ULTRASONIC METER TESTING FOR STORAGE APPLICATIONS

Final Report

(January 1997 – March 1998)

by

Terrence A. Grimley

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for

U.S. Department of Energy
Morgantown Energy Technology Center
P.O. Box 880
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Morgantown, West Virginia 26507-0880

under

DOE Cooperative Agreement No. DE-FC21-96MC33033

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Approved by

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Department of Fluids Engineering

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Disclaimer

Abstract

In the United States, nearly one third of all natural gas consumed during peak usage periods is delivered from gas storage. Accurate and efficient measurement of these large volumes of gas is critical to the cost-effective use of gas storage. More frequently, ultrasonic flow meters are becoming the meter of choice for gas storage applications since they can measure bi-directional flows over large ranges, with essentially zero flow blockage and no moving parts. Ultrasonic flow meters may provide lower capital costs than conventional measurement technologies, since a single ultrasonic meter can, in many instances, take the place of multiple conventional meters. Also, since ultrasonic meters have no moving parts and minimal flow blockage, they may provide operation and maintenance cost savings over the long term.

Because ultrasonic flow meters are relatively new to the natural gas industry, there is less test information available than for conventional meter types, such as orifice meters and turbine meters. Laboratory tests of commercially available 8-inch diameter single- and multipath ultrasonic flow meters were conducted as part of this study to assess their performance in natural gas storage field applications. The lab tests were performed at the Gas Research Institute Metering Research Facility located at Southwest Research Institute in San Antonio, Texas. The Metering Research Facility provides more precise control of test conditions than can be attained in the field. The lab evaluation tests determined the sensitivity of ultrasonic gas flow meters to gas pressure and temperature variations. The performance of the meters under bi-directional flow conditions was also assessed to establish the range over which an accurate flow rate measurement can be obtained. Lab tests were also performed to quantify the magnitude of the volumetric flow rate measurement error caused by the presence of a thermowell upstream of the meter, and to establish guidelines on placement of the thermowell so as to minimize or eliminate this error source.

In addition to collecting ultrasonic flow meter test data at the Metering Research Facility, Southwest Research Institute staff also collected and analyzed field meter performance data from gas transmission pipeline operators in the United States. Several pipeline operators have performed field evaluations of ultrasonic flow meters ranging in size from 304.8 to 508 millimeters (12 to 20 inches) in diameter. Significant findings and observations from these field evaluations are included in this report.

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Executive Summary

In the United States, nearly one third of all natural gas consumed during peak usage periods is delivered from gas storage. Accurate and efficient measurement of these large volumes of gas is critical to the cost-effective use of gas storage. More frequently, ultrasonic flow meters are becoming the meter of choice for gas storage applications since they can measure bi-directional flows over large ranges, with essentially zero flow blockage and no moving parts. Ultrasonic flow meters may provide lower capital costs than conventional measurement technologies, since a single ultrasonic meter can, in many instances, take the place of multiple conventional meters. Also, since ultrasonic meters have no moving parts and minimal flow blockage, they may provide operation and maintenance cost savings over the long term.

Because ultrasonic flow meters are relatively new to the natural gas industry, there is less test information available than for conventional meter types, such as orifice meters and turbine meters. The primary objective of the work described here was to augment the available knowledge base with meter test results pertinent to gas storage applications. Both laboratory and field evaluation test results are presented. The laboratory tests were performed at the Gas Research Institute Metering Research Facility located at Southwest Research Institute in San Antonio, Texas. Several gas transmission pipeline companies operating in the United States performed the field evaluations.

Commercially available single- and multipath meters were tested in the laboratory over a range of gas pressures, temperatures, and flow rates with gas flow in either the "forward" or "reverse" direction. Tests were also conducted to assess the effect on flow measurement accuracy of a thermowell placed upstream of the meter. Test results indicated that variations in the gas pressure and changes in the flow direction could, in certain instances, affect meter accuracy. The magnitudes of these effects were found to be specific to the individual meter design. Variations in gas temperature do not appear to significantly affect meter accuracy. A thermowell placed upstream of an ultrasonic flow meter can also produce a measurement bias error, if the thermowell is placed too close to the meter (i.e., less than about three to five pipe diameters from the meter body) or when it is aligned with an ultrasonic meter's acoustic measurement path.

Although the field meter evaluations were limited in scope, they showed that meter measurement accuracy was typically within expected limits (i.e., about ±1%) for several meter sizes and meter station piping configurations.

The compilation of test results from this study suggest that ultrasonic flow meters can, in many cases, be a viable alternative to the conventional measurement methods used in gas storage field applications. When properly installed, operated, and maintained, ultrasonic meters can measure bi-directional flow rate to an accuracy comparable to traditional measurement methods, such as orifice or turbine flow meters. In addition, ultrasonic meters typically have a broader operational range (i.e., flow rate range) than conventional meter types and may require less maintenance over the long term.

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INTRODUCTION

Natural gas transmission companies use gas storage as a cost-effective way to help meet peak customer demand. Approximately 30% of the total amount of natural gas delivered during peak usage periods in the United States comes from stored reserves. Each year, approximately 3 trillion cubic feet (tcf) of gas moves through the storage facilities in the United States. A recent study by United Energy Development Consultants showed that unaccounted for gas losses, based on the Federal Energy Regulatory Commission (FERC) Form 2 reports completed by storage operators, ranged from 79 billion cubic feet (bcf) to 152 bcf per year. The magnitude of these numbers can be attributed, in part, to errors in the measurement of the amount of gas flowing into and out of the storage facilities. Significant errors in the measurement of the gas volume passing through these storage facilities can result in costly delivery shortfalls.

Gas service providers in the United States are working to improve the measurement accuracy at gas storage sites to help ensure deliverability in times of critical demand. To this end, many gas companies are beginning to use ultrasonic gas flow meters as a viable alternative to conventional storage field measurement technologies. Ultrasonic meters have been used in liquid flow applications for decades, but only recently have they been used for gas applications. Key design attributes of ultrasonic gas flow meters include their ability to accurately measure bi-directional flows over large ranges, no blockage of the flow stream (as is the case with differential meters, such as the orifice), no moving parts to wear or break, and onboard self-diagnostics that are capable of assessing the operational health and performance of the meter. Ultrasonic flow meters may also provide cost advantages over conventional metering technologies. For instance, ultrasonic meters may provide lower capital investment to users, since a single ultrasonic meter may take the place of multiple conventional meters plumbed in parallel (Beeson,[1] Sakariassen[2]). Also, the absence of moving parts within the meter body combined with broad flow rate rangeability (without meter adjustment) may provide users with long-term savings on operation and maintenance, although ultrasonic gas flow meters are still relatively new and their long-term operation and maintenance needs are not yet fully known.

Because of the potentially large operational and economic benefits of ultrasonic gas flow meters, there is a great deal of interest in their application by the natural gas industry of the United States. Certain circumstances are, however, limiting broader use of this technology. For example, the lack of an industry standard covering the construction and use of ultrasonic meters for natural gas measurement has limited the acceptance of this technology on a broad scale. Other issues of concern are the lack of a substantial body of test information, at least in comparison to what is available on orifice meters and turbine meters, and the difficulty in proving the flow performance of very high capacity meters due to flow capacity limitations at most calibration facilities.

Basics of Meter Operation

Ultrasonic flow meters use measurements of the transit time of high frequency (i.e., ultrasonic) energy pulses between one or more pairs of transducers to determine the volumetric flow rate through the meter. The relationship between the measured transit time of an ultrasonic pulse and the average velocity along the pulse path has been well described by others [Freund and Warner,[3] Drenthen,[4] van Dellen,[5] and the American Gas Association (A.G.A.)[6]]. Figure 1 illustrates the basic concepts.

The critical meter dimensions, lengths L and X in Figure 1, are measured on the meter body. Electronic timing circuits onboard the flow meter measure the upstream and downstream transit times, t_U and t_D. Equations 1 through 3 show that the measured quantities are inherently bi-directional and are based on the relative magnitudes of t_U and t_D. Equation 1 also shows that the measured path velocity is independent of the speed of sound of the flowing medium and, therefore, is independent of the gas composition. As the meter size or velocity increases, the measured transit times and the difference in transit times also increase, respectively. Both of these effects can lead to improved measurement accuracy, but a limit occurs when the transmitted pulses no longer reach the receiving transducer. At high velocities, excessive 'bending' of the beam path causes the pulses to miss the receiving transducer. Large meter diameters also require high acoustic signal strength to ensure that the transmitted ultrasonic pulses reach the receiving transducer on the other side of the pipe. Another operational concern is that the transit times are determined from the detection of high frequency pulses, so noise in the spectrum used by the ultrasonic transducers can interfere and cause errors in the measurement of the transit time. One example of a problem of this type is when a 'low-noise' pressure or flow control valve (that shifts audible noise to higher frequencies, in the ultrasonic range) is placed in close proximity to an ultrasonic flow meter. The noise produced by the valve can mask the meter pulses, making them hard to detect.

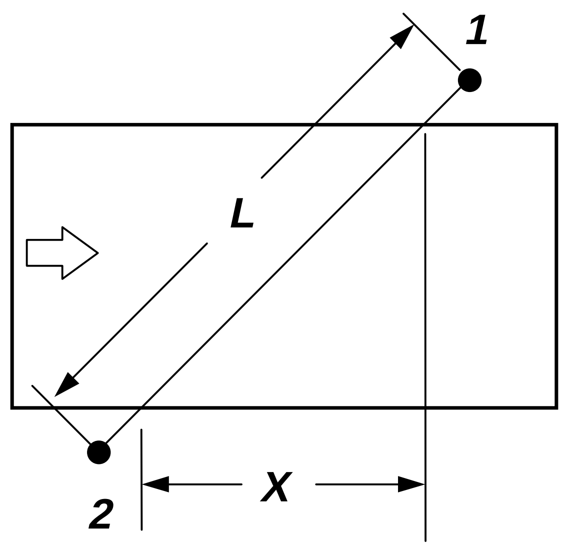

Figure 1 - Ultrasonic meter geometry with transducers located at positions 1 and 2

$$\text{average path velocity, } \bar{v} = \frac{L^2}{2\,X}\frac{(t_U - t_D)}{t_U\,t_D} \qquad (1)$$

$$\text{measured speed of sound, } c = \frac{L}{2}\frac{(t_U + t_D)}{t_U\,t_D} \qquad (2)$$

$$\text{meter average velocity, } V = \sum_{i=1}^{N} w_i\,\bar{v}_i \qquad (3)$$

where N = number of ultrasonic paths
w = weighting function (path specific)

Since ultrasonic meters measure the average velocity along one or more pulse paths (i.e., the velocity determined from Equation 1), a calculation is required to convert this (these) measured value(s) to the average axial velocity (the velocity used to calculate the volumetric flow rate). A weighting function, *w*, is typically used to combine the contribution of each measured path velocity to the average axial velocity.

Although the basic relationships given in Equations 1 through 3 are common to all transit time ultrasonic flow meters, there is considerable variation in path configuration, transducer type and placement, transit time measurement algorithm, and flow calculation method used by the various commercially available meters. These differences are due to the different strategies used by the meter manufacturers to achieve the target accuracy of the meter, which is typically stated as being in the range from ±0.5% to ±1.0% (i.e., comparable to the accuracy level achieved by orifice and turbine meters). Since all of the geometric parameters needed for the flow rate calculation can be determined, and the non-dimensional scaling of fluid velocity profiles is understood, the meters are capable of achieving this level of accuracy without flow calibration, at least in certain installations. Differences in meter configuration and data processing methods can affect meter accuracy, rangeability, repeatability, and susceptibility to error due to less-than-ideal piping installation configurations.

Project Objectives

When ultrasonic flow meters are used in gas storage field applications, wide flow rate rangeability may be required when there are significant differences in gas flow rates for injection and withdrawal. Meters are also exposed to a substantial variation in operating pressure and temperature as a storage field is charged or depleted. These operational factors, as well as the need for bi-directional flow measurement, are some of the unique characteristics of gas storage metering.

The primary objective of this project was to expand the database on the performance of ultrasonic gas flow meters used in gas storage applications. The effects of line pressure and gas temperature variations, flow rate variation, and reverse flow have been investigated. The minimum acceptable upstream separation distance between a thermowell and an ultrasonic meter has also been determined. In addition, field meter performance data have been obtained from gas transmission pipeline companies to supplement the test data acquired in the flow laboratories, where test conditions are similar to, but not exactly like those observed in the field.

Ultrasonic gas flow meter test results published prior to this study [including those by van Bloemendaal and van der Kam,[7] van der Kam et al.,[8] Vulovic et al.,[9] and others well documented in the European Gas Research Group (GERG) monograph[10]] provided information on meter performance for a variety of upstream flow disturbances and a variety of meter configurations and diameters. These results suggested that the meters are capable of accuracies within ±1%. These test results also suggested that upstream piping configuration effects can induce measurement bias errors of ±0.2% to ±0.8%. The magnitude of error depends on the severity of the disturbance of the flow field, the meter location relative to the upstream piping disturbance, and the meter transducer configuration and orientation. However, prior to this study, there were few published results concerning the bi-directional performance of ultrasonic meters. Karnik et al.[11] found deviations between forward and reverse flow direction calibrations, although the magnitude of the deviations was within the meter's repeatability limits. One of the goals of the study described here was to provide more insight into the performance limits of meters operated in a bi-directional mode.

In uni-directional gas flow applications, the flowing gas temperature is measured by a sensor placed in a thermowell located several pipe diameters downstream of the flow meter. However, when the flow direction is reversed (for example, from injection to withdrawal) the gas flows across the thermowell prior to entering the meter. The flow wake produced by a thermowell can cause a measurement bias error when the meter is downstream. The minimum acceptable separation distance between a thermowell and an ultrasonic gas flow meter (i.e., the distance required to prevent a measurement bias error from occurring due to velocity profile distortion) was established during this study.

The technical information provided here is intended for ultrasonic meter manufacturers, flow meter operators, and industry standards writing groups. As stated earlier, one issue that has prevented wider acceptance of ultrasonic flow meters in the natural gas industry has been the lack of a standard covering their use for custody transfer applications. The American Gas Association recently published a recommended practice (i.e., A.G.A. Report No. 9[12]), thus providing some guidance on the application of ultrasonic flow meters for the measurement of gas. However, the A.G.A. report acknowledges that even though a significant amount of testing has been conducted to date on ultrasonic gas flow meters, additional information is still needed for further development of industry standards.

Lab Test Methods

The laboratory tests were performed in the Gas Research Institute (GRI) Metering Research Facility (MRF) High Pressure Loop (HPL) located at Southwest Research Institute (SwRI). Test conditions at the MRF approximated the operational conditions observed in the field. Field test evaluations were also part of the work scope and are discussed in detail in a later section of this report.

The ultrasonic flow meters evaluated at the GRI MRF were installed in the Test Section of the HPL. Transmission-grade natural gas was used in all tests. Flow data were collected simultaneously from the ultrasonic meters and from the HPL critical flow nozzle bank, which served as the flow reference. The HPL's five binary-weighted sonic nozzles were calibrated in situ**,** at different line pressures, against the HPL weigh tank system (Park et al.[13]). An on-line gas chromatograph and equations of state from A.G.A. Report No. 8[14] were used to determine gas properties for all calculations.

The static line pressure, relative to a reference line pressure measured elsewhere in the HPL system, was measured two pipe diameters downstream of each test meter. The gas temperature was measured three pipe diameters downstream of each meter using a 3.2-mm diameter probe. The temperature and pressure measurements were used in combination with the measured gas composition and the volumetric flow rate reported by the ultrasonic meter to calculate the mass flow rate at the ultrasonic meter. The test meter mass flow rate was compared to the rate determined by the critical flow nozzles to establish the flow measurement error.

Instromet Ultrasonic Technologies, Inc., and Daniel Industries, Inc., each provided two 8-inch diameter flow meters for testing, at no cost to this program. All four of the test meters were commercially available in the United States as of the date of this report. ***None of the meters had been flow calibrated prior to being tested as part of this program***. Table 1 summarizes the meter configurations for the two multipath and two single-path test meters. The meters all had identical flange-to-flange dimensions (800.1 mm in length) and inside diameters (202.7 mm ± 0.127 mm) in order to simplify the interchange of the meters at the different test locations in the HPL piping. The manufacturers provided the meter setup parameters based on their particular procedures for mechanical, electrical, and other measurements. At the time of the tests, the profile correction parameters used for meter M2 were under review by the manufacturer. Parameters specific to the operating pressure and temperature (i.e., fluid properties used internally by the meter calculation algorithm) were adjusted for each test condition, as required.

Table 1 - Test meter geometry

Meter No.	Manufacturer	No. of Paths	Acoustic Path Arrangement
M1	Instromet	3	Two mid-radius double-reflecting, one centerline single-reflecting
M2	Instromet	1	Centerline, single-reflecting, 60° incident angle, -30° from vertical
M3	Daniel	4	Parallel, non-reflecting, horizontal
M4	Daniel	1	Centerline, single-reflecting, 60° incident angle, +45° from vertical

The test meters reported volumetric flow rate at manufacturer-specific time intervals. Meters M1 and M2 provided an updated data message at a rate of one per second. Meters M3 and M4 had to be polled to determine the current values of the measured variables. This polling was performed at a rate of once every 5 seconds, which corresponded to the internal update rates for these meters. Reported values of actual flow rate were averaged over multiple samples to determine the average volumetric flow rate. Individual path status, velocity, and speed of sound data were also recorded for all tests.

A typical test sequence consisted of recirculating gas through the MRF test flow loop for a sufficient period of time to allow the gas temperature, pressure, and flow rate to stabilize. Steady flow was established by selecting and choking different HPL sonic nozzle combinations. A test point consisted of the average values of flow rate and other variables computed over a period of 90 seconds. Test points were typically repeated six times, back-to-back, to calculate average values and standard deviations. Data were also collected simultaneously from two 304.8-mm (12-inch) diameter turbine meters placed in series with and downstream of the test meters. The turbine meter data were used to verify the consistency of the experiments, including the long-term reproducibility of the test meters.

Lab Test Configuration

Figure 2 displays a plan view of the MRF HPL Test Section piping arrangement used for the baseline tests. All piping was fabricated from 202.7-mm (7.98-inch) inside diameter, schedule-40, carbon steel pipe with all internal welds ground smooth. The test meters were installed 40D, 59D, 78D, and 97D [where "D" denotes *nominal* pipe diameters, i.e., in this test scenario, D = 203.2 mm (8 inches)] downstream of a single, long-radius, 90° elbow. The piping immediately upstream of the 90° elbow consisted of a nominal 304.8-mm × 406.4-mm × 254-mm (12 × 16 × 10-inch) diameter Sprenkle flow conditioner followed by a nominal 254-mm × 203.2-mm (10 × 8-inch) diameter concentric reducer, and then 43 diameters of straight, nominal 203.2-mm (8-inch) diameter pipe.

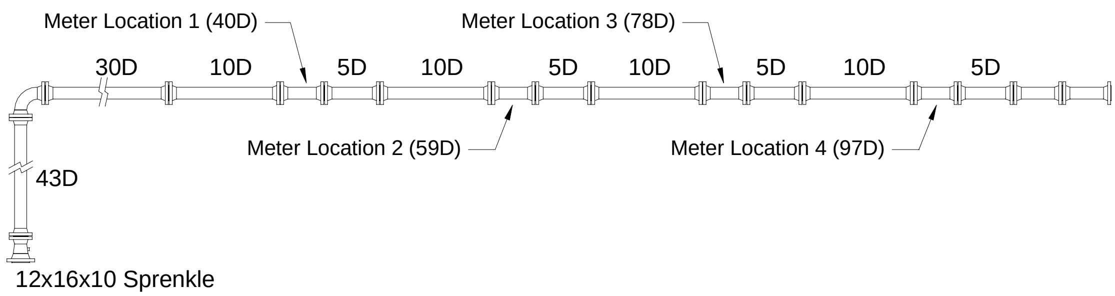

Figure 2 – MRF HPL meter installation configuration
(Plan view)

Figure 2 indicates the locations where the ultrasonic meters were installed. Other test results (Grimley[15]) have shown that the meter measurement bias error is a function of the installation location relative to the upstream 90º elbow.

RESULTS AND DISCUSSION

Bi-directional Flow Test Results

The bi-directional test results for meter M1 are given in Figure 3. The figure shows the meter error (compared to the HPL critical flow nozzles) as a function of the average gas velocity flowing through the meter. The maximum test velocity of 20.4 m/s corresponds to a standard flow rate of 1,601 mscm/d (56.5 mmscf/d) at a gas temperature of 21°C and a line pressure equal to 2,758 kPa. The data indicate that there was no significant difference in the results when the meter was reversed. At the low-pressure condition, a difference of roughly 0.2% was observed between the forward and reverse flow results, but this was close to the level of repeatability expected for this meter. The figure indicates that there was no temperature dependence for this meter over the range tested, that is, from 4°C to 38°C. The data reflect that the error curve changed by about 0.5% as the pressure decreased from 6.2 MPa to 1.3 MPa. Even with the slight differences in performance between the different test pressures, and between forward and reverse flow, the data all fit within a ±0.25% band when the absolute velocity is above 3 m/s (or 235 mscm/d at 21°C and 2,758 kPa). Figure 4 shows the measured error in speed of sound reported by the meter, as compared to the speed of sound (SOS) values calculated by using the measured gas composition, line pressure, and temperature. The figure indicates that the SOS error was independent of the bulk gas velocity, and also independent of line pressure and temperature over the tested SOS range of 402 m/s to 438 m/s.

The measurement characteristics of multipath meter M3 in bi-directional flow are shown in Figure 5. The meter error depended on gas velocity, and had similar dependence with both forward and reverse flow. There were differences of about 0.5% between the forward and reverse flow calibrations for the 1.3 MPa tests. Gas temperature did not have a significant influence on flow meter error, since the small differences in the error curves for the forward direction were within the repeatability of the tests. There did appear to be some temperature dependence at low velocities. That effect is also demonstrated in the SOS comparison curves shown in Figure 6. The differences caused by extreme temperatures at low flow rates may have been a result of the transducer surface being located slightly out of the main gas flow stream. This may have allowed the ambient temperature to influence the gas temperature within the transducer cavity, thus causing the measured gas temperature to be slightly different than the bulk gas temperature. The SOS agreement for meter M3 was different than the agreement for meter M1, with an average difference of about 0.25% for M3, compared to an average difference of 0.1% for meter M1.

A summary of the bi-directional results for the single path meters is given in Figures 7 through 10.

The changes in meter error for meter M2 did not appear to be a function of either gas pressure or temperature, since the differences were all within the allowable data scatter. The measurement error when the meter was exposed to reverse flow became larger as the velocity approached zero. This trend was also observed in the forward direction, but the character of the curve was different in the reverse direction, where there was a more gradual change with change in velocity, rather than the abrupt increase in error at low flow rates that occurred in the forward direction tests. The mean error in the forward direction was about -1.5%, while the mean error in the reverse direction was approximately -1%. The error in SOS was dependent on the gas velocity and changed from a positive to a negative value as the absolute value for velocity increased in both the forward and reverse directions. The mean error in the SOS was less than 0.1% and all data were in the range of -0.1% to 0.2%.

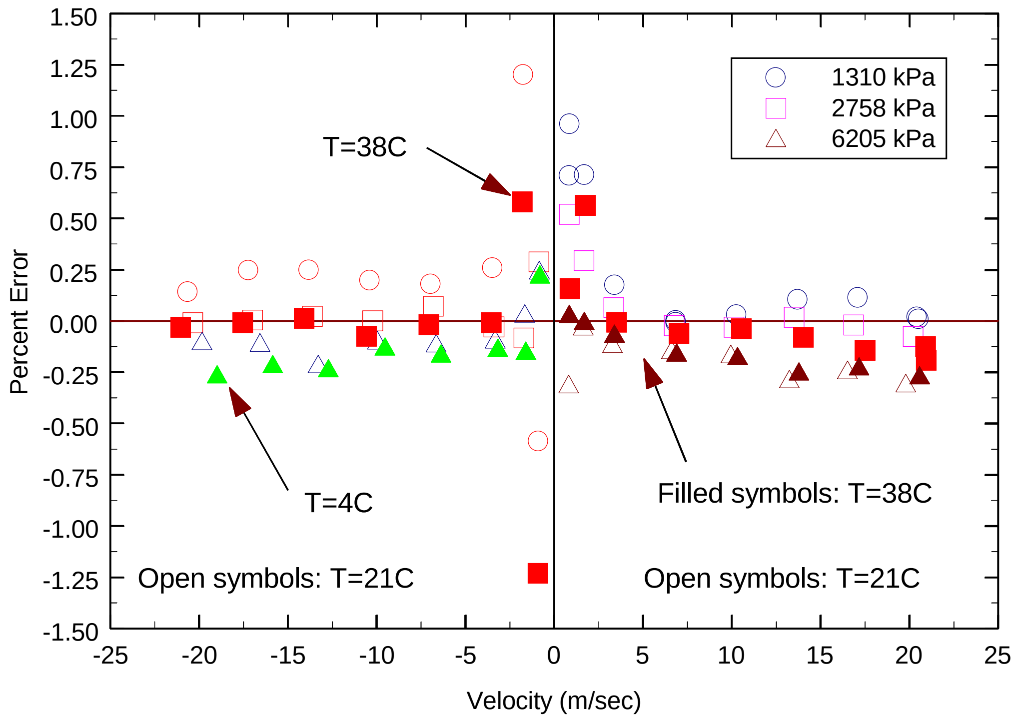

Figure 3 – Bi-directional performance for ultrasonic meter M1

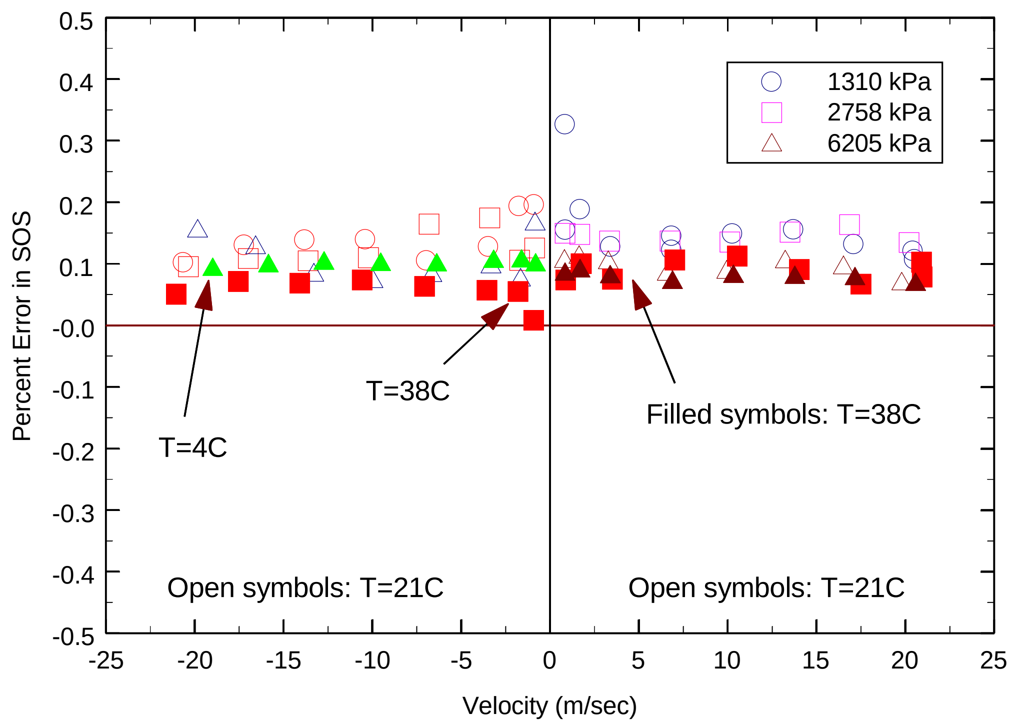

Figure 4 – Ultrasonic meter M1 speed of sound comparison

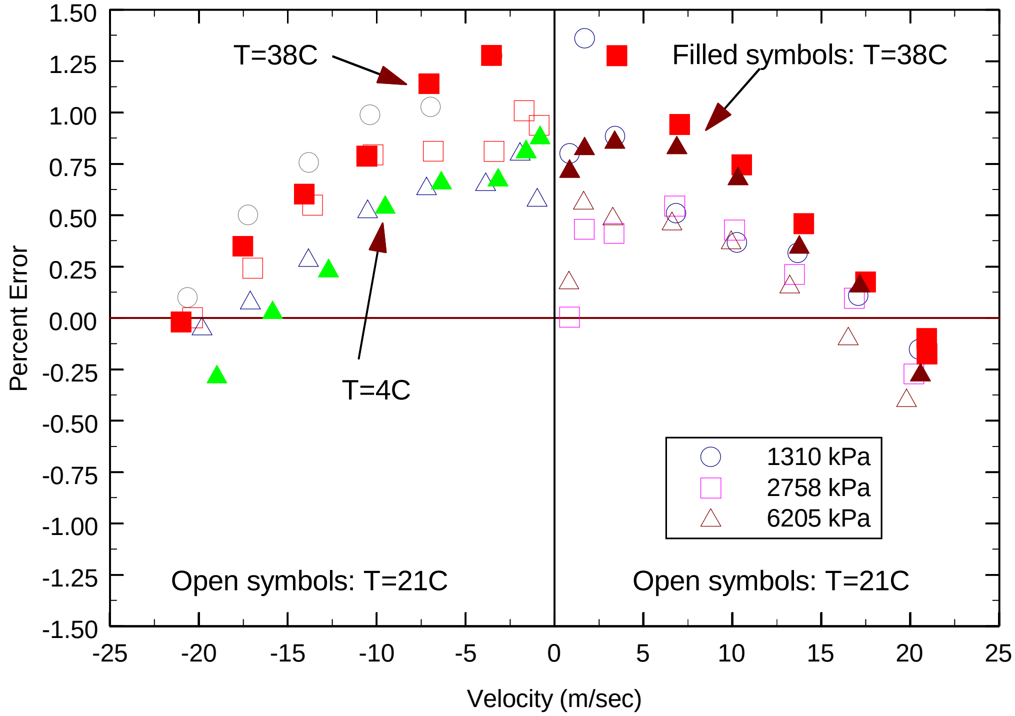

Figure 5 – Bi-directional performance for ultrasonic meter M3

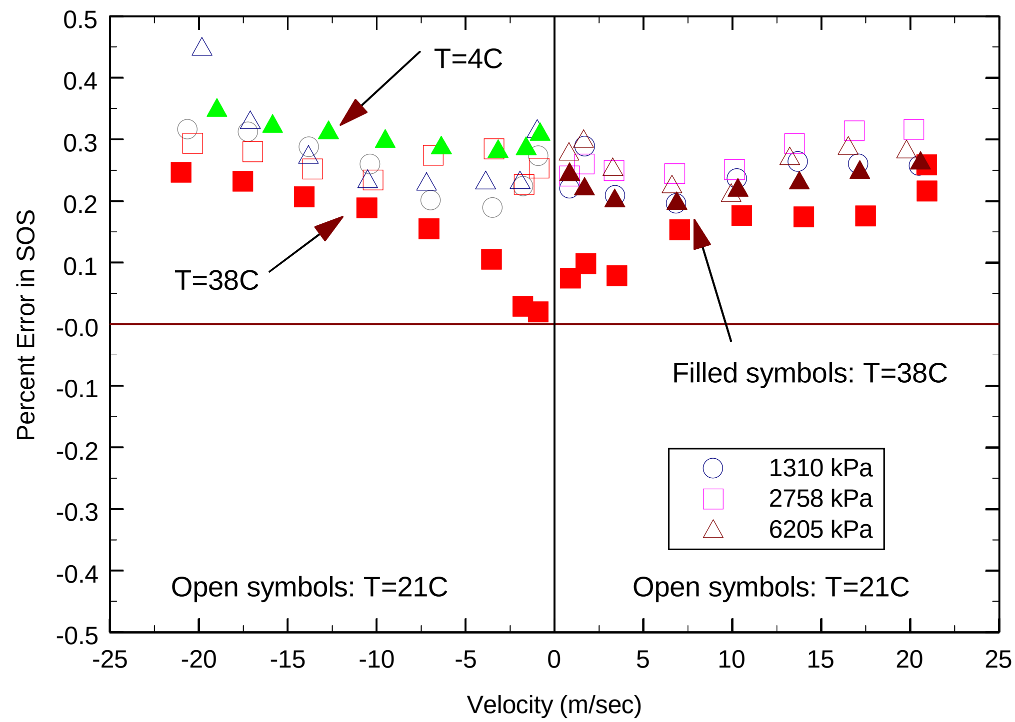

Figure 6 – Ultrasonic meter M3 speed of sound comparison

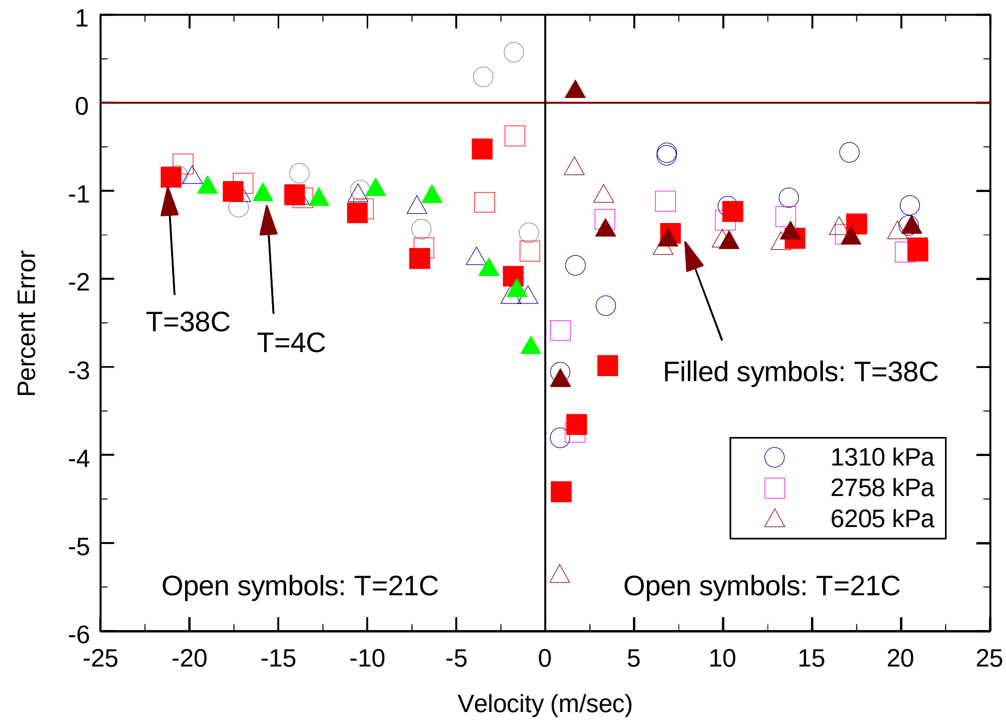

Figure 7 – Bi-directional performance for ultrasonic meter M2

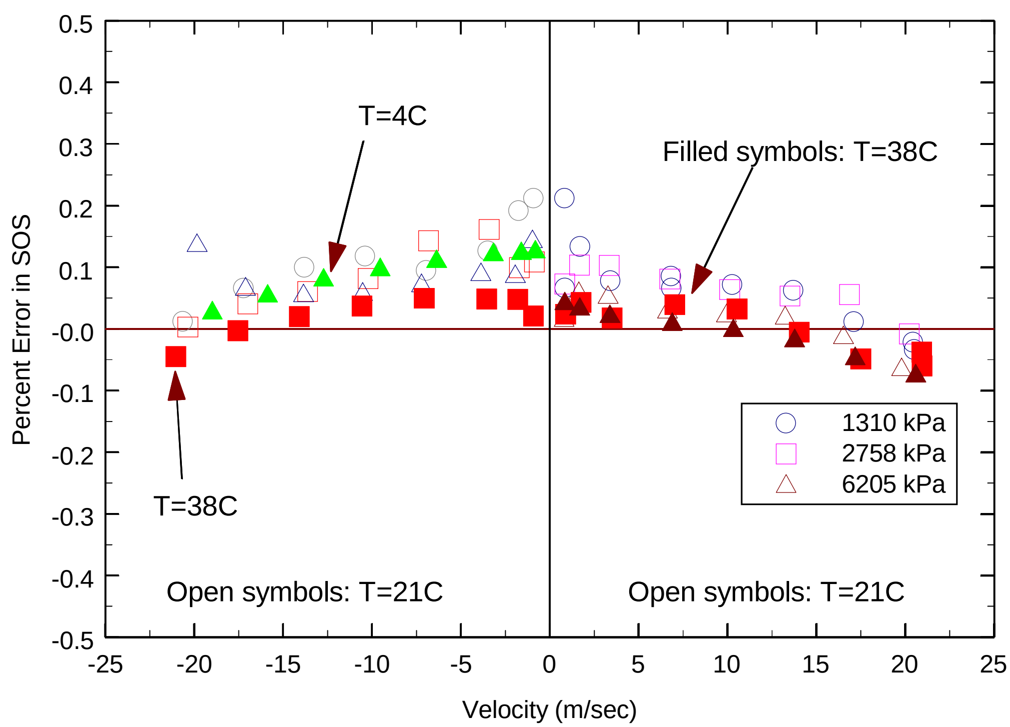

Figure 8 – Ultrasonic meter M2 speed of sound comparison

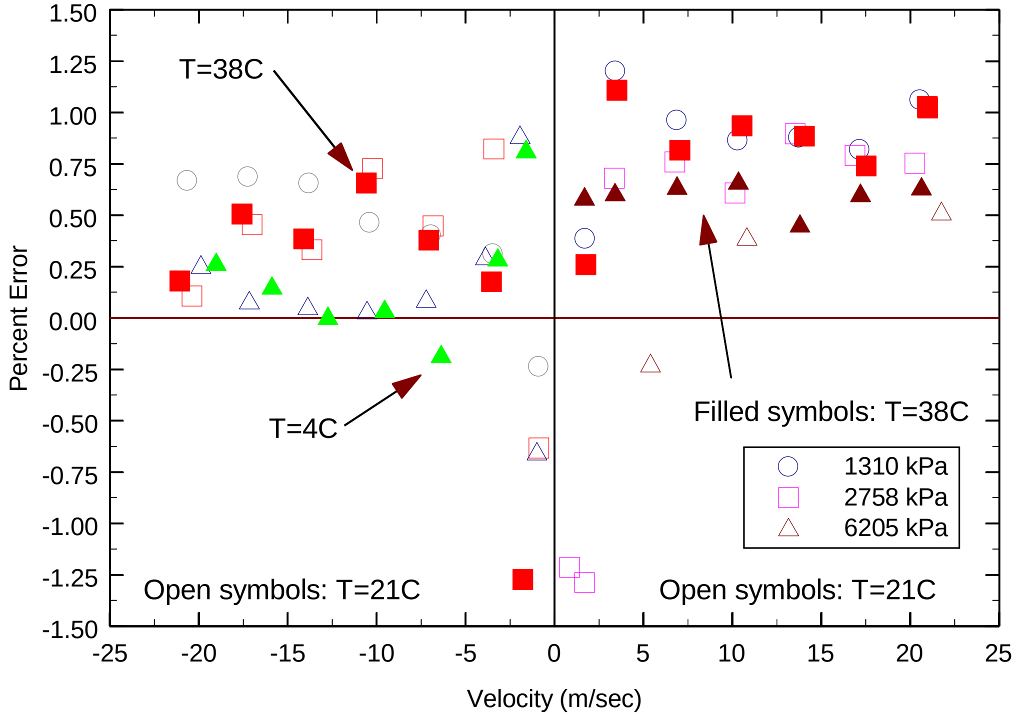

Figure 9 – Bi-directional performance for ultrasonic meter M4

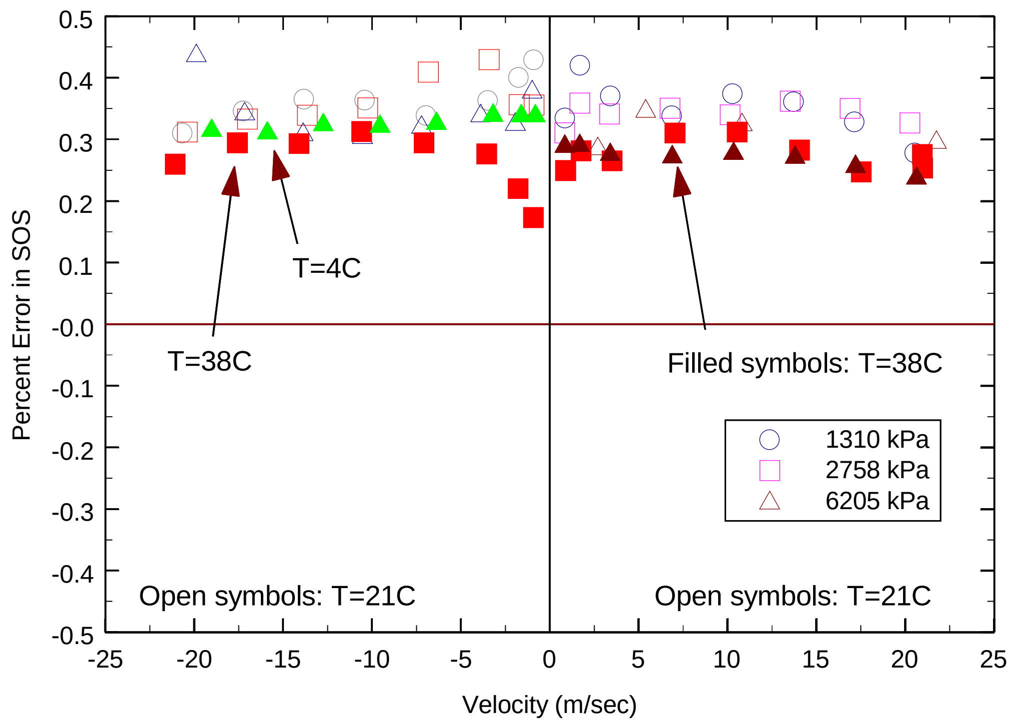

Figure 10 – Ultrasonic meter M4 speed of sound comparison

The results for meter M4 are shown in Figures 9 and 10. There was approximately a 0.5% change in the meter error between the results for the forward and reverse flow directions, when all of the test results were considered. However, the bulk of the data were located between zero and +1% error. The data also reflected a change in performance as a function of line pressure, with a slight decrease in error as the pressure increased. Variations in gas temperature did not have a significant effect. SOS errors shown in Figure 10 indicate that the measurement error was independent of gas pressure, temperature, and velocity variations, with the mean error being on the order of 0.3%.

Low Flow Test Results

Since ultrasonic flow meters have the ability to measure flow in two directions, they can detect the minimal flow rates that occur as the bulk flow changes direction. The accuracy and repeatability of ultrasonic meters operated at these low flow rates had not been well documented. Therefore, tests were conducted to assess meter performance at gas velocities between 0.046 m/s (or 1.67 mscm/d at 21°C, 1,310 kPa) and 20.4 m/s (or 739 mscm/d at 21°C, 1,310 kPa), which was the operational limit of the MRF HPL.

The repeatability of ultrasonic meters at extremely low flow rates may be limited by the resolution of the differential transit time measurement. Following is an example of the velocity measurement error associated with the time measurement resolution of an ultrasonic meter. A single-path meter, using a 60º incident angle in a 202.7-mm diameter pipe with a single bounce off the pipe wall, will have an axial path length equal to 234.1 mm, and an overall path length of 468.1 mm. For a bulk gas velocity of 0.3 m/s, with a typical natural gas mixture [where the gas speed of sound, c, is approximately 421 m/s], the resultant ultrasonic transit times will be 1,113.387 and 1,112.580 microseconds for signals traveling upstream and downstream, respectively. If the resolution of the transit time measurement is 10 nanoseconds, then the error in the 806.6-nanosecond differential delay time is potentially ±1.24%. When the velocity drops to 0.046 m/s, the potential error increases to ±8.3%. It is important to note that, as the meter size is increased, the potential error due to transit time resolution will decrease, since the resolution error is inversely proportional to the meter diameter. For example, a meter having an inside diameter of 381.0 mm will have a resolution error of ±4.4% when the nominal velocity is 0.046 m/s.

The low flow tests conducted in the MRF HPL were performed using a special pipe spool designed to hold four small-bore (ranging from 2.8- to 7.8-mm diameter) critical flow nozzles. The four flow nozzles were previously calibrated, individually, using the MRF Low Pressure Loop (LPL) weigh tank system as a flow calibration reference. Use of the HPL small nozzle spool allowed various combinations of the four nozzles to be opened, thus providing various reference flow rates for the test meter calibrations.

Gas storage in the HPL piping between the test and reference meters was a potential problem at low flow rates. To reduce the pipe volume available for storage, the small-nozzle pipe spool was installed in the HPL Header Section, just downstream of the Test Section. Even with a relatively small piping volume between the test meters and the small-nozzle pipe spool used as a flow reference, flow rate measurement errors associated with gas storage could have been as large as 0.8% at the 0.046 m/s test point for a 0.11°C change in the gas temperature. This level of temperature variation was common during the tests.

The low flow test results are shown in Figures 11 through 14. These data indicate that there was a considerable increase in the data scatter at low flow rates, as was expected from the previous discussion on transit time resolution. The averaging that occurred with the multipath meters reduced the scatter for meters M1 and M3 to values lower than the scatter observed for the two single-path meters, M2 and M4. At the low flow rates [i.e., below 1 m/s], none of the meters displayed a systematic shift in the measurement error between the forward and reverse flow test conditions. The deviations between the forward and reverse flow tests were smaller than the overall data scatter.

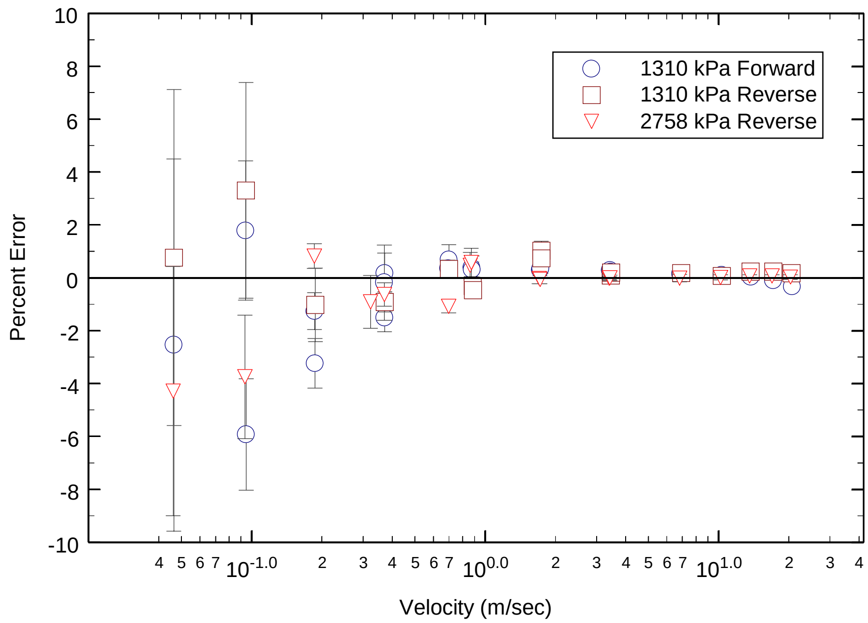

Figure 11 – Low flow performance for ultrasonic meter M1

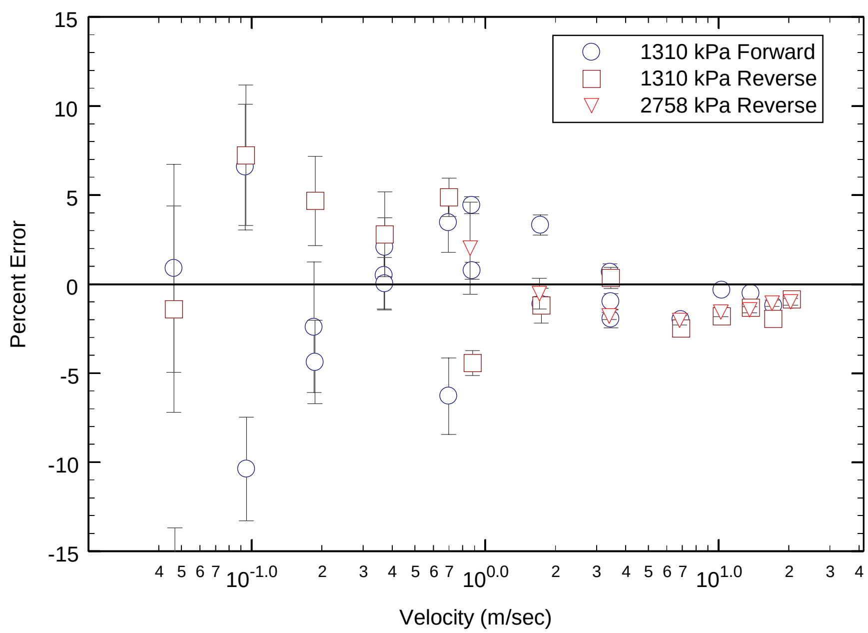

Figure 12 - Low flow performance for ultrasonic meter M2

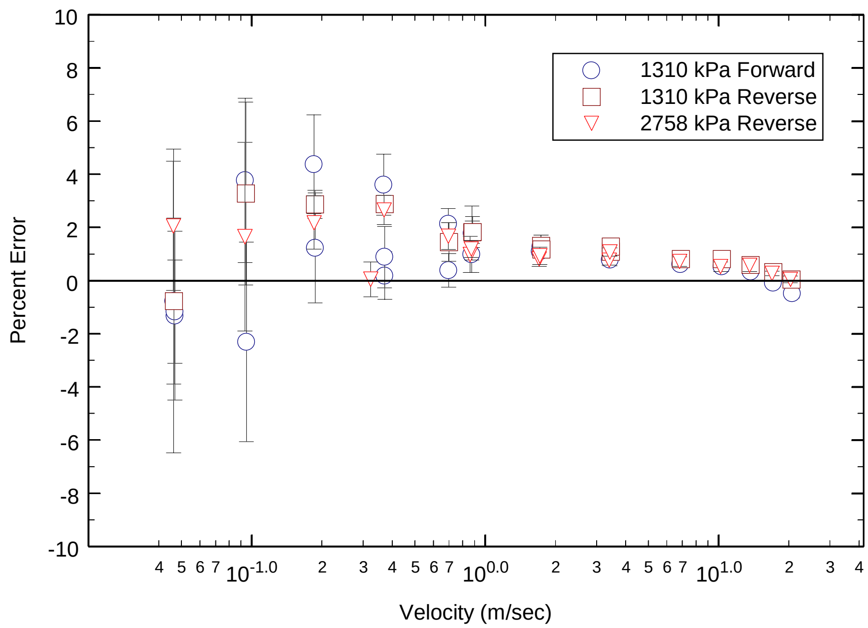

Figure 13 - Low flow performance for ultrasonic meter M3

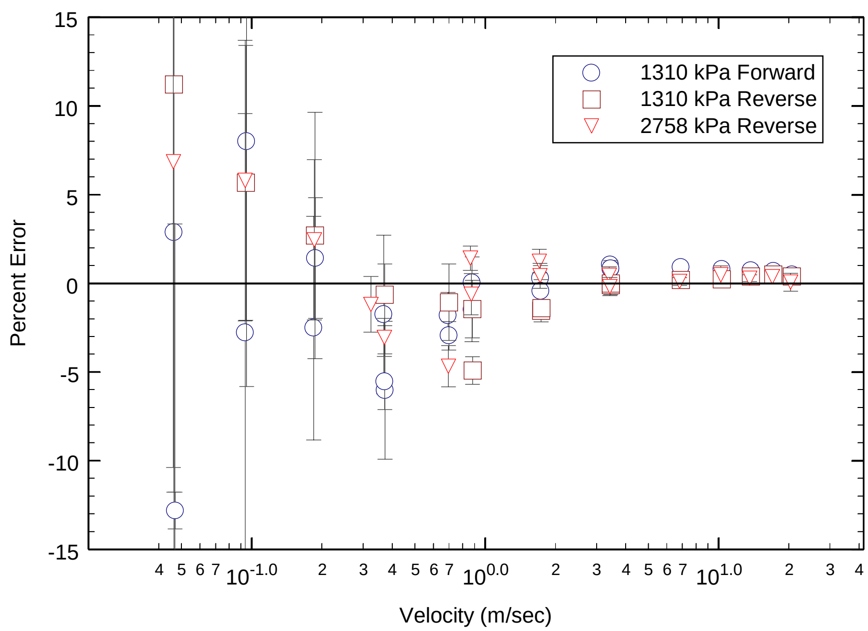

Figure 14 - Low flow performance for ultrasonic meter M4

Thermowell Influence Test Results

Thermowells are typically installed a few diameters downstream of a flow meter to provide a representative measurement of the temperature of the gas flowing through the meter. As previously noted, in bi-directional applications, one flow direction will necessarily have a thermowell protruding into the gas stream upstream of the flow meter. Since the thermowell disturbs the downstream flow field, there is a possibility of introducing additional measurement error at the meter. The thermowell effect tests performed during this study did not consider flow rate measurement error introduced by an incorrect temperature determination.

To assess the effect of thermowell protrusion on test meter performance, a special piping spool was constructed with nine thermowell access locations at three axial locations (one, three, and five pipe diameters) from the end of the spool, and three angular positions (0°, 45°, and 90° from vertical). A simulated thermowell was mounted in the pipe spool. The simulated thermowell was a 12.7-mm diameter rod that could be inserted or retracted from the pipe spool interior, at the various mounting points, without depressurizing the HPL Test Section. A gauge block was used to set the insertion depth of the simulated thermowell at either one-half pipe diameter (101.3 mm) or one-third pipe diameter (67.6 mm) in from the pipe spool wall. These two insertion depths represent flow blockages of 4% and 2.7% for the one-half and one-third diameter insertion depths, respectively. This special thermowell pipe spool was installed upstream of the test meter. The test meter was installed at the 97D location shown in Figure 1. For each test flow rate, baseline performance data (acquired without a temperature probe inserted in the flow field upstream of the test meter) were collected before and after 18 flow tests were run with the simulated thermowell inserted in the flow. For each thermowell test position, six repeat data sets were collected and compared to the baseline data.

Figure 15 shows the orientation between the thermowell locations and the ultrasonic paths for each of the test meters. The thermowell influence results for meters M1, M3, and M4 are presented in Tables 2, 3, and 4, respectively. These tables document the meter error relative to the baseline meter error, for each of the thermowell test positions. The data obtained for single-path meter M2 are not presented because the meter did not operate properly during the thermowell tests.

The tabulated results indicate the thermowell influence was greater at lower gas velocities than at higher velocities. Increased turbulence at the higher velocities reduced the size and length of the wake produced by the flow around the thermowell. At the lower test velocities, the wake persisted further downstream and produced larger metering errors. Tests were also performed at a nominal gas velocity of 0.86 m/s (2.6 ft/s). At that test velocity, the scatter in the data masked any potential influence of the thermowell, so the data were not included in this report.

The largest errors experienced by the multipath meters occurred at the low velocity condition with the thermowell at the 1D position (i.e., one pipe diameter upstream of the meter). Errors as large as 0.8% were measured, with multipath meter M1 showing a negative shift, and multipath meter M3 showing a positive shift. As expected, as the distance between the thermowell and the meter increased, the shift in measurement error decreased. It appeared that the 3D location was a sufficient distance away for meters M1 and M3, as long as the 45° thermowell position was avoided for meter M3.

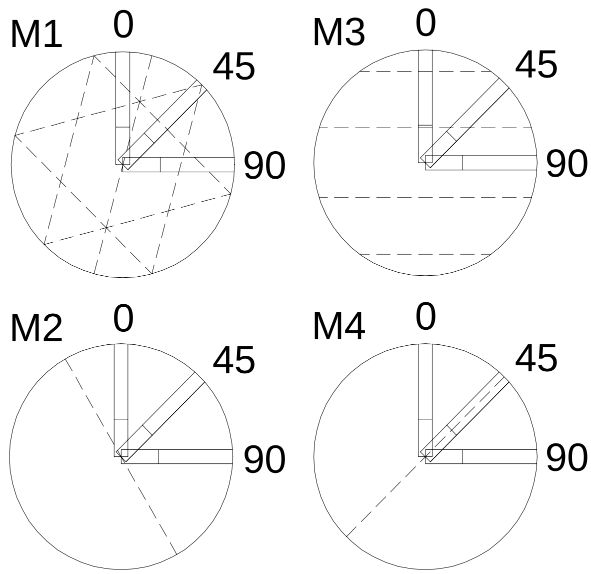

Figure 15 – Relationship between ultrasonic path location and thermowell position
(Meter cross-section views with the ultrasonic paths shown as dotted lines)

Table 2 – Multipath ultrasonic meter M1 relative error for various upstream thermowell positions

Position		**1D**		**3D**		**5D**	
Vel.	Angle	1/2	1/3	1/2	1/3	1/2	1/3
3.4	0	-0.76	-0.17	-0.39	-0.06	-0.02	0.20
	45	-0.69	-0.43	-0.13	-0.21	-0.14	-0.02
	90	-0.23	-0.51	-0.22	-0.28	-0.17	-0.26
10	0	0.03	-0.01	-0.12	-0.05	-0.02	0.19
	45	0.10	-0.36	0.08	-0.04	0.37	-0.09
	90	0.28	-0.08	0.00	-0.13	-0.02	-0.09
20	0	0.03	0.13	-0.11	-0.04	-0.15	0.23
	45	0.11	-0.48	0.03	-0.21	0.13	0.00
	90	0.09	-0.37	-0.11	-0.20	-0.06	-0.28

The single-path meter M4 produced larger relative errors than did the multipath meters. The largest relative errors occurred with meter M4, when the thermowell was directly aligned with the measurement path. Relative errors as large as -1.6% are shown in Table 4 for the 1D position, with the probe at 45° and a thermowell insertion depth of one-half pipe diameter. When the insertion depth was reduced to one-third the pipe diameter, the relative error was reduced by nearly 1%. The results for single-path meter M4 suggest that when the thermowell is not aligned with the ultrasonic measurement path (i.e., the 0° and 90° positions), the influence of the thermowell on the flow measurement error was negligible.

Table 3 – Multipath ultrasonic meter M3 relative error for various upstream thermowell positions

Position		1D		3D		5D	
Vel.	Angle	1/2	1/3	1/2	1/3	1/2	1/3
3.4	0	-0.01	0.14	-0.07	-0.05	-0.01	0.02
	45	0.78	0.66	0.66	0.51	0.58	0.42
	90	-0.23	-0.09	-0.11	-0.09	-0.14	-0.07
10	0	-0.19	-0.06	-0.01	-0.03	-0.02	0.10
	45	-0.11	-0.04	0.02	0.11	0.08	0.09
	90	-0.06	-0.13	0.01	-0.10	0.01	0.04
20	0	-0.25	0.02	-0.15	0.07	-0.21	0.00
	45	0.05	0.41	0.21	0.33	0.07	0.14
	90	-0.14	-0.11	-0.03	-0.03	0.10	0.04

Table 4 – Single-path ultrasonic meter M4 relative error for various upstream thermowell positions

Position		1D		3D		5D	
Vel	Angle	1/2	1/3	1/2	1/3	1/2	1/3
3.4	0	0.14	0.36	0.01	0.04	-0.06	-0.18
	45	-1.59	-0.68	-0.76	0.16	-0.08	0.68
	90	-0.06	0.33	-0.04	0.07	0.10	0.00
10	0	0.14	0.20	-0.04	0.09	-0.13	-0.04
	45	-1.31	-0.35	-0.35	0.26	-0.52	-0.03
	90	-0.05	0.17	0.03	0.09	0.02	-0.04
20	0	0.03	0.26	0.11	0.08	0.31	0.00
	45	-1.38	-0.59	-0.61	0.42	-0.58	0.35
	90	-0.39	0.16	0.23	0.04	-0.46	0.18

Summary of Field Test Results

The gas industry's interest in ultrasonic gas flow meters has caused several companies to perform their own in-house tests to gain experience with the meters prior to widespread deployment. Test data collected by individual companies are not always reported industry-wide. The primary purpose of this task was to collect and report, in as consistent a manner as possible, any unreported data collected by various gas transmission pipeline companies in the United States.

The maximum flow rate of the MRF limits testing of 12-inch diameter ultrasonic gas meters to flow rates less than about 30% to 40% of meter capacity. Larger meter sizes can only be tested over a very limited range in the MRF. For example, a 16-inch diameter meter could only be tested at nominal flow velocities up to about 5.2 m/s (15.8 ft/s), or approximately 16% of a typical meter's capacity. It was anticipated that field test data would provide information on the performance of larger meters at flow rates greater than those available at the MRF.

Several criteria were used to assess the validity of any field data. First, a reference meter of some type was required for comparison purposes. This meant that the operator needed to have the ultrasonic meter installed in-line with, and in close proximity to, another flow meter. Second, the data were to be recorded over acceptably short time intervals. Third, the data were to include measurements of at least the gas pressure, temperature, flow rate, and composition. Fourth, documentation of the installation configuration was to be provided, including information on the placement of the reference flow meter(s), the ultrasonic flow meter, and all secondary instrumentation. Fifth, the data were to be of recent vintage. Finally, information regarding the secondary instrumentation was to be provided, including specifications on the pressure and temperature sensors, the flow computer, and the calculation methods used to reduce the measured data to engineering units.

The intent was to use the detailed field test data to estimate the level of measurement uncertainty in the reference meter and to then use that information to help assess the field performance of the ultrasonic meter.

Summary of Contacts and Participation

A total of 42 people from over 30 gas transmission pipeline companies in the United States were contacted. Eight companies expressed an interest in participating in the study. Following is a summary of the interactions with these companies and the outcome of the field evaluations.

Company 1

Company 1 has performed several studies on multi-path ultrasonic meters and although there was an interest expressed in providing data to SwRI, none have been received to date. Company 1 also stated that it was planning to construct a facility to test ultrasonic gas meters.

Company 2

Company 2 has several comparison-type studies planned for the future. One in particular involves a 610-mm (24-inch) diameter ultrasonic meter placed in series with bi-directional orifice meters in a storage application. Not all of Company 2’s proposed studies are within the scope of this study. To date, no test data have been provided to SwRI.

Company 3

Company 3 has a 508-mm (20-inch) multipath ultrasonic meter in bi-directional service at a storage facility. It is being compared against three 304.8-mm (12-inch) diameter orifice runs installed sometime around 1958. The results to date are described in the following section.

Company 4

Company 4 performed some tests using a 406.4-mm (16-inch) diameter insertion-type, single-path ultrasonic meter plumbed in series with a 406.4-mm (16-inch) diameter orifice meter. The test results are described in the following section.

Company 5

Company 5 has a 203.2-mm (8-inch) diameter ultrasonic meter plumbed in series with a three-run orifice meter station. Although Company 5 expressed an interest in sharing their test data, none have been received to date by SwRI.

Company 6

Company 6 has done some comparative studies using turbine meters as the reference. Although Company 6 expressed an interest in sharing their test data, none have been received to date by SwRI.

Company 7

Company 7 has three 914-mm (36-inch) diameter ultrasonic meters installed at a gas odorization site. Each ultrasonic meter is installed in series with an averaging Pitot tube, which serves as a reference. SwRI was offered an opportunity to conduct site tests to acquire comparative data and perform velocity profile measurements. After reviewing the configuration of this particular meter station, SwRI concluded that site tests would not be an appropriate use of funds under the scope of this study. The principal reasons for dropping this installation from further consideration were (1) the lack of an available standard meter type (e.g., an orifice or turbine meter) that could be used as a reliable flow reference and (2) the potential for significant flow pulsations caused by a nearby compressor station.

Company 8

Company 8 provided field test data on a 560-mm (22-inch) diameter multipath meter being used for system balance purposes. There was no reference meter in close proximity to the ultrasonic meter that could be used for comparison. The performance of the ultrasonic meter could only be evaluated by comparing it to several other meters located throughout the pipeline network. The measurement uncertainties associated with each meter in the system were difficult to quantify from the information provided to SwRI. This circumstance combined with other operational issues, such as the unspecified amount of line pack between the various meters in the system, resulted in a reference flow rate uncertainty determination that was considered to be too large to accurately assess the ultrasonic meter's performance.

Company 9

Company 9 provided comparative data between a 12-inch diameter multipath meter and a bank of 12-inch diameter orifice meters. The test results are described in the following section.

Review of Relevant Field Data Sets

Data Provided by Company 3

Company 3 placed a multipath ultrasonic meter upstream of a bank of three orifice meters. Their field study was intended to compare the difference between the orifice meters and the ultrasonic meter. The meters were installed in a bi-directional storage application. Note that throughout this section, the term "upstream" will be relative to injection into the storage facility.

The 304.8-mm (12-inch) diameter orifice meter installation consisted of three parallel meter runs installed in 610-mm (24-inch) diameter headers both upstream and downstream. Each orifice run had 21 diameters of straight pipe upstream and 17 and 3/4 diameters of straight pipe downstream. The upstream header was about 6.6 meters (20 feet) downstream of a 45º elbow. The meters were set up to measure bi-directional flow and were installed around 1958. The orifice fittings were originally designed to use 3.175-mm (1/8-inch) thick orifice plates, but were later fitted with 6.35-mm (1/4-inch) thick plates. The 6.35-mm thick plates were used for the ultrasonic meter comparison tests. There was a 45º elbow about one meter (3 feet) downstream of the downstream header.

The 508-mm (20-inch) diameter ultrasonic meter run was placed approximately 5 meters (15 feet) downstream of the 45º elbow located downstream of the orifice meter header. The ultrasonic meter was located 9.5 pipe diameters downstream of two 90º elbows, in plane. There were another 10 diameters of straight pipe downstream of the ultrasonic meter, followed by two more 90º elbows, in plane.

Since the test site was a storage facility, there was a compressor located nearby. The magnitude of compressor-induced flow pulsations present at the test flow meters was not measured.

Figures 16 and 17 show the daily flow rate and percent deviation for the data collected by Company 3. The open squares represent the flow rate as measured by the orifice meters. The solid triangles represent the percent difference between the ultrasonic meters and the orifice meters, using the orifice meters as the reference.

Figures 16 and 17 indicate that the level of agreement between the orifice meters and the ultrasonic meter remained fairly constant over each time interval. This steadiness, or repeatability, remained at about +1% to +2%, even though the flow rate varied from nearly zero to approximately 4.5 mmscm/d (160 mmscf/d).

Figure 18 shows the hourly data corresponding to the daily data in Figure 17. The dashed lines represent the 95% confidence interval for the data set and the solid line represents the mean of the data set. The x-axis shows the standard flow rate and the percentage of maximum standard flow rate for the ultrasonic flow meter.

The scatter in the data increased as the gas flow rate decreased. This is reasonable to expect, given the increased variability in the orifice and ultrasonic meters as they approach the lower operational limits of their respective flow rate ranges.

Data Provided by Company 4

The tests conducted by Company 4 involved placing a single-path, insertion-type ultrasonic meter upstream of an orifice meter. The field study investigated the effects of several different piping configurations on orifice meter accuracy. Those tests are not particularly relevant to this study. However, the data provide good information on the field performance of the ultrasonic meter.

The orifice meter installation configuration consisted of 15 pipe diameters of 406-mm (16-inch) diameter bare meter tube run both upstream and downstream of the orifice fitting. There was an additional 15 diameters of 406-mm (16-inch) diameter straight pipe located upstream of the meter tube. There were two 45° elbows installed upstream of the additional

406-mm (16-inch) diameter pipe, with a 406-mm (16-inch) diameter plug valve installed between them.

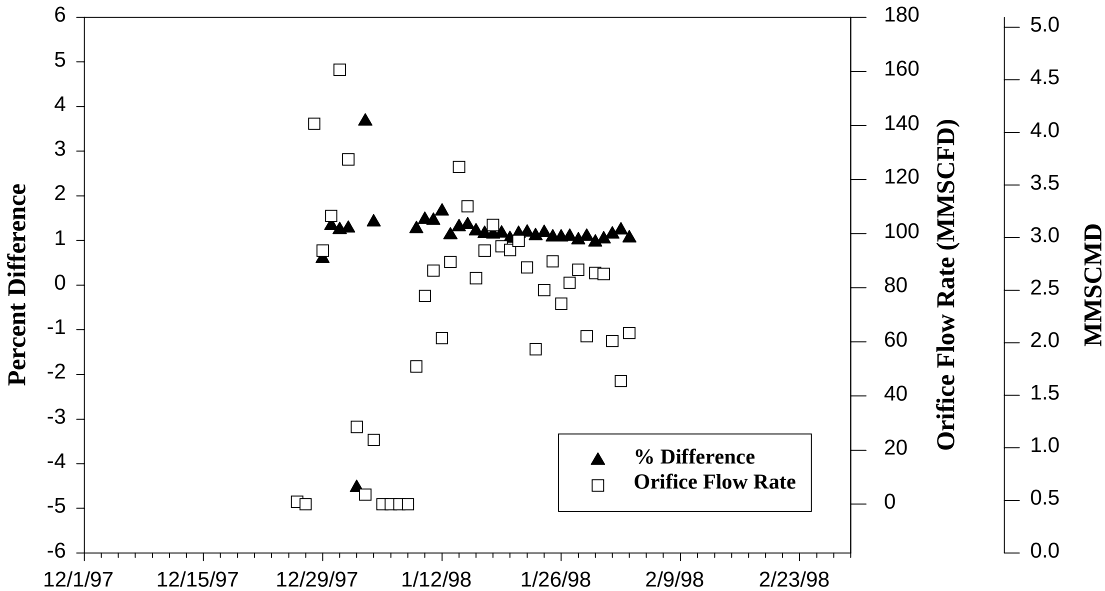

Figure 16 – Company 3 ultrasonic meter daily readings from December 1997 to January 1998

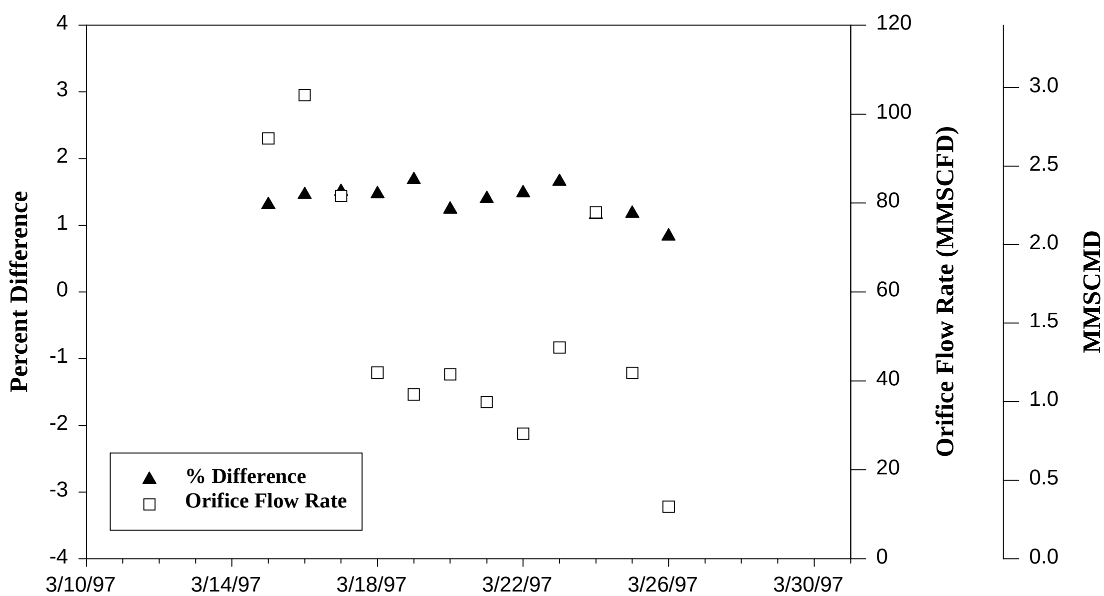

Figure 17 – Company 3 ultrasonic meter daily readings for March 1997

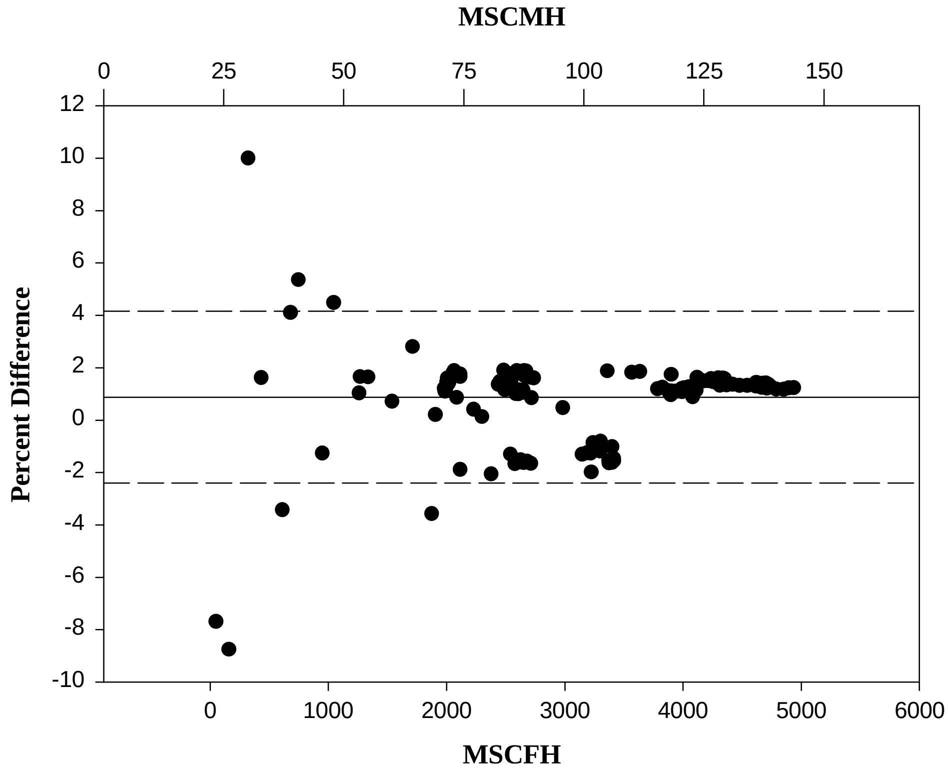

Figure 18 – Company 3 ultrasonic meter performance compared to an orifice meter bank

The insertion-type ultrasonic meter was installed approximately 10 pipe diameters downstream of the second 45° elbow. No flow conditioner was installed upstream of the ultrasonic meter.

There was a compressor station located about 295 meters (900 feet) downstream of the meter station. However, the compressor was only used when the pipeline pressure dropped below a certain level during peak loads.

Figure 19 shows the daily flow rate and percent deviation for the data collected by Company 4. The tests were conducted between February and July of 1997. The open squares represent the flow rate as measured by the orifice meter. The solid diamonds represent the percent difference between the ultrasonic meter and the orifice meter, using the orifice as the reference. The circled intervals are discussed later.

Each vertical line in Figure 19 represents a change in the test configuration. These changes included modifications to the orifice meter configuration, and changes in the ultrasonic meter configuration, including replacement of the electronic module. Each time the test conditions were modified, the percentage difference between the two meters changed. However, the true impact of each change is difficult to ascertain because a sufficient baseline condition was never established.

Figure 19 suggests that the difference in meter reading between the ultrasonic meter and orifice meter remained fairly constant during each time interval. This steadiness or repeatability remained, even as the flow rate varied substantially.

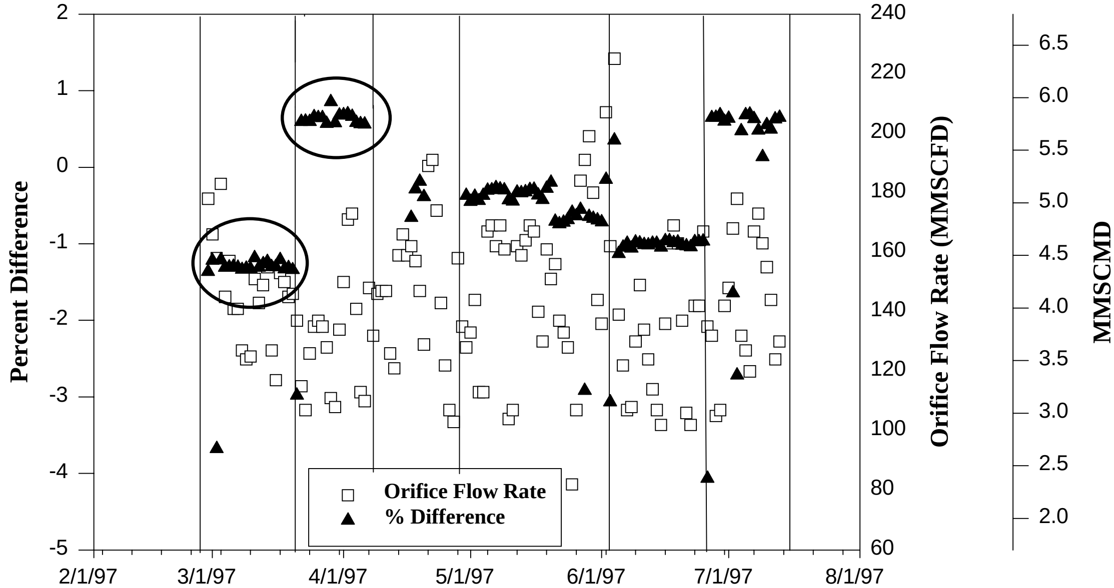

Figure 19 – Company 4 ultrasonic meter daily readings from February 1997 to July 1997

Figures 20 and 21 show the circled intervals from the previous figure in greater detail. The dashed lines in these figures represent the 95% confidence interval and the solid line represents the mean of the data set. The x-axis shows the percentage of maximum ultrasonic meter capacity. Each point represents a velocity averaged over a 15-minute period.

The measured velocities shown in Figures 20 and 21 range from 15% to over 50% of the total flow range of the ultrasonic meter. Over the tested range, the difference between the ultrasonic meter and the orifice meter was independent of velocity.

In Figure 20, the 95% confidence interval spans a range of ±0.3% around the mean. In Figure 21, the 95% confidence interval spans a range of ±0.4% around the mean. Both figures indicate repeatability that is reasonable for a comparison between a single-path meter and an orifice meter.

Data Provided by Company 9

Field test data were collected by Company 9 for a 304.8-mm (12-inch) diameter orifice meter run fitted with a nominal 0.6 beta ratio plate, a 304.8-mm (12-inch) diameter turbine meter, and a 304.8-mm (12-inch) ultrasonic meter. The test data were acquired over a three-month period. The piping configuration was such that the ultrasonic and turbine meters were always in series and exposed to the same flow stream. Under certain test conditions, the gas that flowed through the orifice meter also passed through the other two meters. Because of some questions about the integrity of the data from the turbine meter, comparisons made in this report are relative only to the orifice meter. The data were recorded on an hourly basis and a logbook indicated when the conditions were such that a valid comparison existed between the orifice meter and the ultrasonic meter.

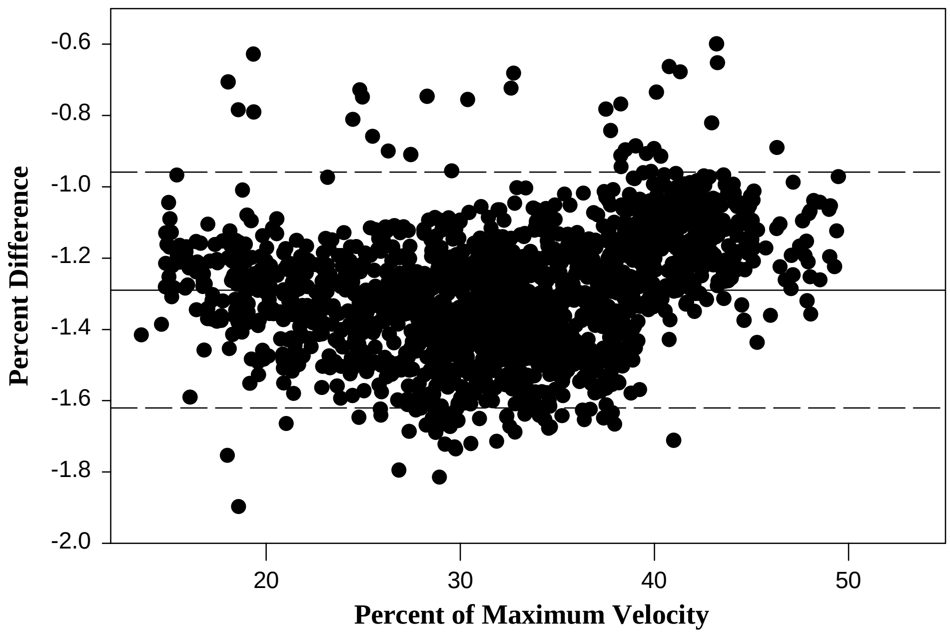

Figure 20 – Company 4 ultrasonic meter performance relative to an orifice fitting (data from 3/3/97 to 3/20/97)

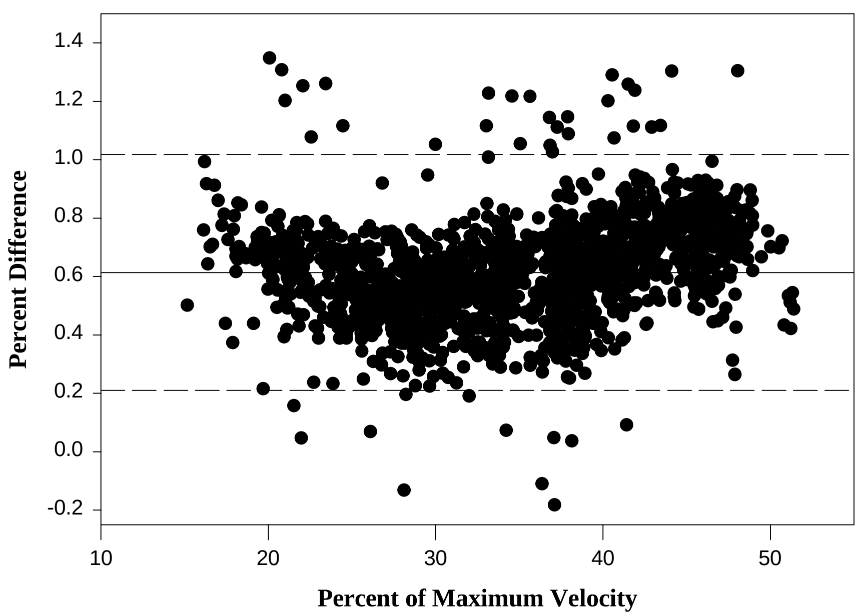

Figure 21 – Company 4 ultrasonic meter performance relative to an orifice fitting (data from 3/22/97 to 4/6/97)

The field test results indicate relatively good agreement between the orifice meter and the ultrasonic meter. Measurement differences between the two meters were in the range of ±2% for flow rates above 56.6 mscm/h (2,000 mscf/h). A portion of this difference can be attributed to transient flow conditions that were present. These transient effects resulted in some gas storage in the piping between the two meters. Overall, the test results show that the ultrasonic flow meter appeared to be functioning correctly.

The difference between the standard flow rate reported by the orifice meter and the ultrasonic meter is shown in Figure 22. The differences were calculated using the orifice meter standard flow rate measurements as the reference.

The lines plotted in Figure 22 represent the results of a least-squares curve fit of the data and the 95% confidence bounds for that curve fit. To remove a portion of the bias in this comparison, the standard flow rate data for the ultrasonic meter were recalculated based on the gas composition information that was logged with the orifice meter. The error attributed to the use of fixed composition information in the ultrasonic meter flow computer was estimated to be between 0.2% and 0.5%. Pipeline transients likely caused a portion of the large errors indicated in Figure 22. As was previously mentioned, the station configuration was such that the gas measured by the orifice bank had more than one branch, one of which included the ultrasonic meter. In many cases, the large errors occurred at the start or end of a measurement period, when the flow was switched such that the orifice and ultrasonic meters could be directly compared.

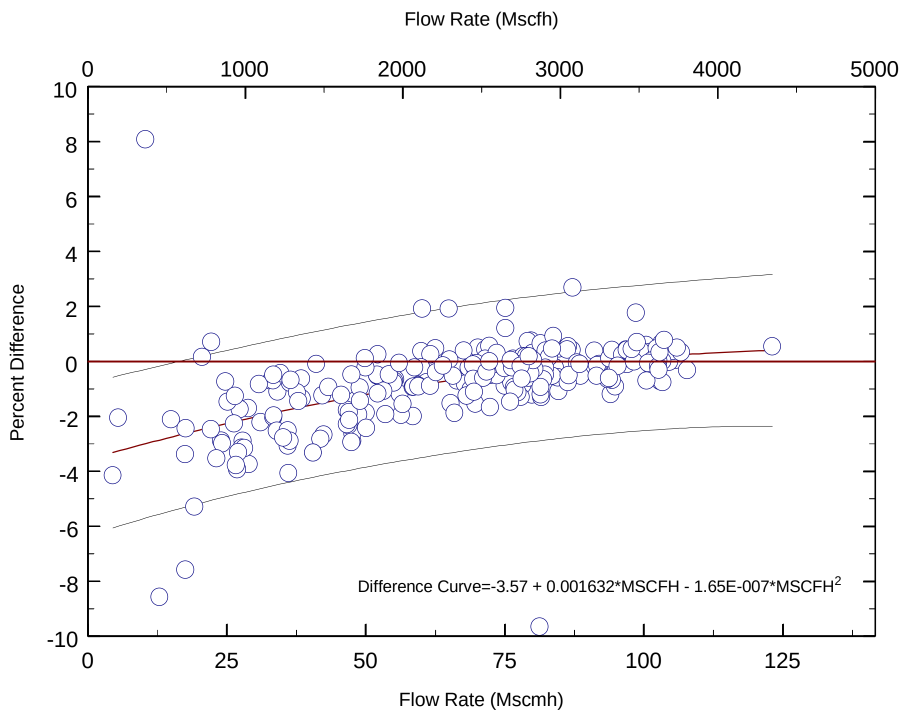

Figure 22 – Ultrasonic meter difference relative to orifice meter as a function of flow rate

Line packing between the orifice meter and the ultrasonic meter was estimated based on an assumed pipe volume of 36.19 cubic meters (997 cubic feet), and changes in the gas density were estimated based on the indicated average pressures and temperatures over each of the one hour sampling periods. Data with finer time increments would be required to correct for line packing on a point by point basis. The estimated line-pack error shown in Figure 23 was, therefore, curve fit as a function of the flow rate. The curve fit of the storage error data was used to adjust the difference data shown in Figure 22. The fitted storage data were not expected to completely remove the scatter caused by the flow transients, but were intended to remove the bias error caused by the transients.

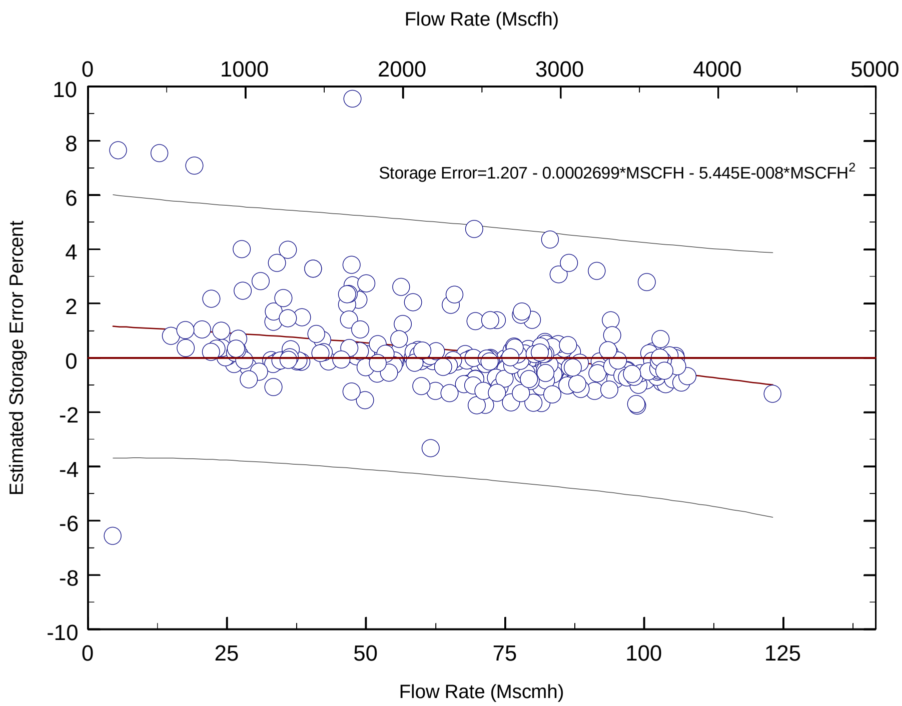

Figure 23 – Estimated storage error as a function of flow rate

Figure 24 displays the results of this comparison, along with measurement uncertainty estimates for the comparison between the two meters types. The results indicate that a large portion of the data fell within the estimated uncertainty bands, but that at low flow rates there was a consistent difference between the results of the two meters, with the ultrasonic flow meter indicating a value less than that of the orifice meter. A least-squares curve fit of the data, which represents the average meter performance, fell within the estimated uncertainty bands. The uncertainty bands are based on a simplified calculation using the system parameters shown in Tables 5 and 6. The dashed lines in Figure 24 indicate the sum of the bias uncertainty for both the ultrasonic meter and the orifice meter. Data falling within the dashed lines are within the estimated uncertainty limits for these results.

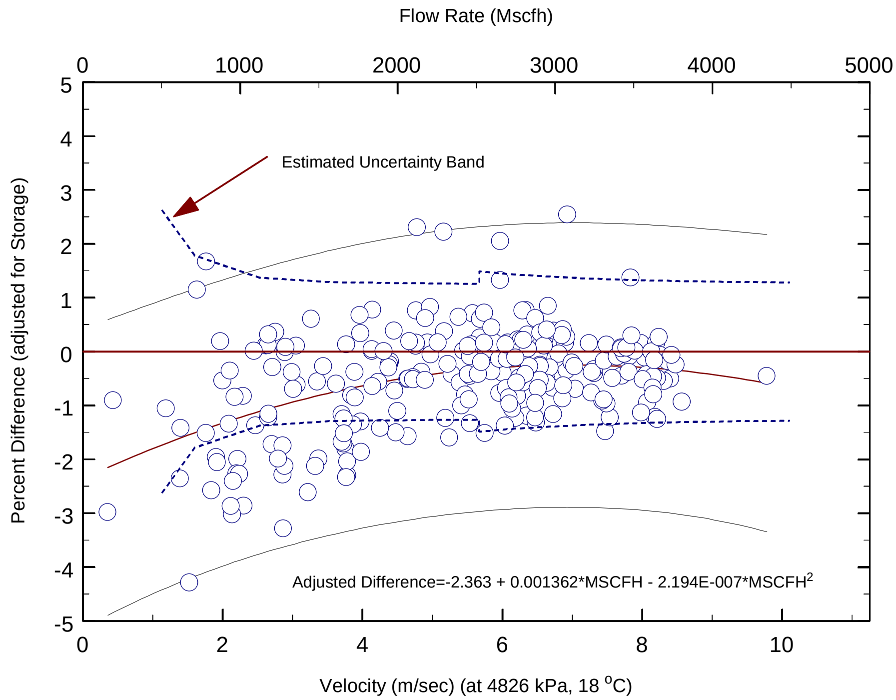

Figure 24 – Ultrasonic meter difference relative to orifice meter after storage correction, as a function of flow rate

Table 5 – Orifice meter uncertainty estimate

Parameter	Comments and Assumptions	Bias Uncertainty
Orifice C_D	Per A.G.A. Report No.3	0.44%
Pressure	0.25% at 1,500 psi (10,342 kPa)	0.47% at 800 psi (5,516 kPa)
Temperature	1 °F at 70 °F (0.5 °C at 21 °C)	0.19%
Differential Pressure	0.10% of 50 in. (1,270-mm) H_2O 0.25% of 150 in. (3,810-mm) H_2O	Function of flow rate, switch over at 35 in. (889-mm) H_2O
Total Bias Uncertainty	Root sum of squares of above with appropriate sensitivity coefficients (1/2) for pressure, temperature and differential pressure	Function of flow rate

Table 6 - Ultrasonic meter uncertainty estimate

Parameter	Comments and Assumptions	Bias Uncertainty
Ultrasonic Meter	Per Manufacturer's Literature	0.50%
Pressure	0.25% at 1,500 psi (10,342 kPa)	0.53% at 700 psi (4,826 kPa)
Temperature	1 °F at 56 °F (0.5 °C at 13 °C)	0.2%
Total Bias Uncertainty	Root sum of squares of above	0.75%

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CONCLUSIONS

Rangeability

The results of this study have helped determine the sensitivity of ultrasonic flow meters to variations in gas pressure and temperature. The test results have also helped bound the normal operational range over which these meters can provide an accurate measure of volumetric flow rate, including reverse flow conditions. Although the test results for extremely low flow rates (i.e., less than 1% of full scale) showed a considerable increase in the data scatter, the results for the multipath meters remained reasonably well bounded, with measurement errors typically less than 5%. The results for reverse flow conditions indicated that there may be changes in the meter error of approximately 0.25 to 0.5%. The bulk of the testing indicated that variations in the gas temperature had no measurable effect on measurement accuracy. The test results also showed that the measurement bias error changed by as much as 0.5% as the line pressure was varied from 1,310 kPa (200 psia) to 6,205 kPa (900 psia). The magnitude of the line pressure effect was meter specific.

Thermowell Influence

The effect of an upstream thermowell on ultrasonic meter accuracy was quantified for both single-path and multipath meters. The data suggest that, in most cases, a thermowell located three pipe diameters upstream of the meter will produce minimal additional bias error in the flow rate measurement. However, the thermowell wake and its effects may persist for more than three pipe diameters, so when the wake is aligned with the ultrasonic measurement path of a single-path meter, additional bias error can result.

Field Tests

The limited amount of field data compiled and analyzed as part of this project demonstrated that meter performance for several different meter sizes and meter station configurations was within expected measurement uncertainty limits (i.e., total measurement uncertainty in field service is usually on the order of ±1% to ±2%). Improvements in field-test procedures and data collection methods could significantly reduce the measurement uncertainty levels associated with future field-test comparisons.

Many of the companies contacted during the field evaluation phase indicated that more in-house field evaluations will be performed in the future and that ultrasonic meters will see expanded use.

Overall

The test results reported here indicate that ultrasonic meters can meet the performance requirements for most bi-directional gas storage applications, if the meters are properly installed, operated, and maintained. Additional research, sponsored by GRI, is ongoing. The goals of the current GRI work are (1) to define specific meter station piping configurations that do not produce additional measurement bias and (2) to develop a performance verification test for new ultrasonic meters. The European Gas Research Group is sponsoring other ongoing research. Their efforts are currently focused on problems relating to the use of ultrasonic meters in the presence of ultrasonic noise (generated by “quiet” pressure-reducing valves). Additional research is needed to develop test methods that operators can use to verify when an ultrasonic meter is functioning properly after it has been installed in the field. More information pertaining to the long-term stability, reliability, and maintenance of ultrasonic meters is also needed. This type of information should become more plentiful as more meters are installed in the field.

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