

VALIDATING UNCERTAINTY ANALYSES FOR GAS FLOW STANDARDS VIA INTRA- AND INTER-LABORATORY COMPARISONS

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Abstract

The Fluid Flow Group (FFG) at NIST maintains flow standards to perform calibrations of gas flowmeters over the 3.7×10^{-2} L/min[®] to 78,000 L/min flow range. Uncertainty analyses based on the propagation of uncertainties method show that the uncertainties of the provers range from 0.16% to 0.19%. The results of inter-laboratory comparisons and intra-laboratory comparisons (i.e., “crossover tests” between two different provers within the NIST laboratory) are examined to verify the uncertainty analysis results. The concepts of short- and long-term crossover tests and comparison tolerance are discussed. The comparison test results support the uncertainty specifications for the FFG gas flow standards.

Introduction

The NIST Fluid Flow Group uses piston provers, bell provers, and a Pressure-Volume-Temperature-time (PVTt) facility to provide gas flow calibrations. Uncertainty analyses based on the propagation of uncertainties approach^(1, 2) have been performed for these calibration facilities. The propagation of uncertainties approach identifies significant sources of measurement uncertainty and quantifies them through experiments, instrumentation specifications, educated estimates, and handbook values of uncertainty. These uncertainty components are combined by root-sum-square (RSS) and multiplied by a coverage factor to obtain the desired confidence level uncertainty for the measurand.

[®] All volumetric flows are stated for conditions of 293.16 K and 101.325 kPa.

But no thorough practitioner of metrology would believe their work was done at this point and rest comfortably. It is necessary to carry out comparisons with other qualified calibration facilities to see if the two systems are in good agreement with each other and thereby verify that the facilities are indeed performing to the level expected based on the propagation of uncertainties analyses.

In the case of the NIST FFG, there is considerable overlap in the flow measurement ranges of adjacently sized flow calibration systems. Hence, a single flowmeter can be calibrated by two largely independent systems and the results of the calibrations compared (an *intra*-laboratory comparison or crossover test). A flowmeter can be calibrated at another flow laboratory as well as in the NIST FFG facilities to produce an *inter*-laboratory comparison. If the differences in the calibration results found in these comparisons are greater than the combined uncertainties of the two facilities (and any extra uncertainties due to the flowmeter transfer standard), there is need to investigate further. Unexpectedly large differences could indicate overlooked or underestimated components in the propagation of uncertainties analysis or components of the process not under control. Intra- and inter-laboratory comparison results are a continuous effort considered a necessary part of maintaining measurement quality.

In the following text, the results of intra- and inter-laboratory comparisons are presented in support of the propagation of uncertainty analyses performed for the NIST FFG gas flow calibration facilities.

Piston Prover, Bell Prover, and PVTt Uncertainties

The NIST FFG uses three piston provers to cover gas flows from 3.7×10^{-2} L/min to 30 L/min, three bell provers for flows between 16 L/min to 1400 L/min, and a Pressure-Volume-Temperature-time (PVTt) facility which covers flows from 860 to 78,000 L/min. The methods of operation and uncertainty analyses for the FFG primary standards have been presented previously^(3, 4) and will only be briefly reviewed here.

The three piston provers are mounted together in a console and connected by a manifold to a single inflow line. In the piston prover system, the metered gas is diverted (using a valve) into a glass cylinder to raise a mercury-sealed piston. As the piston rises through the cylinder, it successively starts and stops a timer used to measure the gas collection interval. The temperature and pressure of the gas entering the collection volume are measured. These temperatures and pressures are used to calculate the density of the collected gas, and the density is used to convert the measured volumetric flow into a mass flow. The bell provers have instrumentation requirements and operational procedures analogous to the piston provers but they utilize an oil seal and an inverted bell to contain the collection volume. The collection timer is triggered by signals generated by an optical switch system.

The mass flow measurements made with the piston and bell provers are subject to uncertainties in the determination of the collection volume, the timing interval, and the density. The uncertainty of the gas density is due to uncertainties in the measurement of

the temperature and pressure of the gas within the collection volume, as well as the goodness of fit of the best fit function used to calculate the density, and the quality of the experimental data used to determine the function. The uncertainties in temperature and pressure measurements are related to calibration quality, sampling errors, and sensor drift over time. The uncertainty of the collection volume is due to uncertainties in measuring the diameter of the cylinder or bell and in the stroke length of the piston or bell, as well as the effects of thermal expansion due to temperature variations. The uncertainty of the timing interval measurement can be traced to the uncertainty of the timer calibration, the uncertainties of its actuation by the start and stop switches, and any rocking of the piston or bell as it passes the switches. There are also uncertainties due to “storage effects” related to non-zero changes in density within the connecting piping (or “inventory volume”) between the meter and prover during the collection period (due to changes in the temperature and pressure in the connecting piping). These uncertainties have been studied experimentally and quantified. The results of the uncertainty analysis for the piston and bell show that the relative uncertainty of the flow measurement is between 0.16% (2σ) and 0.19% (2σ)[®], depending upon which prover is in use.

The NIST FFG also operates a PVTt system to calibrate flowmeters at higher flows. In this system, flow is diverted with a valve into an evacuated tank and a timer is started simultaneously. When the pressure in the tank reaches a prescribed upper value, flow is diverted away from the tank again and the timer is stopped. Initial and final pressure and temperature measurements made in the collection tank are used along with an equation of state to obtain initial and final gas densities. The densities are multiplied by a carefully measured tank volume to obtain the initial and final mass of gas in the tank. The difference in mass divided by the collection time, along with corrections for mass changes in the connecting volume between the meter under test and the tank, quantifies the mass flow.

The uncertainty of the PVTt mass flow measurement has components due to the uncertainty of the pressure and temperature measurements made in the tank and inventory volumes, the uncertainty of the volumes of both the tank and inventory, the uncertainty of the timer and its actuation by the diverter valve, and uncertainties due to the equation of state used to calculate density. An unpublished uncertainty analysis of the NIST PVTt system gives a relative uncertainty of 0.19% (2σ) for this facility.

Description of Intra- and Inter-laboratory Comparisons

In an intra-laboratory or crossover test, an appropriately sized flowmeter is set up along with necessary instrumentation, and the flowmeter is calibrated with two different flow standards (Fig. 1). In the NIST FFG, critical flow venturis (CFV) are the most common flowmeters used as a transfer standard during a crossover test, but laminar flow elements (LFE) and turbine flowmeters are common as well.

[®] To reduce confusion about the confidence level of uncertainties quoted within this paper, uncertainty values will be followed by the symbol “ 1σ ” for nominally 67% or $k = 1$ values and by “ 2σ ” for nominally 95% confidence or $k = 2$ values.

Different versions of the intra-laboratory test are possible that explore different aspects of the flow standard uncertainties. At one extreme, a *short-term* test can be conducted in which as many parameters as possible, are held constant. For this test, the flow is redirected between the two flow standards using valves, so that there is essentially no change in the flow conditions at the transfer standard during the test. A single operator runs the test. The test is completed in as short a time as practical so that variations in ambient conditions (such as room temperature) are minimized. The short-term test allows one to isolate differences between flow standards related to a certain, reduced set of uncertainty components. For instance, uncertainties due to temporal drift in pressure and temperature instrumentation or those caused by the effects of room temperature changes are practically eliminated. At the opposite extreme, a *long-term* test allows the normal variations in ambient conditions, operator, and other parameters to take place, thereby giving one a practical measure of differences between flow standards that might happen during a normal meter calibration. The normal variation of the test parameters is most easily accomplished by conducting the intra-laboratory test over a period of more than one day, hence the name long-term test.

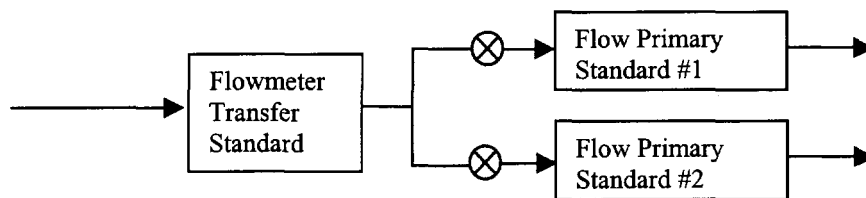


Figure 1. Equipment arrangement for intra-laboratory or crossover test. Valves may be used to redirect flow without disturbing steady state conditions at the transfer standard.

In an inter-laboratory test, a transfer standard is shipped from the laboratory with primary standard #1 to the laboratory with primary standard #2. Hence there is the possibility for damage or calibration shift caused by shipment and the issue of temporal drift is a more serious concern. In some cases, different instrumentation (for instance for measuring flowmeter pressures and temperatures) is used by laboratory #1 versus #2. The transfer standard may be used in different environments, i.e. different ambient conditions, different flow media, or different approach conditions and hence different inlet flow profiles. Although the inter-laboratory test is less convenient to conduct, it has an irreplaceable advantage over the intra-laboratory test: it delivers a nearly completely independent flow measurement. This allows one to assess systematic uncertainty components such as pressure calibration uncertainties or gas property calculations that are shared by flow standards within the same laboratory that are likely to go undetected by an intra-laboratory test.

The greater demands of the inter-laboratory comparison have led to methods that use two or more flowmeters in the flow transfer standard. This allows comparisons between the

meters for assessment of flowmeter damage during shipment. Also, if the meters are placed in series and their order is reversed during the course of the tests so that calibration data is produced for each meter in each position, some assessments of the presence of the flow profiles entering the meters can be made.⁽⁵⁾

Comparison Tolerance for Inter- and Intra-laboratory Tests

When one conducts a comparison between two facilities, a natural question arises: how well should the calibration results from the two facilities agree if the propagation of uncertainties method calculations are reasonable? Let us define a comparison tolerance, Δ ,

$$\Delta = k \cdot \sqrt{u_{Cd1}^2 + u_{Cd2}^2 + u_{temp}^2}, \quad (1)$$

where u_{Cd1} is the relative standard uncertainty in the transfer standard discharge coefficient when measured with primary standard #1, u_{Cd2} is the discharge coefficient uncertainty for primary standard #2, u_{temp} represents the uncertainty related to temporal calibration drift (in flowmeter or instrumentation) between usage at locations #1 and #2, and k is a coverage factor for the desired level of confidence. The temporal drift term represents changes in the transfer standard calibration due to the passage of time or due to shipping and handling (ideally, assessed by pre- and post-calibrations at location #1). The uncertainty of the discharge coefficient measured via primary standard #1 can be written as,

$$u_{Cd1} = \sqrt{u_{PS1}^2 + u_{instr1}^2 + u_{TC1}^2 + u_{R1}^2}, \quad (2)$$

where u_{PS1} is the relative standard uncertainty of primary standard #1, u_{instr1} is the relative standard uncertainty due to the transfer standard instrumentation, u_{TC1} accounts for transfer standard uncertainties caused by the test conditions at location #1, and u_{R1} represents the transfer standard repeatability[®]. Of course, an analogous expression can be written for u_{Cd2} . Equation 2 breaks the discharge coefficient uncertainty into three type B components (u_{PS1} , u_{instr1} , u_{TC1}) and into a type A uncertainty (u_{R1}) which is evaluated from the statistics of the calibration and is due to both the primary and transfer standards.

Equation 1 can also be written in the following form:

$$\Delta = k \cdot \sqrt{u_{PS1}^2 + u_{PS2}^2 + u_{TS}^2}, \quad (3)$$

where the subscripts 1 and 2 indicate locations #1 and #2 and u_{TS} represents uncertainties that can be attributed to the transfer standard. The term u_{TS} can in turn be written as:

[®] Repeatability is herein defined as standard deviation of a set of successive multiple measurements with the flow maintained at steady state. Reproducibility is defined as the standard deviation of a set of measurements with the flow changed and then returned to the same nominal value. See references 1 and 2.

$$u_{TS} = \sqrt{u_{instr1}^2 + u_{instr2}^2 + u_{TC1}^2 + u_{TC2}^2 + u_{R1}^2 + u_{R2}^2 + u_{temp}^2} . \quad (4)$$

With this equation, estimates of the type B uncertainty components and statistically derived values for the u_{R1} and u_{R2} terms can be used to obtain a measure of the uncertainty with which a transfer standard can convey a flow calibration from primary standard #1 to primary standard #2. In Equation 4, uncertainties due to repeatability have been assigned to the transfer standard although some of this uncertainty is actually due to the primary standards.

Whether the terms u_{instr1} , u_{instr2} , u_{TC1} , u_{TC2} , and u_{temp} are significant or negligible depends upon the type of comparison undertaken. The term u_{instr1} accounts for uncertainties in for instance, the pressure and temperature instrumentation used with the transfer standard and its magnitude will vary with the quality of the instrumentation calibrations and the type of comparison. For a short-term intra-laboratory comparison, the same transfer standard instrumentation is used so that systematic errors in the instrumentation are the same for both of the primary standards tested and do not affect the comparison. For a long-term intra-laboratory comparison and for an inter-laboratory comparison conducted with instrumentation that travels along with the transfer standard, the u_{instr1} term can again be neglected, but the temporal term in Equation 1 must account for possible instrumentation drift or damage. Finally, in the case of the inter-laboratory comparison conducted *without* traveling instrumentation, two different sets of instrumentation with two different traceability chains are in use, and the u_{instr1} and u_{instr2} terms must not be neglected.

Examples of uncertainties due to test conditions (u_{TC1} , u_{TC2}) are: a non-ideal flow profile at the inlet to the transfer standard, uncertainties related to gas composition or humidity, uncertainties in methods of calculation (such as in gas property correlations), or effects on the flow measurement through ambient temperature conditions. All of these effects are likely to cause added uncertainty in the transfer standard and since they are related to the flowmeter, they generally are not included in the primary standard uncertainty. If the comparison is an intra-laboratory test, the test conditions are normally stable enough during the course of the test for the u_{TC1} and u_{TC2} terms to be considered negligible.

Regarding the term u_{R1} , in crossover tests where the flow is redirected from flow standard #1 to #2 by means of valves and the flow conditions at the flow standard are maintained at steady state during the crossover, the transfer standard repeatability should be used. For a long-term test or an inter-laboratory comparison, the transfer standard reproducibility is appropriate as this accounts for the day to day variability in the transfer standard instrumentation and test conditions.

Hence, in a short-term crossover test, the comparison tolerance, Δ , is dominated by the RSS of the two facility uncertainties. A value of u_{TS} (and Δ) for a long-term intra-laboratory test will be larger due to the inclusion of temporal drift, reproducibility, and other components.

Finally, it should be noted that more sophisticated analyses of comparison results, such as Youden plots, are possible if flow transfer standards with more than one flowmeter are used. But these methods will not be utilized herein since the majority of the available data is based on single flowmeter systems.

Method of Data Presentation and Analysis

As previously stated, comparison tests are performed using a flowmeter (such as a critical venturi), sized so that flow collections can be taken using more than one primary flow standard. Plots of the resulting flowmeter discharge coefficients (Cd) versus Reynolds number (Re) for the two calibrations are compared. As can be seen in Figure 2, multiple flow collections are gathered at each flow (between 5 and 10).

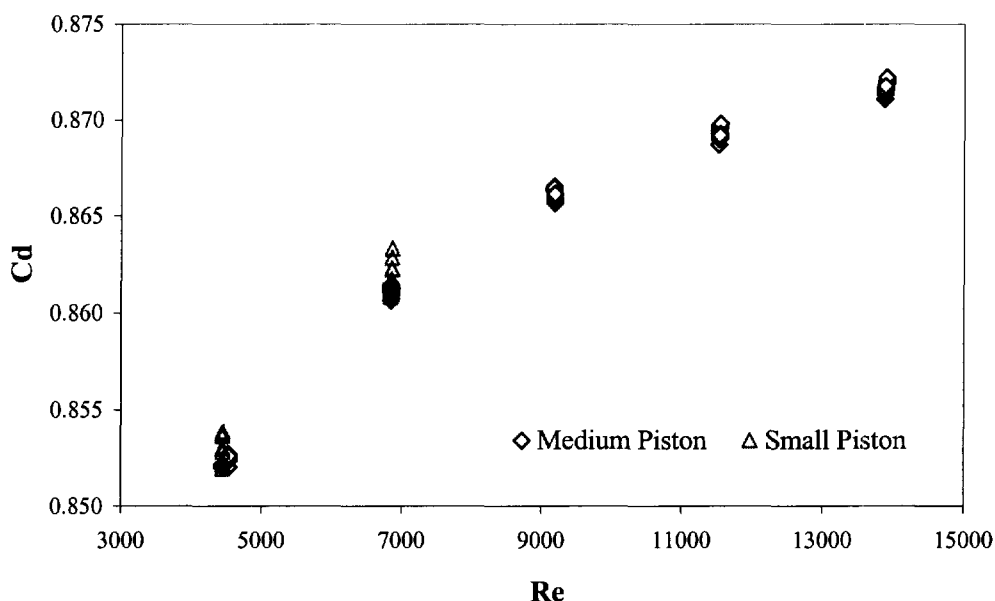


Figure 2. A sample discharge coefficient versus Reynolds number plot for a crossover test between the small and medium piston provers.

To quantify the differences between the two flow standards in the tests presented herein, an average discharge coefficient has been calculated for each primary standard from the multiple flow measurements ($\overline{Cd1}$, $\overline{Cd2}$) made at the same nominal flow. The difference between the two discharge coefficients was normalized by the RSS of the relative standard uncertainties of the two primary standards to give a normalized difference between the two primary standards, R :

$$R = \frac{\overline{Cd2} - \overline{Cd1}}{\sqrt{u_{PS1}^2 + u_{PS2}^2}} \quad (5)$$

For an ideal transfer standard (i.e. a transfer standard with u_{TS} of zero), approximately 67% of the R values should be less than 1, and approximately 95% of the R values should be less than 2 if the propagation of uncertainty calculations for the two primary standards are reasonable. This normalized presentation has the advantage of allowing data from numerous comparisons to be examined simultaneously, despite different values for the comparison tolerance. The magnitude of the error bars (M) attached to the data points is proportional to the transfer standard uncertainty and it has been normalized in a manner consistent with the calculation of R :

$$M = \frac{u_{TS}}{\sqrt{u_{PS1}^2 + u_{PS2}^2}}. \quad (6)$$

The calculation of u_{TS} has been based on the best available information and will be discussed in more detail in subsequent sections. Adding error bars to the comparison data illustrates the inability of the transfer standard to perfectly transfer the flow calibration results from primary standard #1 to primary standard #2.

Intra-laboratory Results

Intra-laboratory or crossover comparisons are routinely done at NIST to verify that the flow standards are performing as expected and giving results consistent with the stated uncertainties. In addition to using critical venturis owned by the FFG for crossovers, whenever a customer's flowmeter spans two flow standards, it is calibrated on both systems, generating crossover data. Since the small bell prover has not been used recently, crossover data is available for small (SP) to medium piston (MP), medium to large piston (LP), large piston to medium bell (MB), medium bell to large bell (LB), and large bell to PVTt. A summary of the recently performed intra-laboratory comparisons performed by the FFG is given in Table 1 and the results are shown in Figure 3. Figure 3 is a plot of the normalized flow difference, R , defined in Equation 5, along with error bars sized to M , the normalized transfer standard uncertainty defined in Equation 6. Figure 3 also presents delineating vertical marks and labels which show the ranges of flow covered by the piston provers (PP), bell provers (BP), and the large PVTt facility. For the remainder of this paper, the uncertainty values given in tables and in figures (as error bars) are generally 67% confidence level or 1σ values to simplify analysis.

Table 1 lists the value of the normalizing quantity, the estimated uncertainty of the transfer standard, and the difference between the two average discharge coefficients for the two primary standards. In cases where more than one flow rate was measured for the crossover, a range of uncertainties is given in Table 1. To calculate the transfer standard uncertainties, the standard deviation of the discharge coefficients were used for u_{R1} and u_{R2} , u_{temp} was assumed equal to 0.02% (1σ) for the long-term crossovers, zero for the short-term crossovers, and instrumentation and test condition components were assumed to be negligible for long- and short-term crossovers.

Table 1. Intra-laboratory comparisons for the NIST FFG gas flow standards, 1997 to present.

Primary Stds	Date	Flow (L/min)	Transfer Std type	Long- or Short-term	Gas	$\sqrt{u_{PS1}^2 + u_{PS2}^2}$ (1 σ) (%)	u_{TS} (1 σ) (%)	$\overline{Cd2} - \overline{Cd1}$ (%)
SP MP	5/98	0.6 - 1.0	CFV	short-term	Air	0.12	0.09 - 0.10	-0.07 - +0.02
SP MP	1/99	1.5	CFV	long-term	Air	0.12	0.04	-0.13
MP LP	5/98	3.0 - 4.6	CFV	short-term	Air	0.12	0.03 - 0.03	-0.06 - +0.03
MP LP	11/98	3.5 - 5.7	CFV	short-term	Air	0.12	0.02 - 0.02	0.00 - +0.15
MP LP	1/99	7.5	CFV	long-term	Air	0.12	0.1	+0.15
LP MB	12/97	23 - 46	CFV	long-term	Air	0.12	0.03 - 0.14	-0.01 - +0.27
LP MB	4/98	34 - 41	CFV	short-term	Air	0.12	0.05 - 0.10	+0.08 - +0.15
LP MB	11/98	23 - 34	CFV	short-term	Air	0.12	0.02 - 0.03	+0.10 - +0.12
LP MB	1/99	23 - 70	CFV	long-term	Air	0.12	0.03 - 0.11	-0.03 - +0.16
MB LB	1/98	560	CFV	long-term	Air	0.12	0.12	+0.11
MB LB	1/99	180 - 560	CFV	long-term	Air	0.12	0.03 - 0.06	-0.07 - +0.02
LB PVTt	3/98	3100 - 4500	CFV	long-term	Air	0.12	0.07 - 0.11	-0.05 - +0.01

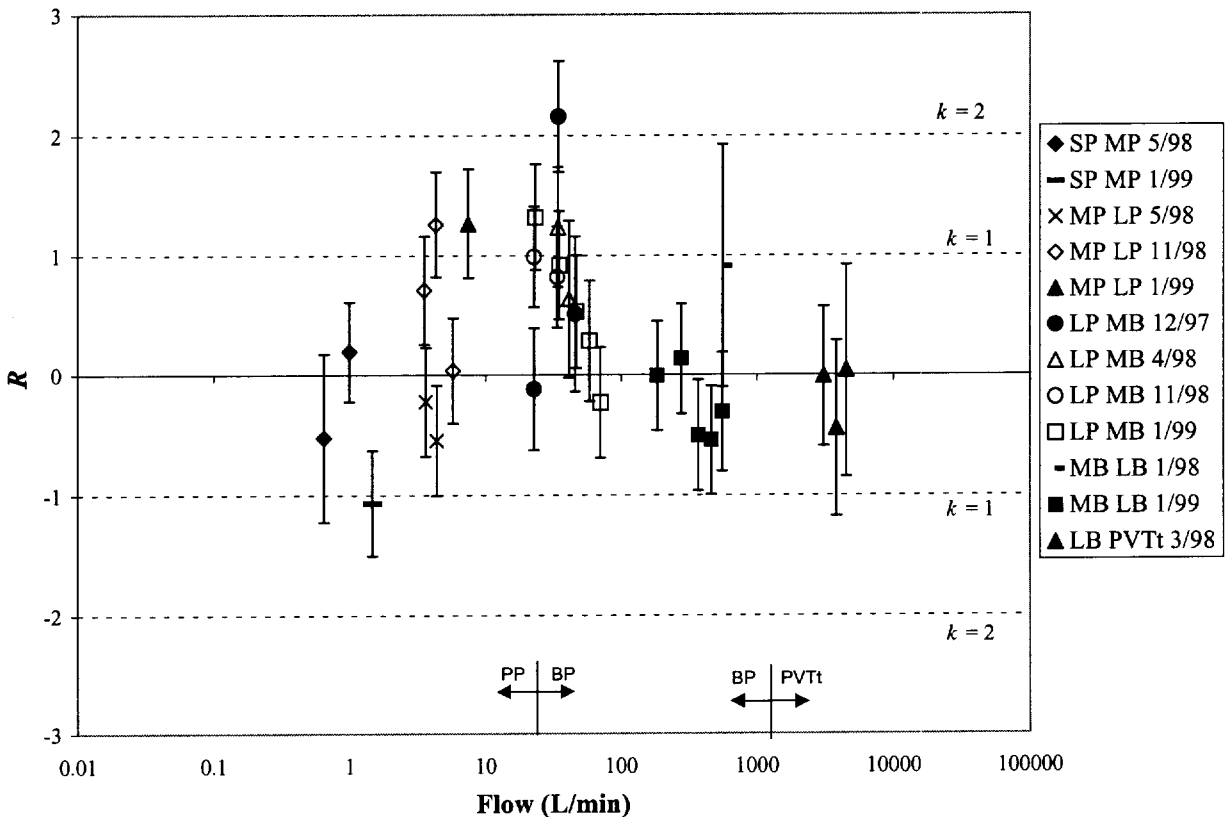


Figure 3. Intra-laboratory (crossover) test results.

For the intra-laboratory calculations of R , the smaller of the two provers has been used as the reference ($\overline{Cd1}$). Note that the normalizing quantity in R has remained the RSS of the *total* uncertainties of the two primary standards. The actual uncertainty of the primary standards may be less for an intra-laboratory test (especially a short-term test), since some sources of uncertainty are shared between provers and would cancel. Also, the provers have often been used at flows that are beyond their normal flow range in order to obtain crossovers at more flow points, which may cause the actual uncertainty to be larger than that assumed here. Therefore the values of R must be considered approximations. Nevertheless, it can be seen in Figure 3 that more than 67% of the data points fall within the $k = 1$ bounds (27 out of 34 or 79%), and all but 1 point (97%) fall within the $k = 2$ bounds. These results validate the uncertainties calculated by the propagation of uncertainties method for the FFG gas flow standards.

Both short- and long-term intra-laboratory tests are presented in Figure 3. Comparing the long- and short-term crossovers in Figure 3, one observes that, as expected, the long-term crossovers tend to show larger differences than the short-term crossovers. For the SP to MP and MP to LP crossovers, short-term differences are generally 0.05% or less, while long-term differences are about 0.15%. Based on this information, day to day variations in the operation of the primary standard contribute about 0.1% to the uncertainty. This figure compares well with an RSS combination of the components that are subject to day to day change, primarily through room temperature variations.⁽³⁾ These components include temperature sampling, thermal expansion, and flowmeter reproducibility.

Inter-laboratory Results

A summary of inter-laboratory comparisons from 1996 to present involving the FFG is given in Table 2. Many of these data sets were collected without formal intentions to perform inter-laboratory comparisons; rather they were possible because NIST and the other laboratory both had calibrated the same flowmeter within a reasonable timeframe.

Some details regarding each comparison listed in Table 2 will now be discussed. The NIST Pressure and Vacuum Group (PVG) offers flow calibrations at flows less than 1 L/min and disseminates this range with a laminar flowmeter transfer standard.⁽⁶⁾ This transfer standard is periodically used to compare the flow standards at the crossover flows between the FFG and the PVG. The 4/96 inter-comparison with NRLM is documented in a prior publication⁽⁷⁾ and was conducted using a CFV based transfer standard developed by NRLM. The comparison with CEESI results from both laboratories calibrating a four-CFV transfer standard developed for the U.S. Air Force Metrology Calibration Program. CEESI offers calibrations at different uncertainty levels, and this particular calibration was done at their largest uncertainty level (0.5%, 2σ), hence the large value for the normalizing quantity. The CENAM comparison was conducted with three CFV's belonging to CENAM. The remaining comparisons dated 1/99, are based on data from a set of three CFV's (commonly called the Ford MAP) owned by Visteon Automotive Systems.^(8, 9) The Ford MAP was previously tested by NIST in 11/94 and was calibrated again in 1/99. Numerous national metrology

laboratories have tested the Ford MAP over the past 6 years, making comparisons to these other laboratories possible. Since the Ford MAP is a tandem flowmeter system that is used to generate data that is equivalent to reversing the meters as mentioned previously, a Youden plot analysis is possible for its inter-laboratory comparison data. The Youden analysis is not presented herein to allow presentation of all of the inter-laboratory results in a consistent format, but the data presented in the Youden format is available elsewhere.⁽¹⁰⁾ Only the upstream CFV of the tandem transfer standard was used for the present comparison analysis.

Table 2. Inter-laboratory comparisons involving the NIST FFG gas flow standards, 1996 to present.

Lab [®]	Date at NIST	Flow (L/min)	Transfer Std type	Gas	$\sqrt{u_{PS1}^2 + u_{PS2}^2}$ (1 σ) (%)	u_{TS} (1 σ) (%)	$\overline{Cd2} - \overline{Cd1}$ (%)
PVG	5/98	0.04 - 0.30	LFE (1)	N2	0.11	0.05 - 0.16	-0.22 - +0.20
NRLM	4/96	0.35 - 9.9	CFV (3)	N2	0.12	0.09 - 0.09	-0.13 - +0.09
PVG	2/97	0.42 - 1.0	LFE (1)	N2	0.11	0.05 - 0.13	-0.03 - +0.20
NPSL	1/98	34 - 1100	CFV (2)	Air	0.13	0.08 - 0.12	-0.05 - +0.20
CEESI	8/98	0.37 - 810	CFV (4)	Air	0.27	0.08 - 0.13	-0.38 - +0.42
CENAM	11/98	1.4 - 69	CFV (3)	Air	0.13	0.08 - 0.13	+0.01 - +0.23
CEESI	1/99	5700 -14000	CFV (3)	Air	0.11	0.09 - 0.09	-0.12 - -0.03
NEL	1/99	5700 -14000	CFV (3)	Air	0.17	0.08 - 0.08	-0.10 - +0.01
KRISS	1/99	5700 -14000	CFV (3)	Air	0.15	0.08 - 0.08	-0.25 - -0.15
CMS	1/99	5700 -14000	CFV (3)	Air	0.14	0.08 - 0.08	-0.06 - -0.02
NRLM	1/99	5700 -14000	CFV (3)	Air	0.11	0.06 - 0.07	+0.05 - +0.09

The uncertainty values for the non-NIST laboratory were determined using the best available information. In some cases, fairly thorough uncertainty analyses (with the sub-components broken down and quantified) for the measured discharge coefficient were available. In other cases, only a total uncertainty for the discharge coefficient or the uncertainty of the primary standard was available. If no better information was available, the estimated uncertainty values given in Table 3 were used to calculate the transfer standard uncertainty. It should be noted that in cases where actual values were available from the non-NIST laboratory, they did not differ greatly from those calculated by the estimated uncertainties given in Table 3, and as can be seen in Table 2, the u_{TS} values were normally about 0.09% and did not vary a great deal around this value.

[®] PVG = NIST Pressure and Vacuum Group,
 NRLM = National Research Laboratory of Metrology (Japan),
 NPSL = Navy Primary Standards Laboratory (San Diego),
 CEESI = Colorado Engineering Experiment Station, Inc.,
 NEL = National Engineering Laboratory (England),
 KRISS = Korea Research Institute of Standards and Science,
 CMS = Center for Measurement Standards (Taiwan).

Table 3. Values of uncertainty components assumed (when necessary) for inter-laboratory analysis.

Lab	Uncertainty component	Does instrumentation travel w/ TS?	
		No	Yes
NIST	u_{instr1}	0.025	0
	u_{TC1}	0.03	0.03
	u_{R1}	Std deviation of data	Std deviation of data
Non-NIST	u_{instr2}	0.025	0
	u_{TC2}	0.03	0.03
	u_{R2}	0.05	0.05
	u_{temp}	0.01	0.03

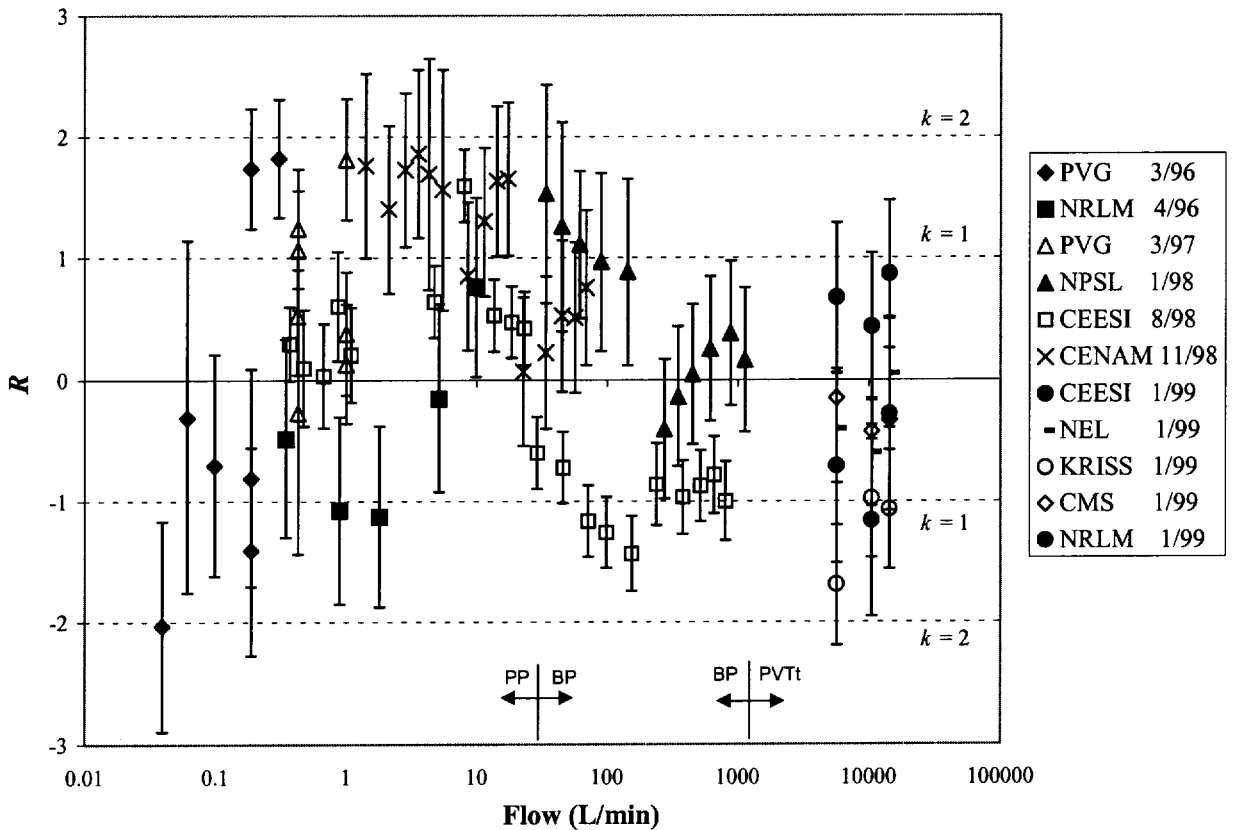


Figure 4. Inter-laboratory test results.

A plot of the normalized flow difference, R , for the inter-laboratory comparisons versus the NIST FFG flow is shown in Figure 4. The discharge coefficient differences were calculated as follows. For most of the CFV based transfer standards, results from other laboratories were reported as Reynolds number and discharge coefficient values. These

data were fit with a least squares correlation so that the discharge coefficient for an input Reynolds number could be readily calculated. The CFV pressure and temperature measured during testing at NIST were used along with the least squares correlation to calculate the discharge coefficient based on the other laboratory's calibration. In the case of the Ford MAP, all of the participant laboratories have tested at nominally the same three Reynolds numbers. Further, several laboratories have reported a pattern of discharge coefficients that are not monotonically increasing with Reynolds number and hence are not well fit by the traditional inverse of a power of the Reynolds number function. Therefore, for these data, simple averages of the discharge coefficients for each laboratory at the low, medium, and high Reynolds numbers were used instead of the best-fit function.

As was the case for the intra-laboratory comparisons, analysis of Figure 4 indicates that the uncertainty specifications for the NIST FFG gas flow standards are reasonable. One of the 80 comparison points lies beyond the $k = 2$ level, and 53 of the points (66%) fall below the $k = 1$ level.

Conclusions

Intra- and inter-laboratory comparisons are essential elements for maintaining flow measurement quality. One can calculate a comparison tolerance for intra- and inter-laboratory comparisons by considering the uncertainties of the two flow standards being compared as well as uncertainties related to the flow transfer standard. Comparisons that fall within the calculated tolerance validate uncertainty calculations developed through the propagation of uncertainty method. A method for analyzing comparison data has been used which normalizes both the differences measured with a transfer standard and the transfer standard uncertainty. This method permits analysis of data from numerous comparisons on a consistent basis, despite differences in the uncertainties of the primary and transfer standards from test to test.

The uncertainty specifications for the NIST FFG gas flow standards have been validated by the recent intra- and inter-laboratory tests presented in this study since the normalized differences between standards fall within the comparison tolerance. For the intra-laboratory data, 79% of the comparison results fall below the $k = 1$ level, and 97% fall below the $k = 2$ level. For the inter-laboratory results, 66% fall below the $k = 1$ level, and 99% fall below the $k = 2$ level. The uncertainty performance of the FFG gas flow standards has also been confirmed by the calibration histories of flowmeters calibrated at NIST repeatedly and over long time periods.⁽⁴⁾

Intra-laboratory or crossover tests can be designed to include or exclude certain components of uncertainty and thereby confirm uncertainty levels attributed to them in propagation of uncertainty analyses. *Short-term* crossovers hold as many influence quantities as stable as possible and have the effect of isolating the measured differences to unshared systematic ones, such as errors in the collection volume. *Long-term* crossovers are conducted over a period of days and allow normal variations in the calibration environment to manifest themselves in the crossover differences. For the FFG

gas flow standards, the differences between facilities for a long-term crossover can be as much as 0.1% larger than those for a short-term test. Changes of this magnitude are reasonable when compared to the uncertainty components that come into play between the short- and long-term tests (including transfer standard reproducibility / repeatability differences). Similarly, if one examines the magnitude of differences for the short-term tests, they are generally less than 0.1%, and this figure is less than the RSS of the appropriate terms of the propagation of uncertainty method analysis.

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