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The Effects of Upstream Straight Pipe Length on Magnetic Flow Meter Accuracy

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THE EFFECTS OF UPSTREAM STRAIGHT PIPE LENGTH ON MAGNETIC FLOW METER ACCURACY

by

Bradley C. Clawson

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Steven L. Barfuss Major Professor	Michael C. Johnson Committee Member
John D. Rice Committee Member	Mark R. McLellan Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2016

ABSTRACT

The Effects of Upstream Straight Pipe Length
on Magnetic Flow Meter Accuracy

by

Bradley C. Clawson, Master of Science

Utah State University, 2016

Major Professor: Steven L. Barfuss
Department: Civil & Environmental Engineering

In closed conduit water systems, being able to accurately measure flow is absolutely essential. For many meter designs, including electromagnetic induction meters (also known as magnetic flow meters), the greatest accuracy is achieved when the device is calibrated correctly. Optimal meter accuracy often depends on the flow conditions associated with the upstream geometry in the pipe system. Manufacturers typically give standards for the length of straight pipe required upstream of the meter. These standards vary, however, and do not address every possible configuration that may be installed upstream of the straight pipe requirement.

An investigation on the effects of the length of straight pipe between a single 90° elbow and the upstream side of magnetic flow meters was completed in this research. Eleven 10-inch meters were chosen for testing. The procedure included a baseline test with more than forty diameters of straight pipe between the elbow and the meter. The accuracy of the meter was determined over a range of flow velocities typical for operation of this type and size of meter. Further tests were performed with the meter installed only three diameters downstream of the elbow. These tests constitute Phase I. In Phase II, four meters were tested with the upstream pipe length varying from a close-coupled installation to ten diameters of straight pipe between the elbow and the meter to observe variances in accuracy with distance from the elbow.

The intent of the research was to show whether manufacturer accuracy specifications are achievable in actual application. It was determined that very few meters meet the manufacturer’s specification for accuracy even when installation requirements were met. Post-factory calibrations and minimization of velocity profile disruption through consideration of upstream geometry is recommended.

(49 Pages)

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ACKNOWLEDGMENTS

Working as a Research Assistant at the Utah Water Research Laboratory under Steven Barfuss has opened my field of view, not only to the techniques and subtleties of Civil Engineering Hydraulics, but also to what I can accomplish as I venture forward with my career. A special thanks to Steve, as well as Zac Sharp, Dr. Mike Johnson, and Dr. John Rice for the time and advice contributed to this project. Also, I want to thank my colleagues, Jordan Jarrett and Jared Justensen for their assistance with testing.

I want to thank my family and friends for encouraging me to continue with my education. I could not have accomplished this without the immense support of my wife, who stood by me through my doubts and long hours away from home.

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NOTATION

l = length of conductor (meters)

v = velocity (meters per second)

B = magnetic flux density (Tesla)

e = Voltage

Mfr = manufacturer

US = upstream

DS = downstream

1D = one diameter

2D = two diameters

3D = three diameters

5D = five diameters

6D = six diameters

10D = ten diameters

CC = close coupled

PVC = polyvinyl chloride

cfs = cubic feet per second

lbs = pounds

s = seconds

pcf = pounds per cubic foot

Q = flow rate (cfs)

W = weight of water (lbs)

t = time (s)

γ = unit weight of water (pcf)

mA = milliamps

Hz = hertz

Range = range of the multimeter

AD = average difference

AAD = adjusted average difference

STDV = standard deviation

MD = max difference

accy = accuracy

spec = specification

fps = feet per second

min = minimum

vel = velocity

DC = direct current

AC = alternating current

CHAPTER I

INTRODUCTION

Purpose

In closed conduit water systems, such as those used in irrigation or municipal water distribution, being able to accurately measure flow is extremely important. Even small errors when managing large volumes of water will result in either revenue losses or utility overcharges.

Widespread application of magnetic flowmeters has been available for many years. In recent years, electromagnetic induction meters (known as magnetic flow meters or “mag” meters) have improved in accuracy and decreased in cost, according to Thorn (2000). Magnetic flow meters commonly advertise high accuracy ratings and non-invasive measurement with little or no head loss, making them a competitive option for closed conduit flow measurement.

For many meter designs, including magnetic flow meters, ideal flow stream is required to eliminate errors in measurement. “Ideal” flow is defined by Kelner (2003) as having a fully developed, axisymmetric, swirl free velocity profile. Controlling flow conditions within the meter depends in part on the upstream geometry of the pipe system. Manufacturers typically give standards for the length of straight pipe required upstream of the meter. These standards vary, however, and do not address every case of what may be installed upstream of the straight pipe requirement. Often the specifications are given with little or vague instruction for when installation conditions are not ideal. Figure 1 is an example of what a manufacturer may describe as an installation requirement:

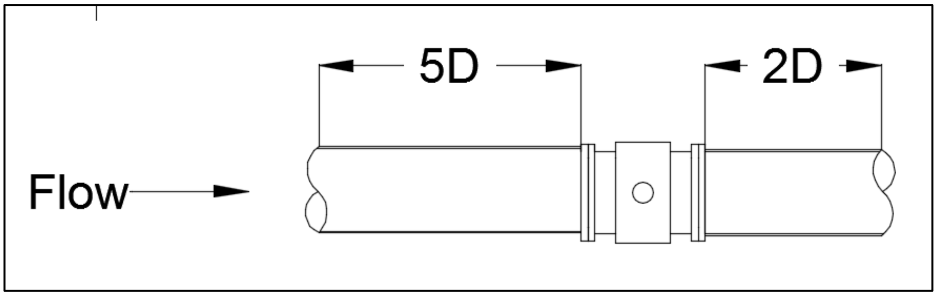

Figure 1. Example Installation Requirement Schematic

Different fixtures have very different effects on the flow profile. In some cases, the fixtures that apply to the requirement are stated, but not always. This is critical because, for example, an offset of pipe inside diameter does not carry the same effect as a butterfly valve at 25% open. The meters are typically tested in the manufacturer’s facilities. Manufacturers often recommend that additional laboratory calibrations are not necessary.

Disturbances in flow caused by upstream geometry installations can cause errors in flow measurement. Meters may be installed in a wide variety of circumstances. Pipe diameter offsets, elbows, valves, and meter orientation are just some of the factors that affect flow conditions. Kelner (2003) describes *installation effects* as the potential deviation in measurement due to such conditions. When space is limited, meters may not be installed using recommended practices.

Objective

The primary objective of this research was to add quantified data pertaining to the installation effects of at least one possible pipe setup for magnetic flow meters. For the meters tested, in many cases the expected accuracy in measurement is not reached, even when meters are installed according to manufacturer specification. The research shows that calibrations of meters in situ, or in exact replications of the flow conditions they will be operated in, may be necessary to ensure expected accuracy performance. This is due to the meter’s sensitivity to changes in the approach velocity profile.

This paper examines the effects of one common installation setup: a meter oriented vertically (with electrodes at the springline of the pipe) placed downstream of a single 90° angle elbow oriented horizontally. Laboratory tests were performed with varying lengths of straight pipe between the meter and elbow. Recommended conditions were studied based on manufacturer specifications. A range of non-recommended (shorter) pipe lengths to pipe lengths greater than required were also tested to gain an overall perspective of the effect of the elbow. The installation effects also are a function of water velocity. A range of flow velocities up to approximately 16 feet per second were tested in each pipe setup.

CHAPTER II

LITERATURE REVIEW

Several books and studies have provided recommendations on magnetic flow meter installation practices. The requirements for straight pipe length upstream and downstream of the meter are either based on empirical testing or on the manufacturer’s internal studies and recommendations. The figures vary slightly, but fall within the same general range to achieve a specified level of accuracy. Liptak (2003) gives a conservative estimate of 3 to 5 diameters upstream and 2 to 3 diameters downstream for accurate results. Thorn (2000) gives 5 diameters upstream and 5 diameters downstream as a rule of thumb for straight pipe sections. A study performed by Hanson (1998) suggests 8 to 10 diameters upstream based on information gathered from manufacturers. BS EN 29104 (1993) was referenced for the study conducted by Bates (2000), citing that the meter must be installed at least 10 diameters from any upstream disturbance and 5 diameters from any downstream disturbance.

Hanson (1998) performed tests using a range of meter types downstream of a 90° elbow to show its effect on flow measurement. A pitot tube was used to measure water velocity profiles across the horizontal pipe diameter. At two diameters, distortion of the velocity profile was noted with larger velocities corresponding with the outside edge of the elbow. The flow was shown to normalize for the 5 and 10 diameter tests. Hanson showed that the distortion had little effect on the error made by the various meters, which did not include magnetic flow meters. Flow separation (i.e. eddies, vortices) was not measured in the scope of this study.

In the study by Kelner (2003), pipe flow velocity profiles were found to be affected by installation conditions. Totalized flow measurement was found to be off up to several percent due to disturbances from an upstream 90° elbow. A long-radius elbow was used in Kelner's study, as opposed to a short radius elbow used in this research. Kelner (2003) states that, in this setup, flow in an ideal state will change to one that has two counter-rotating vortices and an asymmetric or skewed velocity profile. Disturbances decay in straight pipe. Pipe wall friction and turbulent diffusion over relatively long distances without the introduction of additional disturbances causes the decay. In Figure 1, Kelner (2003) illustrates the length of straight pipe required for the effect of the elbow to no longer persist. Kelner states that, in the conditions of this study, this occurs at approximately 59 pipe diameters.

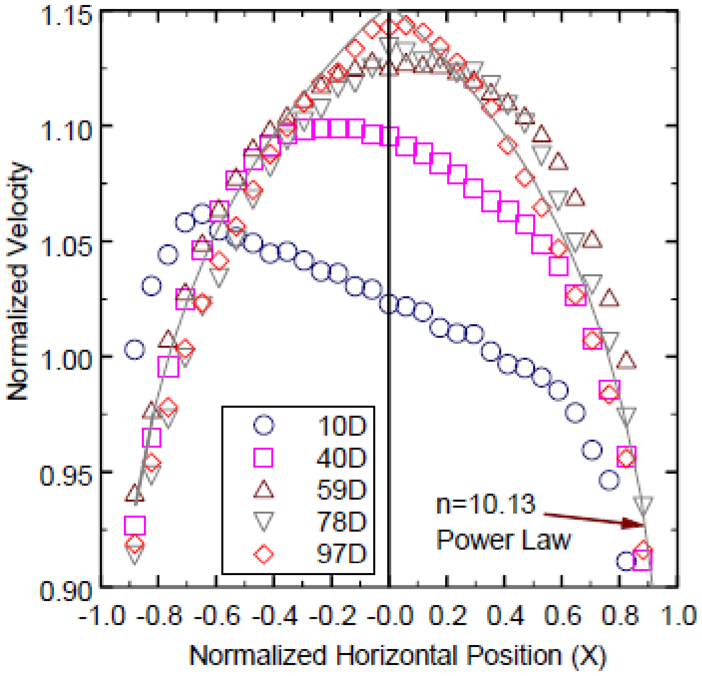

Figure 2. Decay of the effect of a single, 90° long radius elbow. (Kelner, 2003)

CHAPTER III

EXPERIMENTAL SETUP AND PROCEDURE

Meters

Magnetic flowmeters are sought after for high accuracy and true non-invasive measurement. Non-invasive refers to the full or near full pipe bore diameter within the meter itself, allowing for the flow profile to pass undisturbed through the meter with negligible head loss. Magnetic flowmeters operate based on Faraday's Law of induction, which states that if a conductor of length l (meters) is moving at velocity v (meters per second), perpendicular to a magnetic field of flux density B (Tesla), then a voltage e is induced across ends of a conductor (Thorn, 2000). This is shown in the equation:

$$e = Blv \qquad \text{Eq. 1}$$

Applied to the meter, water acts as the conductor moving past sensors within the meter. The magnetic field is generated by external magnets. Meters selected for this study were designed with two opposing electrodes located at the springline of the meter to read the induced voltage. Many of the meters also had additional sensors located at the crown and invert of the pipe to provide grounding and full pipe status. Alternative electrode configurations were not a part of this research.

All meters used in this research were donated by anonymous manufacturers. For the Phase I tests, eleven 10-inch nominal meters were tested. They are distinguished in the remainder of the paper by using the key in the following table. The meters are listed along with their manufacturer specifications:

Table 1. Meter Accuracy Specifications and Installation Requirements

			Requirements				
				Straight Pipe		Single Elbow	
Meter Key	Signal Type (AC/DC)	Accuracy	Flow (fps)	US (Diam.)	DS (Diam.)	US (Diam.)	DS (Diam.)
Mfr A-1	AC	0.25%	> 1.64	3	2	3	2
Mfr A-2	DC	0.50%	> 1.64	3	2	3	2
Mfr B	AC	0.25%	>3	5	2		
Mfr C-1	AC	0.40%	>3	5	3		
Mfr C-2	DC	0.40%	>3	5	3		
Mfr D	AC	0.50%	>0.2	1	0		
Mfr E	AC	0.50%	>3	3		3	
Mfr F	AC	0.20%	>1.31	3	2	3	2
Mfr G	DC	1.00%	>2.84	2	1	2	1
Mfr H	DC	1.00%	>1.64	2	1	2	1
Mfr I	DC	0.30%		5	2	5	
▨	Meters Tested in Phase II						

For the Phase II tests, a total of four meters were tested. The Mfr B and Mfr F meters were retested. The Mfr G and Mfr H meters were also tested as new meters of the same model represented in Phase I testing.

Experimental Setup

Separate procedures, installations, and meters were used for the Phase I and Phase II test groups. Pipe setups included 10-inch standard wall carbon steel pipe for all testing except where specified in the setup descriptions. Baseline runs are referred to as the Straight test in both test groups. All other runs are denoted based on the length of straight pipe immediately upstream of the meter. For example, “1D” refers to the segment of straight pipe as one diameter in length (ten inches), “3D” refers to three diameters, and so

Figure 3. Phase I Straight Pipe Test Setup (flow left to right)

Figure 4. Phase I 3D Pipe Test Setup (flow left to right)

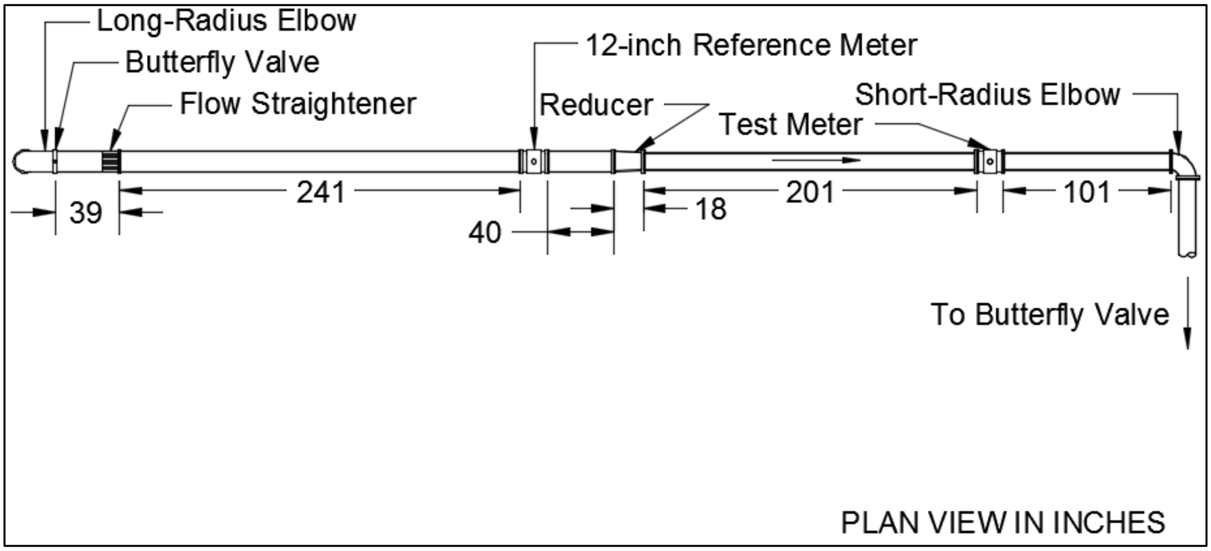

Figure 5. Phase II Straight Test Pipe Setup

forth. Where the meter is installed close coupled with the elbow, the run is denoted as "CC."

For Phase I testing, two pipe configurations were installed. The Straight test setup included 38 feet of straight pipe upstream of the meter location and 7 feet of straight pipe downstream of the meter location. Additionally, 15 feet of straight 12-inch pipe was installed upstream of the 10-inch pipe. For the 3D test, a short radius 90°, 10-inch horizontal elbow was installed upstream of the meter. The upstream flange of the meter was installed 30 inches downstream of the elbow flange.

The Phase II Straight test setup included the following pipes and fixtures in order, starting with the most upstream component:

1. 12-inch vertical long-radius 90° elbow
2. Butterfly valve

3. 12-inch diameter spool which was 39 inches long with a 9 inch long flow straightener installed on the downstream end
4. 12-inch diameter PVC spool which was 241 inches long
5. 12-inch reference magnetic flowmeter
6. 12-inch diameter spool which was 40 inches long
7. Reducer which was 18 inches long
8. 10-inch diameter spool which was 201 inches long

The test meter was then installed, with ten diameters of straight pipe on the downstream side. Visualization of this setup can be found in Figure 5.

The Phase II Elbow test used the same setup up to the 201-inch spool. At that point a short radius elbow was installed followed by one of five different lengths of pipe (See Figure 7). The test meter and another section of varying length pipe at least six diameters long completed the setup.

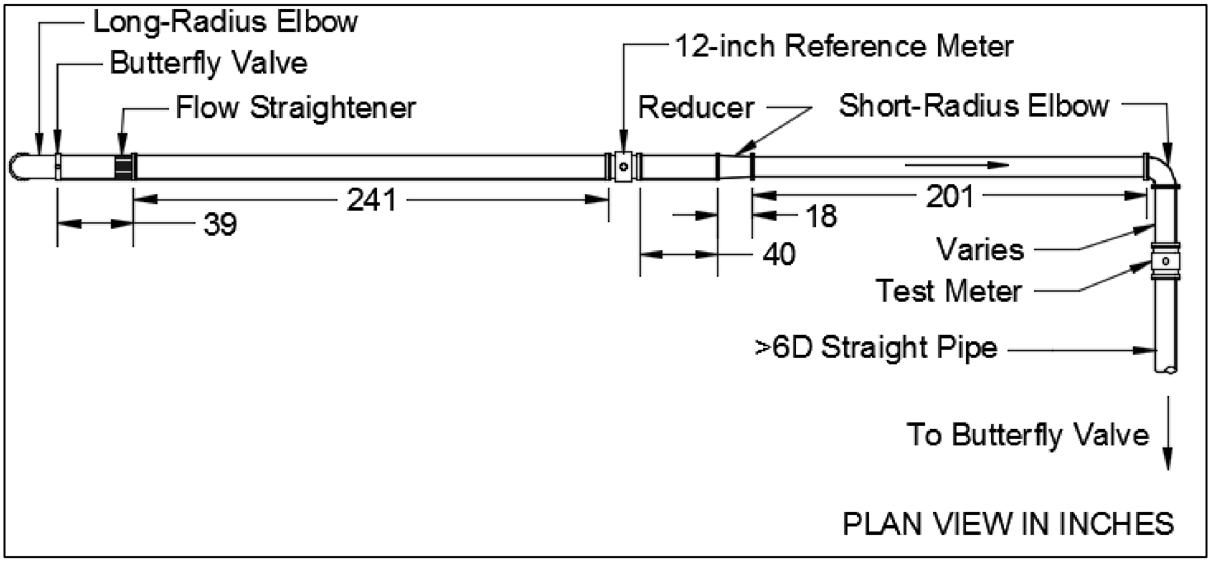

Figure 6. Phase II Elbow Test Upstream Pipe Setup

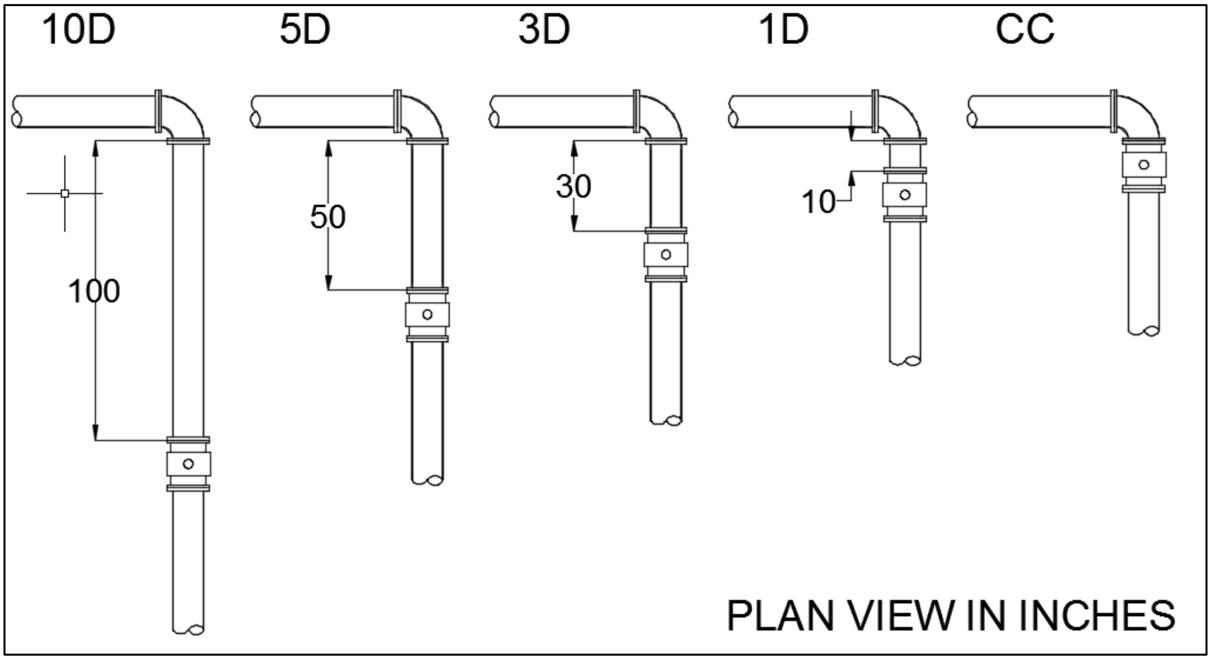

Figure 7. Variations in Pipe Length for Phase II Elbow Test

Figure 8. Phase II Straight Pipe Test Setup (flow top to bottom)

Figure 9. Phase II Elbow Setup for 5D Test (flow left to right)

Procedure

Phase I Test

A laboratory weigh tank was used to measure discharge volume as the reference for the Phase I test. Regular calibrations are performed on the weigh tank according to the National Institute of Standards and Technology. The tank capacity is 250,000 pounds. Uncertainty in the results encountered from the tank ranged from ±0.12% to ±0.14%. The flow rate calculated from the volumetric measurement and the indicated flow rate from the test meter were measured for each run. Flow was calculated as:

$$Q = W/(t * \gamma) \qquad \text{Eq. 2}$$

Where Q is flow rate in cubic feet per second (cfs), W is the weight of water in pounds (lbs), t is time in seconds (s) of the test period, and γ is unit weight of water measured in pounds per cubic feet (pcf), calculated using a water temperature reading during the test. A Fluke multimeter was used to average the frequency or 4-20 mA signal, depending on the meter, from the test meter. For meters recorded using a frequency signal, the flow was calculated as:

$$Q = \frac{1}{2} * Hz \qquad \text{Eq. 3}$$

where Q is flow rate and Hz is the frequency reading (hertz). For milliamp readings, the flow was calculated as:

$$Q = \frac{Range}{16} * (mA - 4) \qquad \text{Eq. 4}$$

where Q is flow rate, *Range* is the range of the flowmeter, and mA is the milliamp reading. Equations 3 and 4 apply to both the Phase I and Phase II tests. The steps in obtaining measurement data are outlined as follows:

1. A butterfly valve downstream of the test section was used to set the target flow rate.
2. The flow was diverted into the weight tank.
3. Simultaneous to the flow diversion, the multimeter was set to average the mag meter output.
4. Test duration lasted a minimum 180 seconds to reduce sensitivity to random standard uncertainty.
5. The flow was re-diverted out of the weigh tank.
6. Averaged meter output, weight measurement, and temperature were recorded.

Five target flow rates spanning the laboratory range were tested during the Straight test series. Fifteen target flow rates were tested during the 3D test series. A second set of data was taken at several flow rates to show repeatability in measurement.

Phase II Test

A 12-inch magnetic flow meter was used to measure discharge volume as the reference for the Phase II test. The meter was calibrated against the weigh tank used in Phase I as shown in Figure 10.

During testing, the reference flow rate and the indicated flow rate from the test meter were measured for each run. Fluke multimeters were used to average the frequency or 4-20 mA signal, depending on the meter, from both the test meter and the reference meter. The steps in obtaining measurement data are similar to the Phase I test, substituting the magnetic meter reading for the weight tank reading. They are outlined as follows:

1. A butterfly valve downstream of the test section was used to set the target flow rate.
2. The multimeters for each flow meter were set to average the flow rate simultaneously.
3. Test duration lasted a minimum 180 seconds, based on the flow rate, to ensure accurate results.
4. Averaged meter outputs were recorded and compared.

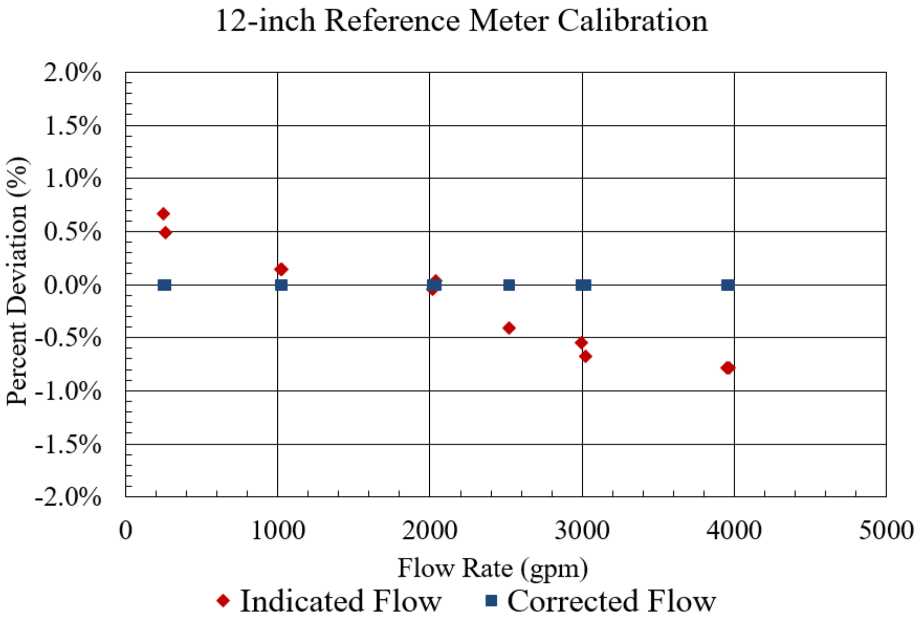

Figure 10. Reference Meter Calibration

CHAPTER IV

RESULTS AND DISCUSSION

The data are represented graphically for each specific meter used in the accuracy tests. General use of the results may be applied to the category of magnetic flow meters, but specific results only apply to the meters tested. The range of manufacturers selected for testing were chosen to show the effect of installation practices for magnetic flow meters generally. Many of the manufacturers are represented here by only one meter. Two manufacturers have a second model each represented in the study.

Both the Phase I and Phase II testing are reported as percent deviations from the reference meter. The reference meter is represented as the horizontal axis at 0.00%. Manufacturer accuracy and minimum velocity specifications are included as horizontal and vertical linear bands, respectively. A “passing” status, as used in this report, refers to the points across all velocities for a given test all falling within the manufacturer’s accuracy specification.

Above the minimum velocity, it was expected that the data would converge on an approximate value per test, ideally within the manufacturer’s specification. Maximum velocities for the range of the meters were not reached in these tests because of laboratory capacity limitations. All data taken at velocities lower than minimum was done to show the divergence in accuracy at low velocities.

It would be expected that the further the elbow is away from the meter, the more accurate the reading will be. This is due to the straight pipe between the two fixtures allowing for velocity profile development. The results verify that, generally, as the meter is installed closer to the elbow, the deviation from the straight test increases.

Phase I Tests

The test protocol for this series was limited to a baseline (straight pipe) test and a 3D test, despite the varying manufacturer upstream pipe length requirements. The 3D length was chosen simply to provide information on what performance can be expected in that condition, rather than match the recommendations for each meter. A common standard for an upstream length requirement is 3D, though this is not the requirement for every meter tested. In some cases where the data falls outside the given accuracy specification, the meter may still perform according to the specification when the installation requirements are met. On the other hand, some passing results may fall outside the specification if an upstream pipe length requirement shorter than 3D was tested.

It can be seen in Figure 11 that Mfr A-1 did not have any of the data fall within the specifications. The data for the Straight test levels out near the 0.25% specification, but only near the highest velocities. No data fell inside specifications for the Mfr A-2 meter, as seen in Figure 12. A lot of scatter can be observed in the 3D test, the source of which is unknown. The only meter where all data fell inside the specifications was Mfr B, as seen in Figure 13. All data was found to be within ±0.25%. Mfr C-1, seen in Figure 14, saw all data within specification in the Straight test and just outside in the 3D test. Both data sets show consistent readings across all velocities above minimum. Most of the Straight test data fell within specification for Mfr C-2, seen in Figure 15. The 3D test shows good consistency with a little scatter across all velocities above minimum. The Straight test for Mfr E, seen in Figure 17, fell primarily just outside the specification. Both tests show consistent data across all velocities above minimum. No data fell within specification for the Mfr F meter, seen in Figure 18. A large amount of scatter and a negative trend as velocity increased were observed with the Mfr G meter, seen in Figure 19. Only a portion of the data fell within specification. All Straight test data fell within specification for the Mfr H meter, seen in Figure 20. The 3D showed some data falling just outside the specification. A negative trend as velocity increases was observed in both tests. No data fell within specification for the Mfr I meter, seen in Figure 21. Some scatter was observed at the lower velocities.

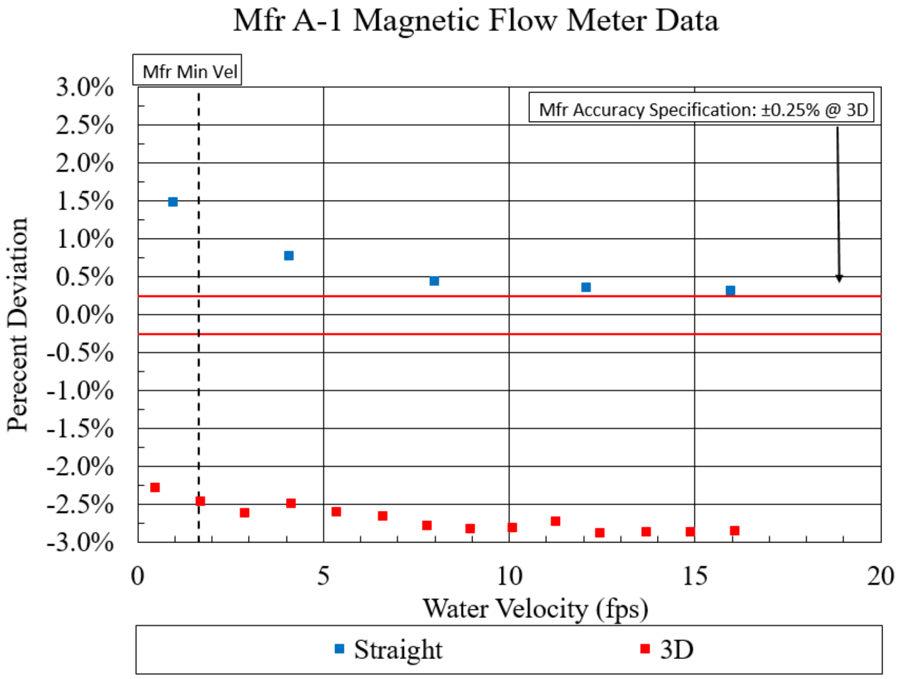

Figure 11. Phase I Test Data for Mfr A-1

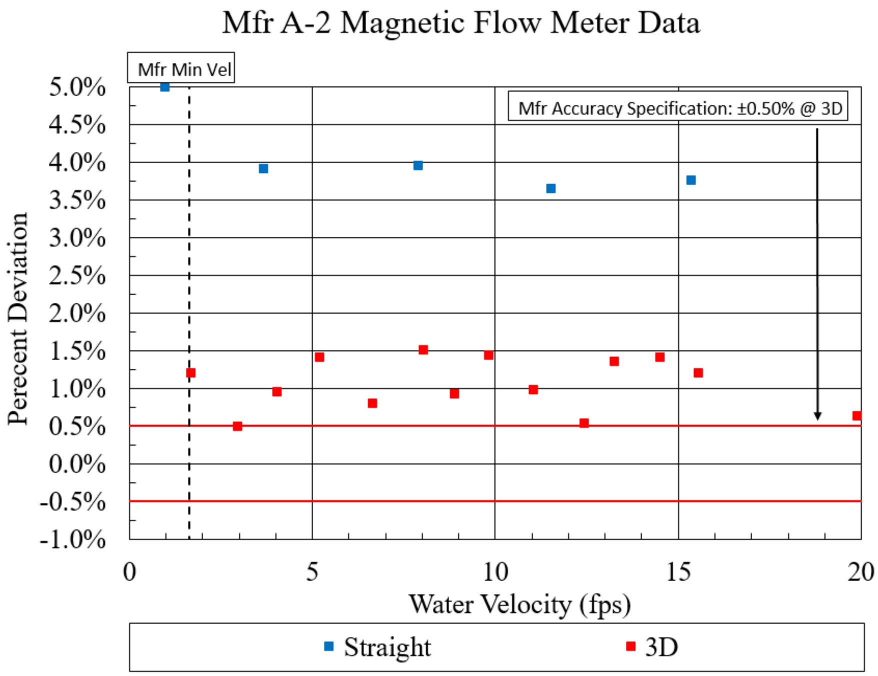

Figure 12. Phase I Test Data for Mfr A-2

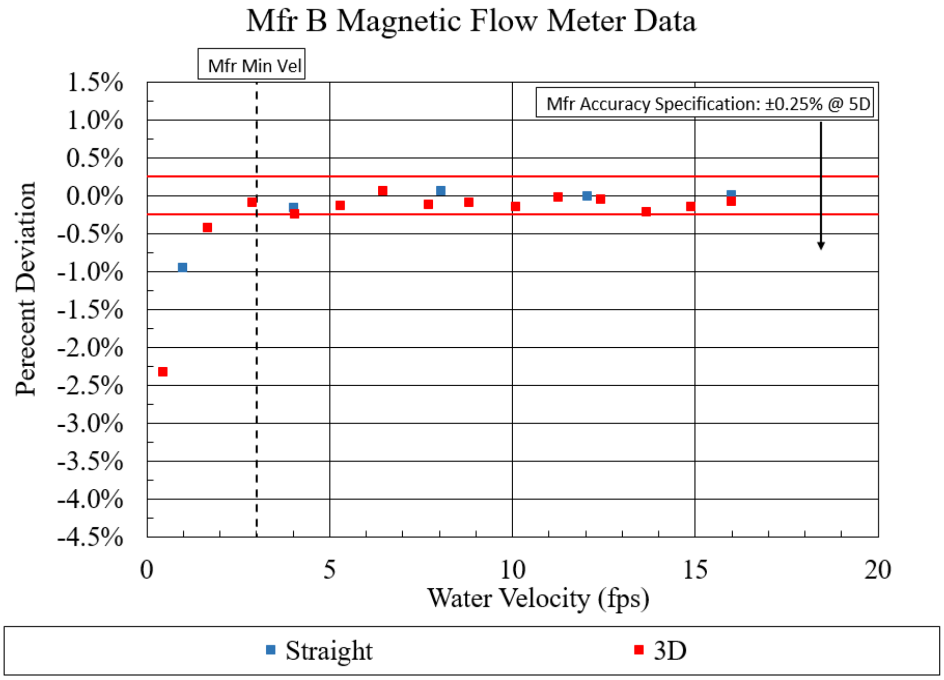

Figure 13. Phase I Test Data for Mfr B

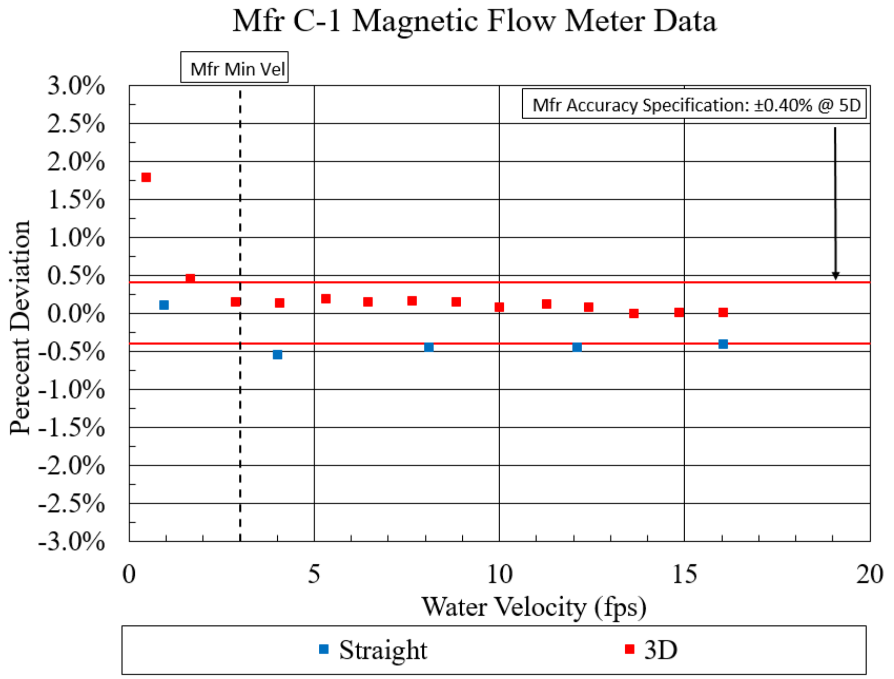

Figure 14. Phase I Test Data for Mfr C-1

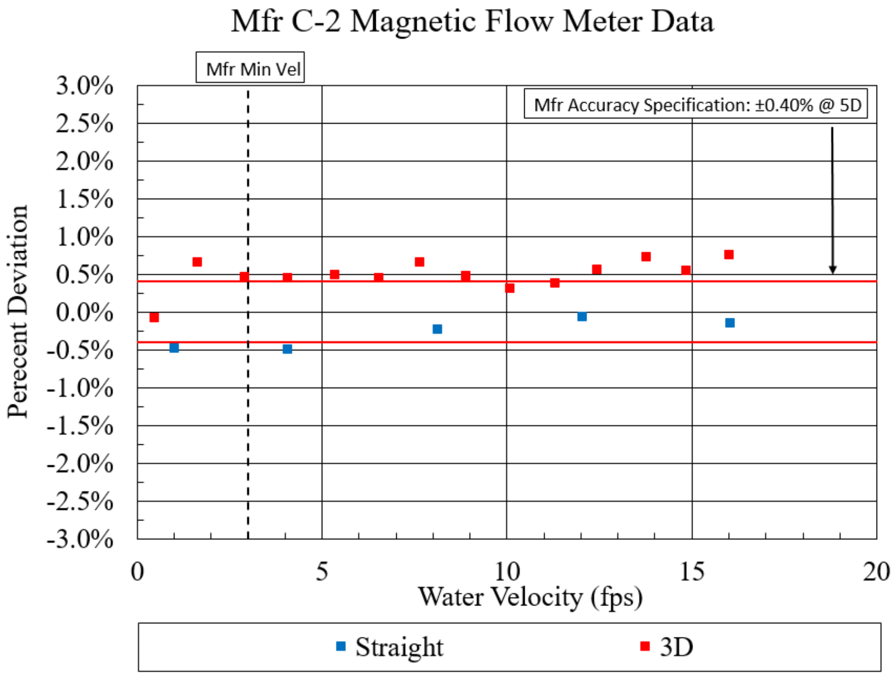

Figure 15. Phase I Test Data for Mfr C-2

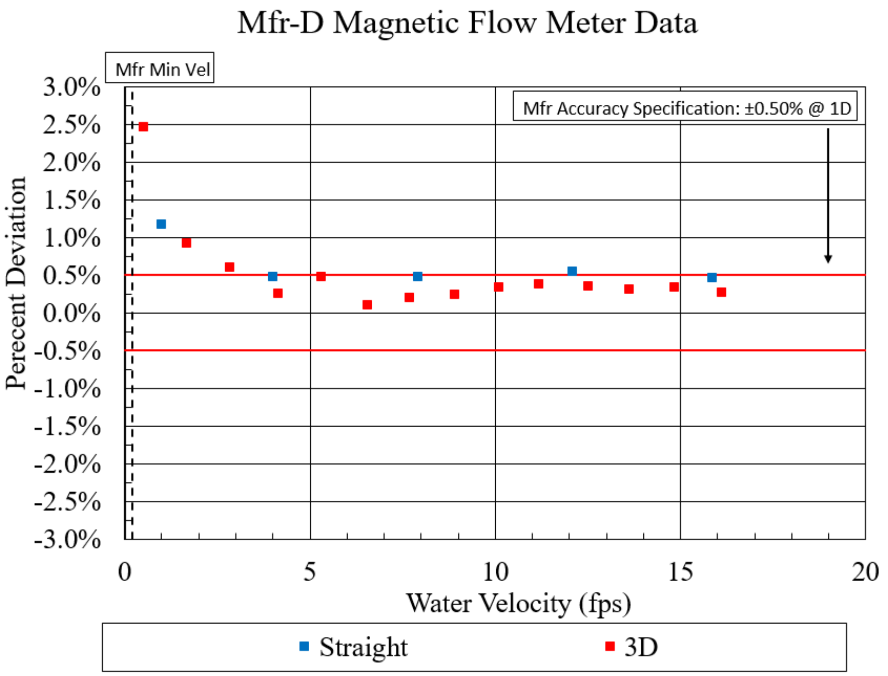

Figure 16. Phase I Test Data for Mfr D

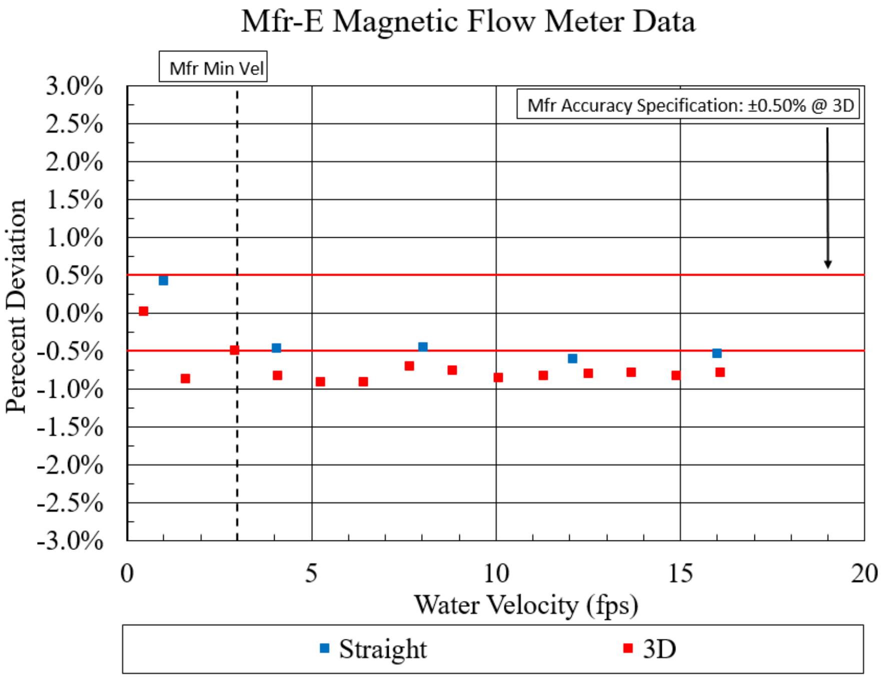

Figure 17. Phase I Test Data for Mfr E

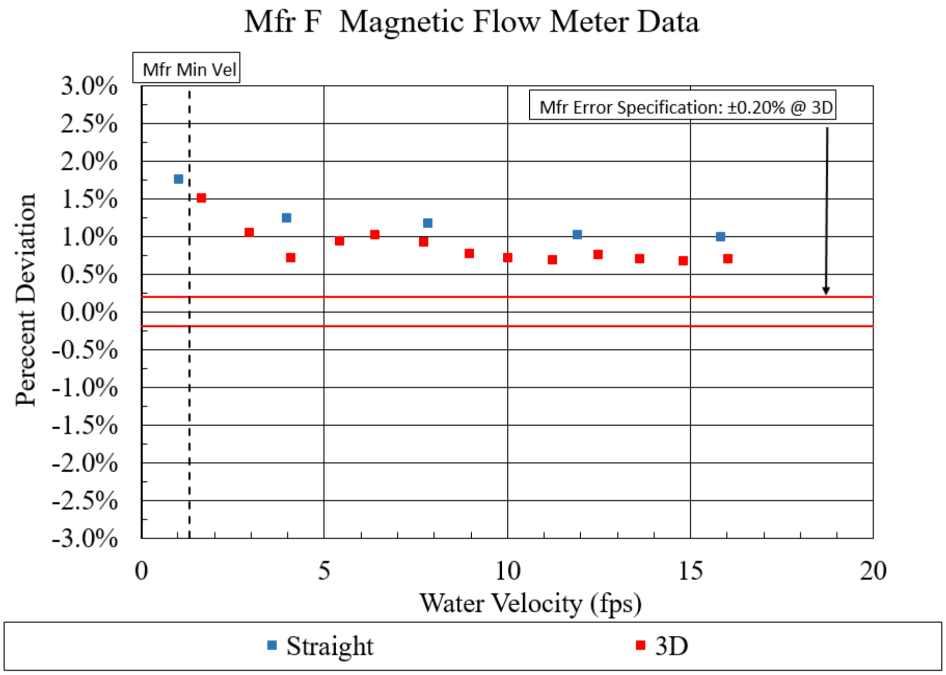

Figure 18. Phase I Test Data for Mfr F

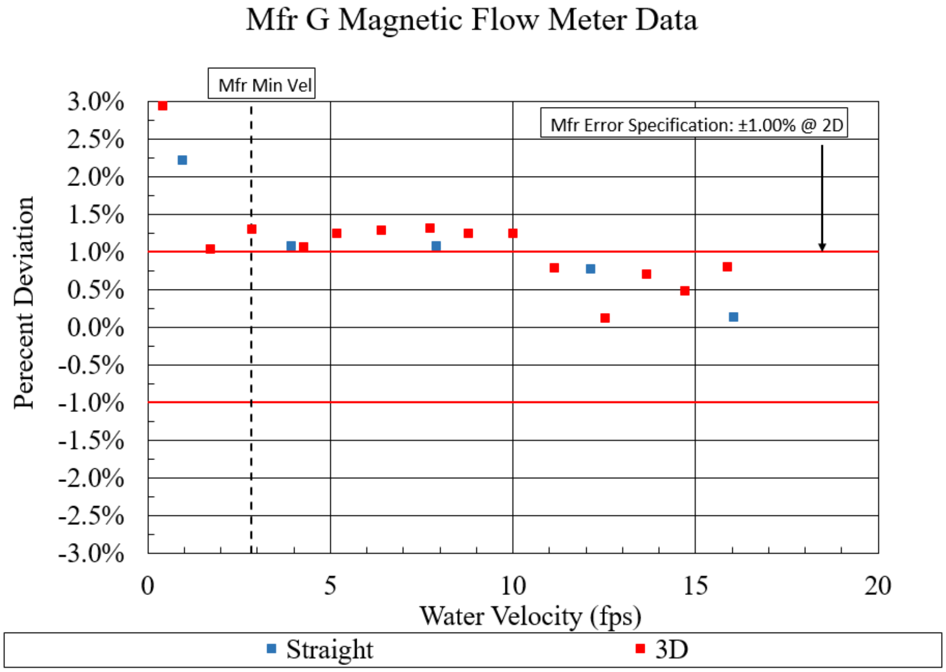

Figure 19. Phase I Test Data for Mfr G

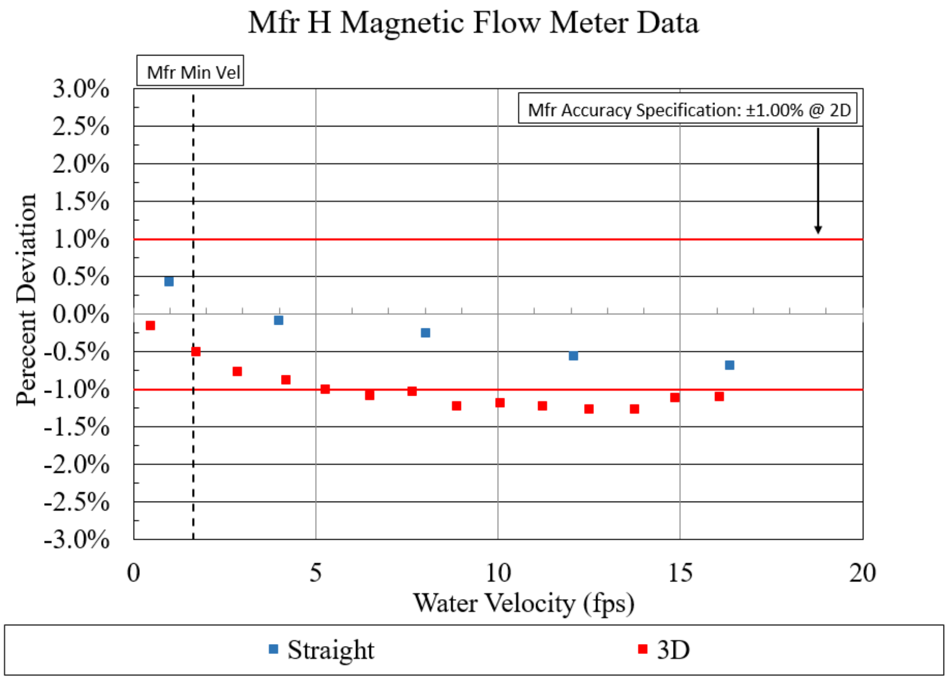

Figure 20. Phase I Test Data for Mfr H

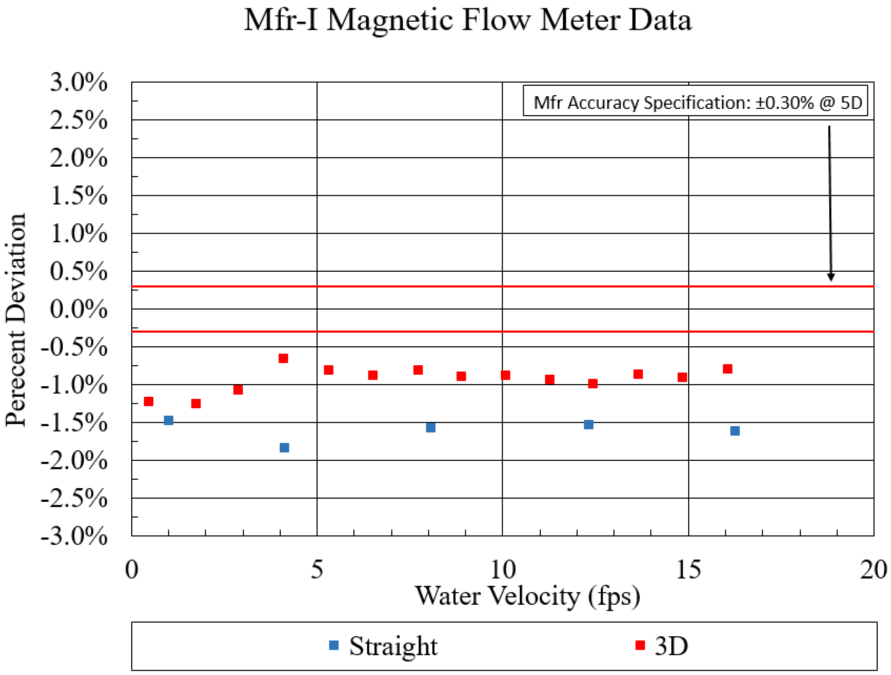

Figure 21. Phase I Test Data for Mfr I

The Phase I testing can be summarized using the metrics represented in Table 2. Data recorded at velocities below the manufacturer's minimum were not included in the calculated values. The Average Difference from 0% (AD) was calculated as a simple average of the difference of the observed data point relative to 0% for each meter and configuration across the velocity range. The Adjusted Average Difference (AAD) was calculated by shifting the straight test AD value to 0% and shifting the other test by the same factor. The Max Difference from AD (MD) was calculated as the maximum difference between each data point and the corresponding AD value. The Standard Deviation from AD (STDV) was calculated as a typical standard deviation of the AD value. AD and AAD values are highlighted in red where the average exceeds the manufacturer specification. AD values highlighted in green refer to all data values falling within the specification. For the purposes of this report, green values represent "passing" status for the test.

At first glance, it can be seen that only Mfr B passes both Straight and 3D tests. The AD values for Mfr G both fall within the manufacturer specification. However, by looking at the full dataset for Mfr G (Figure 19), it can be seen that many of the data points actually fell outside of the specification. The upper velocity points bring the average value within the specification. The MD and STDV can be used as a way of seeing how the accuracy changes with velocity. The MD and STDV of Mfr G are the largest of Phase I for both tests, pointing to the least consistency across the range of velocities.

One possible source of scatter in the measurements may be the signal type. The signal type for each meter can be found in Table 1. Taking a simple average of the MD and STDV for DC type meters resulted in 0.41% and 0.21% respectively. For AC type meters, the averages were roughly half of the DC values, at 0.19% and 0.10% respectively.

Table 2. Phase I Test Statistical Data Summary

Meter	Accy Spec	Test	AD	AAD	MD	STDV
Mfr A-1	**±0.25%@3D**	**Straight**	0.47%	0.00%	0.30%	0.18%
		3D	-2.75%	-3.22%	0.29%	0.13%
Mfr A-2	**±0.50%@3D**	**Straight**	3.80%	0.00%	0.18%	0.13%
		3D	1.03%	-2.77%	0.56%	0.32%
Mfr B	**±0.25%@5D**	**Straight**	-0.03%	0.00%	0.13%	0.08%
		3D	-0.12%	-0.09%	0.17%	0.08%
Mfr C-1	**±0.40%@5D**	**Straight**	-0.48%	0.00%	0.09%	0.05%
		3D	0.07%	0.55%	0.10%	0.07%
Mfr C-2	**±0.40%@5D**	**Straight**	-0.25%	0.00%	0.26%	0.16%
		3D	0.53%	0.78%	0.22%	0.13%
Mfr D	**±0.50%@1D**	**Straight**	0.62%	0.00%	0.17%	0.04%
		3D	0.35%	-0.26%	0.27%	0.19%
Mfr E	**±0.50%@3D**	**Straight**	-0.52%	0.00%	0.09%	0.06%
		3D	-0.84%	-0.32%	0.34%	0.07%
Mfr F	**±0.20%@3D**	**Straight**	1.09%	0.00%	0.14%	0.11%
		3D	0.83%	-0.26%	0.23%	0.12%
Mfr G	**±1.00%@2D**	**Straight**	0.76%	0.00%	0.64%	0.39%
		3D	0.96%	0.20%	0.96%	0.44%
Mfr H	**±1.00%@2D**	**Straight**	-0.24%	0.00%	0.45%	0.24%
		3D	-1.12%	-0.88%	0.34%	0.12%
Mfr I	**±0.30%@5D**	**Straight**	-1.62%	0.00%	0.23%	0.12%
		3D	-0.93%	0.69%	0.26%	0.08%

AD=Average Difference from 0%
AAD=Adjusted Average Difference from 0%
MD=Max Difference from AD
STDV=Standard Deviation of AD

Upon visual inspection, the data curves for the 3D and Straight tests for each meter appear to be separated by a vertical shift in most cases. The Mfr A-2 meter shows exception due to high levels of scatter in the 3D data. This shows high repeatability across all testing.

Figure 22 shows how each meter performs at three diameters in relation to a straight pipe configuration. Each 3D data point is shown as a deviation from the Straight test, where the Straight data is represented as an average value of the data for that meter. 3D data is represented as a simple difference between each data point and the average Straight value. The data is corrected, meaning the Straight data is set to 0%. This was done so that all 3D data could be referenced from the same location. It can be seen that most meters are within a range of ±1.0% of the straight data.

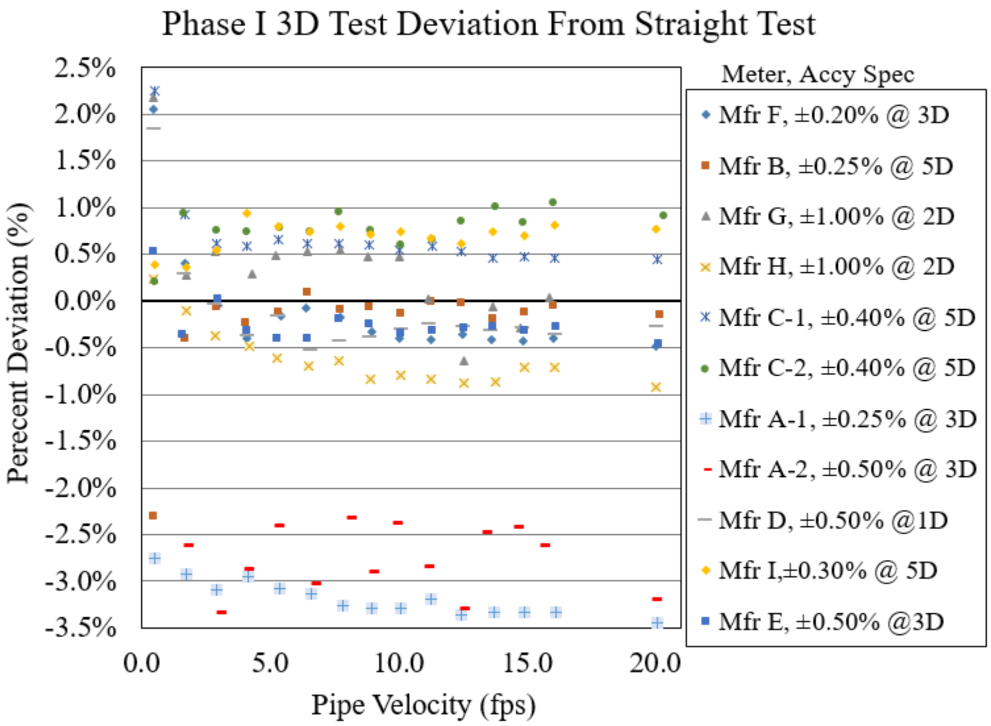

Figure 22. Phase I 3D Test Deviation From Straight Test

Four of the meters read a positive difference, while the other 7 read a negative difference. In other words, in the 3D elbow test, the meters are more likely to read less flow rather than more flow, than during the Straight test. The meters retested in Phase II all read consistently positive or negative at the 3D installation.

Phase II Tests

Plots of Phase II were formatted in a similar fashion to Phase I. It can be seen that for Mfr F (Figure 23) and Mfr B (Figure 24) neither meter passes "out of the box." For this to happen, all points from the installation requirements (3D and 5D, respectively) would have to fall within the accuracy specification. It can be seen in in the plot for Mfr G (Figure 25) that all of the data falls within the accuracy specification, making this the only meter to pass "out of the box." In Figure 26, the Mfr H meter passes in the 5D, 10D and Straight tests, but does not pass in the 3D test. The pattern of deviation suggests that it also may not pass at the installation requirement of 2D. Error bars were added to each plot to show the maximum range of difference, also given as values represented above each tested velocity. By looking at the plots for Mfr F (Figure 23) and Mfr B (Figure 24), it can be seen that the maximum difference is consistently around three percent. This is in contrast with Mfr G (Figure 25) and Mfr H (Figure 26), where the maximum differences are one to one and a half percent, respectively. Surprisingly, Mfr H and Mfr G, which have ±1.00% accuracy specifications, had much narrower bands of deviation across all tests than the two meters with higher standards.

One possibility to this outcome is that the meters with higher standards are configured to work in more ideal conditions. This is supported by the upstream pipe

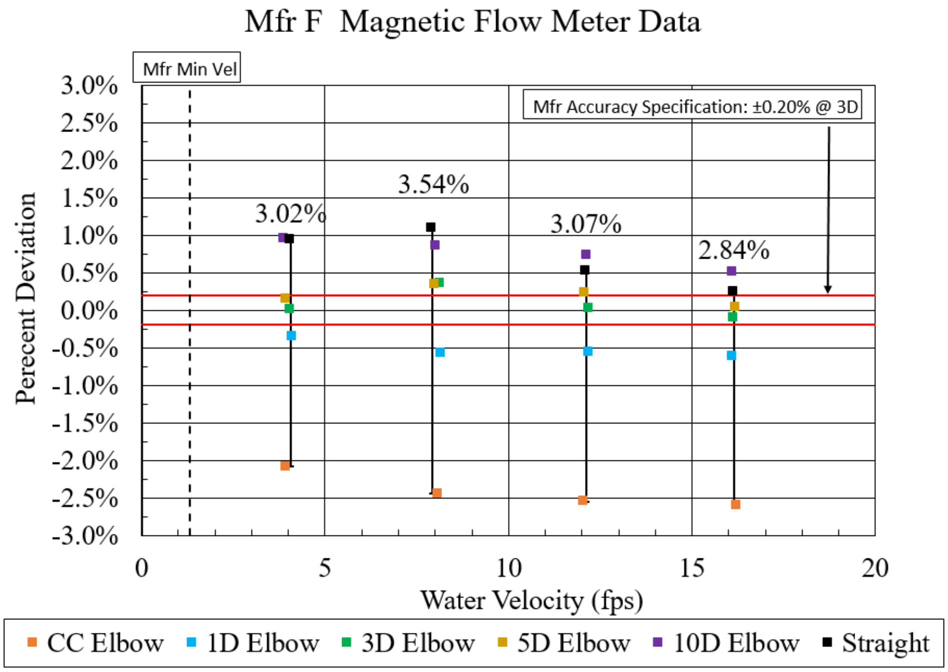

Figure 23. Phase II Test Data for Mfr F

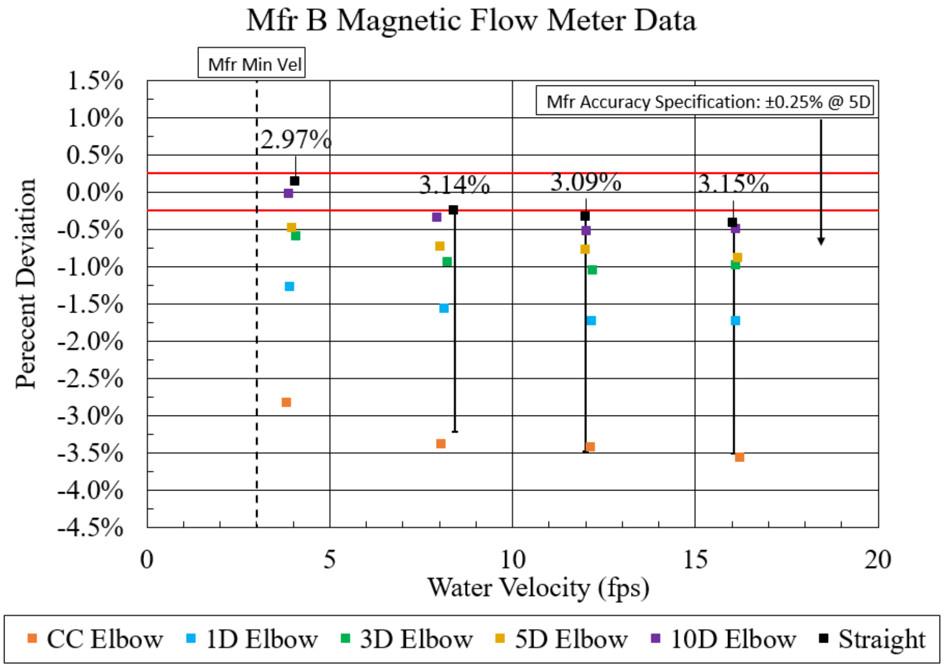

Figure 24. Phase II Test Data for Mfr B

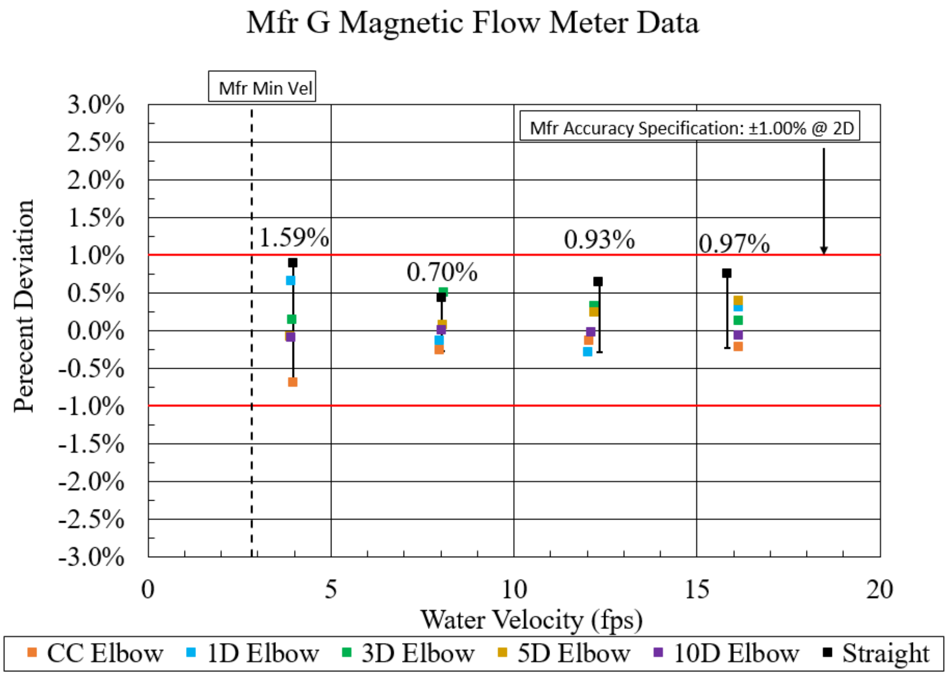

Figure 25. Phase II Test Data for Mfr G

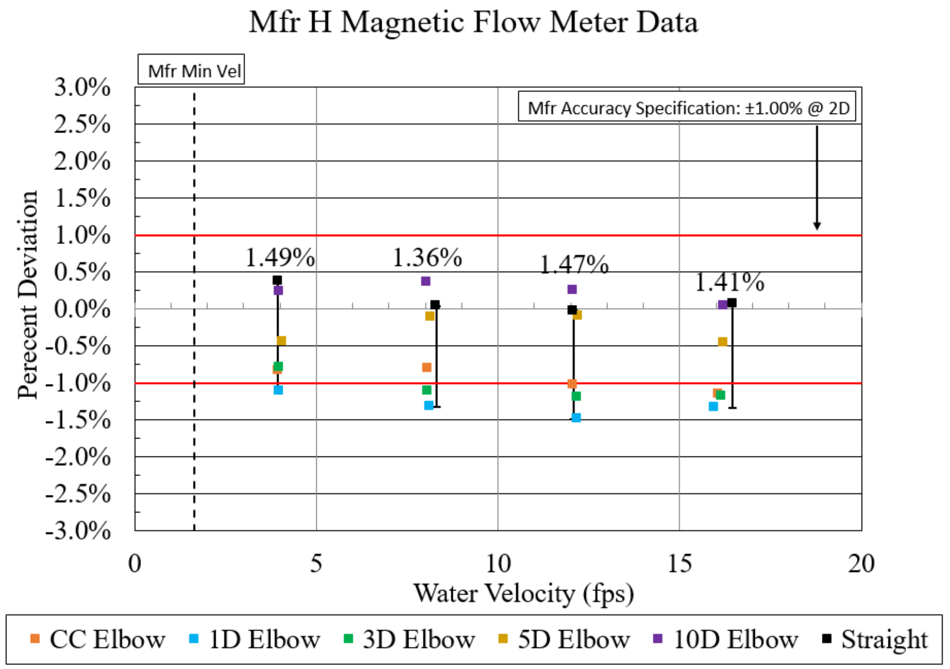

Figure 26. Phase II Test Data for Mfr H

length requirement. The lower standard meters both have a requirement of two diameters, while the higher standard meters have requirements of three and five diameters, respectively.

The Mfr F and Mfr B meters show, at nearly every velocity, the deviation increases as upstream pipe length decreases from 10D to close coupled. The Mfr H meter also showed similarly ordered deviations with the exception of the close-coupled data sometimes having a smaller deviation than the 1D or even 3D test. The Mfr G meter generally showed a correlation of shorter upstream pipe length to greater deviation, though the results showed a more mixed order of pipe lengths in the range of deviation. In the other three meters, the 10D test showed negligible differences from the Straight test.

It is unclear from the nature of this study, what exactly is occurring to cause departure from the length to deviation relationship. Kelner (2003) states that vortices are formed through flow separation downstream of the elbow. The size and exact location of the vortices cannot be determined from this study. Changes in the flow profile caused by the vortex at the location of measurement within the meter could result in a wide range of uncertainty. In other words, the changes could result in a very large deviation, or none at all. This could be the case in the example of the Mfr G meter at approximately 4 feet per second, seen in Figure 25. The 1D and 3D data show a -0.24% and -0.75% deviation, respectively, from the straight test, ahead of the longer distances of 5D and 10D, at -0.98% and -0.99% respectively. Other sources of noise within the data could include inconsistencies within the meter itself or other unknown distortions in the velocity profile.

Table 3 summarizes the Phase II data using the same metrics in Table 2 for Phase I. According to the table, Mfr G passes at all tested lengths. Mfr F passes at the 3D requirement using AD, though the Mfr B was the only meter to show improvement at the upstream length requirement, increasing from -0.73% to -0.51%. The meters with requirements not tested were evaluated based on data from tests with the next length longer and shorter than the requirement.

Despite the shift from AD to AAD, Mfr G remains the only meter that passes by its own manufacturer specification. If the remaining meters were to have changes applied to their installation requirements, the meters could still be claimed to meet the advertised accuracy. For example, Mfr H does not pass at 2D, as recommended, but would easily pass if 5D of straight pipe were required instead. Similarly, Mfr B and Mfr F would require 10D instead of 5D and 3D respectively. The adjusted data was given as an example, therefore, values were not highlighted.

The standard deviation and max difference are metrics that show how consistent the meter reads across the range of velocities. From the table, the standard deviations ranged from 0.11% to 0.37%. Max difference for the set ranged from 0.17% to 0.52%. Mfr H showed the highest rate of repeatability with an average standard deviation of 0.15%. While Mfr G tied with Mfr F for the highest average standard deviation, it also carried the highest single standard deviation as well as the highest maximum mean deviation, making it the least likely to produce repeatable results.

Table 3. Phase II Statistical Data Summary

	Test	AD	AAD	MD	STDV
Mfr H (±1.00%@2D)	**CC**	-0.95%	-1.07%	0.19%	0.14%
	1	-1.31%	-1.43%	0.20%	0.13%
	3	-1.07%	-1.19%	0.27%	0.16%
	5	-0.28%	-0.40%	0.18%	0.17%
	10	0.22%	0.10%	0.18%	0.11%
	Straight	0.12%	0.00%	0.26%	0.15%
	Average			0.21%	0.15%
Mfr B (±0.25%@5D)	**CC**	-3.31%	-3.09%	0.48%	0.28%
	1	-1.58%	-1.36%	0.30%	0.19%
	3	-0.89%	-0.67%	0.30%	0.18%
	5	-0.73%	-0.51%	0.24%	0.15%
	10	-0.35%	-0.13%	0.32%	0.20%
	Straight	-0.22%	0.00%	0.36%	0.21%
	Average			0.33%	0.20%
Mfr G (±1.00%@2D)	**CC**	-0.33%	-1.01%	0.36%	0.22%
	1	0.13%	-0.55%	0.52%	0.37%
	3	0.27%	-0.41%	0.23%	0.15%
	5	0.15%	-0.53%	0.24%	0.18%
	10	0.63%	-0.05%	0.20%	0.13%
	Straight	0.68%	0.00%	0.25%	0.17%
	Average			0.30%	0.20%
Mfr F (±0.20%@3D)	**CC**	-2.42%	-3.12%	0.33%	0.20%
	1	-0.52%	-1.22%	0.17%	0.10%
	3	0.07%	-0.62%	0.29%	0.17%
	5	0.19%	-0.51%	0.16%	0.11%
	10	0.76%	0.07%	0.26%	0.17%
	Straight	0.70%	0.00%	0.46%	0.34%
	Average			0.28%	0.18%

AD=Average Difference from 0%
AAD=Adjusted Average Difference from 0%
MD=Max Difference from AD
STDV=Standard Deviation of AD

CHAPTER V

CONCLUSION

Meter accuracy is critical to the various applications they are used in. Meters may not always be installed in ideal circumstances. Information on what can be expected when non-ideal circumstances occur is highly valuable to the user. This information provided by the manufacturer does not always match what occurs in the field. Testing revealed that the distance between an upstream short-radius 90° elbow and a magnetic flow meter does have an effect on the meter's accuracy. These results are based on a sampling of meters made by different manufacturers with varying specifications and installation requirements.

Results Summary

- Most of the "off-the-shelf' meters that were tested during this study did not pass their given manufacturer specification when installed according to requirements given by the manufacturer. In fact, most of the meters did not pass the specification when the meter was installed with 20+ diameters of straight pipe. It is suggested that a secondary in situ or laboratory calibration be performed to improve results especially when conditions are non-ideal.
- When the meters were installed with three diameters between the upstream side of the meter and a short-radius 90° elbow, it can be expected that the meters will often read within ±1.0% accuracy of a reading when 20+ diameters of straight pipe are installed upstream of the meter.

- Decreasing the length of straight pipe upstream of the meter increases the deviation in flow measurement from the starting reference. Generally, a shift in accuracy occurs across all flow rates with the change in pipe length. Therefore, for any velocity, effects on meter accuracy should follow the same expectations whether the pipe length is at, longer, or shorter than ideal.
- One factor affecting repeatability may be the type of signal output of the meter. In Phase I, the DC type meters were found to have roughly twice the average max difference (MD) and standard deviations (STDV) as the AC type meters.

Need for Further Research

The results for this study would be fortified by testing a more comprehensive range of meters in a test matrix and pipe setup similar to Phase II. It is recommended that additional testing is done using similar pipe setups with variations in other parameters. For example, the meter could be oriented with the sensors vertical rather than horizontal, or, a double elbow, in or out of plane, could be installed upstream. Research could also be done on a similar configuration of smaller or larger pipe diameters to see if similar effects take place. There are innumerable conditions that could be studied, relating to upstream pipe setup, to better understand their effects on the accuracy of mag meters.

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