

# INSTALLATION AND OPERATION ERRORS IN GAS MEASUREMENT

Class 1190

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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. Next, let the same sensor be used to measure the temperature of natural 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 will occur between the pipe wall and the sensor, and convection heat transfer will occur between the sensor and the flowing gas. In this example, the sensor would not be in thermal equilibrium with the flowing gas and the sensor temperature would be different from the flowing gas temperature.

Flow meter installation errors can occur when a meter is calibrated in one piping configuration and then 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 understand better the magnitude and direction of installation errors for orifice flow meters, turbine flow meters, and ultrasonic flow meters. The research results were critically reviewed by industry measurement standards committees and served as the basis for affirmation or revision of the applicable installation specifications. This paper reviews some types of installation and operation errors found for orifice flow meters, gas ultrasonic flow meters, and turbine flow meters.

## Orifice Flow Meters

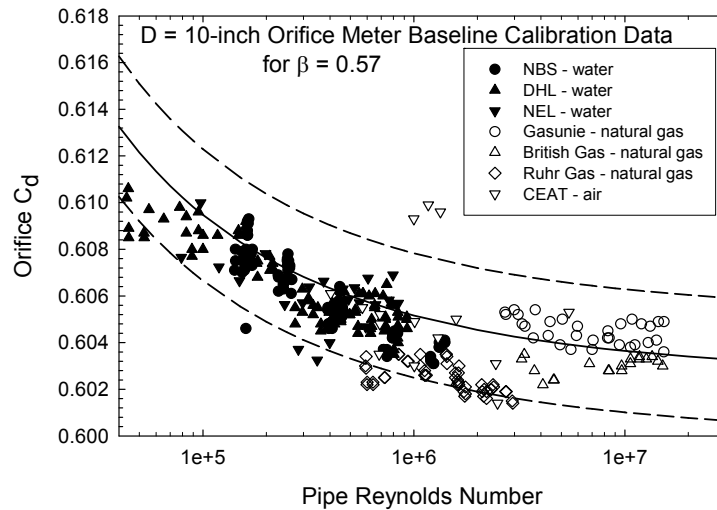
Orifice meters are seldom flow-calibrated, either in a laboratory or in-situ, before being installed in the field. Instead, orifice coefficient values,  $C_d$ , are calculated (as a function of pipe diameter, beta ( $\beta$ ) ratio, and Reynolds number) using the Reader-Harris Gallagher (a.k.a., RG) correlation of orifice meter “baseline” flow calibration data, as described in American Gas Association (AGA) Report No. 3, Part 1 [1990]<sup>(1)</sup>.

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 (where D represents nominal pipe diameter). There were 5,734 data points taken for flange taps alone. The “baseline” tests were carried out using commercial orifice plates with  $\beta$  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 ratio equal to 0.57. Three labs performed tests flowing water and 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.

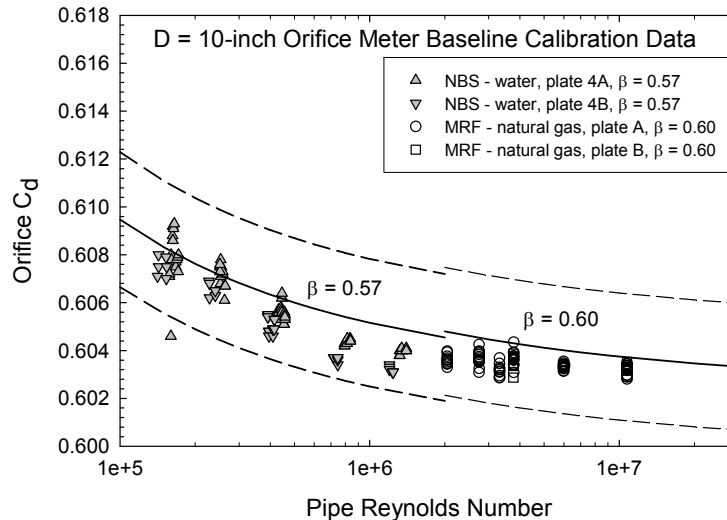
When the baseline calibration tests were performed, long straight lengths of meter tube and flow conditioners were installed upstream of the orifice plates. Whetstone<sup>(2)</sup> reported that the tests performed by the National Bureau of Standards (NBS - now the National Institute of Standards and Technology, NIST) had upstream meter tube lengths longer than 40 diameters and a Sprengle 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.



**Figure 1. Baseline Orifice Coefficient Data for D = 10-inch Diameter Meter Tubes and  $\beta = 0.57$  Orifice Plates**

If an orifice flow meter is installed in a baseline configuration with a commercial meter tube and a plate that meet the specifications of AGA Report No. 3, Part 2 [2000]<sup>(3)</sup>, 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 Southwest Research Institute (SwRI) Metering Research Facility (MRF) using a 10-inch diameter 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 diameter NBS water tests. The MRF results for  $\beta = 0.60$  are compared in Figure 2 to the NBS data for  $\beta = 0.57$ . The dashed curves represent the 95% confidence limits for the RG orifice equation. The MRF natural gas data for  $\beta = 0.60$  lie slightly below the RG equation curve, as do the NBS water calibration data for  $\beta = 0.57$ .



**Figure 2. 10-inch Diameter Orifice Meter Calibration Data from NBS for  $\beta = 0.57$  and SwRI MRF for  $\beta = 0.60$**

Few orifice meter field installations have 45D 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 the 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.

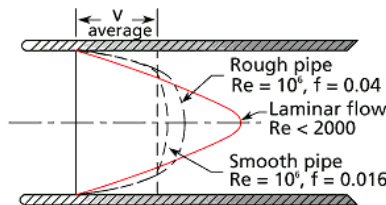
Values of installation error can be determined experimentally. The percent installation error with respect to the orifice meter baseline  $C_d$  value is defined in Equation 1.

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

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, as illustrated in Figure 3.



**Figure 3. Example Axi-symmetric, Swirl-free, Fully-developed Turbulent and Laminar Velocity Profiles**

One representation of the fully developed velocity profile is the power-law profile in Equation 2.

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

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 also 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  $2^\circ$  (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

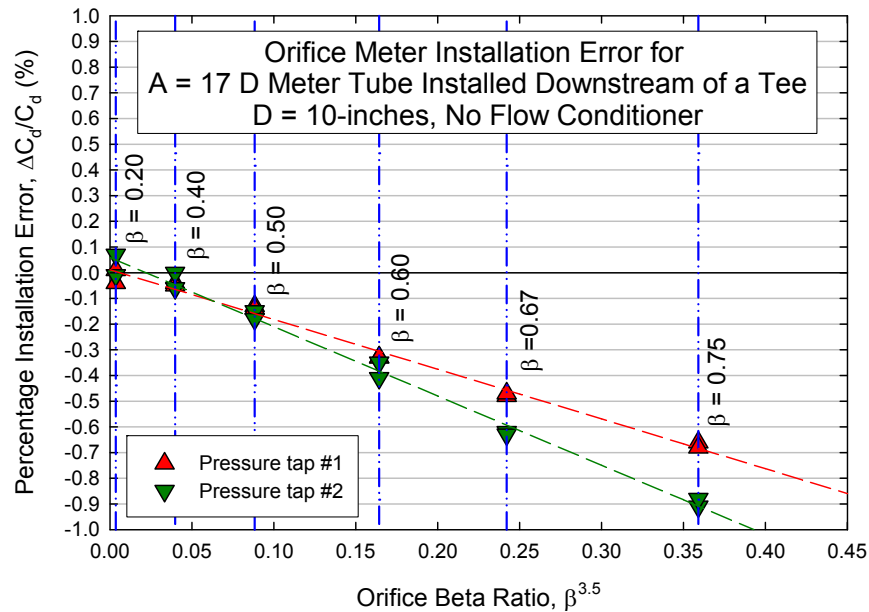
For non-swirling pipe flow, Reader-Harris<sup>(4)</sup> showed that the percentage installation error is related to the percentage deviation,  $\Delta U/U$  (%), of the axial velocity profile from the baseline axial profile.

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

For a given percentage of velocity profile deviation, Equation 3 shows that the percent installation error is greater for high  $\beta$  values ( $\beta \sim 0.75$ ) than for low  $\beta$  values ( $\beta \sim 0.20$ ). The strong dependency of the percentage installation error on orifice  $\beta$  ratio explains why minimum upstream meter tube lengths recommended for particular piping installations often increase with increasing  $\beta$ . 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., the profile is affected by pipe wall roughness), (2) non-swirling asymmetrical flows (e.g., the profile is affected by a partially closed valve followed by a tube bundle flow-straightener), and (3) flows with Type 2 swirl (e.g., the profile is affected by a single upstream 45° or 90° elbow or a tee).

Figure 4 shows orifice meter installation test results for six  $\beta$  values from  $\beta = 0.20$  to  $\beta = 0.75$  for a short,  $A = 17D$  orifice meter tube installed directly downstream of a tee.<sup>(5)</sup> 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 psia. A separate set of baseline calibration tests was performed for an upstream meter tube length of  $A = 45D$  downstream of a Sprengle 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.



**Figure 4. Orifice Meter Installation Error as a Function of  $\beta$  for an  $A = 17D$  Bare Meter Tube Downstream of a Tee**

The reference to the 'A' dimension above (and other reference dimensions found later in this paper) is per the recommended orifice flow meter installation configurations specified in AGA Report No. 3, Part 2, as shown in Figure 5.

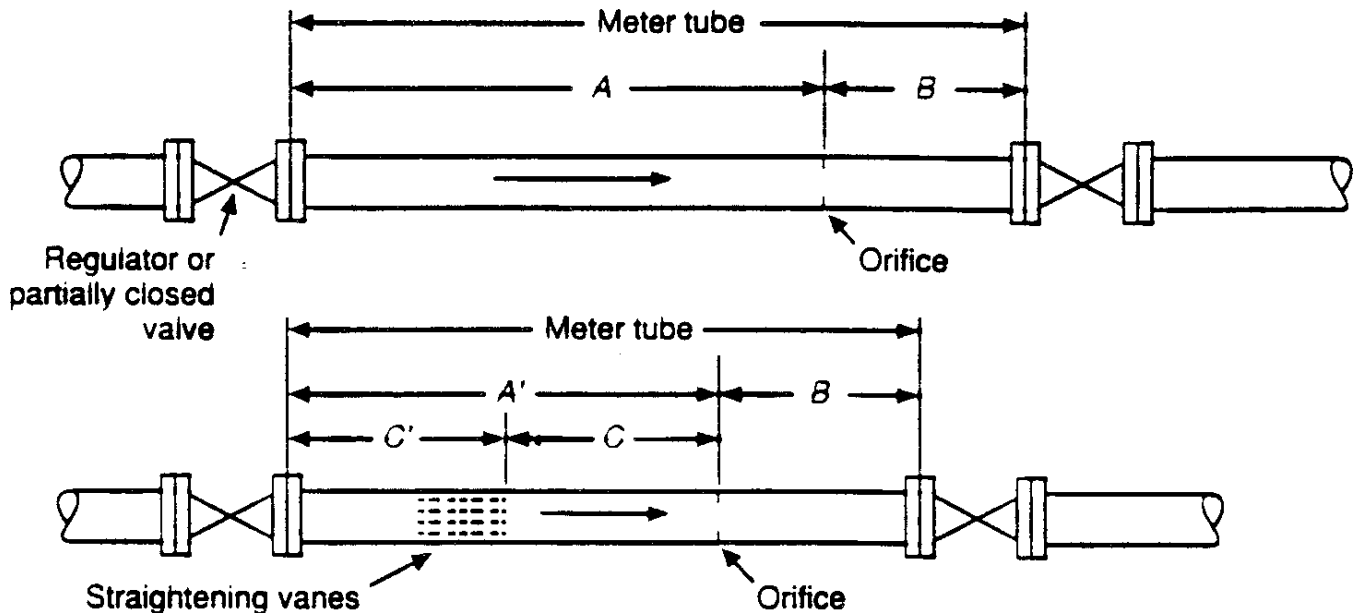


Figure 5. Orifice Meter Installation Reference Dimensions as Specified in AGA Report No. 3, Part 2

**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  $\pm 2^\circ$ , the flow is considered swirl-free. Mattingly and Yeh<sup>(6)</sup> described two generic types of swirling flows produced by elbows upstream of the meter tube.

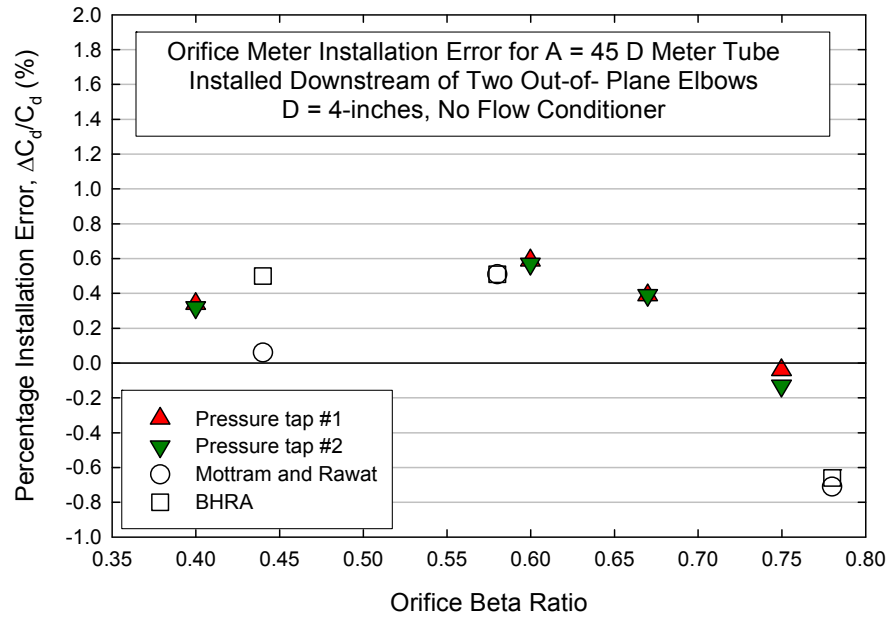
- Type 1 swirl has a single swirl or vortex pattern with a center close to the center of the pipe. Two closely coupled out-of-plane elbows produce this type of swirl. Mattingly and Yeh<sup>(6)</sup> reported measuring swirl angles of about  $\pm 20^\circ$  near the pipe walls and  $\sim 0^\circ$  in the core region around the center of the pipe.
- 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<sup>(6)</sup> reported values of swirl angle ranging from  $-14^\circ$  near the center of the pipe to  $+8^\circ$  near the pipe wall.

Mattingly and Yeh<sup>(6)</sup> 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  $2^\circ$  within a distance of about 12D. This explains why the installation error results in Figure 4 follow Equation 3, a correlation for swirl-free flow. However, for Type 1 swirl, a much greater distance of 89D would be needed to reduce the maximum swirl angle to less than  $2^\circ$ .

Figure 6 shows data for a long,  $A = 45D$  meter tube without a flow conditioner downstream of two out-of-plane  $90^\circ$  elbows. The triangles are data<sup>(5)</sup> from the MRF. The circles and squares are results reported by Mottram<sup>(9)</sup> for a 3-inch diameter orifice meter at Surrey University and an 8-inch diameter orifice meter at BHRA. The results are similar for all three laboratories despite differences in pipe roughness and Reynolds number. Mottram<sup>(9)</sup> also tested a 3-inch diameter 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  $A = 45D$ , the magnitudes of installation error produced by Type 1 swirl were even greater.<sup>(7,8, and 9)</sup> Figure 7 shows installation error results for an upstream meter tube length of  $A = 17D$  (MRF) and  $19D$  (Surrey University and BHRA). Note particularly that the sign of the installation error in

Figures 6 and 7 shifts from positive (i.e., under-registration of the flow rate) to negative (i.e., over-registration of the flow rate) as the  $\beta$  ratio increases from  $\beta = 0.4$  to  $\beta = 0.75$ .



**Figure 6. Effect of Type 1 Swirl on Orifice Meter Installation Error for an A = 45D Bare Meter Tube**

For the test results shown in Figures 8 and 9, a short, straight spacer distance,  $s$ , less  $2D$  in length, separated the first and second out-of-plane elbows. Mattingly and Yeh<sup>(6)</sup> 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 8 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  $A = 45D$  long orifice meter. Comparing Figures 6 and 8, it is clear that swirl effects are significant for  $s = 1.6D$ , but negligible for  $s = 15D$ .

Figure 9 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  $A = 17D$  long orifice meter. Comparing Figures 7 and 9, 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  $90^\circ$  elbow.

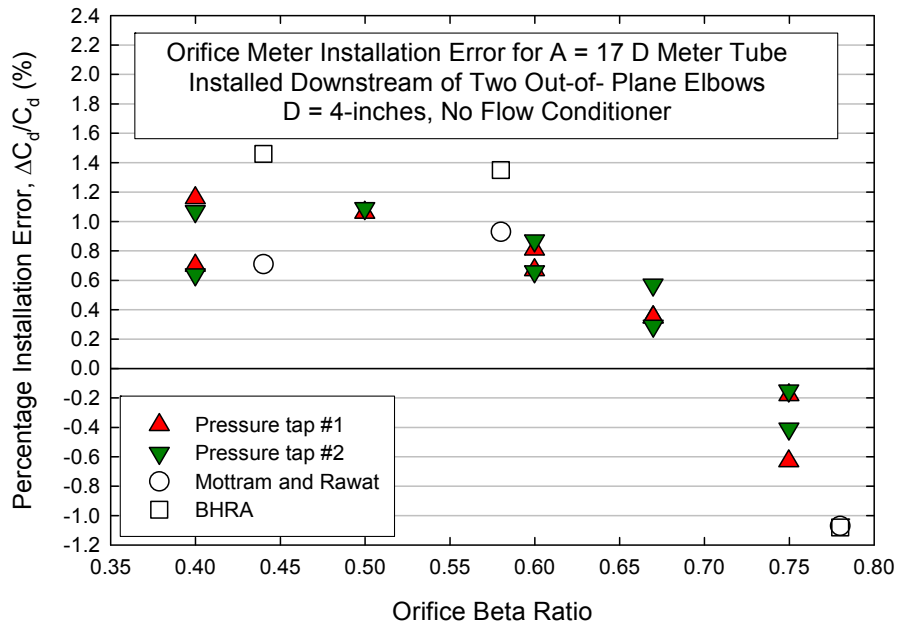


Figure 7. Effect of Type 1 Swirl on Orifice Meter Installation Error for an A = 17D Bare Meter Tube

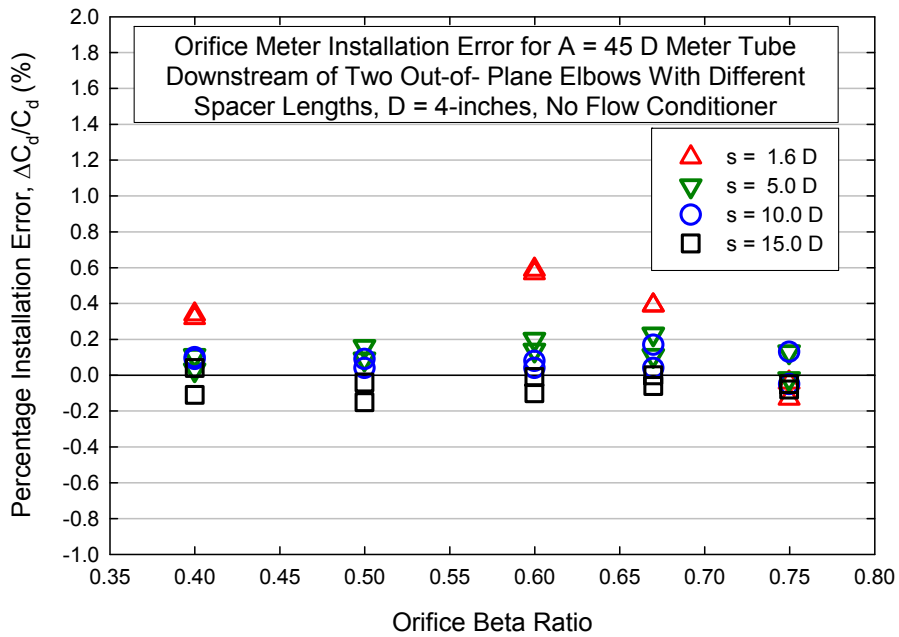
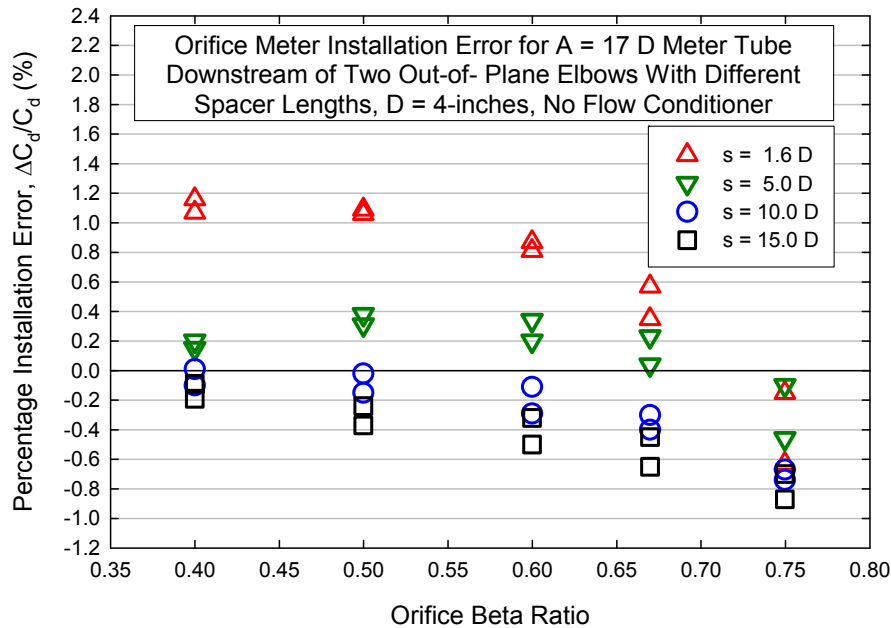


Figure 8. Effect of Spacer Length, s, Between Two Out-of-plane Elbows on Orifice Meter Installation Error for an A = 45D Bare Meter Tube



**Figure 9. Effect of Spacer Length,  $s$ , Between Two Out-of-plane Elbows on Orifice Meter Installation Error for an  $A = 17D$  Bare Meter Tube**

### Headers

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

Williamson, et al.,<sup>(10)</sup> 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 the direction of flow resembled that from two spaced 90° elbows.

Williamson, et al.,<sup>(10)</sup> 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 created in the meter tube. When a swirling, secondary flow was present in the header, stronger (unexpected) secondary flows were found in the meter tube.

### Flow Conditioners

AGA Report No. 3, Part 2, Fourth Edition<sup>(3)</sup> 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.<sup>(11)</sup> The geometrical specifications for the 19-tube bundle straightening vane, used to remove swirl from the velocity profile upstream of an orifice plate, were tightened. Research by Stuart, et al.,<sup>(12)</sup> showed that different sizes and arrangements of straightening vanes could change the sign as well as the magnitude of the installation error in short,  $A = 17D$  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 conditioning device for which a geometrical design is specified in AGA Report No. 3, Part 2, Fourth Edition.<sup>(3)</sup> 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.<sup>(3)</sup>



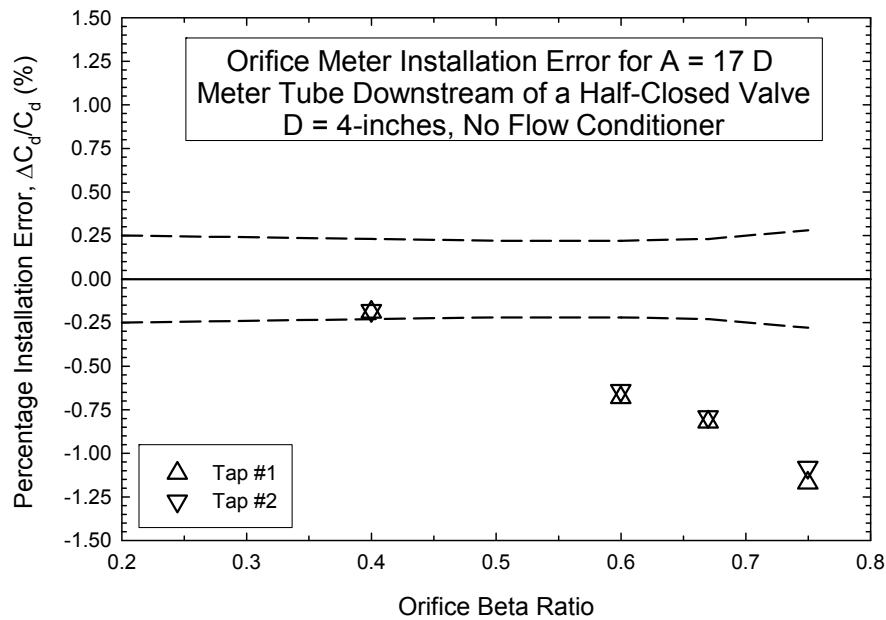
The Gas Research Institute (GRI) sponsored the development of a flow conditioner performance test<sup>(7)</sup> on which to base a performance specification. Four test configurations were recommended for flow conditioner performance tests. These were:

- 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.<sup>(10)</sup>)

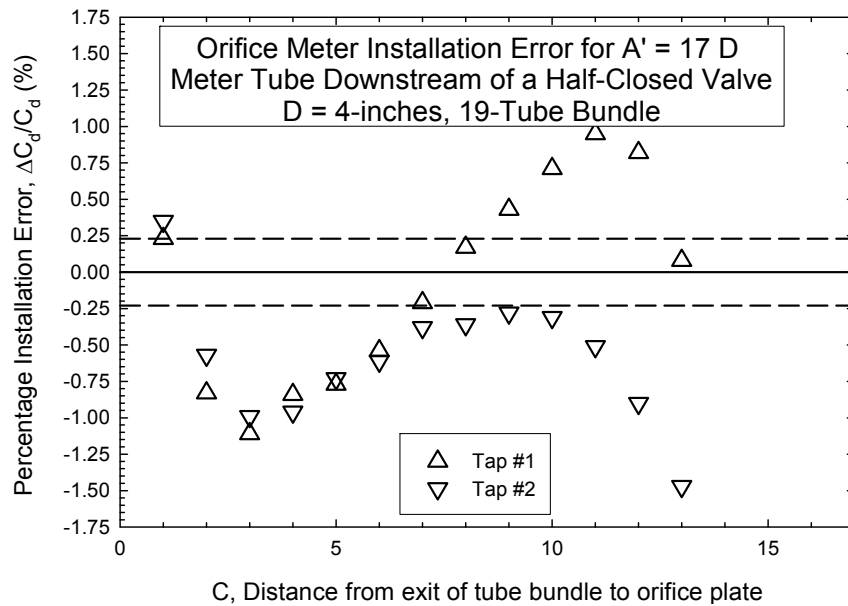
The “sliding vane” technique, in which a small push rod is attached to the upstream side of the flow conditioner to change the location of the flow conditioner in the meter tube, was used for these tests. The tests were performed with no flow conditioner, a 19-tube bundle straightening vane, and prototype versions of three proprietary flow conditioner designs (i.e., 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 10 shows the orifice meter installation error for a short,  $A = 17D$  meter tube downstream of a 50% closed gate valve as a function of orifice  $\beta$  ratio. The dashed lines represent the limits of acceptable performance, equal to 50% of the  $2\sigma$  uncertainty for the RG orifice meter equation at that value of  $\beta$ . For  $\beta = 0.67$ , the installation error is approximately  $-0.8\%$ . The negative sign indicates a flow rate over-measurement error.

Figure 11 is a plot of the sliding vane results for a short,  $A' = 17D$  meter tube downstream of a 50% closed gate valve for a 19-tube bundle straightening vane for  $\beta = 0.67$ . The dashed lines represent the limits of acceptable performance, equal to 50% of the  $2\sigma$  uncertainty for the RG orifice meter equation for  $\beta = 0.67$ . 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  $\Delta C_d$  is approximately 0.0% for tap 1 and  $-0.4\%$  for tap 2.



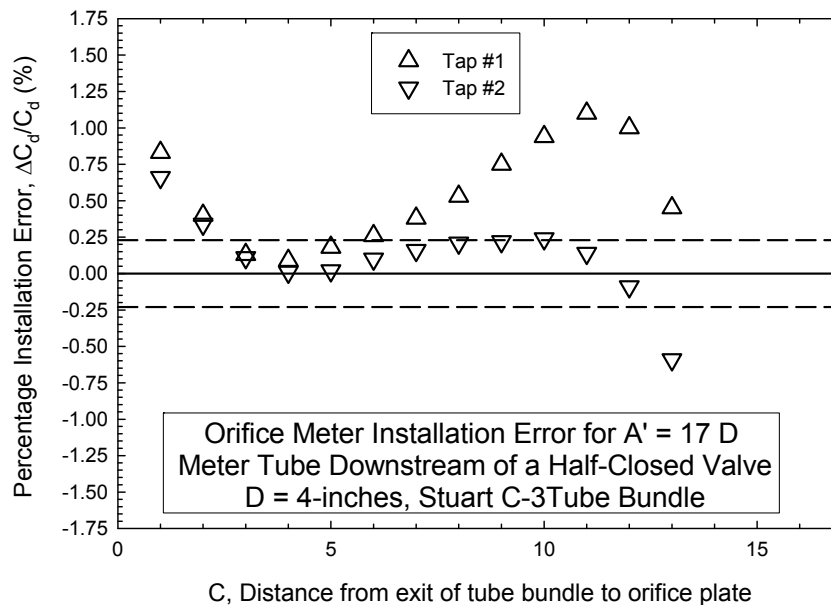
**Figure 10. Orifice Meter Installation Error as a Function of  $\beta$  for  $A = 17D$  Bare Meter Tube Downstream of a Gate Valve Closed 50%**



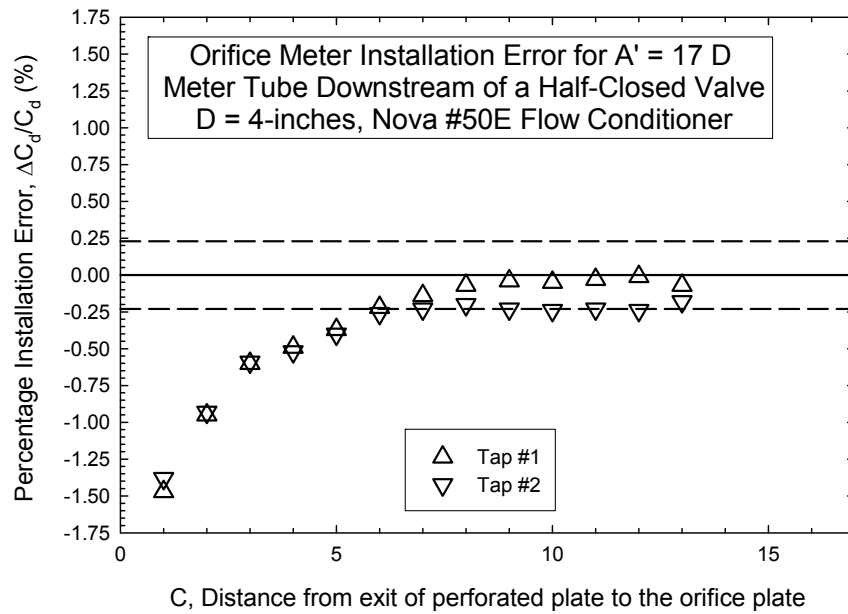
**Figure 11. Performance of 19-tube Bundle Straightening Vane Downstream of a Gate Valve Closed 50% for  $\beta = 0.67$  and Upstream Meter Tube Length  $A' = 17D$**

Figure 12 is a plot of the sliding vane results for a short,  $A' = 17D$  meter tube downstream of a 50% closed gate valve for a Stuart C-3 tube bundle straightening vane for  $\beta = 0.67$ . 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 13 is a plot of sliding flow conditioner results for a short,  $A' = 17D$  meter tube downstream of a 50% closed gate valve for a Nova #50E perforated plate flow conditioner for  $\beta = 0.67$ . The asymmetry in  $C_d$  values downstream of the 50% closed gate valve is smaller than in Figures 11 and 12. 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.



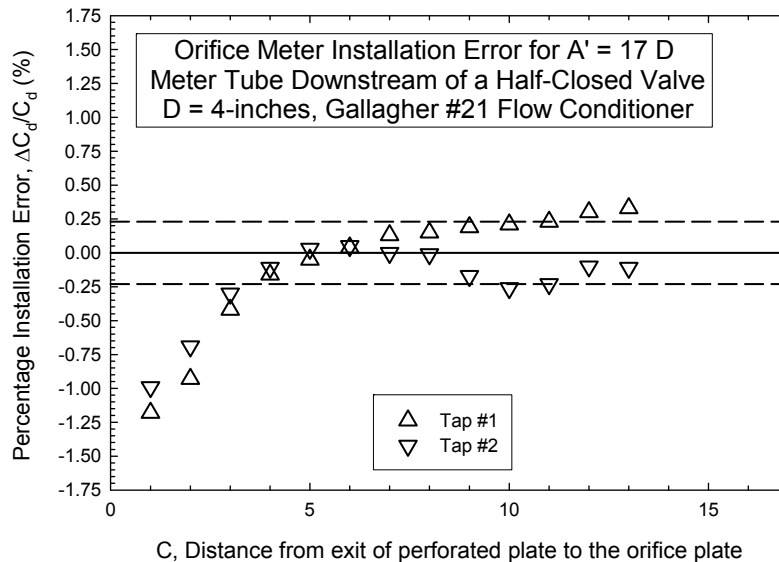
**Figure 12. Performance of Stuart C-3 Tube Bundle Straightening Vane Downstream of a Gate Valve Closed 50% for  $\beta = 0.67$  and Upstream Meter Tube Length  $A' = 17D$**



**Figure 13. Performance of Nova #50E Flow Conditioner Downstream of a Gate Valve Closed 50% for  $\beta = 0.67$  and Upstream Meter Tube Length  $A' = 17D$**

Figure 14 is a plot of sliding flow conditioner results for a short,  $A' = 17D$  meter tube downstream of a 50% closed gate valve for a Gallagher #21 perforated plate and (anti-swirl) tube bundle device for  $\beta = 0.67$ . The asymmetry in  $C_d$  values downstream of the 50% closed gate valve is larger than in Figure 13, but smaller than in Figures 11 and 12. 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 10 through 14 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.



**Figure 14. Performance of Gallagher #21 Flow Conditioner Downstream of a Gate Valve Closed 50% for  $\beta = 0.67$  and Upstream Meter Tube Length  $A' = 17D$**

## 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. In addition, 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 acoustic 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.,<sup>(13)</sup> 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 individual path velocities. The chord locations and the weighting coefficients are specified by numerical integration techniques. The measured mean velocity is calculated as<sup>(13)</sup>:

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

The values of the weighting coefficients,  $w_i$ , and the chord locations are listed in Moore, et al.,<sup>(13)</sup> for two to five parallel paths and for three different numerical integration methods. Zanker<sup>(14)</sup> compared the value of measured velocity for Gaussian integration and the mean velocity for an asymmetrical velocity 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.,<sup>(13,15)</sup> 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<sup>(13,15)</sup>:

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

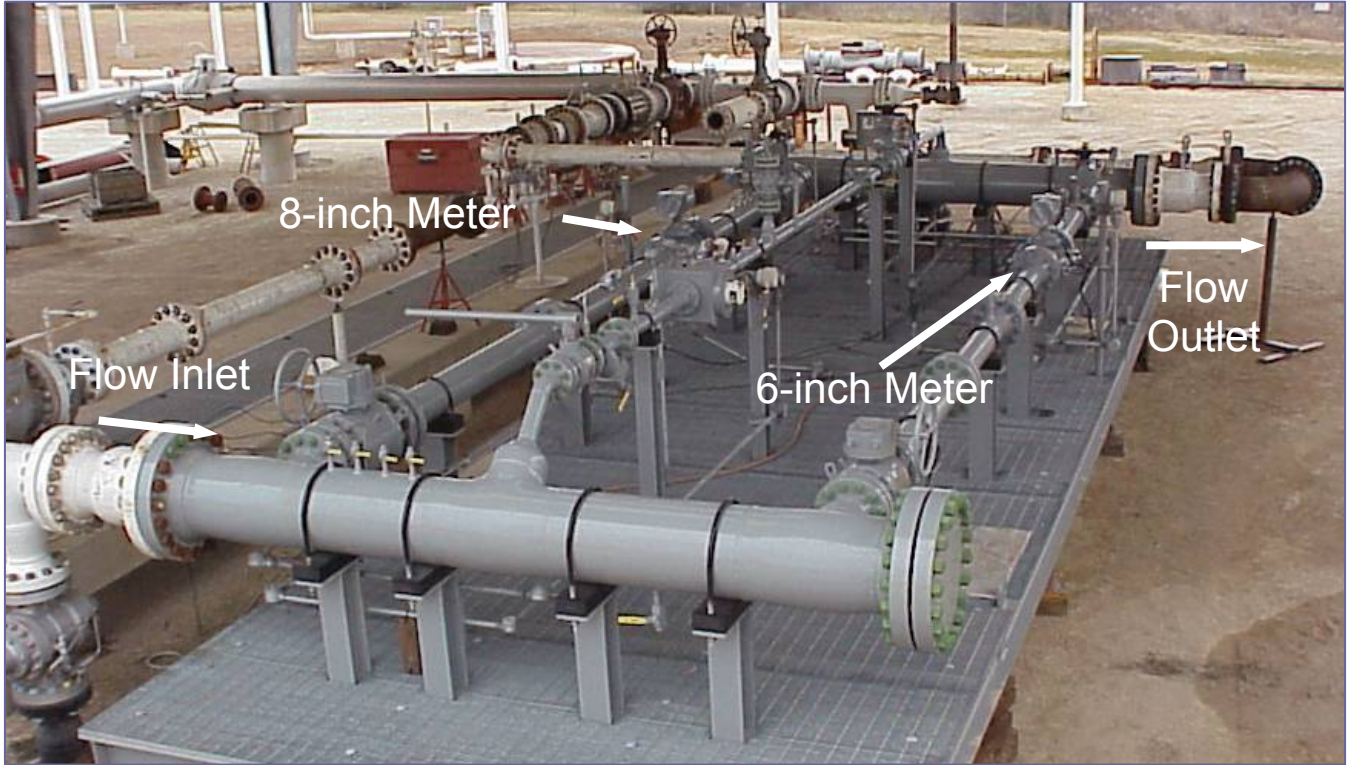
According to Moore, et al.,<sup>(13,15)</sup> the most effective path arrangements with equal weighting for asymmetrical flow were the “double triangle” and “five-pointed-star” with angular sensitivities of 1% or less. These results were calculated by varying the angular orientation of the velocity profile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

Bowen<sup>(16)</sup> 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.<sup>(16)</sup>

The industry-accepted recommended practice applicable to gas multi-path ultrasonic meters is AGA Report No. 9.<sup>(17)</sup> For 12-inch diameter and larger meters, the report states that the maximum error should be within  $\pm 0.7\%$  of reading, without flow calibration, between specified maximum and minimum flow rate limits. Lansing<sup>(18)</sup> reported finding this level of measurement accuracy from 71 “as-found” 12-inch diameter multi-path flow meter calibrations. After flow calibration, the meter measurement uncertainty approached that of the calibration laboratory.

However, flow meter calibration again raises the question of installation effects. 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<sup>(19)</sup> recommended that a flow conditioner be used to minimize the profile distortion resulting from the actual field installation. Grimley's<sup>(19)</sup> 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 the field installation.

This approach to calibrating meters for field use was investigated by Morrow<sup>(20)</sup> with an 8-inch diameter and a 6-inch diameter multi-path ultrasonic meter installed in parallel between headers on a measurement skid (see Figure 15). Both meters were flow calibrated (i.e., 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<sup>(19)</sup> was shown to be valid for a realistic field installation with a header upstream of the flow meter.



**Figure 15.** Ultrasonic Flow Meter Skid with Parallel Meter Runs

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 diameter multi-path ultrasonic meter out of the skid with each of three different flow conditioners.<sup>(20)</sup> 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 that is 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.

The recently revised edition of AGA Report No. 9 provides guidance regarding a “default” multi-path ultrasonic meter installation configuration 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 due to space limitations. Multi-path ultrasonic meter performance can be adversely affected by surface roughness and dirt accumulation<sup>(21,22)</sup>, by acoustic noise in the ultrasound frequency spectrum<sup>(23)</sup> generated by control valves, and by temperature stratification of gas in the meter tube at low nominal flow velocities – on the order of less than 1 meter per second.<sup>(24,25)</sup>

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 meter operator to a change in meter performance. A good introduction is provided by Zanker,<sup>(26)</sup> who discusses, in detail, the diagnostic ability of a four-path ultrasonic meter.

## **Gas Turbine Flow Meters**

Gas turbine flow meters are used to measure natural gas flow rate at pressures ranging from low (i.e., near atmospheric pressure) to high (i.e., transmission pipeline 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 rotor(s) spins (spins), a sensor counts rotor blade “passings,” and the blade passing frequency can be related to the volume rate of flow. AGA Report No. 7<sup>(27)</sup> is the industry standard covering the use of gas turbine meters for natural gas measurement.

Gas turbine meters may also be susceptible to errors associated with installation and/or operational effects. AGA Report No. 7<sup>(27)</sup> provides information on three different recommended gas turbine meter installations. In the first configuration, a minimum of 10 diameters of straight pipe, with a straightening vane to remove swirl, is recommended upstream of the meter. A minimum of five diameters of straight pipe downstream of the meter is recommended. Two more recommended installations involve risers upstream and downstream of the meter. They also require both a straightening vane and a flow conditioner integral to the turbine meter to remove swirl.

George<sup>(28,29, and 30)</sup> 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 the GRI.

The first report<sup>(28)</sup> covered 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,<sup>(28)</sup> the largest combined effect on flow measurement accuracy was found to be within  $\pm 1\%$  of the meter reading. When high-swirl, asymmetric flow was introduced upstream of a test meter, integral flow conditioning at the meter inlet was generally effective in reducing measurement bias to about  $\pm 0.25\%$ . 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 meter 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 typical transmission pipeline pressure.

George’s second report<sup>(29)</sup> gave 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, represented the maximum possible errors in measurement when Reynolds number and density effects were not accounted for. The maximum changes were within  $\pm 2.5\%$  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  $\pm 1\%$  accuracy allowed by AGA Report No. 7. George<sup>(29)</sup> concluded that commercial turbine meters might not achieve an accuracy specification of  $\pm 1\%$  with a single value of K factor. In addition, 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<sup>(30)</sup> 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 the pipeline 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  $\pm 0.01\%$  to  $\pm 0.35\%$  about the midpoint K value. Approximately half of the observed spread in calibration factor was 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 measurement errors associated with the effects of the installation configuration when the circumstances of the field installation differ significantly from those of the baseline calibration. Installation errors are *bias* errors, not *random* errors. For this reason, special attention should be paid to minimizing installation effects measurement errors. Both installation and operational errors have been considered by the standards writing groups of the AGA Transmission Measurement Committee. The recommendations in each standard for meter installation configuration and meter operation should be followed to minimize the likelihood of measurement errors.

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