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MULTIPATH ULTRASONIC FLOW METER PERFORMANCE

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SUMMARY

Commercially available Daniel and Instromet 12-inch multipath ultrasonic flow meters have been tested at the Gas Research Institute (GRI) Metering Research Facility (MRF) in baseline and disturbed flow installations. This paper presents test results to assess baseline accuracy and repeatability over a range of flowrates and pressures, and the influence of one piping configuration on meter performance. Comparisons are also made between the speed of sound as measured by the test meters and values calculated based on gas composition.

1. BACKGROUND

Ultrasonic flow meters (USM) are of interest because they offer the potential to significantly reduce installation and operating costs of meter stations while providing accuracy levels consistent with, or better than, other traditional metering methods (Beeson,[1] Sakariassen [2]). A significant barrier to wide-spread use of ultrasonic meters in the natural gas industry is the lack of a standard covering their use for custody transfer applications. There is work in progress at both the American Gas Association (A.G.A.) (Ultrasonic Meter Task Group of the Transmission Measurement Committee) and the American Petroleum Institute (API) (Alternate Meters Working Group) to assess USM technology and establish a direction for the potential development of a standard. The A.G.A. recently published an Engineering Technical Note[3] covering a range of topics related to the use of ultrasonic meters for natural gas applications. A significant contribution to the development of an ISO standard is the Groupe Européen de Recherches Gazières (GERG) Technical Monograph 8,[4] "Present Status and Future Research on Multi-path Ultrasonic Gas Flow Meters," which suggests functional requirements for manufacturers to target and identifies "gaps" in the available information.

Of the 193 publications listed in the GERG monograph, only 21 concern testing, calibration, installation effects, and long term performance. This suggests that, as compared to other commonly used natural gas meter types (orifice, turbine), there is not a large published information base on the performance of ultrasonic flow meters. The tests published to date (including those by van Bloemendaal and van der Kam,[5] van der Kam et al., [6] Vulovic et al. [7]) have been conducted on a variety of upstream disturbances and on different meter types and sizes.

Overall, the published results indicate that under good flow conditions the meters provide measurements well within ±1%, and in typical disturbed flow configurations (without pressure reducing flow control valves) the deviation of the meter from the good flow results is on the order of 0.5%. Performance test results show that the meter type, particular installation configuration, and meter size can all influence the amount of meter deviation from baseline or reference conditions. Therefore, the need remains for more information on ultrasonic flow meter performance over a wide range of operating and installation conditions.

The purpose of the tests reported here was to expand the information available on the performance of ultrasonic flow meters over a range of operating conditions and configurations. These test data are intended to contribute to standards development efforts.

2. INTRODUCTION

Ultrasonic flow meters use measurements of the transit time of high frequency pulses between one or more pairs of transducers to determine the volumetric flowrate in 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 (including Freund and Warner,[8] Drenthen,[9] van Dellen,[10] and A.G.A.[3]). A weighting function is typically used to combine the individual path velocities to form the meter average axial velocity, which is used to calculate the volumetric flowrate.

Although the basic relationships 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 different commercially available meters. These differences are the result of the use of different strategies to achieve the meter's target accuracy, which is typically stated as 0.5 to 1.0%. Differences in meter configuration and data processing methods can affect meter accuracy, rangeability, repeatability, and susceptibility to error due to less-than-ideal installation configurations.

The Daniel multipath ultrasonic meter, which is designed around the use of four-parallel chordal paths, exploits a numerical integration technique to form a weighted average of the path measurements without an assumption of the velocity profile. The method, described by several references including the GERG Technical Monograph 8 [4], specifies the transducer locations and results in a fixed set of weighting coefficients. The Instromet five-path ultrasonic meter utilizes the measurements from three single-reflection diametral paths and two double-reflection chordal (mid-radius) paths to form an average velocity based on a combination of theoretically and experimentally determined weighting factors (Drenthen[9]).

3. TEST METHODS

Tests for this program were conducted in the GRI MRF High Pressure Loop (HPL) located at Southwest Research Institute. Test meters were installed in the 12-inch reference flow leg of the MRF HPL and tested with pipeline quality natural gas. Data were collected simultaneously on the ultrasonic meters and on the HPL critical flow nozzle bank, which served as the flow reference. The five binary weighted sonic nozzles were calibrated in situ at different pressures against the HPL weigh tank system (described by Park et al.[11]). The total uncertainty for the nozzles is estimated to be approximately 0.2%. An on-line gas chromatograph and equations of state from A.G.A. Report 8[12] were used to determine gas properties for all calculations. Static pressure and temperature were measured at the meters. The volumetric flowrate reported by the ultrasonic meter was acquired using different methods, depending on the meter options available from the manufacturer. For the Daniel USM, a "calibration mode" was used, whereby the meter internally totalized the gas volume and the time during which a specific register was toggled. The average flowrate was then calculated from the totalized numbers. For the Instromet USM, reported values of actual flowrate (which were provided at a rate of one per second) were averaged to determine the average volumetric flowrate. Speed of sound measurements taken by both meters were also recorded.

A typical test sequence consisted of recirculating gas through the flow loop for a period of time to allow the gas temperature to stabilize. Steady flow was established by selecting and choking different nozzle combinations. A test point consisted of the average values of flowrate and other variables, computed over a period of 90 to 120 seconds. Test points were repeated a minimum of five to ten times to calculate an average value and standard deviation. Data were collected simultaneously from other flow measurement devices in the flow loop (typically one 10-inch orifice meter and two 12-inch turbine meters), which aided in establishing the validity and consistency of the data.

The ultrasonic meters were tested as received from the manufacturers, and all tests were conducted without the use of flow conditioners. The Daniel four-chordal path USMs were "dry calibrated" by the manufacturer. The dry calibration included measuring the various lengths required for the calculations and characterizing the timing delays for the ultrasonic transducer pairs. These meters had not been exposed to flowing gas prior to installation at the MRF. The Instromet five-path USM (two double-reflecting chordal paths and three single-reflecting diametral paths) had previously been flow calibrated and tested at several European laboratories. As received, the meter was set up for approximately 2.8 MPa operating conditions by the specification of density and viscosity values that are used for a Reynolds number calculation, which is part of the algorithm for calculation of the flowrate.

4. TEST RESULTS

4.1 Baseline Tests

The baseline tests were conducted with the meters installed approximately 68 diameters downstream of an in-plane tee. This corresponds to meter location 3, as shown in plan-view in Figure 1. The pipe 17 diameters upstream of the meter had a surface roughness of approximately 3.8 μm and an inside diameter of 304.8 mm, which matched the diameters for Daniel meters A1 and A2 and was slightly smaller than the 306.3 mm inside diameter of Instromet meter B. The baseline testing for meters A1 and A2 was conducted with the two meters in series. The first meter was located at location 3 (Figure 1),

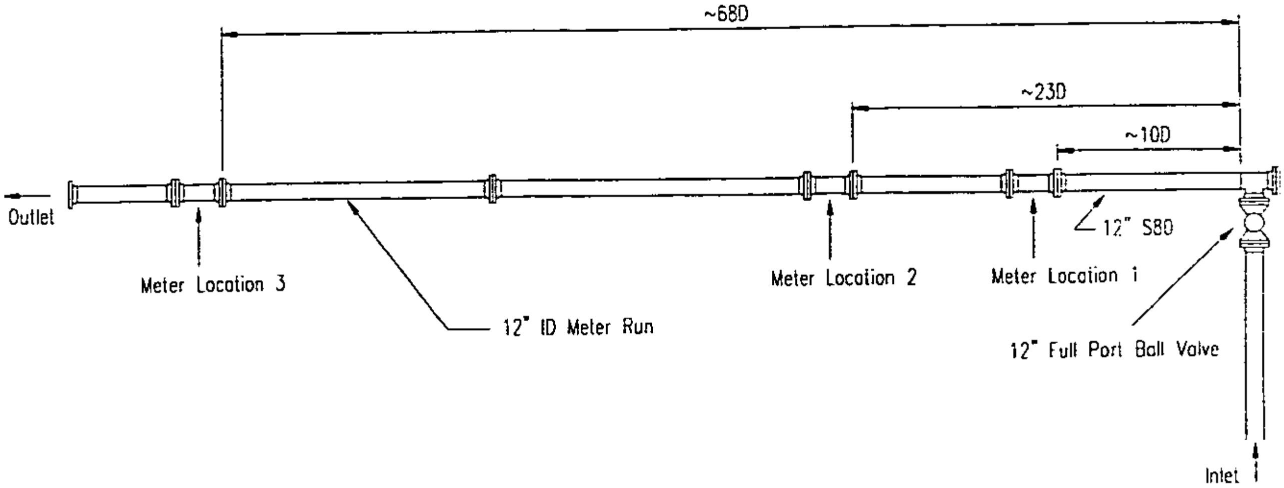

Figure 1. Meter installation for baseline and disturbed flow conditions.

and the second meter was located 10 diameters downstream from the first. The meters were oriented such that the chords were aligned in a horizontal plane. Baseline testing on meter B was conducted while meters A1 and A2 were installed at locations 1 and 2 (Figure 1).

Figure 2 shows the baseline performance of meters A1, A2, and B over the range of flowrates achievable in the MRF (which is 30 to 40% of full scale for a 12-inch meter). The error percentages shown are calculated relative to the nozzle bank reference flowrate.

It is apparent from the curves that all the meters are well within a 1% error tolerance, and for all but the lowest velocity, the points fall within a 0.5% band. The error bars shown on the data represent two standard deviations calculated from the data scatter at each velocity. The repeatability is similar for all the meters, having a value of less than 0.25% above approximately 1.5 m/sec. At low velocities there tends to be more scatter in the data, which is likely an effect of the resolution of the transit time measurements.

Figure 2 also shows that for meter A1, there is a small zero offset present in the meter. The offset is indicated by curvature in the meter error curve. The error changes steadily, from 0.3% when the velocity is above 1.5 to 3 m/sec, to -0.5% as the velocity approaches 0.5 m/sec. It is important to note that the zero offset present in this meter, which would normally be eliminated during the dry calibration at the factory, was knowingly left in this meter to verify its effect on the meter calibration curve. At 6.2 MPa, the estimated offset for meter A1 is 0.003 m/s.

Baseline testing was conducted at line pressures of 1.7, 2.8, and 6.2 MPa to assess any effect of pressure on the meter calibration. Figure 3 indicates the average meter error, for velocities above 2.7 m/s as a function of pressure. The data reflect a shift in the average error of about 0.4% over the 4.5 MPa range of pressures tested.

As the pressure is increased, the gas density, and therefore the Reynolds number, will also increase. Since the velocity profile will change as a function of the Reynolds number, profile dependent errors should collapse when the error data are plotted against the Reynolds number. Figures 4, 5, and 6 present the same data with the percent error plotted as a function of Reynolds number. Since the zero offset in meter A1 would somewhat obscure the Reynolds number dependence, the data in Figure 4 has been corrected for a 0.003 m/s offset (assumed to be independent of pressure.) The figures show some Reynolds number dependence and tend to collapse slightly as the Reynolds number increases; however, the curves for individual pressures remain separate.

The calculation method employed by meter B uses corrections that are dependent on the velocity profile and therefore dependent on the Reynolds number. Because the density and viscosity values used by the meter were set to values appropriate for

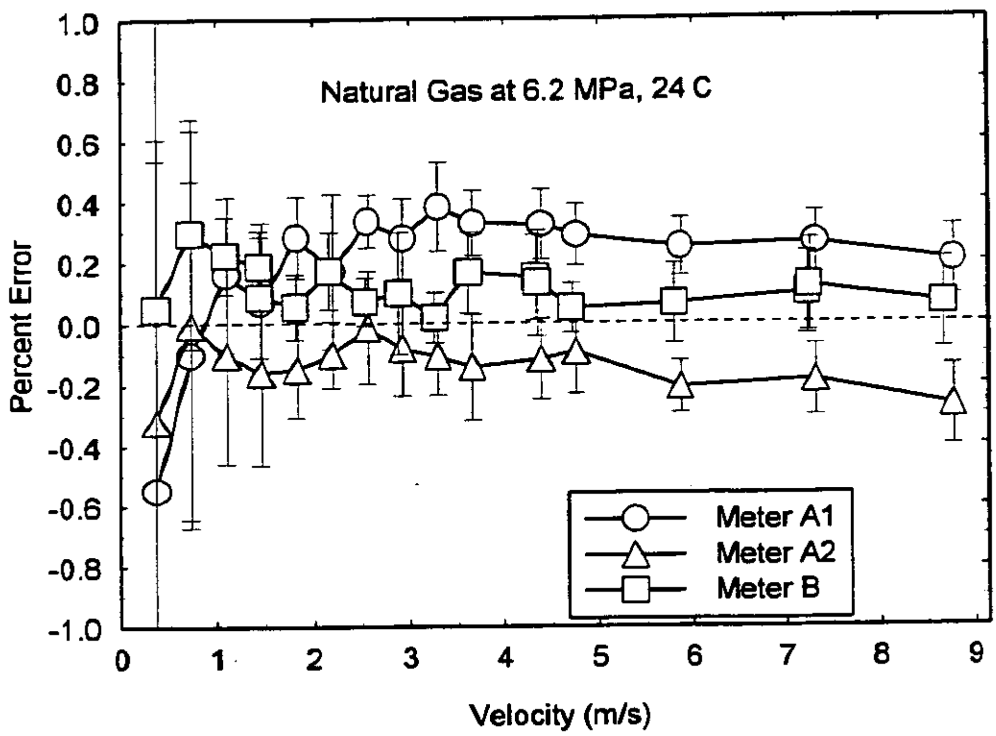

Figure 2. Baseline results at 6.2 MPa for meters A1, A2, and B.

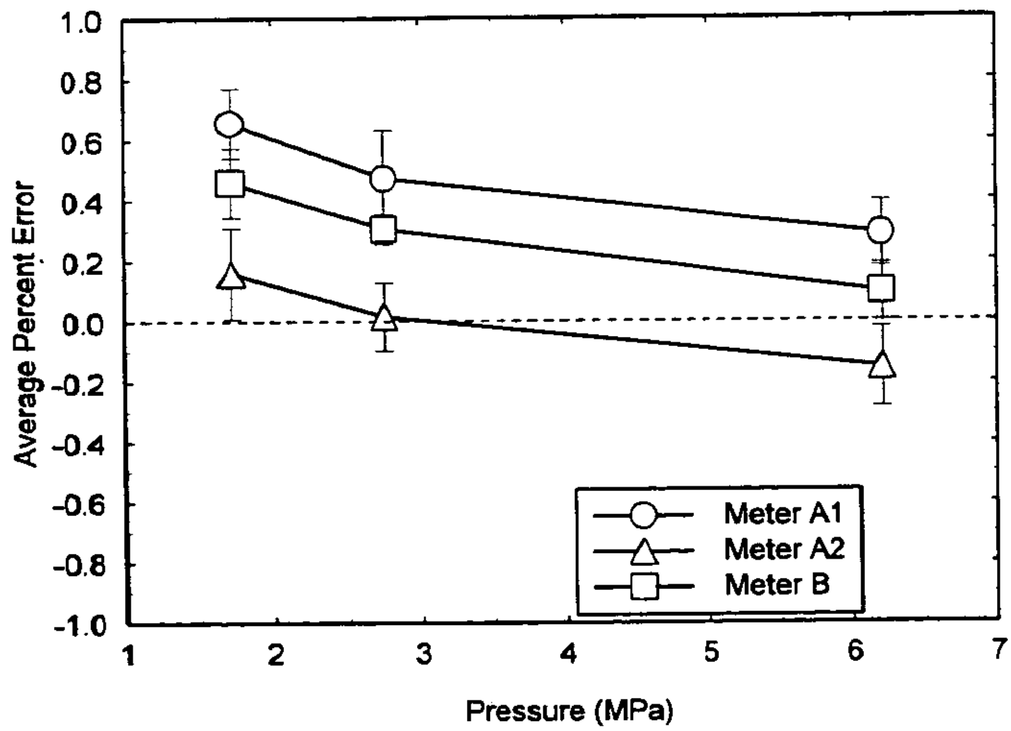

Figure 3. Average meter error as a function of pressure.

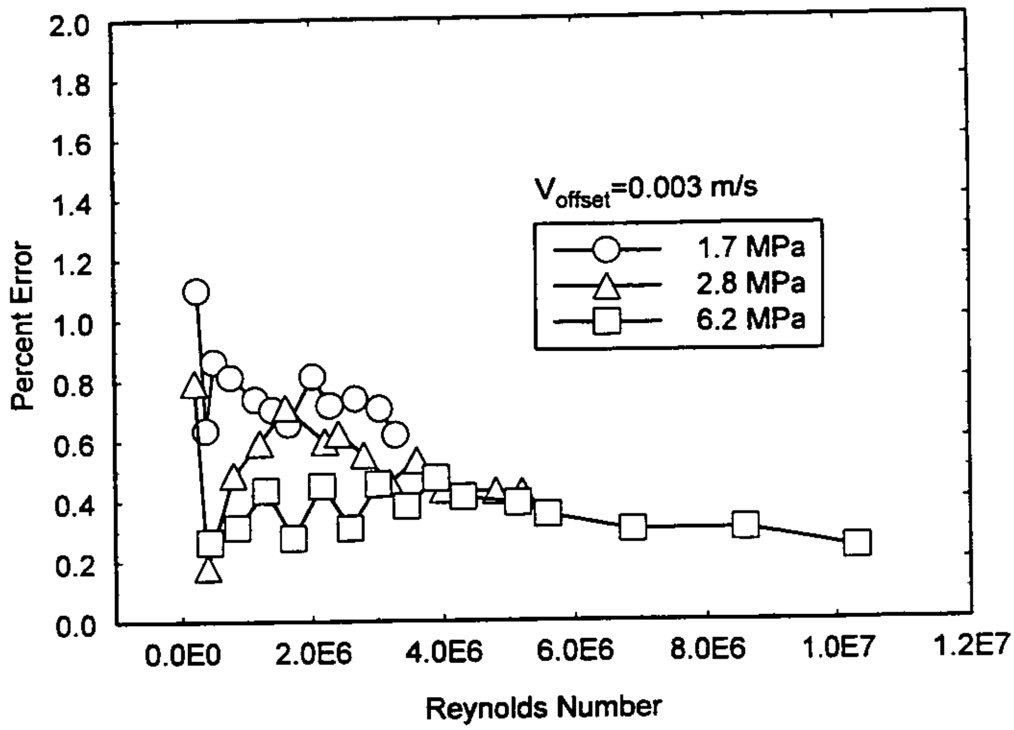

Figure 4. Effect of pressure on meter A1 after correcting for velocity offset.

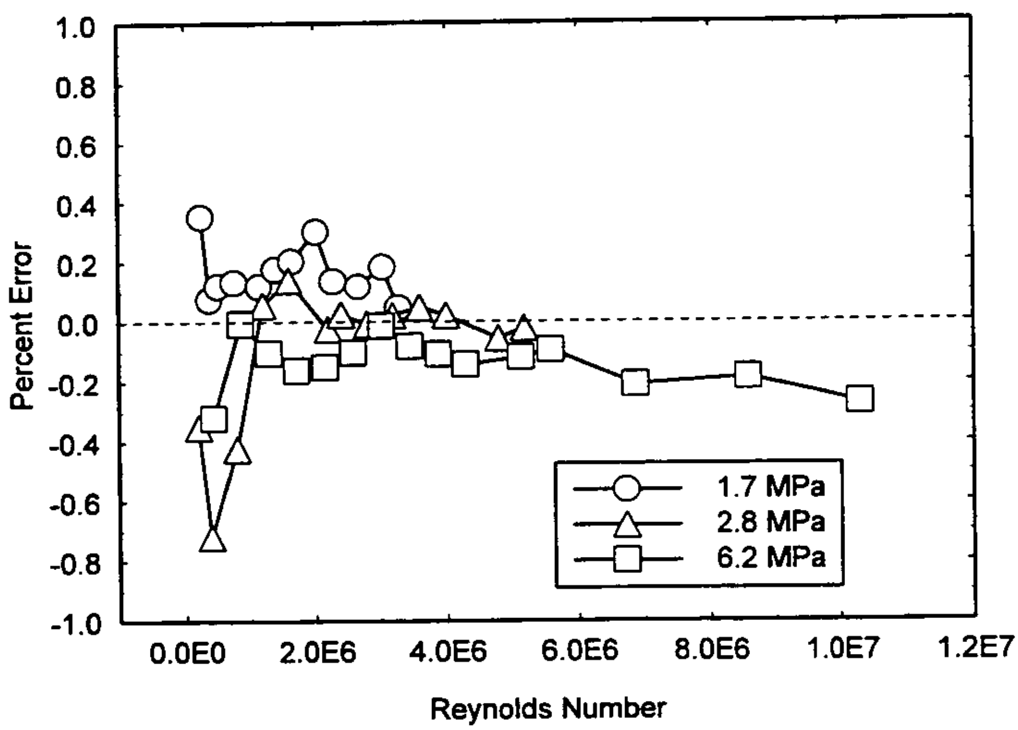

Figure 5. Effect of pressure on meter A2 plotted as a function of pipe Reynolds number.

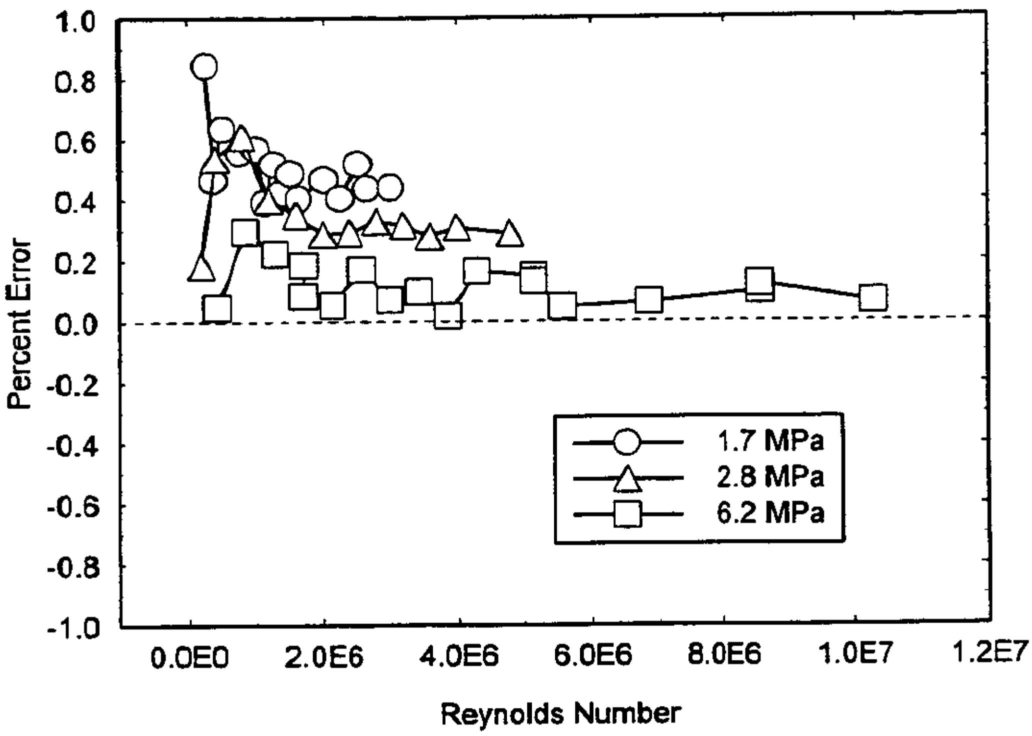

Figure 6. Effect of pressure on meter B plotted as a function of pipe Reynolds number.

2.8 MPa operation, a portion of the pressure shift for meter B can be attributed to the fixed values, preventing the meter from making proper corrections. A limited set of additional tests were conducted with meter B at 1.7 and 6.2 MPa, with the baseline values for the density and viscosity and then with property values, consistent with the pressure. The data indicate shifts of roughly 0.1 percent towards the 2.8 MPa line for the 1.7 MPa case and essentially no change for the 6.2 MPa case. These results, and Figure 6, suggest that the Reynolds number based profile correction does not completely account for the effect of pressure on the meter error. Calculations, similar to those done by van Dellen,[10] demonstrate that the theoretical performance of the integration method used by meters A1 and A2 is largely independent of velocity profile over the Reynolds number range (and therefore the pressure range) involved in these tests. Calculations to assess the profile dependence were made by integrating an assumed profile (Bogue and Metzner[13]) for different Reynolds numbers and different path locations. Figure 7 shows the "path factor" for several different locations as a function of Reynolds number for the locations used by the Daniel and Instromet meter designs. The path factor is calculated from the ratio of the average velocity to the calculated velocity along a path. Figure 8 shows the overall calculated meter factor using the method of meters A1 and A2 and the path factor for the mid-radius path (believed to have the most importance in the calculation method for meter B.) Since the method used by meter B to calculate the average velocity is proprietary, the curve in Figure 8 is a path factor and not an overall meter factor. The curves indicate the four-path weighted method should have very little pressure shift over the 4.5 MPa range of pressures. The mid-radius path has a shift in the path factor of about 0.05% over the 4.5 MPa range. These calculations indicate that the meter variation with pressure observed in the test data is not explained by changes in velocity profile shape.

The path calculations are based on the assumption that the transducers are located at the exact design location and that the transit times are measured from a point at the center of the transducer. A further assumption is that the ultrasonic beam has no thickness (volume.) These assumptions should be investigated further to assess their validity and their effect on the calculations.

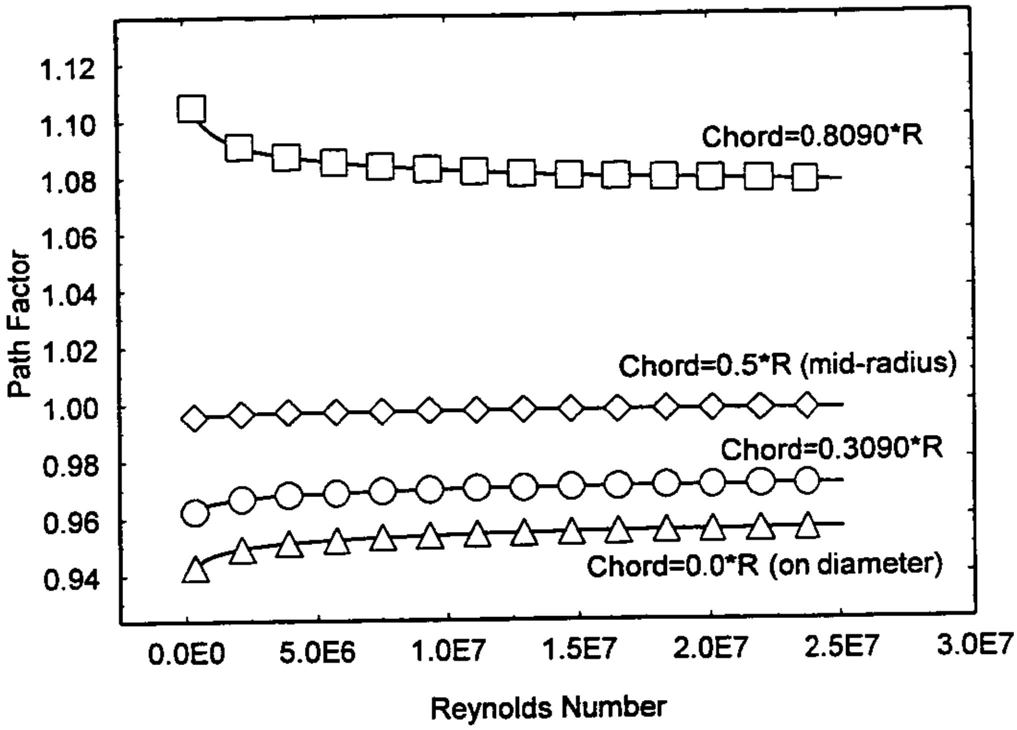

Figure 7. Calculated path factors as a function of Reynolds number for different path locations.

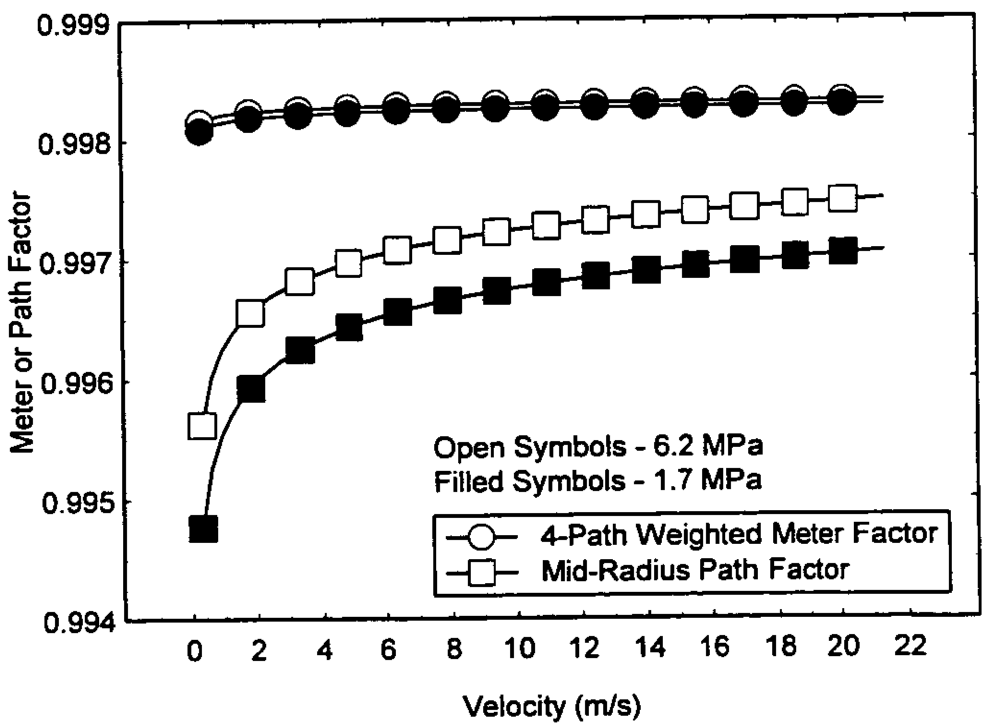

Figure 8. Calculated effect of pressure on meter or path factor.

The change in the path length and meter body diameter as the pressure is increased also introduces an error into the measurement. However, the estimated change in calibration, due to mechanical deformation, is less than 0.05% for the 4.5 MPa change in pressure. These results are contrary to the findings of other testing (van Bloemendaal and van der Kam,[5] Vulovic et al.[7]) where no consistent dependence on pressure was identified (although there were variations in the mean error at different pressure levels.) Because the data available in the aforementioned studies came from multiple laboratories and were presented in summary fashion, it is difficult to distinguish differences that are related only to pressure versus differences that are a result of small biases between laboratories. The results from the five test facilities show variations of about ±0.6% over a 10:1 turndown in the meter operating range for pressures between 1 and 6 MPa. The effect of pressure needs to be investigated further to fully explain the data. Additional work to accurately model the measurement process used by ultrasonic meters may offer possible explanations.

4.2 Speed of Sound

Figure 9 shows the percent error between the speed of sound reported by the meters and that derived from A.G.A. Report 8[12] density calculations based on the measured pressure, temperature, and gas composition. The figure shows that the error is typically less than 0.2% for both test meter types, with each meter type having its own bias relative to the calculated value. The figure confirms that the reported speed of sound is not dependent on the gas velocity. The meter velocity was used as the independent axis in the figure because of the limited range of speed of sound information available from the data shown in Figure 9 (sound velocities ranged from 414 to 430 m/sec). The data for meter A1 show more scatter than the meter B data. Although not presented, the data for meter A2 were similar to those for meter A1. There does not appear to be a large dependence on pressure, with about 0.1% shift between the 6.2 MPa data and the results for the other pressures.

These results indicate the level of agreement that can be expected under controlled conditions is on the order of the uncertainty in the speed of sound calculated from the gas composition. It should be recognized, however, that because of the relationship between the path velocity and path speed of sound measured by the meter, good agreement between the calculated speed of sound and that reported by the meter is not a sufficient condition for accurate flow measurement.

4.3 Disturbance Tests

Figure 1 showed that the location of the meters for the disturbance tests was 10 diameters downstream of a tee (i.e., meter location 1 on Figure 1) that was located just downstream from a 12-inch diameter full-port ball valve. Tests were conducted with the ball valve open, and at two partially closed positions (to increase the level of flow disturbance entering the test meter). No flow conditioner was installed upstream of the meter. The piping between the tee and the meter was 12-inch schedule 80 pipe having a nominal inside diameter of 288.9 mm (and surface roughness of approximately 8.9 μm). Therefore, when located at the position 10 diameters down from the tee, the meter was subjected to a combination of the effects of the 15.9 mm concentric step in diameter (an 11% increase in area), the tee, and for some tests, a partially closed valve. Tests were conducted at the same three pressures used for the baseline calibrations. A set of scoping tests were also performed with the meter located 23 diameters downstream from the tee (meter location 2 on Figure 1.)

Meter A1 was tested in two different orientations relative to the tee. The 0 degree position had the chords aligned in a horizontal plane along with the tee. The meter was also rotated 90 degrees, so that the chords were aligned in a vertical plane. Meter B was tested in only one orientation.

Figure 10 displays the results for the upstream disturbance testing at 2.8 MPa. Although the data appear to differ from the initial baseline, additional baseline data collected just prior to the initiation of the disturbance tests revealed a shift. (It was later discovered that this shift may have been due to a failing chord.) The data at 23D can be considered as the revised baseline. Relative to the 23D (revised baseline) results, the data for 10D with the chords horizontal (0°) are shifted by about 0.1% to 0.2%. The results for the dependence on the meter orientation indicated a shift of about -0.4% when the chords are vertical (90°). The fact that there are differences dependent on the chord orientation relative to the disturbance is not surprising, and these differences have been measured by others (van Bloemendaal and van der Kam[5]). Since the transit time measured by the meter for a particular path is dependent on the average velocity along the path, the paths cutting across the disturbance tend to average out the effect of

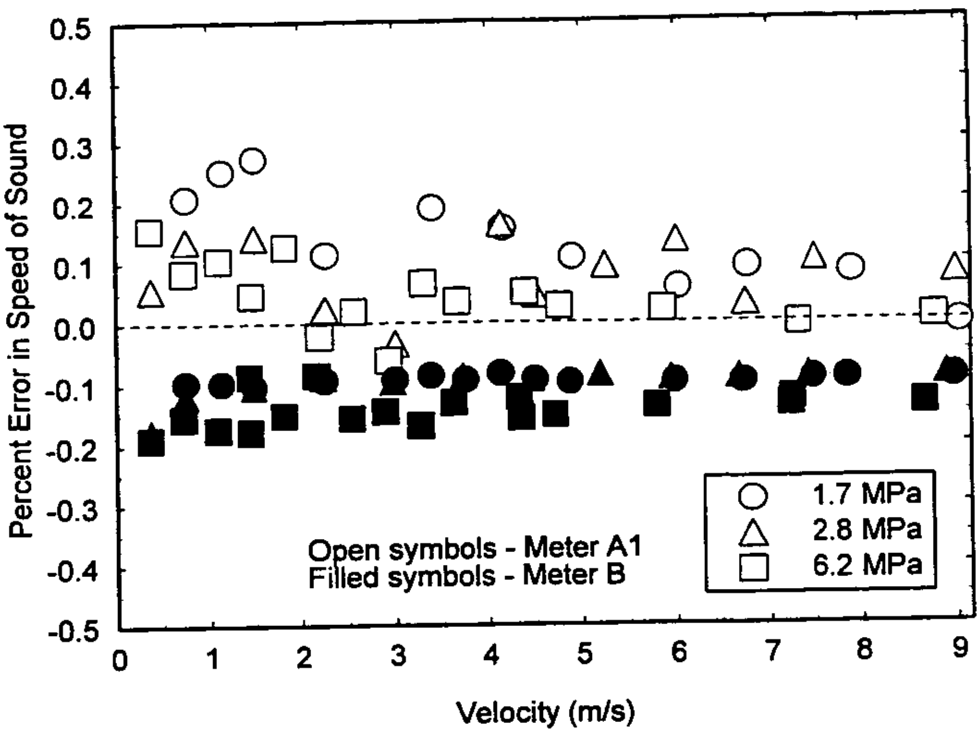

Figure 9. Comparison of speed of sound for meters A1 and B.

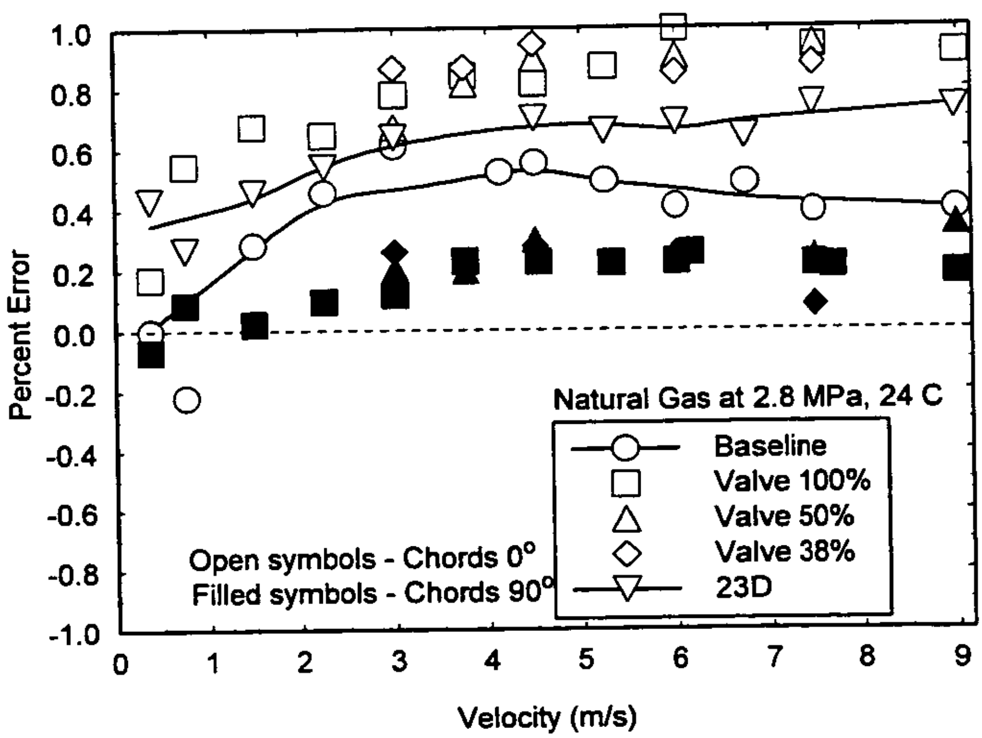

Figure 10. Performance of meter A1 10D downstream of a tee at 2.8 MPa.

the disturbance. When the paths are vertical and the primary direction of velocity disturbance is horizontal, the ability of the integration method to accurately resolve the average velocity has more of an effect on the results.

Also shown in Figure 10 is the effect of the partially closed valve on the meter performance. The results indicate that the valve position had little effect on the average error of the repeated runs, but there was a small increase in the data scatter, suggesting that turbulence levels were increased as a result of closing the valve. Table 1 lists, for velocities above 2.7 m/sec, the average percent error and twice the average standard deviation (2σ) of the data for the different axial installation locations, meter orientations, and valve positions.

Figure 11 gives the results for meter B installed 10D down from the tee. The results show a shift of about 0.6% from the baseline with the valve fully open and a shift of about 0.4% from the baseline when the valve is partially closed (50% and 38% open). The result was unanticipated, since the partial blockage by the valve was expected to increase the flow distortion. Table 2 shows that although the valve position did influence the absolute value of the error, it did not have a significant effect on the data scatter of the repeated runs. Data reported by Vulovic, Harbrink, and van Bloemendaal[7] showed a deviation of 0.3% relative to the baseline when the meter was installed 10D down from an elbow. The effect of the 15.9 mm step change in pipe diameter in the MRF installation may account for the difference in results as compared to those of Vulovic et al., where no step was indicated in the description of the test.

Table 1. 2.8 MPa data for meter A1.

Dist D	Valve %	Orient °	Error %	Error 2σ
10	100	0	0.880	0.205
10	50	0	0.875	0.286
10	38	0	0.883	0.329
10	100	90	0.208	0.222
10	50	90	0.253	0.250
10	38	90	0.217	0.332
23	100	0	0.684	0.167
68	100	0	0.288	0.114

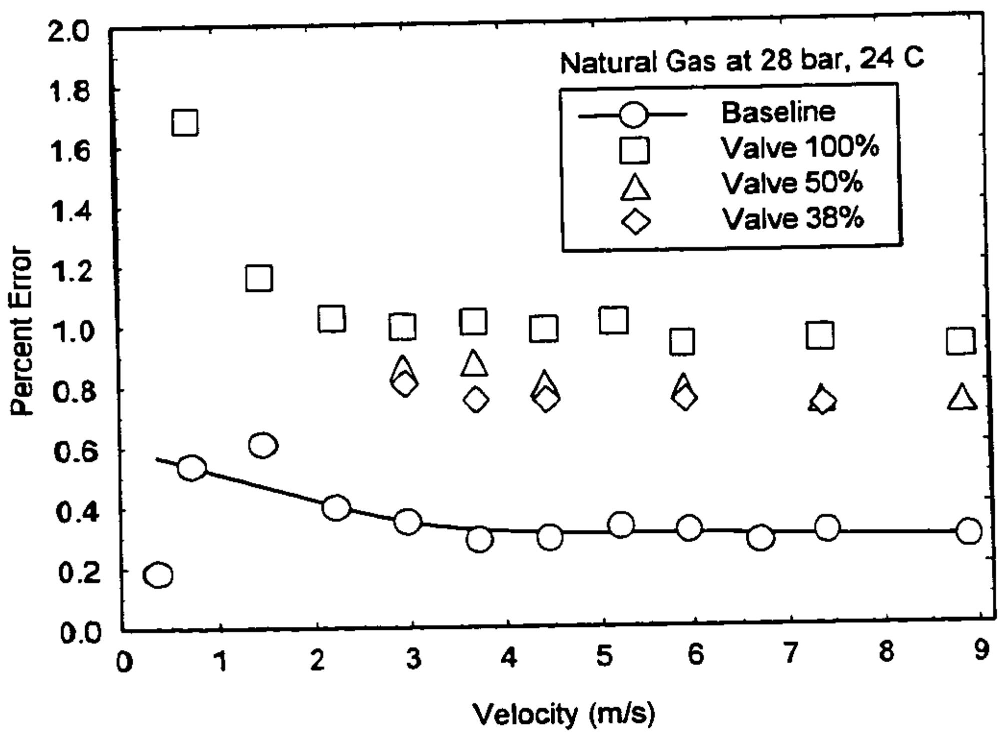

Figure 11. Performance of meter B 10D downstream of a tee at 2.8 MPa.

Table 2. 2.8 MPa data for meter B.

Dist D	Valve %	Orient °	Error %	Error 2σ
10	100	0	0.969	0.097
10	50	0	0.800	0.106
10	38	0	0.755	0.126
68	100	0	0.306	0.134

The results of the disturbance testing conducted at 1.7 and 6.2 MPa indicate results similar to those shown here for 2.8 MPa for both meter types.

5. CONCLUSIONS AND RECOMMENDATIONS

These data demonstrate that the test meters are capable of accuracies well within a 1% tolerance and have repeatability of better than 0.25% when the flowrate is above about 5% of the meter capacity. The data indicate that pressure may have an effect on meter error. Both meter types showed shifts of 0.4% over a 4.5 MPa static pressure variation, but remained within a 1% tolerance. These results suggest that flow calibration of each meter at or near the field operating conditions may be necessary for reducing any unacceptable measurement bias. If the target is to produce a dry calibrated meter with a bias error on the order of a few tenths of a percent, then a more complete understanding of the relationships between various operating parameters and the meter design may be required.

The data suggest that both the magnitude and character of errors introduced by flow disturbances are a function of meter design. Shifts of up to 0.6% were measured for meters installed 10 diameters from a tee without a flow conditioner. Better characterization of the effects of flow disturbances on the measurement accuracy is needed to more accurately define the installation requirements necessary to achieve meter performance within a specified tolerance. This should involve additional tests of different installations with and without flow conditioners.

Additional details on these results can be found in GRI Topical Report GRI-96/0291[14]. Plans to extend this work include addressing the effects of flow disturbances on meter performance with and without flow conditioners. This work will utilize smaller meters, which can be tested over more of their velocity range. This work may also be extended to include testing specific to the application of ultrasonic meters to gas storage reservoirs, with funding provided by the U.S. Department of Energy.

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