THE EFFECTS OF PIPEWALL OFFSETS ON WATER METER ACCURACY

by

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

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in

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                             Dean of the School of Graduate Studies

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ABSTRACT

The Effects of Pipewall Offsets on Water Meter Accuracy

by

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Utah State University, 2014

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Accurate flow measurement is essential for the management of any type of fluid system. In order for a meter to accurately measure the flow, some installation requirements must be met. These installation requirements are meant to produce a condition where there are limited flow disturbances as the fluid enters the meter. If flow disturbances do occur, the meter may produce inaccurate measurements.

This research investigated the effect on accuracy that different types of 12-inch flow meters have as a result of being installed in pipelines of differing inside diameter. The types of meters chosen for this research were the portable ultrasonic meter, the magnetic meter, and four types of differential pressure meters: classical Venturi, Halmi Venturi Tube, V-cone, and the wedge meter. Each meter was tested for accuracy with ten different pipe schedules installed upstream forming a pipewall offset varying
between +0.125 inches and 0.937 inches. Ten flow rates between 400gpm and 6,550gpm were considered for each test setup. The meters’ accuracy during each test series was compared to the specified accuracy as defined by the manufacturer of the meter. All results were displayed graphically for comparison.

In general, most of the meters tested were affected by the disturbances caused by the pipewall offsets, and some meters were more affected than others. The measurement error was found to be as high as 8% for the ultrasonic meter type. This research demonstrated that for accurate flow measurement, most flow meters require that the inside diameter of the piping be the same as the inside diameter as the meter. Laboratory tests showed that the wedge meter was not dependent upon the upstream pipe installation. Normally, it is recommended that laboratory calibrations be performed to ensure the accurate use of any meter type.

(73 pages)
In order for a meter to accurately measure flow, certain installation requirements must be met. The purpose of the installation requirements is to ensure that upstream flow disturbances are minimized so that the flow meter has the best chance for accurately measuring the flow rate. If flow disturbances do occur upstream of the meter, inaccurate results may result. The purpose of this research was to investigate the effects on accuracy that different types of 12-inch meters have as a result of being installed in pipelines of differing inside diameter.

The types of meters chosen for this research included the portable ultrasonic meter, the magnetic meter, and four types of differential pressure meters: classical Venturi, Halmi Venturi Tube, V-cone, and the wedge meter. In each test setup, the meter was installed immediately downstream of a pipe that had a different inside diameter.
diameter than the meter. Ten test setups were examined with each meter. Pipe wall offsets ranged between +0.125 inches and 0.937 inches. Each meter test setup was calibrated at ten flow rates at equal intervals between 400gpm and 6,550gpm.

Test results showed that most meter types are sensitive to sudden changes in diameter upstream. The wedge meter was the only meter that saw negligible effects on meter accuracy as a result of the upstream pipe wall offset disturbances. This research demonstrated that for accurate flow measurement, most flow meters require that the inside diameter of the piping be the same as the inside diameter as the meter.

Jesse M. Pope
ACKNOWLEDGMENTS

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Finally, I would like to thank my parents and my wife. My parents taught me the importance of education and have encouraged me to keep going. My beautiful wife, Rebecca, has been a constant support. It is because of her that I have made it this far.

Jesse M. Pope
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NOTATION

$A$ = cross sectional area in square feet
$C$ = discharge coefficient
$D$ = diameter in feet
$D_H$ = hydraulic diameter of the meter inlet in feet
$g$ = gravity constant in feet per second squared
$Hz$ = hertz
$Hz_{max}$ = maximum hertz
$ID$ = inside diameter in inches
$mA$ = milliamps
$P$ = pressure in pounds per square inch
$Q$ = flow rate in cubic feet per second
$Q_{gpm}$ = flow rate in gallons per minute
$Q_{actual}$ = actual flow rate
$Q_{ind}$ = flow rate indicated by the meter
$Range$ = range of the differential transmitter in inches
$Re$ = Reynolds number
$S$ = allowable stress in pounds per square inch
$span$ = span of the multimeter
$t$ = time in seconds
$W_{H2O}$ = weight of water in pounds
$\beta$ = beta ratio of the meter
\( \Delta H \quad = \quad \text{difference in total head} \)

\( \lambda_{H2O} \quad = \quad \text{unit weight of water in pounds per cubic foot} \)

\( u \quad = \quad \text{kinematic viscosity of the water in square feet per second} \)
Purpose

Accurate flow measurement is essential for the effective management of any type of fluid system. The oil, water, and gas industries are a few of many examples of industries who manage large volumes of fluids every day. Even a small percentage error in measurement may cost the producer or consumer a large sum of money if the inaccurate measurements are not corrected.

In closed conduits, many methods and meter-types are available to measure the flow. Examples of these types of meters include magnetic, ultrasonic, and several types of differential pressure meters. Each meter uses different technology which, in turn, means that flow is calculated differently with each meter. The equations for calculating flow which coincide with each meter assume that the conditions are ideal. In a full pipe flow, these conditions assume that the flow is fully developed. Laboratory flowmeter calibrations provide a means for accurately determining the discharge characteristics of the flowmeter under piping configurations into which the meter is to be installed.

Flow conditions are affected by pipe elbows, valves, and sudden changes in pipe diameter, to name just a few. These disturbances, if placed immediately upstream of a meter, may cause swirl or irregularities within the meter which, in turn, may cause the meter to produce incorrect measurements. These measurement errors may be as high
as several percent. Such disturbances that affect a meter are termed *installation effects.*

In order to successfully measure fluid accurately with any meter and avoid installation effects, some installation requirements must be met. Hanson and Schwankl (1998) are among a large list of researchers who have studied the effects on meter accuracy and recommend installation requirements for the flowmeter. The requirements vary depending on the meter type and the cause of the flow disturbance (valves, elbows, reducers, etc). However, a general rule of thumb for all cases states that there must be at least 8-10 pipe diameters of straight pipe upstream of the meter and an additional 2 pipe diameters downstream (Hanson and Schwankl 1998). This general rule helps the flow to be as ideal as possible as the fluid moves through the meter. Another important factor is the inside diameter of the pipe. When the inside diameter of the upstream pipe differs from the inside diameter of the meter itself, meter accuracy may also be affected.

Meters are usually constructed based on the pressure rating of the pipe in which they are installed. A pipe with higher pressure reading needs a thicker pipewall. If, for any reason, the meter is ever incorrectly installed or has a different inside diameter than the pipeline, the fluid will experience a sudden increase or decrease in pipe diameter. As fluid flows across this sudden change in diameter, streamlines separate causing a less than ideal condition as the fluid moves through the meter.
Pipe Sizing

The original system established to designate pipe dimensions was known as Iron Pipe Size (IPS). Under this system, the pipe size was based on the approximate inside diameter. All pipe sizes had the same pipewall thickness which became known as standard (STD). Eventually, industries required pipe that could withstand higher-pressure fluids. To accommodate this new requirement, two additional pipewall thicknesses were manufactured. One was called extra strong (XS) or extra heavy (XH), and the other was called double extra strong (XXS) or double extra heavy (XXH). The outside pipe diameter remained unchanged while the inside diameter decreased due to the increased pipewall thickness.

In 1927, the American Standards Association replaced Iron Pipe Size (IPS) with Nominal Pipe Size (NPS) and many pipewall thicknesses were made available. Nominal Pipe Size is a dimensionless indicator of the size of the pipe based on the outside pipe diameter without an inch symbol. Note that for pipe sizes greater than 12-inches, the NPS specifies the pipe’s outside diameter exactly. For sizes below 14-inches, the outside diameter is somewhat greater than the name indicates. For example, NPS 18 pipe has an outside diameter of 18-inches while NPS 6 pipe has an outside diameter of 6.625-inches. In all cases, the inside diameter varies depending on the thickness of the pipewall as shown in Figure 1.

The term schedule was created to indicate the thickness of the pipewall. The schedule number gives the approximate value of 1000 P/S in which P is the pressure and
Figure 1. Pipes of Different Pipe Schedules

S is the allowable stress, both terms measured in pounds per square inch. The pipe schedules available for each pipe size are 5s, 5, 10s, 10, 20, 30, standard (STD), 40, 60, 80s (also known as XH), 80, 100, 120, 140, 160, and XXH. The schedule indicators followed by the letter s may or may not have the same thickness of the schedule without the s. The s was added per ASME B36.19M. and these pipe sizes are generally used for stainless steel pipe (Nayyar 2000).

Objective

The main objective of this research was to quantify the extent of the effects that various types of meters will experience when they are installed in pipelines having a
pipe schedule that is different from standard. It is understood that meters are commonly calibrated before they are installed and used in an industrial setting. However, unless the laboratory calibration was performed in the same pipe schedule as the pipeline in which they are to be installed in the field, significant errors may exist in the meter reading. This research proves that it is essential for some meter types to calibrate the meter in laboratory pipe that matches the inside diameter of the meter.

This study has evaluated pipe inside diameter effects on six types of 12-inch meters. The types of meters chosen for this research are the portable ultrasonic meter, the magnetic meter, and four types of differential pressure meters: classical Venturi, Halmi Venturi Tube, V-cone, and the wedge meter. Each meter was tested for accuracy with ten different pipe schedules installed upstream. The pipe schedules that were tested upstream of each of the meter types were 20, 30, STD, 40, 60, 80, 100, 120, 140, and 160. The same flow rate range was tested for each test setup for comparison purposes (from 400gpm to 6550gpm). This study was based upon the premise that the meters would display increasing error as the change in diameter increased between the pipe and the meter inlet.
CHAPTER II

METER DESCRIPTIONS

The meters in this analysis were donated by anonymous manufacturers. This section describes the meters, describes the general principles of fluid measurement with each technology, and provides the equations used to calculate the flow. Important specifications such as the location of the measuring components will also be shown (pressure taps, transducers, electrodes, etc.). It is important to note that while the fundamental principles are generally the same for all meters of the same meter type, the scenarios used in this analysis are unique and cannot be applied to all meters. Different manufacturers may build the same type of meter differently. For example, the Venturi meter design specifies that the location of the upstream pressure tap can be between $0.5D \pm 0.05D$ (Miller 1996). This means the upstream tap may be anywhere between 5.4-in and 6.6-in upstream of the converging section on a 12-in meter. Additionally, the length of straight pipe before the converging section may be different if the meter was custom made to fit in an existing pipeline. Upstream piping effects may also vary between the same types of meters due to the installation method, flange sizes, differing beta ratios, etc. For these reasons, the results in this analysis only apply to these meters in this scenario. However, it will show to what degree each metering technology may be affected. This will be valuable to decide whether a currently installed meter may need to be re-calibrated to get more accurate readings.
Portable Ultrasonic Meter

The portable ultrasonic flowmeter measures volumetric flow using the principles of the Doppler Effect. The clamp-on design allows the meter to measure the flow from the outside of the pipe (nonintrusive) without creating disturbances in the pipe that may cause flow distortions. The meter consists of a pair of transducers which act as both a transmitter and a receiver. The two transducers are installed on the outside of the pipe parallel to the flow. The upstream transmitter propagates an ultrasonic pulse or beam across the pipe at an angle in the direction of the flow. Conversely, the downstream transmitter propagates an ultrasonic beam across the pipe at an angle against the direction of flow. Those beams move along a single path until they are received by the opposite transducer. The fluid flowing through the beam's path and cause its velocity to increase or decrease; increased if moving in the direction of flow, decreased if moving against the flow. The difference in transit times between the upstream and downstream moving ultrasonic beams is used to calculate the velocity of the fluid.

The ease of installation and usage gives this meter many advantages in field use. Since it clamps to the outside of the pipe, it does not produce any head loss in the system. Additionally, it is not a permanent meter. It can easily be removed and reinstalled, which allows one meter to be used in multiple areas. Different methods of installing the meter exist depending on the size of the pipe and as defined by the manufacturer (Figure 2). In this case, the V-method was used. For the purpose of this
study, the meter was installed on a pipe spool of STD schedule with the locations of the sensors shown in Figure 3. This spool was installed in the test setup as explained in the next chapter. The manufacturer of the meter used in this analysis claims a maximum error of ±1.0% (Anonymous Manufacturer).
The magnetic flowmeter (also called the electromagnetic flowmeter or mag meter) measures flow using Faraday’s Law of magnetic induction which states that a conductor moving through a magnetic field experiences an electromagnetic force perpendicular to their direction of motion and creates a voltage. Two electric coils in the meter generate a constant magnetic field over the entire cross section of the tube. When the water is flowing through the magnetic field, charged particles in the fluid undergo the electromagnetic force and form a voltage. Two electrodes installed within the meter on the pipewall detect and measure the voltage. The voltage is directly proportional to the velocity of the fluid which is used to calculate the flow rate.

This technology is an effective way to measure the flow. First, it allows water to flow through the meter with almost no head loss caused by obstructions in the tube.
Secondly, it measures the total flux through the meter tube instead of measuring flow across a specified path as with the ultrasonic meter.

The meter in this study generates the magnetic field across the center of the meter. These electrodes are mounted directly across from each other on the pipewall at a center height from the bottom of the tube (Figure 4). The manufacturer claims the meter to have a maximum error of ±0.20% (Anonymous Manufacturer).

**Differential Pressure Meters**

Differential Pressure (DP) meters are among the most common types of flow measuring tools in closed conduits and have been used worldwide for over 100 years. Because they have no moving or electrical parts that may wear down over time, they have a significantly long life. Many of the older designs installed in pipelines many
decades ago are still in use today.

The flow rate for differential producing meters is calculated using the relationship between potential and kinetic energy. When kinetic energy increases, the potential energy decreases to satisfy the principles of the conservation of energy. The change in energy is created by geometric restriction placed inside the meter – a change in pipe diameter – which causes the water velocity to increase. This, in turn, results in a decrease in pressure which is mostly recovered (varying greatly, depending on the design of the meter) when the flow returns to an unrestricted pipe section. The fluid pressure is measured in two locations where a sufficient pressure differential caused by the restriction is obtained. With these measurements, the flow in the throat of the meter is calculated using the following equation:

$$Q = \frac{CA\sqrt{2g\Delta H}}{\sqrt{1-\beta^4}}$$  \hspace{1cm} \text{Eq. 1}

where $Q$ is the flow in cubic feet per second, $C$ is the discharge coefficient, $A$ is the cross-sectional area in square feet, $g$ is the gravity constant (32.17 feet per second squared), $\Delta H$ is the meter differential pressure reading in feet, and $\beta$ is the beta ratio. The area and the beta ratio values are calculated differently depending on the meter type. These values to be applied into Equation 1 are explained in the meter descriptions below.

A wide variety of geometric restrictions are used to generate the pressure drop in differential producing meter types. The different designs are specific to the desired
affects of the meter, and they each have their strengths and weaknesses. In this report, the four types of DP meters considered all have a 0.6 beta ratio.

**Classical Venturi Meter**

The Venturi meter is one of the oldest and most popular types of DP meters. It consists of a long converging section to the throat of the meter, a short cylindrical section, and a long diverging section back to the original pipe diameter. The long, conical sections are meant to increase the velocity of the fluid and return it back to its original state without causing excessive head loss. A small amount of head loss due to friction does occur in this process, mostly in the diverging section, but the overall head loss is relatively low. The differential pressure is measured between the meter inlet before the converging section and the meter throat. The value of \( A \) as applied in Equation 1 is based upon the cross sectional area of the meter throat. The beta ratio is defined as the ratio of the throat diameter to the meter inlet diameter.

The classical Venturi meter is normally larger than other DP meters, but the design offers very accurate readings for all types of fluids, including high viscous fluids and those with high solid content. The Venturi meter for this analysis is made of fabricated steel with a specified accuracy of \( \pm 0.25\% \) between Reynolds numbers 200,000 and 6,000,000 (Anonymous Manufacturer). The locations of the pressure taps are shown in Figure 5.
Halmi Venturi Tube

The Halmi Venturi Tube (HVT) is a modern, innovated version of the classical Venturi meter. The converging and diverging sections of the meter are much shorter than the classical Venturi meter which makes the total length shorter with minimal added head loss. This makes the meter an ideal candidate for replacing failed magnetic meters, ultrasonic meters, or other devices. Equation 1 is applied to this meter in the same manner as it is applied to the classical Venturi meter with the area referenced to the throat and the beta ratio being defined as the ratio of the throat diameter to the meter inlet diameter. For this study, the 12-inch HVT is made of fabricated steel with pressure tap locations as shown in Figure 6. The specified accuracy is ±0.25% for Reynolds numbers above 75,000 (Anonymous Manufacturer).
A wedge type flowmeter is a simple design built specifically for measuring highly viscous fluids such as asphalt, sludge, or cement. However, it is capable of accurately measuring all types of fluids. The head loss associated with a wedge meter is high compared to the classical Venturi meter and the HVT since the differential pressure is caused by a protrusive wedge shape fabricated within the meter tube. The area as applied in Equation 1 is the area of the open pipe under the center of the wedge shape. Because the wedge does not make a circular opening in the meter tube, the beta ratio is defined as the equivalent diameter of the area under the wedge tip over the diameter of the meter inlet. The meter used in this research is made of fabricated steel with a specified accuracy of ±0.50% (Anonymous Manufacturer). The pressure tap locations are given in Figure 7.
The V-cone meter is a straight pipe with a suspended cone shape in the center; the tip of the cone pointing upstream. The purpose of the cone restriction is to prevent swirls and other irregular streamlines as the water flows through the meter that may increase metering uncertainty. This is particularly useful if the conditions do not allow a sufficient amount of straight pipe to exist upstream of the meter.

The differential pressure is measured from a point upstream of the cone at the meter wall to the center of the downstream end of the cone. Similar to the wedge meter, the cone shape does not make a circular area in the meter tube. The area applied in Equation 1 is defined as the donut-shaped open pipe area located at the largest diameter of the cone. The beta ratio is the equivalent diameter of that same area over the meter inlet diameter. The V-cone meter used in this study was made of
carbon steel with a stated accuracy of ±0.50% (Anonymous Manufacturer). The differential head is measured at the locations shown in Figure 8.

Figure 8. V-cone 12-inch Meter Pressure Tap Locations
Experimental Setup

All laboratory equipment used was calibrated and was traceable to the National Institute of Standards and Technology. The meter was installed in the laboratory’s 12-inch test line (Figure 9). Water was supplied to the test line from a reservoir near the hydraulics laboratory. Over thirty feet of straight standard wall carbon steel 12-inch pipe (12.000-inch ID) was installed upstream of the test setup. A full set of carbon steel pipe spools was constructed, each spool being a different schedule with inside diameters shown in Table 1. The length of each spool was at least five diameters long as

Figure 9. The 12-inch Laboratory Test Line (Flow Left to Right)
Table 1. Pipe Schedule Dimensions of 12-inch Pipe

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Pipewall Thickness (in)</th>
<th>Inside Diameter (in)</th>
<th>Cross-Sectional Area (sq-in)</th>
<th>Offset Length Referenced to STD (in)</th>
<th>Change in Area Referenced to STD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.250</td>
<td>12.250</td>
<td>117.859</td>
<td>-0.125</td>
<td>4.21%</td>
</tr>
<tr>
<td>30</td>
<td>0.330</td>
<td>12.090</td>
<td>114.800</td>
<td>-0.045</td>
<td>1.51%</td>
</tr>
<tr>
<td>STD</td>
<td>0.375</td>
<td>12.000</td>
<td>113.097</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>0.406</td>
<td>11.938</td>
<td>111.932</td>
<td>0.031</td>
<td>-1.03%</td>
</tr>
<tr>
<td>60</td>
<td>0.562</td>
<td>11.626</td>
<td>106.157</td>
<td>0.187</td>
<td>-6.14%</td>
</tr>
<tr>
<td>80</td>
<td>0.687</td>
<td>11.376</td>
<td>101.641</td>
<td>0.312</td>
<td>-10.13%</td>
</tr>
<tr>
<td>100</td>
<td>0.843</td>
<td>11.064</td>
<td>96.142</td>
<td>0.468</td>
<td>-14.99%</td>
</tr>
<tr>
<td>120</td>
<td>1.000</td>
<td>10.750</td>
<td>90.763</td>
<td>0.625</td>
<td>-19.75%</td>
</tr>
<tr>
<td>140</td>
<td>1.125</td>
<td>10.500</td>
<td>86.590</td>
<td>0.750</td>
<td>-23.44%</td>
</tr>
<tr>
<td>160</td>
<td>1.312</td>
<td>10.126</td>
<td>80.531</td>
<td>0.937</td>
<td>-28.79%</td>
</tr>
</tbody>
</table>

shown in Figure 10. The length of the test spools was to provide a flow that was near uniform as it approaches the meter. Each test had one of the spools installed immediately upstream of the meter (Figure 11). Approximately fifteen feet of straight standard wall pipe was always installed downstream of the meter. Additionally, a calibrated 12-inch magnetic flowmeter and a 12-inch control valve were installed farther downstream to assist in setting the target flow rates. The discharge pipe directed flows to a 250,000-lb capacity weight tank.

The test flowmeters were installed as recommended by the manufacturer. Care was also taken to ensure that each flowmeter was installed concentrically with the upstream pipe spool. This was to assure that the diameter offset was the same around the entire circumference of the meter inlet. The differential pressure transmitter output was measured using a Fluke multimeter. The output reading from the
Figure 10. Test Spools of Different Pipe Schedules

Figure 11. Experimental Setup in the Laboratory 12-inch Test Line
multimeter was different depending on the meter: either Hz (magnetic) or mA. These output readings were converted to flow using equations given later in this chapter.

**Procedure**

The span of the multimeter was established so that the uncertainty of the reading was minimized. The multimeter settings and the equations used for calculating the indicated flow rate of the meter were as follows:

- **Portable Ultrasonic Meter** – The span of this meter was set to 6600. The output of the meter was read in milliamps and the flow was calculated using Equation 2:

\[
Q_{gpm} = \frac{\text{span}}{16} (mA - 4) \quad \text{Eq. 2}
\]

where \(Q_{gpm}\) is the flow in gallons per minute, \(\text{span}\) is the span of the meter, and \(mA\) is the meter output in milliamps.

- **Magnetic Meter** – The output of the magnetic flowmeter was read in frequency (Hz). The span and the maximum frequency were set to 8,000 and 10,000, respectively. The flow was calculated using the equation:

\[
Q_{gpm} = Hz \times \frac{\text{span}}{Hz_{\text{max}}} \quad \text{Eq. 3}
\]

where \(Q_{gpm}\) is the flow in gallons per minute, \(\text{span}\) is the span of the meter, \(Hz\) is the meter output in hertz, and \(Hz_{\text{max}}\) is the maximum hertz value set in the meter.

- **Differential Pressure Meters** – The head differential was measured using a Rosemont differential transmitter. The range of the transmitter was specified depending on the flow rate as shown in Table 2. (Note: The range is defined as the maximum...
Table 2. Range Values of the Rosemont Transmitter at Specified Flow Rates

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Range (inches):</td>
<td>5</td>
<td>50</td>
<td>250</td>
<td>1000</td>
</tr>
</tbody>
</table>

possible amount of measured head difference the transmitter will read during the test run. However, if the range is set too high, the uncertainty in the head measurement increases.) The transmitter was connected to the multimeter with output readings in milliamps. The meter’s differential was calculated using:

\[
\Delta H = \frac{\text{Range}}{16} \left( mA - 4 \right)
\]

Eq. 4

where \(\Delta H\) is the differential, \(\text{Range}\) is the range of the transmitter, and \(mA\) is the meter reading in milliamps. Using the differential, the flow rate was calculated using Equation 1.

For each test run the flow rate and water temperature were measured. The unit weight of water varies depending on its temperature. With a known unit weight of water, the actual flow rate is calculated by

\[
Q = \frac{W_{H2O}}{t \gamma_{H2O}}
\]

Eq. 5

where \(W_{H2O}\) is the weight of water in the weight tank (pounds), \(t\) is the time of the test (seconds), and \(\gamma_{H2O}\) is the unit weight of water (pounds per cubic foot).

After the flow rates from the meters and the volumetric weight tank are calculated, the coefficient is found from the equation

\[
C = \frac{Q_{Actual}}{Q_{Indicated}}
\]

Eq. 6
where $Q_{\text{Actual}}$ is the flow rate as calculated from the weight tank and $Q_{\text{Indicated}}$ (or $Q_{\text{theoretical}}$) is the flow rate from the meter reading.

In addition to the flow rates and the coefficients, the Reynolds number was also calculated at the inlet of the meter for each test. The equation for calculating Reynolds number is

$$Re = \frac{QD_H}{\nu} \quad \text{Eq. 7}$$

where $Q$ is the flow (cubic feet per second), $D_H$ is the hydraulic diameter of the meter inlet (ft), $A$ is the cross sectional area of the meter inlet (square feet), and $\nu$ is the kinematic viscosity of the water (square feet per second). The step-by-step procedure for obtaining the results for each test follows:

1. The target flow rate was set using the 12-inch flow control valve and the 12-inch magnetic reference meter.

2. The water was diverted into the laboratory 250,000-lb volumetric weight tank to begin the test. The appropriate amount of time the flow was being diverted was set based on minimizing uncertainty in the results: 400 seconds for the lowest flow rate, 200 seconds for all other flows rates.

3. The output of the Fluke multimeter was averaged over the entire duration of the test.

4. At the end of the test, the water ceased flowing into the weight tank. The weight and water temperature were measured and the actual flow rate was calculated from Equation. 5.
5. The averaged output of the Fluke multimeter was used to calculate the indicated flow rate with the appropriate equation (Equations 1-4).

6. The indicated flow rate was compared with the actual flow rate calculated from the volumetric weight tank and the discharge coefficient value was calculated with Equation 6.

7. The Reynolds number was calculated for each run at the inlet of the meter with Equation 7. Before the flow rate was changed the correction coefficient was plotted against the Reynolds number. This is to verify the coefficient readings are within the spread of the meter’s specified accuracy.

The procedure was repeated for every combination of meter and each of the nine different upstream pipe schedules. Ten main data points were collected for each setup at near equal intervals of flow rates between 400gpm and 6,550gpm. Most test series also include repeat data points to verify results or show the repeatability.
CHAPTER IV
RESULTS AND DISCUSSION

The results are shown graphically and the uncertainty is given for each meter type (American 2006). Please note that these results apply to the specific meters tested during this study only, and not to all meters of the same type. However, it is expected that similar results would be found if multiple meters of the same type were tested. The values for the discharge coefficient (C) were plotted based on their percent difference from the value of C with the meter in “ideal conditions” – installed in a pipeline of STD pipe schedule. In other words, the charts show how the meter readings differ from how it read when installed in a STD schedule pipe. Thus, the differential values of C when installed downstream of a STD schedule pipe are represented by a straight line at 0.0% in the charts. The values of C in these ideal conditions were determined using linear interpolation of the results when the meter was installed in STD schedule pipe. This was to assure the differentials between C values were being compared at equal Reynolds numbers. Values above the red STD line which were caused by the effects of the pipewall offset indicate that the meter is under-calculating the flow; i.e., more fluid is passing through the meter than the reading indicates. Conversely, values below the red line indicate the meter is over-calculating the flow; i.e., less fluid is passing through the meter than the reading indicates. The shaded region in each chart represents the specified range of accuracy for the meter.
Portable Ultrasonic Meter

The ultrasonic flowmeter results are shown in Figure 12 with a maximum uncertainty of 1.12% and a typical range of 0.10% - 1.12%. The meter is resilient to small, negative offsets of smaller pipe schedules and positive offsets less than 0.187-in (pipe schedules below 60). At least, the effects caused by these diameter changes are within the meter’s specified accuracy of ±1.0%. However, at Reynolds numbers below 200,000, the meter’s accuracy is affected by the change in diameters caused by pipe schedules 30 and 40. The manufacturer does not give a range of Reynolds numbers for the meter, but the meter is over-calculating the flow by up to 1.9%. In all other cases, the meter is over-calculating the flow anywhere from 1.1% to 8.0%. Each dataset shows the effects are largest at lower Reynolds numbers. The results are predictable in the sense that the greater the diameter offset, the greater the effect except for one instance. For an unknown reason, the effect caused by being installed in a schedule 120 pipe is greater (up to 1.8% greater) than if it was installed in a schedule 140 pipe.

A number of data points were retested to confirm results. Most of the retested values confirmed the results. However, the dataset for a schedule 160 pipe shows significant differences in the retested data points. Some ultrasonic meters are known for having repeatability issues (Miller 1996). This may be the case, but the spread shows the repeatability error is much larger in some areas than in others. This may be due to the location of the flow separation in reference to the meter transducers.
Figure 12: Effects of Pipewall Offsets on the Portable Ultrasonic Flowmeter
The distances the flow separation effects reach downstream depend on the flow rate and the intensity of the flow separation. As the flow rate increases, the streamline separation reaches further into the meter (Figure 13). At the right flow rate, the turbulence generated by the pipewall offset may be at or very near the transducers, which may cause significant error in meter reading. At higher flows, these flow separations may be pushed further downstream from the transducers. This would explain why the repeatability is much more severe in some flow rates than others. However, more experimentation and analysis will need to be done for this to be proven.

**Magnetic Meter**

The magnetic meter results are shown in Figure 14 with a maximum uncertainty of 0.15% and a typical range of 0.07% - 0.15%. Any pipewall offset, positive or negative, causes the meter to under-calculate the flow by up to 1.9%, well outside its specified ±0.2% accuracy range. However, this effect only occurs at certain Reynolds numbers for some datasets. For example, the effects caused by installing a schedule 30 pipe upstream of the meter mostly occur for Reynolds numbers above 400,000. Also, at Reynolds number 75,000, the datasets for all pipe schedules below 140 are shifted upwards nearly 0.50%. The manufacturer does not specify a range of accurate metering based on Reynolds numbers. The results also show that the effects of pipe schedule mismatch on this meter hold relatively constant between pipe schedules 20 and 60.
Figure 13. Possible Flow Separation in the Portable Ultrasonic Meter
Figure 14: Effects of Pipewall Offsets on the Magnetic Flowmeter
However, significant effect occurs between pipe schedules 60 and 80 (a -4.25% change in area) while there appears to be no change in effect when comparing the results from pipe schedules 80 to 100 (an additional 5.41% change in pipe area). The results also show that schedule 140 causes a greater effect than schedule 160 at Reynolds numbers below 800,000. Beyond that, schedule 140 has a downward trend, meaning the effects of schedule 140 decrease as Reynolds number increases.

**Differential Pressure Meters**

The following data displays the effects of the pipe diameter offsets on pressure differential meters. In most cases, the effects cause the meter to under-calculate the flow. This is expected based from the DP technology. In order for pressure to be accurately measured, the streamlines must be orthogonal to the pressure taps. As flow enters the meter from a smaller diameter pipe, the streamlines are separated and eddies form along the meter wall and, coincidentally, at the pressure tap locations as shown in Figure 15.

![Figure 15. Streamline Separation from Positive Diameter Offsets](image)
The flow separation causes the flow to be non-orthogonal to the pressure taps and extra velocity head is added to the measurement. The higher velocities cause the pressure taps to read a lower pressure. As a result, the differential pressure between the upstream and downstream pressure taps is reduced. By modifying Equation 1, the correction or discharge coefficient for DP meters is calculated by

\[ C = \frac{Q\sqrt{1-\beta^4}}{A\sqrt{2g\Delta H}} \]  
Eq. 8

in which \( Q \) is the flow rate in cubic feet per second, \( \beta \) is the beta ratio, \( A \) is the open cross sectional area in the tube in square feet, \( g \) is the gravity constant (32.2 feet per second squared), and \( \Delta H \) is the meter differential pressure in feet. This equation shows that as the differential pressure decreases, the coefficient value increases. Also, the greater the intensity of the eddy, the greater the change in head. The intensity of the eddy is much higher as the flow experiences a greater sudden change in pipe area. As shown in this section, the percent error in which the meter under-calculated the flow increased as the pipewall offset increased.

**Classical Venturi Meter**

Results for the classic Venturi meter shown in Figure 16 were gathered with a maximum uncertainty of 0.20% ranging between 0.11% - 0.20%. A noticeable trend change occurs at the lowest tested Reynolds number; all of the data is shifted downward to a significant degree. This coincides with the meter’s specifications in
Figure 16: Effects of Pipewall Offsets on the Classical Venturi Flowmeter
which the discharge coefficient holds constant at Reynolds numbers between 200,000 and 6,000,000.

The meter shows little to no effect from the negative diameter changes and the smaller positive diameter changes. The first sign of the meter error being outside the specified accuracy of ±0.25% occurred when pipe schedule 100 was installed upstream. The meter under-calculated the flow by up to 0.34%. The subsequent data of pipewall offsets greater than 0.468-inch followed a predictable pattern of nearly parallel which shows that the meter error increased as the pipewall offset increases. The error in flow measurement ranges from 0.26% to 3.59%.

**Halmi Venturi Tube**

Results shown for the Halmi Venturi Tube in Figure 17 have a maximum uncertainty of 0.20% and a range of 0.11% - 0.20%. The results immediately show an upward trend in several datasets at Reynolds numbers below 400,000. In this range, the meter is affected by negative, upstream diameter offsets caused by the smaller pipe schedules installed upstream. The meter is over-calculating the flow by as much as 1.00% in these conditions. Curiously, the datasets for schedules 40 and 60 also cause the meter to over-calculate the flow in this range even though they both have larger diameters than the ideal standard schedule (a positive pipewall offset). The HVT is claimed to have a constant discharge coefficient for Reynolds numbers above 75,000. For this reason, the sloping trend reaching as far as 500,000 in some cases seems irregular.
Figure 17: Effects of Pipewall Offsets on the Halmi Venturi Tube
With the exception of the aforementioned irregularities, the results are similar to those of the classical Venturi meter. At Reynolds numbers above 500,000, the meter shows little to no effect from the negative diameter changes and the smaller positive diameter changes. With pipe schedule 80 installed upstream, the error in flow measurement first begins to drift outside the specified accuracy of ±0.25%. The following datasets above schedule 80 follow the predictable pattern of increased error from 0.26% to 3.89%.

**Wedge Meter**

Results for the wedge meter shown in Figure 18 have a maximum uncertainty of 0.19% and a range of 0.10% - 0.19%. The results show that the meter is not significantly affected by any diameter offsets upstream of the meter. The reason for such resilience may be because of the locations of the pressure taps. Both pressure taps are located in line with the wedge shape restriction inside the meter. The wedge shape already causes such significant amounts of flow separation that the added separation caused from the diameter offsets may seem insignificant.

**V-Cone Meter**

Calculated uncertainty for all measurements for the V-cone meter has a maximum value of 0.21% and a range of 0.16% - 0.21%. The results are shown in Figure 19. At some point, every pipewall offset will cause the meter to under-calculate the flow. The errors in flow measurement are as much as 3.26% for the tested Reynolds
Figure 18: Effects of Ptwall Offsets on the Wedge Flowmeter
Figure 19: Effects of Pipewall Offsets on the V-cone Flowmeter
numbers in this analysis. Each dataset shows that the meter error in flow measurement increases as Reynolds number continues to increase beyond 500,000. It is possible that the error may continue to increase if the upward trend continues. Also, there does not appear to be any identifiable pattern from the data. For example, schedule 60 and schedule 140 cause nearly the same effect, but schedule 120 causes a larger effect than schedule 140 in most cases. Another obvious result shows the much larger effect from schedule 160 than all other pipe schedules. There are also repeatability issues when installed in a schedule 160 pipeline. This may be the case with other pipe schedules, but there is not sufficient data to support this.
Standard schedule flowmeters being installed in pipes with schedules other than STD may affect the meter’s ability to accurately measure the flow unless the meter was calibrated in pipe representative of the actual installation. These results are based on how the meter performs while installed in a pipeline of schedule other than STD versus how it would perform if it were installed in STD schedule pipe. Again, the results of the analysis apply to the specific meters in this research scenario only. Meters of the same type may respond differently due to the method of installation into the pipeline and locations of the flow measurement components (pressure taps, transducers, etc) in reference to the sudden change in diameter.

Results Summary

In most cases, the meters are mostly resilient to negative diameter offsets from the smaller pipe schedules (i.e. a sudden decrease in pipe area). However, results show positive diameter offsets have considerable effects on flow metering. As expected, the greater the change in pipe area, the greater the effect in most cases. The sudden pipe expansion the flow experiences as it enters the meter causes flow measurement error by as much as 8.0% depending on the meter type and the specific upstream pipe size. If meters in these conditions are not corrected, the fluid system cannot function properly. The 12-inch meters chosen for this study include the portable ultrasonic meter,
magnetic meter, and four types of differential pressure meters: classic venturi, Halmi venturi, V-cone, and wedge. The general conclusions for each tested meter are summarized as follows.

**Portable Ultrasonic Meter**

Test results showed that the portable ultrasonic meter was most affected by the diameter offsets as compared to all of the tested meters. The effects first begin to have significant values when the change in area exceeds -6.0%. The effects cause the meter to over-calculate the flow, meaning that less fluid is passing through the pipeline than the meter reads. If the meter were installed immediately downstream of a schedule 160 pipeline, the measurement may be as much as -8.0% difference than if it were installed in a pipeline of STD pipe schedule. The effects from sudden change in diameter also cause the meter to have repeatability issues at certain flow rates. This may be due to the specific condition of the meter in this test (location of the transducers with respect to the change in diameter), but more research is needed for that to be proven. Also, this meter was a single path meter, meaning the ultrasonic beam only follows one path within the meter. Other ultrasonic meters have more than one path which may make them more resilient to the pipewall effects than the one used in this analysis.

**Magnetic Meter**

The accuracy of the magnetic flowmeter is affected by any differing pipe schedule installed upstream. However, the effects only occur at specific Reynolds
numbers for pipe schedules below 80. For all other pipe schedules, the meter consistently under-calculates the flow outside its specified range of accuracy. In other words, more flow is passing through the pipeline than the meter indicates. The error may be up to 2.0% depending on the pipe schedule.

**Differential Pressure Meters**

**Classical Venturi Meter**

The classical Venturi meter is resilient to a sudden decrease in diameter for the ranges tested in this analysis. The effects of the diameter offset on the Venturi meter begin to be significant when being installed in a pipe schedule 100 and above, in which case the meter is under-calculating the flow. Or, more flow is passing through the pipeline than the meter indicates. The error was found to be between 0.3% when installed in a schedule 100 pipe and 3.59% when installed in a schedule 160 pipe.

**Halmi Venturi Tube**

The Halmi Venturi flowmeter is the only meter tested in this analysis that shows it is somewhat affected by the slight, sudden contraction caused by being installed in a smaller schedule pipe. However, the effects only occur at Reynolds numbers lower than 500,000. The meter is also affected by positive diameter offsets, specifically at pipe schedules 80 and above. The error for these offset ranges was found to be between
0.25% to nearly 4.0% between pipe schedules 80 and 160. The meter was under-calculating the flow in these cases.

**Wedge Meter**

The wedge meter shows no significant effects caused by any change in diameter. This may be due to the wedge shape in the center of the meter. Such significant flow separation occurs near to where the pressure taps are located that the extra flow separation caused from a slight change in pipe area may be insignificant.

**V-Cone Meter**

The V-cone meter is affected by all changes in pipe schedule at some point in the tested range. At Reynolds numbers above 500,000, the effects increase as the Reynolds number continues to increase. The meter under-calculated the flow by as much as 3.26%, depending on the upstream pipe schedule. This error may be even increase at higher Reynolds numbers. More analysis is needed to show this.

Overall, the results of this study prove that flowmeters should always be installed in piping that has the same pipe schedule as the meter itself. If a standard wall classical Venturi meter that was calibrated in standard wall pipe was then installed in a pipeline that contained 120 schedule steel pipe, flow deviation of as much as 1.0% could be expected. If this example were applied to a natural gas company, it is common for a compressor station to move over 700 million cubic feet of natural gas every day on a continuous basis. To quantify the costs associated with these errors, if the gas sells for
approximately $4.00 per thousand cubic foot, the company could be losing over $10.2 million per year. If it were using a schedule 160 pipe, it would lose up to $37.8 million per year.

**Need for Further Research**

The following are recommendations for further research:

- The results of this analysis show that the diameter offsets affect not only the ultrasonic flowmeter’s accuracy, but also repeatability. More testing is recommended determine the cause.

- Much research has been done on installation effects caused by valves and pipe elbows which give minimum upstream pipe lengths for meter installation. However, limited research has been done to determine the minimum upstream pipe length needed to reduce the effects of sudden pipe diameter changes.

- More meter types that may be included in this analysis include the ultrasonic meter (non clamp-on design), orifice plates, propeller, etc.

- Testing meters of sizes other than 12-inches to determine if the effects show the same patterns as the meters in this analysis.

- Performing the same analysis on differential pressure meters with different beta ratios may increase understanding of the effects on DP meter accuracy.

  Continuing research on water meter accuracy will help to understand how to more effectively manage a fluid system.
REFERENCES


APPENDICES
After each test run, the resulting discharge coefficient values were plotted compared to Reynolds numbers. The following plots show the resulting plots of each test run.
Figure A1: Discharge Coefficient Values of the Portable Ultrasonic Flowmeter
Figure A2: Discharge Coefficient Values of the Magnetic Flowmeter
Figure A3: Discharge Coefficient Values of the Classical Venturi Flowmeter
Figure A4: Discharge Coefficient Values of the Halmi Venturi Tube
Figure A5: Discharge Coefficient Values of the Wedge Flowmeter
Before a meter is used in an industrial setting, it is calibrated to provide more accurate measurements. The calibration likely occurred with the meter installed in a test line of STD pipe schedule. The calibrated coefficient value is calculated over several tests of different Reynolds numbers. The final coefficient is found by taking the average of all of those values.

The following plots show the deviation of the coefficient values if the meter were then placed in a pipeline with a different pipe schedule other than STD. For example, Figure B1 shows results for the portable ultrasonic flowmeter. At Reynolds number 600,000, the meter would be reading at a -1.0% error if the meter were installed in a schedule 60 pipeline. At the same Reynolds number, it would have an error of -3.3% if installed in a schedule 140 pipeline. And averaging all of the deviations of the “STD” dataset in each plot, the deviation would be 0.0%.
Figure B3: Deviation of the Discharge Coefficient Values of the Classical Venturi Flowmeter
Figure B4: Deviation of the Discharge Coefficient Values of the Halmi Venturi Tube
Figure B5: Deviation of the Discharge Coefficient Values of the Wedge Flowmeter
Figure B6: Deviation of the Discharge Coefficient Values of the V-cone Flowmeter