

REDUCING THE UNCERTAINTY OF A GRAVIMETRIC PRIMARY STANDARD

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Abstract

CEESI operates a gravimetric primary standard for high pressure compressible flow measurement. A program is underway to reduce the uncertainty. A knife edged balance requires human position observation; an optical sensor will provide an electronic indication. A set of ball valves transfer the flow source from a start-up supply to the gravimetric pressure vessel. The upgrade will include monitoring pressure and temperature transients while the valves reposition. A series of “trapped volumes” contain fluid that is not included in the direct mass determination, but flows through the test section. Improved volume, pressure and temperature measurements are being implemented.

Background

Colorado Engineering Experiment Station, Inc. (CEESI) has operated a gravimetric primary system for compressible flow for over 40 years. The system has been used to maintain the traceability of calibration standards used at the laboratory and to provide low uncertainty commercial calibrations.

The gravimetric primary system will be used to establish independent traceability to support a new traceability chain. The new traceability chain is being established to provide low uncertainty calibrations at the CEESI Iowa High Flow Natural Gas Facility. A set of small critical flow Venturis (CFV) have been calibrated at NIST in the USA using a PVTt system [1]. The small CFVs will be used in parallel to calibrate 16 larger CFVs. The final step will be to use the larger CFVs, calibrated at high throat Reynolds numbers, to calibrate the standards at CEESI’s Iowa High Flow Natural Gas Calibration Facility. The process will be the same as described by Johnson [2] but will utilize a lower uncertainty starting point.

The gravimetric system has been used in a similar manner in the past. In 1980 Stevens [3] developed a flow standard for Boeing that was composed of 162 CFVs in parallel. The design of the Boeing system allowed the measurement of the mass flow of air from 0.0182 kg/sec up to 18 kg/sec. The calibration of the CFVs was conducted using the CEESI gravimetric primary system. The final discharge coefficient uncertainty was well under 0.1%.

In 1993, Kegel [4] performed an analysis of the gravimetric system to determine the uncertainty in the measurement of mass flowrate. The uncertainty analysis drew upon the work of Stevens and other testing programs where random effects had been carefully managed. Kegel’s analysis produced an estimated uncertainty in the measurement of mass flowrate of 44 to 150 ppm at a 95% level of confidence.

In 1998 a major upgrade of system components on the gravimetric system was conducted. Pressure gages were replaced with pressure transducers and valve switching was improved. Figure 1 shows data taken on a critical flow venturi over a 4 year period since the upgrade. The data in Figure 1 supports CEESI’s current estimate of $\pm 0.1\%$ for commercial calibration services. Random effects from several sources explain the difference between Kegel’s estimate of uncertainty in the measurement of mass flowrate and the results shown in Figure 1. The goal of the present work is to identify significant sources of random effects and implement changes in hardware and procedures which will reduce the uncertainty in the discharge coefficient of CFVs to approximately $\pm 0.05\%$. Uncertainties at this level will allow the system to be used to provide independent traceability to the CEESI Iowa High Flow Natural Gas Facility.

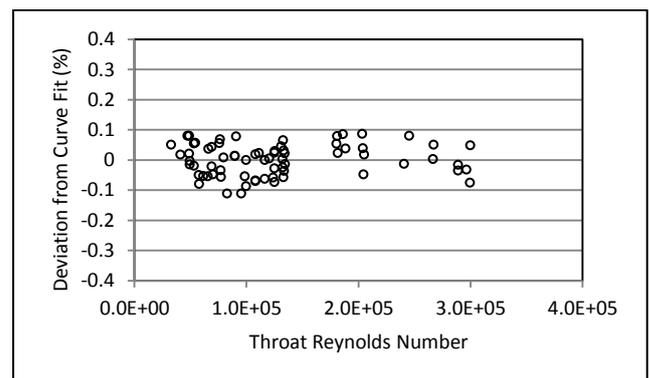


Figure 1. Current Gravimetric System Performance

Gravimetric Primary System

Basic Operation

The gravimetric system operation is illustrated in Figure 2 below. The flow of gas through the system is established from the start-up tank. After achieving steady state

flowing conditions at the inlet of the customer's meter the source of gas flowing through the system is switched from the start-up tank to the gravimetric system sphere. The valves used to change the source of gas are operated by common actuator and are referred to as quick change valves. The motion of the valves starts timers which record the total time gas is drawn from the gravimetric system sphere. The minimum mass of gas drawn from the gravimetric system sphere and the minimum test time required to achieve the stated uncertainty are determined prior to testing. When the mass and time criteria have been satisfied the flow of gas from the sphere and the timers are stopped. The mass of the gravimetric system sphere is determined before and after testing.

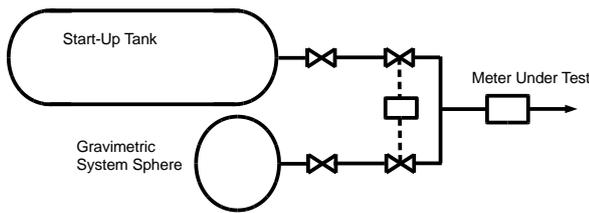


Figure 2. Gravimetric System Layout

The piping connecting the start-up tank and the gravimetric system sphere to the unit under test (UUT) can be divided into discrete volumes referred to as trapped volumes. At the start of a test the trapped volumes contain gas that flows through the UUT but did not come from the gravimetric system sphere. At the end of a test the trapped volumes contain gas that did come from the gravimetric system sphere but did not pass through the UUT.

The final mass value is found by adding the change in trapped volume mass to the change in gravimetric system sphere mass. The average mass flowrate is the difference between initial and final mass determinations divided by the total time.

Random Effects

Scale Operation The operation of the scale on the gravimetric system is the most difficult part of the system for operators to learn. The scale operation is sensitive to its positioning which can change during the mass determination process. Providing the operators with a tool to alert them to abnormal scale behavior was the most important aspect of this project.

The scale used to measure the mass of the gravimetric system spheres is a balance beam. The beam rests in a cradle when not in use. A hydraulic piston raises and lowers to pick the beam up out of the cradle. A knife edge at the center of the beam supports the beam when in the raised position. The knife edge rests on a hardened steel surface which is raised and lowered by the hydraulic piston. The cradle provides repeatable knife edge positioning on the hardened steel bearing surface.

Picking up the spheres must be done carefully. The center of gravity of the sphere must be directly under the hook used to attach the sphere to the beam. If the sphere is not aligned correctly with the balance beam the resulting horizontal force can pull the beam out of its proper position.

Clearances between the balance beam and the support structure are small. Any contact or rub between the moving balance beam and the support structure results in incorrect mass readings.

The scale is normally read twice for each mass determination. After the first reading the balance beam is lowered into the cradle and rotated 180 degrees permitting the sphere and tare weights to be suspended from the opposite ends of the beam. The mass from the two measurements are averaged. Determining the mass in this manner eliminates scale error. The scale can be read additional times allowing the results to be compared to previous readings. Since the beam is placed into the cradle each time the beam is rotated there is some independence between readings.

The balance beam must be in motion in order to get an accurate reading. A fixed scale and pointer mounted to the beam allow the operator to observe the motion of the beam. If the travel up or down is greater than the travel in the opposite direction the operator will add or remove fixed weights. When the travel upward is equal to the travel downward the beam is determined to be in balance. There are two sizes of system spheres used with the gravimetric system. The larger size is approximately 300 liters and the smaller size is approximately 100 liters. Damping will reduce the magnitude of the beam oscillation over time. When using the larger sphere the oscillation of the beam is very slow and the damping is very small. Judging equal distances upward and downward can be done reasonably well. When using the smaller sphere the oscillation is much faster and the damping of the motion is greater. Observing equal upward and downward travel does not indicate the beam is balanced.

The motion of the balance beam is now monitored using an optical encoder. The characteristic of the damping can be approximated using a viscous damping model. The motion of the end of the balance beam is modeled using the following equation:

$$x = X_0 e^{-\zeta \omega_n t} \cos(\omega_n t) \tag{1}$$

where:

- x = amplitude of the beam at time = t
- X_0 = amplitude of the beam at time = 0
- ζ = damping factor
- ω_n = undamped natural frequency

The plot in Figure 3 shows the beam motion modeled using Equation 1. Experimental data was used to determine the amplitude, natural frequency and the damping factor.

Figure 3 shows beam motion in an unbalanced condition. The offset shows the masses on each end of the beam are

not equal. As the mass values are changed the variation in offset should be repeatable and predictable. The ratio of successive amplitude measurements should be a constant and is used to determine the damping factor using the following equation:

$$\ln\left(\frac{x_0}{x_1}\right) = \zeta 2\pi n \quad [2]$$

Successive amplitudes are shown in Equation 2 with $n = 1$. Errors in the determination of the damping factor can be reduced by using amplitude values spread further apart and using the appropriate value of n .

Three diagnostic parameters can be drawn from the preceding discussion. The first is changes in the offset. A prediction of the final balance mass can be made from a preliminary analysis of encoder readings. If the anticipated change is not seen when the weights are adjusted then the weights are put back to the previous condition and the offset is checked. If the offset has changed then a rub between the balance beam and the support structure is present. The second diagnostic is variations in the damping factor. The beam has a range of allowable amplitudes. If a rub between the beam and the support structure is present during a portion of the oscillation then the damping factor will vary between observations. The third diagnostic is the short term variations in the amplitude ratios. Variations in amplitude ratio are often an indication of excessive air motion in the enclosed working space. These three diagnostic parameters can be used to ensure accurate mass determinations can be made in a short time.

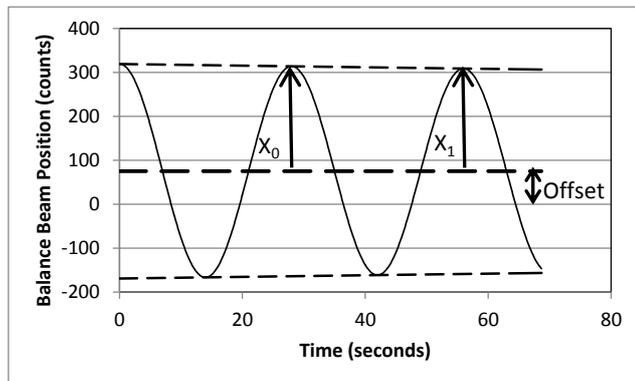


Figure 3. Balance Beam Diagnostics

Temperature Temperature measurement has been performed using Type T thermocouples in conjunction with an isothermal reference junction or zone box. The temperature measurements of the probes are verified prior to the start of a test using a portable temperature bath. If the duration of the test is short then variations in temperature measurement are likely to be small. A single test on the gravimetric system can last up to 8 hours. Longer test times can result in variations in temperature measurement when using a zone box. The use of thermocouples will continue to be supported but when lower uncertainties are required temperature will be measured using a thermistor. The uncertainty in temperature measurement when using Type T

thermocouples is $\pm 0.017\%$. The use of thermistors has reduced the uncertainty in temperature measurement to $\pm 0.005\%$.

System Sphere Temperature The mass of gas in a sphere is determined prior to flow testing after the sphere has been pressurized with the test gas and after the flow test when the sphere has undergone some depressurization. The rate of pressurization is controlled to minimize the heat of compression. At the conclusion of a test the sphere may be very cool, especially if the mass flowrate during the test was high. The sphere must be at thermal equilibrium with the room temperature during a mass determination. If the temperature difference between the sphere and the air in the test area is large enough convective air cells may be established. The force resulting from the motion of air across the sphere surface can lead to an error in measurement.

A blower drawing air from the test area is used to speed up the heat transfer process and ensure the sphere is close to room temperature. The temperature of the sphere is monitored periodically using infrared temperature measurement. When the temperature of the sphere has stopped changing with time the mass determination is performed. The time required for the spheres to achieve thermal equilibrium with the room is the parameter which limits the number of test points per day. Typically, no more than 5 data points can be taken in one day when using all the system spheres.

Trapped Volumes There are currently four trapped volumes monitored in the system. Each system sphere also has a segment of tubing which is monitored as a trapped volume. The trapped volumes are shown in Figure 5. The instrumentation in the trapped volumes is used primarily to quantify the mass inventory in the piping at the beginning and end of a test. The trapped volume instrumentation can also be used to monitor pressure and temperature stability during a test.

The volume of Trapped Volumes 1 through 4 and each of the tank trapped volumes is small. Even large pressure or temperature changes do not affect the test results significantly. The piping volume between the manual flow control valves and the UUT is relatively large and has been added to the data reduction software as Trapped Volume 5. Although the operator can ensure that the initial and final pressures in this region are close to the same value the temperature can vary, especially at higher mass flowrates. Variations in temperature alone can result in mass storage which can have as much as a 0.02% effect on the final mass values.

A pressure regulator and manual flow control valves are shown downstream of the of the quick change valves. The pressure upstream of the pressure regulator will decrease as gas is drawn from the gravimetric system sphere. The pressure between the pressure regulator and the manual flow control valves, or Trapped Volume 3, was historically maintained at 700 kPa above the pressure to the UUT on every test. If the regulator performs well then adjustments to the manual flow control valves will be

infrequent. Figure 5 shows the variation in the Trapped Volume 3 pressure as a function of the velocity across the pressure regulator. The dimensionless ratio of differential pressure to static inlet pressure across the pressure regulator is used as an estimate of gas velocity across the pressure regulator. The data in Figure 5 show that if the ratio of dp/P is greater than 0.6 then the variability in the pressure downstream of the pressure regulator increases. Reducing the variability in Trapped Volume 3 will reduce the frequency of adjustments to the manual flow control valve. A new parameter specifying that the pressure drop across the regulator should not exceed 50% of the inlet pressure is now in use.

Variations in Trapped Volume 1 and 4 pressures before and after a test starts can indicate valve seat leakage in the quick change valves. The quick change valves are ball valves with soft seats. The seats need to be replaced after the valves have been switched around 500 times. Diagnostic algorithms are being developed to analyze pressure data in these trapped volumes to alert the operator that the valve seats require maintenance.

Additional analysis of the trapped volume pressure variations is being performed on data acquired using high speed data acquisition. Variations in trapped volume pressures as the quick change valves switch can be used to adjust the timing of valve actuation and relative pressure levels in Trapped Volumes 1 and 4 prior to the start of a test.

Conclusions

The gravimetric primary system operated by Colorado Engineering Experiment Station, Inc. will be used to provide independent traceability to a new low uncertainty traceability chain. Consistent performance with uncertainties of approximately 0.05% will be required to meet this goal. An uncertainty analysis has shown that the gravimetric primary system can produce data with uncertainties at this level but only if additional uncertainty, contributed by random effects is minimized. Significant sources of random effects have been discussed and the steps necessary to minimize their effect are being implemented.

References

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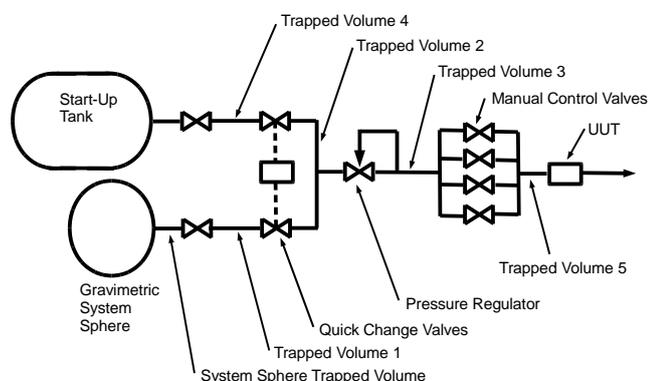


Figure 4. Gravimetric System Trapped Volumes

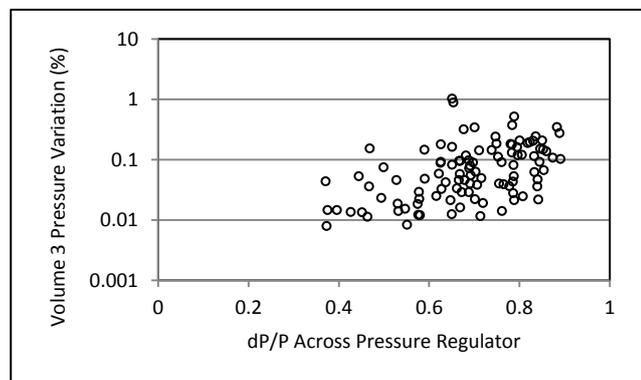


Figure 5. Trapped Volume Stability