INSTALLATION AND OPERATION ERRORS IN GAS MEASUREMENT
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Introduction

Installation errors may occur when an instrument is used in a manner different from how it was calibrated. For example, suppose that a temperature sensor is calibrated in a stirred, constant temperature bath. During calibration, the sensor is in thermal equilibrium with the circulating fluid, and the fluid and sensor temperatures are the same. However, let the same sensor be used to measure the temperature of gas flowing through a pipe at low velocity. If the pipe wall temperature is different from the flowing gas temperature, convection heat transfer will occur between the gas and the pipe wall, radiation heat transfer between the pipe wall and the sensor, and convection heat transfer between the sensor and the flowing gas. The sensor is not in thermal equilibrium with the flowing gas and the sensor temperature will be different from the flowing gas temperature.

Flow meter installation errors can occur when a meter is calibrated in one piping configuration, and then is used in a different configuration. Installation errors often occur when the flow meter measurement is sensitive to the shape of the gas flow velocity profile.

Between 1980 and 2005, considerable research was performed to better understand the magnitude and direction of installation errors for orifice meters, turbine meters, and ultrasonic meters. The research results were critically reviewed by industry measurement standards committees, and served as the basis for affirmation or revision of the installation specifications. This paper reviews some types of installation and operation errors found for orifice meters, gas ultrasonic meters, and turbine meters.

Orifice Meters

Orifice meters are seldom flow-calibrated either in a laboratory or in-situ before being installed in the field. Instead, orifice coefficient, C_d, values are calculated (as a function of pipe diameter, β ratio and Reynolds number) using the RG correlation of orifice meter "baseline" flow calibration data in AGA Report No. 3, Part 1 [1990](1).

The RG equation is a least-square-error correlation of 10,192 "baseline" flow calibration data points taken in the United States and in Europe for orifice meters with flange taps, corner taps and/or D and D/2 pressure taps. There were 5,734 data points taken for flange taps alone. The "baseline" tests were carried out using commercial orifice plates with β values between $\beta = 0.10$ and $\beta = 0.75$ and commercial meter tubes with diameters from D = 2-inches to D = 10-inches flowing either liquid or gas.

Figure 1 shows a graph of the baseline calibration data from seven different laboratories for a 10-inch diameter meter tube and $\beta = 0.57$. Three labs performed tests flowing water; four labs flowed air or natural gas. C_d values calculated from the RG orifice equation are shown by the solid curve. The upper and lower 95% confidence limits for the RG equation are shown as dashed lines. Note the scatter in the baseline data. The data are correlated by the RG equation, but few points lie exactly on the solid curve.

When the baseline calibration tests were performed, long straight lengths of meter tube and flow conditioners were installed upstream of the orifice plates. Whetstone(2) reported that the tests performed by the National Bureau of Standards (now the National Institute of Standards and Technology) had upstream meter tube lengths longer than 40 diameters and a Sprenkle flow conditioner between the meter tube and an inlet header. The flow conditioner removed swirl that might have been produced by the header, and the long upstream length allowed a turbulent pipe-flow velocity profile to develop in the meter tube. Typical orifice meter installations in the European baseline calibration tests had even longer lengths of straight pipe upstream of the orifice plate.

If an orifice flow meter is installed in a baseline configuration, with commercial meter tube and plates that meet the specifications of AGA Report no. 3, Part 2 [2000](3) then it is expected that the C_d values will lie within the upper and lower 95% confidence intervals for the RG equation. In 1992, orifice meter calibration tests were performed in the High Pressure Loop of the GRI Metering Research Facility (MRF) using a 10-inch commercial meter tube and orifice plates. The upstream meter tube length was 45 D, and a Sprenkle flow conditioner was installed ahead of the meter tube. This installation configuration was similar to the baseline configuration used in the 10-inch NBS water tests. The MRF results for β = 0.60 are compared in Figure 2 to the NBS data for β = 0.57. The dashed curves represent the 95% confidence limits for the RG orifice equation. The MRF natural gas data for β = 0.60 lie slightly below the RG equation curve, as do the NBS water calibration data for β = 0.57.

Few orifice meter field installations have 45 D of straight pipe upstream of the orifice plate. Many installations have shorter upstream lengths with pipefittings or a header upstream of the meter tube that may produce swirl and/or distort the axial velocity profile. Such field installations may produce an installation error (distinct from the RG equation uncertainty) because the field installation differs from the baseline installations used in generating the orifice coefficient database.

Orifice Meter Installation Error

The shape of the axial pipe flow velocity profile and the swirl velocity component can affect orifice coefficient. Installation factors that influence axial and swirl velocity components include pipe wall roughness and the proximity to the orifice plate of upstream pipefittings such as tees, elbows, valves, reducers, expanders and headers.

Values of installation error can be determined experimentally. The percent installation error with respect to the orifice meter baseline C_d value is defined in equation (1).

$$\Delta C_d\left(\%\right) = 100 * \left(\frac{C_d - C_{d\,baseline}}{C_{d\,baseline}}\right) \qquad (1)$$

The reference "baseline" C_d value is an experimental value determined from a calibration test using the same orifice plate at the same value of Reynolds number in a baseline orifice meter installation. Note that the reference value is not the value of C_d calculated from the RG equation for the same value of beta ratio and Reynolds number.

Ideal (Baseline) Velocity Profile

The baseline velocity profile in an orifice meter tube is the axial velocity distribution several diameters upstream of an orifice plate for a baseline meter calibration installation. The baseline profile is expected to be close to a "fully-developed", turbulent pipe flow velocity profile. The fully developed velocity profile is symmetrical about the pipe centerline with a zero swirl velocity component. One representation of the fully developed velocity profile is the power-law profile in equation (2).

$$\frac{u}{U} = \left(1 - \frac{r}{R}\right)^{\frac{1}{n}}, \text{ and } \frac{1}{n} = \sqrt{f} \qquad (2)$$

In this equation, R is the pipe radius, r is the distance from the pipe centerline, and u is the axial velocity and U is the velocity on the pipe centerline. The exponent n is a function of the wall friction coefficient, f , which is itself a function of the pipe Reynolds number and the surface roughness.

Non-Ideal Velocity Profile

For orifice meters, a velocity profile that deviates significantly from the shape of the baseline or fully developed profile is a non-ideal profile. Examples of non-ideal profiles for orifice metering include:

- Flat profile, u/U = 1 (the ideal turbulent, pipe-flow velocity profile is rounded)
- Peaked profile (e.g. downstream of a reducer)
- Asymmetrical profile (e.g. downstream of a partially closed gate valve)
- Profile with swirl angles greater than 2° (e.g. downstream of two out-of-plane elbows)
- Profile with a combination of swirl and axial profile distortion (downstream of a header).

The magnitude and sign of the installation error depends on several factors and whether the velocity profile upstream of the orifice plate contains a swirl velocity component.

Non-Swirling Flows

For non-swirling pipe flow, Reader-Harris[4] showed that the percentage installation error is related to the percentage deviation, $\Delta U/U$ (%), of the axial velocity profile from the baseline axial profile.

$$\frac{\Delta C_d}{C_d}(\%) = const. * \beta^{3.5} * \frac{\Delta U}{U}(\%) \qquad (3)$$

For a given percentage of velocity profile deviation equation (3) shows that the percent installation error is greater for high β values (β ~ 0.75) than for low β values (β ~ 0.20). The strong dependency of the percentage installation error on orifice β ratio explains why minimum upstream meter tube lengths recommended for particular piping installations often increase with increasing β. Longer upstream pipe length between the disturbance and the orifice plate help to reduce the percentage velocity profile deviation from the baseline profile and reduce the percentage installation error.

This dependence of installation error on $\beta^{3.5}$ appears to be valid for (1) non-swirling axially symmetric flows (e.g. profile affected by pipe wall roughness), (2) non-swirling asymmetrical flows (e.g. profile is affected by a partially closed valve followed by a tube bundle flow-straightener) and (3) flows with type-2 swirl (profile is affected by a single upstream 45° or 90 ° elbow or a tee).

Figure 3 shows orifice meter installation test results for six β values from β = 0.20 to β = 0.75 for a short, A = 17 D orifice meter tube installed directly downstream of a tee[5]. Data were collected for two sets of differential pressure taps aligned in the same horizontal plane as the tee. Tests were performed flowing natural gas in the MRF at a pressure of 900 psi. A separate set of baseline calibration tests was performed for an upstream meter tube length of A = 45 D downstream of a Sprenkle flow conditioner. The results are plotted as percentage installation error versus $\beta^{3.5}$. Note that the percentage installation error is linear with $\beta^{3.5}$ and that the sign of the error is negative. This means that the actual values of C_d were lower than the baseline values, and that the gas flow rate would be over predicted.

Swirling Flows

The term "swirl" refers to a time-average component of velocity in the cross-flow plane perpendicular to the axis of the meter tube. If the maximum swirl angle measured over the cross-section is less than ± 2°, the flow is considered swirl-free. Mattingly and Yeh[6] described two generic types of swirling flows produced by elbows upstream of the meter tube.

- Type 2 swirl has a dual-eddy swirl pattern with two counter-rotating vortices on either side of the center plane of the elbow. A single, standard long radius elbow produces this type of swirl. Mattingly and Yeh[6] reported values of swirl angle ranging from -14° near the center of the pipe to +8° near the pipe wall.
- Type 1 swirl has a single swirl or vortex pattern with a center close to the center of the pipe. Two closely coupled out-of-plane elbows produce this type of swirl. Mattingly and Yeh[6] reported measuring swirl angles of about ± 20° near the pipe walls, and ~ 0° in the core region around the center of the pipe.

Mattingly and Yeh[6] noted that the swirl decay rates are very different for these two swirl types. For type 2 swirl, the maximum swirl angle would be reduced to less than 2° within a distance of about 12 D. This explains why the installation error results in Figure 3 follow equation (3), a correlation for swirl-free flow. However, for type 1 swirl, a much greater distance of 89 D would be needed to reduce the maximum swirl angle to less than 2°.

Figure 4 shows data for a long, A = 45 D meter tube without a flow conditioner downstream of two out-of-plane 90° elbows. The triangles are data[5] from the MRF. The circles and squares are results reported by Mottram[9] for a 3-inch orifice meter at Surrey Univ. and an 8-inch orifice meter at BHRA. The results are similar for all three laboratories despite differences in pipe roughness, and Reynolds number. Mottram[9] also tested a 3-inch pipe artificially roughened by sand paper. He found that the swirl decayed more rapidly in rough than in smooth pipe.

For upstream meter tube lengths shorter than A = 45 D, the magnitudes of installation error produced by type 1 swirl were even greater[7,8,9]. Figure 5 shows installation error results for an upstream meter tube length of A = 17 D (MRF) and 19 D (Surrey Univ. and BHRA). Note particularly that the sign of the installation error in Figures 4 and 5 shifts from positive (under-registration) to negative (over-registration) as the β ratio increases from β = 0.4 to β = 0.75.

For the test results shown in Figures 4 and 5 a short, straight spacer distance, s, less 2 D in length, separated the first and second out-of-plane elbows. Mattingly and Yeh[6] noted that swirl produced by spaced double out-of-plane elbows is a composite of type 1 and type 2 swirl, depending upon the spacer distance. This suggests that the installation error also varies as a function of spacer length.

Figure 6 is a plot of installation effects results for two out-of-plane elbows with spacer lengths of 1.6D, 5D, 10D and 15D in an A = 45 D long orifice meter. Comparing Figures 4 and 6 it is clear that swirl effects are significant for s = 1.6D, but negligible for s = 15.

Figure 7 is a similar plot of installation effects results for two out-of-plane elbows with spacer lengths of 1.6D, 5D, 10D and 15D in an A = 17 D long orifice meter. Comparing Figures 5 and 7 it is clear that swirl effects are now significant for s = 1.6D and 5D. However, for s = 10D and 15D, the installation effects errors become similar to that for a single 90° elbow.

Headers

Headers are used to measure a high total rate of flow using lower capacity flow meters arranged in parallel. While a header may distribute the flow rate evenly to several meter tubes, the velocity profile at the meter tube inlet is seldom ideal. Flow straighteners and flow conditioners are frequently used to modify the velocity profile upstream of the orifice plate.

Williamson et al[10] investigated the flow from a header configuration commonly used in the gas transmission industry. Gas in a horizontal header barrel flowed out through a vertical tee junction into a riser. From the riser the gas flowed through a 90° elbow into the orifice meter tube. The meter tube was perpendicular to the header barrel, so that the direction of flow resembled that from two spaced 90° elbows.

Williamson et al[10] found that the length of the riser between the header tee and the 90° elbow leading into the meter run had an important effect on the flow field in the meter run. When the riser length exceeded 8D, the flow field in the meter run was dominated by the last elbow producing a type 2 swirl pattern. When the flow field in the header barrel was symmetric and swirl free and the riser length was less than 8D, a type 1 swirl pattern was found in the meter tube. When a swirling, secondary flow was present in the header itself, stronger, unexpected secondary flows were found in the meter tube.

Flow Conditioners

AGA Report No. 3, Part 2, Fourth Edition[3] provides for the use of tube bundle straightening vanes and flow conditioners to minimize the installation error associated with several field meter configurations. This standard was revised in 2000 based upon an extensive review of data on orifice meter installation effects published by Studzinski et al[11]. The geometrical specifications for the 19-tube bundle straightening vane, used to remove swirl from the velocity profile upstream of the orifice plate, were tightened. Research by Stuart et al[12] showed that different sizes and arrangements of straightening vanes could change the sign as well as the magnitude of the installation error in short, A' = 17 D orifice meters. Stuart's tube bundle designs were all within the design specifications of AGA Report No. 3, Part 3, Third Edition, published in 1990.

The 19-tube bundle straightening vane is the only flow conditioner device for which a geometrical design is specified in AGA Report No. 3, Part 2, Fourth Edition[3]. Stuart's collection of tube bundle designs, and other flow conditioners that use perforated plates or other devices to shape the axial velocity profile are also permitted if they comply with a performance-based specification in AGA Report No. 3, Part 2, Fourth Edition[3].

Gas Research Institute sponsored the development of a flow conditioner performance test[7] on which to base a performance specification. Four test configurations were recommended for flow conditioner performance tests. These were:

- Good flow conditions
- Double out-of-plane elbows (swirl)
- 50% closed gate valve (axial profile asymmetry), and
- High swirl and asymmetry (to simulate the type of velocity profile found in headers by Williamson et al[10].

The "sliding vane" technique was used in which a small push rod is attached to the upstream side of the flow conditioner to change the location of the flow conditioner in the meter tube. Tests were performed with no flow conditioner, a 19-tube bundle straightening vane, and prototype versions of three proprietary flow conditioner designs, a Stuart "C-3" tube bundle, a Nova 50E perforated plate flow conditioner, and a Gallagher #21 perforated plate and tube bundle flow conditioner.

Figure 8 shows the orifice meter installation error for a short, A = 17 D meter tube downstream of a 50% closed gate valve as a function or orifice β ratio. The dashed lines represent the limits of acceptable performance, equal to 50% of the 2σ uncertainty for the RG orifice meter equation at that value of β. For β = 0.67, the installation error is approximately –0.8%. The negative sign indicates an over-measurement error.

Figure 9 is a plot of the sliding vane results for a short, A' = 17 D meter tube downstream of a 50% closed gate valve for a 19-tube bundle straightening vane for β = 0.67. The dashed lines represent the limits of acceptable performance, equal to 50% of the 2σ uncertainty for the RG orifice meter equation for β = 0.67. As the tube bundle is drawn close to the 50% closed gate valve the axial velocity profile asymmetry downstream of the valve is captured by the straightening vanes, and the asymmetry persists to the orifice plate. The best location for the 19-tube bundle is about C = 7.5. At this location ΔC_d is approximately 0.0% for tap 1 and –0.4% for tap 2.

Figure 10 is a plot of the sliding vane results for a short, A' = 17 D meter tube downstream of a 50% closed gate valve for a Stuart C-3 tube bundle straightening vane for β = 0.67. Although the tube bundle still captures the asymmetry downstream of the 50% closed gate valve the effect is less than for the 19-tube bundle. The best location for the Stuart C-3 tube bundle is between C = 3 and C = 5 where the installation error is within the acceptable range.

Figure 11 is a plot of sliding flow conditioner results for a short, A' = 17 D meter tube downstream of a 50% closed gate valve for a Nova #50E perforated plate flow conditioner for β = 0.67. The asymmetry in C_d values downstream of the 50% closed gate valve is smaller than in Figures 9 and 10. The best locations for the Nova #50E flow conditioner are between C = 7 and C = 13 where the installation error is within (or on the edge of) the acceptable range.

Figure 12 is a plot of sliding flow conditioner results for a short, A' = 17 D meter tube downstream of a 50% closed gate valve for a Gallagher #21 perforated plate and (anti-swirl) tube bundle device for β = 0.67. The asymmetry in C_d values downstream of the 50% closed gate valve is larger than in Figure 11, but smaller than in Figures 9 and 10. The best locations for the Gallagher #21 flow conditioner are between C = 4 and C = 11 where the installation error is within (or on the edge of) the acceptable range.

Figures 8 through 12 are examples of the level of installation error performance that can be attained with and without flow conditioners. Reference 7 tabulates the results of the tests performed during performance test development. Flow conditioner manufacturers can provide performance results and installation recommendations for their devices.

Gas Multi-Path Ultrasonic Flow Meters

Gas multi-path ultrasonic transit-time flow meters are used in new meter installations and as replacements for traditional orifice and turbine meters. These flow meters are not manufactured according to a common, standardized design like an orifice meter. They are proprietary devices with hardware and software features unique to each flow meter manufacturer. Also, they are being improved continually as the user experience base increases.

Multi-path ultrasonic meters measure the differences in ultrasound transit time along two or more paths in both the upstream and the downstream directions. The average gas velocities measured along each path are related to the differences between upstream and downstream transit times. Moore et al(13) reviewed the theory upon which the use of multi-path ultrasonic flow meters with different path configurations is based. It is possible to estimate the installation error for ultrasonic meters using theoretical asymmetrical velocity profiles, or asymmetrical profiles computed by CFD, to calculate the difference between measured and actual mean velocities.

One class of meters uses two or more parallel (chordal) paths. The average velocity measured over the meter cross-sectional area is calculated as a weighted average of the path velocities. The chord locations and the weighting coefficients are specified by numerical integration techniques. The measured mean velocity is calculated as(13):

$$v_{mean} = \sum_{i=1}^{n} w_i \left(v_{path} \right)_i \qquad (4)$$

The values of the weighting coefficients, w_i, and the chord locations are listed in Moore et al(13) for two to five parallel paths and for three different numerical integration methods. Zanker(14) compared the value of measured velocity for Gaussian integration and the mean velocity for an asymmetrical profile. The maximum error for four chordal paths was 0.2% independent of the orientation of the asymmetry relative to the ultrasound paths.

A second class of meters uses equally weighted paths. Moore et al(13,15) investigated the installation error for asymmetrical profiles for several different ultrasound path configurations. Paths may pass through the center of the pipe (a diametral path), or bounce off the inside pipe surface to form a triangular or star pattern. For equally weighted paths the measured velocity is calculated from[13,15]:

$$v_{meas} = \frac{1}{n}\sum_{i=1}^{n}\left(v_{path}\right)_i \qquad (5)$$

According to Moore et al[13,15] the most effective path arrangements with equal weighting for asymmetrical flow were the "double triangle" and "five-pointed-star" with angular sensitivities of 1% or less. These results were calculated by varying the angular orientation of the velocity profile asymmetry (without changing the average velocity) relative to the fixed ultrasonic paths.

Bowen[16] discussed the velocity profile sensitivity for multi-path ultrasonic meters with two triangular bounce paths and either one or three single bounce diametral paths. For these particular meters, the triangular (swirl) paths are weighted more heavily than the diametral paths in the calculation of measured average velocity[16].

The industry standard applicable to gas multi-path ultrasonic meters is AGA Report No. 9[17]. For 12-inch diameter and larger meters, the standard states that the maximum error should be ±0.7%, without flow calibration, between specified maximum and minimum flow rate limits. Lansing[18] reports finding this level of measurement accuracy from 71 "as-found" 12-inch multi-path flow meter calibrations. After flow calibration, the meter's measurement uncertainty approaches that of the calibration laboratory.

But, flow calibration raises the question of installation effects again. Will the flow calibrated meter be installed in the field with the same geometric configuration as used in the laboratory during the flow calibration? As a conservative approach to installation effects, Grimley[19] recommended that a flow conditioner be used to minimize the profile distortion resulting from the actual field installation. Grimley's[19] installation effects tests showed variations in performance of up to 0.3% when a meter was calibrated with and without a flow conditioner. He concluded that it is important to calibrate the meter and flow conditioner together, as a system if a flow conditioner will be used in a field installation.

This approach to calibrating meters for field use was investigated by Morrow[20] with an 8-inch and a 6-inch multi-path ultrasonic meter installed in parallel between headers on a measurement skid. Both meters were flow calibrated (meter, flow conditioner and meter tubes together) out of the skid and again in the skid. The flow calibrations for the 6-inch diameter meter repeated to 0.1% in and out of the skid. The flow calibrations for the 8-inch diameter meter repeated to within 0.2% in and out of the skid. So the calibration approach recommended by Grimley[19] was shown to be valid for a realistic field installation with a header upstream of the flow meter.

What might happen if a meter is calibrated with one flow conditioner and installed with a different flow conditioner in the field? Flow calibrations were performed with the 6-inch multi-path ultrasonic meter out of the skid with each of three different flow conditioners[20]. The calibration results differed by as much as 0.4% from one flow conditioner to another. Flow conditioners are not interchangeable. Each produces a velocity profile characteristic of its design. This shows the importance of flow calibrating a meter with the same flow conditioner that will be used in the field.

AGA Report No. 9 is being revised as this paper is written. The most recent edition of AGA Report No. 9 should be consulted for guidance regarding standard multi-path ultrasonic meter installation configurations and the use of flow conditioners to minimize installation error.

As operating experience is gained with multi-path ultrasonic meters, operational effects information is accumulated and published. Only a few of these effects can be noted here. Multi-path ultrasonic meter performance may be affected by surface roughness and dirt accumulation[21,22], by acoustic noise in the ultrasound frequency spectrum[23] generated by control valves, and by temperature stratification of gas in the meter tube at low velocities less than 1 m/s[24,25].

The availability of flow diagnostics with multi-path ultrasonic flow meters has received considerable attention. Path velocities, signal to noise ratio, values of automatic gain control, and values of sound speed are all useful for alerting the operator to a change in conditions. A good introduction is provided by Zanker[26] who discusses the diagnostic ability of a four-path ultrasonic meter in detail.

Gas Turbine Flow Meters

Gas turbine flow meters are used to measure natural gas flow rate at pressures ranging from low (near atmospheric pressure) to high (transmission line pressure). Turbine meter designs are proprietary with one or more rotors that spin in response to the rate of gas flow through the meter. As the rotors spin, a sensor counts rotor blade “passings”, and the blade passing frequency can be related to the volume rate of flow. AGA Report No. 7[27] is the industry standard covering the use of gas turbine meters for natural gas measurement.

Gas turbine meters may also display installation and/or operational effects. AGA Report No. 7[27] provides information on three different recommended gas turbine meter installations. In the first configuration, a minimum of 10 diameters of straight pipe, with straightening vanes to remove swirl, is recommended upstream of the meter. A minimum of 5 diameters of straight pipe downstream of the meter is recommended. Two more recommended installations involve risers upstream and downstream of the meter, and they require both a straightening vane and a flow conditioner integral to the turbine meter to remove swirl.

George[28,29,30] published three reports of gas turbine meter research data acquired under the direction of the AGA Turbine Meter Task Group and sponsored by the Gas Research Institute. The research findings are summarized below. The full topical reports are available from GRI.

The first report[28] covers turbine meter performance tests involving the three installation configurations recommended in AGA Report No. 7. Meters were tested with “well conditioned” flow and also with high-swirl, jetting flow upstream of the recommended installations. According to George[28] the largest combined effect on flow measurement accuracy was found to be within ±1% of the meter reading. When high-swirl, asymmetric flow was introduced upstream of a test meter, integral flow conditioning at the meter inlet was effective in reducing measurement bias to about ±0.25%. The report concluded that integral flow conditioners should be required for the “short-coupled” and “close-coupled” gas turbine meter installations described in AGA Report No. 7.

George also initiated a study of line pressure related gas density effects on meter calibration curves. Shifts in calibration were observed with changes in line pressure for all meters tested. The behavior of the shifts was a function of meter design and gas density, and indicated that the use of an uncorrected low-pressure calibration curve could lead to significant errors at transmission line pressure.

George’s second report[29] gives the results of tests on 4-inch and 8-inch diameter meters calibrated in air at pressures between atmospheric pressure and 99 psi, and in natural gas between 30 psi and 700 psi. The air tests were performed at the Colorado Engineering Experiment Station (CEESI) and the natural gas tests were performed in the Metering Research Facility at Southwest Research Institute. George analyzed the data to find the maximum change in calibration for each meter from its asymptotic value at high Reynolds number. These changes, when plotted as a function of actual volumetric flow rate, represent the maximum possible errors in measurement when Reynolds number and density effects are not accounted for. The maximum changes were within ±2.5% for flow rates above 20% of maximum meter flow rate. Midpoint K factors were computed from data. For five of eight test meters the uncertainty in midpoint K-factor was outside the ±1% accuracy allowed by AGA Report No. 7. George[29] concluded that commercial turbine meters may not achieve an accuracy specification of ±1% with a single value of K factor. Also, the research results showed a potential for significant bias errors in flow rate measurement when gas turbine meters are not calibrated at the pressure at which they will be used.

In the third GRI Topical Report, Siebenaler and George[30] investigated changes in gas turbine meter calibration when the turbine cartridge is replaced by another cartridge in the same turbine meter body. The practice of cartridge replacement is common in industry. Each turbine cartridge was tested in three different meter bodies and the calibration factors were compared. The results were a function of the brand and model of the meter. The percentage spread in primary rotor calibration factors ranged from ±0.01% to ±0.35% about the midpoint K value. Approximately half of the observed spread in calibration factor can be attributed to test reproducibility and the other half to dimensional variations in bodies and cartridge change out practices. The meter model with the smallest variation in K factor also had the smallest variation in critical meter dimensions between meter bodies.

Conclusions

Flow meters are subject to installation errors when the circumstances of the field installation differ significantly from those of the baseline calibration. Installation errors are bias errors and not random errors. For this reason special attention should be paid to minimizing installation errors. Both installation and operational errors have been considered by the standards writing working groups of the AGA Transmission Measurement Committee. The standard’s recommendations for meter installation and operation should be followed to avoid measurement errors.

References

1. "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids, Part 1 General Equations and Uncertainty Guidelines" AGA Report No. 3, Part 1 Third Edition, American Gas Association, Washington, DC, 1990.
2. Whetstone, J.R., Cleveland, W.G., Baumgarten, G.P., Woo, S., and Croarkin, M. C., "Measurements of Coefficients of Discharge for Concentric Flange-Tapped Square-Edged Orifice Meters in Water Over the Reynolds Number Range 600 to 2,700,000, NIST Technical Note 1264, Washington, D.C., June 1989.
3. "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids, Part 2 Specification and Installation Requirements," AGA Report No. 3, Part 2 Fourth Edition, American Gas Association, Washington, D.C., April 2000.
4. Reader-Harris, M. J., Sattary, J. A., Woodhead, E., "The Use of Flow Conditioners to Improve Flow Measurement Accuracy Downstream of Headers," 3rd International Symposium on Fluid Flow Measurement, Mar. 20 – 22, 1995, San Antonio, TX.
5. Morrow, T. B. "Orifice Meter Installation Effects: Ten-Inch Sliding Flow Conditioner Tests", GRI Report No. GRI-96/0391, Gas Research Institute, Chicago, IL, Nov. 1996.
6. Mattingly, G.E., Yeh, T. T., "Effects of Pipe Elbows and Tube Bundles on Selected Types of Flowmeters," Flow Measurement and Instrumentation, Vol. 2, Jan. 1991, pp. 4-13.
7. Morrow, T. B., "Orifice Meter Installation Effects: Development of a Flow Conditioner Performance Test," GRI Report No. GRI-97/0207, Gas Research Institute, Chicago, IL, Dec. 1997.
8. Morrow, T. B. "Orifice Meter Installation Effects: Effect of Variable Spacer Length Between Two 90° Ells Out-Of-Plane," GRI Report No. GRI-97/0293, Gas Research Institute, Chicago, IL, Feb. 1998.
9. Mottram, R. C., Rawat, M. S., "Attenuation Effects of Pipe Roughness on Swirl and the Implications for Flow Meter Installation," International Symposium on Fluid Flow Measurement, Nov. 16-19, 1986, American Gas Association, Washington, DC.
10. Williamson, I. D., Botros, K. K, Price, G. R., "Flow Characteristics and Orifice Meter Error Caused by Upstream Headers in Multi-Run Meter Stations," ASME Fluids Engineering Division – Vol. 181, 1993, pp. 1-11.
11. Studzinski, W., Karnik, U., LaNasa, P., Morrow, T., Goodson, D., Husain, Z., Gallagher, J., "Orifice Meter Installation Configurations With and Without Flow Conditioners: White Paper Prepared for API 14.3, Part 2," Topical Report GRI-99/0262, Gas Research Institute, Chicago, IL. March 2001.
12. Stuart, J. W., Park, J. T., Morrow, T. B., "Experimental Results of an Improved Tube-Bundle Flow Conditioner for Orifice Metering," FLOMEKO'94, June 14, 1994, NEL Flow Centre, East Kilbride, Glasgow, Scotland.
13. Moore, P. I., Brown, G. J., Stimpson, B. P., "Ultrasonic Transit Time Flowmeters Modelled with Theoretical Velocity Profiles: Methodology," Measurement Science and Technology, Vol 11, 2000, pp. 1803-1811.
14. Zanker, K., "The Effect of Flow Profile Asymmetry on Single and Multi-Path Ultrasonic Meters," available online http://www.emersonprocess.com
15. Moore, P. I., Brown, G. J., Stimpson, B. P., "Modelling of Transit Time Ultrasonic Flowmeters in Theoretical Asymmetric Flow," FLOMEKO 2000, Salvador.
16. Bowen, J. P., "A Preliminary Assessment of the Effects of Profile Distortions on Gas Ultrasonic Meter Accuracy," AGA Operations Conference, paper 03-OP-61.
17. "Measurement of Gas by Multipath Ultrasonic Meters," AGA Report No. 9, American Gas Association, Washington, DC, June 1998.
18. Lansing, J., "Ultrasonic Meter Station Design Considerations," Western Gas Measurement Short Course, 2003. Available online http://www.emersonprocess.com
19. Grimley, T. A., "Ultrasonic Meter Installation Configuration Testing," AGA 2000 Operations Conference, May 8-10, Denver, CO.

20. Morrow, T. B., “Pressure Effects and Low Flow Tests on 8-inch and 6-inch Ultrasonic Flow Meters,” GRI Topical Report No. GRI-04/0043, Gas Research Institute, Chicago, IL, Dec. 2004.

21. Lansing, J., “Dirty vs. Clean Ultrasonic Gas Flow Meter Performance,” AGA Operations Conference, Chicago, IL 2002. Available online http://www.emersonprocess.com

22. Witte, J. N., “Ultrasonic Gas Meters from Flow Lab to Field: A Case Study,” AGA Operations Conference, Chicago, IL 2002, paper 02-OP-34.

23. Warner, K., Zanker, K., “Noise Reduction in Ultrasonic Gas Flow Measurement,” 4th International Symposium on Fluid Flow Measurement, Denver, CO June 27-30, 1999.

24. Morrison, G. L., Brar, P., “CFD Evaluation of Pipeline Gas Stratification at Low Flow Due to Temperature Effects,” GRI Report No. GRI-04/0185, Sept. 2004.

25. Morrow, T. B., “Line Pressure and Low-Flow Effects on Ultrasonic Gas Flow Meter Performance,” GRI Topical Report No. GRI-05/0133, March 2005.

26. Zanker, K. J.,”Diagnostic Ability of the Daniel Four-Path Ultrasonic Flow Meter,” South East Asia Fluid Flow Workshop, available online http://www.emersonprocess.com .

27. “Measurement of Gas by Turbine Meters,” AGA Report No. 7, American Gas Association, Washington, DC, 1996.

28. George, D. L., “Turbine Meter Research in Support of the Planned AGA Report No. 7 Revision,” GRI Topical Report No. GRI-01/0226, Jan. 2003.

29. George, D. L., “Effect of Line Pressure and Gas Density on Turbine Meter Measurement Accuracy at Conditions from Atmospheric Air to 700 psig Natural Gas,” GRI Topical Report No. GRI-03/0172, Aug. 2004.

30. Siebenaler, S. P., George, D. L., “Effects of Turbine Meter Cartridge Change-out on Measurement Uncertainty,” GRI Topical Report GRI-04/0207, Mar. 2005.

Figures

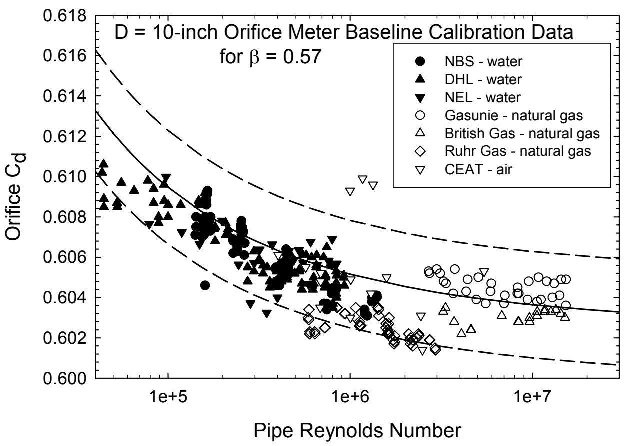

Fig. 1 Baseline orifice coefficient data for D = 10-inch meter tubes and β = 0.57 orifice plates.

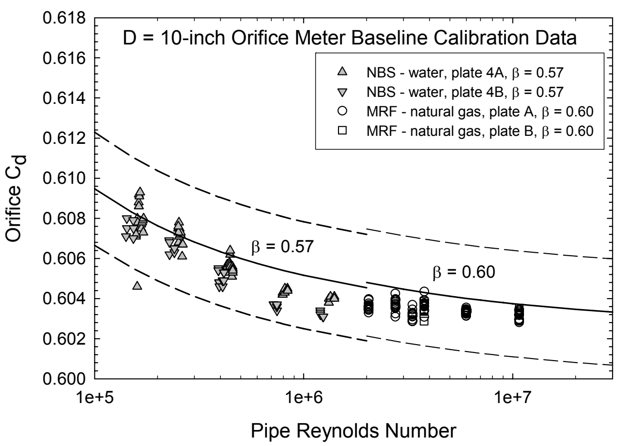

Fig. 2 10-inch orifice meter calibration data from NBS for β = 0.57 and GRI MRF for β = 0.60.

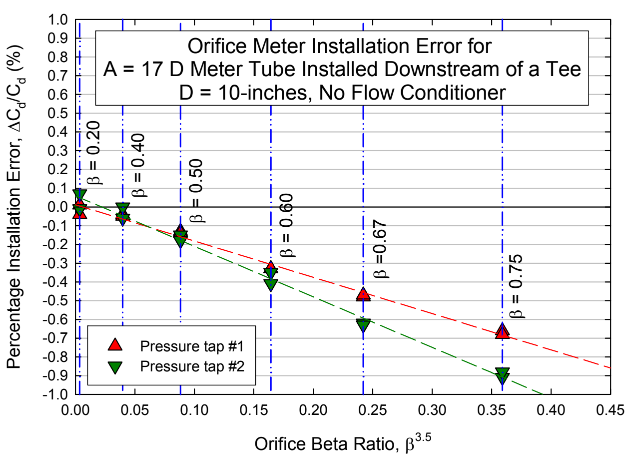

Fig. 3 Orifice meter installation error as a function of β for an A = 17 D bare meter tube downstream of a tee.

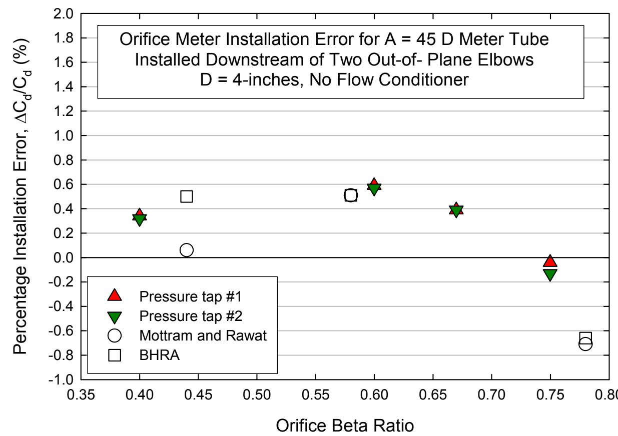

Fig. 4 Effect of type 1 swirl on orifice meter installation error for an A = 45 D bare meter tube.

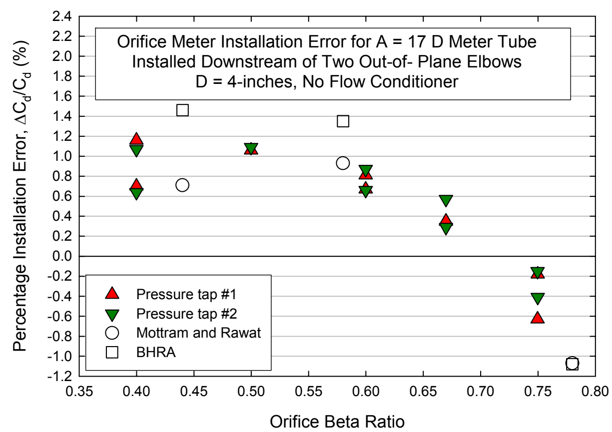

Fig. 5 Effect of type 1 swirl on orifice meter installation error for an A = 17 D bare meter tube.

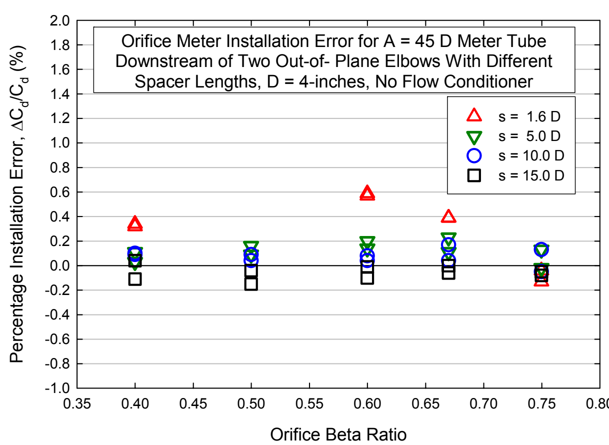

Fig.6 Effect of spacer length s between two out-of-plane elbows on orifice meter installation error for an A = 45 D bare meter tube.

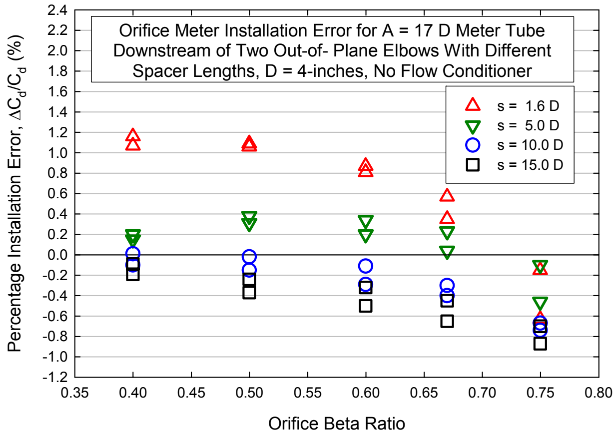

Fig. 7 Effect of spacer length s between two out-of-plane elbows on orifice meter installation error for an A = 17 D bare meter tube.

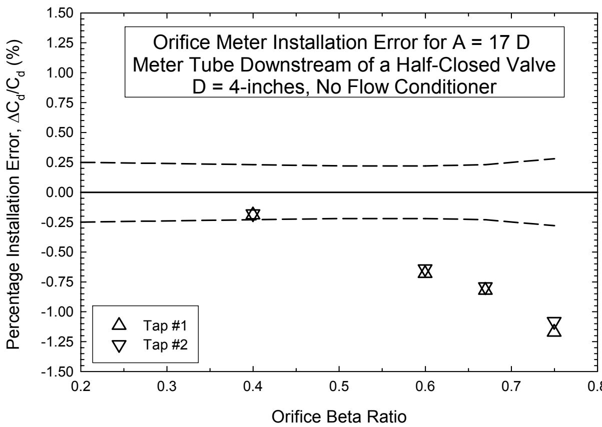

Fig. 8 Orifice meter installation error as a function of β for A = 17 D bare meter tube downstream of a gate valve closed 50%.

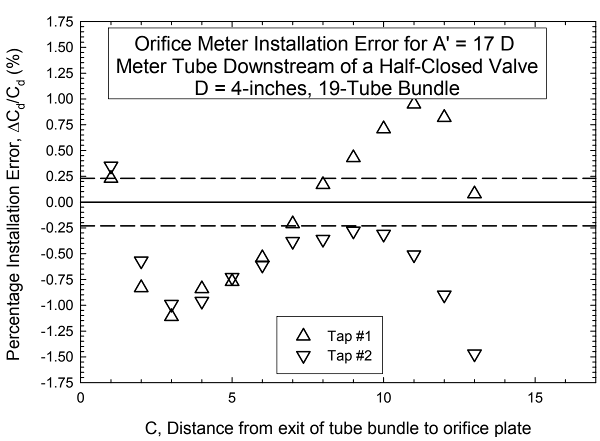

Fig. 9 Performance of 19-tube bundle straightening vane downstream of a gate valve closed 50% for β = 0.67. Upstream meter tube length A' = 17 D.

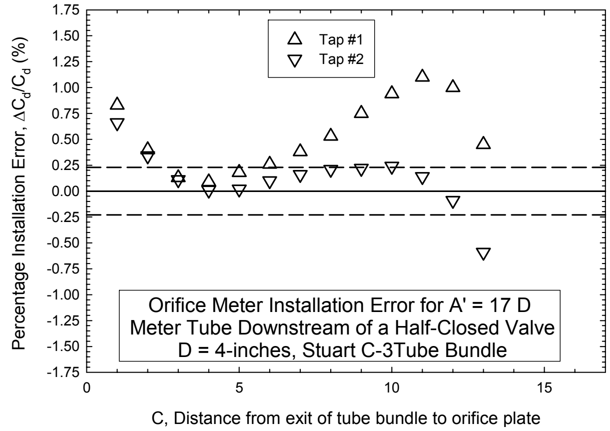

Fig. 10 Performance of Stuart C-3 tube bundle straightening vane downstream of a gate valve closed 50% for β = 0.67. Upstream meter tube length A' = 17 D.

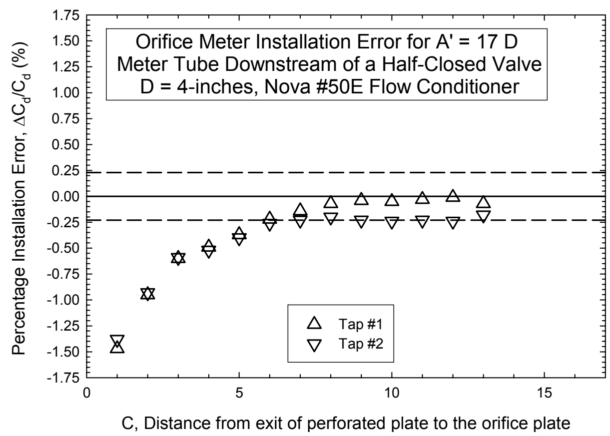

Fig. 11 Performance of Nova #50E flow conditioner downstream of a gate valve closed 50% for β = 0.67. Upstream meter tube length A' = 17 D.

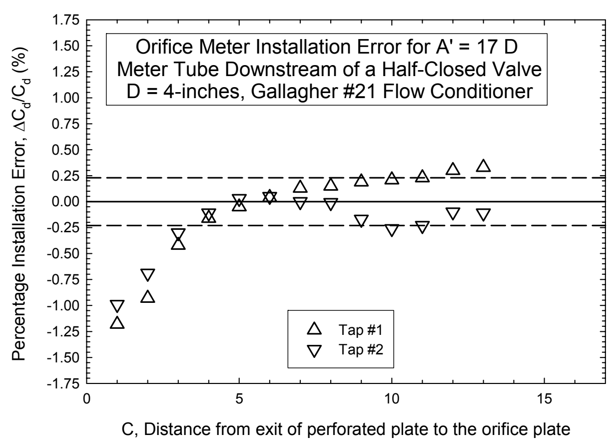

Fig. 12 Performance of Gallagher #21 flow conditioner downstream of a gate valve closed 50% for β = 0.67. Upstream meter tube length A' = 17 D.