Interpreting Compressible Fluid Calibration Results: Ultrasonic, Coriolis, Turbine and Differential Meters

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Abstract

Over the years CEESI has published a number of similar papers where flow measurement experience is applied to the analysis of calibration results. Meter technologies include ultrasonic, Coriolis, turbine and a variety of differential producing elements. A typical analysis involves a mix of calibrations: 1) a large quantity of data from one meter, or a few meters, and 2) a smaller quantity of data from many meters. This paper is a summary of the important findings and compares and contrasts the meter technologies.

By definition a compressible fluid will exhibit variable density. The variation in density results in the potential for changes in meter performance. The CEESI database quantifies typical density effects in differential, turbine and Coriolis meters and the apparent lack of density effects in ultrasonic meters. With sufficient data the proper correlating parameter for a meter can be selected. Potential gas meter correlating parameters include Reynolds number, Mach number, flowrate or velocity.

1. Introduction

Over the years CEESI has organized databases summarizing calibration results based on CEESI owned meters as well as blinded results from calibrations, On a periodic basis the results are published for the benefit of the measurement community. This paper combines some the results from four different meter technologies.

CEESI analyses are important to the measurement community because they are based on calibration data and are produced independent of particular manufacturers and user. They are valuable for inclusion in measurement standards and to provide guidance to the selection of the proper meter for a particular application. The numerical values help fill in blanks in uncertainty analyses. Finally, ongoing publication of the information allows for contribution to the industries that have helped make CEESI a commercial success.

This paper is organized into two main parts. The first part briefly describes the four meter types and summarizes the data available for each. The second part compares and contrasts the meters based on analysis of four performance parameters.

2. Meter Types

2.1 Differential Producer

The differential producing class of meters consist of primary elements that operate based on the Bernoulli effect. The flow through a primary element changes direction resulting in a differential pressure between one or more pressure tap pairs. The differential pressure is proportional to kinetic energy; the meter can be classified as a kinetic energy meter. Instruments to measure static and differential pressure and temperature are called secondary elements. The mass flowrate (q_m) is calculated from the output of the secondary elements using the following equation:

$$q_m = \left(\frac{\pi}{4}\right)\frac{C_d Y_2 d^2}{\sqrt{1-\beta^4}}\sqrt{2\rho_2 \Delta P} \qquad \text{[Eq.1]}$$

where:

C_d = discharge coefficient
Y_2= gas expansion factor, based on downstream tap
β = d/D
d = throat/bore diameter
D = inlet/tube diameter
ρ_2 = density based on downstream tap
ΔP = differential pressure

The general differential producing class of meters includes a variety of primary elements. The venturi meter is the oldest differential design [1] while the square edged concentric orifice is the most common. Some other designs include the nozzle, cone and wedge. While the earliest applications were limited to liquid; gas applications appeared over time. As the operating pressure of industrial processes increased, compressibility increased in importance.

The present study is based on “Herschel” venturi meters [2]. Calibration data were collected from 76 meters and separated into four categories based on visual judgement of the plotted calibration results.

2.2 Turbine Meter

The turbine meter operates based on a set of rotor blades mounted to a freely rotating axis. The turbine blades are oriented at an angle to the flow. The flowing gas impacts the blades impart a rotational force proportional to gas kinetic energy

A better understanding of turbine meters comes from two sources of information [3]. First, CEESI calibrates 700-900 gas turbine meters per year. This database offers limited data from each of a large number of meters. Second, CEESI has operated an ultrasonic meter (USM) calibration facility since 1999 [4]. The permanent standards and check meters include multiple DN300 (12 inch) turbine meters. This database offers large quantities of data from a limited number of meters.

2.3 Legacy Meters Designs

In the present analysis the turbine and differential producers are considered legacy meters because they have been in use for many years. Beyond that basic classification there are significant differences between the meters. The venturi is based on well defined open source geometry [5,6] while turbine meters are available in a wide variety of proprietary designs. A turbine meter design includes rotating parts with bearings that represents a failure mode. A primary differential element is a machined piece of metal with no moving parts.

2.4 Ultrasonic Meter

An ultrasonic pulse is transmitted in one direction across the flowing gas, a second pulse is transmitted along same path in the opposite direction. The propagation time difference is proportional to the integrated velocity along the path. The speed of sound cancels out assuming conditions do not change between pairs of pulse transmissions. Improved averaging over the entire flowing area is achieved based on multi-path designs.

The basic technology, first defined in 1965, was initially limited to liquid applications. The first widespread applications to gas measurement appeared in the late 1990s; the calibration market has been dominated by large line sizes measuring natural gas.

CEESI has operated an ultrasonic meter (USM) calibration facility since 1999 [4] that utilizes multiple DN300 (12 inch) turbine meter standards. Over years the facility has calibrated thousands of meters providing a very large database. In addition to calibrating USM, the facility uses USM as check standards; the resulting data analyses integral to uncertainty of the facility [7].

2.5 Coriolis Meter

The earliest Coriolis meter designs operated based on the phase shift between two curved vibrating tubes. Over time some designs appeared based on single tubes, other designs used straight tubes. The first meters appeared on the market in the 1980s, typically limited to liquid measurement. Application to gas has been steadily increasing over the past ten years.

The database includes limited data from each of a large number of meters (46) and larger quantity of data from each of a few meters [8,9].

2.6 New Technology Meters

The ultrasonic and Coriolis represent the newest technologies with widespread use in measurement of gas flowrate. Being relatively new the need for independent performance analyses is greater than with the established legacy meters.

3. Performance Parameters

The analyses described in this paper are base on four performance parameters described in this section.

The signature curve relates the meter input and output. The output can be well defined, like the pulses produced by a turbine meter or more complex such as the discharge coefficient of a differential producer. The appropriate meter input varies depending on the appropriate correlating parameter. The correlating parameter relates conditions present during calibration with installed conditions; examples include differences in pressure, temperature, flowrate and gas species. The most common correlating parameter is the Reynolds number (*Re*) others are used depending on application and meter operating principles.

The combination of signature curve and correlating parameter defines the basic linearity and rangeability and allows them to be defined based on uncertainty. With computerized data processing non-linearity can be corrected, a process often called linearization. Selecting the proper correlating parameter is important to the integrity of the linearization process.

Repeatability quantifies the consistency in meter response when exposed to unchanging conditions. Reproducibility quantifies the consistency in meter response when exposed to changing conditions. The changing conditions are generally specified, the formal term being "reproducibility conditions". The passage time generally introduces reproducibility conditions.

The signature curve and correlating parameter represent systematic effects while repeatability represents random effects. The uncertainty of a random effect can be reduced by obtaining more data; thus the repeatability and can be reduced. The uncertainty of a systematic effect can be reduced by calibration, obtaining additional data does not help. In general repeatability is relatively easy to measure in the calibration laboratory while reproducibility is more important to the user. Reproducibility is often made up of both random and systematic effects, the random effects can be systematic depending on time interval. A random effect observed over a period of months may be systematic when observed over a period of minutes. As a result reducing the uncertainty due to reproducibility can be more difficult.

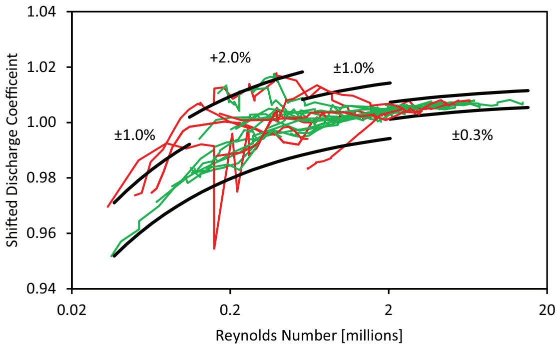

Figure 1: Venturi calibration data

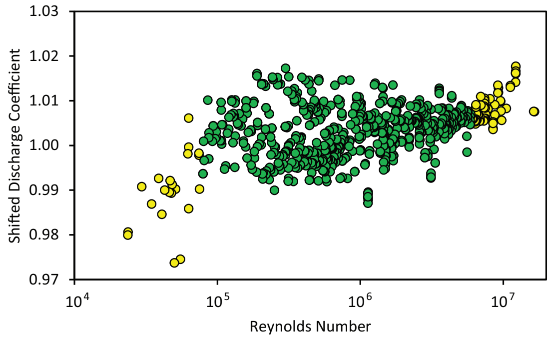

Figure 2: Venturi calibration data

4. Signature Curve and Correlating Parameter

This section is organized based on the four meter designs.

4.1 Venturi

The discussion begins with calibration data of Herschel venturi meters shown in Figure 1. The "as built" throat diameters were not measured in conjunction with these calibrations. From Equation 1 variations in the diameter squared will inversely affect C_d. The C_d values in Figure 1 were mathematically shifted to provide visually agreement of the data at high *Re* values. The shift is assumed to account for the true value of *d*. As a result the data do not reliably represent absolute values; they are a good indication of signature curve shape.

The green and red lines connect data points that make up individual meter calibrations. The black lines represent several statistical intervals that are intended to contain 95% of the data shown in green. Data in red represent a sample of data that follow the basic trend but fall outside the statistical interval.

The data fit a consistent curve with shape defined by the thickness of the boundary layer in the venturi throat. Boundary layer thickness varies with Reynolds number which in turn correlates the calibration data very well. For higher *Re* values the boundary layer is turbulent, very little variation with *Re* is predicted, and C_d is nominally constant. For lower *Re* values the boundary layer is laminar, the thickness and C_d vary more with *Re*. A "transition hump" (110,000 < Re < 570,000) is present in approximately 45% of the green calibrations.

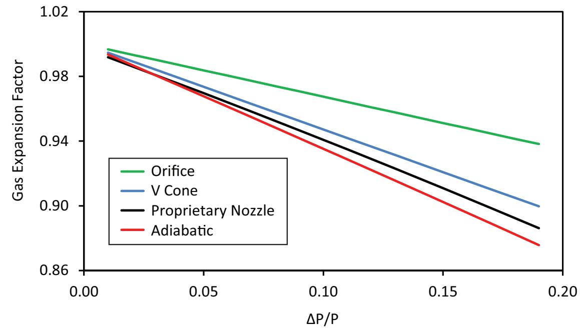

Figure 3: Gas expansion factor for several primary elements

Figure 2 shows venturi calibrations that didn't fit the curve of Figure 1. They represent 37% of the total. Each symbol represents a single data point; the green data result in a signature curve that can be represented by C_d = constant. The yellow data show slight variations in C_d but overall the results are quite different from those in Figure 1.

Some high velocity applications require a second correlating parameter to identify the best value of gas expansion factor (*Y*). While C_d accounts for boundary layer thickness and is correlated with *Re,* the symbol *Y* represents the gas expansion factor which accounts for the change in density between the two pressure taps [10]. The subscript of Y in Equation 1 is the result of using pressure from either tap to calculate *Y*. The gas expansion factor is sometimes represented as a correlation with Mach number.

Figure 3 shows *Y* values for four different primary element designs. The abscissa is the ratio of differential to static pressure, the ordinate is expansion factor. It is noted that *Y* approaches unity as flowing pressure increases or differential pressure decreases. The relative importance of the expansion factor therefore varies based on the application. Returning to Figure 3, the "adiabatic" value assumes the gas flow between the taps is a reversible process with no heat transfer. The orifice [6] and V-Cone values [11] are based on published experimental data. The final curve corresponds to a proprietary meter design calibrated by CEESI [12]. Clearly the expansion factor varies with the design of the primary element; in some applications a calibration is designed to determine both $C_d(Re)$ and $Y(M)$.

4.2 Coriolis Meter

Figure 4 shows curve fits of multiple Coriolis meter calibration data that represent nearly 80% of the database.. The abscissa is tube velocity, the ordinate is the difference in mass flowrate between meter indication and laboratory standard. The green lines represent a statistical interval with ±0.16% width. The black lines represent calibrations that are visually judged to fit the statistical interval;

Table 1: Ultrasonic meter calibration data scope

Nominal Diameter [mm]	Quantity Meters	Data Points	Interval Width [%]
600	13	118	0.45
500	9	62	0.40
400	28	200	0.38
300	77	577	0.66
250	31	232	0.77
200	38	276	0.84
150	55	385	1.08
100	17	122	0.88

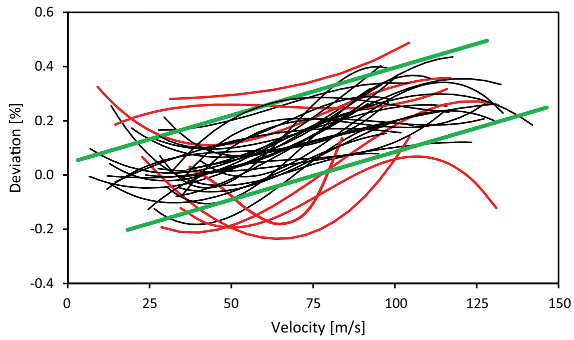

Figure 4: Coriolis meter calibration data

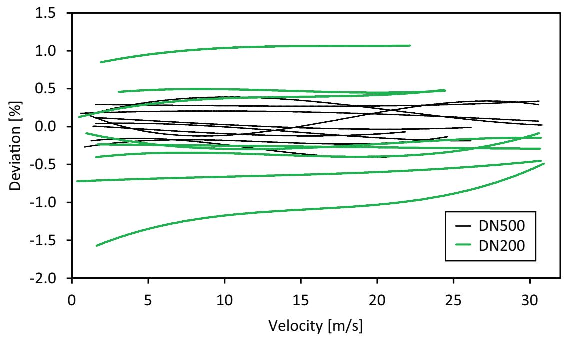

Figure 5: Calibration data for two sizes of ultrasonic meter

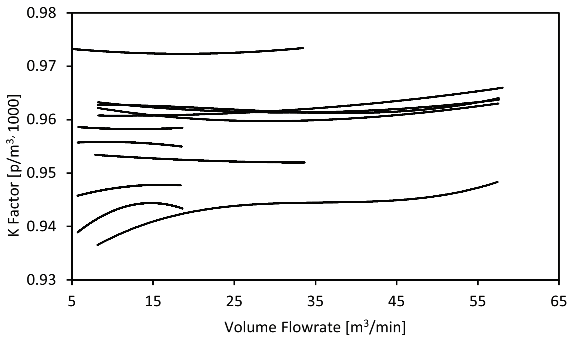

Figure 6: Calibration data for multiple DN150 turbine meters

the red lines represent calibrations that are judged to fit the general trend but fall outside the statistical interval. The curves of Figure 4 represent nearly 80% of the calibrations in the database. A clear trend with velocity is evident indicating a potential correlating parameter.

The manufacturers state maximum recommended tube Mach number, a typical value is $M < 0.30$. Assuming a nominal value of 350 m/s for the speed of sound in air, the data of Figure 11 correspond to maximum Mach numbers between 0.3 and 0.4. It is noted that Mach number is directly proportional to velocity when constant temperature gas is considered. The best correlating parameter might be Mach number, testing with a different gas would be required to provide confirmation.

4.3 Ultrasonic Meter

Figure 5 shows calibration data of a number of ultrasonic meters. The abscissa is average velocity, the ordinate is the difference in volume flowrate between meter indication and laboratory standard. The black lines represent curve fits of all the DN500 (20 inch) meters in the database, the green lines represent a selection of DN200 (8 inch) meters. The curves of Figure 5 are quite flat but not well centered about zero. There does not appear to be a consistent shape attributed to a physical behavior like the venturi.

The data of Figure 5 represent two sizes, the entire database is summarized in Table 1. The "Interval Width" column represents the ±2s, where s is the standard deviation of all the calibration points. It decreases as the meter size increases, as noted in Figure 5. Most size dependent ultrasonic meter uncertainties arise from the need to measure smaller time differences with smaller meters.

Prior to shipment from the factory an ultrasonic meter is statically tested using compressed nitrogen, speed of sound measurements are used to finalize various meter settings. The data of Figure 5 represents the limits to the static testing and demonstrate the need to calibrate. After calibration a velocity based correction is installed in the meter; the pre-calibration curve shape serves no measurement purpose. Some users evaluate the pre-calibration as a measure of the manufacturing process quality; a well controlled process should produce static test results that agree with the final laboratory results.

In the interest of completeness it is noted that the data of Figure 5 and Table 1 is quite old (2006) and does not necessarily reflect current day limits to static testing.

An important consideration related to selection of a correlating parameter is the gas pressure. Concerns have been rased about calibration at one pressure and operation at a different pressure. The flow community, including CEESI, has not produced data that shows the presence of a pressure effect.

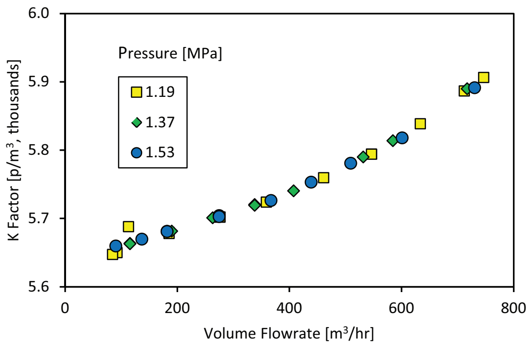

Figure 7: Calibration data for Turbine Meter A

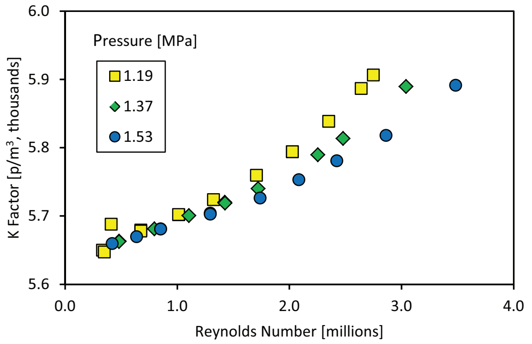

Figure 8: Calibration data for Turbine Meter A

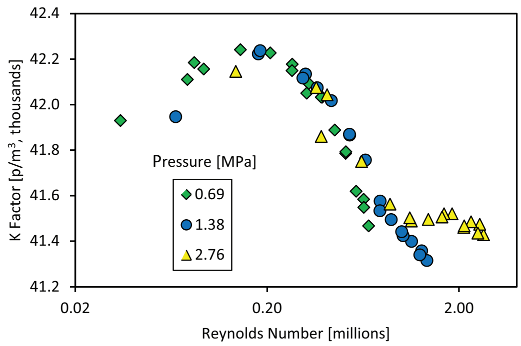

Figure 9: Calibration data for Turbine Meter B

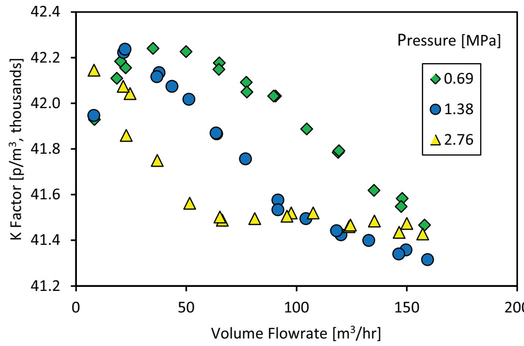

Figure 10: Calibration data for Turbine Meter B

4.4 Turbine Meter

Figure 6 shows calibration data of a number of turbine meters. The abscissa is volumetric flowrate and the ordinate is the K-Factor. The calibrations are all DN150 (six inch) size meters from the same vendor.

A boundary layer building on the rotor blade surface can result in a signature curve similar to the venturis in Figure 1. While such shapes have been observed, they are not common. None of the data of Figure 6 indicate boundary layer behavior, several explanations are proposed. First, bearings create drag that will affect the signature curve, the details depend on how the drag varies with velocity and density. The interaction of rotor, bearing and flow field is complex and possibly unique to each meter. Second, turbine meters predate widespread use of field based computing. The linearity (constant K-Factor) was very important when only simple analog electronics are available. Over time the vendors have likely optimized their mechanical designs for linearity as observed in Figure 6. Generally, of the four meter, the turbine is the most likely to show variation as a result of proprietary design features.

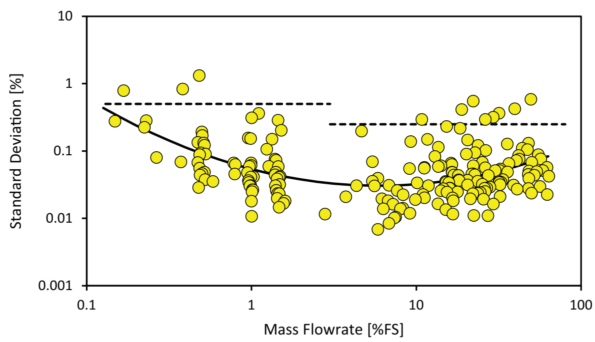

Figure 11: Repeatability of multiple Coriolis meters

The optimum turbine meter correlating parameter can vary based on meter design, pressure, temperature and molecular weight. For example, the calibration data of two meters over a range of pressures are shown in Figures 7 - 10. The calibration data of Meter A correlates better with volume flowrate than with Reynolds Number. The calibration data of Meter B correlates better with Reynolds Number than with volume flowrate. The best solution is to calibrate the meter over a range of conditions.

5. Repeatability

The largest repeatability database assembled by CEESI represents multiple individual Coriolis meters. Figure 11 shows repeatability data from a representative portion (26 meters) of the CEESI database. Each symbol represents the standard deviation associated with multiple readings obtained at a constant flowrate. The dashed lines represent limits required by the AGA 11 [13] natural gas industry standard, most of the data comply. The solid line represents a curve fit of the data.

The manufacturers state maximum recommended tube Mach number (M < 0.30). A maximum Mach number

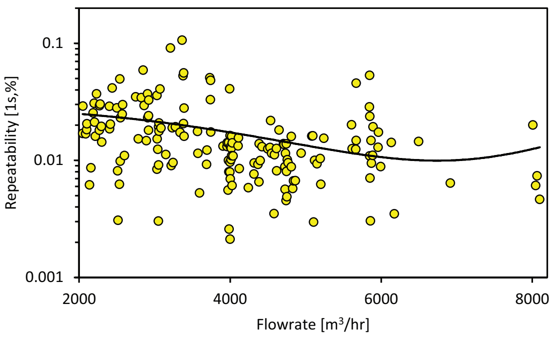

Figure 12: Repeatability of a turbine meter

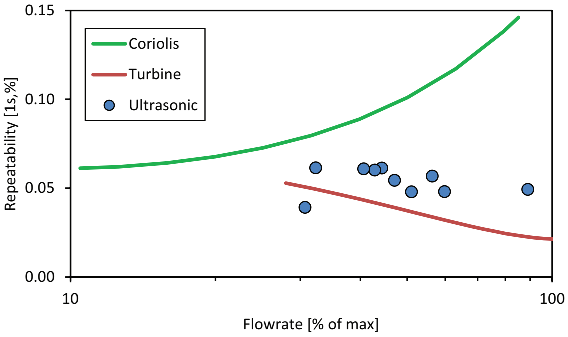

Figure 13: Repeatability of three meters

combined with flowing density establishes a maximum mass flowrate. Is is likely the maximum mass flowrate in Figure 11 (65% FS) is a result of the maximum Mach number. This is speculative because the calibration flowrate ranges are defined by the customer.

The CEESI Iowa facility provides large quantities of turbine and ultrasonic meter data. Figure 12 contains selected data of a single DN300 check standard in use for several years. Each symbol represents the standard deviation associated with multiple readings obtained at a constant flowrate. The value of data such as that in Figure 12 is that it has been obtained over a long time interval.

Figure 13 compares the curve fits of Figures 11 and 12 with data from a DN300 ultrasonic check standard identified as TM103. The ordinate represents one standard deviation expressed as a percentage. The USM data were divided by flowrate into groups containing approximately 500 data points. The goal is to define a large enough group to ensure statistical validity, while maintaining a relatively constant flowrate. The Coriolis and turbine data were not organized to enable the exact same analytical process.

Table 2: Meter reproducibility data scope

File	Time Interval	Data Points
UM137a	Jun 12 - Apr 13	6080
UM137b	Jan 14 - Jun 15	8925
UM730a	Jan 14 - Jul 15	3830
UM730b	Jan 14 - Feb 16	4280
TM103	Jul 03 - Jul 04	600

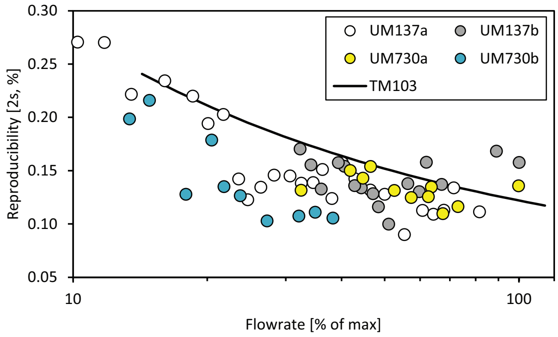

Figure 14: Reproducibility data for three meters

Plotting the data in Figure 13 requires definition of the maximum flowrates form each meter. For the ultrasonic meters the maximum volume flowrate values correspond to maximum velocities of 30.5 m/s. For turbine meter the published value is 7080 m^3/hr. For the Coriolis meter the 65%FS represents the maximum mass flowrate as discussed above. Over the 30-100% range the turbine repeatability is slightly less than ultrasonic and both show a similar trend to increase as flowrate decreases. The Coriolis repeatability is considerably larger and trending in the opposite direction. For flowrates below 20% the Coriolis repeatability is lowest of the three.

The analysis of individual venturi and turbine meter calibration data has not yet been expanded to include repeatability. Some analysis of individual ultrasonic meter calibration data has been completed and will be reported at a later date.

6. Reproducibility

As mentioned previously reproducibility is a more important parameter than repeatability. The laboratory calibration of a meter takes place over a relatively short period of time while the final installation may be unchanged for years. The laboratory measures repeatability while the user is more concerned with reproducibility. A second consideration is important for CEESI day-to-day operation. The reproducibility data presented discussed below represent an important component of the uncertainty analysis, in particular the Iowa facility.

Figure 14 shows reproducibility data from five [14,14] meter databases. The solid line is a curve fit of data from the TM103 turbine meter check standard. The open symbols represent data from two USM check standards (UM137 and UM730) that are organized based on constant flowrate intervals as described in Section 5. The details of the databases are summarized in Table 2. The UM730a data are based on multiple turbine meter standards while the UM730b data are based on a single turbine meter standard.

The time intervals of Table 2 are important in evaluating reproducibility. As the time interval increases a larger number of reproducibility factors are introduced and the estimated uncertainty becomes more realistic. This is particularly true when data are obtained over a full year and various seasonal effects can be included.

The four USM data sets agree to within ±0.04% of each other. Both UM137 data sets are very close indicating consistency over a multiple year period. The overall trends with flowrate are very similar, reproducibility decreases as flowrate increases. The Iowa facility uses turbine meter standards therefore all the data include one or more turbine meters. Assuming the reproducibility is equally attributable to each meter, the reproducibility values can be reduced by 30% for each meter.

Summary

Four basic gas meter designs have been compared and contrasted based on four performance parameters. The comparisons are based on databases containing a variety of calibration data.

The meters are:
- venturi
- turbine
- ultrasonic
- Coriolis

The performance parameters are:
- signature curve
- correlating parmeter
- repeatability
- reproducibility

References

1. Herschel, C., The Venturi Meter, American Society of Civil Engineers, 1887.
2. Kegel, T.M., “The ISO 5167 Compliant Design Venturi – A Further Summary of Calibration Experience,” FLOMEKO, 2010.
3. Kegel, T. and Seidl, W., “Gas Turbine Meter Operating Characteristics, Results from a Large Database,” International Symposium on Fluid Flow Measurement, 2015.
4. Kegel, T., “Uncertainty Analysis for the CEESI Iowa High Flow Test Facility,” International Symposium on Fluid Flow Measurement, 1999.
5. ISO 5167: Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full, 2003.
6. ASME MFC-3M: Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi, 2004.
7. Kegel, T. M. and Johansen, W.R, “Reducing the Uncertainty of a High Pressure, High Flowrate Calibration Facility,” FLOMEKO, 2016.
8. Kegel, T and Baldwin, S,. ”Compressible Flow Effects in Coriolis Meters,” International North Sea Flow Measurement Workshop, 2014.
9. Kegel, T. “Compressible Flow Effects in Coriolis Meters:, A Continuing Study,” Gasmexico Congerss and Exhibit, 2015.
10. Benedict, R.P., Fundamentals of Temperature, Pressure and Flow Measurements, (John Wiley & Sons), 1984.
11. Stewart, D.G., Reader-Harris, M, and Peters, R.J.W., “Derivation of an Expansibility Factor or the V-Cone Meter,”FLow Measurement 2001 - International Conference.
12. Kegel Thomas, “Compressible Flow Effects in Subsonic Venturis,” 4th International Symposium on Fluid Flow Measurement, Denver, Colorado, June 27–30, 1999.
13. AGA 11: Measurement of Natural Gas by Coriolis Meter, 2013
14. Kegel, T. M. and Johansen, W.R., “Monitoring the Repeatability and Reproducibility of a Natural Gas Calibration Facility,” FLOMEKO, 2013.