UNDERSTANDING AGA REPORT NO. 10, *SPEED OF SOUND IN NATURAL GAS AND OTHER RELATED HYDROCARBON GASES*

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Introduction

The speed of sound in natural gas is the velocity a sound wave travels in the gas. There are a number of gas properties that affect the speed of sound and they include the composition of the gas, the pressure of the gas and the temperature of the gas. The American Gas Association Report No. 10 *Speed of Sound in Natural Gas and Other Related Hydrocarbon Gases* provides an accurate method for calculating the speed of sound in natural gas and other related hydrocarbon fluids.

Purpose of AGA Report No. 10

The development of ultrasonic flow meters prompted the development of AGA Report No. 10. The ultrasonic meter determines the speed of sound in the gas as it calculates the flow of gas through the meter. In order for one to check the accuracy of the speed of sound measured by the ultrasonic meter, it was necessary to have an accurate method to calculate the speed of sound in natural gas. AGA Report No. 10 was developed to do just that. The speed of sound calculated by the method in AGA Report No. 10 compares very favorably to the speed of sound determined by the highly accurate research that was the basis for the report. The information in AGA Report No 10 is not only useful for calculating the speed of sound in natural gas but also other thermodynamic properties of hydrocarbon fluids for other applications such as the compression of natural gas and the critical flow coefficient represented by C*.

The audience for AGA Report No. 10 is measurement engineers that are involved with the operation and startup of ultrasonic meters, sonic nozzles and others that are involved in applying the principles of natural gas thermodynamics to production, transmission or distribution systems.

The methods for calculating the speed of sound in AGA Report No. 10 are an extension of the information contained in AGA Report No. 8, *Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases* and it does contain excerpts from AGA Report No. 8. This is especially true since the speed of sound is related to the compressibility of the gas.

Applicable Gas Compositions

The calculations described in AGA Report No. 10 are only recommended for gases with characteristics within the ranges outlined in Table 1. The average expected uncertainties for gases whose composition are within the normal range column will correspond to the uncertainties shown in Figure 1. When the gas compositions fall within the expanded range, higher uncertainties can be expected, especially outside of Region 1. It is not recommended to use AGA Repot No. 10 outside of the gas composition ranges shown in Table 1.

There is not an accepted database for water, heavy hydrocarbons or hydrogen sulfide in natural gas for determining the uncertainties of the calculated gas properties. Therefore the method in this document is only for the gas phase. With that in mind the speed of sound calculated by AGA Report No. 10 is limited to gas compositions where the mole percent water is below the water vapor dew point, when the mole percent heavy hydrocarbons is below the hydrocarbon dew point and for pure hydrogen sulfide.

The application of this method for calculation of the speed of sound outside of the ranges shown in Figure 1 should be verified by experimental tests to insure their accuracy. It is not recommended using this calculation method near the critical point. For pipeline quality gas that is usually not a constraint because seldom do pipeline operating conditions come close to the critical point.

Table 1 Range of Gas Mixture Characteristics Consistent with AGA Report No. 10

Quantity	Normal Range	Expanded Range
Relative Density'	0.554 to 0.87	0.07 to 1.52
Gross Heating Value ••	477 to 1150 Btu/scf	0 to 1800 Btu/set
Gross Heating Value •••	18.7 to 45.1 MJ/m3	0 to 66 MJ/m3
Mole Percent Methane	45.0 to 100.0	0 to 100.0
Mole Percent Nitrogen	0 to 50.0	0 to 100.0
Mole Percent Carbon Dioxide	0 to 30.0	0 to 100.0
Mole Percent Ethane	0 to 10.0	0 to 100.0
Mole Percent Propane	0 to 4.0	0 to 12.0
Mole Percent Total Butanes	0 to 1.0	0 to 6.0
Mole Percent Total Pentanes	0 to 0.3	0 to 4.0
Mole Percent Hexanes Plus	0 to 0.2	0 to Dew Point
Mole Percent Helium	0 to 0.2	0 to 3.0
Mole Percent Hydrogen	0 to 10.0	0 to 100.0
Mole Percent Carbon Monoxide	0 to 3.0	0 to 3.0
Mole Percent Argon	#	0 to 1.0
Mole Percent Oxygen	#	0 to 21 .0
Mole Percent Water	0 to 0.05	0 to Dew Point
Mole Percent Hydrogen Sulfide	0 to 0.02	0 to 100.0

* Reference Conditions: relative Density at 60° F, 14.73 psia.
** Reference Conditions: Combustion at 60° F, 14.3 psia; density at 60° F, 14.73 psia
***Reference Conditions: Combustion at 25° C, 0.101325 MPa; density at 0° C, 0.101325 MPa
The normal range is considered to be zero for these compounds

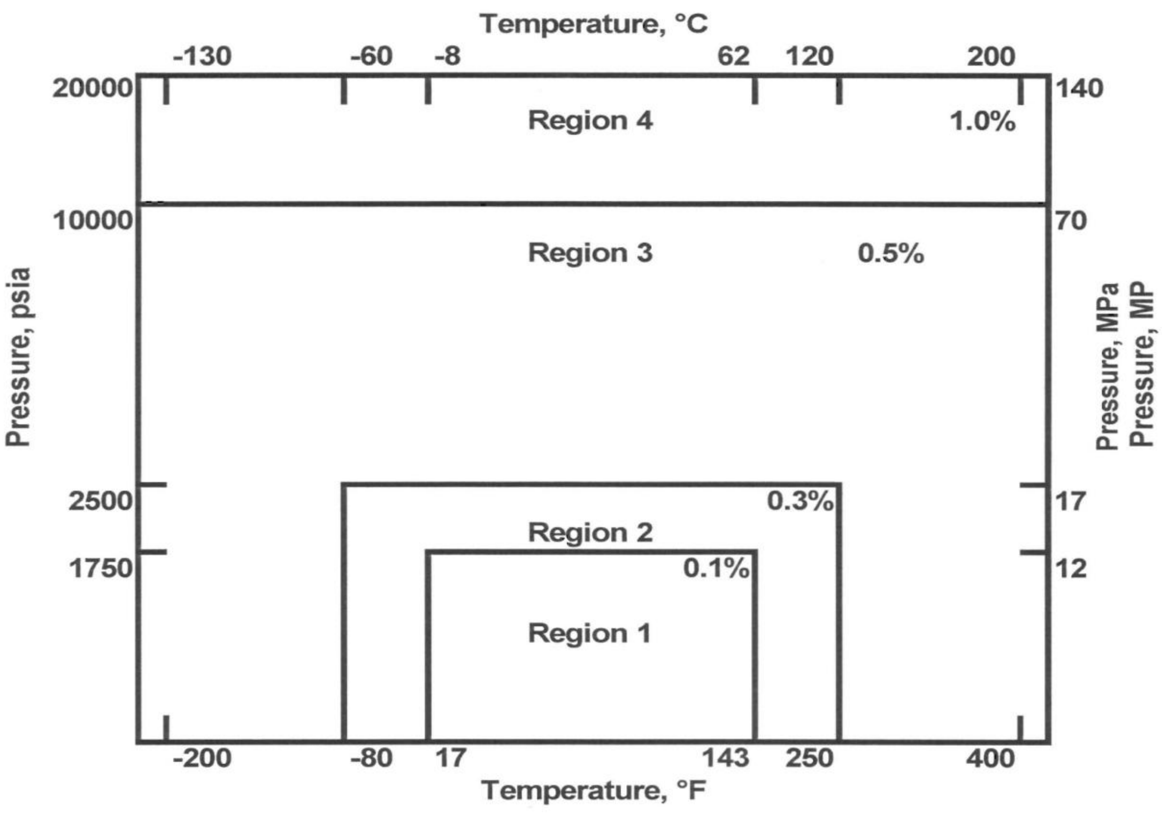

Figure 1: Targeted Uncertainty for Natural Gas Speed of Sound Using the AGA Report No. 10 Method

Calculation Method

The method used in AGA Report No 10 to calculate the speed of sound is the detailed characterization of the gas composition. This limits the use of this document to the methods provided the AGA Report No. 8, "Detailed Characterization Method."

The equations that are shown are extremely difficult to solve without the use of a computer. They are best solved using programs that are available from various sources. They make the job of calculating the speed of sound a rather simple task once you have the accurate input data outlined in the next paragraph.

The reliability of the calculation results is dependent on the accuracy of the determination of the composition, the flowing temperature and the flowing pressure data of the natural gas under consideration. The flowing pressure has a lesser degree of an effect on the accuracy of the calculations than changes of the same amount in either of the other two inputs. In other words an error of 1 psi in the flowing pressure measurement has a much less effect on the accuracy of the speed of sound calculation than an error of 1 degree in the flowing temperature measurement.

A description of the calculations that are required for determining the speed of sound follows. These are included to give one the idea of the complexity of the equations. There are several partial derivatives solved during the computation. Five of these partial derivatives are $\partial Z/\partial T$, $\partial B/\partial T$, $\partial^2 Z/\partial T^2$, $\partial^2 B/\partial T^2$ and $\partial Z/\partial \rho$. The formulas for these calculations are shown below.

The general procedure for computing the speed of sound at the flowing or operating conditions is as follows:

1. Input the operating temperature (T), the operating pressure (P) and the gas composition
2. Calculate the molar mass of the mixture
3. Calculate the compressibility and density of the fluid at the operating conditions
4. Calculate the ideal gas constant pressure heat capacity at the operating temperature
5. Calculate the real gas constant volume heat capacity at the operating conditions
6. Calculate the real gas constant pressure heat capacity at the operating conditions
7. Calculate the ratio of heat capacities, c_p/c_v, at the operating conditions
8. Calculate the speed of sound based on the results of the preceding steps
9. Calculate the isentropic exponent, **k**

Formulas for Calculation of the Speed of Sound

As one can see from the formulas on the following pages these calculations are for people that are expert mathematicians. These equations are duplicated directly from AGA Report No. 10. The are extremely difficult for people without a degree in mathematics to perform and then it would take a while if they do the calculations without the use of a computer. It is certainly something that most people would not want to attempt without access to a computer. There are a number of commercially available programs that can be purchased and used for these calculations. It is relatively easy to make the calculations using the computer programs. The inputs required are a complete gas analysis at least through C_6+ or higher, the flowing pressure and the flowing temperature.

Ultrasonic Meter Operation

An ultrasonic meter uses transducers to create sound pulses that travel across the flowing gas stream both with the flow and against the flow of gas. The difference in the transit times can be used to calculate the velocity of the gas in the pipe. The speed of sound in the gas can be calculated by dividing the distance between the transducer faces, known as path length, by the time required for a pulse to travel that distance. The path lengths are measured very accurately in the manufacture of the meter. One of the meter diagnostics is comparing the speed of sound determined by the meter to the theoretical speed of sound in the gas as calculated by AGA Report No. 10.

As mentioned earlier, the three inputs to the equations are gas composition, flowing pressure and flowing temperature. Below is a table that demonstrates what effect a change in the temperature and a change in the pressure can have on the calculation of the speed of sound. The gas composition used for these calculations is the Gulf Coast Gas shown in Table 3.

The basic speed of sound relation can be expressed as:

$$W = \left[\left(\frac{c_p}{c_v}\right)\left(\frac{RT}{M_r}\right)\left(Z + \rho\left(\frac{\partial Z}{\partial \rho}\right)_T\right)\right]^{0.5} \quad (3.1)$$

The isentropic exponent may be expressed in terms of its relationship to the speed of sound:

$$\kappa = W^2 \frac{M_r}{ZRT} \quad (3.2)$$

The quantities c_v and c_p are the constant volume and constant pressure heat capacities of the gas.

$$c_v = c_p^{\,o} - R\left\{1 + T\int_0^{\rho}\left[\frac{T}{\rho}\left(\frac{\partial^2 Z}{\partial T^2}\right)_\rho + \frac{2}{\rho}\left(\frac{\partial Z}{\partial T}\right)_\rho\right]d\rho\right\} \quad (3.3)$$

$$c_p = c_v + \left(\frac{T}{\rho^2}\right)\frac{\left[\left(\frac{\partial P}{\partial T}\right)_\rho\right]^2}{\left[\left(\frac{\partial P}{\partial \rho}\right)_T\right]} \quad (3.4a)$$

or, expressed in terms of compressibility:

$$c_p = c_v + R\frac{\left[Z + T\left(\frac{\partial Z}{\partial T}\right)_\rho\right]^2}{\left[Z + \rho\left(\frac{\partial Z}{\partial \rho}\right)_T\right]} \quad (3.4b)$$

Note that the ideal gas specific heat ratio, $\frac{c_p^{\,o}}{c_v^{\,o}}$, real gas specific heat ratio, $\frac{c_p}{c_v}$, and the isentropic exponent, κ, are related but separate quantities. In certain gas industry applications, the ratio of ideal gas specific heats is assumed to be synonymous with the isentropic exponent.

The pure fluid constant pressure ideal gas heat capacity is computed as:

$$c_p^{\,o} = B + C\left[\frac{D/T}{\sinh(D/T)}\right]^2 + E\left[\frac{F/T}{\cosh(F/T)}\right]^2 + G\left[\frac{H/T}{\sinh(H/T)}\right]^2 + I\left[\frac{J/T}{\cosh(J/T)}\right]^2 \quad (3.5)$$

The pure fluid ideal gas enthalpy is computed as:

$$H^o = A + BT + CD\coth(D/T) - EF\tanh(F/T) + GH\coth(H/T) - IJ\tanh(J/T) \qquad (3.6)$$

The real gas enthalpy is computed as:

$$H = H^o + RT\left[(Z-1) - \int_0^{\rho}\frac{T}{\rho}\left(\frac{\partial Z}{\partial T}\right)\partial\rho\right] \qquad (3.7)$$

The pure fluid ideal gas entropy is computed as:

$$\begin{aligned} S^o &= K + B\ln(T) + C[(D/T)\coth(D/T) - \ln(\sinh(D/T))] \\ &- E[(F/T)\tanh(F/T) - \ln(\cosh(F/T))] \\ &+ G[(H/T)\coth(H/T) - \ln(\sinh(H/T))] \\ &- I[(J/T)\tanh(J/T) - \ln(\cosh(J/T))] \end{aligned} \qquad (3.8)$$

The entropy of mixing is computed as:

$$S_{mixing} = -R\sum_{i=1}^{N} X_i \ln(X_i) \qquad (3.9)$$

The real gas entropy is computed as:

$$S = S^o + S_{mixing} - R\ln(\frac{P}{ZP^o}) - R\int_0^{\rho}\left(\frac{(Z-1)}{\rho} + \frac{T}{\rho}\left(\frac{\partial Z}{\partial T}\right)\right)\partial\rho \qquad (3.10)$$

where P^o = 0.101325 MPa

The coefficients for computing the ideal gas constant pressure heat capacity, enthalpy and entropy are given in Table 4. In this table, the unit of measure for energy is the thermochemical calorie (1 $cal_{(th)}$ = 4.184 J).

The basic equation for the compressibility factor, from AGA Report No. 8, is:

$$Z = 1 + \frac{DB}{K^3} - D\sum_{n=13}^{18} C_n^* T^{-u_n} + \sum_{n=13}^{58} C_n^* T^{-u_n}\left(b_n - c_n k_n D^{k_n}\right)D^{b_n}\exp\left(-c_n D^{k_n}\right) \qquad (3.11)$$

where

$$B = \sum_{n=1}^{18} a_n T^{-u_n} \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j E_{ij}^{u_n}\left(K_i K_j\right)^{\frac{3}{2}} B_{nij}^* \qquad (3.12)$$

The first partial derivative of Z with respect to T is:

$$\left(\frac{\partial Z}{\partial T}\right)_d = \frac{D}{K^3}\left(\frac{\partial B}{\partial T}\right)_d + D\sum_{n=13}^{18} u_n C_n^* T^{-(u_n+1)} - \sum_{n=13}^{58} u_n C_n^* T^{-(u_n+1)}\left(b_n - c_n k_n D^{k_n}\right) D^{b_n} \exp\left(-c_n D^{k_n}\right) \tag{3.13}$$

where

$$\left(\frac{\partial B}{\partial T}\right)_d = -\sum_{n=1}^{18} u_n a_n T^{-(u_n+1)} \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j E_{ij}^{u_n}\left(K_i K_j\right)^{\frac{3}{2}} B_{nij}^* \tag{3.14}$$

The second partial derivative of Z with respect to T is:

$$\left(\frac{\partial^2 Z}{\partial T^2}\right)_d = \frac{D}{K^3}\left(\frac{\partial^2 B}{\partial T^2}\right)_d - D\sum_{n=13}^{18} u_n\left(u_n+1\right) C_n^* T^{-(u_n+2)} + \sum_{n=13}^{58} u_n\left(u_n+1\right) C_n^* T^{-(u_n+2)}\left(b_n - c_n k_n D^{k_n}\right) D^{b_n} \exp\left(-c_n D^{k_n}\right) \tag{3.15}$$

where

$$\left(\frac{\partial^2 B}{\partial T^2}\right)_d = \sum_{n=1}^{18} u_n\left(u_n+1\right) a_n T^{-(u_n+2)} \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j E_{ij}^{u_n}\left(K_i K_j\right)^{\frac{3}{2}} B_{nij}^* \tag{3.16}$$

The first partial derivative of Z with respect to ρ is:

$$\left(\frac{\partial Z}{\partial \rho}\right)_T = K^3\left\{\left[\frac{B}{K^3} - \sum_{n=13}^{18} C_n^* T^{-u_n}\right] + \sum_{n=13}^{58} C_n^* T^{-u_n}\left(-c_n k_n^2 D^{(k_n-1)}\right) D^{b_n} \exp\left(-c_n D^{k_n}\right) + \sum_{n=13}^{58} C_n^* T^{-u_n}\left(b_n - c_n k_n D^{k_n}\right) b_n D^{(b_n-1)} \exp\left(-c_n D^{k_n}\right) - \sum_{n=13}^{58} C_n^* T^{-u_n}\left(b_n - c_n k_n D^{k_n}\right) D^{b_n}\left(c_n k_n D^{(k_n-1)}\right) \exp\left(-c_n D^{k_n}\right)\right\} \tag{3.17}$$

TEMP → / PRESS ↓	30°F	31°F	35°F	40°F	60°F	70°F	90°F	100°F	120°F
200 PSIG	1351.1	1352.6	1358.5	1365.9	1394.4	1408.3	1435.1	1448.1	1473.4
201 PSIG	1351.0	1352.5	1358.4	1365.8	1394.3	1408.2	1435.0	1448.0	1473.4
202 PSIG	1350.9	1352.4	1358.3	1365.7	1394.3	1408.1	1434.9	1448.0	1473.3
205 PSIG	1350.5	1352.0	1358.0	1365.4	1394.0	1407.9	1434.8	1447.8	1473.2
210 PSIG	1350.0	1351.5	1357.5	1364.9	1393.6	1407.5	1434.4	1447.5	1472.9
500 PSIG	1321.6	1323.4	1330.4	1339.1	1372.4	1388.4	1418.9	1433.6	1461.9
501 PSIG	1321.5	1323.3	1330.3	1339.0	1372.4	1388.3	1418.9	1433.6	1461.9
502 PSIG	1321.4	1323.2	1330.3	1338.9	1372.3	1388.3	1418.8	1433.5	1461.9
505 PSIG	1320.7	1323.0	1330.0	1338.7	1372.1	1388.1	1418.7	1433.4	1461.8
510 PSIG	1320.7	1322.5	1329.6	1338.3	1371.8	1387.8	1418.5	1433.3	1461.7
1000 PSIG	1296.3	1298.4	1306.8	1317.1	1356.2	1374.6	1409.7	1426.4	1458.3
1001 PSIG	1296.3	1298.4	1306.8	1317.0	1356.2	1374.6	1409.7	1426.4	1458.3
1005 PSIG	1296.2	1298.4	1306.7	1317.0	1356.2	1374.7	1409.7	1426.4	1458.4
1010 PSIG	1296.2	1298.3	1306.7	1317.0	1356.2	1374.7	1409.7	1426.5	1458.5

Table 2 Speed of Sound in Ft/Sec

From Table 2 above, one can see that the speed of sound is affected much less by a small pressure change than it is by a small temperature change. For example, a one pound change in pressure from 200 PSIG to 201 PSIG only changes the speed of sound by 0.1 ft/sec, if at all whereas a temperature change of one degree Fahrenheit can change the speed of sound at 200 PSIG from 1.5 ft/sec to as much as 2.1 ft/sec at 1000 PSIG. At pressures in the 1000 PSIG range it can require more than a 10 PSI change in pressure to cause the speed of sound to change by 0.1 ft/sec.

This shows that if a calculated speed of sound is used to verify that the speed of sound determined by your meter is correct, you must have very accurate temperature measurements. The pressure is also very important in calculating the standard volumes but a change does not affect the speed of sound calculation nearly as much as does a corresponding change in the temperature. Stated another way, a 1 PSI change in pressure does not affect the speed of sound calculation nearly as much as a 1 degree change in the temperature. The speed of sound determined by the meter should agree with the speed of sound calculated by using AGA Report No. 10 within ±0.2%.

The composition of the gas used to calculate the speed of sound in Table 2 above is the Gulf Coast Gas composition from AGA Report No. 10. This composition was determined by averaging a large number of gas samples collected by various companies that operate facilities both onshore along the Gulf of Mexico Coast and offshore in the Gulf of Mexico. The GRI reference compositions of the Gulf Coast Gas, the Ekofisk Gas, the Amarillo Gas and Air are shown below in Table 3.

Components in Mole Percent	Gulf Coast Gas	Ekofisk Gas	Amarillo Gas	Air
Speed of Sound @14.73 & 60°F	1412.4	1365.6	1377.8	1118.05
G_r	0.581078	0.649521	0.608657	1.00
Heating Value	1036.05	1108.11	1034.85	
Methane	96.5222	85.9063	90.6724	
Nitrogen	0.2595	1.0068	3.1284	78.03
Carbon Dioxide	0.5956	1.4954	0.4676	0.03
Ethane	1.8186	8.4919	4.5279	
Propane	0.4596	2.3015	0.8280	
i-Butane	0.0977	0.3486	0.1037	
n-Butane	0.1007	0.3506	0.1563	
i-Pentane	0.0473	0.0509	0.0321	
n-Pentane	0.0324	0.0480	0.0443	
n- Hexane	0.0664	0.0000	0.0393	

Table 3 Reference Gas Compositions

A comparison of how the composition of a gas affects the speed of sound in the gas is shown in Table 4. The comparison is made at several pressures and temperatures. The composition of the Ekofisk gas has a high Ethane content, nearly 8.5 mole percent as compared to the Ethane content of 1.8 mole percent in the Gulf Coast gas. The Ekofisk gas has no hexanes and heavier hydrocarbon components whereas the composition of the Gulf Coast gas contains a small amount of n-Hexane. The Ekofisk gas also has five times the amount of propane and the other components are also greater except for the hexanes and the Methane which is only 85.9063 mole percent compared to 96.5222 mole percent in the Gulf Coast gas. As one can see from the values in Table 4, there can be a significant difference in the speed of sound calculated for the same conditions when the gas composition is changed.

Temp →	30° Gulf Coast	30° Ekof	60° Gulf Coast	60° Ekof	120° Gulf Coast	120° Ekof
Press ↓						
200 PSIG	1351.1	1260.3	1394.4	1301.8	1473.4	1377.1
201 PSIG	1351.0	1260.2	1394.3	1301.7	1473.4	1377.1
205 PSIG	1350.5	1259.6	1394.0	1301.2	1473.2	1376.8
210 PSIG	1350.0	1258.9	1393.6	1300.6	1472.9	1376.4
500 PSIG	1321.6	1220.0	1372.4	1270.6	1461.9	1358.7
501 PSIG	1321.5	1219.9	1372.4	1270.5	1461.9	1358.7
505 PSIG	1320.7	1219.4	1372.1	1270.2	1461.8	1358.5
510 PSIG	1320.7	1218.8	1371.8	1269.7	1461.7	1358.2
1000 PSIG	1296.3	1180.0	1356.2	1241.7	1458.3	1345.5
1001 PSIG	1296.3	1179.9	1356.2	1241.7	1458.3	1345.5
1005 PSIG	1296.2	1179.8	1356.2	1241.7	1458.4	1345.5
1010 PSIG	1296.2	1179.8	1356.2	1241.6	1458.5	1345.5

Table 4 Comparison of Speed of Sound in Gulf Coast Gas and Ekofisk Gas at Same Conditions

Figure 2 below shows the speed of sound for the Gulf Coast gas mixture plotted for four different temperatures and for pressures from near 0 PSIA to 1500 PSIA. In this figure you can clearly see how the speed of sound varies with the changes in temperature and pressures. This covers a large span of the normal operating pressures and temperatures except for most gas storage operations.

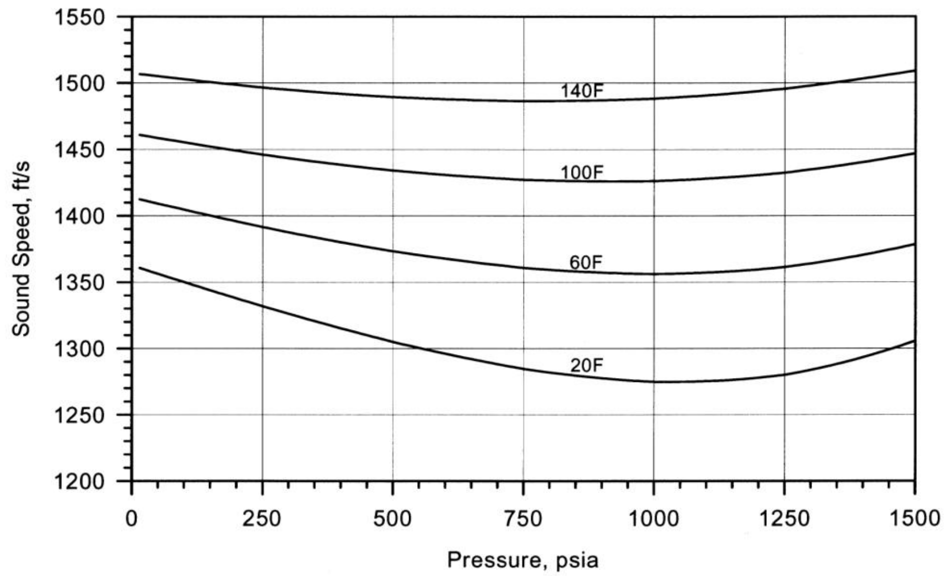

Figure 2 – Speed of Sound in 0.58 G_r "Gulf Coast" Gas below 1500 psia

Figure 3 below shows the speed of sound in four different gasses including air from near 0 PSIA to 1500 PSIA at 60°F. This demonstrates in graphical form how the speed of sound varies for gasses with different compositional mixtures at various pressures. Air, being composed of primarily of nitrogen, carbon dioxide and oxygen is included as a reference.

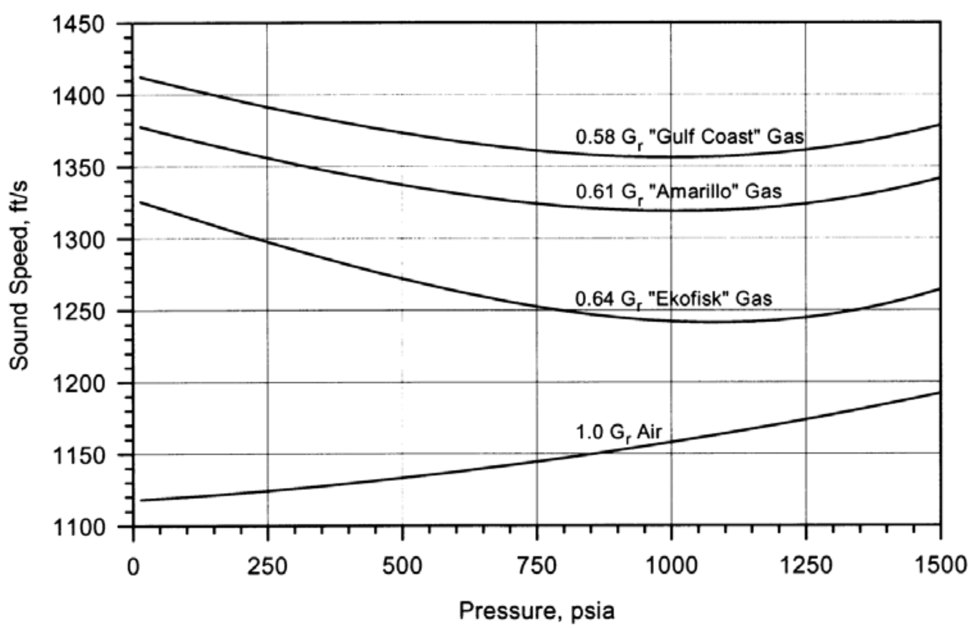

Figure 3 – Speed of Sound in Various Gases at 60° F

As stated previously, one of the diagnostics available in the ultrasonic meter is the speed of sound calculated by the meter. One meter manufacturer also has the ability to connect to pressure and temperature transmitters, as well as a gas chromatograph and bring those inputs into the meter electronics. The meter software then uses the AGA 10 calculation method, along with pressure, temperature and gas composition to compute a theoretical or calculated speed of sound. The AGA 10 calculated speed of sound is then compared to the ultrasonic meter's speed of sound. This comparison is one of many diagnostics available in the ultrasonic meter. By using this diagnostic (along with the other available diagnostics), the ultrasonic user can then determine the meter's overall health and functionality. Advanced users trend this data over time to observe any potential drifts occurring in the ultrasonic meter. A drift in the meter's speed of sound calculation can point to a number of potential problems including deposit buildup on the wall of the meter or face of the transducers, liquid inside the meter, or possibly a transducer that may be beginning to fail. Figure 4 below shows one manufacturer's software that does a live comparison of the meter's speed of sound compared to the AGA 10 calculated speed of sound.

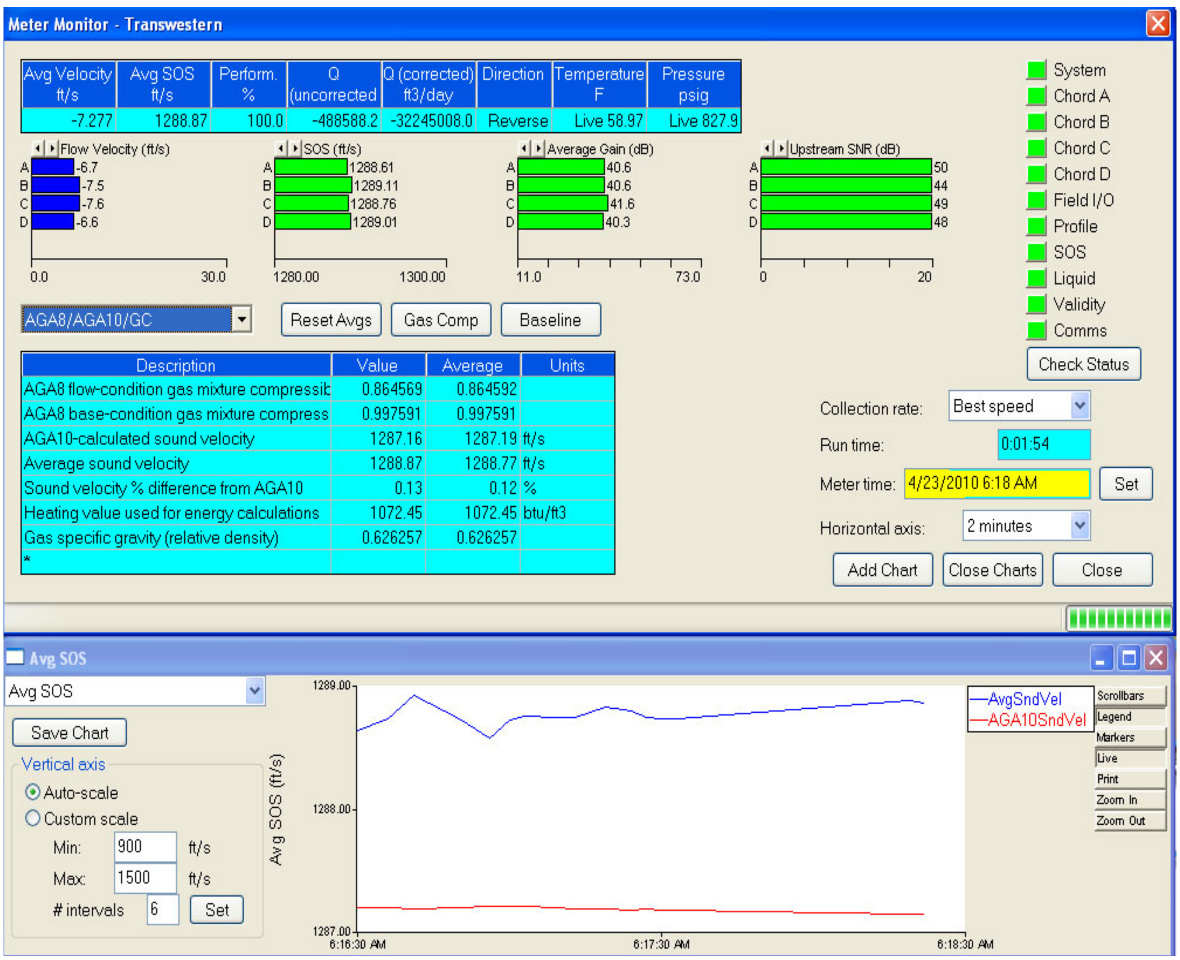

Figure 4 – Ultrasonic Meter Software Plotting Meter Speed of Sound vs. AGA 10 Calculated Speed of Sound

Summary

AGA 10 was conceived following the development and wide use of ultrasonic meters for custody transfer measurement. AGA Report No. 10 provides the equations and calculation methods necessary to compute the speed of sound in natural gas and other hydrocarbon gases. By using the equations laid out in the AGA Report No. 10 document, users can accurately calculate speed of sound and, in turn, compare the calculated speed of sound to that of devices such as ultrasonic meters for diagnostic purposes.

References

1. AGA Report No. 8, *Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases,* 2nd Printing, July 1994
2. AGA Report No. 9, *Measurement of Gas by Multipath Ultrasonic Meters,* Second Edition, April 2007
3. AGA Report No. 10, *Speed of Sound in Natural Gas and Other Related Hydrocarbon Gases,* January, 2003