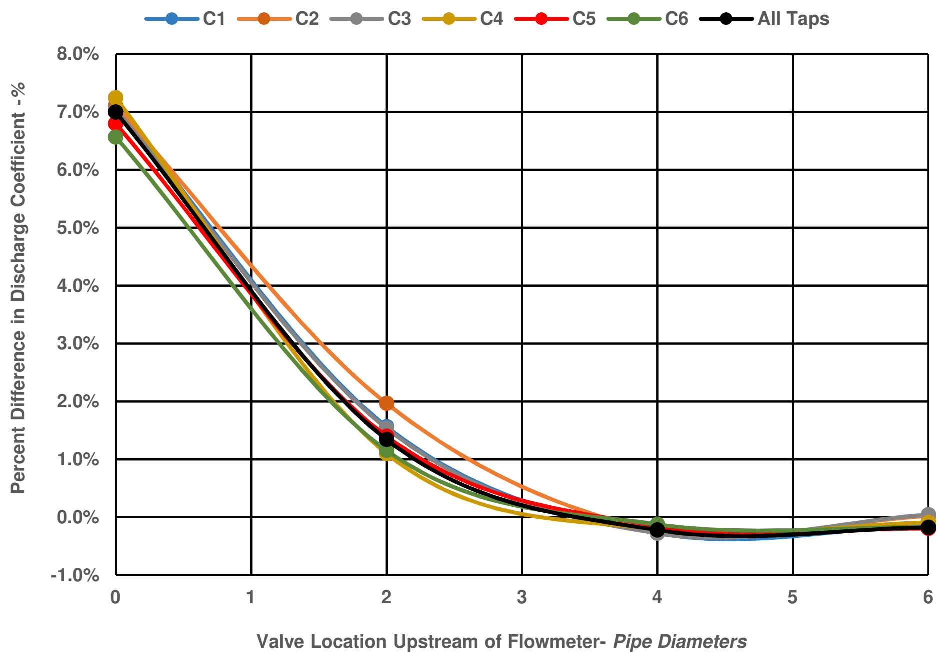

Figure 16. Percent difference versus location of valve upstream

CHAPTER V

DISCUSSION

Flowmeter Calibration Options

It is always recommended to install a Venturi flowmeter with sufficient upstream piping that is the same diameter as the flowmeter and that has no means to create a disturbance in the flow. When the meter is installed in the ideal conditions the discharge coefficient provided by the meter manufacture should yield accurate flow measurement. When the meter is installed in non-ideal conditions, the meter accuracy is benefitted by having it physically calibrated at a qualified hydraulic laboratory. It is best to perform the calibration in the actual piping configuration that the meter will be installed in the field. If the meter is manufactured with several pressure tap sets, then the laboratory calibration will provide an accurate discharge coefficient for each tap set and will accurately measure flow rate.

Often it is not possible to perform a laboratory calibration because of cost, extreme size of the meter and pipe set-up, or because it is not possible to remove the meter from operation. Without a laboratory calibration there is a wide range of uncertainty for flowmeters operating with a flow disturbance upstream. When this is the case, applying the results from the research can beneficial for system operators and designers.

The recommended procedure to apply the research results to a flow meter in non-ideal conditions is to use a combination of physical and numerical modeling. The flow meter should be installed with six tap sets and set up with instrumentation to measure the hydraulic average of the cross-sectional pressure. Physical modeling of the same model of flow meter can be calibrated in a laboratory to establish the baseline conditions. The physical model meter should be installed in ideal conditions then only one tap set will provide a reliable baseline. Numerical modeling can then be used to create a simulation to replicate the baseline conditions and the installed field conditions. Then by applying the hydraulic average to both models the percent shift caused by the flow disturbance can be found and applied to the baseline conditions of the physical model. As shown in the study, the hydraulic average of multiple tap sets of the numerical model and the physical model can find the percent shift within 0.25 % of the assumed actual percent shift.

When it is not possible to perform a laboratory calibration then using several tap sets to create a hydraulic average may be the most reasonable option to improve the flowmeter's performance. Using several pressure taps to measure a hydraulic average of the static pressures at the two tap locations reduces the error of the measurement of the discharge coefficient by half.

Any differential producing flowmeter that is installed with an upstream flow disturbance can have large inaccuracies in the flow measurement. The wide spread between the percent errors in the flow rate for the individual tap sets can be as large as 4% or perhaps even larger for more extreme installations. That means that at the same flow rate the measured flow rate can vary by as much as 4% depending on the location of

the tap set. When the differential pressure is measured using a hydraulic average of multiple tap sets, the measured flow rate always lies in the middle of the wide range of uncertainty. The stated 4% of uncertainty from the location of the tap sets becomes halved to 2% of uncertainty in the flow rate.

High performance flowmeters can often measure the flow rate within 0.25% accuracy or better. Even when a high performance flowmeter is used, if installed in a pipe set up with a severe flow disturbance near the inlet of the meter then the accuracy of the flowmeter will decrease greatly. The ideal piping set up is not always possible due to many different factors and results in a certain level of uncertainty in the flow measurement which must be accepted. Without needing to perform a costly redesign of the pipe set up; the flowmeter and instrumentation can be modified to measure a hydraulic average of the pressure at the cross sectional location of the taps. This low-cost solution can be implemented and reduce a large portion of the inaccuracy.

Predicting performance with CFD

While CFD is not a suitable replacement for a laboratory calibration, this study demonstrated that CFD methods, when coupled with laboratory testing, can be effective at predicting the shift in discharge coefficient caused by an upstream disturbance. The baseline CFD simulations are created with no flow disturbance upstream of the test meter as to establish a baseline calibration. Then with a flow disturbance added, the results of the calibration are compared to the baseline calibration. Comparing the two calibrations

provided the percent error (amount of shift of the discharge coefficient) that the flow disturbance caused. The percent error of the discharge coefficient found from the CFD testing can then be applied to available discharge coefficient data for the flowmeter.

The CFD testing should be accompanied with physical laboratory testing to ensure reliable results. CFD can provide good visuals and quick results, but it is easy for errors to be made in the simulations. As shown in this study similar testing methods were performed in the laboratory and with CFD simulations. The results of the two testing methods yielded similar values for the percent error caused by a flow disturbance. Confidence is added to the data when the CFD data matches well with the physical data.

Additional Research

The research limited the number of tap sets to six spaced 60 degrees apart. Six tap sets was chosen because it seemed to cover the cross sectional area well and would be able to record an accurate hydraulic average. Additional research could be performed on how the number of tap sets would affect the measurement of the differential pressure. Having more than six taps may be able to record a hydraulic average which more accurately represents the average pressure. It may be difficult to construct a meter with more than six tap sets due to lack of space along the circumference. Less than six tap sets may be able to measure a similar result as six tap sets.

The research only looked at adding several tap sets to Venturi flowmeters. There are several different types of differential pressure producing flowmeters which may be

benefited by adding several tap sets. The research may be furthered by performing tests on different types of flowmeters that have multiple tap sets installed.

CHAPTER VI

CONCLUSIONS

Venturi flowmeters are used often in the flow measuring industry. Large amounts of research have been conducted on Venturi meters, which has increased the accuracy of these meters. This study was focused on when a Venturi flowmeters is installed with a flow disturbance close to the inlet of the meter and how to increase the accuracy and certainty of the flow measurement. Typically the Venturi is manufactured with one set of taps, occasionally two sets of taps. The study used a Venturi having six sets of taps

The research used two types of testing methods, physical and numerical. The physical testing was performed at the UWRL on 2-inch diameter and 14-inch diameter Venturi flowmeters. The numerical testing was conducted using Star-CCM+ and tested for a wider range of flow rates and different diameter sizes than were tested physically. The results of the testing were plotted and showed how each individual tap set produced a different measured flow rate for a constant actual flow rate. The flow measurement became dependent upon the circumferential location of the tap set.

The individual tap sets were then connected to a common plenum and used to measure a hydraulic average of the static pressure for the cross section. The hydraulic average represented true average pressure of the cross section. When the hydraulic average was used to find the differential pressure, the measured flow rate consistently

resulted as an average of the measured flow rates of the individual tap sets. With the hydraulic average the measured flow rate no longer becomes dependent upon the circumferential location of the tap sets. The uncertainty and inconsistency of the individual tap sets is decreased by half when using several tap sets to measure the hydraulic average.

When an installed flowmeter has an upstream flow disturbance with high levels of uncertainty in the flow measurement, and it is not possible to perform a laboratory calibration on the meter, this research is beneficial. Implementing the method of the hydraulic average of several tap sets is simple, cost effective, and does not require a change in current pipe set-up.

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APPENDICES

Appendix A: Physical and Numerical Data

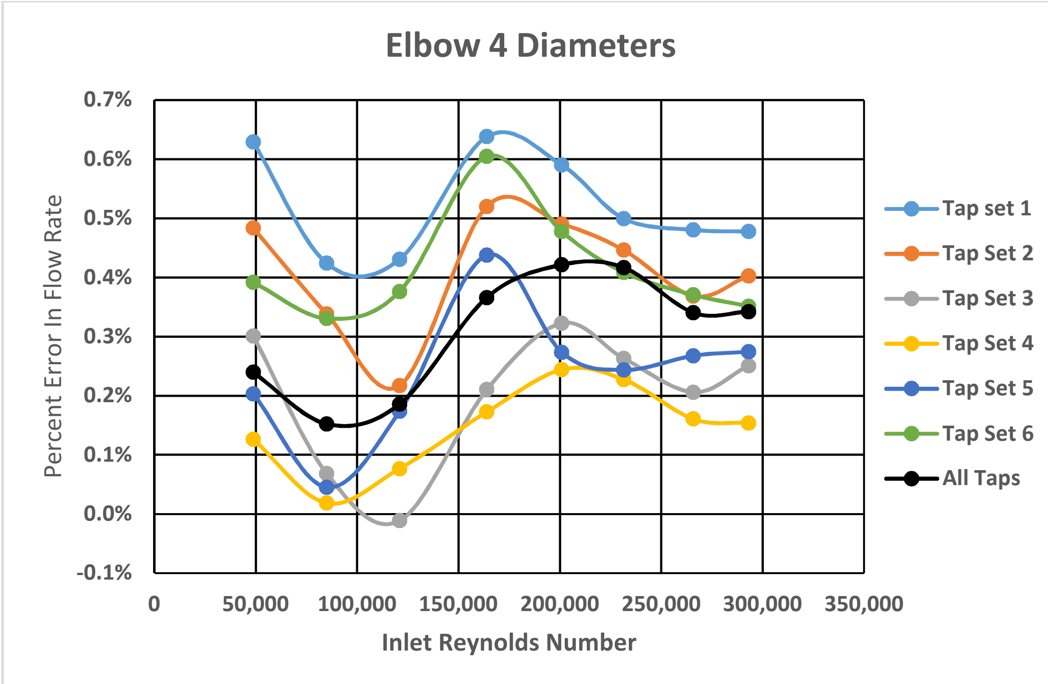


Figure 17. Measured flow rate vs actual flow rate with elbow 4 diameters

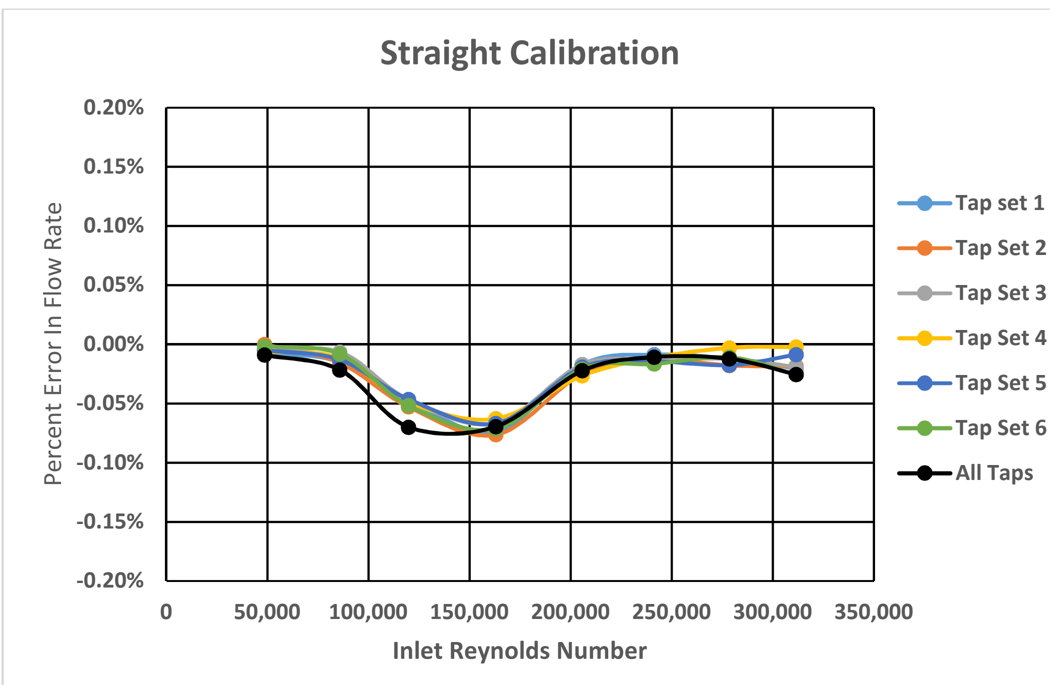


Figure 18. Percent error of measured vs actual flow rate for straight calibration

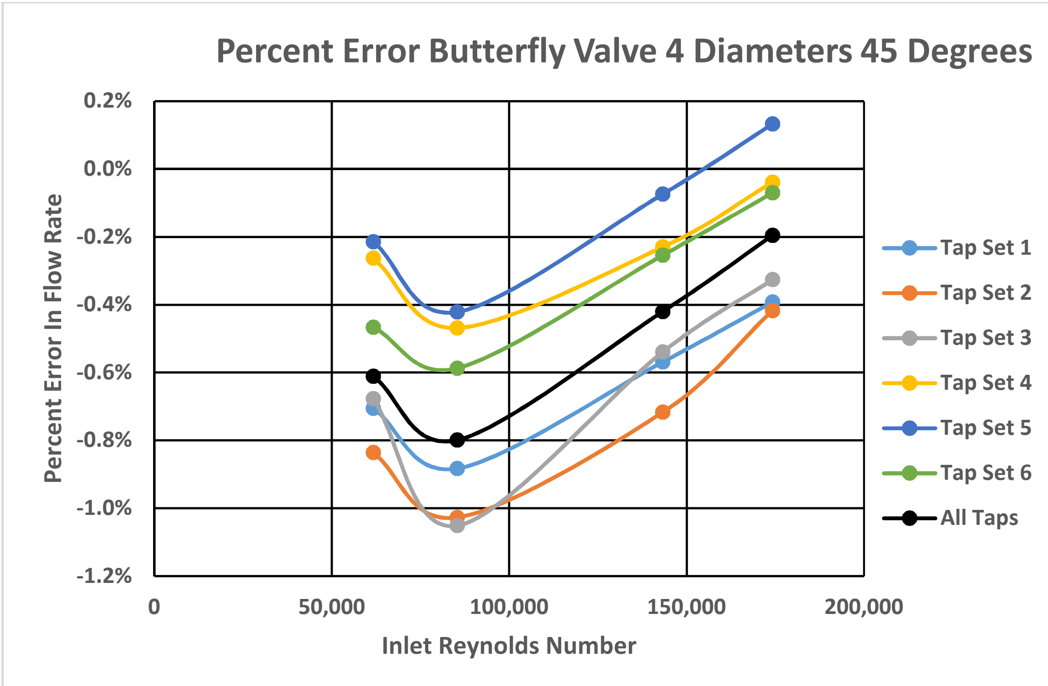


Figure 19. Measured vs actual flow rate with butterfly valve 4D upstream 45 deg

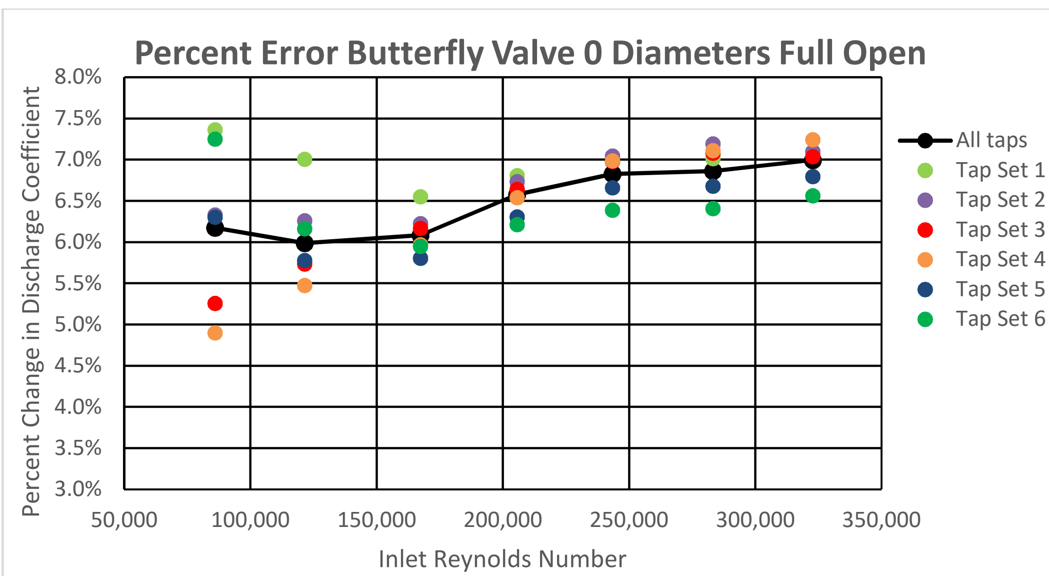


Figure 20. Measured vs actual flow rate with butterfly valve 0D full open

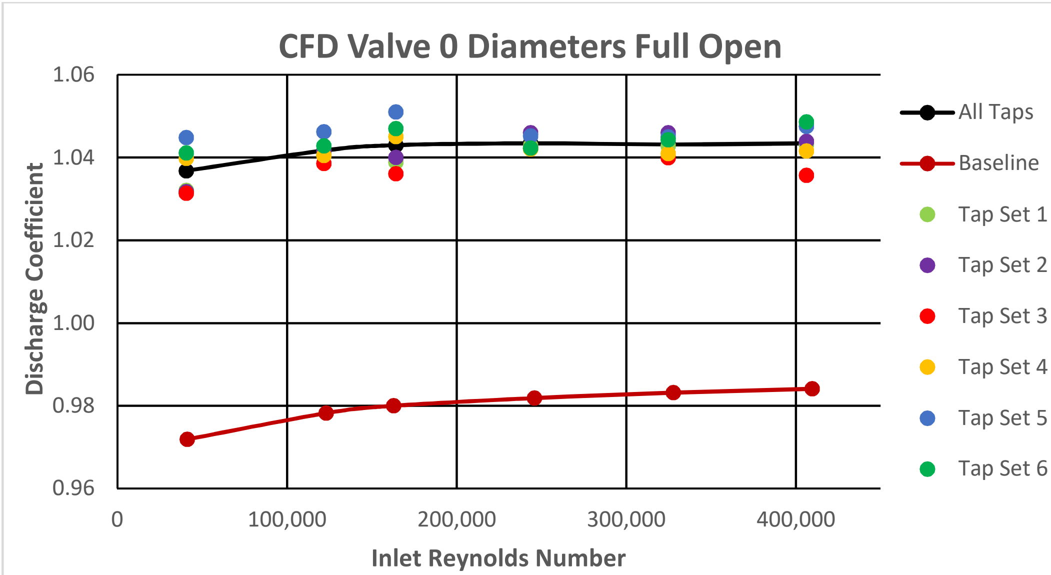


Figure 21. CFD calibration of 2-inch Venturi tap sets valve zero diameters

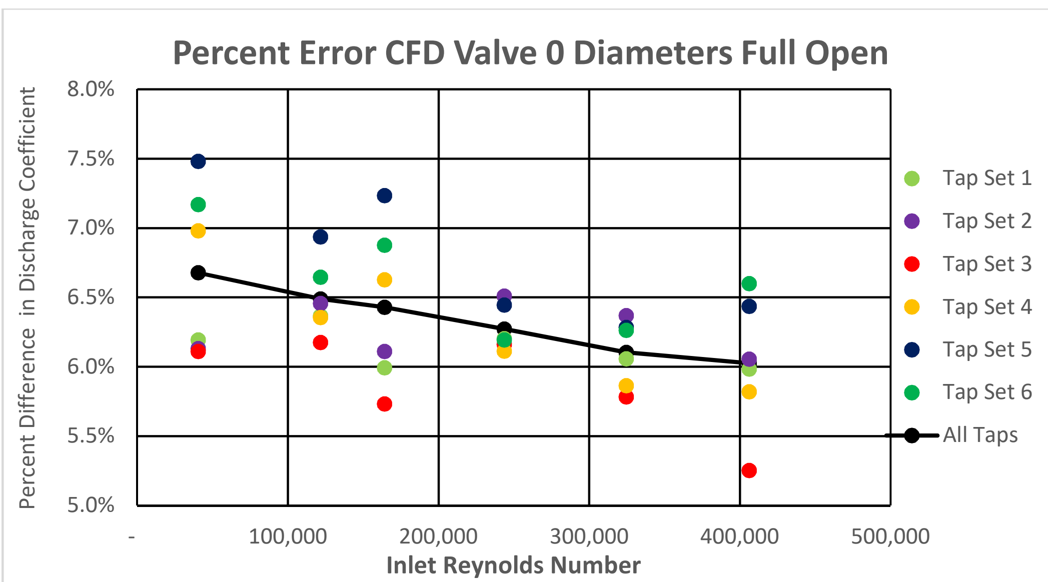


Figure 22. CFD difference in discharge coefficient from baseline for valve 0D

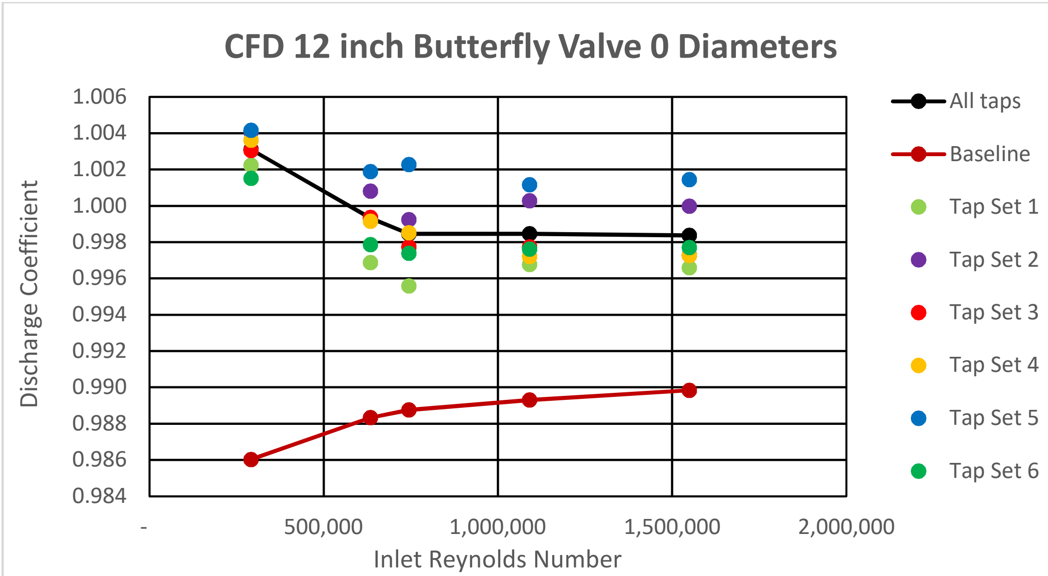


Figure 23.CFD calibration of 12-inch Venturi tap sets valve 0D upstream

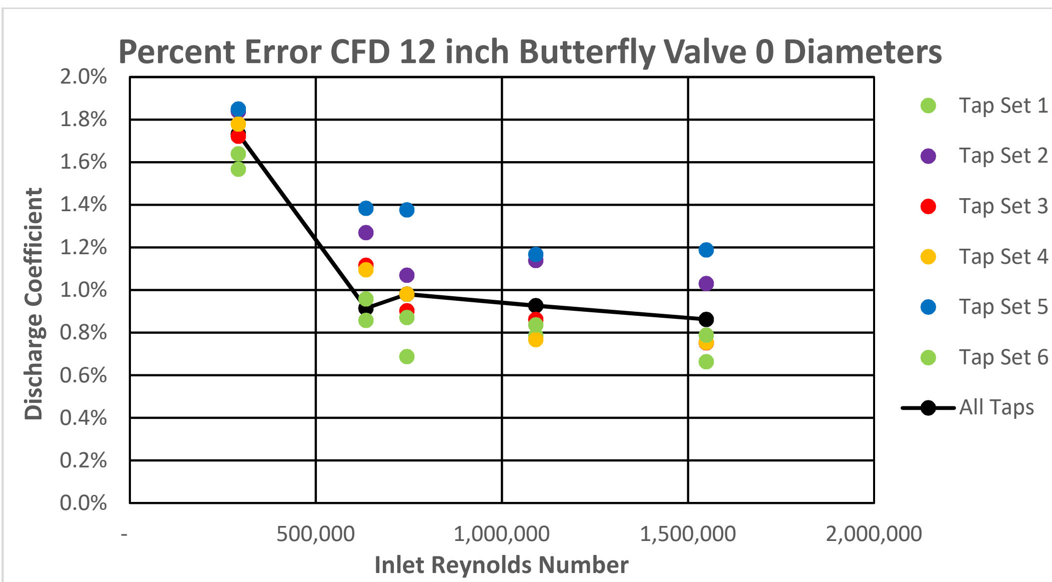


Figure 24. CFD difference in discharge coefficient from baseline for valve 0D

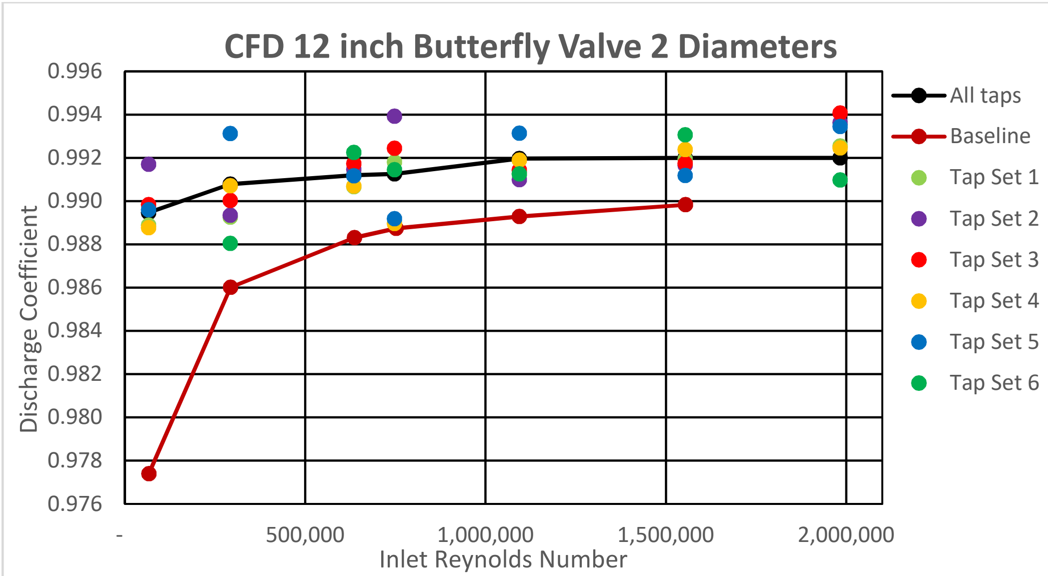


Figure 25.CFD calibration with valve two diameters upstream

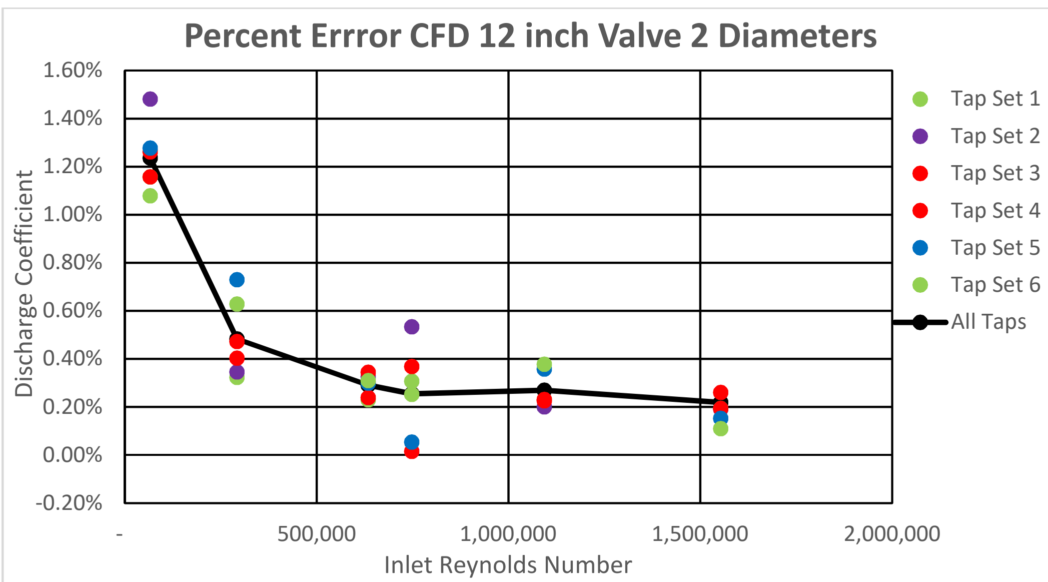


Figure 26. CFD difference in discharge coefficient from baseline with valve 2D

Appendix B: Numerical Modeling Images

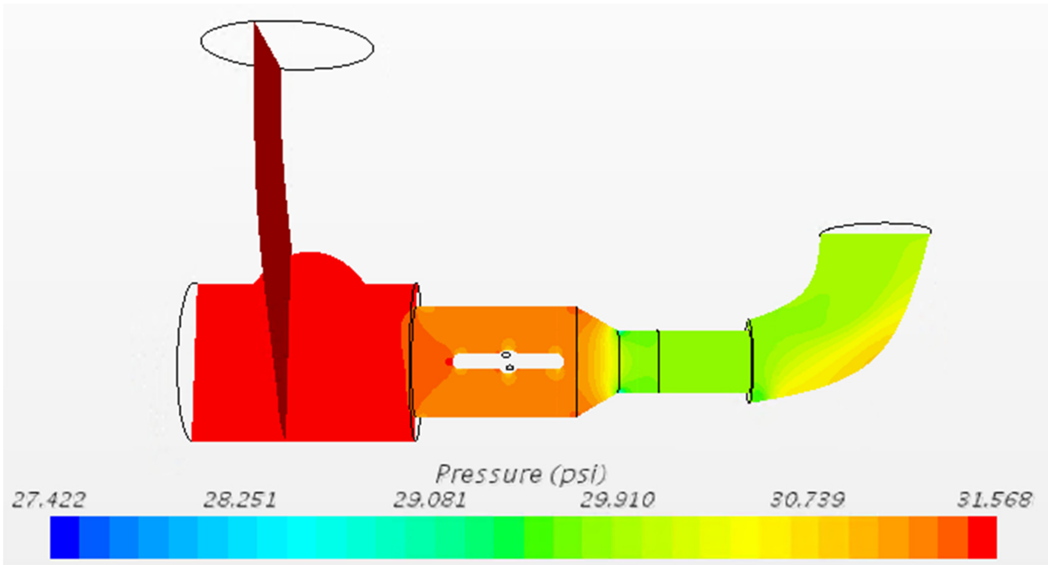


Figure 27. Pressure profile of combined flow set up with 2340 gpm

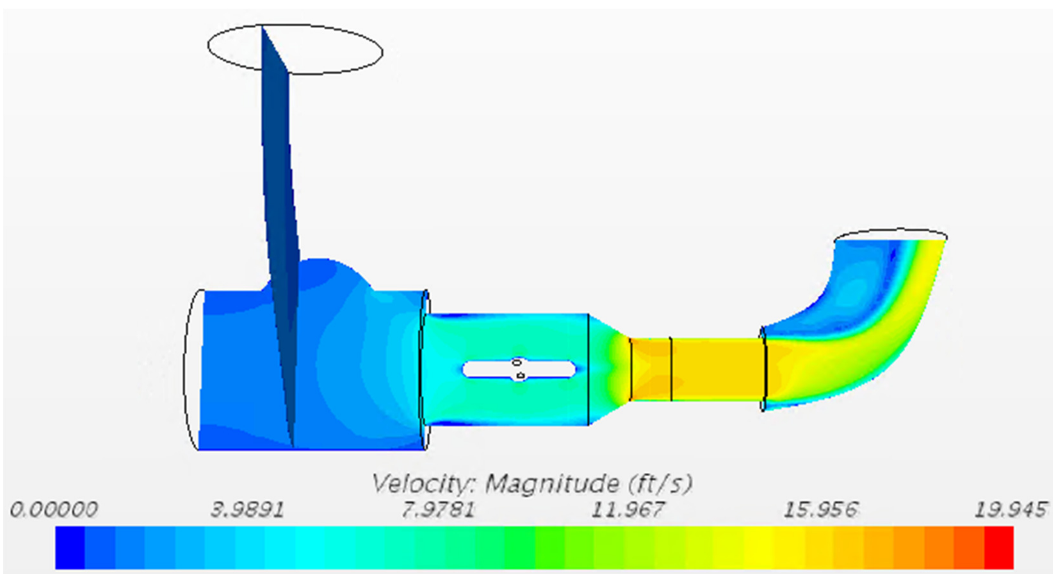


Figure 28. Velocity profile of combined flow set up with 2340 gpm

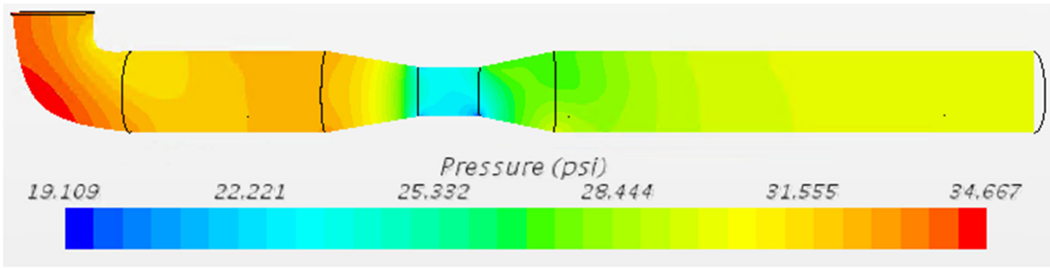


Figure 29. Pressure profile of 2 inch Venturi with elbow 2D at 150 gpm

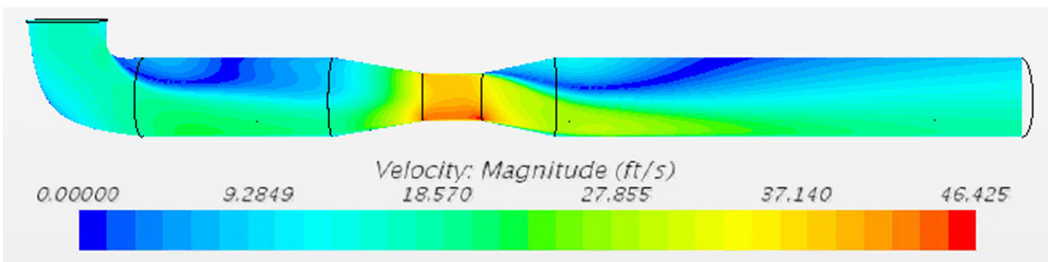


Figure 30. Velocity profile of 2 inch Venturi with elbow 2D upstream at 150 gpm

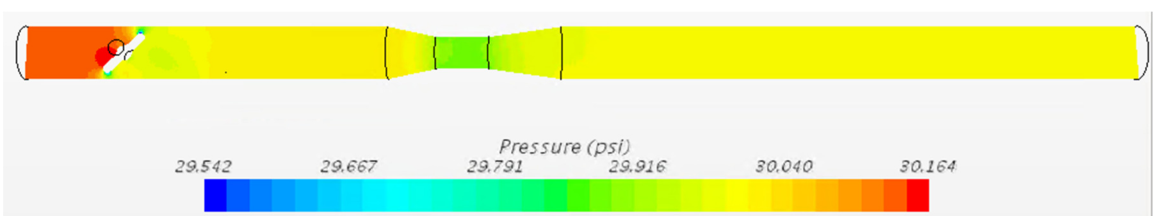


Figure 31. Pressure profile of 12 inch Venturi with valve 45 degrees open 4D

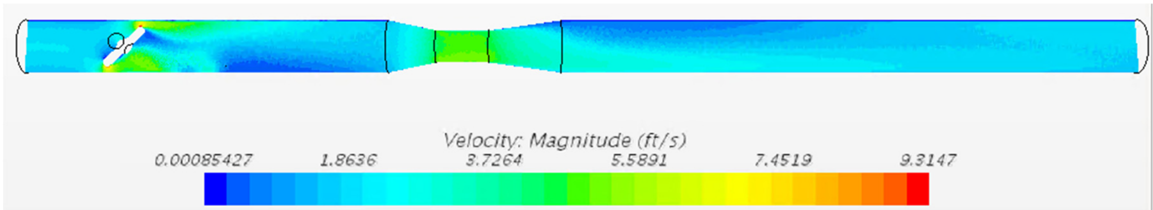
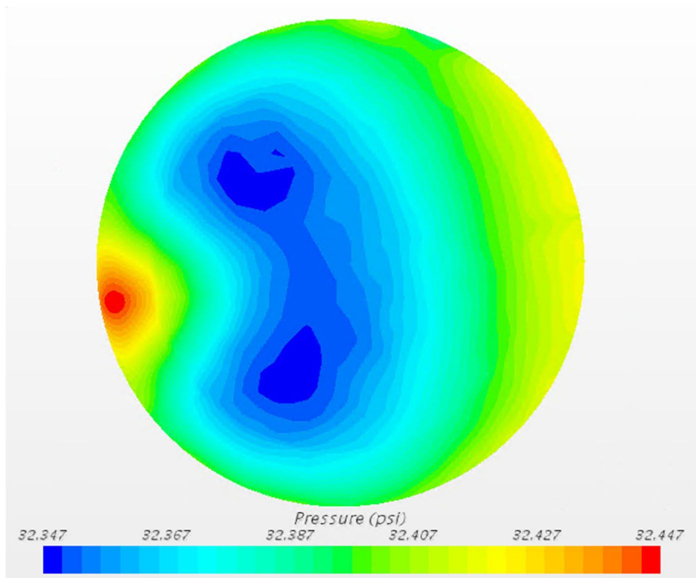


Figure 32. Velocity profile of 12 inch Venturi with valve 45 degrees open and 4D



Appendix C: Test set-up images

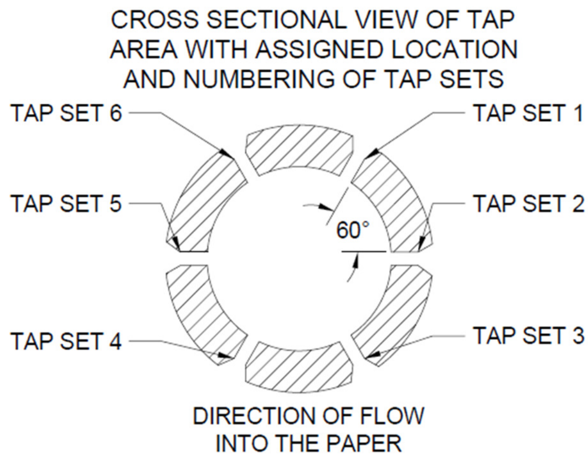


Figure 33. Assigned orientation of tap sets 1-6

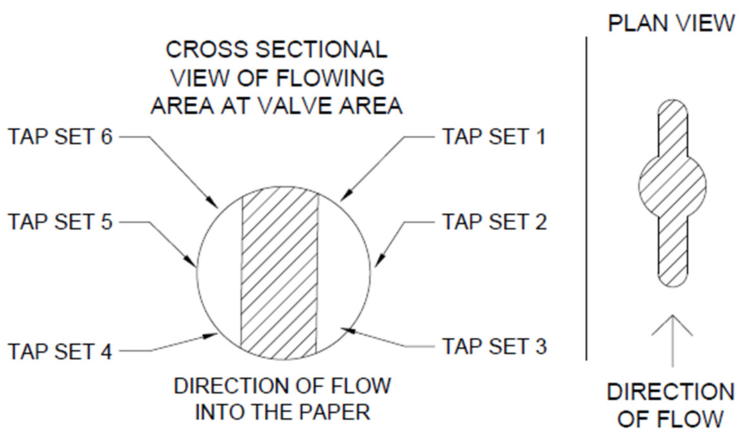


Figure 34. Orientation of valve with respect to tap set location

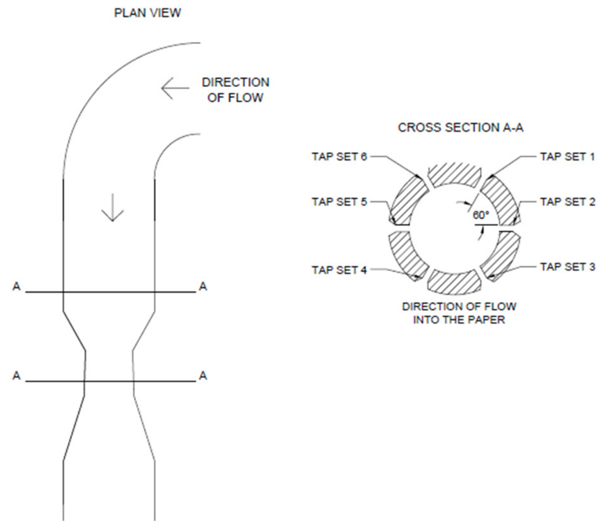


Figure 35. Plan and cross-section view of meter with elbow and tap orientation

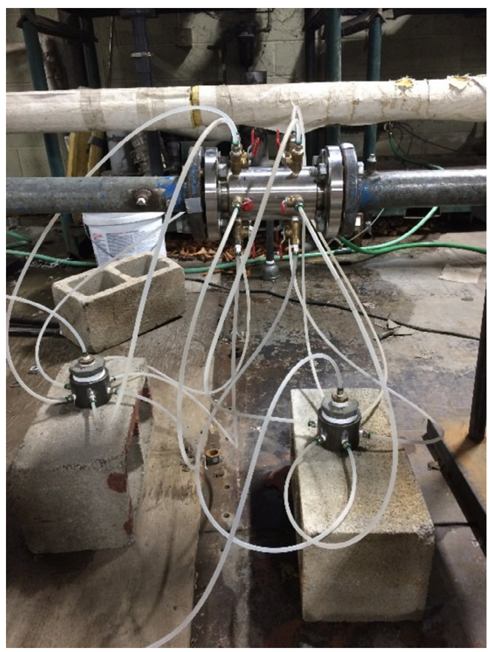


Figure 36. Baseline calibration of 2-inch Venturi

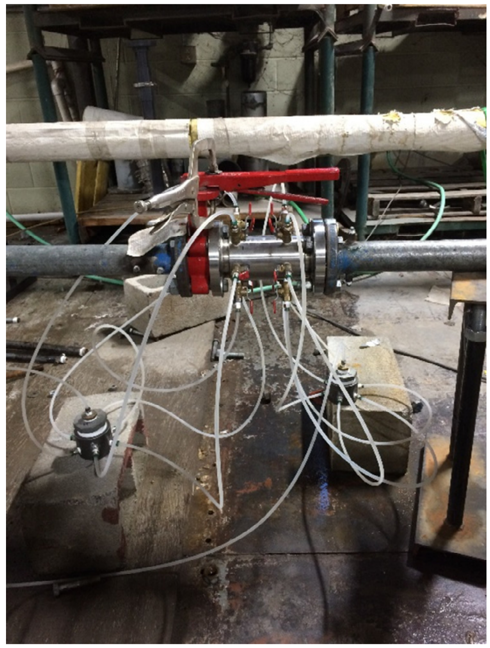


Figure 37. Calibration of 2-inch Venturi with valve zero diameters

Figure 38. Calibration of 2-inch Venturi with valve two diameters

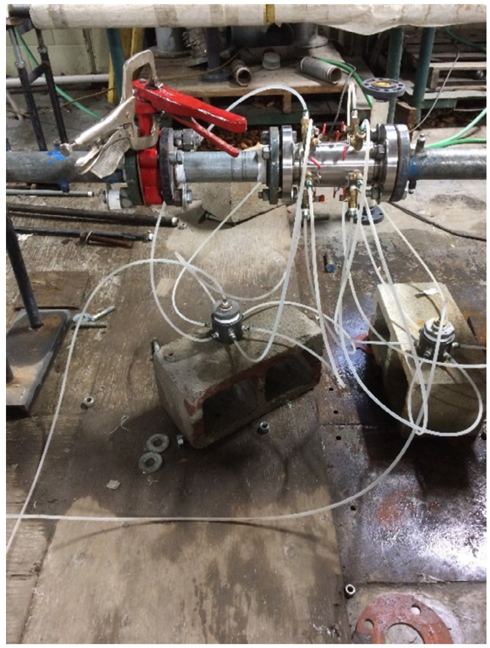


Figure 39. Calibration of 2-inch Venturi with valve four diameters

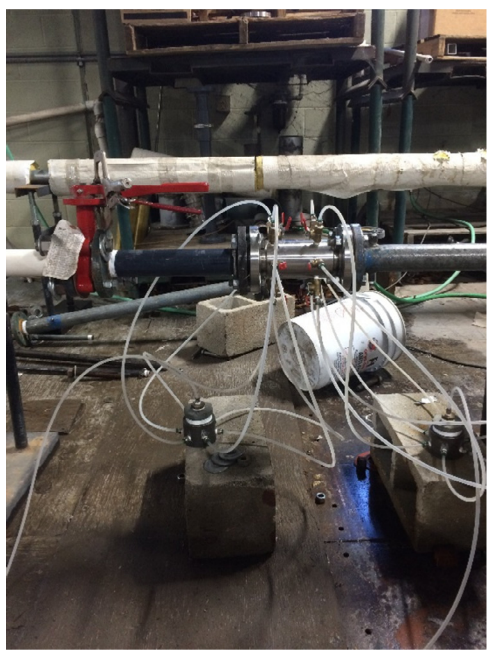


Figure 40. Calibration of 2-inch Venturi with valve six diameters

Figure 41. 2-inch butterfly valve used in physical testing