RESEARCH ARTICLE OPEN ACCESS

# Classical Venturi Meter Performance Downstream of a Bifurcating Tee Junction

Matthew P. Day*, Michael C. Johnson**, Zachary B. Sharp***
*(Department of Civil and Environment Engineering, Utah State University, and Logan Utah
Email: 14mattday@gmail.com)
** (Department of Civil and Environment Engineering, Utah State University, and Logan Utah
Email: michael.johnson@usu.edu)
*** (Department of Civil and Environment Engineering, Utah State University, and Logan Utah
Email:zachary.sharp@usu.edu)

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## Abstract:
A study was performed to analyze the capabilities of Star CCM+ to accurately model the performance of a Venturi meter installed downstream of a tee junction on the through leg. Physical data was collected on a 6-inch BIF Universal Venturi Tube (UVT) closed coupled to and five diameters downstream from a round cornered tee junction to determine actual flow coefficients for a range of total flow rates and varying flow splits through the tee junction. CFD simulations of the physical data were conducted and verified, CFD was then used to numerically determine discharge coefficients for setup variations by changing the tee junction to sharp cornered, the meter type, meter beta ratio, and overall scale. Discharge coefficient ratios. Or correction factors, were calculated based on these analyses and applied to the flow equation to improve metering accuracy installed downstream of a tee junction on the through leg.

*Keywords* **—Classical Venturi, Bifurcating, Tee Junction, C-Values**

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## I. INTRODUCTION

The ability to accurately measure flow rate in pressurized pipelines is a critical aspect of many companies and organizations that extract, transport, or produce fluid resources such as crude oil, or products like drinking water or gasoline. Miscalculations in flow rate at any point throughout these processes may reduce overall revenue, result in over billing, and jeopardize product quality. Along with analysing current operating conditions, accurate flow rate measurements also help guide future planning and construction. Flow rate data collected over many years is an indicator to determine if existing infrastructure had adequate capacity to meet projected demands or if the infrastructure needs to be improved or replaced.

There are many different types and styles of flowmeters, each unique in form, mechanisms, accuracy, and cost to meet varying project constraints. Pereira provides a list of many types of meters and how they function, some of which include: differential pressure producing meters, turbine meters, positive displacements meters, and ultrasonic meters [1].

Classical Venturi meters are simple, reliable, cost effective and commonly used throughout the industry. These meters are highly accurate when properly installed following established standards, created by the American Society of Mechanical Engineers (ASME), the International Organization for Standardization (ISO), and even certain meter manufacturers, that require a certain number of nominal lengths of straight pipe upstream and downstream of the meter ([2]&[3]). When these standards are not followed and a meter is installed too close to upstream flow disturbances, like elbows and tee junctions, flow rate measurement accuracy may be compromised. To avoid decreased measurement accuracy in these types of installations, the meter must be calibrated in a research facility using the same pipe configurations and flow conditions. Laboratory calibrations require additional costs and time but remain the best alternative for assessing a flowmeter's performance.

There is some research available covering how metering capabilities for Classical Venturi meters, Halmi Venturi tubes, Wedge meters, Venturi Cone meters, HBX-1 meters, electromagnetic flowmeters, and ultrasonic meters are directly influenced by certain upstream flow disturbances such as pipe offsets and elbows. However, there is little research done that analyses metering capabilities of a Classical Venturi meter downstream of a tee junction on the through leg, demonstrated in Fig. 1.

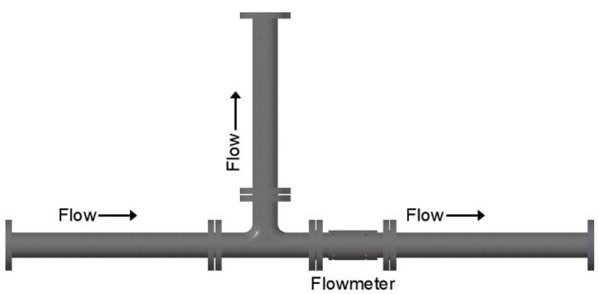


Fig. 1 Rendering of Classical Venturi meter installed zero diameters (0D) downstream of a round cornered tee junction.

The purpose of this research is to use computational fluid dynamics (CFD) to produce a cost-effective alternate approach to mathematically improve a flowmeter's capabilities when industry standards of meter installation cannot be met due to spatial and economic constraints which prevent a laboratory or adequate filed calibration.

The Utah Water Research Laboratory (UWRL) at Utah State University provided the resources needed to perform this research including instrumentation, pipes, meters, valves, computers, and software.

## II. LITERATURE REVIEW

Differential pressure producing flowmeters are widely used around the world, especially the Classical Venturi meter. Because of the extent to which this product is used, the American Society of Mechanical Engineers ([2]-[4]) and International Organization for Standardization[5] developed standards of installation and use. These standards indicate that the required length of upstream pipe from a Classical Venturi meter is dependent on the meter's beta ratio. When these standards cannot be met and a meter must be installed closer to an upstream disturbance than prescribed by code, the meter performance may be compromised. The following provides a summary of research relating to flowmeter performance installed downstream of flow disturbances.

S.N. Singh et al. examined the performance of a V-cone meter installed at various downstream distances from a gate valve at different opening conditions [6]. He concluded that the discharge coefficient of the meter is unaffected when the gate valve is installed at or more than 10 diameters upstream.

Bradford et al. researched the effects that a single elbow has on the accuracy of a Halmi Venturi Tube [7]. Bradford's studies proved that meter accuracy in adverse installation conditions is largely dependent on the beta ratio of the meter. In addition, Bradford demonstrated that Halmi Venturi Tubes perform well when installed in conditions contrary to those suggested by ASME and ISO for Classical Venturi meters. Neither ASME or ISO have produced standards for any proprietary short-form Venturi meters such as the Halmi Venturi Tube or the Universal Venturi Tube.

Radle investigated the performance of a Wedge flowmeter installed with different orientations at varying distances downstream from a double elbow out of plane (DEOP) disturbance. Radle found that the Wedge meter performance is not only controlled by distance of upstream pipe but also the orientation of the wedge. The results showed that the effect of the DEOP is reduced when the wedge is installed in plane with the second elbow [8].

  

Day et al. supplemented the information in Radle's research by further examining the effects that the DEOP has on other meters such as a Halmi Venturi tube, Venturi Cone meter, Classical Venturi meter, and a HBX-1 meter. Day showed that the DEOP disturbance effects each meter in a unique manner and that some of those meters perform well in this installation [9].

Stauffer viewed this topic differently. Instead of looking at how disturbances directly affect a meter, Stauffer et al. investigated the possibility of mitigating errors caused by upstream disturbances by using multiple tap sets on a Classical Venturi meter instead of the industry standard of a single tap set. By doing so, Stauffer decreased the uncertainty and inconsistency of using one tap set by half when using the average of multiple tap sets [10].

Sandberg conducted a study examining the effects that a bifurcating tee junction has on a 24-inch Classical Venturi meter installed on the branch leg. This research proved CFD is an effective tool to model flow and that creating contour plots of correction factors for overall flows against flow split ratios mathematically improves the meter's accuracy in those installations [11].

Further research is needed to evaluate the effects that a bifurcating tee junction has on a Classical Venturi meter installed downstream of the through leg. The procedures and tools used in Sandberg's research will be used for this research due to the conditional similarities.

## III. METHOD

Because a 6-inch Classical Venturi meter was not available for use in the laboratory, physical data was collected on a 6-inch universal Venturi tube (UVT) with a beta value of 0.7 installed in a straight-line installation, as seen in Fig. 2, to determine the meter's actual discharge coefficient, $C_{d(straight)}$. $C_{d(straight)}$ is calculated by comparing the actual flow rate to the calculated flow rate as seen in the equation

$$C_{d(straight)} = \frac{Q_{actual}}{Q_{calculated}}$$

where $Q_{actual}$ is determined either from a reference meter that was previously calibrated or capturing the flow in a NIST traceable weigh tank. The volumetric flow rate equation for $Q_{calculated}$ is found in the Flow Measurement Engineering Handbook by Miller [12]

$$Q_{calculated} = A_t * \sqrt{\frac{2 * g_c * \Delta P}{\rho_f * (1 - \beta^4)}}$$

Where, $A_t$ is the cross-sectional area of the meter's throat in feet squared, $g_c$ is the conversion constant $32.17405 \frac{lb_m * ft}{lb_f * s^2}$, $\Delta P$ is the differential pressure in pounds per square feet, $\rho_f$ is the fluid density in pounds mass per cubic foot, and $\beta$ is the meter beta ratio.

Fig. 2 Physical Testing Straight-line Calibration

Following the physical straight-line calibration, the UVT meter is installed at zero diameters (0D) and five diameters (5D) downstream from the through leg of a round cornered tee junction, as seen in Fig. 3 and Fig. 4 respectively. These tests were conducted at a high Reynolds number around 700,000, and a low Reynolds number around 200,000 with flow splits of 100%, 80%, 60%, 40%, and 20%. When flow splits are mentioned, it refers to how much of the total flow entering the tee junction is being directed through the meter.

  

The same procedure is followed as for a straight-line calibration, however, now the discharge coefficient is referred to as the $C_{d(0D)}$ and the $C_{d(5D)}$ . For all physical tests the differential pressure, actual flow rate, and temperature data points were collected to determine each discharge coefficient and the respective measurement uncertainty was determined following ASME Performance Test Code 19.5-2004.

The $C_{d(straight)}$ values were then interpolated based on the meter Reynolds number to match the meter Reynolds number of each run at 0D and 5D. Once the interpolation for each run is complete, the percent deviation from the straight-line calibration can be calculated using

$$Deviation = 100 * \frac{C_{d(0D or\ 5D)} - C_{d(straight)}}{C_{d(straight)}}$$

and plotted against the ratio of flow rate through the meter to the total flow rate.

Fig. 3 Physical Testing 0D Setup

Fig. 4 Physical Testing 5D Setup

The physical data collected is then used to verify and validate CFD simulations of the exact same setup and flow conditions. Once the CFD is verified, it can be used as an economically viable tool to run simulations on the setup variations needed for this research including changes in tee junction geometry, meter type, beta ratio, and pipe size.

It is important to note that tap set locations for this study are consistent through the physical and CFD simulations. Fig. 5 shows the orientation and reference number for each tap set location used in this study. The straight-line calibrations have tap set locations in the same places omitting the branch of the tee junction.

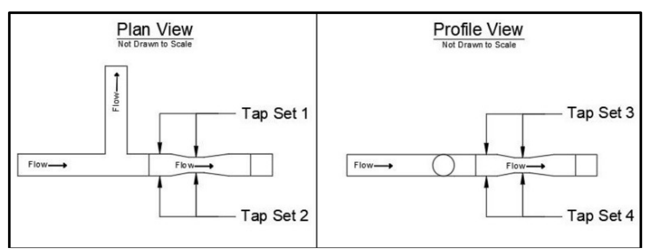


Fig. 5 Orientation of Tap Sets

An in-depth explanation of how-to setup CFD simulations and how the software functions is beyond the scope of this paper. For any information regarding how to use CFD or how CFD works, the reader is referred to Siemens CFD documentation [13] or to any other peer reviewed published articles that discuss CFD, Navier-Stokes equations, or any of the turbulence models the reader may encounter. The physical models used in the simulations for this research are constant density, exact wall distance, gradients, K-epsilon turbulence, liquid, realizable K-epsilon two-layer, Reynolds-averaged Navier-Stokes (RANS) segregated flow, steady state, three dimensional, turbulent, and two-layer all y+ wall treatment.

CFD uses a collection of volume cells to run calculations for governing equations such as continuity, momentum, and conservation of energy. The collection of cells is known as the mesh, which can be altered based on user-specified inputs. As the cells get smaller, the computation time increases. On the other hand, when cells become too large, the accuracy of the model is compromised. Finding a balance between the user's acceptable model accuracy and run-time is important. One way to achieve this balance is by performing a grid convergence method (GCI) developed by Celik[14].

A GCI analyses the results from the same simulated flow condition with cell base size in successive order 1.3 times smaller than the last. The results of the GCI procedure provide the user with a numerical value that represents the uncertainty of the simulations results based on the middle cell sized used. For all 6-inch diameter simulations, the maximum uncertainty based on a cell base size of 0.35-inches was 0.87%. Additionally, all 24-inch diameter simulations had a maximum calculated uncertainty of 0.82% for a cell base size of 2-inches.

Once CFD had been verified with the physical data, the following setup variations were conducted at both 0D and 5D at various Reynolds numbers:

1) The same UVT meter tested downstream of a sharp cornered tee junction
2) A 6-inch Classical Venturi meter, beta 0.7, downstream of a sharp cornered tee junction
3) A 6-inch Classical Venturi meter, beta 0.5, downstream of a sharp cornered tee junction
4) A 24-inch Classical Venturi meter, beta 0.7, downstream of a sharp cornered tee junction

The results of these setup variations and all the previously mentioned data is organized and presented in one of two ways. First, the data is presented on plots that correlate each runs percent deviation from the straight-line calibrations to the flow split at the specific run. This form of data presentation allows each setup variation to be compared and analysed efficiently to determine the major and minor variables. Secondly, the data is consolidated into contour plots of correctional factors plotted against both meter Reynolds number on the y-axis, and flow split on the x-axis. The contour plots are user friendly and provide a method to apply the results in real-world applications as seen in the example section.

## IV. RESULTS

Proving that CFD can be used as a predictive tool for this research was the first objective of the study. CFD simulations were able to predict $C_{d(straight)}$ for the UVT meter used in physical testing for all tap sets to within 1.44%. Additionally, the trends developed by the physical data for percent deviation from the straight-line test for both the 0D and 5D installations were closely predicted by CFD as seen in Fig. 6 and Fig. 7 respectively. Note the y-axis scale difference between the two figures.

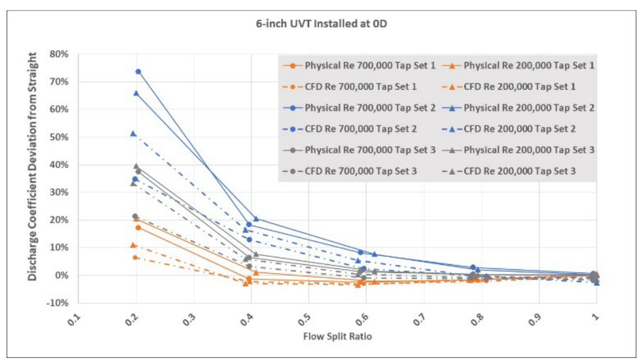

Fig. 6 Plot of Discharge Coefficient Deviation from Straight for 6-inch UVT Meter with Beta Value of 0.7 Installed 0D Downstream of a Round Cornered Tee Junction

  

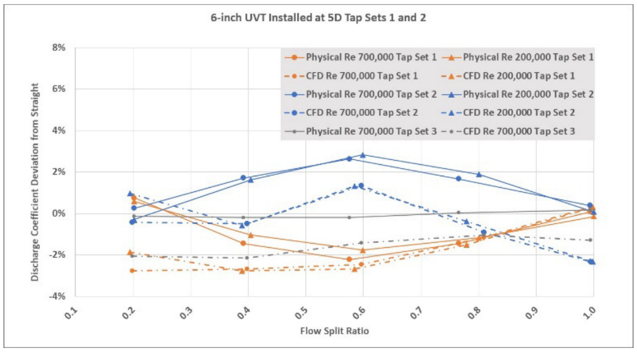


Fig. 7 Plot of Discharge Coefficient Deviation from Straight for 6-inch UVT Meter with Beta Value of 0.7 Installed 5D Downstream of a Round Cornered Tee Junction

It is important to note that CFD did not output the same absolute values as the physical data, especially at 40% flow splits and lower. This research is not focused on obtaining absolute answers, but rather analysing the trends that occur with changes in setup. For this reason, CFD, based on these results, is verified, and validated as a useful tool for the remainder of the data collection. In this way, CFD can be used to perform a straight-line meter evaluation and then a simulated pipe evaluation and provide information on how the discharge coefficient may need to be corrected.

One variable to analyse is how different meters perform under the same installation conditions. For this analysis a 6-inch UVT meter and a 6-inch Classical Venturi meter, both with a beta value of 0.7, were simulated at 5D from a round cornered tee junction with a main inlet Reynolds Number of 700,000.

The results from these simulations is presented in Fig. 8. The information in this graph shows that each type of meter has specific benefits and disadvantages. The 6-inch UVT meter has well-developed trends for each tap set over the entire range of flow splits with one exception, Tap Set 2 at 60% flow split. However, the deviation from the straight-line calibration between each tap set is 2.5% to 4% over most of the flow splits. This shows that each tap set has unique metering capabilities, and some may be more accurate than others.

The 6-inch Classical Venturi meter, on the other hand, has a spread of at most 1.5% between data points at the same flow split, with most points falling within 0.5% of one another. The challenge that the Classical Venturi meter faces is the unpredictability in the trend line at the 60% flow split. If the trend were stable, then the points at a flow split of 60% would be around -2.6% deviation from straight, however, these points lie between -0.2% and +1.5% deviation from straight.

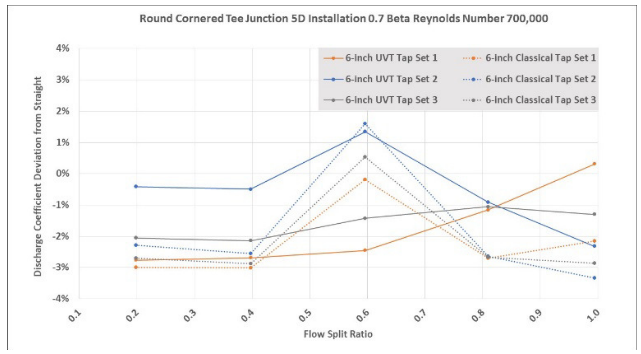


Fig. 8 Plot of Discharge Coefficient Deviation from Straight for 6-inch UVT and Classical Venturi Meter with Beta Values of 0.7 Installed 5D Downstream of a Round Cornered Tee Junction

To analyse the effects of beta value on the solution, two 6-inch UVT meters are modelled at 5D, one with a beta value of 0.7 and the other having a beta value of 0.5 with Reynolds Number of 700,000 in the pipe entering the tee junction. These are typical high and low beta values for Classical Venturi meters.

Fig. 9 demonstrates that as the beta value of the meter decreases, or in other words the diameter of the throat relative to the inlet decreases, meter accuracy increases over the entire range of flow splits for every tap set. Tap Set 1 shows 60% improvement in accuracy for flow splits between 20% and 60%, a 50% improvement for the 80% flow split, and an 80% improvement when all flow is directed through the meter. Tap Set 2 has varying magnitudes of improvement over the entire flow range, but most notably, the peak at 60% flow split is improved by 65%. Tap Set 3 on average has 65% greater accuracy with a beta value of 0.5 than with a beta value of 0.7.

It is important to consider for this analysis that at 5D, all data points still land between +2.8% and -4.8% of the straight-line calibration. The trends from the 0.7 beta and 0.5 beta do not change much, however, the increase in accuracy for every tap over the entire flow range indicates that a meter's beta value is a critical factor for metering accuracy when installed downstream of a tee junction on the through leg.

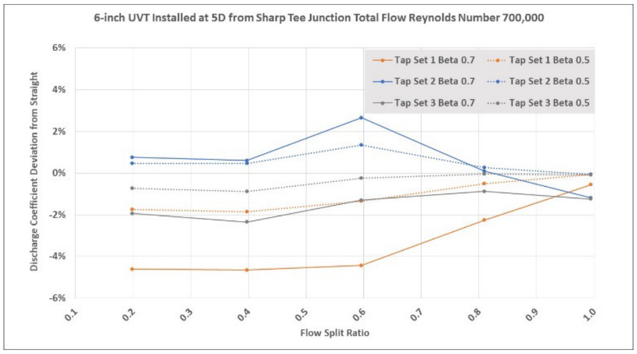


Fig. 9 Plot of Discharge Coefficient Deviation from Straight for 6-inch UVT Meter with Both a Beta Value of 0.7 and 0.5 Installed 5D Downstream of a Sharp Cornered Tee Junction

The results from the physical data collected with the UVT meter installed downstream of a round cornered tee junction and the CFD simulations conducted with the same UVT meter downstream of both a round and sharp cornered tee junction, show that the change in tee junction geometry from round cornered to sharp cornered had a minor effect on the final solution. On average both the sharp and round cornered CFD models at 5D were within 1.55% of the physical data and had an average spread between the two CFD datasets of 0.12% with a maximum spread at a flow split of 40% of 1.97%.

Additionally, the results demonstrate that the overall pipe size has little effect on the outcome of the simulations. The CFD simulations of a 6-inch Classical Venturi meter and a 24-inch Classical Venturi meter, both with beta value of 0.7, have a maximum spread of 0.64% between data points at a flow split 40%. The average spread between the two datasets is 0.32%.

## V. EXAMPLE

This example shows this process by using the physical and CFD data collected on the 6-inch UVT meter with 0.7 beta ratio on Tap Set 1 installed 0D. The data point selected to analyse for this example was at a total flow rate of 1745.0 gpm and a differential pressure across the UVT of 0.261 psi. From the data collected, it is known that 349 gpm is flowing through the UVT. The meter has a straight-line calibration Cd of 0.981 provided by the manufacturer. This means that under these conditions, the indicated flow would be calculated as follows.

First convert the differential pressure from units of pound per square inch to pounds per square foot.

$$0.261\frac{lb}{in^2} * 144\frac{in^2}{ft^2} = 37.584\frac{lb}{ft}$$

Now calculate the flow rate in gallons per minute.

$$Q = C_d * A_t * \sqrt{\frac{2 * \Delta P * g_c}{\rho(1-(\beta)^4)}}$$

$$Q = 448.831\frac{gpm}{cfs} * \ 0.981 * 0.0983\ ft^2 * \sqrt{\frac{2 * 37.584\frac{lb}{ft^2} * 32.17405\frac{ft}{s^2}}{62.4034\frac{lb}{ft^3 ft^2} * (1-(0.6962)^4)}}$$

Consolidate the units.

$$Q = \ 448.831\frac{gpm}{cfs} * \ 0.981 * 0.0983\ ft^2 * \sqrt{50.66\ \frac{ft^2}{s^2}}$$

$$Q \ = 448.831\frac{gpm}{cfs} * \ 0.981 * 0.0983\ ft^2 * 7.12\ \frac{ft}{s}$$

$$Q = 308.05\ gpm$$

The meter indicates that the flow is 308.05 gpm which is 11.73% lower than the actual flow rate. To start the flow rate adjustment process, the meter's Reynolds number and the flow split ratio must be calculated as follows.

$$Reynolds = \left( \frac{\frac{308.05\ gpm}{\frac{448.831 gpm}{\frac{ft^3}{sec}}}}{0.25 * \pi * \left(\frac{6.097\ in}{12\frac{in}{ft}}\right)^2} \right) * \frac{\left(\frac{6.097\ in}{12\frac{in}{ft}}\right)}{.0000137\ \frac{ft^2}{sec}} \approx 125543.1$$

$$SplitRatio = \frac{308.05}{1745.0} = 0.177$$

Once these values are obtained, the Cd adjustment value can be extracted from the contour plot as seen in Fig. 10. In this case, a flow split ratio of 0.2 will be used because there is no data below this point.

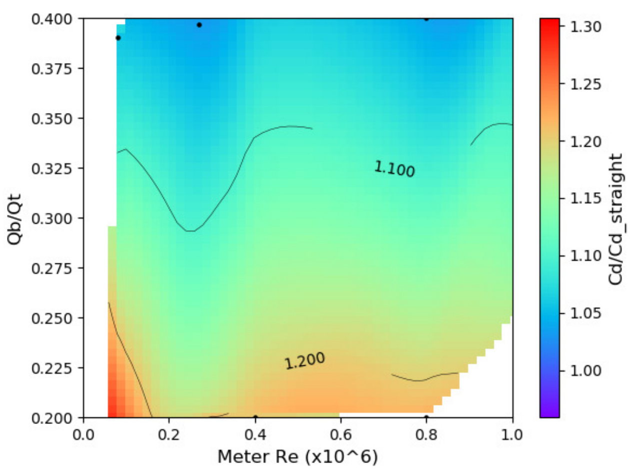


Fig. 10 Contour Plot for Flow Splits Between 20% and 40% of Correction Factors for a 6-inch UVT Meter with Beta Value of 0.7

From Fig. 10 the adjustment factor 1.23 is extracted and used in the following calculation to find a new indicated flow rate.

$$Q_{adjusted} = \frac{C_d}{C_{dstrait}} * C_d * A_t * \sqrt{\frac{2 * \Delta P * g_c}{\rho(1-(\beta)^4)}}$$

$$Q = 1.23 * 448.831 \frac{gpm}{cfs} * 0.981 * 0.0983\ ft^2 * \sqrt{\frac{2 * 37.584 \frac{lb}{ft^2} * 32.17405 \frac{ft}{s^2}}{62.4034 \frac{lb}{ft^3 ft^2} * (1-(0.6962)^4)}}$$

$$Q = 378.9\ gpm$$

After one iteration of this process, the meter shows an adjusted flow rate of 378.9 gpm which is 8.56% higher than the actual flow going through the meter. This process is meant to be iterated until the change in adjusted flow rate from one iteration to the next does not change. To fulfill the purpose of this example one more iteration will be needed. Start the next iteration by calculating the new Meter Reynolds number.

$$Reynolds = \left( \frac{\frac{378.9\ gpm}{\frac{448.831 gpm}{\frac{ft^3}{sec}}}}{0.25 * \pi * \left(\frac{6.097\ in}{12\frac{in}{ft}}\right)^2} \right) * \frac{\left(\frac{6.097\ in}{12\frac{in}{ft}}\right)}{.0000137\ \frac{ft^2}{sec}} \approx 154417.4$$

$$SplitRatio = \frac{378.9}{1745.0} = 0.217$$

Once these values are obtained, the Cd adjustment value can be extracted from the contour plot as seen in Fig. 11.

  

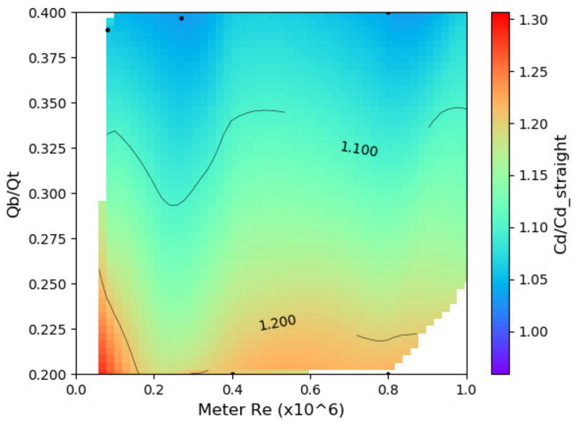


Fig. 11 Contour Plot for Flow Splits Between 20% and 40% of Correction Factors for a 6-inch UVT Meter with Beta Value of 0.7

From Fig. 11 the adjustment factor 1.18 is extracted and used in the following calculation to find a new indicated flow rate.

$$Q_{adjusted} = \frac{C_d}{C_{dstrait}} * C_d * A_t * \sqrt{\frac{2 * \Delta P * g_c}{\rho(1-(\beta)^4)}}$$

$$Q = 1.18 * 448.831 \frac{gpm}{cfs} * 0.981 * 0.0983\, ft^2 * \sqrt{\frac{2 * 37.584 \frac{lb}{ft^2} * 32.17405 \frac{ft}{s^2}}{62.4034 \frac{lb}{ft^3 ft^2} * (1-(0.6962)^4)}}$$

$$Q = 361.96\, gpm$$

After the second iteration of this process, the meter shows an adjusted flow rate of 361.96 gpm which is 3.7% higher than the actual flow going through the meter. This example shows that within two iterations of applying correction factors, there is a 68.3% improvement in flow rate.

## VI. CONCLUSION

Differential pressure producing flowmeters are used in many industrial and municipal applications. Ensuring that these meters accurately measure flow rate is of high importance to provide processes and consumers with high quality products and services. There is much importance placed on accurate flow measurement that standards of installation and use have been created to guide proper hydraulic design both upstream and downstream of the meter. However, meeting these standards is not always practical due to spatial or fiscal constraints.

When pipe systems are designed that place flowmeters in installation layouts contrary to those established by industry or manufacturer standards, the best solution is to perform a laboratory calibration of the meter with the same installation specifications as the design. Laboratory calibrations, like those performed at the Utah Water Research Laboratory, are typically cost effective and timely. However, when setup for a calibration of large-sized pipe requires extra space, manpower, and run time, these calibrations can become expensive. In these cases, performing CFD models, although not as accurate as a laboratory calibration, may be sufficient based on client needs.

For the case studied in this research, a flowmeter installed downstream of a tee junction on the through leg the overall pipe size and tee junction geometry were found to have little to no impact on the results.

On the other hand, there are three variables that require more attention to obtain accurate results from the simulations. First, the meter geometry, including the length of the inlet section, angles of contraction and expansion, and the length of the throat must be modelled as close to the physical dimensions as possible. Second, the flow splits that are going to occur in the tee junction in the field must match those flow splits in the simulations. If this cannot be achieved, it is important to simulate enough flow splits to understand the trend of data over the needed flow split range. Lastly, modelling the meter beta ratio as close to the physical dimensions as possible is important to understand how that meter will perform.

It is important to note that this research has limitations and proper engineering judgement must be used when applying the findings. These limitations include the modelling capabilities of the software, the scope of work only includes an analysis of two-meter types, two beta values, and only incompressible fluids were analysed.

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