Comparisons of Natural Gas Orifice Meter Calculations using 2012 and 1992 US Standards

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Abstract

Research since 1992 has led to the publication in 2012 of new United States standards for orifice meter calculations. The most important change is the use of a new equation for the quantity known as the expansion factor. This paper presents comparisons of natural gas orifice meter calculations for the 2012 and 1992 US standards for permissible ranges of orifice meter sizes and operating conditions where differences between the 2012 and 1992 US standards are greatest. These comparisons should be useful for selection of orifice plate bore diameters to achieve desired differential pressure operating ranges.

Introduction

The focus of this paper is on the differences between the 2012 and 1992 US standards for flange tapped orifice meters, with a primary interest in changes in the equation for the expansion factor and changed limits for the ratio of differential pressure to absolute upstream static pressure. The 1992 standard (1) is Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids, published jointly by AGA (American Gas Association), API (American Petroleum Institute), and GPA (Gas Processors Association). The 2012 standard (2) is Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids – Concentric, Square-edged Orifice Meters, published jointly by AGA and API.

In the following sections of this paper, the equations pertinent to the focus of this paper are first discussed; then calculations and plots are presented which illustrate the differences in the 1992 and 2012 flange tapped orifice meter expansion factors and the limited conditions for which the 2012 standard allows the continued use of the 1992 expansion factor (Y1) equation; then calculations are presented to illustrate orifice meter operation at the limits of the ratio of differential pressure to absolute upstream static pressure (x1) for the 1992 and 2012 standards and the fact that not only is the 2012 standard more accurate than the 1992 standard, but can also be used over a larger range of pipeline pressures without changing the orifice plate.

Discussion of the Differences in the 1992 and 2012 Flange Tapped Orifice Meter Standards

The following equation for the volume flow rate for flange tapped orifice meters Qv is the same for both the 1992 and 2012 US standards. However, as will be discussed subsequently, the calculations of some of the quantities in the equation have been changed in the 2012 standard to achieve improved accuracy.

Equation 1.0 Qv = 359.072* Y1*Cd*Ev*(d^2)*SQRT(RHOTP*Hw)/RHOS

where

Qv is the volume flow rate in cubic feet per hour at reference base conditions (Ts, Ps);

Y1 is the expansion factor (dimensionless);

Cd is the coefficient of discharge for the flange-tapped orifice meter (dimensionless);

d is the orifice plate bore diameter, in inches, calculated at flowing temperature (Tf);

Ev is the velocity of approach factor (dimensionless);

Hw is the orifice differential pressure, in inches of water at 60 °F;

RHOTP is the gas density at upstream flowing conditions (Tf, Pf) in pounds mass per ft^3;

RHOS is the gas density at reference base conditions (Ts, Ps) in pounds mass per ft^3.

A significant difference between the standards is the 2012 standard allows for a larger range for x1, the ratio of differential pressure to absolute upstream static pressure. The 1992 standard had the upper limit criterion x1 (1992 standard) $\leq$0.2. In contrast, the 2012 standard has the upper limit criterion x1 (2012 standard) <0.25.

Differences in the 1992 and 2012 Flange Tapped Orifice Meter Expansion Factors

The figure below shows the 1992 expansion factor versus the diameter ratio with a variety of plots varying based on x1, the ratio of the differential pressure to the absolute static pressure. The calculations for this and subsequent plots utilize k = 1.3 for the value of the isentropic exponent, which is commonly used for natural gases. The ratio x1 is varied from 0.01 to 0.25 by increments of 0.02. The diameter ratio, β is varied from 0.1 to 0.75 in increments of 0.05. The plot extends beyond the 1992 standard upper limit criterion x1 (1992 standard) $\leq$0.2 to allow comparison in the full range of the 2012 standard.

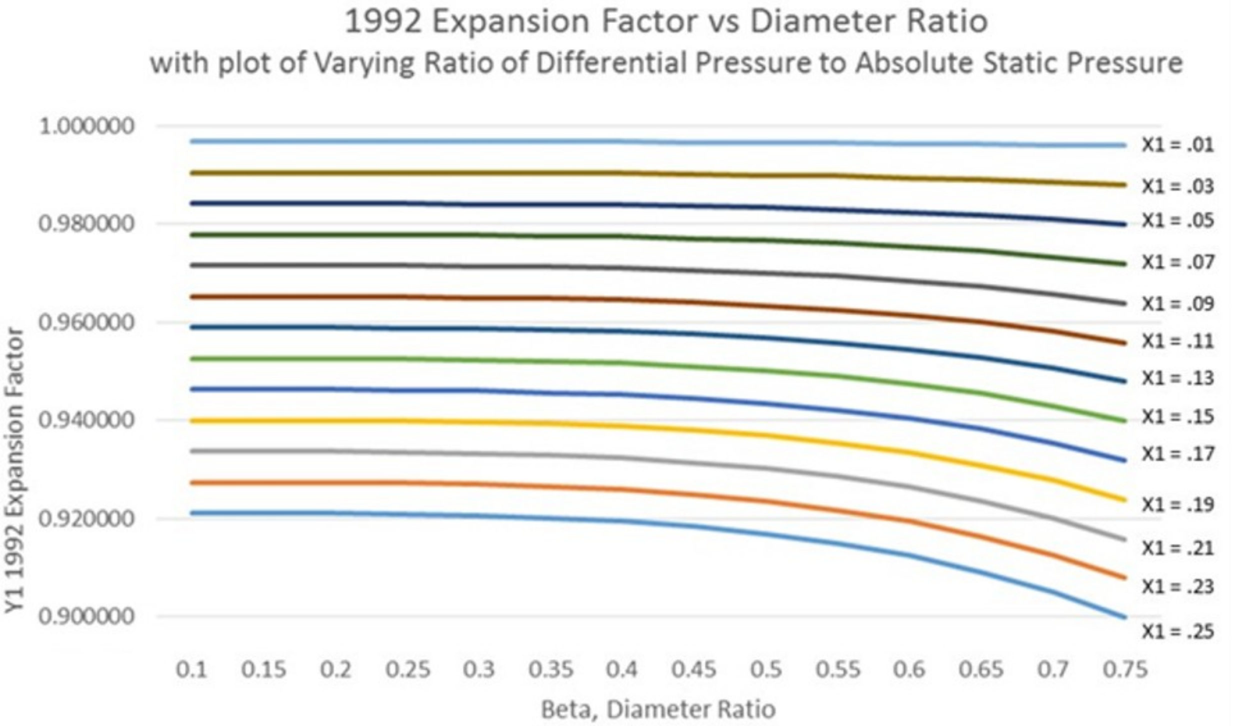

Figure 1: 1992 standard calculation for Y1 with k = 1.3 plotted against β and varying x1

The expansion factor Y1 is calculated in the 1992 standard using the following formula:

Equation 1.1 Y1 (1992 standard) = $1 - (0.41 + 0.35\ \beta^4)\ (x1/k)$

where

Y1 (1992 standard) is the expansion factor (dimensionless) given in the 1992 standard;

β is the diameter ratio (dimensionless);

x1 is the ratio of the differential pressure to the absolute upstream static pressure (dimensionless);

k is the isentropic exponent (dimensionless).

As expected, as the diameter ratio β is increased, the expansion factor decreases – at first gradually, but then as β =0 .75 is approached the decrease is greater with each incremental change to the diameter ratio. The rate of decrease also varies based on x1. The larger the value of x1, then the greater the variation in the expansion factor from $\beta = 0.1$ to $\beta = 0.75$.

The next figure, Figure 2, shows the 2012 expansion factor versus the diameter ratio with a variety of plots varying based on x1, the ratio of the differential pressure to the absolute static pressure. As with the plot already given for the 1992 standard, the ratio x1 is varied from 0.01 to 0.25 by increments of 0.02. The diameter ratio, β is varied from 0.1 to 0.75 in increments of 0.05.

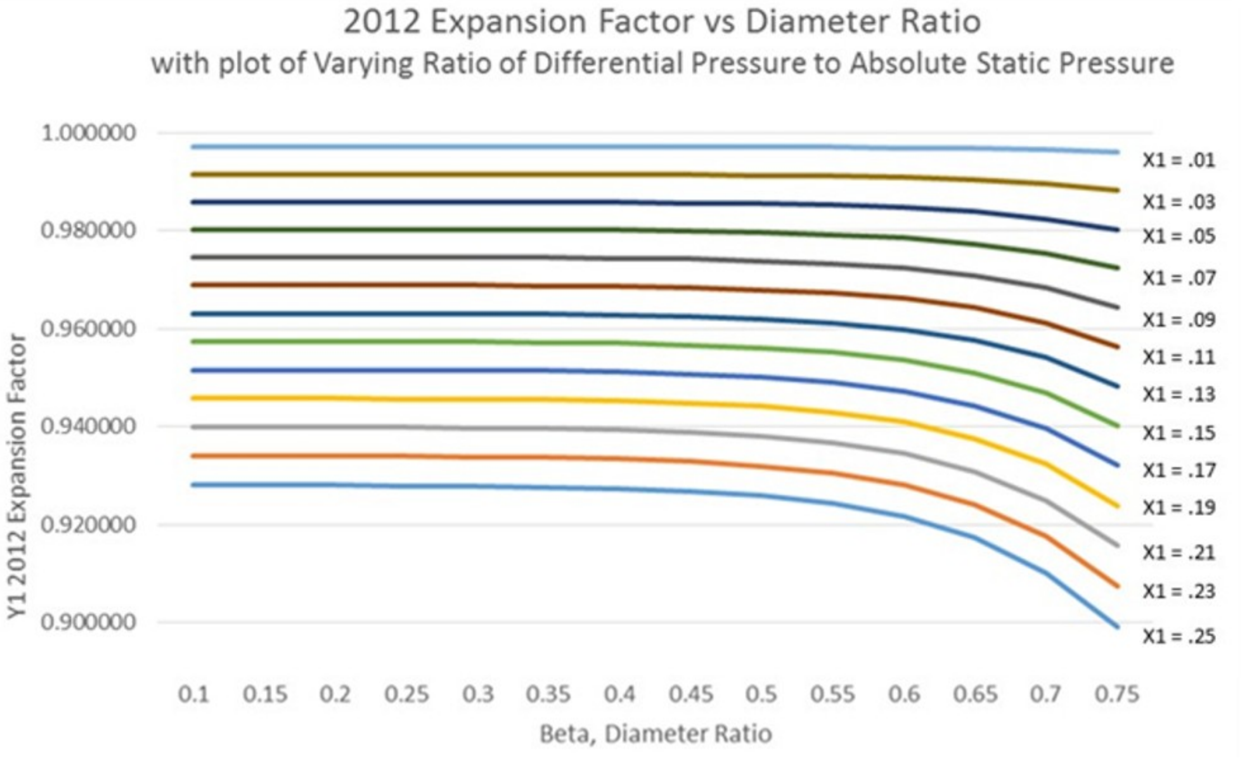

Figure 2: 2012 standard calculation for Y1 with k = 1.3 plotted against β and varying x1

The expansion factor Y1 is calculated based in the 2012 standard using the following formula:

Equation 1.2 $\quad Y1\ (2012\ \text{standard}) = 1 - (0.3625 + 0.1027\ \beta^4 + 1.132\ \beta^8)\ \{1-(1-x1)^{(1/k)}\}$

where

Y1 (2012 standard) is the expansion factor (dimensionless);

β is the diameter ratio (dimensionless);

x1 is the ratio of the differential pressure to the absolute upstream static pressure (dimensionless);

k is the isentropic exponent (dimensionless).

As expected, as the diameter ratio β is increased, the expansion factor decreases – at first gradually, but then as β = 0.75 is approached the decrease is greater with each incremental change to the diameter ratio. The rate of decrease also varies based on x1. The larger the value of x1, then the greater the variation in the expansion factor from β = 0.1 to β = 0.75. The rate of decrease is greater for the 2012 standard versus the 1992 standard.

When deciding on which expansion factor equation to use between the 1992 and 2012 standards, the guidelines provided by AGA/API in the standard titled "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids – Concentric, Square-edged Orifice Meters" states that

"...if the calculated difference between the expansion factor equations exceeds 0.25%, then a variable flow bias, which is a function of diameter ratio (β), isentropic exponent (κ), and $\Delta P / Pf_1$ *ratio* (x_1)*, will be experienced unless the new expansion factor equation is utilized."*

The next figure, Figure 3, shows the difference percentage between the two standards plotted against the diameter ratio (β). The expansion factor difference percentage is calculated by first subtracting the 1992 expansion factor from the 2012 expansion factor. The difference is then divided by 2012 Expansion Factor and the quotient is multiplied by 100. The formula for this is as follows:

Equation 1.3 $\quad \{(Y1\ (1992\ \text{standard}) - Y1\ (2012\ \text{standard})) / Y1\ (2012\ \text{standard})\}\ 100$

As with the previous two figures, x1 is varied from 0.01 to 0.25 by increments of 0.02 and the diameter ratio, β is varied from 0.1 to 0.75 in increments of 0.05.

The figure identifies a general change in difference percentage with β, the diameter ratio, when the β is greater than 0.6. Note that when β is greater than 0.6, the difference percentage curves upward. According to AGA Report No. 3, Part 1 (2012 standard), with respect to the combined uncertainty in the volume flow rate Qv from all sources, including installation effects, *"the lowest relative combined uncertainty levels occur over a diameter ratio range of 0.10 to 0.60."* Therefore, when considering the 1992 and 2012 standards, diameter ratios of 0.6 or less are preferred. Above 0.6, both standards are prone to increased levels in the combined uncertainty in the volume flow rate Qv.

In Figure 3, there is a bold face line drawn (in red if color is available to the reader) horizontally across the plot at the 0.25% point referred to in the referenced quote above. What the plot clearly shows is that only where x1 is 0.05 or less does the 1992 standard yield an estimation of the expansion factor within 0.25% of the 2012 standard for the full range of diameter ratios. Since the expansion factor uncertainty and flowrate uncertainties are directly correlated, then the accuracy issue is also present in the flowrate Qv.

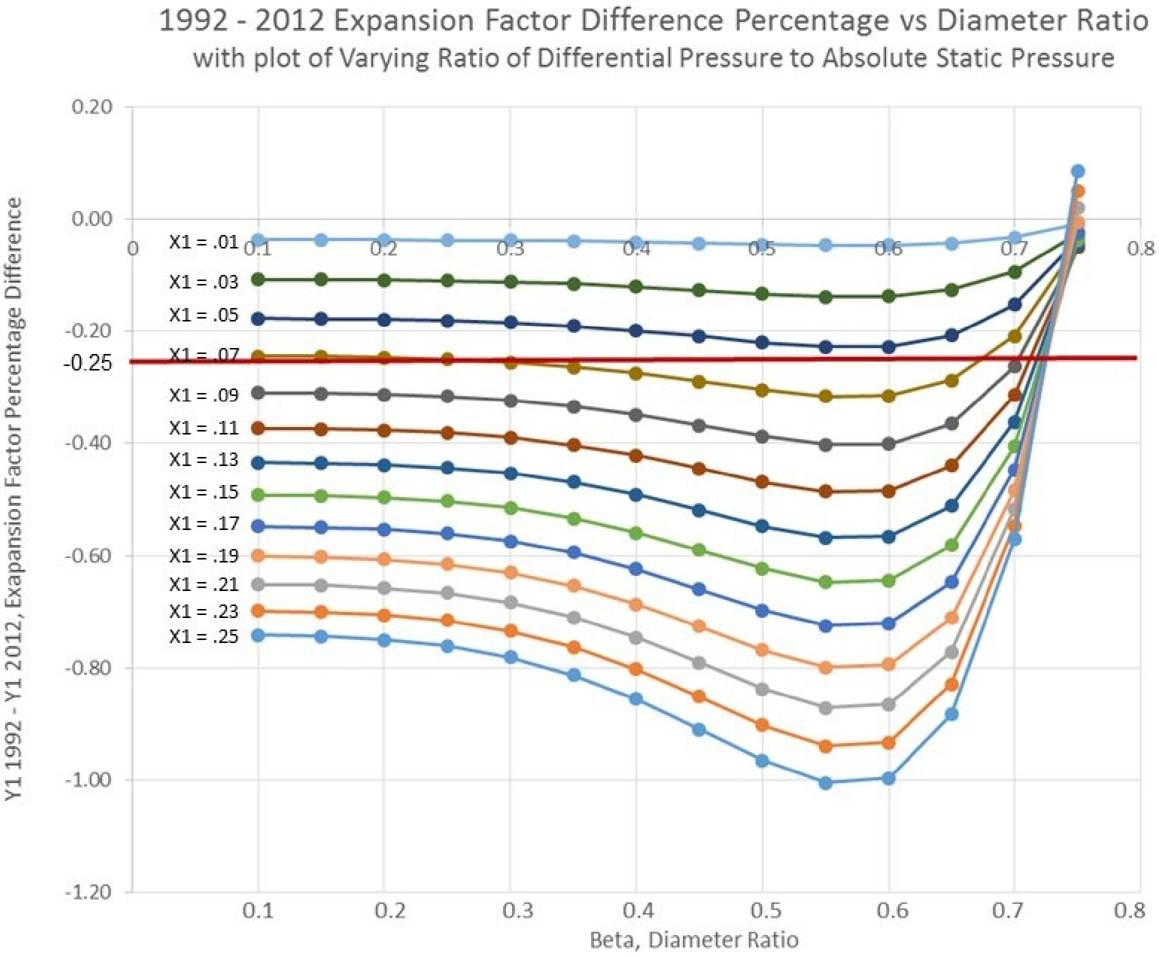

Figure 3: 1992 – 2012 Y1 difference percentage with k = 1.3 plotted against β and varying x1

Orifice Meter Operation at the Limits of the Ratio of Differential Pressure to Absolute Upstream Static Pressure for 1992 and 2012 Standards

Calculations are presented below to illustrate orifice meter operation at the upper limits of x1, the ratio of differential pressure to absolute upstream static pressure, for the 1992 and 2012 standards. The use of equations given in the 1992 and 2012 standards for the uncertainties of the calculated expansion factors will illustrate the fact that the 2012 standard is significantly more accurate than the 1992 standard at the upper limit of x1, the ratio of differential pressure to absolute upstream static pressure, for the 1992 standard. Further, because the upper limit of x1 for the 2012 standard is greater than for the 1992 standard, the 2012 standard can also be used over a larger range of pipeline pressures and/or orifice meter differential pressures without changing the orifice plate.

For the calculations below, the orifice meter consists of a carbon steel meter tube equipped with flange taps and a stainless steel orifice plate. Static pressure measurements are taken from the upstream tap.

Calculations of volume flow rate and other quantities will be performed for four cases, Case A, Case B, Case C, and Case D. The cases are summarized as follows:

- **Case A** – Compares Qv and Y1 using the 1992 and 2012 standards using x1 = 0.2, which is the upper limit of the 1992 standard where $x1 \leq 0.2$. Differences in the flow rate indicate calculations of the flow rate were underestimated when done under the given conditions in the past using the 1992 standard. The calculations were also subject to greater error or uncertainty when using the 1992 standard in comparison to the 2012 standard.
- **Case B** – Calculates Qv and Y1 using the 2012 standard where x1 = 0.249999, which approaches the upper limit of the 2012 standard, $x1 < 0.25$. The larger range of x1 enables a company to accurately calculate flowrates for a given orifice over larger ranges of differential pressure and/or static pressure than the 1992 standard.
- **Case C** – Considers a situation using the 1992 standard where capacity control has been used to achieve the value of the ratio of differential pressure to absolute upstream static pressure, $x1 \leq 0.2$. Capacity control refers to adjusting downstream flow to achieve the differential pressure which yields $x1 \leq 0.2$. The drawback when the static pressure has decreased to adjusting the differential pressure to meet the x1 criterion is it will result in a lower flow rate.
- **Case D** – Also considers a situation using the 1992 standard where the orifice plate is changes to keep flow rate high while simultaneously maintaining $x1 \leq 0.2$. The primary drawback of this alternative is the additional operations cost of the orifice plate change.

Case A: Compare Qv and Y1 using the 1992 and 2012 standards using x1 = 0.2

Case A is characterized by x1 = 0.2 (the 1992 standard upper limit is x1 (1992 standard) ≤ 0.2).

The inputs to the calculations for Case A are listed below. Descriptions of these input variables and how they are used in the calculation of the volume flow rate Qv are presented in the 1992 and 2012 standards.

d is the mean orifice bore diameter at *Tr* of 68 °F, in inches = 1.000.

D is the mean meter tube internal diameter at *Tr* of 68 °F, in inches = 2.000.

Hw is the average differential pressure, in inches of water at 60 °F = 200.0.

Pb is the contract base pressure, in psia = 14.73.

Pf1 is the upstream absolute static pressure, in psia = 36.092.

Tb is the contract base temperature of 60 °F, in degrees Rankine (60 °F + 459.67) = 519.67.

Tf is the flowing temperature of 68 °F, in degrees Rankine (68 °F + 459.67) = 527.67.

k is the isentropic exponent = 1.3.

a1 is the linear coefficient of thermal expansion for the stainless steel orifice plate, in inches per inch-°F = 0.00000925.

a2 is the linear coefficient of thermal expansion for the carbon steel meter tube, in inches per inch-ºF = 0.00000620.

VISC is the dynamic viscosity, in pounds mass per foot-second = 0.0000069, in centipoises = 0.010268.

RHOTP is the gas density at upstream flowing conditions (Tf, Pf) in pounds mass per ft^3 = 0.112734.

RHOS is the gas density at reference base conditions (Ts, Ps) in pounds mass per ft^3 = 0.046578.

x1 is the ratio of differential pressure to absolute upstream static pressure = 0.2; the 1992 standard upper limit is x1 (1992 standard) $\leq$ 0.2).

Calculations were performed for both the 1992 standard and the 2012 standard. The outputs from the Case A calculations which are of interest are the following.

Qv (1992 standard) = 21355.68 cubic feet per hour

Qv (2012 standard) = 21528.16 cubic feet per hour

Y1 (1992 standard) = 0.933558

Y1 (2012 standard) = 0.941115

Y1 (1992 standard) is 0.80% smaller than Y1 (2012 standard). Because all calculations are nearly the same for the 1992 and 2012 standards except for the calculation of Y1, and Qv is proportional to Y1, it follows that Qv(1992 standard) is 0.80% smaller than Qv(2012 standard).

It also is of interest to calculate the uncertainties of Y1 (1992 standard) and Y1 (2012 standard). U [Y1 (1992 standard)] is the %uncertainty of Y1 (2012 standard) at the 95% confidence level. U [Y1 (2012 standard)] is the %uncertainty of Y1 (1992 standard) at the 95% confidence level. The 1992 standard and the 2012 standard utilize the following equations for these uncertainties.

U [Y1 (1992 standard)] = +/- 4.0*x1 = +/- 4.0*0.2 = +/- 0.80%

U [Y1 (2012 standard)] = +/- 2.6*x1 = +/- 2.6*0.2 = +/- 0.52%

These results and the fact that in the calculations above Y1 (1992 standard) is 0.80% smaller than Y1 (2012 standard) indicates that there was bias in Y1 (1992 standard).

Case B: Calculate Qv and Y1 using the 2012 standard where x1 Approaches the Upper Limit

Calculations of volume flow rate will now be performed for Case B. Case B is characterized by the value of the ratio of differential pressure to absolute upstream static pressure, x1 = 0.249999 (the 2012 standard upper limit is x1 (2012 standard) < 0.25).

The inputs to the calculations for Case B are identical to the inputs for Case A except that Pf1, the upstream absolute static pressure, in psia = 28.87. Note that because the upper limit in the 1992 standard is x1 (1992 standard) $\leq$ 0.2, the calculations in Case B will be performed only for the 2012 standard.

The outputs from the Case B calculations which are of interest are the following.

Qv (2012 standard) = 18939.25 cubic feet per hour

Y1 (2012 standard) = 0.925887

Because the static pressure in the Case B calculations is lower than in the Case A calculations, both the density RHOTP of the flowing natural gas and Y1 (2012 standard) are lower and consequently Qv is lower for Case B than Case A.

The calculation of U [Y1 (2012 standard)], the %uncertainty of Y1 (2012 standard) at the 95% confidence level for Case B yields the following result.

U [Y1 (2012 standard)] = +/- 2.6*x1 = +/- 2.6*0.249999 = +/- 0.65%

Note that because the upper limit in the 1992 standard is x1 (1992≤ 0.2, the calculations in Case B should not be performed using Y1 (1992 standard). In fact, in the upstream static pressure range from Pf1= 36.092 psia (Case A) to Pf1= 28.87 psia (Case B), x1 varies from x1=0.2 (Case A) to x1=0.249999 (Case B) so that x1 is outside the xi upper limit in the 1992 standard except when x1 = 0.2. This means that the 2012 standard allows a significant increase in the operating range of the upstream static pressure compared to the 1992 standard. The increased upstream static pressure operating range using the 2012 standard includes conditions which, using the 1992 standard, would have required an orifice plate change in order to achieve the same flow rates.

Without an orifice plate change the largest flow rate possible with the Case B pressure Pf1 = 28.874 psia which is within the 1992 standard limit for x1 is to control Hw at 160.0 inches H2O, so that x1= 0.2. It will be shown in Case C that this scenario results in a significantly lower volume flow rate than in Case B (2012 standard). The scenario of an orifice plate change in order to achieve a defined flow rate using the 1992 standard will be presented in Case D.

Case C – Shows the use of capacity control to maintain x1 (1992 standard) ≤ 0.2

Calculations of volume flow rate will now be performed for Case C. Case C is characterized by capacity control to achieve the value of the ratio of differential pressure to absolute upstream static pressure, x1 = 0.2. The calculations in Case C will be performed only for the 1992 standard.

The inputs to the calculations for Case C are identical to the inputs for Case B except the differential pressure Hw = 160.0 inches H2O to meet the requirement that x1 = 0.2 when Pf1, the upstream absolute static pressure, in psia = 28.874.

The outputs from the Case C calculations which are of interest are the following.

Qv (1992 standard) = 17084.03 cubic feet per hour

Y1 (1992 standard) = 0.933559

U [Y1 (1992 standard)] = +/- 4.0*x1 = +/- 4.0*0.2 = +/- 0.80%

This flow rate, which is the maximum possible flow rate when Pf1=28.874 psia using the 1992 standard, is 9.8% lower than Qv (2012 standard) = 18939.25 cubic feet per hour, calculated in Case B. In the use of the 1992 standard, the orifice plate would require replacement by an orifice plate with a larger bore diameter in order achieve a larger flow rate within the 1992 standard limit, x1 (1992 standard) ≤ 0.2. This calculation is made in Case D.

Case D - Considers change of the orifice plate to keep flowrates up while maintaining x1 (1992 standard) $\leq$ 0.2

Calculation of the minimum orifice plate bore diameter will now be performed for Case D. Case D is characterized by calculations using the 1992 standard to determine the orifice bore diameter which matches Qv (2012 standard) = 18939.25 cubic feet per hour, calculated in Case B, with the requirement x1 = 0.2.

The other inputs to the calculations for Case D are identical to the inputs for Case C including the differential pressure Hw=160.0 inches H2O and Pf1, the upstream absolute static pressure, in psia= 28.874.

The calculated orifice bore diameter for Hw = 160.0 inches H2O is d = 1.049 inches. Because this orifice bore diameter corresponds to the limit x1 = 0.2, a larger orifice bore diameter would be used in practice to allow for a greater operating range. For example, for Hw = 120.0 inches H2O, d = 1.110 inches, for Hw = 80.0 inches H2O, d = 1.204 inches, and for Hw = 40.0 inches H2O, d = 1.377 inches. Although the choice of d=1.377 inches would provide the largest operating range for further decreases in the static pressure at the upstream flange tap, the diameter ratio of 0.689 is in the range of increased combined uncertainty in the volume flow rate Qv from all sources (above 0.6).

Conclusions

This paper has presented comparisons of natural gas orifice meter calculations for the 1992 and 2012 US standards with emphasis on changes caused by the use of a new more accurate equation for the expansion factor. Comparisons of expansion factor calculations using the 1992 and 2012 standards show that the 1992 expansion factors agree with the 2012 expansion factors within +/-0.25% only over about one fifth of the allowed range of the 2012 expansion factors. Only when x1 is 0.05 or less does the 1992 standard yield an estimation of the expansion factor within 0.25% of the 2012 standard over the full range of the diameter ratio.

It is clear from the set of volume flow rate calculations presented in this paper that the new expansion factor equation in the 2012 orifice meter standard provides not only improved accuracy in natural gas flow rate calculations but increases the allowed operating ranges for the differential pressure and/or the static pressure without orifice plate replacements. The improved accuracy is of general benefit to commerce through reductions in bias in custody transfer. The increases in allowed operating ranges are of benefit to the natural gas industry in reducing flow measurement operating costs.

References

1. Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids, Part 1, AGA Report No. 3, Part 1 (American Gas Association Report No.3, Part 1), API 14.3.1 (American Petroleum Institute Manual of Petroleum Measurement Standards, Chapter 14.3.1), and GPA 8185, Part 1 (Gas Processors Association Standard GPA 8185, Part 1), 1992.

2. Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids – Concentric, Square-edged Orifice Meters, Part 1, AGA Report No. 3, Part 1 (American Gas Association Report No.3, Part 1), API 14.3.1 (American Petroleum Institute Manual of Petroleum Measurement Standards, Chapter 14.3.1), 2012.