Reducing the Uncertainty of a High Pressure, High Flowrate Calibration Facility

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Abstract

This paper describes data acquisition and analyses underway with the objective of reducing the uncertainty of the CEESI Iowa high pressure natural gas calibration facility. The current uncertainty is 0.23%, the target is a value less than 0.20%. Three programs are described: The first is intended to reduce the uncertainty associated with the traceability to the Colorado high pressure air facility. A new transfer standard package has been calibrated at both facilities. The second program involves the detailed analysis of extensive check meter data. The analysis results will quantify facility reproducibility. The third program indirectly inter-compares individual standards on a periodic basis. The initial agreement between program results and historical calibrations is encouraging.

1. Introduction

CEESI has been operating high pressure air facilities in Colorado since 1965 and a high pressure natural gas facility in Iowa since 1999. The Iowa facility was originally designed for ultrasonic meters but is available for other meters as well. The facility was constructed adjacent to a pressure control station on a natural gas pipeline. The nominally constant operating pressure and maximum allowable pressure drop are limited by the pipeline operator.

The Iowa facility operates based on ten DN300 (12 inch) meter runs, nine are currently in use. The DN300 standards cover a flowrate range of 396 to 42,475 m^3/hr (14,000 to 1,500,000 acfh). The Iowa facility also operates over a lower flowrate range using a different set of flow standards. The lower flowrate range is not included in the present analysis.

The initial uncertainty of the facility was ±0.30% (95%CL) [1]. After some years of operating experience the uncertainty was reduced to ±0.23% [2]. This paper presents data and analysis leading an uncertainty goal of less than ±0.20%.

2. Transfer Standard Artifacts

When the system was first built the turbine meter standards were calibrated in Colorado using compressed air. Over time each meter was shipped back to Colorado for re-calibration. The risk of shipping damage represented one of several factors that lead to a second approach to maintaining traceability. The critical flow venturi (CFV) represents a more rugged technology, less susceptible to shipping damage. The basic CFV operation principle [3] results in a measurement where the mass flowrate is directly correlated with pressure. The Iowa facility operates with a nominally constant pressure. Without the ability to vary pressure mass flowrate is varied by opening different CFV combinations. The need for multiple CFVs resulted in a rather large and complex transfer standard artifact. A large number of valves created the possibility of leaks. The current approach utilizes a simpler artifact design based on two DN100 (four inch) turbine meters installed in parallel or in series [4].

A second meter, a DN300 (12 inch) ultrasonic meter, will also be utilized as a transfer artifact. This meter, identified as SN137, has been in service as a check meter. It has been replaced by a newer meter and will be calibrated in Colorado. The historical data will be discussed further below.

The turbine meters used as permanent standards (PSTM) and transfer standards (TSTM) are fundamentally different in design. The permanent standards feature a relatively large central blockage that accelerates the flow impacting the blades. The higher velocity produces more kinetic energy which generally results in wider linear rangeability. The TSTM have less blockage which has several implications for the current test program. The TSTM meters have higher flowrate capacity, two DN100 meters have the same flowrate range as one DN300 PSTM. This enables the design of a simpler artifact. With operation at a higher velocity, temperature measurement will require additional data processing, which will be discussed below. In addition pressure drop will increase in proportion to the square of the velocity. The allowable pressure drop in the Iowa facility is limited.

Calibrating the Iowa PSTM against the CFV array proved to be a major effort that typically required at least a week of time. In contrast the turbine meter artifact can be installed and operated when a few hours become available in the schedule. This is a major advantage for a busy commercial laboratory.

Calibrating a turbine meter with a CFV requires density because the CFV is a mass flowmeter while the turbine is a volume flowmeter. Completing the calibration process using air instead of natural gas results in lower uncertainty. This represents another advantage of using turbine meters instead of CFVs to calibrate the Iowa PSTM

The traditional flowmeter calibration process involves varying volume flowrate while maintaining constant pressure. The process requires two valves to control the two variables, adjusting the valves needs to be well coordinated. An additional consideration is the need to balance air consumption while minimizing variations in flowrate and pressure.

The present data are obtained based on a "constant velocity" calibration process. The turbine meter is installed upstream of a CFV with no intermediate control valve. The turbine meter is exposed to same pressure as the CFV inlet. A control valve upstream of the turbine meter controls pressure. The test proceeds based on varying the pressure that results in density and mass flowrate changes while the volumetric flowrate and velocities remain nominally constant. The temperature is controlled with an upstream heat exchanger. The constant velocity test algorithm offers two advantages. First, the downstream control valve is eliminate resulting in easier control and less uncertainty contributed by random variations. Second, there is very little pressure drop between the turbine meter and CFV which reduces temperature changes. A second heat exchanger can be included in a conventional calibration but the added volume generally increases the difficulty in controlling pressure and flowrate.

In the present process mass flowrate is traceable to the SI using a set of CFV standards identified by serial numbers of the 1691-## format. Several from the set have directly calibrated by NIST [5] as well as being traceable to the CEESI gravimetric standard. Each 1691 CFV has a nominal throat diameter of 25 mm (one inch) that corresponds to a nominal flowrate of 5.7 m^3/min (200 ft^3/min). Five CFVs in parallel will produce the maximum rated volume flowrate through a TSTM. The 1691 traceability chain is under review with the objective of reducing the uncertainty.

The Colorado TSTM calibration results are shown in Figures 1 and 2. The meters are identified as TM20 and TM21. Clearly there are differences between the calibration data of the two meters. The TM20 data correlate well with *Re* except the 5.7 m^3/min data. The 17 m^3/min data show a K-Factor increase for $5 < Re < 7$ million. The TM21 data show a flowrate dependent slope in the Re correlation; from positive a low flowrate to negative at higher flowrate. The 28 m^3/min data appear shifted down compared to the other four data sets.

Many years of CEESI calibration experience indicate that turbine meters commonly become more linear with increasing flowrate, density, and diameter. Unfortunately the current TSTM do not follow the trend. While selecting the particular turbine meters resulted in advantages, the non-linearity represents a distinct disadvantage

A review of the calibration data did not immediately identify either any measurement or calculation problems that might account data that didn't fit general trends. A decision was made to move on and obtain data in Iowa and re-calibrate the meters in Colorado at a later date.

Surface fits of $K = f(Re, Re^2, Q, Q^2)$ developed for the two meters were extrapolated to calculate Iowa K Factors. The initial Iowa data processing identified shortcomings in the surface fits and a different approach was adopted. A pair of linear fits were applied to nine data sets; the TM21 28 m^3/min data were excluded. The pairs of fits resulted from abscissa values of *Re* and density; either variable could be the proper correlating parameter. The linear fits were then extrapolated to Iowa conditions of density and *Re.* The resulting K-Factor values differ by up to 0.4%; an uncertainty of ±0.2% is assigned to the curve fitting extrapolation process. This estimate is expected to decrease when additional high pressure data are obtained.

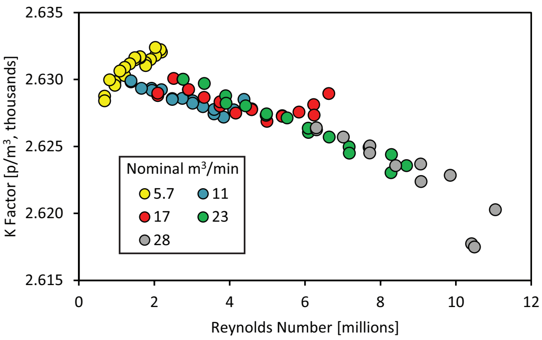

Figure 1: Compressed Air Calibration Data of TM20

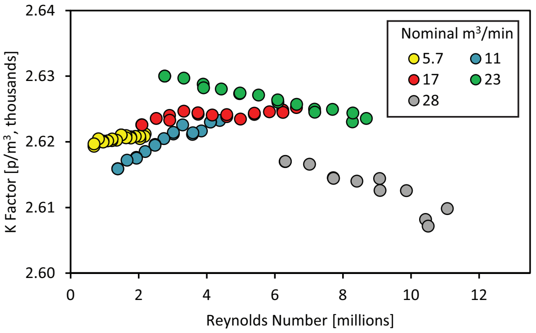

Figure 2: Compressed Air Calibration Data of TM21

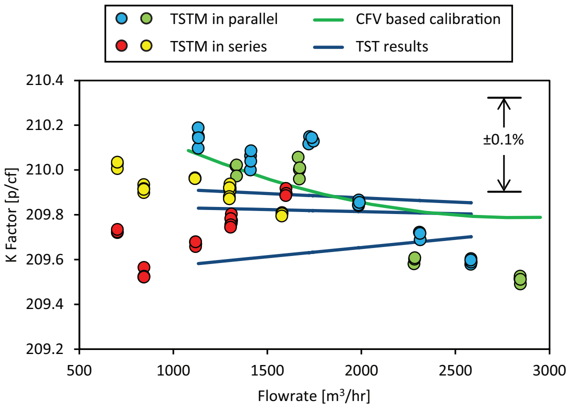

Figure 3: Summarized Calibration Results for TM034

Iowa data from one PSTM, identified as TM034, are contained in Figure 3; the results are typical of other PSTM. The blue solid lines are turbine substitution testing (TST) dara that will be discussed below. The solid green line represents the last published [5] CFV calibration results. The symbols represent calibrations using parallel and series installations of the TSTM. The parallel installation results in higher flowrates while the series installation results in redundant measurements. The parallel TSTM data were the result of two test patterns obtained several weeks apart. With the first pattern, the flow was held steady and valves were actuated so the flow was directed through the PSTM one at a time. The flowrate was then changed and the PSTM sequence repeated. With the second pattern, multiple flowrates were directed through a single PSTM with the flowrate sequence repeated for the other PSTM. Each pattern will subject the process to different reproducibility conditions. Based on the agreement noted in Figure 3 the uncertainty resulting from the reproducibility conditions is very small. Similar results are observed with the other PSTM.

While the averages of the TSTM data agree with the other data within the ±0.1% the general trend in non-linear. The apparent PSTM non-linearity is not observed in the TST data nor to the same degree in the CFV calibration results. One potential source is the extrapolation of Colorado data curve fits, additional high pressure air testing of the TSTM is underway. A second possible source leads into the discussed below. An approximate temperature correction has been applied to the Iowa data, exact corrections have been delayed until the curve fits are improved.

The measurement of temperature is affected by high velocity [6]. The relationship between static (T_S) and indicated temperatures (T_{ind}) is:

$$T_S = T_{ind}\left(1 - \frac{\left(\frac{\gamma - 1}{2}\right) r M^2}{1 + \left(\frac{\gamma - 1}{2}\right) M^2}\right) \tag{1}$$

where M is Mach number, γ is the isentropic exponent and the recovery factor (r) is:

$$r = \sqrt[3]{Pr} \tag{2}$$

where Pr is the Prandtl number.

In the present air testing the maximum velocity is 59.2 m/s (194 ft/s) corresponds to a Mach number of 0.1, the Prandtl number is 0.7. High pressure air testing is currently underway to confirm the applicability of Equation 2 because the recovery factor is a function of the physical structure of the RTD probe.

3. Check Meters

The Iowa facility includes multiple ultrasonic check meters of different sizes to monitor calibration process consistency [7]. All meter technologies features variation in reproducibility with flowrate, ultrasonic meters are no different. In the present analysis the effect of flowrate is reduced by the definition of nominally constant flowrate subsets. The subsets must be small enough to limit the flowrate range but large enough to provide statistical validity. The subsets contain between 200 and 500 data points.

Three check meter analyses are included in the present analysis. The first meter is a DN300 (12 inch) ultrasonic meter identified as SN137. The data under analysis consist of 8925 points obtained between January 2014 and June 2015 covering a flowrate range of 2390 to 8540 [m³/hr]. The typical data contained in Figure 4 cover the 3919 - 4205 [m³/hr] flowrate range. The meter factor (MF) is the ratio of actual to indicated flowrate. The ordinate is the change in MF expressed as a percentage.

The second meter is a DN300 (12 inch) ultrasonic meter identified as SN730; the present analysis consisted of two time intervals. The first consisted of 3830 points obtained between January 2014 and July 2015 over the flowrate range of 1000 to 3330 [m³/hr]. The query constraints limited the data to a single PSTM (identified as TM034).

The second data set utilized a different query structure that include multiple PSTM. The results consisted of

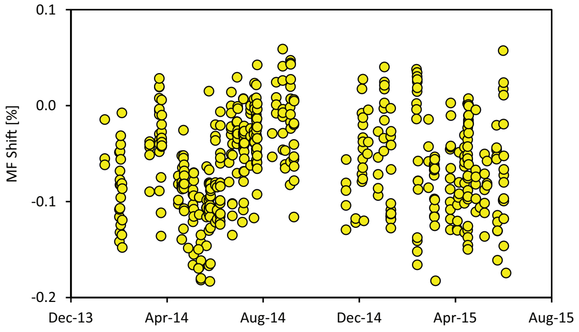

Figure 4: Check Meter SN137 Data, Nominal Flowrate 4060 m³/hr

4280 points obtained between January 2015 and February 2016 over the flowrate range of 2150 to 10,080 [m^3/hr].

The third meter is a DN500 (20 inch) ultrasonic meter identified as SN502. The data consisted of 1494 points analyzed were obtained between March 2014 and June 2016 over flowrate range of 1820 to 16,500 [m^3/hr].

Data from SN730 and SN137 are compared in Figure 5. The ordinate (standard deviation, s) quantifies random effects observed over the entire time interval, they represent reproducibility. The solid lines represent curve fits of the respective data sets, they are interpreted as averaged values. The data identified as SN137-1 are based on a single PSTM while SN137-2 are based on multiple PSTM. The SN730 and SN137-2 data show a similar trend; random effects increase at higher and lower flowrates, with minimum at approximately 5500 m^3/hr. The dashed line represents a standard deviation of 0.7%, the significance of this value is described in the next section.

It is important that the "U-shaped" curves be explained based on physical ultrasonic meter behavior and therefor not likely attributable to the PSTMs. At lower flowrates the elapsed time measurements become smaller and larger amplitude random effects arise from the clock. At higher flowrates several factors are suggested. First, higher Reynolds numbers result in greater turbulence intensity resulting in increased random variation. Second, the trajectory of the sound pulses is distorted, also resulting in increased random variation. Finally, the quantity of data are limited, the subsets covers wider flowrate ranges and are more likely to introduce flowrate dependent effects.

The SN137-2 standard deviation values are larger in amplitude than SN137-1. The difference is assumed to represent the effect of varying PSTM over the time interval. While the difference represents a small effect there is some room for improvement.

From Figure 5 the SN730-2 data show that $s \leq 0.07\%$ for $3600 \leq Q \leq 7030$ m^3/hr. This is interpreted as quantifying the 13 month facility reproducibility based on the optimum USM flowrate range. Similarly the SN137 data show $s \leq 0.07\%$ for $1730 \leq Q \leq 3040$ m^3/hr for 18 months. Not shown in Figure 5, the SN502 data show $s \leq 0.07\%$ for $6830 \leq Q \leq 11,800$ m^3/hr for 27 months.

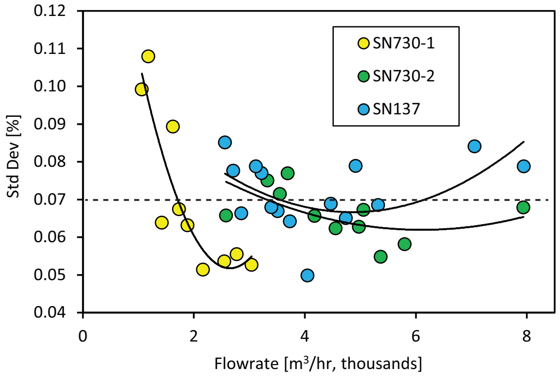

Figure 5: Summary of Check Meter Results

4. Turbine Substitution Testing

Turbine substitution testing (TST) represents a measurement assurance program (MAP) operated in addition to the check meters [7]. Check meter data can include multiple PSTM. The process becomes less sensitive to shifts in individual standards as the number of standards increases. TST supplements the check meter data by allowing individual standard to be compared indirectly.

One major TST advantage is the ability for easy implemented when time in the schedule allows. Availability could result from a last minute cancelation or a test program that is completed earlier than anticipated. This is an important consideration for a busy commercial facility.

Each TST begins with the definition of an artifact (TSTA) consisting of one or more meters in series. The artifact typically includes an MUT and a check meter. The TST process continues by establishing steady flow between one PSTM and the TSTA. Next, without changing flowing conditions, a second PSTM is connected to the TSTA and the first PSTM is disconnected. The process is then repeated for additional PSTM. When time permits the process is repeated for one or more additional flowrates.

The present analysis considered TST obtained between July 2011 and December 2015. Typical data are represented by the solid lines contained in Figure 3. The analysis process divided the data into three groups; the solid lines represent averaged values. The three lines fit within ±0.08%; similar TST data agreement from the other PSTM varies between ±0.03% and ±0.08%.

The consistency demonstrated by the average data represents the most important conclusion from the TST data analysis because it demonstrates the consistency of the facility.

The random variation was also investigated to provide support for the facility reproducibility. The TST random effects are observed to be larger than observed with the check meters. One reason is that TST data are taken much less frequently than check meter data, several hundred per year compared to over ten thousand per year. Essentially the check meters represent a much better sample than TST data. Further, the TST are based in part on MUT artifacts which are constantly changing, and likely contributes additional uncertainty. In contrast check meter data are always based on the same meter. That having been said, the averaged TST data quantify the stability of individual PSTM.

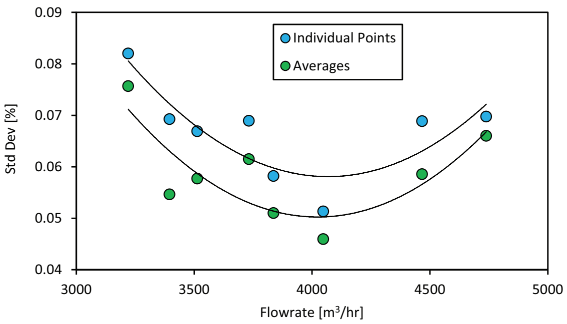

Figure 6: Comparing Individual Points to Averaged Values, SN137

5. Decomposing Random Effects

The observed random effects include contributions from two measurements of flow rate, the lab and an artifact or check meter. The uncertainty analysis requires an estimate of the lab without including the artifact. The simplest approach is to assume equal contributions from both sources, the condition defined by $s \leq 0.07\%$ becomes:

$$s \leq \frac{0.07}{\sqrt{2}} = 0.05\% \tag{3}$$

The data in Figure 5 where $s \leq 0.07\%$ demonstrate system reproducibility of ±0.1% (95%CL). The reproducibility conditions are the result of variations that can occur during time intervals of between 13 and 27 month duration.

The standard customer practice involves using averaged values rather than individual data points. In general averaging data will reduce components of uncertainty that arise from random effects. In the present analysis the query results have been provided as individual readings The standard deviation values presented in the sections above are calculated based on individual readings.

Eight data sets for meter SN137 were analyzed based on average values to quantify the effect of averaging; the results are contained in Figure 6. The blue symbols represent standard deviations based on individual readings, the green symbols are based on averages. The solid lines represent curve fits. On average the difference is 0.008%, a slight reduction in the uncertainty.

Summary

An effort is underway to reduce the uncertainty of the Iowa natural gas calibration facility to a value less than 0.20% (95%CL). Three programs were described. First a new transfer standard artifact provides traceability to the high pressure Colorado air facility. The average values agree with results from turbine substitution testing, the second program. Finally, in the third program a series of check standards, quantify system reproducibility.

References

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