PERFORMANCE OF A GAS FLOW METER CALIBRATION SYSTEM UTILIZING CRITICAL FLOW VENTURI STANDARDS

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Abstract: A set of Critical Flow Venturis (CFVs) were manufactured by Flow Systems and calibrated by NIST in Gaithersburg, MD. Subsequently these flow standards along with pressure and temperature standards have been integrated into a gas flow meter calibration (GFC) system. Performance data and an uncertainty analysis will be discussed. Calibration data on these CFV standards will be used to inter-compare the NIST and CEESI primary facilities.

Keywords: Critical Flow Venturi, Calibration, Uncertainty Analysis

1. Introduction

Flow Systems manufactures between 300 and 400 CFVs on an annual basis. These Venturis are subsequently calibrated by CEESI. In efforts eliminate logistical issues, improve lead times and reduce uncertainty, Flow Systems and CEESI have undertaken a joint effort to design, manufacture and commission an automated gas flow meter calibration system (GFC). The desired uncertainty for a calibration made on a meter-under-test (MUT) was to be less than +/- 0.20%. This requires low uncertainty for the discharge coefficient (Cd) for the CFV, as well as the pressure and temperature instrumentation installed in the GFC.

2. System Design

Eight CFVs with throat diameters ranging from 0.41 mm to 4.5 mm were designed and manufactured in accordance with ISO 9300 and ASME MFC-7M. These CFVs were designed as a binary set such that the throat areas progress by a factor of 2. This set of CFVs is also referred to as the "P Nozzles". These Venturis were calibrated at the NIST FMG facilities located in Gaithersburg, MD using the 677 L *PVTt* system [1]. The uncertainty in the discharge coefficient (Cd) versus throat Reynolds Number (Re) equation for each CFV is less than +/- 0.07% at 95% confidence. Test fluids used by NIST were nitrogen and compressed air. The flowing temperature and was near ambient at approximately 21 °C. Each CFV (P Nozzle) was calibrated over an inlet pressure range of 172 to 827 kPa. Using the same fluids and at the same temperature, the GFC system will service 0.00005 to 0.03 kg/sec.

The main test fluid for the GFC system will be compressed air that is filtered and dried to a pressure dewpoint less than -40 °C. A sensor measuring the dewpoint is used as an alarm in the GFC system. The supply pressure to the system will range from 690 to 900 kPa. This supply will be diffused into several copper tubes which, along with the CFV and MUT Meter Runs are submerged in a water bath designed to be held at the temperature of the room (Figure 1). Environmental conditions in the room are monitored by a separate system. This system provides trending and historical information on ambient conditions and air supply dewpoint.

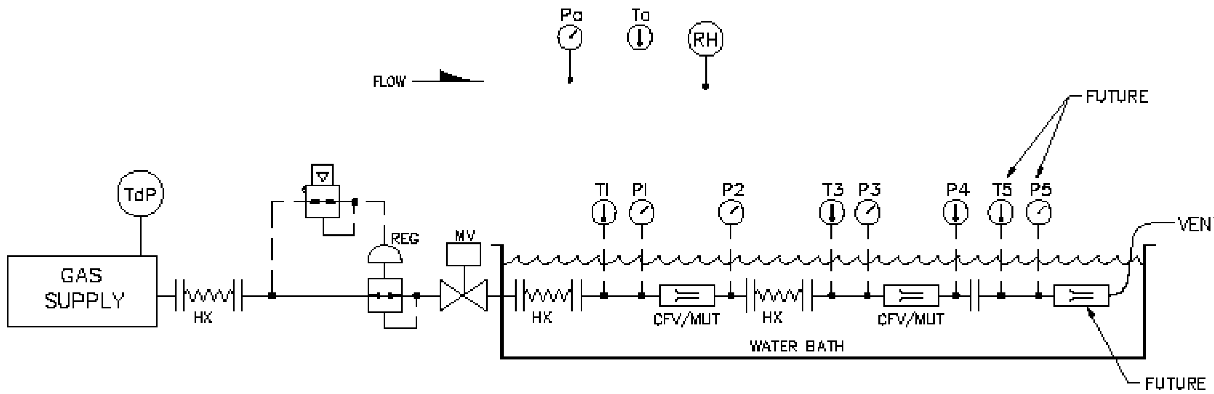

Figure 1

A computer controlled, dome loaded pressure regulator and shut off valve are located upstream of the standard CFVs (P Nozzles) and MUT (Figure 1). The regulator will set and maintain pressure at the inlet of the first CFV in series. There two locations in series where standard CFVs (P Nozzles) and the MUT may be installed (Figure 1). The GFC system uses one CFV (P Nozzle) as the measurement standard during MUT calibrations. At each location the GFC system provides measurement of both inlet static pressure and temperature as well as exit pressure (Figure 1). Downstream of the pressure regulator and the first CFV/MUT location are temperature stabilizing systems similar to the one previously described.

Temperature at each CFV (P Nozzle)/MUT location is measured using a Hart Thermister probe and digital readout. The probes are sheathed in stainless steel and are approximately 3 mm in diameter. The uncertainty this combination is +/-0.007 °C.

The GFC system uses Mensor model 6120 digital output pressure transducers. The uncertainty of each is +/-0.01% of full scale at 95% confidence. There is an absolute sensor ranged to 103 kPa for measuring the barometric pressure. There is a gauge transducer at each of the two CFV/MUT inlet pressure locations (Figure 1). There are two WIKA analog pressure transducers to measure the exit pressure at the exit of each CFV/MUT. The last CFV/MUT in series either exhausts to ambient pressure or into a vacuum receiver. In the latter case another WIKA sensor is used to measure the exit pressure of the CFV/MUT.

The GFC system uses the same universal gas constant, dry air composition and NIST REFPROP 8.1 [2] thermodynamic database that is used by the NIST FMG in Gaithersburg, MD.

3. Diagnostics

The GFC system employs several automated diagnostics. Before the system is pressurized each of the two temperature probes are read to ensure that they agree within their estimated uncertainty of +/-0.007 °C. During this check the system reads, records and adjusts the zero offset of each gauge pressure transducer. These data will be historically tracked for potential use in a measurement assurance program (MAP) for the GFC system.

Since configurations of CFVs (P Nozzles)/MUTs are manually assembled and disassembled a minimum of two times during an MUT calibration, the GFC system will automatically perform pressure-decay type leak tests prior to initiating flow through the system. The operator defines the leak test volume by selecting the CFV (P Nozzle) serial numbers, MUT, MUT test section and all required adapters. These items are cataloged in the system software along with an estimated volume determined from CAD drawings of each. After a cap is installed by the operator at the end of the most downstream test section, the system opens the shut off valve and the regulator slowly pressurizes the entire volume. The leak test pressure set point is 690 kPa. Once the system determines that the total leak test volume has reached equilibrium with respect to temperature, a counter is initiated and all pressures and temperatures within the system are recorded. Provided that the pressure decay is less than a predetermined limit, the test will last 60 seconds. At the end of this interval, the final pressures and temperatures are recorded along with the duration of the test.

If the leak test passes, the GFC system will compare the final readings of the gauge transducers used and verify that they agree within their full scale uncertainty specifications.

4. Validation efforts

The GFC system is programmed using National Instruments LabVIEW software. Data processed using this software was input into spreadsheets that perform identical calculations. GFC system calculations have been compared to spreadsheet values and were found to be less than 10 ppm. Results are archived and are revalidated with each software revision.

5. CEESI Evaluation of P Nozzles with Primary B

Prior to commissioning the GFC system, the CFVs (P Nozzles) were compared to CEESI's Primary “B” system which is a gravimetric system that utilizes dry compressed air at room temperature as the test fluid [3]. Being a mass / time system it has a very short traceability chain to NIST fundamental standards of mass and time. The Primary B system has the good characteristics of low uncertainty and high precision. All of the CFVs have been evaluated by CEESI, but for space limitations, the result for P088 (which is typical of all CFVs) is shown below in Figure 2.

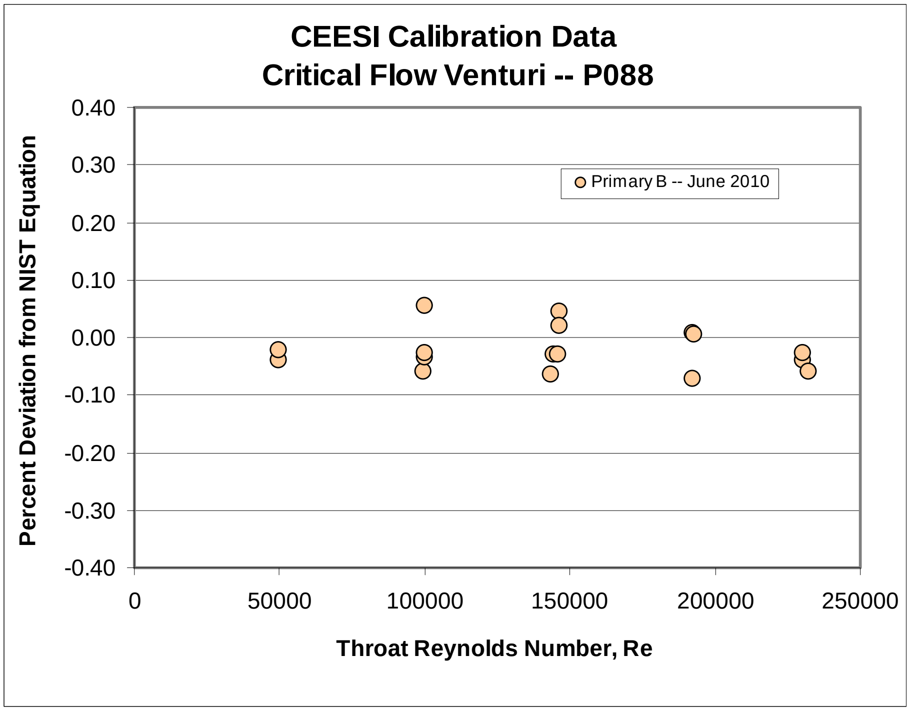

Figure 2

6. FLOW SYSTEMS Evaluation of the GFC with P Nozzles

The initial validation efforts at FSI were focused on mass flow correlation and reproducibility when testing two CFVs (P Nozzles) in series. These efforts yielded insight to the optimum time duration of flow from onset to data capture. Since there are two locations for installing CFVs, it is possible to perform tests with two P Nozzles in series and compare the mass flow that is calculated for each one. This method allows all the instrumentation and the discharge coefficient of both CFVs to be evaluated. Figure 3 shows the results for the P088 nozzle. The mass flow ratio is the mass flow of the P088 nozzle divided by the mass flow of another P Nozzle. If everything were perfect, the mass flow ratio would be unity. As can be seen, most of the data falls within a range of 1.000 to 1.001. This indicates that the pressure and temperature instrumentation at each CFV location is performing in an acceptable manner and the discharge coefficient equations for each CFV is within the stated uncertainty of +/- 0.07%. Due to space limitations, only the P088 data is shown. All other P Nozzles performed in a similar manner.

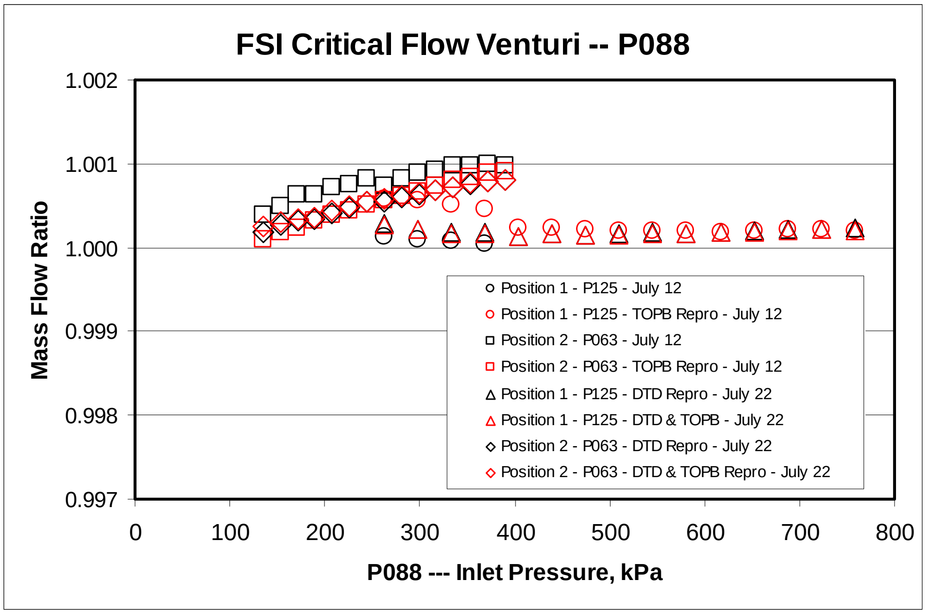

Figure 3

7. Uncertainty Analysis

The uncertainty analysis for the results of these calibrations is a 3 step process. Step 1 is to assess the uncertainty of the mass flow delivered to the Meter Under Test (MUT), i.e., $\dot{m}_{MUT}$. This uncertainty assessment is based on the uncertainties for the measurement components that produce the mass flow, and these produce the Expanded Uncertainty for the mass flow through the MUT at a quoted level of confidence. Step 2 is to assess the uncertainties for the MUT result. Step 3 is to fit the data and then assess the uncertainties associated with using the fitted results.

When the MUT is a CFV, as it is in the result described here, it is handled in the conventional fashion, as described below. The uncertainty of the MUT result will therefore be comprised of both the appropriately replicated (i.e., the DTD (day-to-day) or TOPB (take-out-put-back) reproducibility associated with the different arrangements described in the Diagnostics section) determinations for the MUT result and the combined uncertainty for the mass flow $\dot{m}_{MUT}$, delivered to the MUT, as produced using the GFC. The VIM [4] and the GUM [5] describe the uncertainty details for assessing and combining these component uncertainties.

Using Conservation of Mass principles applied to the Connecting Volume (CV) which is the interior pipe volume between the standard (STD) and the MUT, the mass flow delivered to the MUT is, see [6]:

$$\dot{m}_{MUT} = \dot{m}_{STD}\left[1 \pm \frac{V_{CV}}{m_{STD}}\frac{1}{R}\left(\left\langle\frac{p}{T}\right\rangle_{CVf} - \left\langle\frac{p}{T}\right\rangle_{CVi}\right)\right] \quad \text{and} \quad m_{STD} = \dot{m}_{STD}(\Delta t) = \dot{m}_{STD} t_{calibration}$$

where, in compatible units, the subscripts denote respective quantities, R is the gas constant , and $\left\langle \frac{p}{T} \right\rangle_{CVf} \ldots and \ldots \left\langle \frac{p}{T} \right\rangle_{CVi}$ denote the spatial averages, respectfully, of the pressure to temperature ratios in the CV at the end and the beginning of the calibration interval. In this way the term $\frac{1}{R}\left(\left\langle \frac{p}{T} \right\rangle_{CVf} - \left\langle \frac{p}{T} \right\rangle_{CVi} \right)$ is the fluid density increase in the CV during the calibration. The plus or minus term in the governing equation for $\dot{m}_{MUT}$ depends on whether the STD is upstream or downstream from the MUT; the sign is minus when the STD is upstream of the MUT and it is plus when the MUT is upstream of the STD, see [6].

The relative uncertainty for $\dot{m}_{MUT}$ is therefore written, see [6]:

$$u_r(\dot{m}_{MUT}) = \sqrt{[u_r(\dot{m}_{STD})]^2 + [u_r(1 - \frac{\Delta\rho_{CV} V_{CV}}{m_{STD}})]^2} = \sqrt{[u_r(\dot{m}_{STD})]^2 + [\frac{V_{CV}\, p_{CV}}{m_{STD} R T_{CV}} \{u_r(\langle p_{CV} \rangle) + u_r(\langle T_{CV} \rangle)\}]^2}$$

Data records are to be used to quantify the variances under the radical sign in the above equation, including correlation effects, see [6]. When the STD is a P Nozzle, $\dot{m}_{STD}$ is given by:

$$\dot{m}_{STD} = P_{oSTD} \sqrt{\frac{g_c}{R_U} \frac{M_w}{T_{oSTD}}} A^*_{STD} C_{dSTD} C^*_{STD}$$

where C_{dSTD} is provided via the NIST calibration report on its calibration of the STD.

The relative uncertainty for $\dot{m}_{STD}$ is written, where it is assumed that no correlation effects are present among the component measurements that comprise $\dot{m}_{STD}$ see[6]:

$$u_r(\dot{m}_{STD}) = \sqrt{[u_r(P_{oSTD})]^2 + [0.5u_r(g_c)]^2 + [0.5u_r(M_w)]^2 + [0.5u_r(R_U)]^2 + [0.5u_r(T_{oSTD})]^2 + [u_r(A^*_{STD})]^2 + [u_r(C_{dSTS})]^2 + [u_r(C^*_{STD})]^2}$$

Typical values for these relative uncertainties are used in the tabulation for $u_r(\dot{m}_{STD})$ presented in Table 1, see [6]. The resulting relative Expanded Uncertainty for $\dot{m}_{STD}$ is ± 0.128% at 95% confidence level.

1	2	3	4	5	6	7	8	9	10	11	12	13
Quantity/Symbol	Source of Uncertainty	Units	Value/Range	u(Spec) (%) @ 68% CL	Type Uncrt	Prob Distrb	Divisor	Rel Sens Coeff	u(Symbl) (%)	Degs Frdm	% of Cmbn'd	Note
CFV Stag Press/P_{oSN}	Mfgr Spec on Transducr	F/L^2	172-827 kPa	0.023	B	N	1	1	0.0230	1.00E+06	12.8	1
Grav Const Fctr/g_c	Hdbk	LM/Ft^2	32.1740/9.880	0	NA	NA	1.732	0.5	0.0000	1.00E+06	0.0	2
Molecular Wt for Air/M_w	Hdbk	M	29.92	0.0025	B	R	1.732	0.5	0.0007	1.00E+06	0.0	3
Univers Gas Constant/R_U	Hdbk	nm/kgK	8.1447	0.00009	B	R	1.732	0.5	0.0000	1.00E+06	0.0	4
Nozzle Stag Temp/T_{oSN}	Mfgr Spec on Sensor	F or R	293K	0.0012	B	N	1	0.5	0.0006	1.00E+06	0.0	5
Nozzle Mass Flow Rate												
a. Throat Area	NIST Cal Rept	L^2	0.41 - 4.5 mm	0	NA	NA	1	1	0.0000	1.00E+06	0.0	6
b. Dischrg Coefficient	NIST Cal Rept	Dimles		0.035	B	R	1	1	0.0350	5	29.7	7
c. Crit Flo Funct (C*)	NIST Cal Rept/RefProp	Dimles	0.685	0.023	B	N	1	1	0.0231	1.00E+06	12.9	8
Connecting Vol Term/CV	Estimates	Dimles	1	0.0429	B	N	1	1	0.0429	1.00E+06	44.6	9
Rel Uc(m-dot-MUT)/%	Rel Cmbn'd Stnd. Uncert. (%)					Norm (k=1)		RSS Rows 1-9	0.064	57	100.0	10
Rel Ue(m-dot-MUT)/%	Rel Expnd'd Uncertainty (%)					Norm (95%: k=2)		2xRSS in Row 10	0.128	57		11

Uncertainty Characteristics — Processing Uncertainties — Uncertainty Results

Notes:

1 172 kPa pressure measured with +/-0.01% FS @ 95% CL 103 Kpa Baro & +/-0.01% FS @ 95% CL 690 Kpa gauge
2 Results are for fundamental constant with no uncertainty assigned.
3 Results come from NIST calibration report.
4 Results come from NIST calibration report.
5 Column 5 entry uses +/-0.007C @ 95% CL as mfgr stated accuracy at ambient (0.0012% @ 68% CL)
6 Uncertainty is zero as same values are used as in calibration report.
7 Results come from NIST calibration report.
8 Results come from NIST generated number.
9 Entries are based on "worst case" situation (smallest nozzle @ 172 kPa inlet to CFV.
10 Degree of freedom are computed using the Welch-Sattersthwaite Eqn.
11 Degree of freedom are computed using the Welch-Sattersthwaite Eqn.

Table 1 Uncertainty Results for $\dot{m}_{MUT}$

When a calibration of a P Nozzle is done using other P Nozzles, the calibration result for each nozzle is written:

$$A^*_{Pnzl} C_{dPnzl} = \frac{\dot{m}_{MUT}}{P_{oPnzl} C^*_{Pnzl}} \sqrt{\frac{R_U}{g_c} \frac{T_{oPnzl}}{M_w}}$$

The relative uncertainty for the calibration result $u_r\left(A^*_{Pnzl} C_{dPnzl}\right)$ is written, see [4]:

$$u_r(A^*_{Pnzl} C_{dPnzl}) = \sqrt{\left[u_r\left(\dot{m}_{MUT}\right)\right]^2 + \left[u_r\left(C^*_{Pnzl}\right)\right]^2 + \left[u_r(P_{oPnzl})\right]^2 + \left[0.5u_r(g_c)\right]^2 + \left[0.5u_r(M_w)\right]^2 + \left[0.5u_r(R_U)\right]^2 + \left[0.5u_r(T_{oPnzl})\right]^2}$$

Typical values for these relative uncertainties are used in the tabulation for $u_r(A^*_{Pnzl} C_{dPnzl})$ are presented in Table 2 [4]. The resulting Expanded Uncertainty is ± 0.177% at 95% Confidence Level.

1	2	3	4	5	6	7	8	9	10	11	12	13
Quantity/Symbol	Source of Uncertainty	Units	Value/Range	u(Spec) (%) @ 68% CL	Type Uncrt	Prob Distrb	Divisor	Rel Sens Coeff	u(Symbl) (%)	Degs Frdm	% of Cmbn'd	Note
m-dot-MUT		M/t										
a. Type A Replications (rel uncrt)	Calibration	M/t	0.05%	0.05	A	N	1	1	0.0500	5.0E+00	32.5	1
b. Type B CFV mdot (rel uncrt)	Previous Assessment	M/t	0.07%	0.064	A&B	N	1	1	0.0642	1.1E+02	53.7	2
Critical Flow Funct	NIST Cal Rept/RefProp	Dimles	0.685	0.023	B	N	1	1	0.0231	1.0E+06	6.9	3
Stag Press/P_o	Mfgr Spec on Transducr	F/L^2	172-827 kPa	0.023	B	N	1	1	0.0230	1.0E+06	6.9	4
Grav Const Fctr/g_c	Hdbk	LM/Ft^2	32.1740/9.880	0	NA	NA	1.732	0.5	0.0000	1.0E+06	0.0	5
Molecular Wt for Air/M_w	Hdbk	M	29.92	0.0025	B	R	1.732	0.5	0.0007	1.0E+06	0.0	6
Univers Gas Constant/R_U	Hdbk	nm/kgK	8.1447	0.00009	B	R	1.732	0.5	0.0000	1.0E+06	0.0	7
Stag Temp/T_o	Mfgr Spec on Sensor	F or R	293K	0.0012	B	N	1	0.5	0.0006	1.0E+06	0.0	8
Rel Uc(Cd)/%	Rel Cmbn'd Stnd. Uncert. (%)					N/R (k=1)		RSS Rows 1-9	0.088	42	100.0	9
Rel U(Cd)/%	Rel Expnd'd Uncertainty (%)					N/R (95%: k=2)		2xRSS in Row 10	0.175	42		10
Uncert for Using Fitted Eqns	Fitting Process	Dimles	< 0.03%@95%CL	0.0125%	A	N	1	1	0.0125	58	2.0	11
Rel Uc(Cd & Fit)/%	Rel Cmbn'd Stnd. Uncert. (%)	Dimles							0.089	72	100.0	12
Rel U(Cd & Using Fitted Eqn)	Rel Expnd'd Uncertainty (%)	Dimles							0.177	72		13
Uncertainty Characteristics					Processing Uncertainties				Uncertainty Results			

Notes:

1 Entries in this row are from "Day-To-Day Reproducibility" calibration conditions.
2 Entry in Column 5 is from GFC mass flow uncertainty assessment (table 1)
3 Results come from NIST calibration report.
4 172 kPa pressure measured with +/-0.01% FS @ 95% CL 103 Kpa Baro & +/-0.01% FS @ 95% CL 690 Kpa gauge
5 Results are for fundamental constant with no uncertainty assigned.
6 Results come from NIST generated number.
7 Results come from NIST calibration report.
8 Column 5 entry uses +/-0.007C @ 95% CL as mfgr stated accuracy at ambient (0.0012% @ 68% CL)
9 Degree of freedom are computed using the Welch-Sattersthwaite Eqn.
10 Degree of freedom are computed using the Welch-Sattersthwaite Eqn.
11 Entry in Column 5 is an upper bound from the fit-assessment process, see [7].
12 Degree of freedom are computed using the Welch-Sattersthwaite Eqn.
13 Degree of freedom are computed using the Welch-Sattersthwaite Eqn.

Table 2 Uncertainty Results for $u_r(C_d \ldots and \ldots Fit)$

Recently, the P Nozzles were calibrated using other P Nozzles calibrated by NIST and the results can be conventionally plotted, as typically shown in Figure 4. It should be noted that the “stability” of these metering results is quantified in the legend of Fig 4 by DTD and TOPB Reproducibilities. While these levels of scatter may be larger than “Repeatability” levels, these levels can be considered to be far more typical of what nozzle users may expect in practice using these nozzles, see [6].

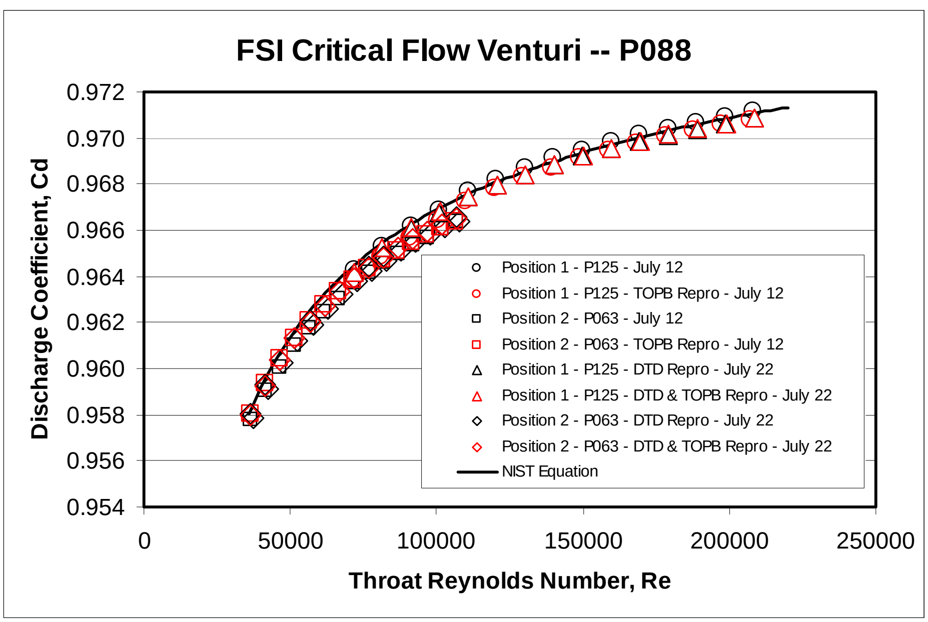

Figure 4

When these calibration results are fitted , using the form, $Cd = A + B\,\mathrm{Re}\ \wedge(-0.5)$, and when the uncertainties associated with using these fits to make future flow measurements, the result for P088 is shown in Figure 5, see also [5].

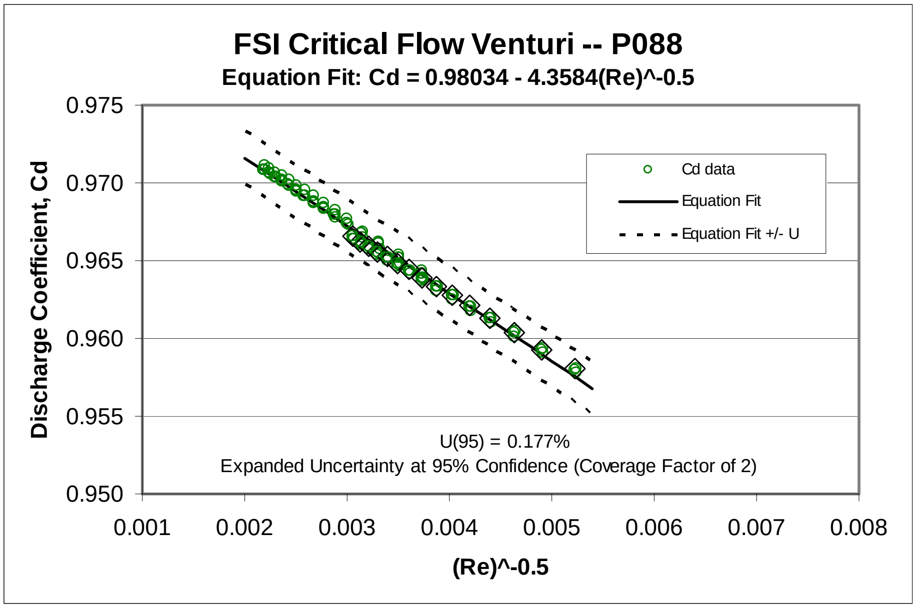

Figure 5

As noted on these figures, the fit form is given together with the maximum uncertainty at 95% confidence level, see [7]. It is noted that these uncertainty levels are only slightly higher than that for $u_r(C_{dPnzl})$; this is the result of the extensive data records from the calibrations and from the fact the fitting form is compatible with the nozzle characteristics.

8. Conclusions

The central conclusion to be drawn from the uncertainty analysis is the fitted forms can be used with a conservative uncertainty specification bounded by ± 0.18% at 95% confidence level.

Calibration results for the P Nozzles shown in Table 3 above using both the GFC and CEESI's Primary B facility showed excellent agreement on both CD and reproducibility

Validation tests, P Nozzle vs. P Nozzle, on the GFC showed results consistent with those achieved at NIST FMG, Gaithersburg, MD, when comparing similar AR facts.

9. Future plans

Motivation exists to scale up the flow of the GFC system using other standards that are traceable to the NIST 677 l PVTt system. The desired value is 0.5 kg/sec while maintaining an MUT uncertainty not greater than +/-0.20% at 95% confidence.

Comparison tests and Youden Analysis to quantify and validate results.

The GFC System will be controlled by a Measurement Assurance Program (MAP) consisting of periodic calibration of the pressure and temperature standards as well as repeating the validation tests as previously described. Initially we will conduct the validation tests on a 3 month interval and calibrate the pressure and temperature standards on a 6 month cycle. The results of the system diagnostic tests discussed in this paper will be analyzed in support of the MAP effort. These analyses may further refine and enhance the value of such diagnostics.

Add pressure control at the most downstream CFV/MUT location to facilitate performing unchoking tests on a MUT(CFV) installed in the intermediate test section. This design also facilitates conducting choking pressure ratio tests when only two nozzles are in series.

Future expansion of MUT types to include differential pressure flow meters.

10. References

[1] Wright, J., Johnson, A., *"NIST Lowers Gas Flow Uncertainties to 0.025% or Less", Measure, www.ncsli.org,* March , 2010.

[2] Lemmon, E. W., McLinden, M. O., and Huber, M. L., *"Refprop 23: Reference Fluid Thermodynamic and Transport Properties," NIST Standard Reference Database 23,* Version 8.1, National Institute of Standards and Technology, Boulder, CO, April, 2007.

[3] CEESI Document Number: MA-002, *"Uncertainty Analysis to Support NAVLAP Accreditation of a Calibration Service based on a Gravimetric System operating over the 0.1 – 10 lbm/min Mass Flowrate Range"*, September 2009. Available via: www.ceesi.com

[4] ISO – IEC Guide 99 *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms*, Int'l Stands Organ (ISO), Geneva, Switz., 2007. Available via: www.bipm.org

[5] ISO – IEC *Guide to the Expression of Uncertainty in Measurement*, Int'l Stands Organ (ISO), Geneva, Switz., 1995. Available via: www.bipm.org

[6] Mattingly, G. E., "Consultant's Report: Uncertainty Analysis for a FSI Gas Flow Calibration (GFC) System Calibrating a Meter Under Test (MUT) using a single "P" Nozzle and a Check Standard (CHK)", Report submitted to Flow Systems Inc, Berthoud, CO, Aug, 2010.

[7] Montgomery, D.C. and Peck, E.A., Introduction to Linear Regression Analysis, 2nd edit.. Wiley, New York, 1992