

Reducing Calibration Uncertainty by Expanding the Use of Critical Flow Venturi Standards

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Abstract: For over forty years CEESI has operated primary calibration standards to provide traceable flow measurement services. Critical flow venturies (CFVs) have always been used as transfer standards to directly calibrate customer meters. Over the past ten years CEESI has invested in the fabrication and calibration of additional CFVs to reduce calibration uncertainty.

This paper discusses test programs based on two sets of critical flow venturies. The first set was calibrated by NIST and used to compare one of the CEESI primary standards to NIST. A second set allows for multiple CFVs to be installed in parallel and provides for calibrations at higher flowrates than a single CFV.

Keywords: Critical Flow Venturi, CFV, Uncertainty, Calibration, Inter-comparison

1. Introduction

The critical flow venturi has long been applied as a transfer standard in many calibration environments. In a traceability chain the CFV transfers the units of mass and time established by a primary system to a meter under test. A primary system provides a typical engineering tradeoff between low uncertainty and complexity of operation. The CFV provides significantly reduced operational complexity along with a slight increase in uncertainty.

Over the past ten years CEESI has been expanding the use of CFVs to reduce uncertainty and improve productivity. The improvement in productivity arises as a result of automation of various calibration processes, and the easy with which a CFV calibration process can be automated. Typical primary systems are not well suited to automation and include long stability limits that prohibit shorter turnaround times.

The first example concerns rather low mass flowrates, expressed in grams per second. The testing utilizes analysis of CFVs installed in series to allow for reducing uncertainty by localizing uncertainty components. The second example concerns much higher mass flowrate, expressed in kilograms per second. The CFVs are installed in parallel to allow for traceable calibrations at much higher mass flowrates

2. Lower Flowrate Calibrations

There are two objectives of the lower flowrate test program. The first is to utilize flow measurement artifacts that inter-compare the CEESI Primary B ^[1] and NIST^[2] calibration facilities. Primary B is a gravimetric based system that has been in operation for thirty five years.

To support this work CEESI fabricated a set of CFVs and sent them to NIST for calibration. The test work described in the present paper involves the following four CFVs from that set:

- Serial number P177, throat $d=0.4496$ cm.
- Serial number P125, throat $d=0.3175$ cm.
- Serial number P088, throat $d=0.2235$ cm.
- Serial number P063, throat $d=0.1600$ cm.

The P series venturies are not intended to be used for day-to-day work due to the risk of damage. They are intended to be used only to establish traceability. To improve productivity of the CEESI calibration business, some primary calibrations are being replaced with secondary calibrations. Secondary calibration processes are typically faster, better suited to computer automation and result in fewer operator based uncertainty sources. The second objective of the test program involves using the P series to calibrate CFV series working standards. Calibration data were obtained for the following working standard CFVs:

- Serial number C088, throat $d=0.2235$ cm.
- Serial number C063, throat $d=0.1600$ cm.
- Serial number C044, throat $d=0.11176$ cm.

It is well understood that multiple CFVs can be installed in series so long as the throat of a downstream venturi is larger than that located upstream. The present analyses are based on three test configurations each utilizing three CFVs installed in series.

- C044, P063, P088
- C063, P088, P125
- C088, P125, P177

Suppose we would like to compare the mass flowrate measurements made by two calibration facilities. We can define ε to represent the difference in mass flowrate:

$$\varepsilon = q_{m1} - q_{m2} \quad [\text{Eq. 1}]$$

where q_{m1} and q_{m2} are mass flowrates reported by the two facilities. The facilities are indirectly compared through the use of an artifact, one or more flowmeters that are calibrated in each facility. Ideally, agreement between the facilities is characterized by $\varepsilon = 0$. In reality there will be uncertainty in the value of ε and the agreement is characterized by $\varepsilon = 0, \pm 2u_\varepsilon$. The standard uncertainty in ε is given by:

$$u_\varepsilon^2 = u_{qm1}^2 + u_{qm2}^2 + u_{art}^2 \quad [\text{Eq. 2}]$$

where u_{qm1} and u_{qm2} are the standard uncertainties in mass flowrate measured by the two facilities and u_{art} is the standard uncertainty contributed by the artifact. In the present test program the series combination of two CFVs is considered to be an artifact in the comparison of NIST and CEESI. The expanded uncertainty ($k=2$) in NIST test data mass flowrate is 0.07%, therefore $u_{qm1} = 0.035\%$. Over the operating range of the current testing the standard uncertainty in mass flowrate of Primary B (u_{qm2}) varies between 0.024% and 0.038%.

The name “Youden plot” has been applied to identify a process used to determine u_{art} , a process that is applied to the current test program^[3]. For each calibration point the difference in discharge coefficient between CEESI and NIST is calculated. Using the second test as an example, Figure 1 shows the deviation of P088 plotted against the deviation of P125. A straight line is fitted through the data, and the residuals are calculated. In Figure 1 the two parallel lines represent the 95% confidence interval about the fitted line. Variations long the lines arise from factors that are common to both P088 and P125. These variations would more likely be attributed to Primary B rather than either CFV. Variations perpendicular to the fitted line represent random effects, the results of the two CFVs are independent. The perpendicular distance between the two lines in Figure 1 represents $\pm 2u_{art}$. Similar analyses were completed for the other two tests.

Figure 2 shows the final results of the inter-comparison testing. The ordinate is mass flowrate and the abscissa is the difference between NIST and CEESI normalized by u_ϵ . The individual CFV results are separated symbolically. A total of ninety six data points are contained on the graph, seven fall outside of the $\pm 2u_\epsilon$ range. One data point deviates significantly (-2.95) and could be considered an outlier, the underlying data are under investigation. A second data point deviates slightly (+2.04). The remaining five data points represent a confidence level very close to 95% associated with the statistical hypothesis that $\epsilon = 0$. In other word, the results provide strong evidence that Primary B agrees with NIST and the associate estimated uncertainty is reasonable.

Figure 3 shows calibration data for the venturi identified as C044. The solid line represents the best fit equation relating C_d and Re . The standard uncertainty associated with random effects is $u=0.038\%$. Three components are assumed to contribute uncertainty in a simplified analysis, the range of estimated values ($k=2$) are listed below. The first two components have been previously discussed. The pressure and temperature uncertainty estimates are from the CEESI NVLAP accreditation analysis.

- NIST mass flowrate, 0.07%
- Random effects, 0.076%
- Pressure and temperature, 0.028 to 0.046%

Combining the three values results in an expanded uncertainty in mass flowrate of 0.11% measured in conjunction with a client meter calibration.

3. Higher Flowrate Calibrations

CEESI fabricated a series of 21 CFVs with nominal throat diameters of 25.4 mm (1 in.). These venturies are identified as the “1691” series, they are serialized as 1691-1, 1691-2 up to 1691-21. A variety of fittings allow for the installation of two, four or all the CFVs to be installed in parallel

The 1691 series have been used to establish direct NIST traceability of the CEESI Iowa natural gas facility using a bootstrap process^[4]. Four CFVs (1691-2, -3, -4 and -5) were directly calibrated by NIST in comparison with a primary standard; these calibrations are identified as Stage 1. Table 1 shows the mass flowrate and uncertainty ranges, the uncertainty range is associated with the measured mass flowrate when a CFV is used to calibrate a client meter. The uncertainty varies with pressure and temperature as well as based on the calibration history of a particular CFV. A particular calibration will have a unique uncertainty; in the present discussion the tabulated ranges are used.

The Stage 2 calibrations, at the CEESI facility, utilized three CFVs installed in parallel to calibrate a fourth. Both the Stage 2 flowrate and uncertainty ranges are increased as shown in Table 1. The process was repeated with all four CFVs (1691-2, -3, -4 and -5). The Stage 3 calibrations, also at the CEESI facility, utilized four CFVs installed in parallel used to calibrate a fifth. A fourth stage utilized up to eight CFVs installed in parallel to calibrate each of nine turbine meter standards in the CEESI Iowa facility. The present discussion will not include the fourth stage calibration results.

The maximum CEESI primary system flowrate capability is approximately 5 kg/s based on a system identified as “Primary A”. Two secondary CFV standards, identified as CFV3 and CFV6, are in regular use providing calibration services at mass flowrates in excess of 5 kg/s. Typical operating pressure and flowrate ranges are contained in Table 2. Primary system calibration data have been used to characterize the low flowrate range (2.5 to 5 kg/s) of CFV6. The remaining CFV6 flowrate conditions as well as the entire range of CFV3 could never be characterized based on direct calibration. The relationship between C_d and Re is based on theoretical considerations^[5]; the 1691 series has allowed for C_d to be determined based on direct calibration.

Three secondary calibrations partially characterize CFV 3. Four 1691 series CFVs installed in parallel, three sets of data were obtained. Data were taken over a period of a few days using the same CFVs and instrumentation for pressure and temperature. The reproducibility conditions reflect parameters that would naturally vary over a few days. The calibrated mass flowrate range was 20 to 50 kg/s, the data of C_d vs Re contained in Figure 4. Two data points shown as solid symbols represent potential outliers, they have not been included in the analysis pending further investigation. The 1691 series CFVs were operated over the Stage 3 flowrate range.

The solid line indicates a fitted curve of the form: $C_d = a + bRe^{-0.5}$. The standard uncertainties associated with random effect are $u = 0.117\%$ (Re : 10 to 15 million) and $u = 0.153\%$ (Re : 6 to 10 million). The same three components as described above are assumed to contribute uncertainty in a simplified analysis. The range of estimated values ($k=2$) are listed below:

- Stage 3 mass flowrate, 0.142 to 0.219%
- Random effects, 0.234% (high Re), 0.306% (low Re)
- Pressure and temperature, 0.028 to 0.046%

Combining the three values results in expanded uncertainties ranges of 0.28% to 0.32% for the high Reynolds number range and 0.34% to 0.38% for the low Reynolds number range. These uncertainties apply to a mass flowrate measured in conjunction with a client meter calibration.

Two sets of secondary calibrations partially characterize CFV 6. The first set consisted of sixteen calibrations based on four 1691 series CFVs installed in parallel operating over a mass flowrate range of 7.9 to 11.0 kg/s. Data were taken over a period of a few days using the same CFVs and instrumentation for pressure and temperature. The reproducibility conditions reflect parameters that would naturally vary over a few days. This set of data is contained in Figure 5 over the 4.8 to 6.9 million Re range. The 1691 standards were operated over the Stage 2 flowrate range. The standard uncertainty associated with random effects is $u=0.06\%$. The simplified uncertainty components are listed below:

- Stage 2 mass flowrate, 0.121 to 0.160%

- Random effects, 0.12%
- Pressure and temperature, 0.028 to 0.046%

Combining the three values results in an expanded uncertainty range of 0.17 to 0.21% in mass flowrate measured in conjunction with a client meter calibration.

A second set of data obtained were over the 2.9 to 4.7 kg/s flowrate range. A single 1691 CFV installed as a standard, data were obtained using five different CFV standards. Reproducibility conditions include changing the CFV as well as parameters that would naturally vary over a few days. This set of data is contained in Figure 5 over the 1.8 to 2.9 million Re range. The 1691 standards were operating over Stage 2 and Stage 3 flowrate ranges. The standard uncertainty associated with random effects is $u=0.027\%$. The simplified uncertainty components are listed below:

- Stage 2 and 3 mass flowrate, 0.121 to 0.219%
- Random effects, 0.055%
- Pressure and temperature, 0.028 to 0.046%

Combining the three values results in an expanded uncertainty range of 0.14 to 0.23% in mass flowrate measured in conjunction with a client meter calibration.

The largest CFVs used at CEESI are permanently installed in holders consisting of inlet and outlet tubes, flow conditioning and fittings for pressure and temperature measurements. The smaller CFVs fit interchangeably into a common sized holder. Prior to obtaining the test data in contained Figure 5 CFV 6 was removed from a smaller diameter (30.5 cm.) holder and reinstalled in a larger (50.8 cm.) holder. The goal of replacing the holder is better performance based on a more favorable beta ratio.

A brief calibration history had been developed for CFV 6 based on operating Primary A over the flowrate range of 3.1 to 7.3 kg/s (Re: 2.9 to 4.8 million). These data were obtained using the smaller diameter CFV holder. The distribution of the data suggests a “transition hump” resulting from the boundary layer transition from laminar to turbulent.

There are three approaches to determine the discharge coefficient over 2.9 to 4.8 million Re range. The first option is to obtain additional data; the testing is planned for the future. The second option is to utilize the curve shape predicted based on primary data obtained using the smaller diameter holder. The third option is to utilize a curve of the form:

$$C_d = a + bRe^{-0.5}$$

The dashed line in Figure 5 represents the shape of the transition hump based on the Primary A data. The solid line best fits the 1691 data. A decision has not yet been made regarding the selection of curve fits associated with the second or third options.

4. Summary

Two sets of critical flow venture data have been presented. One set of data was obtained over a flowrate range of 2-30 grams per second. The second set of data was obtained over

The low flowrate test results provided an artifact based comparison of the CEESI Primary B gravimetric with NIST. In addition the testing provides calibration data for four working standards.

The high flowrate test results have provided calibration data above the range of CEESI primary standards. Two working standards are traceable through direct calibration at flowrate as high as 50 kg/s

CEESI is continuing to reduce the uncertainty in calibration by expanding the use of critical flow ventureries.

5. References

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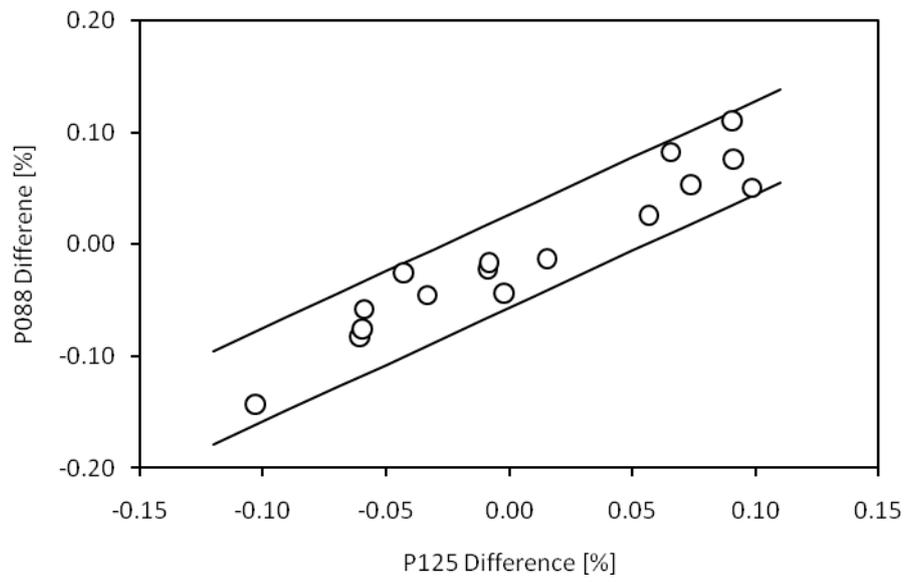


Figure 1: Youden Plot of Two Critical Flow Venturies, Low Flowrate Testing

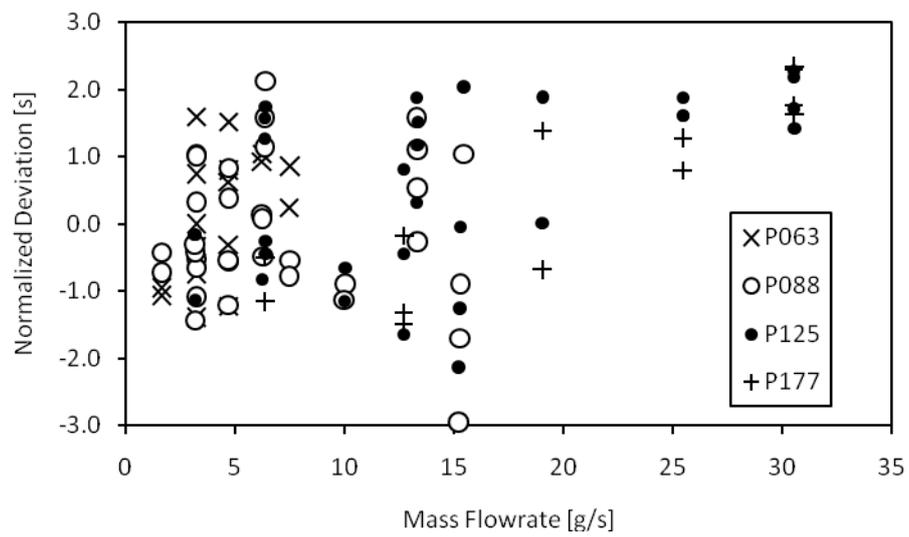


Figure 2: Deviation of Primary B Gravimetric Standard from NIST

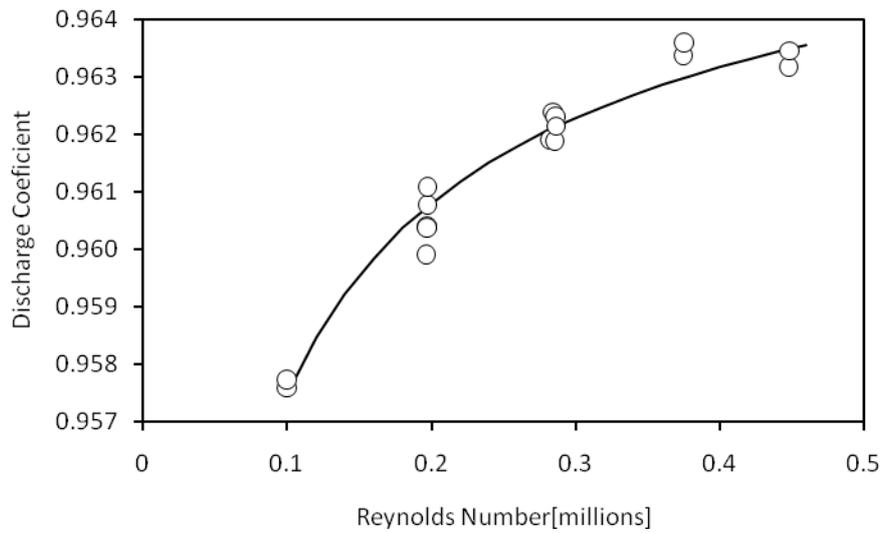


Figure 3: Calibration Data for CFV C044

Table 1: Mass Flowrate and Uncertainty Ranges for 1691 Series CFVs

Stage	Mass Flowrate Range [kg/s]	Uncertainty Range [%, k=2]
1	0.4 – 0.8	0.106 – 0.109
2	1.2 – 3.4	0.121 – 0.160
3	3.6 – 10.8	0.142 – 0.219

Table 2: Operating Ranges of CFV6 and CFV3

	CFV6	CFV3
Throat Diameter [cm]	1.77	3.82
Pressure Range [kPa]	100 - 2400	100 – 750
Flowrate Range [kg/s]	2.5 - 60	13 - 90

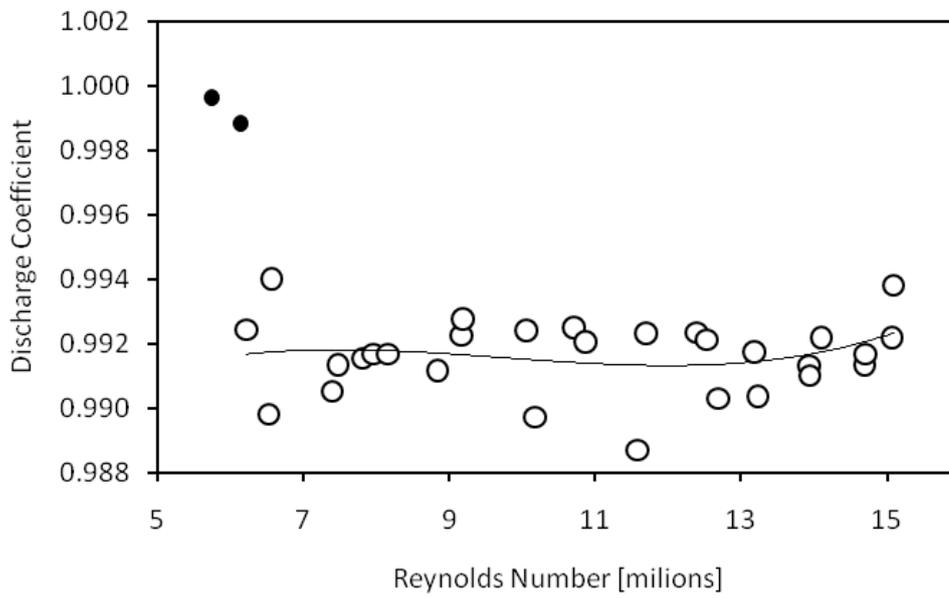


Figure 4: Calibration Results for CFV3

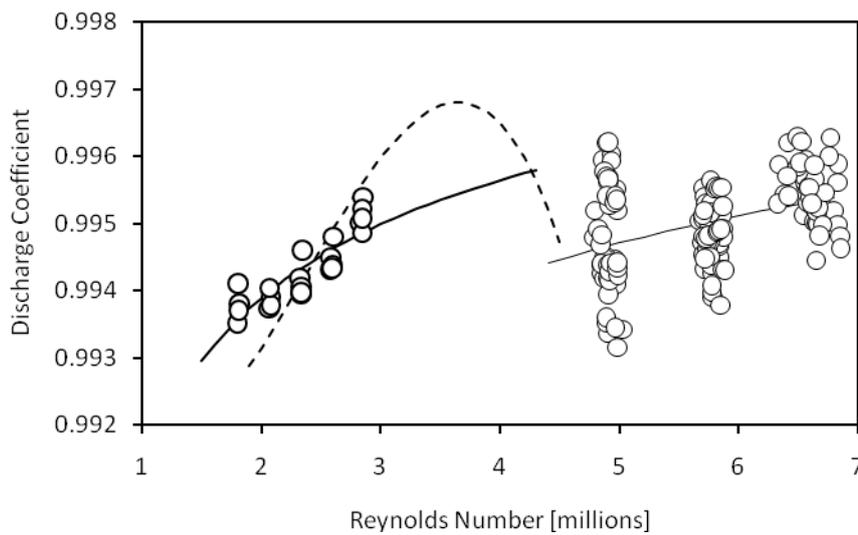


Figure 5: Calibration Results for CFV6