Improvements in the Implementation of Laminar and Sonic Based Gas Flow Meters in the Range of 2 X 10-5 G•S-1 (1 Ncc Min-1) to 100 G•S-1 (5000 Nl•Min-1)

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Abstract: During the middle of the last decade, DH Instruments (now Fluke Calibration) developed an improved primary calibration chain based on dynamic gravimetric measurements and a successive addition technique to provide significantly lower uncertainty in gas flow from 2 x 10-5 g•s-1 (1 Ncc min-1) to 100 g•s-1 (5000 Nl•min-1) [1]. Recently, in order to disseminate the lower uncertainties achieved to the flow measurement community, significant improvements were made to the laminar and sonic based flow meters supported by the gas flow references. The improvements include the use of NIST (USA) Refprop gas property data, a new Reynolds number and pressure characterization, lower uncertainties in absolute and differential pressure monitoring, and filtration designed directly into the meter. These improvements decreased the uncertainty of the population of these instruments and should also improve their reliability. This paper discusses these advances and the benefits to gas flow metrology.

Keyword: Laminar Flow Element, Sonic Nozzle, calibration chain, gas flow, traceability, gravimetric flow standard, successive addition.

1. Introduction

The laminar flow elements (LFEs) and sonic nozzles described in this paper refer to DH Instruments molbloc-L and molbloc-S gas flow transfer standards available from Fluke Calibration. In order to keep context of the technology intact throughout this paper they are referred to specifically as LFEs and sonic nozzles respectively.

In the 1990s a gap in the traceability path for low gas flow measurements was filled by the introduction of laminar flow element transfer standards with unequaled characteristics of repeatability and stability [2]. These transfer standards were supported by static gravimetric referencing and a calibration chain of the laminar flow elements disseminating traceability to customers worldwide. However the maintenance of the calibration chain with static gravimetric measurements was very difficult and overly time consuming [3]. Throughout the 2000s a dynamic gravimetric reference and new style calibration chain was developed. The calibration chain was greatly expanded because sonic nozzles were introduced to this product line extending traceability in gas flow to 4000 slm and more. A technique called successive addition was implemented to provide traceability from 10 to 4000 slm, and also from 10 to 1 sccm [1]. Verification both at the low and high end of the calibration chain demonstrated that new low uncertainties were reliable.

The uncertainties resolved in the new gas flow calibration chain were as low as they had ever been. However there had not been any improvements in the laminar and sonic based transfer standards delivered to customers. The final effort of this sequence of improvements was to ensure that the transfer standards could disseminate the low gas flow measurements with the lowest uncertainty and the best reliability.

2. Improvements in Traceability

The improvements in traceability and uncertainty are discussed in “A Primary Calibration System For The Support Of High Performance Gas Flow Transfer Standards” [1] given at the International Symposium on Fluid Flow Measurement in 2006. The paper describes the method of traceability completely and the following is a summary.

There are two parts of the calibration chain; one maintains traceability through LFEs and the other through sonic nozzles. The LFE calibration chain was first developed in the mid ‘90s, and as mentioned before was traceable to a static gravimetric standard. The sonic nozzle calibration chain was first created in 2003 for nitrogen and air and for the most part has stayed the same to present day using the successive addition technique.

The modern day LFE calibration chain was changed significantly and was completed in 2008 for N2 and Air and completed for Argon, Helium, CO2 and SF6 in 2009. The main difference was that the gravimetric standard was changed to a GFS dynamic gravimetric standard that took significantly less time to perform complete gravimetric calibrations than the static gravimetric system. In addition, the portion of the calibration chain that supported the lowest flows of 1 to 10 sccm is traceable through a successive addition test from 20 to 1 sccm with the GFS reference at 10 sccm. This was done in order to eliminate having to perform extremely lengthy GFS referencing at flows below 10 sccm. And finally, all of the calibration chain LFEs had been replaced with LFEs that have the performance improvements described in this paper.

The modern day sonic nozzle calibration chain is very similar to its original completed in 2003. As stated in [1], traceability is transferred from the 5 and 10 slm gravimetric points performed on the lowest range sonic nozzles and transferred up through the ranges using the successive addition technique. The most recent determinations were late 2006 and early 2007 for Air and N2 and 2008 and 2009 for Argon, Helium, CO2 and SF6.

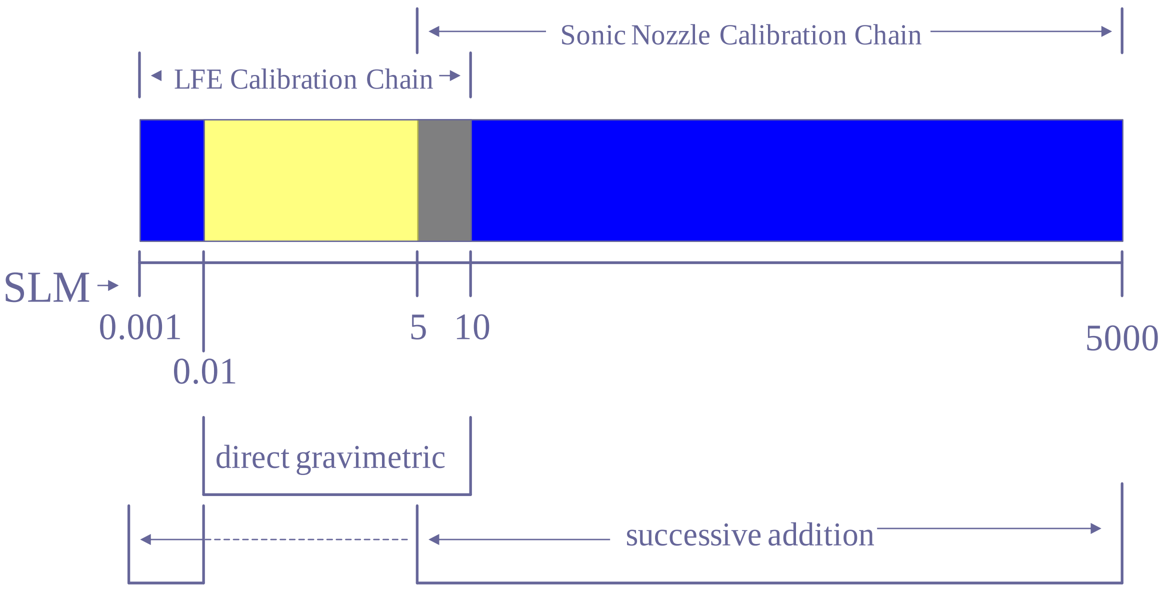

Figure 1. Diagram showing calibration chain traceability.

Figure 1 shows how traceability is supported for the LFE and sonic nozzle calibration chains. Without giving the complete uncertainty analysis here the uncertainties maintained vary depending on the flow, but in general the uncertainties range from ±0.05% to ±0.08% at k=2. This uncertainty is not for the GFS, but for the actual calibration chain LFEs and sonic nozzles after characterization using GFS and successive addition. These specific LFEs are called No. 1s and mostly only used for calibrating other working standards of the same type.

Validation of the calibration chains are presented in [1], however that paper was published before the completion of the latest (modern) LFE calibration chain in 2008. For the most part the original and modern style of LFE calibration chains agree within their uncertainties. However at the lowest flows (below 10 sccm) there were some discrepancies between them. To resolve the difference NIST was contracted to perform measurements on an LFE calibrated by the latest calibration chain from 1 to 100 sccm in November of 2008. The references used by NIST were the PVTt, ROR and gravimetrically linked references. Figure 2 shows the agreement with the calibrated LFE with the NIST references. The result was that the LFE calibrated by the modern LFE calibration chain was within stated uncertainties.

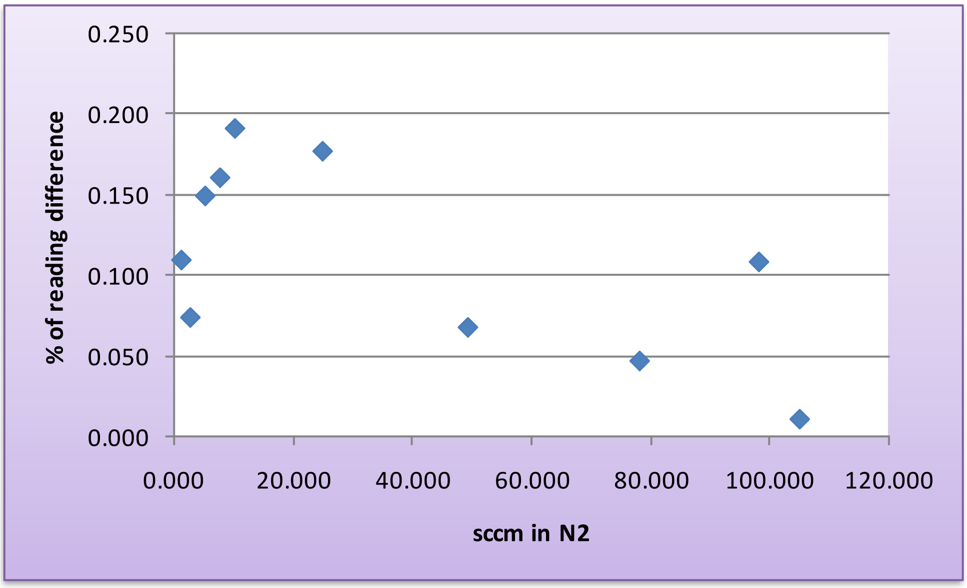

Figure 2. Results of 100 sccm LFE tested by NIST

For the original sonic nozzle calibration chain the uncertainties were validated by comparisons with PTB (Germany) and CESSI. No other significant comparisons have been made in the ranges supported by the sonic nozzle calibration chain. However, stability can be shown and linked to the original calibration chain. Table 1 shows the changes in sonic nozzle calibration chain from 2003 – 2004 and from 2004 – 2006 at four flows in the range of the calibration chain. Since the original uncertainty was on the order of ±0.13 % of measured flow it was felt that both the sonic nozzles and the calibration chain successive addition method were stable.

Table 1. Changes in flow measurements from the sonic nozzle calibration chain

Nom Qm	2003-2004	2004-2006	2003 – 2006
[slm]	[%]	[%]	[%]
10	0.048	0.001	0.049
100	0.053	0.029	0.082
1000	0.075	-0.021	0.053
4000	0.043	-0.029	0.014

3. Improvements in Laminar and Sonic Gas Flow Meter Design and Characterization

With proven lower uncertainties realized with the new calibration chains, the opportunity was taken to offer lower uncertainties in the LFE and sonic nozzle product lines available to customers. Lower uncertainties on references helped to produce lower uncertainties on product but this was not significant enough after all influences were analyzed. This section explains the changes made to the available products to both lower the uncertainty and also to improve the reliability of the available uncertainties.

The products being described here include the flow calculator which also measures absolute and differential pressure and temperature of the LFEs and sonic nozzles. The original device is called a molbox1. All changes described here are for a product release named molbox1+.

3.1 Gas Properties

The first change to molbox1 originated with the introduction of the sonic nozzles in 2003. molbox1 uses gas properties to calculate density and viscosity based on pressure and temperature measurements taken at the time of flow measurement. The original gas properties were developed from gas property tables offered by Air Liquide, a distributor of bottled gas, in the late ‘80s and early ‘90s. For the most part the uncertainty, or lack of data, of those gas properties did not have a significant effect on gas flow uncertainties because the flow elements were calibrated by a reference, hence cancelling out the majority of error introduced by the air Liquide gas properties. However there was some error from deviations of conditions where the calibration was performed. For instance if an LFE was calibrated and the measured temperature of the gas was 20˚C, it is possible there was some uncertainty if the LFE was used at 15˚C. This influence was worse with gases that were not very well known at the time such as SF6.

When sonic nozzles were introduced in 2003 it was decided to use NIST’s Refprop7 [6] gas properties database specifically for the sonic nozzles for calculations of density and viscosity.. However at the time a conversion from Air Liquid to Refprop7 was not made for the LFEs.

With the development of the new LFE calibration chain and also the release of molbox1+ Refprop7 was implemented globally in 2009. It was realized that Refprop8, a more recent revision of the database [6] was available but was not used because there was not a significant advantage to re-characterizing the LFE and sonic nozzle calibration chains.

The improvements experienced by using Refprop7 have not necessarily been quantified or measured to a degree that can be reported. However, the next section discusses a new method for characterization of the LFE and sonic nozzles. The success of the new characterization is dependent on the uncertainty of the density, viscosity and critical flow coefficients with variations of temperature and pressure experienced during the characterization.

3.2 Flow Element Characterization

Table 2 gives the fundamental equations for calculating flow for an LFE and a sonic nozzle used with the molbox1 or molbox1+.

Table 2. Equations for LFEs [2] and sonic nozzles [5] used with molbox1 and molbox1+

LFEs	Sonic Nozzles
$qm = \frac{P \cdot (P_1 - P_2) \cdot \rho_N \cdot T_N \cdot Z_N}{T \cdot Z_{(P,T)} \cdot \eta_{(P,T)} \cdot P_N} \cdot C_G$ eq. 1	$qm = \frac{A \cdot C \cdot C_* \cdot P_0}{\sqrt{\left(R/M\right) \cdot T_0}}$ eq. 2
where:	where:
q_m = Mass flow [kg s^{-1}]	qm = Mass flow [kg s^{-1}]
P_1 = Upstream absolute pressure [*Pa*]	A = Nozzle throat area [m^2]
P_2 = Downstream absolute pressure [*Pa*]	C = Discharge coefficient: a – b * Re^{-n} [-]
P = $\frac{(P_1 + P_2)}{2}$ [*Pa*]	C_* = Critical flow function [-]
T = Absolute temperature of gas [*K*]	P_O = Stagnation pressure [Pa]
T_N = Standard temperature, 273.15 K [*K*]	R = Ideal gas constant [j • kg^{-1} • mole^{-1} • k^{-1}]
ρ_N = Standard gas density [kg•m^{-3}]	M = Molecular mass [kg • mole^{-1}]
$\eta_{(P,T)}$ = Dynamic gas viscosity under *P,T* conditions [Pa•s]	T_O = Stagnation temperature [K]
P_N = Standard pressure, 101325 Pa [Pa]	n = 0.5 [-]
Z_N = Gas compressibility factor under standard conditions [–]	
$Z_{(P,T)}$ = Gas compressibility factor under *P,T* conditions [–]	
C_G = Experimentally determined geometrical constant [m^3]	

For an LFE the coefficient that maintains flow traceability is Cg (geometrical constant) shown in equation 1. Cg is dependent upon the density of the gas and also the Reynolds number at a gas flow. The model of Cg is proprietary and is not shown in equation 1.

When initially calibrating an LFE, a test that included variations in flows at different line pressures would modelize the LFE and adjust coefficients associated with Cg. After the pressure model was completed it was necessary to adjust the Cg at specific absolute line pressures of atmosphere, 270 kPa or 525 kPa, over the flow range of the LFE. These tests showed that the linearity errors experienced were; different for ranges, line pressures and gases; but very much the same as long as the range, gas and line pressure were the same. Figure 3 shows the change in Cg for four LFEs of the same range, gas and at the same line pressure.

Considering the above there are two assumptions that were made. One is that the uncertainty due to changes in line pressure was the lowest when the LFE was used at the line pressure where the Cg was finally adjusted. The other is that the consistency of the linearity under similar conditions between LFEs suggested that the Cg model had detectable systematic imperfections that could conceivably be corrected.

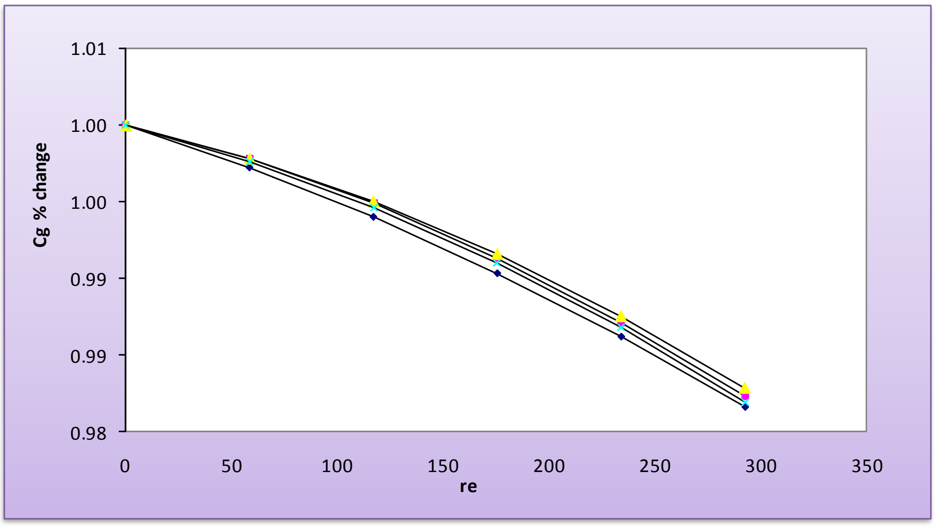

Figure 3. Change in Cg with Re for four LFEs of the same range, gas and pressure

An attempt was made in the '90s to create a fundamental model of Cg that would improve the linearity of the LFEs. This was unsuccessful; however for the molbox1+ LFEs it was determined that instead of improving the Cg model, it could be left alone and new set of coefficients based on Re and gas density could be used to specifically correct the linearity errors experienced by the Cg model. The original Cg modelization test was replaced with a multiple pressure and flow characterization test that adjusted the Cg model and also added linearization coefficients. The results are lower uncertainties due to linearity and also lower uncertainties due to changes in gas density with line pressure. In addition, the uncertainty due to line pressure was no longer the lowest at the final verification line pressure and is considered the same throughout the specified line pressure range for the calibration option chosen. Figure 4 is an example of a comparison of a characterized LFE and a non-characterized LFE of the same range. The deviations shown are from as left measurements compared to a reference. Note that the as left deviations would not be used as an uncertainty from linearity, but the residuals errors of fitting the same data.

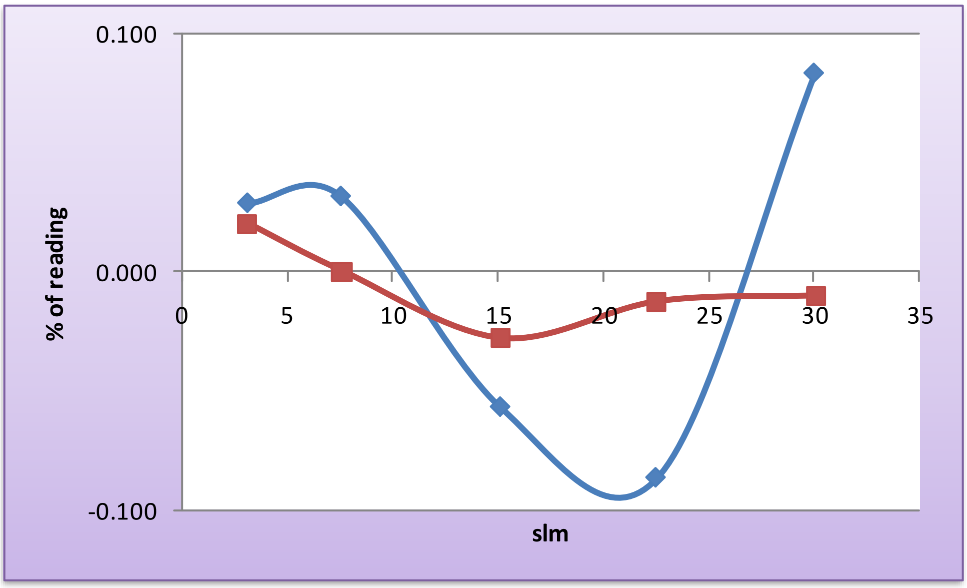

Figure 4. Comparison of characterized (red) and non-characterized (blue) LFE

For the sonic nozzles the coefficient that maintains flow traceability is the discharge coefficient (C) in table 2 equation 2. C is not a function of pressure and the model is not necessarily inherently non-linear as with LFEs. But C is a function of the inverse square root of Reynolds number and the characterization is used to straighten any non-linearities that can be present in the lower flow ranges of the sonic nozzles.

3.3 Pressure Transducers

The pressure transducers in the molbox1 are the same pressure transducers used in Fluke-DHI transfer standard pressure products pre-2002. For molbox1+ it was decided to use Q-RPTs, which are characterized quartz resonating transducers. Q-RPTs have a percent of reading uncertainty whereas the molbox1 pressure transducers were a percent of full scale.

The most significant benefit realized using the characterized transducers is with the sonic nozzles, where absolute pressure has a direct effect on flow throughout its range. For an LFE the influence on absolute pressure is close to constant at a specific line pressure (see Table 2).

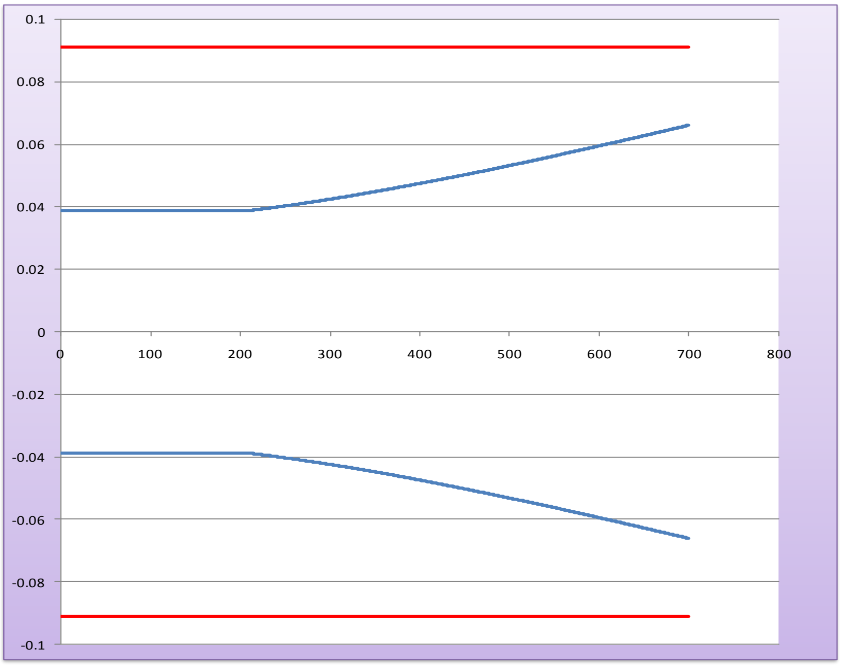

Figure 5. Comparison of absolute pressure specifications of a molbox1 (red) and a molbox1+ (blue). Y and X axis are in kPa.

As can be seen in Figure 5 the absolute uncertainty decreases as flow decreases for a sonic nozzle when used with a molbox1+. Note that the uncertainty in this chart is using parallel mode uncertainty where the absolute pressure uncertainty is less because it is using two absolute transducers to measure one absolute pressure. Some of the uncertainties associated with the pressure measurement are considered uncorrelated and are reduced by a factor of the square root of 2. The same relationship exists with the two existing ranges, 700 kPa and 350 kPa. For the molbox1 the product uncertainty for parallel mode is ±0.013% of FS, and for a molbox1+ is ±[0.008% of reading or 0.0024% of span, whichever is greater) + 0.0036% of span]. For the molbox1+ a range of 2 MPa was added as an option to be used with sonic nozzles exclusively. In this case there is always only one transducer measuring absolute pressure so parallel mode does not apply and the product uncertainty is ±[0.01% of reading or 0.003% of span, whichever is greater) + 0.005% of span]. The 0.005% of span part of the specification can be significantly reduced using an AutoZero function, which is a one-point correction at atmospheric pressure using a barometer.

The addition of the option of the 2 MPa absolute transducer in the molbox1+ is significant in the sense that it provides extended useable range of the sonic nozzles without the use of a vacuum pump downstream of the nozzle. A version of this system is currently in use by the National Association of Proficiency Testing (USA). Designed with two sonic nozzles the artifact provides possible comparisons from 10 to 1000 slm.

For an LFE the uncertainty in absolute pressure decreases as line pressure decreases. Some of the same benefit is realized when measuring differential pressure on an LFE. The improvement is mostly realized with better linearity for differential pressure.

3.4 Filtration

For the LFEs, one of the most significant causes of change in output after calibration is contamination that effectively changes Cg. This influence tends to be more significant for lower ranges because the gap (Cg) is smaller and contamination from the same particle size has a larger relative affect.

In general there is always a significant amount of focus on the use of filtration with the molbox1 systems. However, since lower uncertainties were going to be realized with the molbox1+, it was decided to force the issue and design filters in the upstream connection of the LFEs. Section 5 of this paper discusses the benefits of this added feature in more detail.

4. Improvement in Uncertainty in Gas Flow

Tables 3 and 4 show the product uncertainty budget for the molbox1+ LFEs and sonic nozzles [4]. The reductions in uncertainty are primarily from:

- Absolute Pressure
- Differential Pressure (LFE only)
- Pressure Model
- Linearity
- Reference Uncertainty

Only part of the complete uncertainty budget is shown in Tables 3 and 4 to conserve space here. Shown are the premium class of LFE and premium class with AutoZero on for the sonic nozzles. The product uncertainty for the premium class is ±0.125% of reading for sonic nozzles and ±0.125% of reading or 0.0125% of FS, whichever is greater for LFEs. Note that the product uncertainty analysis for sonic nozzles applies only from 10% to 100% of range and LFEs start from zero flow.

Table 3. Example (part of) Product Uncertainty Budget for molbox1+ LFEs.

molbox1+ molbloc-L		**molbox1+ Premium molbloc-L**		
Variable or Parameter	**Type Unc**	**molbox-1 A350k**	**molbox-1 A700k**	**molbox-1 A700k Downstream**
(relative unc's)		% of reading	% of reading	% of reading
absolute pressure	L1	0.010	0.020	0.020
differential pressure	L2	0.010	0.010	0.010
pressure model	L3	0.025	0.025	0.025
molbox resistance	L4	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005
molbloc-L linearity	L6	0.020	0.020	0.020
ref uncertainty	L7	0.040	0.040	0.040
molbloc-L stability	L8	0.018	0.018	0.018
Cg determination	L9	0.015	0.015	0.015
COMBINED		0.060% of rdg or 0.0042 %FS	0.063% of rdg or 0.0084 %FS	0.063% of rdg or 0.0047 %FS
COMBINED & EXPANDED FOR (K=2)		0.121% of rdg or 0.008 %FS	0.126% of rdg or 0.0168 %FS	0.126% of rdg or 0.009 %FS
(absolute Unc's)	-----	Pa / %FS	Pa / %FS	Pa / %FS
Differential Pressure	L2	2.1	4.2	4.2
Nom FS DP = 50 kPa	-----	0.0042%	0.0084%	0.0047%

Table 4. Example (part of) Product Uncertainty Budget for molbox1+ sonic nozzles.

molbox1+ Sonic Premium		With use of AutoZero	
Variable or Parameter	**Type Unc**	**molbox1+ A350k**	**molbox1+ A700k**
(relative unc's)		% of reading	% of reading
molbox resistance	S2	0.004	0.004
throat area	S3	0.002	0.002
molbloc-S linearity	S4	0.015	0.015
reference flow	S5	0.050	0.050
molbloc-S stability	S6	0.006	0.006
discharge coefficient	S7	0.013	0.013
Absolute Pressure	S1	0.005	0.005
COMBINED		0.054% of rdg + 0.002%FS	0.054% of rdg + 0.002%FS
COMBINED & EXPANDED FOR (K=2)		0.109% of rdg + 0.003%FS	0.109% of rdg + 0.003%FS
(absolute Unc's)	----------	% Span	% Span
Absolute Pressure	S1	0.0016	0.0016
Pressure Stability	S1	0.0000	0.0000

5. Improvements in Reliability

The realization of lower uncertainties was very important to this product improvement. However the improvement of reliability is just as important. Sonic nozzles already have excellent reliability which is difficult to improve on but there are a number of improvements that should improve the reliability of the LFEs even with the lower uncertainties.

Filtration designed into the upstream fitting of the LFE should be the most significant reason for improvement of reliability. Since the release of the molbox1+ is relatively new it is not possible to measure the improvement of reliability for LFEs. But evidence shows that almost all (approximately 70%) out of tolerances observed on molbox1 LFEs are due to contamination. This can be true even when a filter is used upstream of the LFE. The reason for this is that if a filter is connected in the flow path upstream of the LFE and the LFEs connections or other fittings between the filter and LFE are disconnected and reconnected at times, there may be particles generated from the LFE upstream male (or female) threads that collect and can make their way into the flow path downstream of the filter. This is especially true if the threads are damaged or deformed as is shown in Figure 6. The filter embedded in the upstream fitting of the new LFE design, shown in Figure 7, protects against contamination entering the LFE.

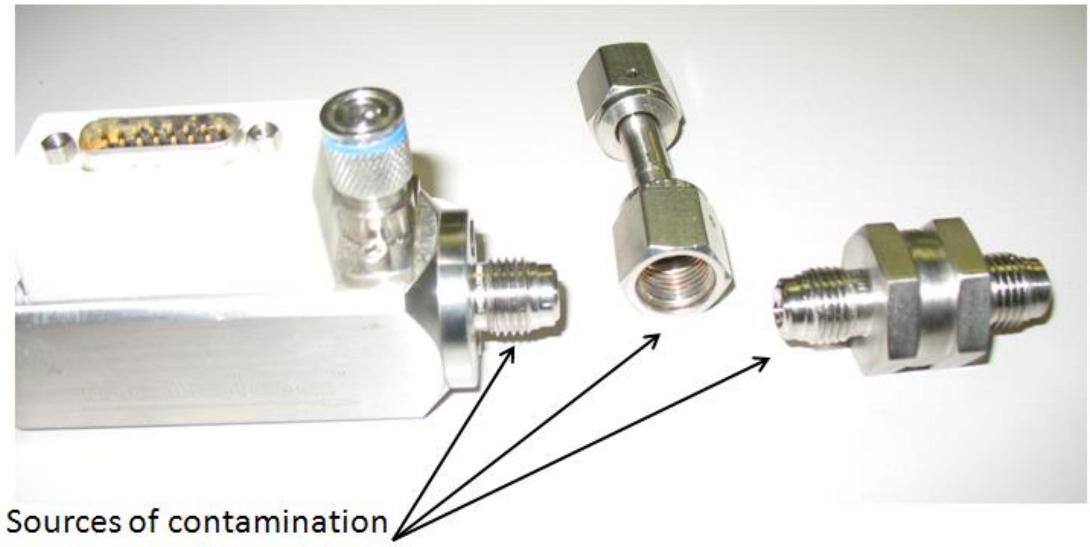

Figure 6. Sources of contamination from deformed or damaged threads.

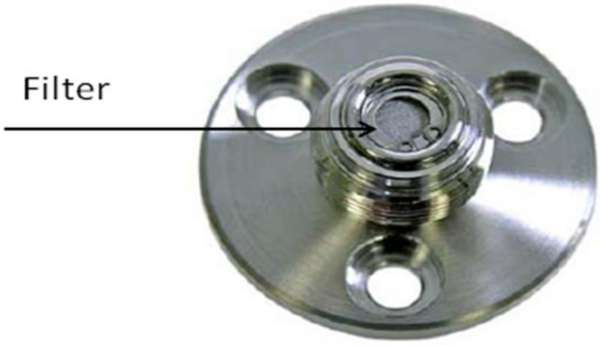

Figure 7. Picture of embedded filter in the upstream end cap of a molbox1+ LFE.

Another reason to expect better reliability is because of better linearity. If an LFE drifts over time there is a greater chance that a non-linear LFE such as in Figure 4 will force part of the range out of tolerance. For molbox1+ there is an uncertainty class called standard class that is ±0.2% of reading or 0.02% full scale whichever is greater. For LFEs, this class has the same uncertainty and characterization for linearity that the premium class has. But the uncertainty is larger due to a slightly larger reference uncertainty and the uncertainty used for stability. This should significantly reduce out of tolerances in the field.

6. Conclusion

Realizing lower uncertainties due to improvements made over eight years to the gas flow calibration chains was a significant accomplishment. But this means very little if the instruments being supported do not benefit from the improvements. Also, the lower uncertainties on the instruments being calibrated are not that useful unless they are reliable.

Not all of the improvements were mentioned in this paper due to the fact that they were more in the category of features in lieu of uncertainty and reliability. However it is worth mentioning that there was a significant effort to simplify the operation of these flow meters, reduce leaks and offer multiple types of calibrations for one or more gases.

It is hopeful that the lower uncertainty and the proposed better reliability of the LFEs and sonic nozzles will be useful to the gas flow measurement community. The uncertainty is there and validated, the only question remaining is whether the reliability is improved as suspected.

9. References

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