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PERFORMANCE TESTING OF ULTRASONIC FLOW METERS

Authors:
Terrence A. Grimley, Southwest Research Institute, USA

Organiser:
Norwegian Society of Chartered Engineers
Norwegian Society for Oil and Gas Measurement
Co-organiser:
National Engineering Laboratory, UK

Performance Testing of Ultrasonic Flow Meters

Terrence A. Grimley
Southwest Research Institute
San Antonio, Texas, U.S.A.

ABSTRACT

This paper presents a portion of the ultrasonic flow meter research results from work sponsored by the Gas Research Institute (GRI) and the U.S. Department of Energy, conducted at the Metering Research Facility (MRF). Single and multipath 8-inch diameter ultrasonic flow meters were evaluated in baseline flow conditions, and in other piping installations with and without flow conditioners. In addition, tests were conducted to assess the effect on measurement accuracy of configurations with a thermowell upstream of the meter.

The results reported in this paper are intended to aid in the definition of installation requirements for single-path and multipath ultrasonic flow meters. The meters were installed in various piping configurations with single- or double-elbow combinations upstream of the meter, and in configurations with a thermowell upstream of the meter. Tests were performed both with and without a flow conditioner installed upstream of the test meters.

Baseline tests were conducted to define a reference condition to which the other piping configurations could be compared. The results for the baseline tests suggest that the velocity profile was not fully developed 59 pipe diameters downstream of a single, long-radius 90° elbow, and that the test meters were sensitive to the subsequent profile development.

The test results for the 8-inch diameter multipath flow meters indicate that, depending on the meter type and location relative to a flow disturbance, flow conditioners can improve the measurement accuracy. However, combinations also exist where the inclusion of a flow conditioner in the piping configuration would result in increased measurement errors.

The results for the single-path meters show potential for achieving flow measurement accuracies better than 0.5% in well-ordered flow fields. The results for single-elbow and two-out-of-plane-elbow configurations demonstrate shifts in flow measurement errors of 1 to 4% relative to the baseline tests. The results also indicate the level of improvement achievable when a flow conditioner was included in the piping configuration.

INTRODUCTION

Ultrasonic flow meters derive the volumetric flow rate of gas from time-of-flight measurements of ultrasonic energy pulses transmitted through the flow stream. Because the accuracy of the flow rate determination is a function of the meter design and calculation method, the upstream piping requirements for an ultrasonic flow meter may differ from those of more traditional measurement devices. For instance, orifice meters require symmetric, non-swirling flow to measure flow rate to within the accuracy of the established discharge coefficient equations. American Gas Association (A.G.A.) Report No. 3[1] recommends that a minimum length of straight pipe be placed upstream of an orifice meter in order to establish proper flow characteristics, so that accurate flow measurements can be obtained. The sensitivity of the orifice meter to flow disturbances increases as the orifice size (i.e., beta ratio, β) increases (Morrow[2]) because there is less flow blockage and, therefore, less reshaping of the velocity profile caused by the presence of the plate. Turbine meters also reshape the flow profile by forcing the flow through an annulus. Even with their ability to reshape the inlet flow profile, turbine meters are sensitive to asymmetry in the velocity profile (Dijsterlbergen and Bergervoet[3]). Furthermore, A.G.A. Report No. 7[4] requires the use of a flow conditioner with a turbine meter to eliminate flow swirl at the meter inlet. Since an ultrasonic meter has essentially no flow blockage that can affect the inlet flow, the meter does not change the flow profile. Therefore, a meter of this type must rely on robust calculation methods to accurately determine the flow rate, based on the portion of the flow sampled by the meter.

In the design of multipath ultrasonic flow meters, manufacturers have attempted to optimize the meters so as to reduce their sensitivity to flow disturbances. If the meters can correctly compensate for all flow disturbances, then the need for flow conditioners is eliminated. However, the use of flow conditioners in combination with ultrasonic flow meters remains of interest, since there is little published documentation on how flow conditioners affect the performance of multipath ultrasonic flow meters. The potential benefits of flow conditioners have been mostly inferred from experience with other meter types. There is also interest in using flow conditioners in combination with less-expensive, single-path ultrasonic meters as a cost-effective alternative to multipath flow meters. Again, there are limited test data available to confirm the performance of single-path meters when used with flow conditioners.

The results presented in this paper are from a test plan designed to experimentally determine the performance of 8-inch diameter single-path and multipath ultrasonic flow meters when installed in various piping configurations and when used in combination with a flow conditioner. The meter tests described here were run with single- and double-elbow piping combinations upstream of the test meters. Tests were performed both with and without a flow conditioner installed upstream of the test meters.

TEST METHODS

Tests for this program were conducted in the GRI MRF High Pressure Loop (HPL) located at Southwest Research Institute. The meters were installed in the Test Section of the HPL and tested with transmission-grade natural gas. Data were collected simultaneously from the ultrasonic meters and from the HPL critical flow nozzle bank, which served as the flow reference. The five binary-weighted sonic nozzles were calibrated in-situ, at different line pressures, against the HPL weigh tank system (Park et al.[5]). An on-line gas chromatograph and equations of state from A.G.A. Report No. 8[6] were used to determine gas properties for all calculations. The static pressure, relative to a reference pressure in the HPL system, was measured two pipe diameters downstream of each 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 against the rate determined by the critical flow nozzles to establish the flow measurement error.

The volumetric flow rate reported by each ultrasonic meter was acquired using different methods, depending on the meter options available from the manufacturer. The internal calibration mode of meters M3 and M4 was used to instruct the meter to totalize gas volume and time during the period when a specific register in the meter electronics was toggled. The average flow rate was then calculated from the totalized values. For meters M1 and M2, reported values of actual flow rate (which were provided at a rate of one per second) were averaged to determine the average volumetric flow rate. Individual path status, velocity, and speed of sound data 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 and pressure to stabilize. Steady flow was established by selecting and choking different 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 12-inch turbine meters. The turbine meter data were used to verify the consistency of the experiments, including the long-term reproducibility.

Instromet Ultrasonic Technologies, Inc., and Daniel Instruments, Inc., each provided two 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 paper. ***None of the meters had previously been flow calibrated prior to being tested as part of this program***. Table 1 summarizes the meter configurations for the two multipath meters and two single-path meters. The meters were fabricated such that all had identical flange-to-flange dimensions (800.1 mm in length) and inside diameters (within 0.127 mm) to simplify the interchange of the meters at the different installation locations. 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 electronics) were adjusted for each test condition, as required.

Table 1 – Test meter geometry.

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

BASELINE TEST CONFIGURATIONS

To determine the flow measurement error associated with a particular flow meter piping arrangement, it is necessary to have baseline meter performance data to compare against. Baseline performance is determined by testing a flow meter and its secondary instrumentation under established test conditions. The test is then repeated using the same meter and instrumentation, and the piping installation of interest. The measurement error caused by the piping installation is then determined by comparing the results for the piping configuration of interest to those for the baseline test.

Figure 1 displays the piping arrangement for the baseline tests used in this investigation. All piping spools were fabricated with 8-inch diameter, schedule-40, carbon steel pipe (having a nominal 202.7-mm inside diameter) with all internal welds ground smooth. The test meters were installed at 40D, 59D, 78D, and 97D [nominal pipe diameters, where D = 203.2 mm (8 inches)] downstream of a single, long-radius, 90° elbow. The piping immediately upstream of the elbow consisted of a 12"x16"x10" Sprenkle flow conditioner followed by a 10"x8" concentric reducer, and then 43D of straight 8-inch diameter pipe.

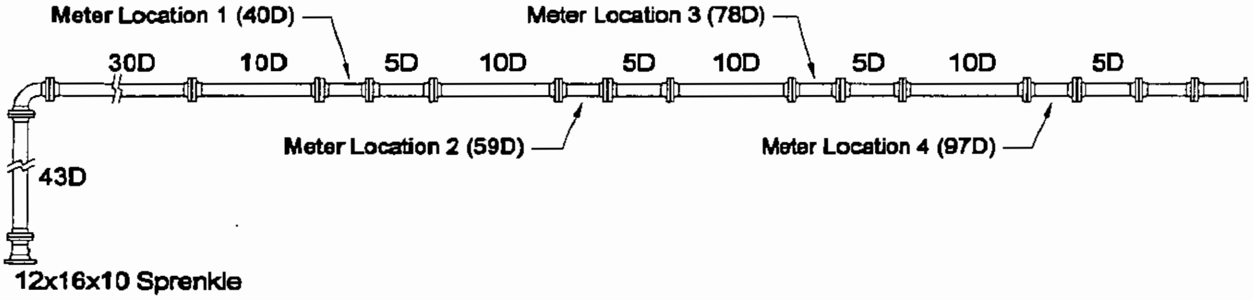

Figure 1 – Baseline meter installation.

Initial baseline testing was performed with the meters at the locations indicated in Table 2. The complete test plan calls for each meter to eventually be tested at all four locations. When the meters were moved from one axial location to another, the upstream and downstream spools (10D and 5D long, respectively) remained bolted to the meters so that there was no change in flange alignment immediately upstream or downstream of each meter. The pressure and temperature transducers associated with each meter also remained with the meter during changes in the baseline meter arrangement, to help minimize measurement bias errors. Roughly two months after this initial testing, all meters were tested at the 97D position as part of a separate test sequence.

Table 2 – Baseline test location by meter designation.

Meter	40D	59D	78D	97D
M1		X		X
M2	X		X	
M3		X		X
M4	X		X	

BASELINE TEST RESULTS

Figures 2 and 3 show the performance of the two multipath meters (M1 and M3, respectively) in the baseline configuration. The meter data are displayed as percent error, relative to the MRF HPL critical flow nozzles, as a function of the average velocity through the meter. The points shown represent the average of six repeats at each flow rate, and the error bars indicate the 95% confidence limits, based on six repeats (i.e., 2.6 times the standard deviation).

Figure 2 indicates that, at velocities above 3 m/sec, all the data for meter M1 fall within a 0.4% band, independent of velocity. The upward swing in the error curve below about 3 m/sec appears to be an artifact of the correction algorithm that does not fully account for velocity profile differences at the low flow rates. Examination of the flow calibration curves also reveals about a 0.2% difference between the flow measurement error when the meter was installed at 97D and when the meter was installed at 59D. The magnitude of the error is greater (i.e., more negative) at the 97D location than at the 59D location. A similar difference in measurement error exists between the 2.8 MPa and 6.2 MPa test cases. Subsequent testing, just prior to the start of the two-elbow-out-of-plane tests, with the meter installed at 97D, showed a difference of approximately 0.3% relative to the initial testing. It is not clear if this behavior is due to slight differences in the 97D installation, or to long-term variability in the meter performance. Other MRF HPL reference meters showed no shift for the same test dates.

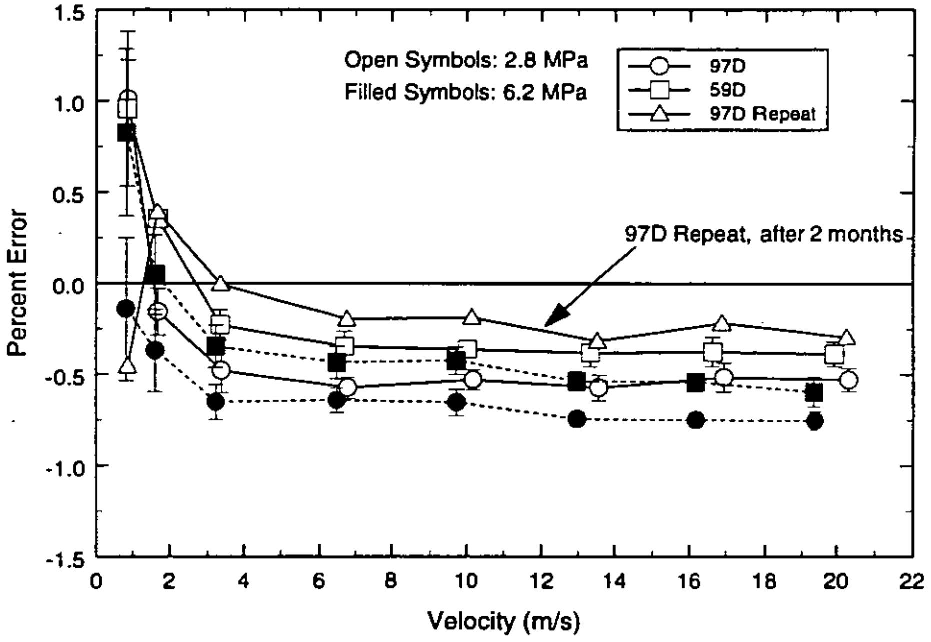

Figure 2 – Baseline results for multipath meter M1.

Figure 3 indicates that the measurement error for meter M3 was dependent on the meter velocity. The nonlinear characteristics of the measurement error for this meter were different from those observed for 12-inch diameter meters of similar design that were previously tested at the MRF (Grimley[7]) and elsewhere (van Bloemendaal and van der Kam[8]). Except for the data collected at 2.8 MPa with the meter installed at 59D, the error values for average gas flow velocities above 3 m/sec all fall within a 0.3% wide band that slopes downward as the velocity increases. Individual path status information for the 59D, 2.8 MPa data set shows that the signal processor rejected some of the measurements on the outer paths because the measured transit times had failed an internal consistency check. This is likely the cause of the deviation from the other data sets. The data, including the problematic set, remain within a 0.5% wide band for velocities above 3 m/sec. The data also show flow measurement differences of about 0.2% as the pressure increases from 2.8 to 6.2 MPa. The 6.2 MPa results show a measurement difference of about 0.1% between the results when the meter was at 59D and the results when the meter was at 97D. The repeat 97D data collected for meter M3 indicate that, for velocities above 6 m/sec, there is essentially no change in the meter performance. Below 6 m/sec, the data fall within the increased error range of the previous runs.

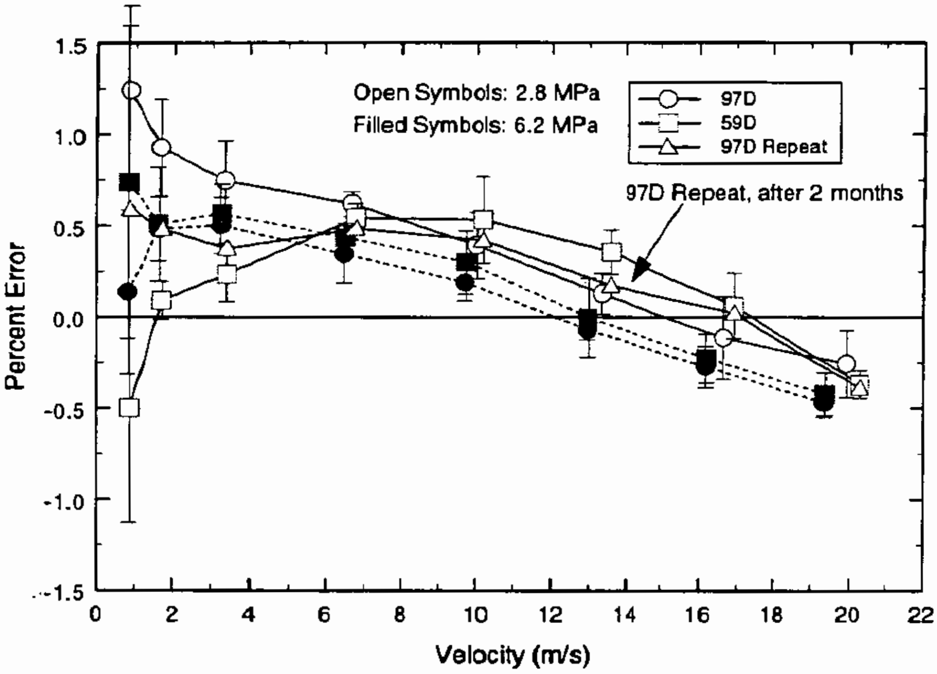

Figure 3 – Baseline results for multipath meter M3.

A potential explanation for the axial dependence of the meter is that the velocity profile was continuing to develop past the 59D location. Insight into the profile shape can be gained by comparing ratios of the individual path velocities. The ratio of the path velocities nearest the axial centerline of the pipe, to the average of the outer path velocities, increases with axial location for both meters. The smaller ratios for the data recorded at the 59D location suggest a flatter velocity profile than that at the 97D location. Velocity profile measurements are currently in progress to aid in the comprehension of these results.

Figures 4 and 5 contain the baseline information for single-path meters M2 and M4, respectively, at two operating pressures and two axial distances downstream of a single 90° elbow. Figure 4 indicates that the single-path meter M2 had an offset of about –1.2% when installed at the 78D position, and about –1.8% when installed at the 40D position. The test results for this meter suggest that, within the data scatter, the flow measurement error is independent of pressure, but dependent on the axial location. The subsequent 97D tests conducted with this meter appear to be consistent with the trend shown in the original data with an error of about –0.5%.

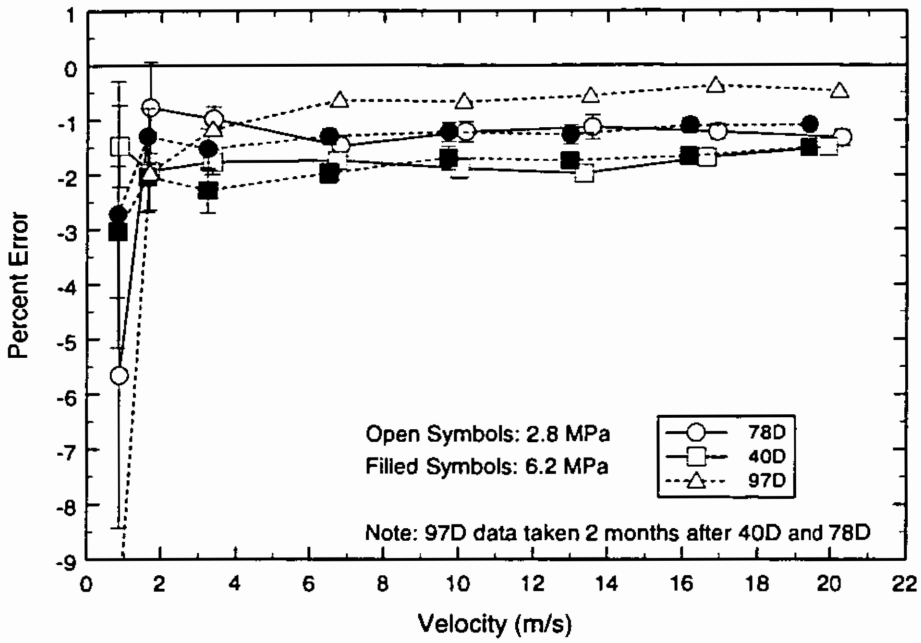

Figure 4 – Baseline results for single-path meter M2.

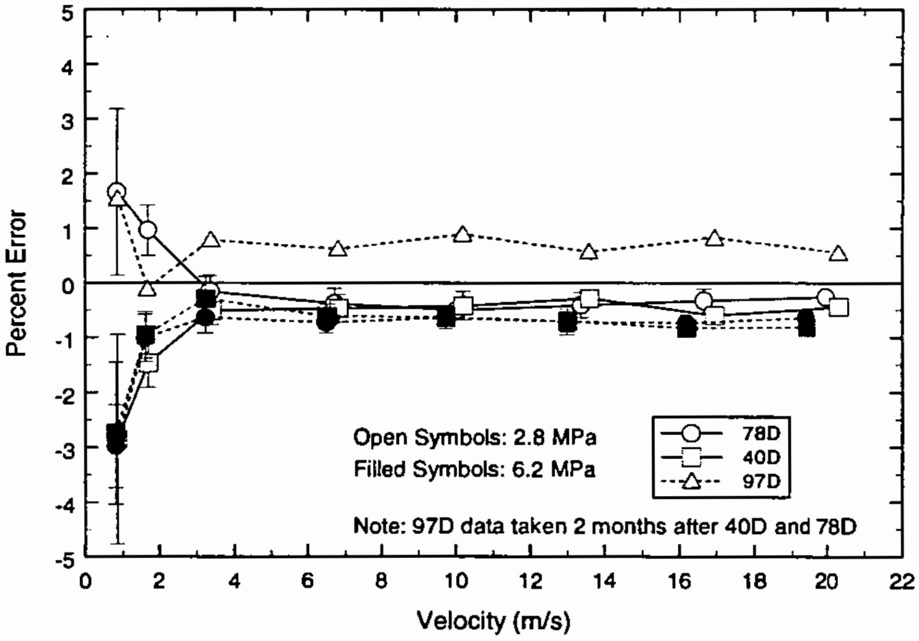

Figure 5 – Baseline results for single-path meter M4.

The results for meter M4 contained in Figure 5 indicate a mean offset of about –0.5%, which appears to be more dependent on line pressure than on the axial distance between the 90° elbow and the meter. The 2.8 MPa, 78D data appear to be inconsistent with the other results at velocities below 3 m/sec where there was a deviation of more than 2% between the two groups. The subsequent 97D data taken with this meter suggest that the meter baseline had shifted, since the earlier data set showed no significant dependence on axial position. Further testing of this meter in the baseline configuration will be conducted to verify this apparent change.

In general, the single-path meters exhibit more scatter in their data than do the multipath meters. The increased data scatter in the single path meters is likely related to the fact that these meters do not have the benefit of multiple ultrasonic paths over which to average the gas flow velocity.

INSTALLATION EFFECTS TEST CONFIGURATIONS

Figures 6 and 7 show plan views of the test configurations used for the installation effects flow tests. For the configuration shown in Figure 6, the single-path meters were tested in two different orientations at locations 1 and 2 (i.e., 10D and 19D, respectively, downstream of the single 90° long-radius elbow). The multipath meters were tested downstream of the two-in-plane-elbow configuration, at locations 3 and 4 (i.e., 10D and 19D downstream of the second elbow). For this configuration, tests were performed with a bare tube, and with two different flow conditioners (19-tube bundle, and GFC™) installed upstream of locations 3 and 4. The flow conditioners were installed such that the outlet was fixed at 5D from the elbow, and therefore, 5D upstream of the first meter (consistent with the minimum installation requirements for turbine meters as described in A.G.A. Report No. 7). The manufacturer of the GFC™ does not recommend this installation for their conditioner, but rather an installation with at least 6.5D between the elbow and the flow conditioner outlet. For convenience, the two-in-plane-elbow configuration for the multipath meter tests was set up with all the piping in the horizontal plane. Since this configuration was meant to represent an installation where the elbows provide a vertical offset, the meters were rotated 90° about their axial centerline to keep the correct orientation of the measurement paths relative to the flow disturbance.

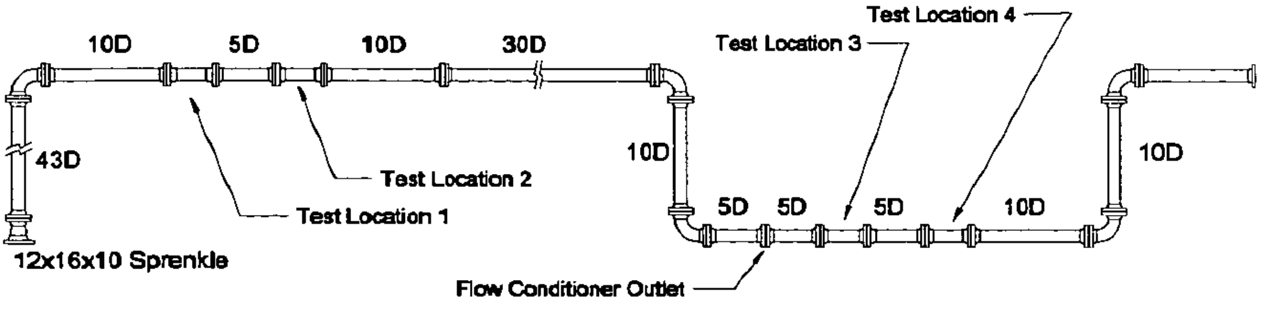

Figure 6 – Single-elbow and two-in-plane-elbow configuration.

Figure 7 displays a plan view of the piping arrangement used for the two-out-of-plane elbow configuration. This test setup also contains four test locations at different axial locations downstream of the disturbance. Three flow conditioners (19-tube bundle, GFC™, and VORTAB™) and a bare meter tube configuration were utilized for these tests. The 19-tube bundle and GFC™ were installed at the 5D location in the same manner as described for the two-in-plane-elbow configuration. The manufacturer's recommendation for the VORTAB™ flow conditioner was followed for this configuration, so the flow conditioner inlet was installed at the outlet flange of the second elbow (at the 0D) position). The meters were all installed in their "normal" orientation relative to vertical. Although data were recorded with each meter in each of the axial positions with the flow conditioners, only a portion of that data will be presented here.

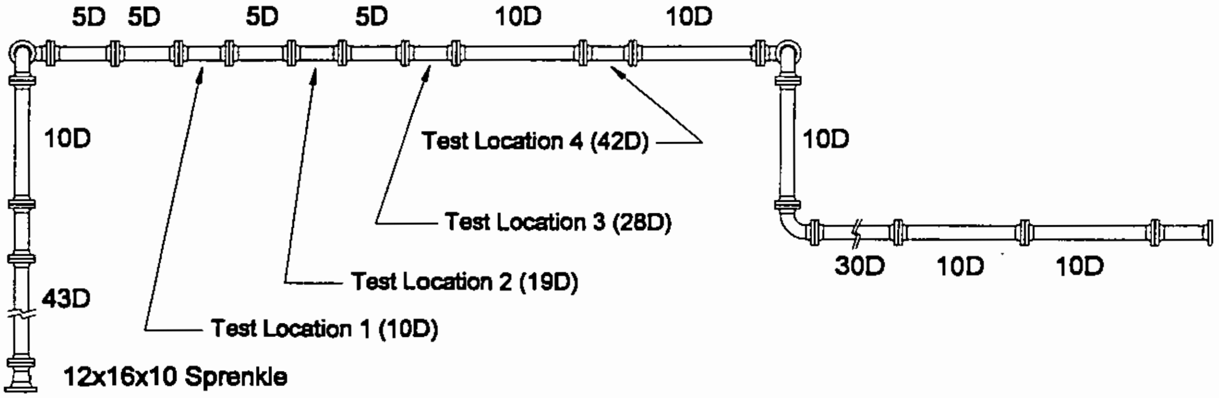

Figure 7 – Two-out-of-plane-elbow configuration.

INSTALLATION EFFECTS TEST RESULTS

The results given in this section are presented in the same error units as those for the baseline data (relative to the sonic nozzle reference flow rate). For reference purposes, the baseline curves (97D for meters M1 and M3, and 78D for meters M2 and M4) are also included on the plots. The results are presented relative to the sonic nozzles because, for some of the meters, there is some ambiguity regarding the location of the baseline curve. This allows comparisons within data sets, for each of the piping configurations, without influencing the results by the choice of the baseline.

Figure 8 displays the results for multipath meter M1 tested 10D and 19D downstream of the two in-plane elbow configuration. The test data indicate that the bare tube arrangement produced a flow measurement error that is independent of the axial location, and within about 0.5% of the baseline, with relative errors being on the order of 0.3% to 0.5%. Lower relative error values occur at higher gas velocities. The absolute error for the bare tube data is less than about 0.25% for velocities above 3 m/sec. There is no significant difference between the results for each of the two flow conditioners when the meter was at 10D with both curves tending towards the baseline at high velocities and deviating by as much as 0.5% at 3 m/sec. However, the results for the 19D position indicate that with the GFC™, the meter error had returned to the baseline value, while the 19-tube results were nearly the same as the bare meter results.

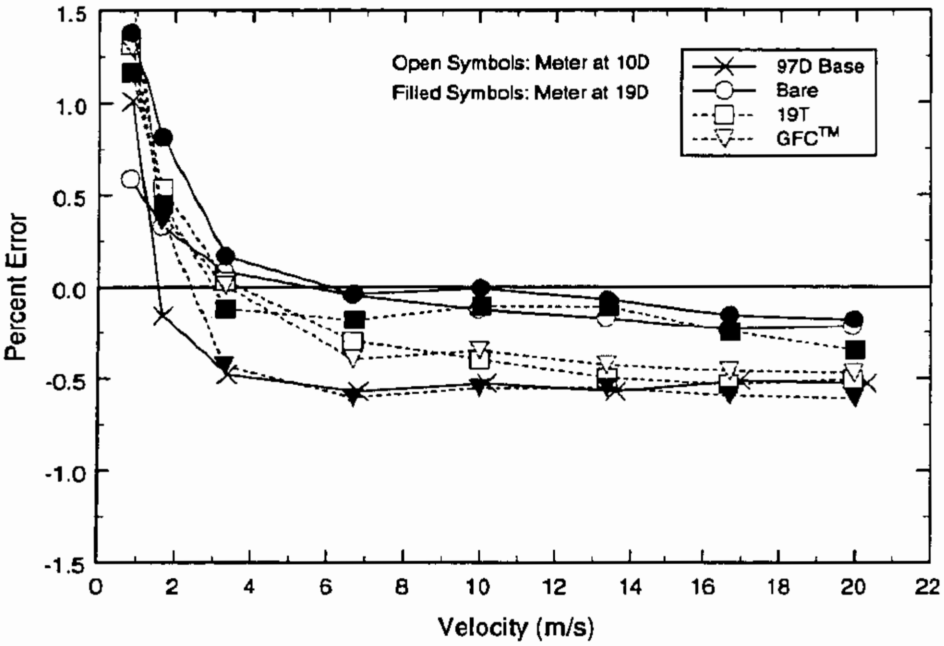

Figure 8 – Multipath meter M1 performance downstream of two in-plane elbows separated by 10D.

The results for multipath meter M1 at various locations downstream of two out-of-plane elbows are shown in Figure 9. These data show that with the meter installed at the 10D position, the results are essentially the same as the baseline results. With the meter further downstream (19D, 28D, and 42D) of the disturbance, the data cluster together in a 0.25% wide band with an absolute error of roughly 0.1%, which is about 0.6% from the baseline. The calculation method used by this meter may account for the large separation in the results at 10D versus the other axial positions. The calculations can be considered to be "active," since different equations can switch in and out of the resulting calculation, depending on the individual path information. The active calculation method may lead to a non-continuous meter response to the continuous changes in the flow properties, which occur downstream of a disturbance. However, a repeat of these tests is suggested to verify their consistency.

Figure 10 indicates that the data with flow conditioners was bounded by the bare tube results at 10D and 19D. The data were all within a 0.7% wide band. A check of the stability number reported by meter M1 indicated that each of the flow conditioners had removed the swirl (as far as the calculation algorithm was concerned) as compared to the cases without the flow conditioners where the meter indicated the presence of a symmetric swirl pattern. The results with the flow conditioners were similar to those for the two-in-plane elbow configuration in that the 19D results with the GFC™ were within about 0.1% of the baseline, as were the VORTAB™ results for the 10D configuration. The results for the 19-tube bundle were offset by 0.25% to 0.4% from the baseline for the 10D and 19D configurations, respectively.

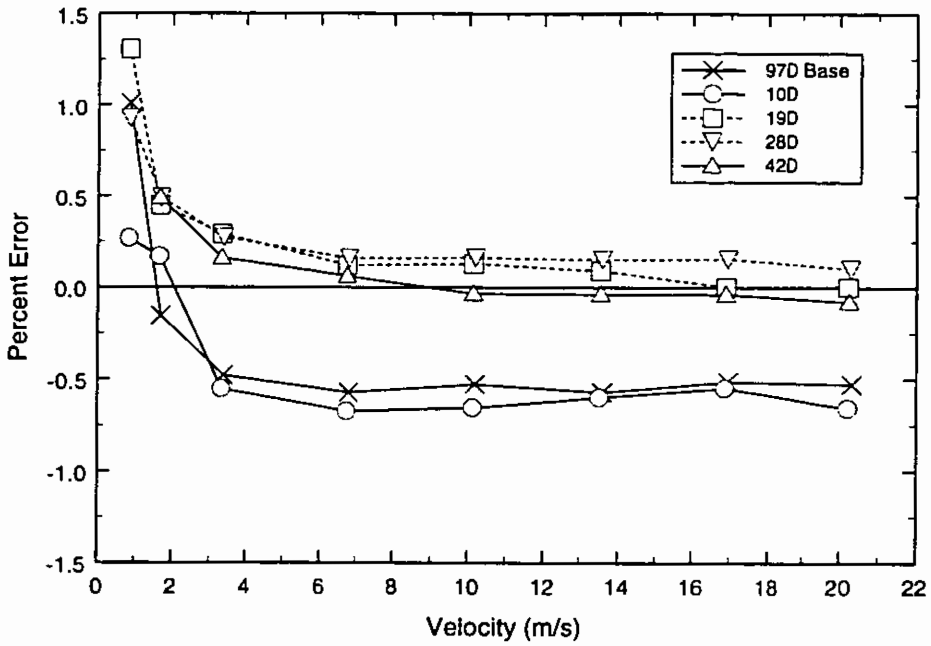

Figure 9 – Multipath meter M1 performance downstream of two out-of-plane elbows.

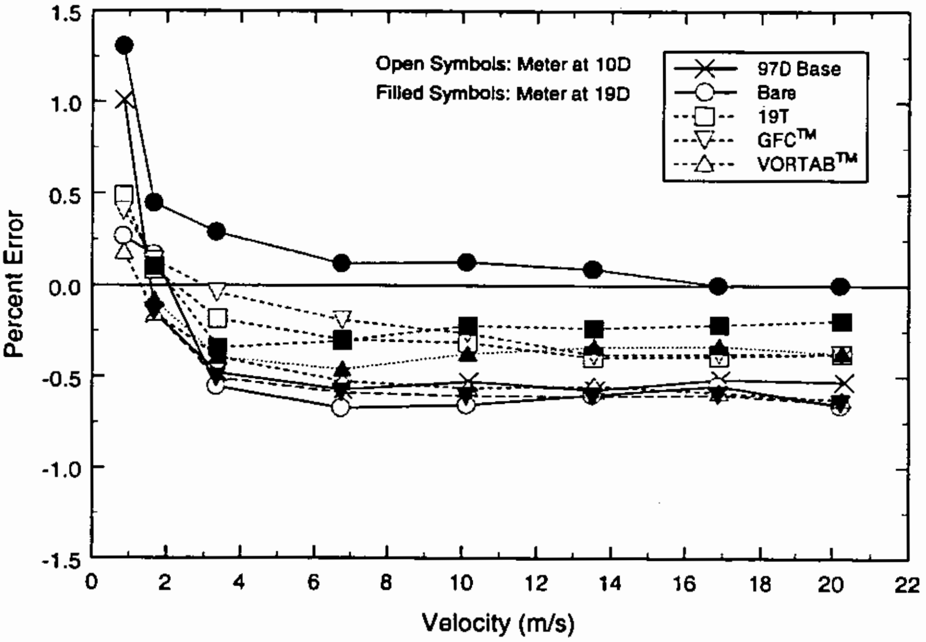

Figure 10 – Multipath meter M1 performance downstream of two out-of-plane elbows.

Figure 11 presents the results for multipath meter M3 when located 10D and 19D downstream of the two in-plane elbow configuration. The figure indicates that with the bare tube, the meter showed less than 0.25% error relative to the baseline, for velocities higher than 6 m/sec. This result is independent of the axial position of the meter. At 10D, the 19-tube bundle and the GFC™ results surround the results of the bare tube, with relative differences of –0.3% and 0.2%, respectively. At velocities lower that about 6 m/sec, there is a departure from the baseline data. Except for the highest test velocities, the data for the 19-tube bundle and the GFC™ are nearly identical for the 19D position. For gas velocities above 14 m/sec, the GFC™ produced measurement errors that are closer to the baseline than the 19-tube bundle.

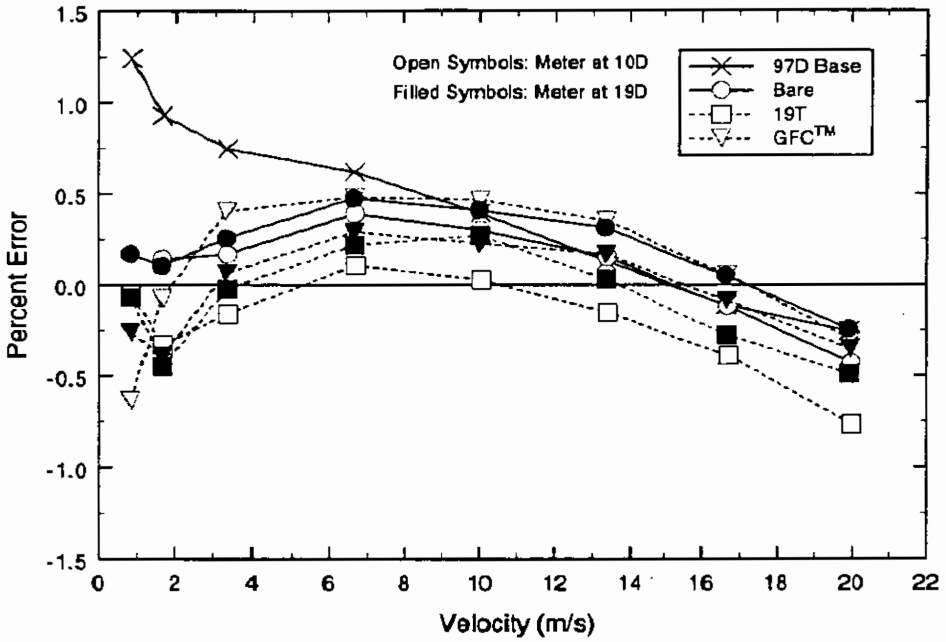

Figure 11 – Multipath meter M3 performance downstream of two in-plane elbows separated by 10D.

Test results for multipath meter M3 in the two-out-of-plane elbow configuration are shown in Figures 12 and 13. The bare meter results of Figure 12 display a mean shift of about 0.4% relative to the baseline data, for velocities above 6 m/sec. The data for the different axial positions are clustered together with a spread of about 0.3%, suggesting that the meter performance for this case is independent of the axial position.

Figure 13 indicates the effect of various flow conditioners on the performance of multipath meter M3 when installed downstream of two out-of-plane elbows. The results with the flow conditioners fall primarily between the 97D baseline data and the bare meter results at 10D and 19D. With the meter installed at 10D, the 19-tube bundle and GFC™ follow the bare meter performance curves. The VORTAB™ conditioner shifted the results close to the baseline curve for the 10D and 19D cases, as did the GFC™ for the 19D position at velocities above 14 m/sec. The 19-tube bundle is also within 0.25% of the baseline for the 19D position.

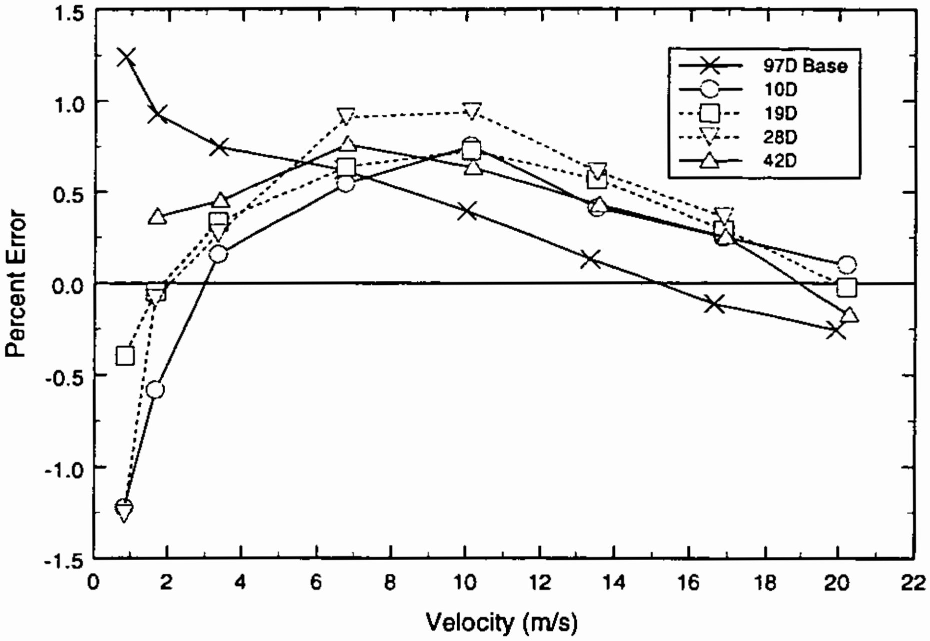

Figure 12 – Multipath meter M3 performance downstream of two out-of-plane elbows.

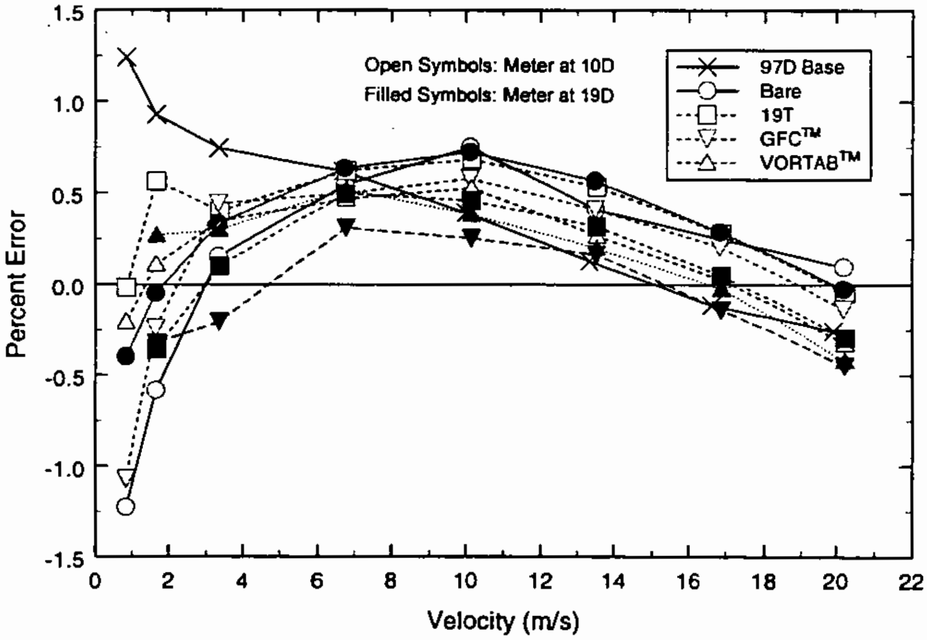

Figure 13 – Multipath meter M3 performance downstream of two out-of-plane elbows.

The results shown in Figures 8 through 13 indicate that, depending on the meter type and location, there are potential benefits to using flow conditioners with multipath ultrasonic flow meters. For some of the above cases, the measurement error shifts relative to the baseline result in absolute measurement errors that are actually closer to zero error than the baseline results. It is not clear if this result is fortuitous, or the result of the meter development having occurred with less than ideal velocity profile conditions.

Figure 14 displays the results of tests performed with single-path meter M2 at locations 10D and 19D downstream of a single 90°, long-radius elbow. The results indicated a measurement error shift of about 2% to 2.2% relative to the 78D baseline error. When the meter was rotated 90° about its axial centerline, there was an additional 1.3% shift in error beyond the results at 0° (i.e. "normal") orientation. Table 1 indicates that the single ultrasonic path of this meter was located 30° from vertical when the meter was installed in its "normal" orientation. Since the major component of the flow asymmetry in this test configuration was in the vertical plane, rotation of the meter 90° caused the path orientation relative to the flow disturbance to change, and therefore, the resulting meter performance to shift.

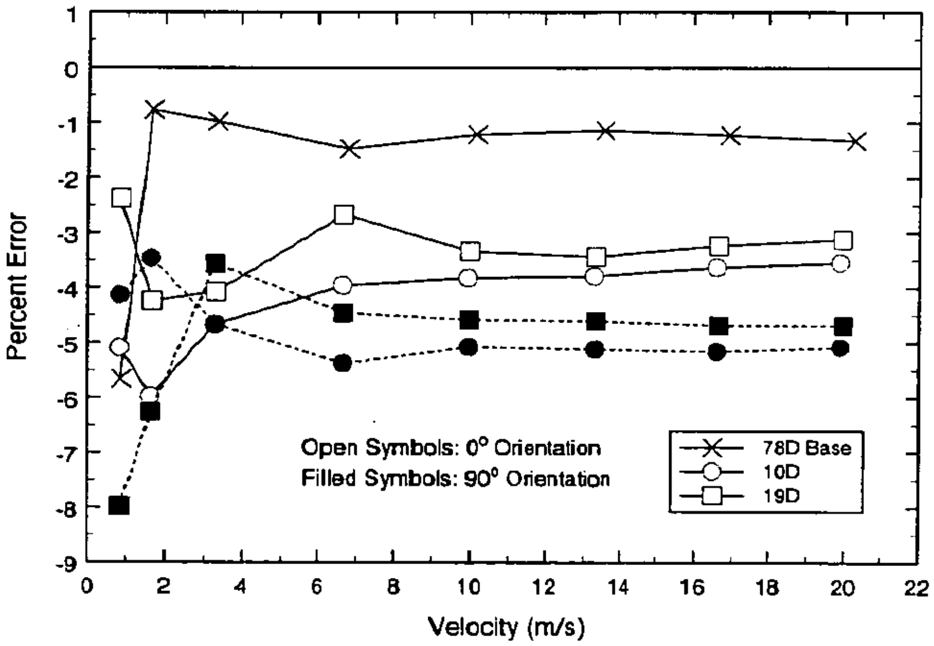

Figure 14 – Single-path meter M2 performance downstream of single elbow.

Figure 15 indicates that when the single-path meter M2 was installed downstream of two out-of-plane elbows, the error increased by 2% relative to the baseline, which is roughly the same amount as was the case for a single elbow (in the 0° orientation). As the axial distance from the disturbance increased, there was little change in the results until the meter was installed at the 42D position where the shift relative to the baseline data was approximately 1%.

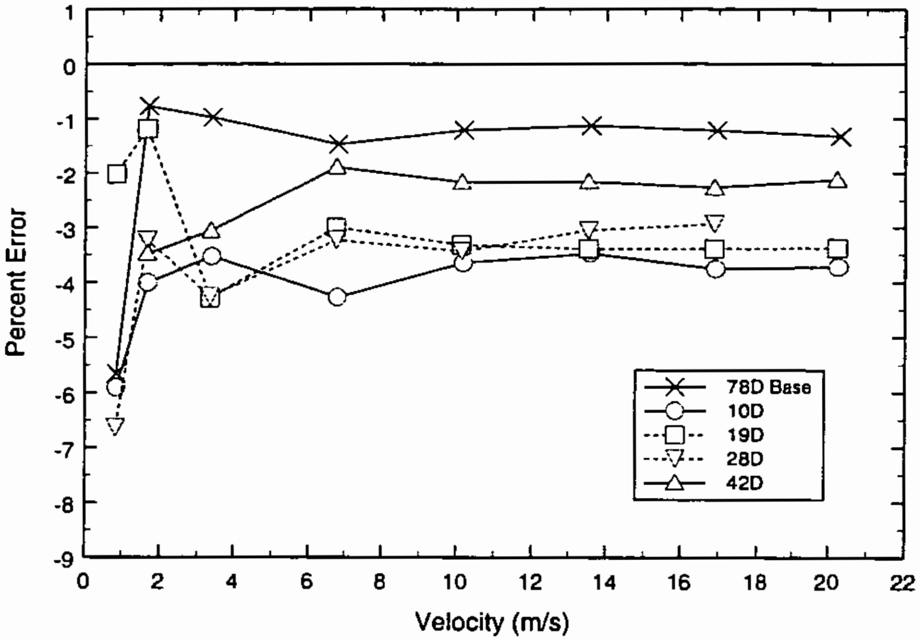

Figure 15 – Single-path meter M2 performance downstream of two out-of-plane elbows.

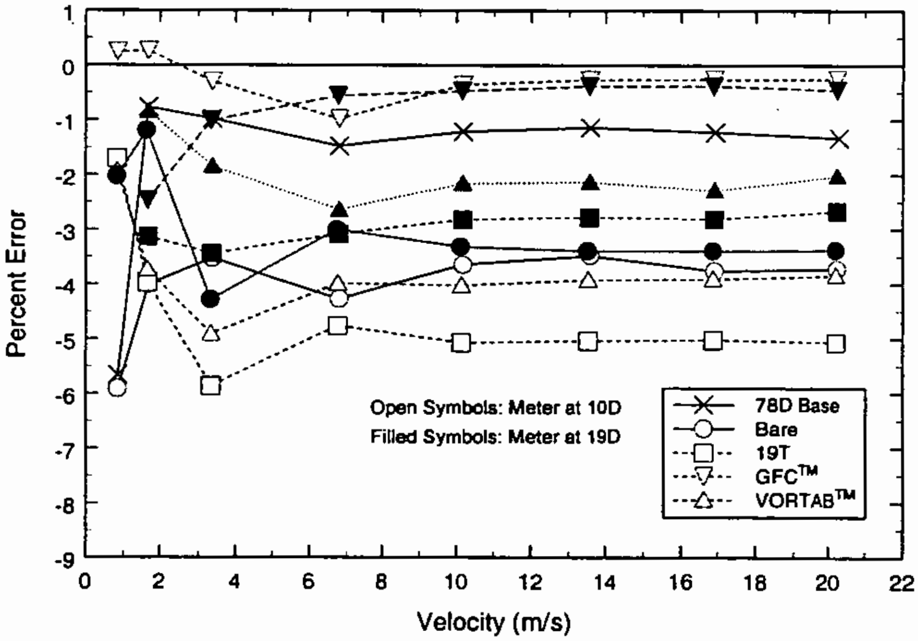

Figure 16 – Single-path meter M2 performance downstream of two out-of-plane elbows.

The results of single-path meter M2 tested with various flow conditioners are shown in Figure 16 for the two-out-of-plane elbow configuration. These results indicate a significant difference in the behavior of the meter with the different flow conditioners. The 19-tube bundle increased the measurement error by 1.5% over that for the bare meter performance when the meter was installed at the 10D position. With the meter at 19D, the 19-tube bundle had decreased the magnitude of the error relative to the 19D bare meter results by about 1%, but still had a negative shift of 1.5% relative to the 78D baseline. The VORTAB™ results are similar to those for the 19-tube bundle, but have less of an error increase at 10D than that for the 19-tube bundle. With the meter at the 19D position, the VORTAB™ results shift by 1% relative to the 78D baseline. Results with the GFC™ indicate a positive shift of 1% relative to the 78D baseline data and are essentially the same as when the meter was installed at 10D and 19D.

Figure 17 presents the results for single-path meter M4 for the single 90° elbow test configuration. With the exception of the 90° orientation tests with the meter installed 19D downstream of the elbow, the results indicate a measurement error shift of about 1.5% to 2% relative to the baseline. This meter showed little dependence on orientation, as should be expected since the measurement path was oriented 45° from vertical. For this meter, the path orientation relative to the disturbance remained the same even when the meter body was rotated about the axial centerline of the meter.

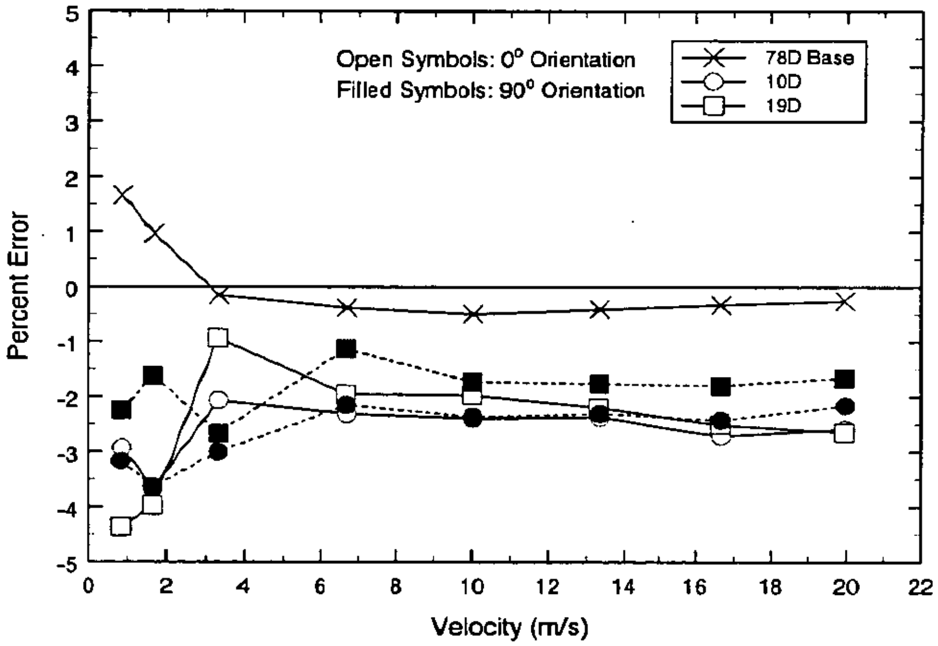

Figure 17 – Single-path meter M4 performance downstream of single elbow.

Figure 18 suggests a systematic dependence of the meter performance on axial position for single-path meter M4 when installed downstream of two out-of-plane elbows. The error magnitude decreased as the meter was moved away from the flow disturbance and the velocity profile had a chance to develop. The maximum absolute error was about –3% at the 10D position and was less than 0.25% at the 42D position.

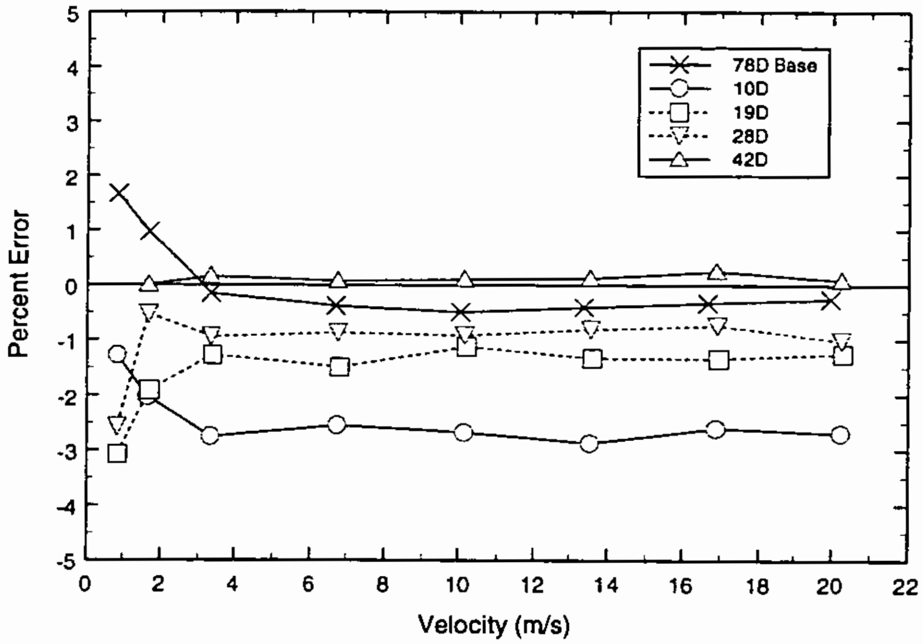

Figure 18 – Single-path meter M4 performance downstream of two out-of-plane elbows.

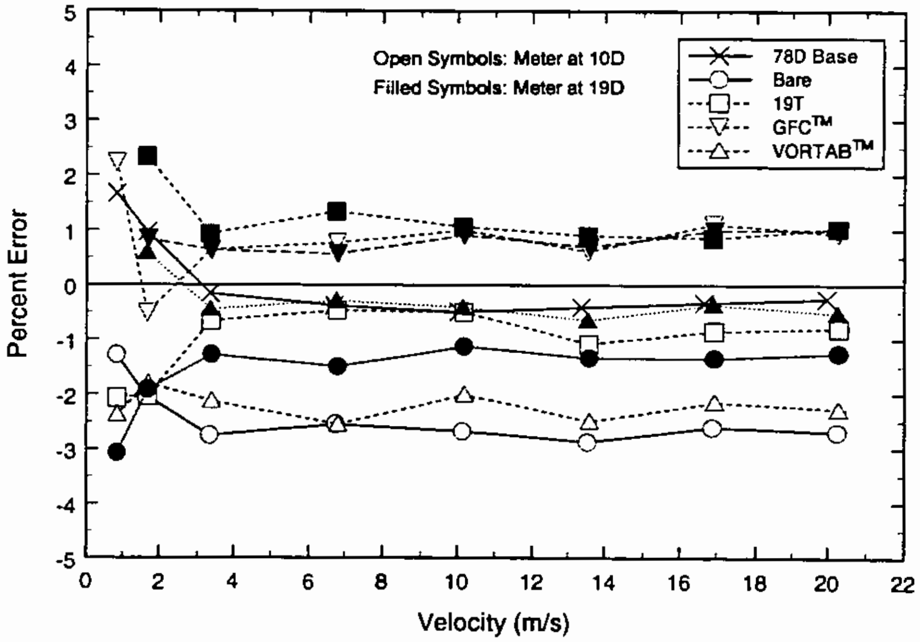

Figure 19 – Single-path meter M4 performance downstream of two out-of-plane elbows

Figure 19 indicates the performance of single-path meter M4 with various flow conditions for the two-out-of-plane elbow configuration. As was the case for single-path meter M2, the GFC™ produced results that were the same for meter installation positions of 10D and 19D. The 19-tube bundle results with the meter installed at 19D matched those for the GFC™ while with the meter at 10D, the 19-tube bundle followed the VORTAB™ results with the meter at 19D. Results for the VORTAB™ with the meter installed at 10D are consistent with those of meter M2 and follow the 10D bare meter data.

In considering the results from the two single-path meters, it is important to acknowledge that the path orientation relative to the disturbance is different for these two meters. Since the types of flow disturbances tested here create flow asymmetries, the results for the two meters should not be expected to be identical. The results of the two meters indicate similar trends and demonstrate the viability of a single-path ultrasonic flow meter with a flow conditioner.

THERMOWELL INFLUENCE TEST RESULTS

Thermowells are typically installed within a few diameters downstream of the meter to provide a representative measurement of the gas temperature at the meter. In bi-directional applications, one flow direction will necessarily have a thermowell protruding into the gas stream upstream of the flow meter. Since the presence of the thermowell will disturb the flow, there is a possibility of introducing additional error into the meter's volumetric measurement. The tests here do not consider the error introduced by an incorrect temperature determination at the meter.

To assess the effect on the meter performance of this protrusion, a special piping spool was constructed with nine thermowell access locations at three axial locations (1D, 3D, and 5D) from the end of the spool, and three angular positions (0°, 45°, and 90°). Thermowells were simulated by using 12.7-mm diameter rods that could be inserted or retracted from the flow at the various test locations, without depressurizing the pipe section. A gauge block was used to set the insertion level at either 1/2D (101.3 mm) or 1/3D (67.6 mm). These two insertion depths represent flow blockages of 4% and 2.7% for the 1/2D and 1/3D levels, respectively. The special piping spool was installed upstream of the test meter with the test meter at the 97D location, as previously shown in Figure 1. For each test flow rate, baseline data (without a probe in the flow) were collected before and after the series of 18 tests with the simulated thermowells inserted into the flow. For each position, six repeat data sets were collected and referenced to the baseline data.

Figure 20 indicates the relationship between the thermowell location and the ultrasonic paths for each of the test meters. The thermowell influence results for meters M1, M3, and M4 are presented in Tables 3, 4, and 5, respectively. These tables indicate 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 was not operating properly during the thermowell tests.

The tabulated results indicate the thermowell influence is larger at lower velocities than at higher velocities. This effect can be explained by increased turbulence that occurs at high velocities, which reduces the size of the wake produced by the flow around the thermowell. At lower velocities, the wake persists downstream and results in metering error.

The largest errors indicated for the multipath meters occur for the low velocity condition with the thermowell at the 1D position. Errors as large as 0.8% are indicated, 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 increases, the shift in measurement error decreases. It appears 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.

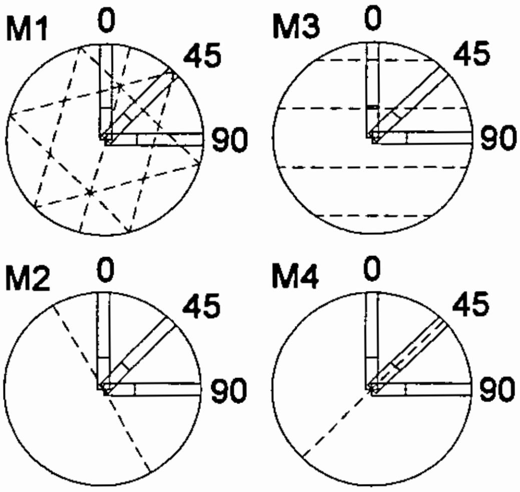

Figure 20 – Meter path orientation relative to thermowell test locations.

Table 3 – Multipath meter M1 relative error for various upstream thermowell positions.

Position		1D		3D		5D	
Vel.	Ang.	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 showed larger relative errors than did the multipath meters for the thermowell tests. 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 indicated in Table 5 for the 1D position, with the probe at 45° and an insertion length of 1/2D. When the insertion length was reduced to 1/3D, the relative error was reduced by nearly 1%. The results for single-path meter M4 suggest that thermowells at the positions away from the measurement path (i.e., the 0° and 90° positions) did not influence the flow measurement error.

Table 4 – Multipath meter M3 relative error
or various upstream thermowell positions.

Position		1D		3D		5D	
Vel.	Ang.	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 5 – Single-path meter M4 relative error
for various upstream thermowell positions.

Position		1D		3D		5D	
Vel	Ang.	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

CONCLUSIONS

The results for the baseline tests suggest that the velocity profile was not fully developed 59 pipe diameters downstream of a single, long-radius 90° elbow, and that the test meters were sensitive to the subsequent profile development. The baseline results indicate that the accuracy of the 8-inch meters tested can be improved by flow calibration.

The test results for the 8-inch diameter multipath flow meters indicate that, depending on the meter type and location relative to a flow disturbance, there are potential benefits to using flow conditioners to improve measurement accuracy. However, the influence of the flow conditioner is dependent on both the flow conditioner type and the multipath meter type. For certain combinations, the presence of a flow conditioner creates more flow measurement error than would be present without the flow conditioner.

The results for the single-path meters show potential for achieving flow measurement accuracies better than 0.5% in well-ordered flow fields. The level of sensitivity to a simple disturbance was demonstrated by installing test meters 10D and 19D downstream of a single 90° elbow and at various distances for two out-of-plane elbows. In these tests, the flow measurement error ranges from about 1% to 4%, relative to the results for the baseline test configuration.

The effect of using flow conditioners with single-path meters was demonstrated for the two out-of-plane elbow configuration. The results show that accuracy levels close to that of multipath meters could be achieved in meter runs less than 20 pipe diameters long.

The effect on flow metering accuracy of an upstream thermowell has been quantified for single-path and multipath meters. The data suggest that a thermowell located 3D upstream of the meter will result in little additional error in most cases. The error induced by an upstream thermowell aligned with the measurement path of a single path meter persists for more than three pipe diameters.

The apparent shifts in baseline performance of some of the meters need to be investigated further since the long-term stability of the meters is essential to their use in the gas industry.

When drawing conclusions from these results, it is important to note that these results are based on the performance of a single instance of the particular meter designs. Variations in the manufacture and installation of these meters may result in different values for meter bias in the various piping configurations. Therefore, the results should not be generalized in terms of the *absolute* meter performance, but should be considered as indicating the *relative* change in performance for different piping configurations.

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