

The Effect of Using Real Gas Absolute Viscosity and Isentropic Exponent on Orifice Flow Measurement: Proposed Adoption of REFPROP 8.0 as a Standard for the Natural Gas Industry

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Abstract – Constant values for isentropic exponent and absolute viscosity are commonly used for the calculation of gas flow rates through differential producing flowmeters. Errors in flow measurement due to the use of constants for thermodynamic and transport properties are bias errors. Bias errors in natural gas orifice flow measurement due to incorrect isentropic exponent values can exceed 0.15%. When the adiabatic expansion factor is used to calculate natural gas flow rates the bias errors due to the use of a constant isentropic exponent can exceed 2%. Bias errors in natural gas flow measurement due to incorrect absolute viscosity values can approach 0.2% for natural gas. REFPROP 8.0 is recommended as a source of accurate thermodynamic and transport property values. REFPROP 8.0 can be used as a source of live values for use with flow computers or it can be used to select more appropriate constant values to minimize bias errors.

INTRODUCTION

The calculation of flow through orifice and other differential pressure producing flowmeters requires the determination of three thermodynamic and transport properties: compressibility, isentropic exponent, and absolute viscosity. Improved real gas calculations produce very accurate gas compressibility values however, constants are commonly used for isentropic exponent and absolute viscosity. Past use of constant values for isentropic exponent and absolute viscosity are the result of limited real gas thermodynamic property and transport property calculation methods. The use of constant values for isentropic exponent and absolute viscosity can lead to biased flow measurement values.

Isentropic exponent values are used in the calculation of expansion factors for differential producing flowmeters. Errors in flow measurement due to incorrect isentropic exponents will increase as the gas velocity through the meter increases. The gas velocity is measured using the dimensionless ratio of differential pressure to static line pressure, dP/P . At $dP/P = 0.2$, natural gas orifice measurements can have measurement errors of 0.15% at atmospheric pressure. At $dP/P = 0.2$, other natural gas differential producing flowmeters using the adiabatic expansion factor can have measurement errors over 0.25% at atmospheric pressure and over 2.5% at 10 MPa.

High order polynomials are often used to characterize discharge coefficients as a function of Reynolds number. The constant value used by the natural gas industry for absolute viscosity has been shown to be in error by as much as 10% at atmospheric pressure and by as much as 25% at 10 MPa. Large errors in calculated Reynolds number can produce large flow measurement errors when used with a high order polynomial to calculate discharge coefficient.

REFPROP 8.0 [3] incorporates most of the recent improvements in natural gas and pure gas thermodynamic and transport property calculations. Recent publications have shown that REFPROP 8.0 compares well with AGA Report No. 8 and AGA Report No. 10 [1] and is in good agreement with published experimental absolute viscosity values for natural gas [2]. REFPROP 8.0 can be used to provide live values if used in conjunction with flow computer software or it can be used to calculate appropriate constant values for use with flow computers running old software.

THERMODYNAMIC AND TRANSPORT PROPERTY CALCULATIONS

Gas thermodynamic and transport property calculations are an important part of calculating flow through a flowmeter. To achieve lower uncertainties in flow measurement it is necessary to calculate real gas thermodynamic and transport properties correctly at the time a flowmeter is calibrated and when the flowmeter is put into service. Using common sources of real gas thermodynamic and transport property values at the calibration laboratory and when the meter is used has been hard to achieve. Real gas compressibility values have a large impact on accurate flow measurement. This impact was recognized and addressed by the scientific community in the form of improved real gas calculation methods and by the users who adopted the improved calculation methods. Real gas isentropic exponent and absolute viscosity calculation methods have improved and been implemented at calibration facilities but need to be implemented by the users of flow meters at the point of application.

The importance of isentropic exponent when using differential producing flowmeters was recognized long ago and was introduced into the flow measurement calculation as part of the expansion factor. The real gas isentropic exponent is a function of pressure, temperature, and gas composition. The difficulty in calculating real gas isentropic exponents and the assumption that the sensitivity of the calculated flow to isentropic exponent was negligible led to the use of perfect gas isentropic exponents. A perfect gas is an ideal gas that has constant specific heats and is independent of pressure. AGA Report No. 3 not only makes the perfect gas assumption but also recommends the use of $k = 1.3$ for all natural gas compositions. It is common when calculating flow with air to use an isentropic exponent value of 1.4. Using a constant value for isentropic exponent has limited impact on the flow measurement when the gas velocities at the flowmeter are low. The flow parameter used to indicate gas velocity through a differential producing flowmeter is the dimensionless ratio of differential pressure to static line pressure (dP/P). When the value of dP/P is less than 0.02 then the gas velocity and gas expansion is low and the flowing gas behaves like an incompressible fluid. The gas velocity and gas expansion may be much higher, especially if the static line pressure is low. Differential producing flowmeters have typically been limited by standards to values of dP/P less than 0.2. The natural gas industry is considering the adoption of an improved expansion factor that will allow dP/P values as high as 0.25. As the gas velocity and gas expansion in a differential producing flowmeter increase the effect of errors in isentropic exponent will result in higher flow measurement errors.

Real gas absolute viscosity is a function of pressure, temperature, and gas composition. Calculation methods that are only a function of temperature such as Sutherland's equation [9] and Wilke's equation [7] have been used to calculate absolute viscosity values for gases. Sutherland's equation has typically been used for air and pure gas absolute viscosity calculations. Wilke's equation is commonly used for the calculation of natural gas viscosity.

AGA Report No.3 states that if the viscosity of a natural gas composition is between 7.5 and 10.1 uPa-sec then a constant value of 8.78 uPa-sec can be used. It has been assumed by many natural gas flow measurement personnel that the absolute viscosity of all natural gas compositions lie between 7.5 and 10.1 uPa-sec. The absolute viscosity of natural gas has been found [2] to have values much higher than 8.78 uPa-sec in nearly all cases.

The absolute viscosity of a gas flowing through a meter is used to calculate the discharge coefficient of the meter. The discharge coefficient is typically calculated as a function of pipe or throat Reynolds number. If the equation for discharge coefficient uses a form that is based on boundary layer theory then

the sensitivity of discharge coefficient to absolute viscosity is low. If polynomials are used to calculate discharge coefficient then the sensitivity may be much higher.

The use of constant isentropic exponent and absolute viscosity values when calculating flow leads to biases in reported values. When biases are identified they should be eliminated because the errors they introduce are not random and cannot be treated as uncertainty. If a bias cannot be eliminated then it should be reported separately from uncertainty.

NATURAL GAS COMPOSITIONS

Real gas isentropic exponent and absolute viscosity values were calculated using seven natural gas compositions. Five of the natural gas compositions are from AGA Report No. 8 [8], one composition is typical of the gas compositions found at the CEESI Iowa High Flow Natural Gas Facility, and the remaining composition was encountered at CEESI Colorado when the ethane composition was unusually high. The seven compositions are shown in Table 1. Real gas isentropic exponent and absolute viscosity values were also calculated for methane, air, and water.

Table 1. Natural Gas Compositions Used in the Calculation of Isentropic Exponent and Absolute Viscosity Values

Gas Component	Gulf Coast	Amarillo	Ekofisk	High Nitrogen	High N2 High CO2	CEESI Iowa	Colorado High Ethane
Methane	96.5222	90.6724	85.9063	81.441	81.212	95.48452	84.80658
Nitrogen	0.2595	3.1284	1.0068	13.465	5.702	0.005	0.409
Carbon Dioxide	0.5956	0.4676	1.4954	0.985	7.585	0.0154	2.110702
Ethane	1.8186	4.5279	8.4919	3.3	4.303	1.898499	10.67001
Propane	0.4596	0.828	2.3015	0.605	0.895	0.17736	1.767102
Water	0	0	0	0	0	0	0
Hydrogen Sulfide	0	0	0	0	0	0	0
Hydrogen	0	0	0	0	0	0.035	0
Carbon Monoxide	0	0	0	0	0	0	0
Oxygen	0	0	0	0	0	0	0
Iso-Butane	0.0977	0.1037	0.3486	0.1	0.151	0.020134	0.08
Butane	0.1007	0.1563	0.3506	0.104	0.152	0.002998	0.1258
Pentane	0.0473	0.0321	0.0509	0	0	0.002998	0.0115
Pentane	0.0324	0.0443	0.048	0	0	1.598736	0.01
Hexane	0.0664	0.0393	0	0	0	0.599526	0.002
Heptane	0	0	0	0	0	0	0.005
Octane	0	0	0	0	0	0	0.0014
Nonane	0	0	0	0	0	0	0.00045
Decane	0	0	0	0	0	0	0.00045
Helium	0	0	0	0	0	0.1599	0
Argon	0	0	0	0	0	0	0

REAL GAS ISENTROPIC EXPONENT VALUES

Isentropic exponent values were calculated using REFPROP 8.0 for the seven natural gas compositions shown in Table 1. Figure 1 shows isentropic exponent values for the seven gas compositions calculated at a constant temperature of 288.65 K and at pressures varying from 0.101325 MPa to 11 MPa. The natural gas isentropic exponents vary from 1.3 to 1.5 at 10 MPa for a change of 15%. Figure 2 shows the calculated isentropic exponent values for the seven natural gas compositions at 288.65 K at lower pressures. The isentropic gas values vary at atmospheric pressure from 1.28 to 1.31 or a little over 1% about a value of 1.3. Figures 5, 6, and 7 show isentropic exponent values for methane, air, and steam. Isentropic exponent values vary 15% for methane and 6% for air when the pressure is raised from atmospheric pressure to 10 MPa at a constant temperature. Steam is the only gas with calculated isentropic exponent values that are a weak function of pressure.

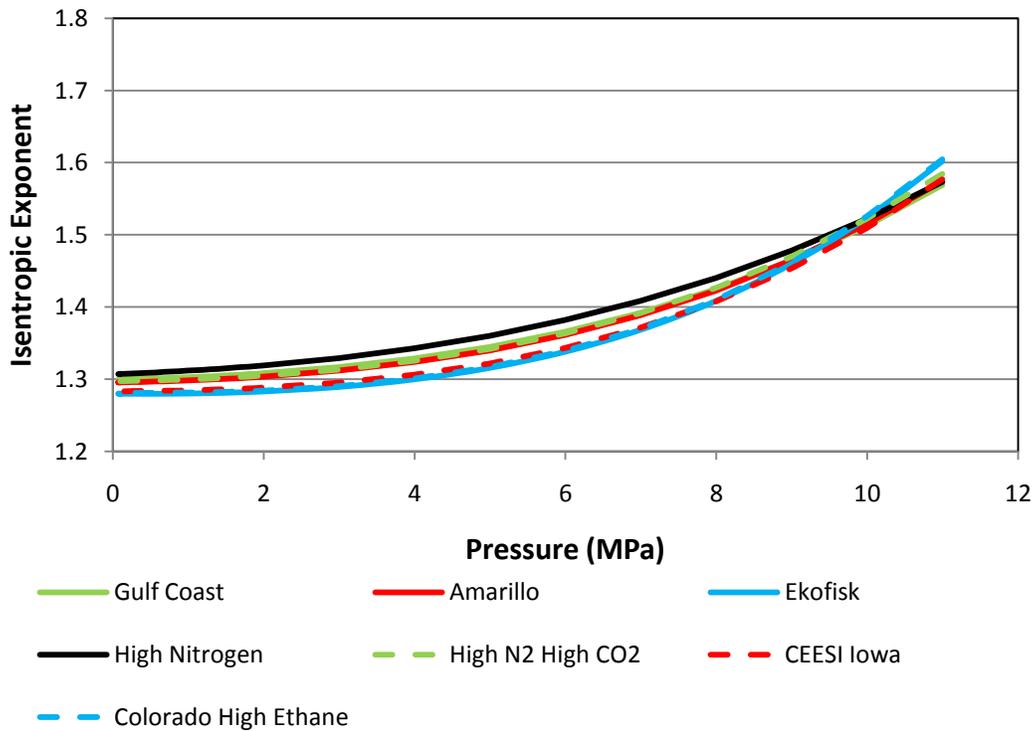


Figure 1. Natural Gas Isentropic Exponent Values at T = 288.65 K

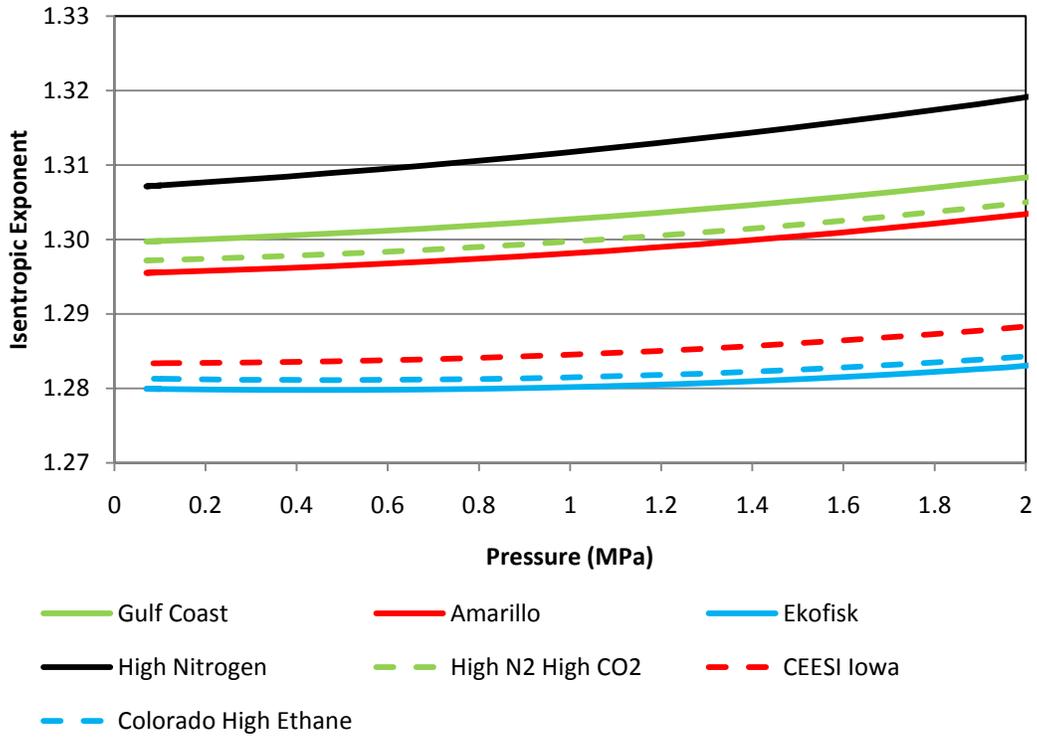


Figure 2. Natural Gas Isentropic Exponent Values at T = 288.65 K

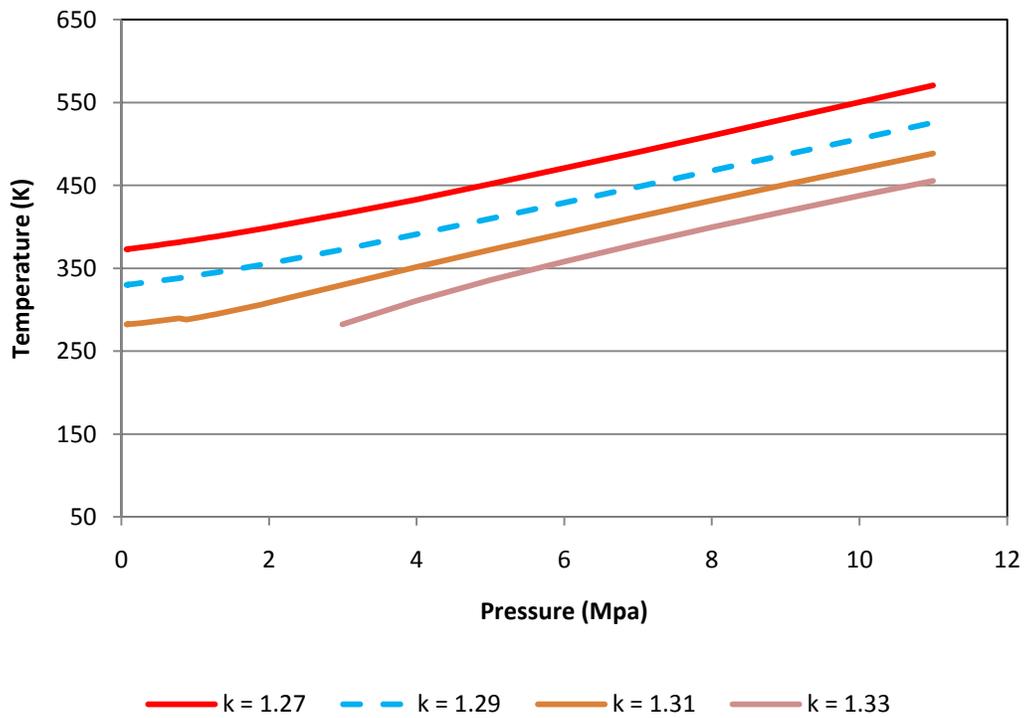


Figure 3. Isentropic Exponent Values for Methane

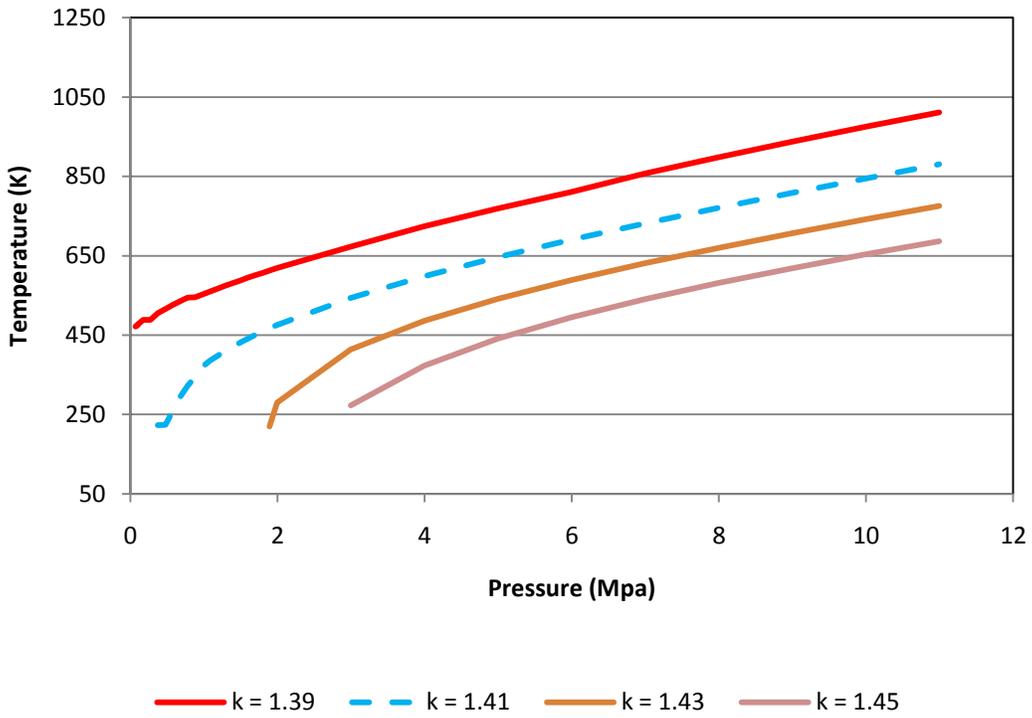


Figure 4. Isentropic Exponent Values for Air

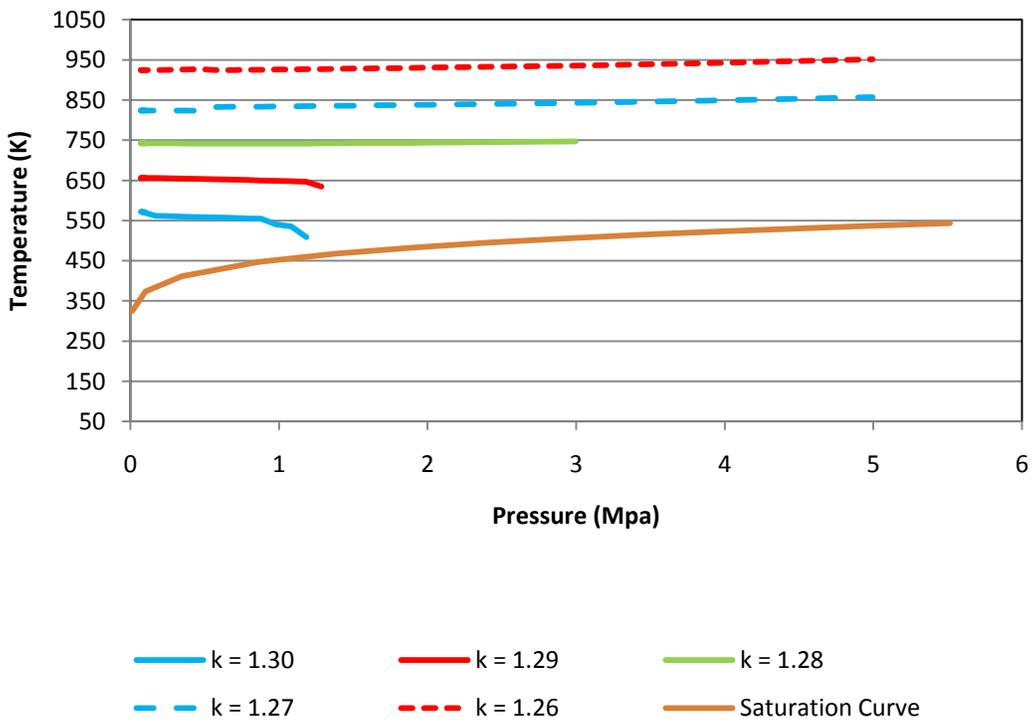


Figure 5. Isentropic Exponent Values for Water

REAL GAS ABSOLUTE VISCOSITY VALUES

Real gas absolute viscosity values were calculated for the seven natural gas compositions shown in Table 1. The absolute viscosity values shown in Figure 6 were calculated using a temperature of 288.65 K and pressures up to 11 MPa. The natural gas absolute viscosity values vary from 10.5 uPa-sec at atmospheric pressure to 15 uPa-sec at 10 MPa. The constant value used for natural gas absolute viscosity of 8.78 uPa-sec is 16% low at atmospheric pressure and 40% low at 10 MPa. The absolute viscosity values for methane, air, and water are shown in Figures 9, 10, and 11. Absolute viscosity values vary 22% for methane and 12% for air when the pressure is increased from atmospheric pressure to 10 MPa at a constant temperature. Steam is the only gas whose absolute viscosity is a weak function of pressure.

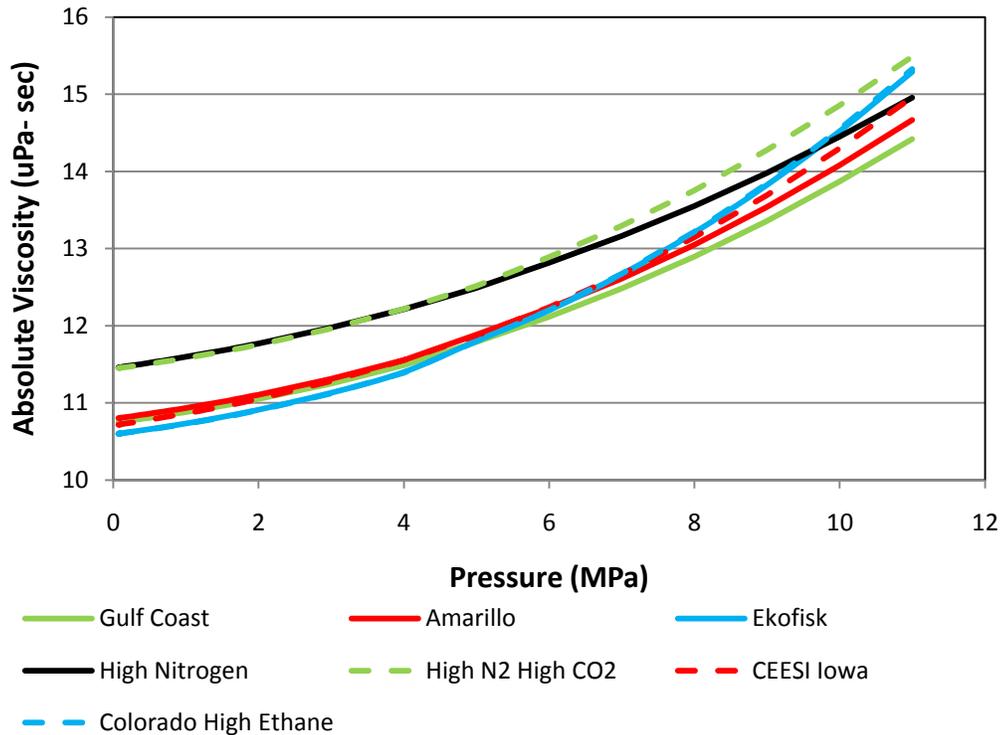


Figure 6. Natural Gas Absolute Viscosity Values at T = 288.65 K

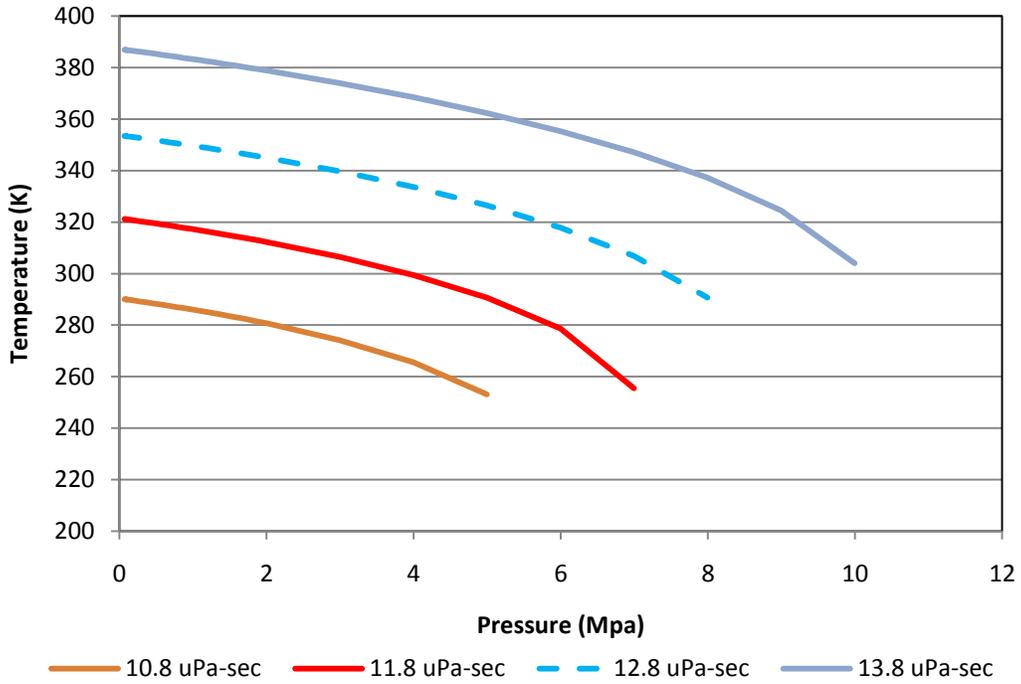


Figure 7. Absolute Viscosity Values for Methane

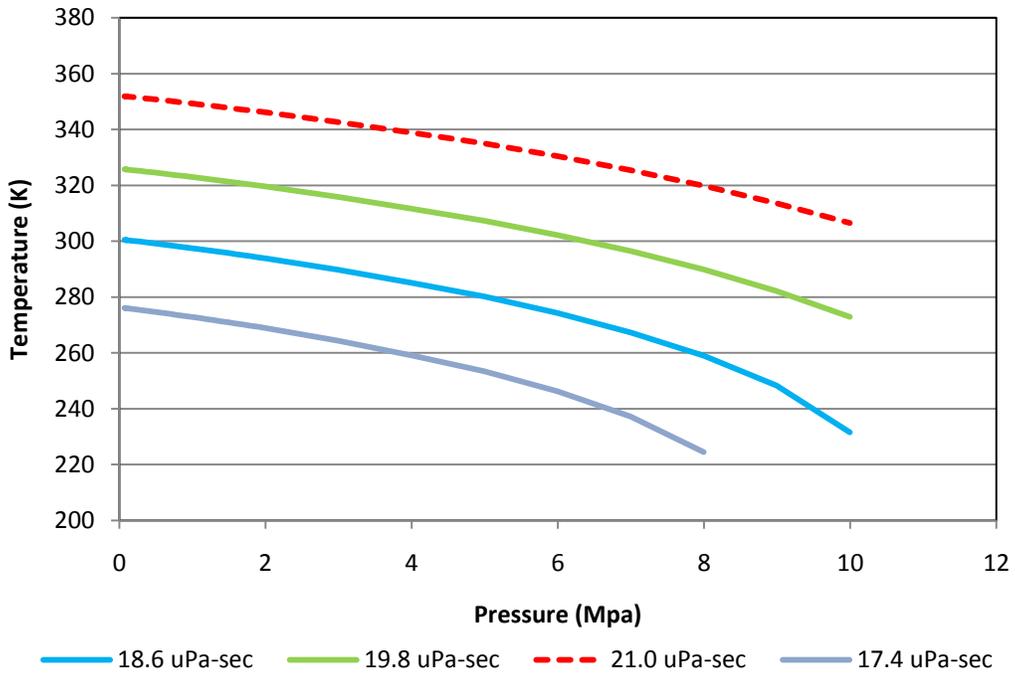


Figure 8. Absolute Viscosity Values for Air

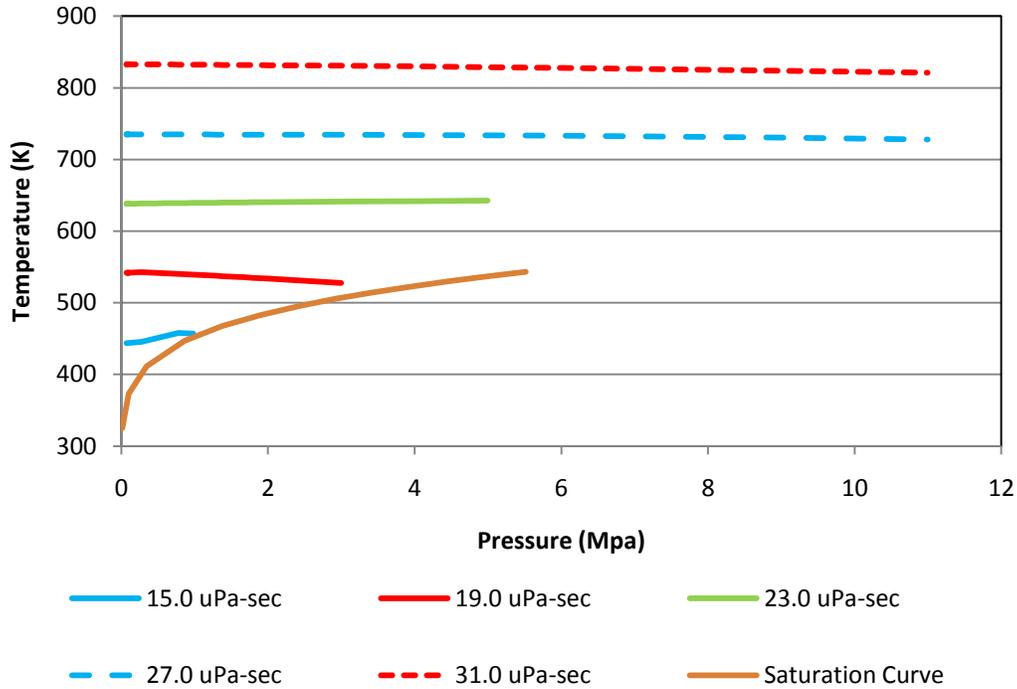


Figure 9. Absolute Viscosity Values for Water

DIFFERENTIAL PRODUCING FLOWMETER EXPANSION FACTORS

The effect of isentropic exponent on three expansion factors will be considered. The three expansion factors are:

Buckingham Expansion Factor (upstream version) – AGA Report No. 3

$$Y = 1 - (0.41 + 0.35 \beta^4) \frac{\Delta P}{Pk} \quad (1)$$

where:

β = diameter ratio, $\frac{\text{bore diameter}}{\text{pipe diameter}}$, dimensionless

k = isentropic exponent, dimensionless

ΔP = differential pressure, MPa

P = static line pressure, MPa

AGA Report No. 3 Proposed Orifice Expansion Factor

$$Y = 1 - (0.3625 + 0.1027 \beta^4 + 1.132 \beta^8) \left(1 - \frac{P_{f2}}{P_{f1}}\right)^{\frac{1}{k}} \quad (2)$$

where:

β = diameter ratio, $\frac{\text{bore diameter}}{\text{pipe diameter}}$, dimensionless

k = isentropic exponent, dimensionless

P_{f2} = downstream static pressure, MPa
 P_{f1} = upstream static pressure, MPa

Adiabatic Expansion Factor

$$Y = \left\{ \left(\frac{k\tau^{\frac{2}{k}}}{k-1} \right) \left(\frac{1-\beta^4}{1-\beta^4\tau^{\frac{2}{k}}} \right) \left(\frac{1-\tau^{\frac{k-1}{k}}}{1-\tau} \right) \right\}^{0.5} \quad (3)$$

where:

β = diameter ratio, $\frac{\text{throat diameter}}{\text{pipe diameter}}$, dimensionless
 k = isentropic exponent, dimensionless
 τ = pressure ratio, $\frac{P_{f2}}{P_{f1}}$, dimensionless

AGA Report No. 3 suggests a value of 1.3 be used for the isentropic exponent value for natural gas. This recommendation is based on the assertion that the expansion factor is not sensitive to small variations in isentropic exponent. Figure 10 shows the sensitivity of the three expansion values shown above to isentropic exponent. The sensitivity values are shown as a function of the dimensionless ratio dP/P . The chart shows the sensitivity values up to a value of $dP/P = 0.3$. AGA Report No. 3 limits the use of the orifice expansion factor to a value of 0.2. The proposed orifice expansion factor is limited to values of 0.25 or less for dP/P .

Isentropic exponent values for natural gas were seen to vary 1% at low pressures from the constant value of $k = 1.3$. High ratios of dP/P are more likely to be experienced at pressures near atmospheric pressure. A bias of 0.1% in natural gas orifice flow measurement could result when using $k = 1.3$ at low pressure with a high dP/P . A bias of 0.15% in natural gas subsonic Venturi flow measurement could result when using $k = 1.3$ at low pressure with a high dP/P .

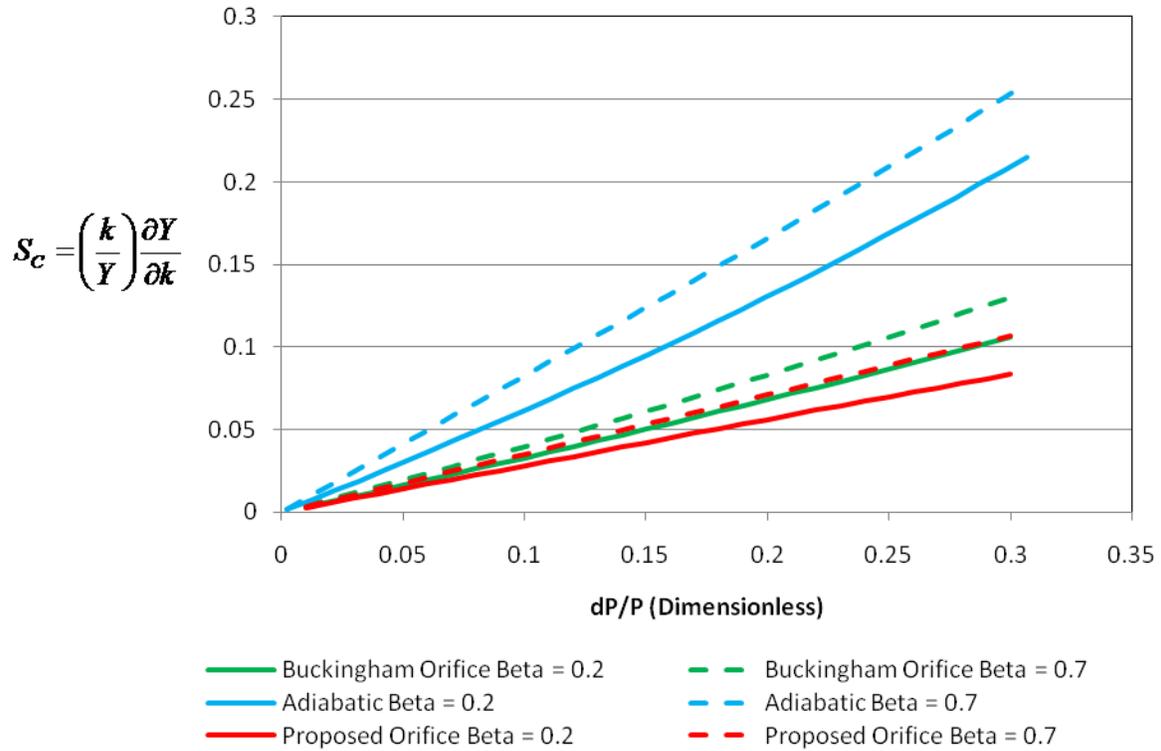


Figure 10. Sensitivity of Expansion Factor Values to Isentropic Exponent at $k = 1.3$

Figure 11 is a plot of expansion factor values calculated using the orifice expansion factor formula and the orifice expansion factor that is being considered for adoption by the natural gas industry. The adoption of the new expansion factor is intended to address the bias in expansion factor that may be as high as 0.5%. The errors in flow measurement due to the use of constant isentropic exponent values are of the same order as the errors being addressed by the proposed expansion factor.

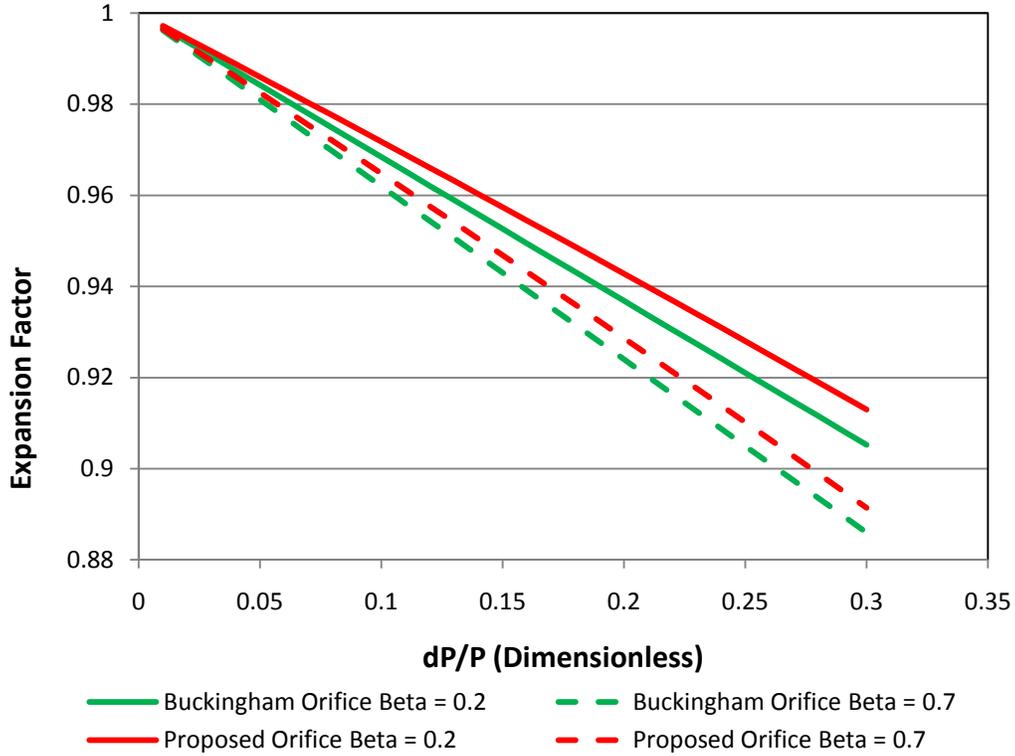


Figure 11. Orifice Expansion Factor Values

DISCHARGE COEFFICIENT VALUES FOR ORIFICE AND SUBSONIC VENTURI FLOWMETERS

The equation for the orifice flowmeter discharge coefficient is given in AGA Report No. 3. The functional form of the equation in AGA Report No. 3 is:

$$Cd = f(\beta, Red^{-0.7}) \quad (4)$$

A theoretical equation for the discharge coefficient of a subsonic Venturi is shown below.

$$Cd = 0.9975 - 0.00653 \left(\frac{1E6}{Red} \right)^{0.2} \quad (5)$$

The sensitivity of the orifice discharge coefficient equation and the subsonic Venturi equation shown in Equation 5 is shown in Figure 12. The sensitivities of the two discharge coefficient equations to absolute viscosity are low but only if equations of the form given in AGA Report No. 3 and in Equation 5 are used. In Equation 4 the pipe Reynolds number has been raised to the -0.7 power. In Equation 5 the throat Reynolds number has been raised to the -0.2 power. The exponents associated with the Reynolds numbers serve to linearize the data in both cases. The linearization results in low sensitivity of calculated discharge coefficient to Reynolds number and therefore low sensitivity to absolute viscosity. If an equation for discharge coefficient is a high order polynomial then the errors in flow measurement could be quite high.

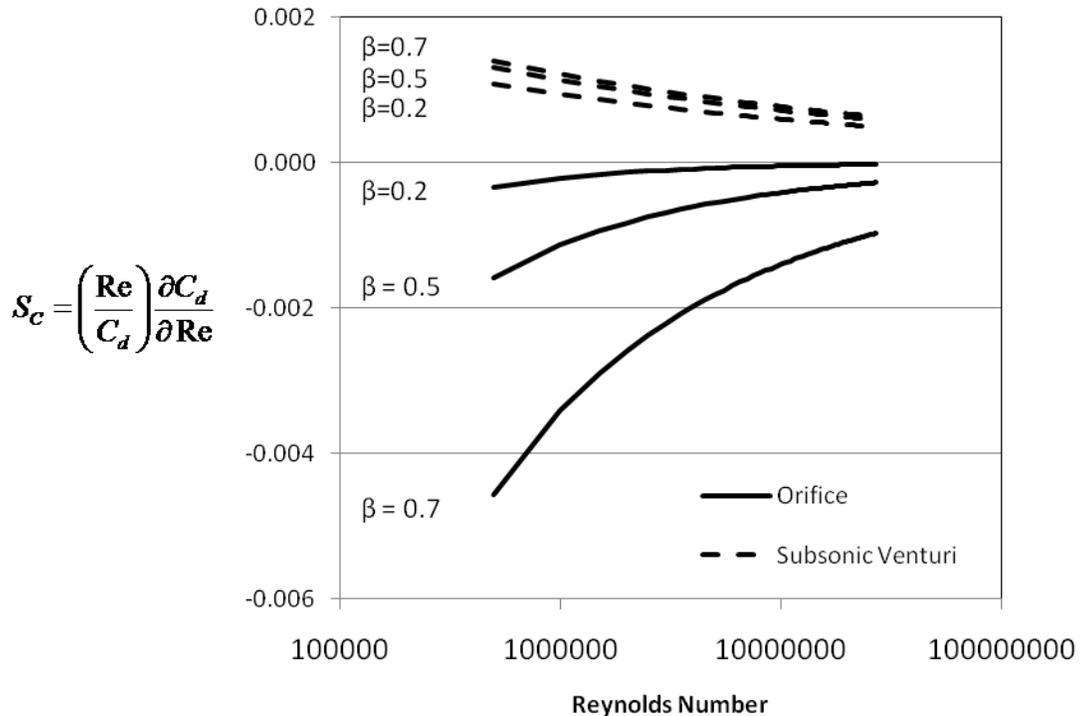


Figure 12. Sensitivity of Orifice and Subsonic Venturi Discharge Coefficient Values to Isentropic Exponent

CONCLUSIONS

Constant values for isentropic exponent and absolute viscosity are commonly used for the calculation of gas flowrates through differential producing flowmeters. The use of constant values is based on perfect gas assumptions and the assumption of low sensitivity. These assumptions are often wrong and can lead to significant errors in calculated flowrate. REFPROP 8.0 is recommended as a source of accurate thermodynamic and transport property values.

The use of constant isentropic exponent values is based on the assumption that perfect gas isentropic gas values would produce accurate flow calculations. Natural gas isentropic exponents have been shown to vary by 15% when pressure is increased from 0.101325 MPa to 10 MPa and varies over a 2% range at atmospheric pressure due to variations in gas composition. Air isentropic exponents were shown to vary by 6% when pressure is increased from 0.101325 MPa to 10 MPa. The dimensionless ratio of differential pressure to static line pressure, dP/P , is used to describe the gas velocity and expansion effects through differential producing flowmeters. At $dP/P = 0.2$ the bias error in natural gas flow measurement due to the use of $k = 1.3$ can be as high as 0.15% at atmospheric pressure. When the adiabatic expansion factor is used to measure natural gas the bias errors in flow measurement can be 0.25% at atmospheric pressure and can exceed 2.5% at 10 MPa. The bias errors in the measurement of air when using the adiabatic expansion factor with $k = 1.4$ can be 1% at 10 MPa.

Substantial bias errors due to the use of constant or incorrect absolute viscosity values can occur if discharge coefficient values are a function of high order polynomials. The constant value used by the natural gas industry has been shown to be low by 10% at atmospheric pressure and by as much as 25% at 10 MPa. The absolute viscosity of air varies by over 6% when pressure is increased from atmospheric pressure to 10 MPa.

REFPROP 8.0 is recommended as a source of live thermodynamic and transport properties for use by the natural gas and other industries. Recent publications have shown REFPROP 8.0 compares very favorably to calculations performed using AGA 8, AGA 10, and experimental natural gas absolute viscosity values.

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