Index

Paper 2.2

Operation of Ultrasonic Flow Meters at Conditions Different Than Their Calibration

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1 ABSTRACT

Currently, calibration of an ultrasonic flow meter for natural gas measurement is conducted under the conditions available at the flow calibration facility. Since almost all of these facilities utilize natural gas flowing in a pipeline, it is usually not possible to vary parameters such as temperature, pressure and gas composition, each of which affect the speed of sound. When the ultrasonic meters are then used in applications where these parameters are different from their calibration values, does the calibration still apply?

In order to quantify the effect of changes in these parameters on the calibration of ultrasonic meters, a series of carefully controlled calibrations have been performed. The first experiment consisted of calibrating a 200mm (8 inch) and two 300 mm (12 inch) ultrasonic meters in the High Pressure Loop at Southwest Research Institute (SwRI) utilizing natural gas at 2.8 MPa (400 psi). As additional references, 200 mm and 300 mm turbine meters were also included in the calibration loop. The fluid was then changed to nitrogen, providing a 16% change in the speed of sound, equivalent to a natural gas pressure of 4.6 MPa (667 psi).

As a further test of potential pressure effects on an ultrasonic meter's calibration, a series of static measurements of the speed of sound was performed on the 300 mm meter at pressures between 1.4 MPa (200 psi) and 7 MPa (1000 psi) using nitrogen. The measured change in the speed of sound over this pressure range was within 0.03% of the calculated value.

In addition, further calibrations were run with changes in the speed of sound introduced through changes in the temperature of the fluid. Natural gas calibrations were performed at 21 ºC (70 ºF) and 10 ºC (50 ºF) and nitrogen calibrations at 21 ºC (70 ºF) and 32 ºC (90 ºF). For each series of calibrations, the average calibration curves are compared to determine the effect of the change. Within the expected reproducibility of the facility and the meters, the calibration of the ultrasonic meters was insensitive to change in speed of sound, temperature and pressure. Evidently, the observed shifts in calibration on changing from natural gas to nitrogen are due to the equations of state used for these gases. These test results justify the procedure of calibration of an ultrasonic meter at one set of conditions and utilizing it under another, including using different gases.

2 INTRODUCTION

Ultrasonic flow meters used for custody transfer measurement of natural gas measure the transit times of ultrasonic waves passing through the gas. The transit time for a wave traveling in the same direction as the gas flow is less than its transit time when traveling against the flow. The difference in these transit times is used to calculate the mean velocity of the gas flow. The actual volume flow can be expressed as:

$$Q = K \bullet \frac{\Delta T}{(T1) \bullet (T2)} \qquad (1)$$

where : K = geometric constant for the meter; ΔT = difference in transit times; T1 = transit time with the gas flow; T2 = transit time against the flow

Because this flow equation contains only the physical dimensions of the meter and the transit times, it is independent of the speed of sound (SOS) in the flowing gas. Therefore, it is assumed that the measurement of the gas velocity is independent of factors that affect the speed of sound in the gas, such as temperature, pressure and gas composition. If this assumption is not correct, the validity of ultrasonic meter calibrations at conditions different than those of actual field operation must be considered.

To a first order, gas velocity measurements are independent of SOS in an ultrasonic meter, but there may be some second order effects due to the following:

- the acoustic impedance (Z) changes the coupling of the signal to the gas
- changes in the Reynolds Number (Re), which is proportional to the specific gravity (SG) divided by the viscosity (Visc)
- the wave length (WL) of the signal changes with gas composition

It is of interest to look at these parameters for different media. The following table is for standard conditions. Notice that for a given pipe size and flow velocity, the Reynolds Number (Re) remains nearly constant.

Table 1 - Gas Properties

Gas	SG	SOS (m/s)	Visc (cP)	Z = SG*SOS	Re ~ SG/Visc	WL (mm)
Nitrogen	0.967	334	0.0170	323	56.9	2.7
Air	1.000	331	0.0178	331	56.2	2.7
Methane	0.553	430	0.0106	238	52.2	3.4
Natural Gas	0.600	400	0.0100	240	60.0	3.2

When changing from natural gas to air or nitrogen, many gas properties change, such as SOS, SG and Visc. However, since they also vary with temperature and pressure, there is considerable overlap in these gas properties over the range of operating conditions of ultrasonic flow meters, indicating that the differences at standard conditions are not so important.

3 RESEARCH OBJECTIVES

The purpose of the research program described in this paper was to investigate the effect of temperature, pressure and fluid (gas) changes on the calibration of gas ultrasonic meters. In addition to verifying the basic assumptions of the ultrasonic flow meter technology, the program has the potential of supporting the calibration of these natural gas meters with nitrogen or air.

Currently there are only two facilities in North America that are capable of flow calibrating ultrasonic flow meters greater than 200 mm diameter over their full flow range. With the projected yearly growth of the installation of these meters exceeding 10% per year, calibration facilities will become a severe limitation in the future. An additional contribution to the demand for these facilities will be possible recalibration of meters that have been in use for several years.

If calibration of ultrasonic flow meters is limited to natural gas facilities, the possibility of building new facilities will be restricted by location and expense. New facilities would have to be constructed utilizing large volume gas pipelines. However, if it can be shown that calibration with other media is equivalent, the possibility of building new facilities is enhanced.

Calibrating natural gas flow meters on air would not be unique to ultrasonic meters. Almost all turbine meters and residential utility meters used for natural gas flow measurement are calibrated on air.

4 FLOW LOOP CALIBRATIONS

In order to accomplish the objectives of this program, experiments were conducted at zero flow and under flowing conditions. The experiments at zero flow were required in order to investigate the potential influence of pressure on the calibration.

4.1 Flow Loop Experiments

Since there are currently no pressurized flow calibration facilities that can calibrate on both air and natural gas in the same test loop, the best alternative was to test on the inert gas nitrogen, that has properties close to air (which contains 78% nitrogen). Southwest Research Institute has a re-circulating system (not part of a gas pipeline) and is the only North American facility that can test with nitrogen and natural gas in the same loop using the same instrumentation. Although the sonic nozzle system has been mass flow-rate calibrated against a weigh-tank system, calculation of the sonic nozzle flow rate requires measurement of the gas composition and state equations to determine the gas properties. It was decided to also use reference turbine meters in the loop to provide a comparison between volumetric meters (e.g. turbine and ultrasonic meters). This reference has less dependence on gas properties than comparisons made using the sonic nozzles.

A series of standard calibrations were run in the High Pressure Loop (HPL) at SwRI using both nitrogen and natural gas as the test fluid. In addition, the temperature was changed to get another variance in the speed of sound. During these calibrations, no changes were made to the test setup including instrumentation, piping, and the data acquisition system.

The HPL already contained two Daniel 300 mm multi-path ultrasonic meters and a Daniel 300 mm gas turbine meter in the reference section. A Daniel 200 mm multi-path ultrasonic meter was installed in the test section of the loop along with a Daniel 200 mm turbine meter. The 200 mm meters were installed in series in the test section of the HPL, which is shaded from the sun. A flow conditioner (Daniel Profiler™) was installed 5D downstream of the reduction from 300 mm pipe to 200 mm pipe. There was a minimum of 5D between meters, leaving up to 24D between the flow conditioner and the ultrasonic meter. The 200 mm turbine meter was installed in the 200 mm section with a minimum of 5D downstream to the expansion to 300 mm pipe.

All calibrations consisted of 7 flow rates with 6 repeat points at each flow rate. The flow rates were 1.68, 3.35, 6.71, 10.1, 13.4, 16.8 and 20 m/s (5.5, 11, 22, 33, 44, 55, and 66 ft/sec) in the 200 mm meter with natural gas, and corresponding lower velocities in the 300 mm meters. These flow rates were measured by the sonic nozzles, which were used for both the natural gas and nitrogen tests. The layout of the loop for these calibrations is shown in Figure 1.

The sequence of calibrations was as follows:

- Calibration with natural gas at 2.8 MPa and 21 ºC.
- Temperature changed to 10 ºC and calibration repeated. The change in temperature lowered the speed of sound in the natural gas, which moved it toward the speed of sound in nitrogen.
- Gas changed from natural gas to nitrogen; calibration in nitrogen gas at 2.8 MPa and 21 ºC. Note that in order to use the same sonic nozzles, the flow rate was reduced in the ratio of the speeds of sound, about 0.84.
- Temperature changed to 32 ºC. The change in temperature raised the speed of sound in nitrogen, which moved it toward the speed of sound in natural gas.

The following information was collected for each of the five meters for each data point:

- Chord SOS and average SOS for the ultrasonic meters
- Average flow rate
- Proof flow rate
- Proof SOS (calculated by SwRI)
- SwRI Temperature & Pressure

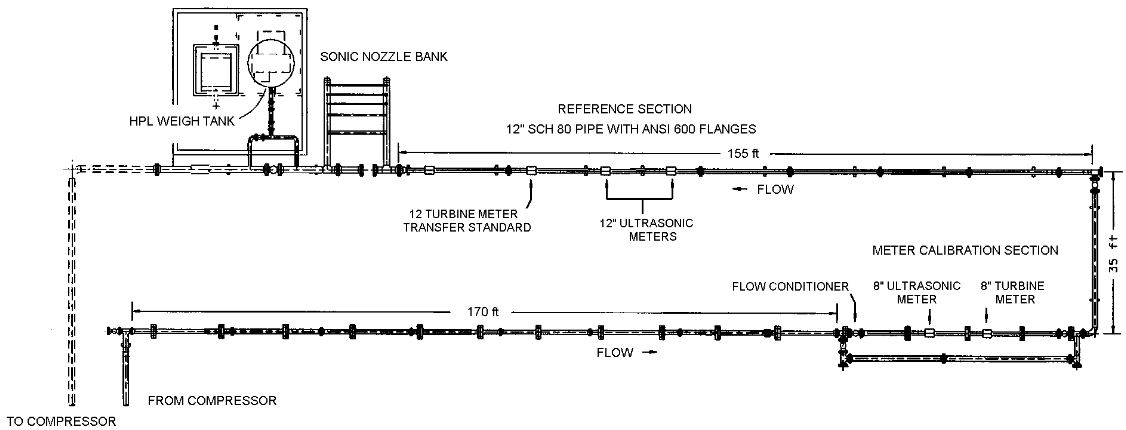

Figure 1. High Pressure Calibration Loop at SwRI

4.2 Data Analysis

Analysis of the calibration data consisted of plots comparing natural gas results with nitrogen results plus analysis of day-to-day and temperature-to-temperature results of the following:

- Flow calibration data (meter vs. sonic nozzles)
- Flow calibration data (ultrasonic meter vs. turbine meter)
- Chord speed of sound data (chord SOS vs. calculated SOS from gas analysis and AGA-8)

SwRI quotes its total uncertainty at about 0.25% at 95% confidence for calibrating a meter. Comparing two calibrations would then give a total uncertainty of 0.35%. However, in this case, the only difference between the calibrations to be compared was the test fluid. The sonic nozzles, turbine meters, piping, instrumentation, data collection, and ultrasonic meters were not changed. By looking at the differences in the calibrations on the same meter, most of the systematic biases are removed. This leaves the uncertainties in the equations of state for nitrogen and natural gas, estimated at 0.1% each, and some random uncertainties in running on different days at different ambient conditions, estimated at 0.14%. This gives a total expected uncertainty of 0.2% for the difference of calibrations on natural gas and nitrogen in the same meter, with the same sonic nozzles, and in the same piping configuration.

4.3 Results

Each of the five meters (2 turbine & 3 ultrasonic) was calibrated 8 times:

- 4 times in natural gas (NG) on 2 days and at 2 temperatures 21 & 10 ºC.
- 4 times in nitrogen (N2) on 2 days and at 2 temperatures 21 & 32 ºC.

The initial calibration in natural gas at 21 ºC was used as the reference for each of the meters. A 2nd-order polynomial fit to the data yielded the calibration coefficients, which were used in all subsequent calibrations. The notation for the calibration plots is the following:

- NG 10 14 = Natural Gas at 10 ºC tested on 14 Aug 2001
- N2 21 17 = Nitrogen at 21 ºC tested on 17 Aug 2001

Figure 2 shows the results of the eight calibration runs on the 200 mm ultrasonic meter in the test section of the loop. The following observations can be made from the plot of these calibration runs:

- day-to-day reproducibility in both gases is very good, averaging about 0.1%
- the difference in calibrations at 10 ºC and 21 ºC is even less than day-to-day variations in both gases, averaging less than 0.1%
- the difference between the calibration curves with natural gas and nitrogen averages less than 0.2 %, agreeing with that predicted in Section 4.3, with the nitrogen calibration lying below that for natural gas.

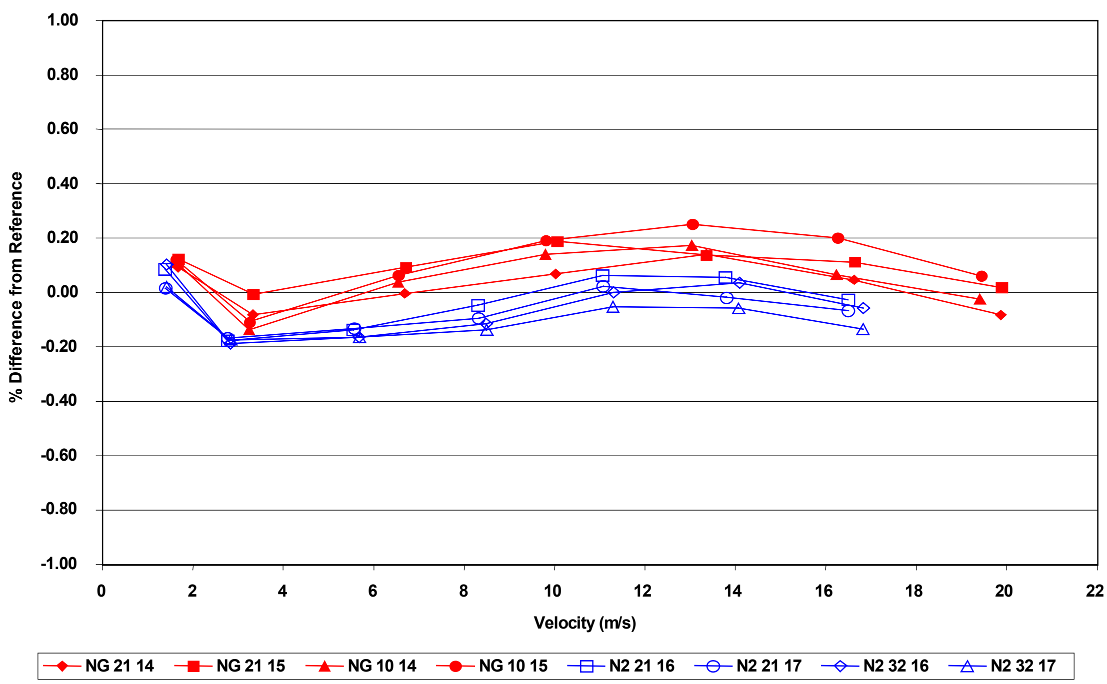

Figure 2 – 200 mm (8 inch) Ultrasonic Meter Calibrations with Natural Gas and Nitrogen

It is interesting to also compare the calibrations of the 200 mm turbine meter with the two gases. These are shown in Figure 3. The deviation of the two 32 ºC nitrogen points at 11.3 m/s is believed to be due to an error introduced by the instrumentation. The repeatability of calibrations for a given gas is excellent. Again, the calibration curve with nitrogen lies below that of the natural gas curve. Since turbine meters have been shown in many prior tests to not exhibit any density effect at these pressures, a gas composition effect on the sonic nozzles is the most likely explanation for the observed shift in the calibration curves for the two gases.

If the turbine meter is used as the reference, the calibrations shown in Figure 2 now become those shown in Figure 4. In this case, the calibration runs in the two gases overlay each other. For the 200 mm meter, the maximum velocity available with natural gas in the High Pressure Loop is 20 m/s. In order to use the same sonic nozzles, this had to be reduced to 16.8 m/s for the nitrogen calibrations.

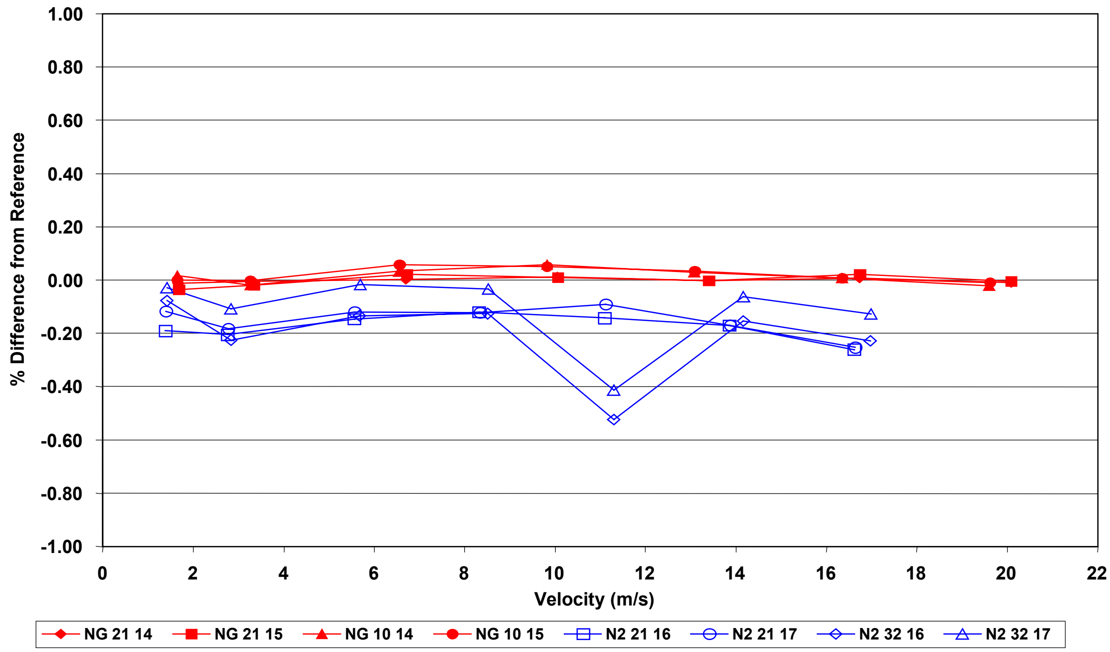

Figure 3 - 200 mm (8 inch) Turbine Meter Calibrations with Natural Gas and Nitrogen

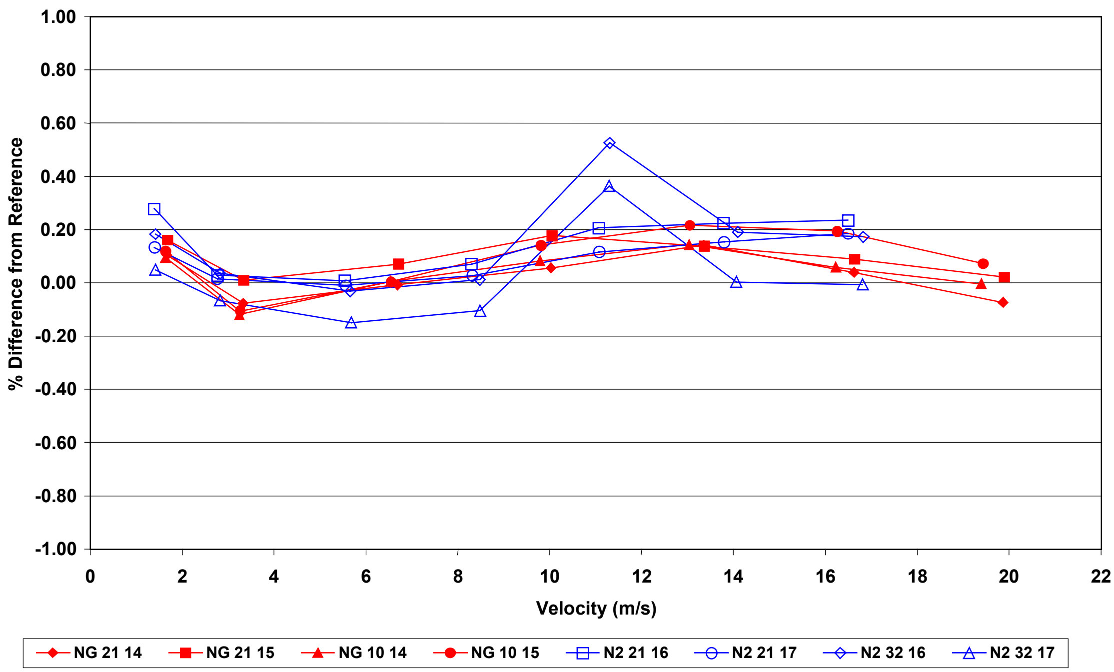

Figure 4 - 200 mm (8 inch) Ultrasonic Meter Calibrations with Natural Gas and Nitrogen (Turbine Meter Reference)

The calibration data from the 300 mm meters gave similar results, but with somewhat greater scatter in the low-flow points due to operation below 33% of the meters' full range and the fact that these meters were in the sun during the runs. Calibration data for one of the 300 mm ultrasonic meters and the 300 mm turbine meter are shown in Figures 5 and 6. Figure 7 shows the ultrasonic meter referenced to the turbine meter, with the natural gas and nitrogen calibration curves overlapping, as was the case with the of the 200 mm meters.

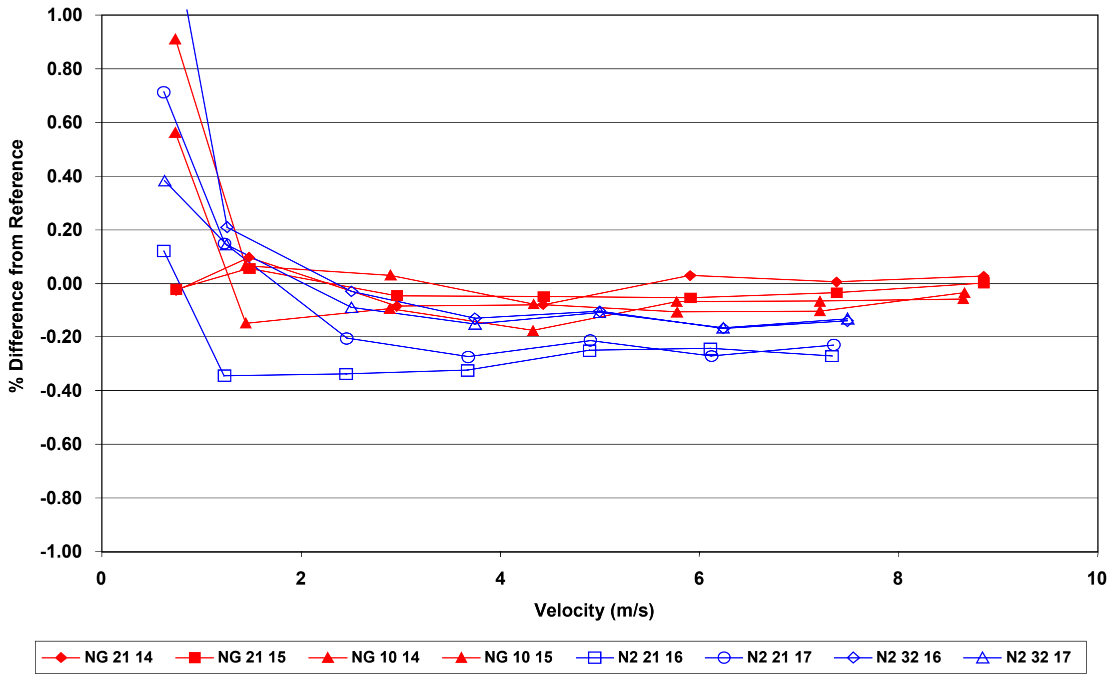

Figure 5 - 300 mm (12 inch) Ultrasonic Meter Calibrations with Natural Gas and Nitrogen

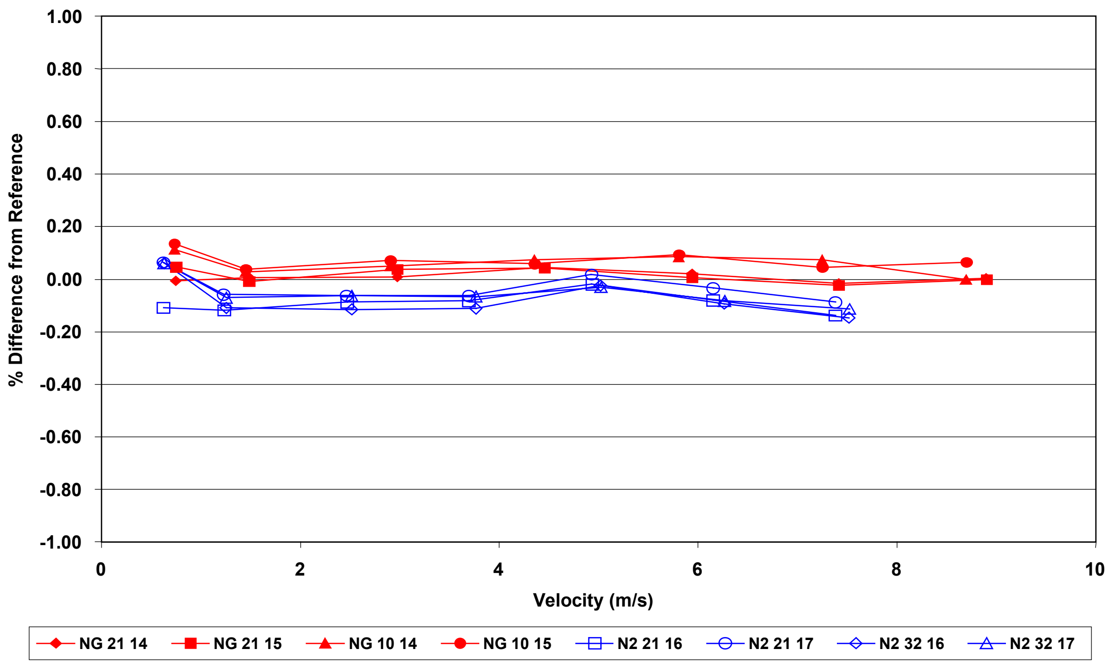

Figure 6 – 300 mm (12 inch) Turbine Meter Calibrations with Natural Gas and Nitrogen

During all of the ultrasonic calibrations, the speed of sound was recorded. A theoretical value was calculated by SwRI using the gas analysis values from an on-line Daniel Danalyzer™ gas chromatograph, the temperature, pressure and the equations of state from AGA Report No. 8. The average difference was within 0.04 %.

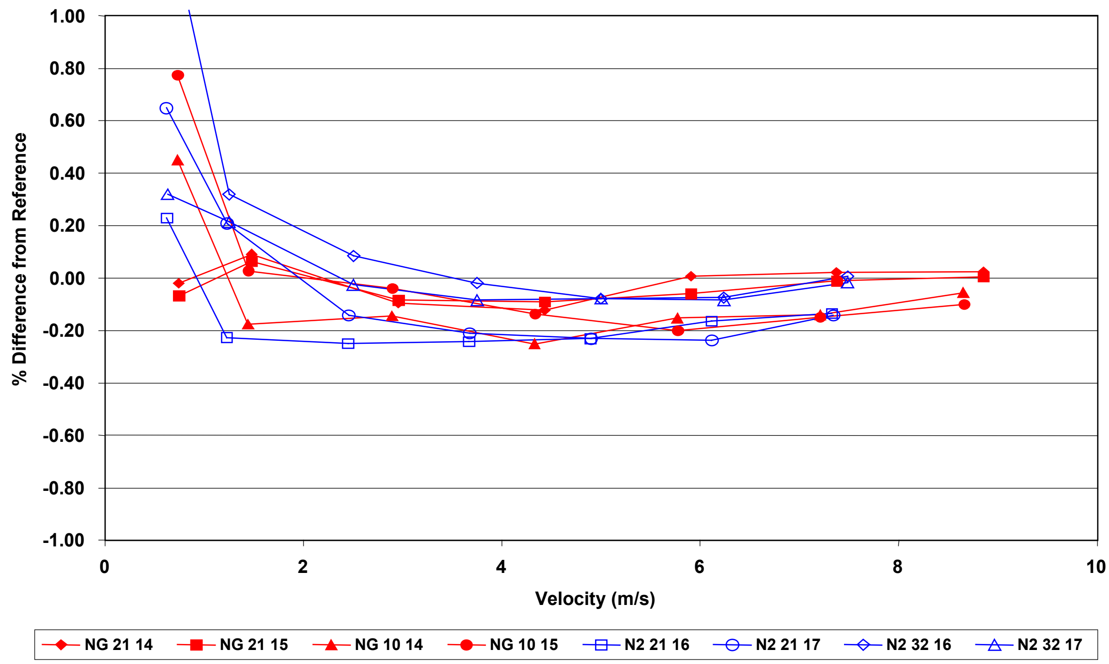

Figure 7 – 300 mm (12 inch) Ultrasonic Calibrations with Natural Gas and Nitrogen (Turbine Meter Reference)

5 PRESSURE MEASUREMENTS

In their 1998 paper, Grimley and Bowles [1] showed calibration data from 200 mm ultrasonic meters of four different configurations. The experiments were designed to examine the effect of various piping and flow conditioner arrangements. The baseline measurements for each meter were taken at 2.8 MPa and 6.2 MPa. The two multi-path meters showed differences of up to 0.5% between the two pressures.

Additional measurements were made by Grimley [2] on multi-path meters from three manufacturers and the results published this year. These measurements were made at 1.4 MPa, 2.8 MPa and 6.9 MPa. It was suggested in the report that a change in transducer characteristics with pressure may explain the results for some of the meters. Although Grimley concluded that this effect was small in the case of the Daniel meter, we decided to look at this effect in more detail. Our experiment is described in the following sections.

5.1 Speed of Sound Measurements

The delay time in an ultrasonic meter is the time between the initiation of the transmitter transducer firing command and the detection of the arrival of the acoustic wave at the receiver transducer **minus** the travel time of the wave in the media. If the delay time changes with pressure on the transducer, an error will be reflected in the measured flow velocity. As shown in Grimley's paper [2], the flow velocity error will be approximately twice any delay time (or speed of sound) error.

During the production of Daniel ultrasonic meters, this delay time is measured for each pair of transducers and the value stored in the meter's electronics. The measurement is made with the meter filled with pure nitrogen at 1.4 MPa. In order to investigate the possible effect of pressure on delay time, measurements of SOS in the nitrogen were also made at 2.8 MPa and 6.9 MPa with a 300 mm diameter ultrasonic meter.

5.2 Results

The results of the SOS measurements as a function of pressure are shown in Figure 8. Also included in the figure is the error curve for the SOS measurements, which was obtained by comparing the speed of sound measured by the meter to calculated values based on AGA Report No. 8 equations of state and knowledge of the pressure, temperature, and gas composition.

As shown in the figure, the measured error over the 5.5 MPa range was 0.03%, which would only account for a 0.06% flow velocity error. These static results agree almost exactly with the flow loop results of Grimley.

Grimley concluded that, for the Daniel meter, any change in SOS due to pressure was too small to cause a noticeable error in measured flow velocity. In addition, he showed that flow profile changes due to pressure were not large enough to cause bias errors for the Daniel meter.

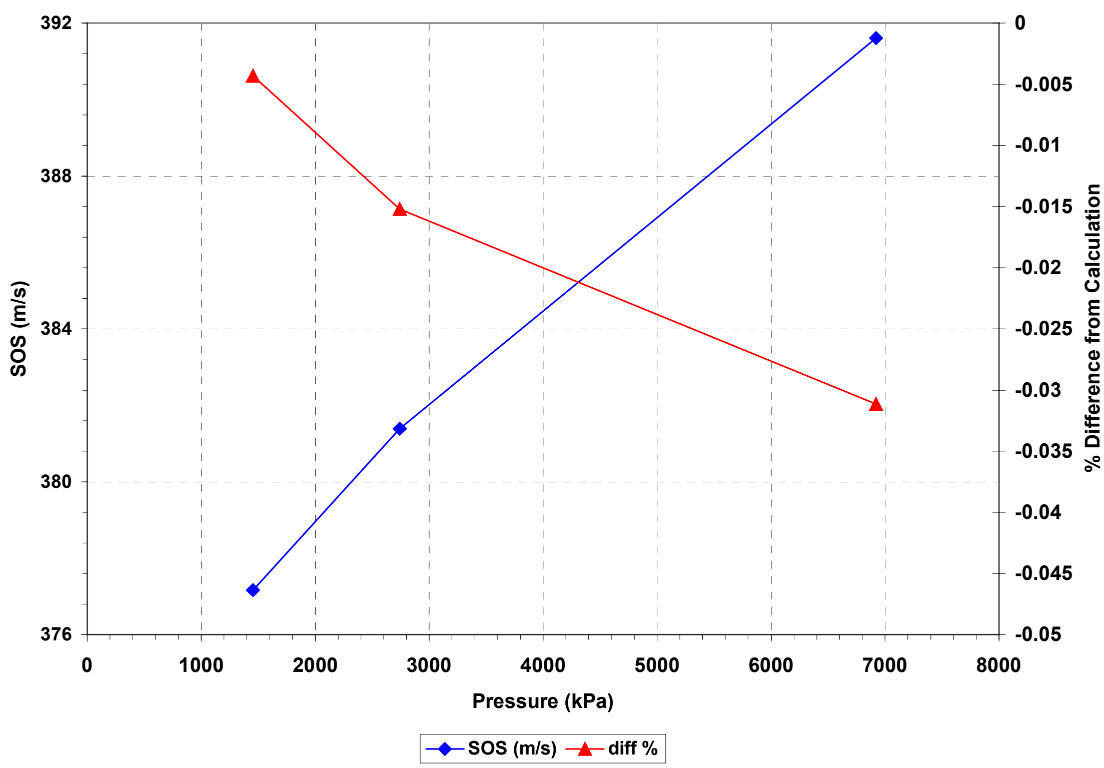

Figure 8 – SOS Measurements and Difference from Calculated SOS

6 CONCLUSIONS

The objectives of the research program were accomplished, allowing the following conclusions:

- The measured speed of sound values recorded during all of the experiments at SwRI agreed with their calculated values to within an average of 0.04%.
- Even though the speed of sound is dependent upon the temperature of the gas, the calibration of the ultrasonic meters exhibited no change in going from 21 ºC to 10 ºC with natural gas and from 21 ºC to 32 ºC with nitrogen.
- Day-to-day variations in calibration results at the SwRI High Pressure Loop were less than 0.1% for both gases, verifying the excellent reproducibility of the facility and the meters.
- When referenced to the turbine meters, a volume-based reference system, the ultrasonic meters' calibrations showed virtually no difference between natural gas and nitrogen
- When referenced to the sonic nozzles, a mass-based reference system, the ultrasonic and turbine meters showed a shift of slightly less than 0.2% when the gas was changed from natural gas to nitrogen, pointing to a small, but possibly significant, gas composition dependence of the sonic nozzles' calibration.
- Analysis of the calibration data from this series of runs at SwRI justifies the procedure of calibrating an ultrasonic meter at one set of conditions and utilizing it under another, including using different gases. This would allow the construction of air calibration facilities in convenient locations. Care must be taken to ensure that the reference system used at the calibration station is appropriate for the application for which the ultrasonic meters will be used.
- Static measurements of SOS in a 300 mm nitrogen-filled meter showed only a 0.03% difference from the calculated values over a 5.5 MPa range. This negates the possibility of a significant pressure effect on the characteristics (delay time) of the ultrasonic transducers.

6 REFERENCES

[1] T. A. GRIMLEY and E. B. BOWLES. Industry Researchers Evaluate Ultrasonic Meter Performance, **Pipe Line & Gas Industry**, December 1998.

[2] T. A. GRIMLEY. Effects of Diameter Mismatch and Line Pressure Variations on Ultrasonic Gas Flow Meter Performance, **GRI-02/0031**, February 2002.