UNCERTAINTY ANALYSIS FOR FLOW MEASURED BY molbloc-L® AND molbloc-S® MASS FLOW TRANSFER STANDARDS

Michael Bair

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FOREWARD

Calculating and reporting uncertainty in measurement according to the "Guide To The Expression Of Uncertainty In Measurement" (GUM) [1] has become a standard requirement for calibrations. For users and potential users of measuring instruments manufactured by **DHI**, it is essential to understand all influences that may significantly contribute uncertainty in the measurements made with those instruments. This information is not only important for the customer to create uncertainty budgets for their own application, but also for **DHI** to develop and publish a realistic typical measurement uncertainty specification that can be easily interpreted and depended upon.

This technical note describes the development of this type of uncertainty analysis for two types of mass flow transfer standard products produced by **DHI**. These are molbloc-L laminar flow elements (LFE) and molbloc-S critical flow nozzles (CFN). The expanded uncertainties from this analysis become Typical Measurement Uncertainties In Flow and are used as product specifications. The user has the option of adopting the Typical Measurement Uncertainty In Flow for their instrument by assuming the environmental conditions and influences of ancillary equipment do not exceed limits defined in the uncertainty analysis, or they can reduce or expand the uncertainty to reflect different limits under which the instruments might be used.

INTRODUCTION

The first step in this uncertainty analysis is to define the calculation method for measuring flow. Since there are two technologies this is done twice. The next step in the uncertainty analysis is to set limits for the environmental conditions of use, system requirements and for the measurement mode that is used. Since the products are intended to be used as transfer standards, the limits are based on typical laboratory conditions. System requirements include the procedural steps required to ensure the instrument is working within acceptable limits. Measurement modes take into account the type of measurements being made and the ancillary equipment being used.

Once the method and limits are defined, all known and relevant uncertainties are described in a section dedicated to each influence. Each section describes the uncertainty and type of distribution for each influence in the units of measure of that parameter, and if required, at what level of confidence. From this information the uncertainty is expressed as one standard uncertainty. The sensitivity for that parameter is presented and multiplied by the standard uncertainty to develop uncertainties in terms of flow.

Once all uncertainties are described, any correlations between influences are considered. Based on this information the uncertainties can then be combined and expanded to a coverage factor of 2 or using effective degrees of freedom to calculate a specific confidence level.

The uncertainties for each parameter are presented in tables that are shown at the end of this document. The tables provide options for use in different modes or and in some cases different ranges. A combined and expanded uncertainty is provided for each in the form of an equation for each measurement mode, i.e. what a component relative to the measured flow plus a constant component. Then, as a product specification, a conservative relative uncertainty is chosen to cover all modes and gases.

CALCULATION OF FLOW

The focus for this paper is transfer standards for the measurement of gas flow. They are molbloc-L laminar flow elements and molbloc-S critical flow nozzles.

molbloc-L - Laminar Flow Elements

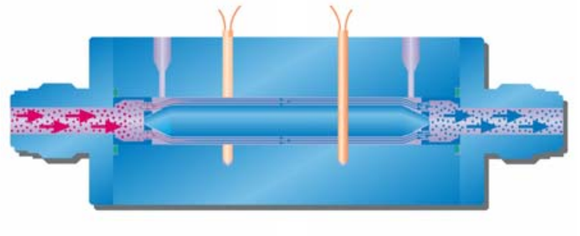

Figure 1 - molbloc-L - LFE

The LFE's design makes use of Poiseuillle's Law and measure laminar flow through an annular gap based on the following equation [2]:

$$qm = \frac{P \cdot \left(P_1 - P_2\right) \cdot \rho_N \cdot T_N \cdot Z_N}{T \cdot Z_{(P,T)} \cdot \eta_{(P,T)} \cdot P_N} \cdot C_G$$

where:

q_m = Mass flow [kg s^{-1}]

P_1 = Upstream absolute pressure $[Pa]$

P_2 = Downstream absolute pressure $[Pa]$

P = $\frac{(P_1 + P_2)}{2}$ $[Pa]$

T = Absolute temperature of gas $[K]$

T_N = Standard temperature, 273.15 K [K]
ρ_N = Standard gas density [kg•m^{-3}]
$\eta_{(P,T)}$ = Dynamic gas viscosity under P, T conditions [Pa•s]
P_N = Standard pressure, 101325 Pa [Pa]
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 molbloc-L the flow is proportional to differential pressure, (P_1 – P_2), created across the laminar flow gap. The relationship of mass flow and differential pressure changes as absolute pressure changes. Through out this paper the molbloc-L LFEs are referred by a model designation, such as 1E1 or 3E4, etc. These designations are necessary to distinguish between uncertainties applicable to specific models or group of models.

molbloc-S - Critical Flow Nozzles

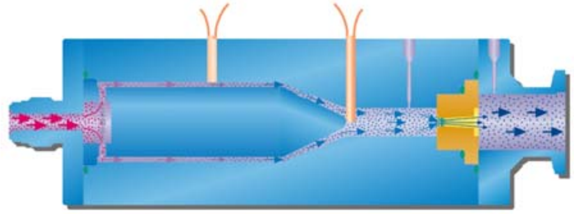

Figure 2 - molbloc-S CFN

Critical flow nozzles, also known as critical flow venturies, measure flow using a geometrically specified flow path where the flow rate is the maximum based on the upstream conditions of the gas [3]. As long as the ratio of the downstream pressure to upstream pressure is low enough, then the flow is "choked", i.e. the speed of the gas is limited to approximate local sonic velocity. Once this condition is met mass flow can be calculated following the equation:

$$qm = \frac{A \cdot C \cdot C_* \cdot P_0}{\sqrt{\left(R/M\right) \cdot T_0}}$$

where:

qm = Mass flow [kg s^{-1}]
A = Nozzle throat area [m^2]
C = Discharge coefficient [-]
C_* = Critical flow function [-]
P_O = Stagnation pressure [Pa]
R = Ideal gas constant [j • kg^{-1} • mole^{-1} • k^{-1}]
M = Molecular mass [kg • mole^{-1}]
T_O = Stagnation temperature [K]

For a molbloc-S, flow is increased or decreased by changing the upstream pressure supplied to the nozzle using either a variable regulator or a variable restriction.

Limits and Measurement Modes

In order to perform a predictive uncertainty analysis for a population of instruments, limits and specific requirements of use must be defined. These limits are applicable when influences are dependent on the environmental conditions, system configuration or measurement mode.

Environmental Limits

There is only one environmental limit that is relevant to this uncertainty analysis. This is:

Ambient temperature: 15 to 25 °C and less than 0.2 °C per minute change

The change in ambient temperature will have an influence on the stability of the flow at the time of measurement. The molbloc-L and molbloc-S design is such that the flowing gas temperature is conditioned and is not significantly affected by fluctuating ambient temperatures. However, instabilities in flow can be experienced from ambient temperature fluctuations affecting the interconnecting tubing upstream or downstream from a molbloc element. This influence is more prevalent at lower flows.

System Requirements

This uncertainty analysis is specific to molbloc-L or molbloc-S when used with molbox1™ or molbox RFM™ support units to provide pressure measurement and measurement of the resistance of the molbloc platinum resistance thermometers. However it is possible to use this uncertainty analysis model as a guide for technologies that are similar to the LFEs or CFNs for which this analysis is written.

In this uncertainty analysis, it is assumed that for molbloc-L, the absolute pressure transducers are tared at either the upstream pressure of an upstream calibrated molbloc or the downstream pressure of a downstream calibrated molbloc. This should be performed at sufficient intervals to ensure the change in tare is no more than what is indicated in the section on uncertainty in differential pressure for that molbox.

Note: Though not a requirement for molbloc-L or molbloc-S to meet specifications, benefit can be realized (lower uncertainties) by zeroing the molbox1 or RFM absolute transducers. This can be done by comparison with a high accuracy barometer that has uncertainty equal to or better than ± 0.01 % of reading.

For both types of molblocs it is assumed in this analysis that leaks are not present. With some gases it may not be possible to completely eliminate all leaks (as may be the case with helium). If this is the case then the magnitude of the leak should be measured by isolating the system with static pressure and measuring the drop in pressure. The additional uncertainty in flow can be calculated by the difference in density from the time duration from start to finish in the pressure check. The change in density multiplied by the isolated volume in the system and divided by the duration of the test will calculate flow error in kg/s. Experience has demonstrated that the change in pressure may be affected by the cyclical changes in gas temperature due to changes in ambient temperature. When this occurs longer periods of pressure measurements should be observed. Also, pressures can be averaged during the pressure leak check to ensure the changes are not from temperature changes.

Gas Media Requirements

This uncertainty analysis assumes the gas being flowed can be selected on the molbox1 or RFM and the purity of the gas is no worse than 99.99 %. However, the added uncertainty when gases that are less pure than 99.99 % can be evaluated. Even if a gas is 99 % pure, i.e. 1 % of impurities, as long as those impurities are known or can be estimated, the error on the flow measurement can be estimated. This may be accomplished by determining the density (for molbloc-L and molbloc-S) and dynamic viscosity (for molbloc-L) of the gas and its impurities and comparing these results to the pure gas. As an example, if the test gas has a density of 1 kg/m^3 at a specific temperature and pressure and the impurity has a density of 0.5 kg/m^3, then the error is approximately 0.5 %, not 1 %. The same is true with dynamic viscosity however it is much easier to predict the errors in density than it is to predict errors in dynamic viscosity due to contamination.

Calibrations Using Air

Of special consideration in the purity of gas is when air is used as a test gas. The calculations used in molbox to determine density and viscosity assumes that air is composed as defined in Table 1.

Component	% of Total
Nitrogen	78.12
Oxygen	20.95
Argon	0.93
CO2 and impurities	< 500 ppm

Table 1 - Composition of normal air

The composition shown in Table 1 is sometimes called normal air and represents a mixture that closely resembles the ratios of gases found naturally in our atmosphere (ambient air) after moisture is removed and other contaminates have been filtered out or determined to be insignificant.

Without the facilities to purify normal air it may be necessary to use air that is mixed by a gas vendor. Most of the time vendor mixed bottled Air has a composition close to that of Table 1 but with significant differences. For example, if UZAM air (ultra zero ambient monitoring) from a gas vendor is used, the gas composition may be as shown in Table 2:

Component	% of Total
Nitrogen	79.10
Oxygen	20.90
Argon	0.00
CO2 and impurities	< 500 ppm

Table 2 - Possible composition of vendor mixed UZAM air

The density of gas mixtures can be calculated as:

$$[(\rho_{(1)} \text{ x } \%gas_{(1)}) + \ldots (\rho_{(x)} \text{ x } \%gas_{(x)})]$$

Note: The same calculation can be performed for the molecular weight of the gas instead of density.

For the composition shown in Table 2 (UZAM air) the calculation of density is:

$$[(1.2505 \text{ x } 0.791) + (1.4289 \text{ x } 0.209)]$$
$$= 1.2877 \text{ kg/m}^3$$

The density at standard conditions for air with the composition from Table 1 (normal air) is 1.2928 kg/m^3. The difference in density between normal air and UZAM air is approximately 0.4%. If a molbloc-S is calibrated in normal air and then used with UZAM air, there would be a systematic error of -0.4%. However, molbloc-L is affected by both the difference in density and the difference in dynamic viscosity. Unlike density, the change in dynamic viscosity would have to be experimentally determined. For UZAM air described above it was experimentally determined that when using UZAM air on a molbloc-L calibrated with normal air the error would be - 0.3 %.

Users of molblocs should be careful when using bottled air from a supplier. Even if the expected composition is well known it is probable that there is an uncertainty as high as 1 % in the percent content of each component. This could introduce systematic variations in flow measurements as high as 0.1 %. However normal air has a composition guaranteed to be within a few hundreds of a percent.

At the release of this technical note **DHI** supports calibrations for both normal and UZAM air described above. Be sure to contact your **DHI** customer service representative to determine which type of air your molbloc has been calibrated.

Measurement Modes

Both molbloc-L and molbloc-S can be calibrated for and used in different pressure dependent modes. For molbloc-L these are:

- Full modelization, upstream, low pressure: The molbloc has been characterized over an upstream pressure range of 200 to 325 kPaa (29 to 47 psia). Full scale flow is based on a nominal differential pressure of 50 kPa (7.25 psi) at an upstream verification pressure of 270 kPa.

- Full modelization, upstream, high pressure: The molbloc has been characterized over an upstream pressure range of 325 to 525 kPa (47 to 76 psia). Full scale flow is based on a nominal differential pressure of 50 kPa (7.25 psi) at an upstream verification pressure of 270 kPa.
- Full modelization, downstream: The molbloc has been characterized with downstream pressure equal to an atmospheric pressure between 90 and 105 kPaa (13.1 to 15.2 psia). Full scale flow is based on a nominal differential pressure of 90 kPa (13 psi) at a downstream verification pressure of 97 kPa.
- Single pressure, upstream: The molbloc has been characterized at a single upstream pressure, ± 10 kPa (1.5 psi), located between 250 and 525 kPaa (36 and 76 psia).

For some of the uncertainties in this analysis there are separate uncertainties for upstream, downstream and single pressure modes of use.

molbloc-S has two separate modes of use:

- Standard Pressure: Characterized from 50 to 500 kPa (7.25 to 72.5 psia) stagnation pressure.
- Low Pressure: Characterized from 20 to 200 kPa (2.9 to 29 psia) stagnation pressure.

For molbloc-S the mode of use does not change the uncertainties calculated. However it should be mentioned that the uncertainties are only valid if the back pressure ratio (BPR), i.e. the ratio of the pressure downstream of the nozzle to the stagnation pressure, is within limits to ensure there is critical flow.

A significant difference between the molbloc-L and the molbloc-S uncertainties is that the molbloc-L specifications are valid to zero flow, thus the reason for molbloc-L needing a two-part typical flow measurement uncertainty. The molbloc-S is only valid in the absolute pressure range it was calibrated and only has a relative part typical flow measurement uncertainty.

UNCERTAINTIES OF MOLBLOC-L

It is important to note for this uncertainty analysis that, even though molbloc-L and molbloc-S follow defined physical principles as described in section 2 and their referenced documents, these instruments are considered transfer standards and are characterized by primary methods either gravimetrically or by comparison with flow standards maintained by national metrology institutes. Because of this, many of the fundamental uncertainties that would have to be included for values of density, dynamic viscosity, geometric constant, critical flow coefficients and throat diameter are either eliminated or are reduced to only the uncertainty contributed from those variables that have changed from conditions that existed at the time the molbloc was calibrated. Therefore, the molbloc-L uncertainties are absolute pressure, differential pressure, pressure modelization, temperature, linearity, reference flow, stability and Cg determination.

L1 - Absolute Pressure

The absolute pressure needed to calculate mass flow for a molbloc-L is measured by two absolute pressure transducers. For a molbox1 these pressure transducers are of a quartz resonating type that contribute low uncertainty and excellent repeatability to provide the lowest uncertainty possible in flow. molbox1 is available in two different pressure ranges, one with transducers having a full scale of 700 kPa and one with 350 kPa. molbox RFM uses 700 kPa absolute transducers that are more compact, higher uncertainty and lower cost, but perform the same function as those in molbox1. Table 3 lists the specifications for absolute pressure measurement by the transducers for each type of molbox available at one standard uncertainty. The combined value in pressure is used to determine the contribution of uncertainty in percent of reading relative to the average absolute pressure for each applicable mode.

molbox Type	**A700k**	**A350k**	**RFM or RFM-M**
Specification	[kPa]	[kPa]	[kPa]
@ 1 std Unc			
*Precision	0.015	0.0075	0.087
Stability (1 yr)	0.030	0.015	0.175
Combined (RSS)	**0.033**	**0.017**	**0.195**
Resulting 1 Std Unc Values for Flow in % rdg			
Mode	[% rdg]	[% rdg]	[% rdg]
High pressure, full mod or single P, @ 500 kPa	0.007	N/A	0.039
Low pressure, full mod or single P, @ 250 kPa	0.013	0.007	0.072
Downstream, @ 140 kPa	0.023	0.012	0.139

* Linearity, repeatability and hysteresis combined

Table 3 - molbox absolute pressure uncertainties

Because these are calibrated pressure transducers, the distribution is considered to be normal with a sensitivity equal to 1 % rdg / % rdg.

Type of uncertainty:	relative type B
Sensitivity:	1 % of rdg / % of rdg
Distribution:	considered normal
Standard uncertainty:	see Table 3

L2 - Differential Pressure

For an LFE, the most significant parameter to measure is the differential pressure. The molbox1 and the RFMs use the same absolute pressure transducers that measure absolute pressure (reference L1 uncertainty) to measure differential pressure. In addition an RFM is available with a low pressure differential transducer as an option and called RFM-M (microrange). This transducer measures differential pressure up to 13 kPa

(1.9 psi), above which the absolute transducers take over. The absolute transducers have the capability to measure differential pressure with sufficiently low uncertainty as long as they are tared one against the other. The taring procedure subjects both transducers to the same absolute pressure (zero differential) by opening or closing specific valves. The pressure can be either the current molbloc-L upstream or downstream pressure. At that pressure, the difference in the indication of the two absolute transducers is recorded and 1/2 the difference used to correct each transducer, in effect nulling them at a given line pressure. This uncertainty assumes typical use in which the molbox pressure transducers are always tared before a test is begun.

When using two absolute transducers to measure differential pressure, the errors contributing to the uncertainty on differential pressure are linearity, hysteresis and repeatability of each transducer (precision) and the stability of the tare between the two transducers. The precision of each transducer is considered independent when not including the uncertainty of the slope of the reference used to calibrate the transducers. When considering the uncertainty due to linearity the closer the differential pressure range is to the calibrated absolute pressure range of the molbox (250 or 600 kPa) the lower the uncertainty in differential pressure contributed by linearity. Therefore, the linearity uncertainty for differential pressure is significantly larger than the linearity uncertainty for the absolute pressure (L1).

The precision of the transducers and the stability of the tare are dependent upon the type and range of the molbox used and the full scale differential pressure. Table 4 lists the uncertainties contributed by each molbox1 and Table 5 lists the uncertainties contributed by RFM and RFM-M. These uncertainties are broken down into two types of uncertainties: relative and absolute. Absolute uncertainties are originally given in pressure units [Pa] to show their significance when compared to the full scale differential pressure range. The nominal full scale pressure range for both upstream and single pressure modes is 50 kPa and is 90 kPa for downstream mode. Note that the uncertainties in pressure remain constant for each molbox but have less significance for the larger differential pressure in downstream mode.

The uncertainties that are relative, i.e. those that are listed as a % of reading, are the same no matter the range of differential pressure. The relative effect of the absolute uncertainties depends on what the differential pressure is at the time of the flow measurement. At the end of this document when uncertainties are combined, the final uncertainty in flow for each type of molbox is given as a percent of reading and as a percent of full scale based on the nominal full scale verification differential pressure for that measurement mode. Even though the combined and expanded uncertainty equations show these uncertainties as being added together, they are considered independent and should be quadratically combined.

Note: It is realized that the slope of the differential pressure measurement (part of the linearity uncertainty) is correlated to the slope of the absolute pressure measurement. The values of linearity for differential pressure are raised slightly to account for this correlation and the fact that a correlation coefficient is not used.

Mode	**Upstream**		**Downstream**	
Molbox Type	**A700k**	**A350k**	**A700k**	**A350k**
Specification	1 standard uncertainty [% rdg]			
Linearity up	0.010	0.0075	0.0075	0.005
Linearity down	0.010	0.0075	0.0075	0.005
Hysteresis up	0.005	0.005	0.005	0.005
Hysteresis down	0.005	0.005	0.005	0.005
Reference	0.003	0.003	0.003	0.003
Combined (RSS)	**0.016**	**0.013**	**0.013**	**0.010**
	1 standard uncertainty [Pa]			
Repeatability up*	1.8	1.25	1.8	1.25
Repeatability down*	1.8	1.25	1.8	1.25
Combined (RSS)	**2.54**	**1.77**	**2.54**	**1.77**

* Includes uncertainties attributed to taring

Table 4 - Differential pressure uncertainties for molbox1

Mode	**Upstream**		**Downstream**	
molbox Type	**RFM**	**RFM M**	**RFM**	**RFM M**
Specification	1 standard uncertainty [% rdg]			
Linearity up	0.05	0.05	0.03	0.03
Linearity down	0.05	0.05	0.03	0.03
Hysterisis up	0.01	0.01	0.01	0.01
Hysterisis own	0.01	0.01	0.01	0.01
Reference	0.01	0.01	0.01	0.01
Combined (RSS)	**0.073**	**0.073**	**0.046**	**0.046**
	1 standard uncertainty [Pa]			
Repeatability up*	7.5	N/A	7.5	N/A
Repeatability down*	7.5	0.3	7.5	0.3
Combined (RSS)	**10.6**	**0.3**	**10.6**	**0.3**

* Includes uncertainties attributed to taring. Not included for RFM-M upstream because specification is for microrange sensor.

Table 5 - Differential pressure uncertainties for RFM

Because differential pressure is determined from calibrated sensors, the standard uncertainties shown are considered to be normally distributed with a sensitivity of 1 % of rdg/ % of rdg or Pa/Pa.

Type of uncertainty:	relative and absolute combined
Sensitivity:	1 % of rdg / % of rdg or Pa / Pa
Distribution:	considered normal
Standard uncertainty:	see Tables 4 an 5

L3 - Pressure Modelization

molbloc-L LFEs are either characterized over a specific absolute pressure range (reference section 3 "Measurement Modes") or calibrated at a specific pressure. In either case this accounts for much of the uncertainty contributed by the lack of knowledge of the change in the properties of gases as pressure changes.

After a molbloc is characterized over a range of absolute pressure, it is checked for residual errors due to imperfections of the molbloc flow calculation model. The amount of residual error detected in this "pressure check" is dependent upon the range and gas of the test. As a limit, a change of no more than ± 0.1 % of reading can be accepted in the calibration.

For molbloc-Ls that are calibrated at a single upstream pressure, or for downstream calibrations, a range is given around the calibration pressure to account for instances when the calibration pressure cannot be repeated by the user of molbloc-L. For an ideal gas viscosity is not influenced by changes in pressure. However for real gases there is a change in viscosity with pressure and in some cases is not very well known. This uncertainty, because of the limited range, can approach ± 0.1 % of reading.

For all cases uncertainty due to pressure modelization is an error that is easily predicted based on how far from the calibration pressure the molbloc-L is when it is being used. If the user is able to keep the upstream pressure (or downstream pressure for molbloc-Ls calibrated downstream) at the calibration pressure shown in the calibration report then this uncertainty becomes insignificant. However for those that cannot meet this requirement the distribution may be considered to be normal with a sensitivity of 1 ppm/ppm and one standard uncertainty of 0.05 % of reading. This uncertainty assumes worse case deviation from the calibration pressure as defined in the pressure ranges in section 3.

Type of uncertainty:	relative
Sensitivity:	1 % of rdg / % of rdg
Distribution:	considered normal
Standard uncertainty:	0.05 % of reading

Gas Temperature

One of the most difficult parameters to measure in an LFE is the temperature of the gas that is flowing through the element. molbloc-L uses a patented technique to determine the temperature of the gas that reduces the contributing uncertainty in temperature.

There are some important considerations when defining uncertainty of the temperature of the gas. The first is that absolute errors of temperature measurement are eliminated at the temperature the molbloc was calibrated. This is true because the influence of temperature is relative and also the influence of Cg is relative. If the temperature measurement at the time of calibration was in error enough to cause a relative error of - 0.05 % of reading, then the Cg would be systematically modified to correct for this error. This is true for the temperature influence in the equation and also the change in compressibility and dynamic viscosity terms.

Considering the above there are two uncertainties that still have to be included. The first is the uncertainty contributed by the molbox1 or RFM that is used to measure the resistance of the platinum resistance thermometers in the molbloc. Because molbox and molblocs are interchangeable, an uncertainty that accounts for the variability of the resistance measurement system between molbox1s must be included.

The second uncertainty applies when the molbloc is being used at a temperature different from the temperature at the time of calibration. Because the molbloc PRTs use a normalized linear slope there is some growth of uncertainty as the temperature moves away from the temperature that was measured at the time of calibration.

L4 - molbox1 and RFM Resistance Measurement

The specification for molbox1 and RFM resistance measurements is ± 0.04 ohms at a coverage factor of 2 from 200 ohms to 230 ohms using a 6 wire PRT resistance measurement that performs the equivalent of two 4 wire PRT measurements. Since this is a calibrated resistance measurement circuit the uncertainty can be considered normal and one standard uncertainty is 0.02 ohms. The sensitivity of change in flow with change in resistance is 0.8 % of reading per ohm.

Type of uncertainty:	relative
Sensitivity:	0.8 % of rdg / ohm
Distribution:	considered normal
Standard uncertainty:	0.02 ohm

L5 - PRT Linearity

The PRTs in the molbloc body are calibrated and used as linear devices as the temperature range is very small. The uncertainty in temperature based on the non-linearity of the PRT in the range of 15 to 25 °C is ± 0.015 °C at K=2 and considering its normally distributed one standard uncertainty is 0.0075 ° using a sensitivity of 0.6 % of reading per °C.

Type of uncertainty:	relative
Sensitivity:	0.6 % of rdg / °C
Distribution:	considered normal
Standard uncertainty:	0.0075 °C

L6 - molbloc Linearity

One of the benefits of a molbloc-L LFE is that it is highly repeatable. Thanks to this, the linearity of a molbloc-L is a parameter that can be carefully examined. These LFEs are designed to measure flow based on the fundamental equations shown in section 2. Due to the model used, linearity of a molbloc-L depends on the range, downstream pressure and gas being flowed, but it is the same every time within the repeatability of the molbloc/molbox system being used. For instance, a 1E4 molbloc-L calibrated as an upstream, low pressure always exhibits the same linearity pattern.

Conforming to the concept of a product uncertainty specification a maximum value for linearity is used as the uncertainty in linearity. Three specifications are used for all molblocs and are shown in Table 6. This shows linearity at the 95 % confidence level and 1 standard uncertainty based on a normal distribution.

It is important to note that in the final uncertainty budget at the end of this document the uncertainty for linearity can be replaced with the actual linearity that is exhibited in the calibration report for a specific molbloc. One easy method is to use max-min of % of reading from the as left data and divide by 2 to obtain one standard uncertainty.

Linearity	U(lin)	1 Std Unc
Range	± [% rdg]	[% rdg]
All modes 1E1 through 1E4 & 3E4 upstream high pressure	0.1	0.05
3E4 upstream low pressure	0.2	0.1
All modes 1E5 & 3E4 downstream	0.25	0.125

Table 6 - Linearity uncertainty specifications

Type of uncertainty: relative
Sensitivity: 1 % of rdg / % of rdg
Distribution: considered normal
Standard uncertainty: see tables

L7 - Reference Uncertainty

molbloc-L LFEs are calibrated using a gravimetrically based calibration chain that is described in a separate publication [4].

Using the calibration chain, standards used to calibrate molbloc-L are never worse than ± 0.1 % of reading at 95 % confidence except for a 1E5 which is ± 0.15 % of reading. Assuming a normal distribution, this leads to a standard uncertainty for the molbloc-L reference of 0.05 % and 0.075 % of reading respectively.

Type of uncertainty: relative
Sensitivity: 1 % of rdg / % of rdg
Distribution: normal
Standard uncertainty: 0.05 or 0.075 % of rdg

L8 - molbloc-L Stability

The uncertainties contributed by the pressure and temperature measurements made with a molbox1 or RFM are based on specifications that include the stability of their measurements over 12 months. As long as these sensors are within the specifications at the time they are calibrated no additional uncertainty is required. If the recalibration of these sensors show that they are different from the specifications shown in this uncertainty analysis, either higher or lower, the uncertainties can be modified in the tables at the end of this analysis to better represent their performance. However this is different from and independent of the stability of the molbloc-L element by itself.

The geometrical flow path of a molbloc that defines (Cg) has a cubic relation to flow, or, has a sensitivity to flow of 3. Aside from trauma, such as contamination, over-pressurizing or shock, a change in Cg may come from stresses of normal use or the natural change of dimensions of the material defining Cg. Considering the pressure applied to a molbloc is limited to 525 kPa, and also considering the stability of the stainless steel used in its manufacture, the predicted change in geometrical space is ± 0.01 % of reading for one year. Stability may be described as having a rectangular distribution leading to a standard uncertainty of 0.006 % of reading.

Type of uncertainty: relative
Sensitivity: 3% of rdg / % of rdg
Distribution: rectangular
Standard uncertainty: 0.006% of reading

L9 - Cg determination

To a great extent the uncertainty in the determination of Cg is already represented in the reference flow, molbloc linearity and pressure modelization. However some uncertainty is contributed by the repeatability of the test used to determine Cg. For upstream calibrations the flow stations used at **DHI** to determine Cg are tested to ensure a worse case repeatability of ±0.05 % of reading using a coverage factor of 2 for 1E1 through 3E4 molbloc-Ls. Because this is experimentally determined, the distribution is considered normal and provides a standard uncertainty of 0.025 % of reading. For a 1E5 this is predicted to be ± 0.2 % of reading and a standard uncertainty of 0.1 % of reading.

For downstream calibrations a method is used that minimizes the uncertainty contributed by the repeatability of the test. It is a method of substitution and is considered to have a worse case repeatability of ± 0.02 % of reading with a standard uncertainty of 0.01 % of reading (1E1 through 3E4) and ± 0.1 % of reading with a standard uncertainty of 0.05 % of reading for 1E5.

Type of uncertainty: relative
Sensitivity: 1 % of rdg / % of rdg
Distribution: considered normal
Standard uncertainty (% of reading):
1E1 through 3E4 upstream: 0.025 %
1E1 through 3E4 downstream: 0.01 %
1E5 upstream: 0.1 %
1E5 downstream: 0.05 %

UNCERTAINTIES OF MOLBLOC-S

As was mentioned in the opening paragraph of section 4., even though the calculations of flow when using critical flow nozzle are based on fundamental concepts, these instruments are calibrated and used as transfer standards that are characterized by references. Therefore many of the fundamental uncertainties are eliminated or reduced to an influence that is only dependent upon the change of that parameter from the conditions that existed at the time of calibration. With this in mind the uncertainty contributions are limited to stagnation pressure, temperature, linearity, reference flow, stability and discharge coefficient.

Since the same molboxes are used with molbloc-S as are used with molbloc-L, the uncertainties contributed by the molbox are the same, however their sensitivity with flow is much different.

S1 - Stagnation Pressure (Absolute Pressure)

molbloc-S flow is proportional to the stagnation pressure as the gas enters the nozzle. The stagnation pressure is the pressure that would exist at the nozzle if the flow of the gas were brought to rest by an isentropic process [3]. The stagnation pressure is calculated from the static pressure that is measured in a tap in front of the nozzle. The pressure can be measured at the exit of the nozzle but only for the purpose of determining the back pressure ratio (BPR). When a molbox1 or RFM measures the upstream pressure of the molbloc-S it uses both transducers and averages them together. As was mentioned in L1 the precision and stability of these sensors are independent. The same uncertainties in L1 are applied to a full scale pressure of either 500 or 200 kPa.

molbox Type	**A700k or A350k**	**RFM or RFM-M**
Specification @ 1 std Unc	**[% of FS]**	**[% of FS]**
Precision *	0.003	0.015
Stability (1 yr)	0.005	0.020
Combined (RSS)	**0.006**	**0.025**

* Linearity, repeatability and hysteresis combined

Table 7 - molbox absolute pressure uncertainties in % of FS

Type of uncertainty: absolute (% of full scale)
Sensitivity: 1 % of FS / % of FS
Distribution: normal
Standard uncertainty: see Table 7

S2 - molbox1 and RFM Resistance Measurement

This uncertainty is identical to L4 with the exception that the sensitivity is four times less. This is because the relationship of flow with temperature is the square root of the temperature. The same standard uncertainty of 0.02 ohm applies with a sensitivity of 0.2 % of reading per ohm.

Type of uncertainty: relative
Sensitivity: 0.2 % of rdg/ohm
Distribution: normal
Standard uncertainty: 0.02

PRT Linearity

Referencing L5 this uncertainty is ± 0.015 °C between the temperature limits of 15 to 25 °C. Considering the sensitivity with temperature is 0.015 % per °C this uncertainty is considered insignificant.

S3 - Throat Area

The calculation of throat area is based on current pressure and temperature of the CFN due to elastic deformation and thermal expansion respectively. The change in throat area with pressure is considered insignificant. However the correction for temperature is large enough to predict a small type B component of uncertainty. A conservative apriori estimate of temperature correction may be ± 20 % of the correction made and one standard uncertainty of 11 %. The correction is 1.6 x 10-5 $°C^{-1}$ with a standard uncertainty of 1.7 x 10-6 $°C^{-1}$. Considering a limit of 15 to 25 °C and the fact the throat area is determined at 20 °C a maximum correction of 5 °C is used to determine this uncertainty. Sensitivity is 100% of reading per $°C^{-1}$ for thermal the thermal expansion coefficient or (0.0005% per °C).

Type of uncertainty: relative
Sensitivity: 0.0005 % of rdg / °C
Distribution: rectangular
Standard uncertainty: 5 °C

S4 - Linearity

molbloc-S linearity depends on the range, gas and mode used. As a limit of conformance in the calibration of a molbloc-S an estimate of ± 0.05 % may be used. Since this is determined by calibration for each molbloc it is considered to be a normal distribution and provides a standard uncertainty of 0.025 % of reading.

As is the case with molbloc-L linearity, it is also true with molbloc-S that the repeatability is more than sufficient to determine the uncertainty contributed by linearity of the molbloc by observing the as left results in the calibration report.

Type of uncertainty: relative
Sensitivity: 1 % of rdg / % of rdg
Distribution: normal
Standard uncertainty: 0.025% of reading

S5 - Reference Flow

Unlike molbloc-L, molbloc-S does not currently have a specific published document describing the system used to calibrate them and establish traceability to the fundamental units of mass and time. However a method similar to the molbloc-L calibration chain is used to maintain traceability for molbloc-S. One difference is that gravimetric measurements cannot be practically maintained at higher flows. A system to be described in a future publication links gravimetric traceability at lower molbloc-S flows to national metrology institutes at the highest flows. This system is successful based on the unprecedented repeatability of molbloc-S and the fact that it is an "extensive" measurand, i.e. has the ability to extend traceability from lower to higher flows by addition of flows measured by lower flow molblocs configured in parallel.

Currently the molbloc-S calibration chain maintains an uncertainty of ± 0.12 % of reading. A normal distribution gives one standard uncertainty of 0.06 % of reading.

Type of uncertainty: relative
Sensitivity: 1 % of rdg / % of rdg
Distribution: normal
Standard uncertainty: 0.06% of reading

S6 - Stability

As mentioned in stability of molbloc-L (L8), the stability of sensors to measure temperature and pressure are already considered in the uncertainty components contributed by the molboxes. What is not considered is the change of throat area due to the natural changes in materials. This can be estimated to be ± 0.01 % of throat area for a 12 month period. Applying a rectangular distribution for stability gives one standard uncertainty of 0.006 % of reading.

Type of uncertainty: relative
Sensitivity: 1 % of rdg / % of rdg
Distribution: rectangular
Standard uncertainty: 0.006% of reading

S7 - Discharge Coefficient

The discharge coefficient for a CFN is defined using the equation [3]:

$$C = a - b\,\mathrm{Re}^{-n}$$

where C is a dimensionless constant based on the determination of a and b in calibration and n is held constant at 0.5. Because a and b are determined in calibration the uncertainties in C are already considered in the reference uncertainty and molbloc linearity. However there is some uncertainty due the repeatability of the test that is used to determine C. This is minimal considering the excellent repeatability of molboc-S and is frequently verified in the **DHI** laboratory to be less than ± 0.025 % of reading. Because this uncertainty is verified it is considered to be a normal distribution with one standard uncertainty equal to 0.0125 % of reading.

Type of uncertainty: relative
Sensitivity: 1 % of rdg / % of rdg
Distribution: rectangular
Standard uncertainty: 0.0125 % of reading

S8 - Moist Air

When measuring flow using ambient air with a molbloc-S, molbox1 and RFM correct the mass flow for moisture content [5]. There is a slight additional uncertainty when this correction is used based on the uncertainty of temperature and pressure measured by the molbox, the uncertainty of the humidity entered in the molbox and the residuals of the calculated difference in mass flow.

The sensitivity of this uncertainty with respect to pressure is 0.0024 % of reading per kPa. Considering the worst case standard uncertainty in pressure is 0.195 kPa (see uncertainty L1) this gives a worst case standard uncertainty in flow of 0.00045 % and may be considered insignificant.

In the case of temperature the sensitivity is 0.016 % of reading per K. Because there is an uncertainty in the absolute temperature that the molbloc PRTs are measuring, this uncertainty needs to be included. molbloc PRTs measure temperature to ± 0.2 K worse case over the life of the molbloc and within the specified temperature limits of 15 to 25 °C. Considering this uncertainty to be worse case, a standard uncertainty of 0.1 K can be used.

For the humidity value entered in the molbox to make the correction there is a sensitivity of 0.005 % per %RH. Most ambient monitoring systems can measure humidity to within ± 10 % with one standard uncertainty of 5 %.

Based on calculations made with this method residuals can be predicted to be less than ± 0.01 % with one standard uncertainty of 0.005 %. Following Table 8 below an additional relative uncertainty can be combined with the tables at the end of the technical note.

Measurement	Sensitivity	1 Std Unc	1 Std Unc
Temperature	0.016 % / K	0.1 K	0.0016
Humidity	0.005 % / % RH	5 % RH	0.025
Residuals	1 % rdg / % rdg	0.005 % rdg	0.005
Combined standard uncertainty in % of rdg			0.026

Table 8 - Uncertainties contributed by air humidity correction on molbloc-S

Note: This correction and uncertainty only apply to molbloc-S, not molbloc-L. This is due to the unknown changes to dynamic viscosity that moist air contributes.

TYPE A UNCERTAINTY

The type A contribution of uncertainty for this predictive uncertainty analysis is not considered as it depends upon the flow hardware that will be used and the actual environmental conditions that will be present when the molbloc is used to measure flow. molbox1s and RFMs use automated averaging functions to help eliminate the uncertainties contributed from unstable flow.

In general, experience with molbloc-L and molbloc-S has shown that averaging data over an appropriate period of time provides type A uncertainty that is insignificant relative to the total uncertainty in flow. To determine type A contribution a number of averaged values can be determined at one flow. The contribution would simply be the standard deviation of the means. Type A also may be calculated for one averaged flow by calculating the standard deviation of the mean where one standard deviation is divided by the square root of the number of data points used to determine the mean. However a significant amount of data points should be taken to ensure sufficient degrees of freedom.

CONCLUSION

In the uncertainty tables provided at the end of this document, each molbloc measurement mode and range is considered for a wide range of flow measurements. These are considered to be worse case and will be improved upon as reference uncertainties are lowered, linearity is improved, and the ancillary hardware is improved. Many of the combinations of range and type of gas may already have much better linearity than what is given as an uncertainty limit. This by itself would significantly reduce the uncertainty for a specific molbloc. Also in the final expanded uncertainty listed, even though the percent of reading indicates that it is added to the uncertainty in percent full scale, these uncertainties are considered independent and should be quadratically combined for the combined and expanded uncertainty in a specific flow.

The combined and expanded uncertainty for molbloc-L apply to the flow range of the molbloc-L down to zero flow. However it will be noted that the absolute uncertainty computed based on the pressure component uncertainty becomes larger as flow is smaller. For molbloc-S the combined and expanded uncertainty only applies from 10 to 100 % of the full scale range for the applicable mode.

With a document such as this one provided by **DHI**, the user of the instrument is given the resources to calculate uncertainty based on the actual conditions and mode of use. This type of document also gives meaning to the specifications of the individual sources of error or uncertainties as the sensors are calibrated. Hence the uncertainties are not just predictions but product specifications to which **DHI** may commit. This is a significant step beyond the common practice of claiming performance characteristics, including measurement uncertainty in a brochure and having no responsibility for the uncertainties calculated according to the GUM [1].

Note: This revision is only to correct a few typographical errors that found its way into the original document. There are no major changes for any of the specifications of the molbloc / molbox mass flow products.

REFERENCES

[1] ANSI/NCSL Z540-2-1997 "US Guide to Expression of Uncertainty in Measurement (GUM)".

[2] Pierre Delajoud and Martin Girard, "A High Accuracy, Portable Calibration Standard For Low Mass Flow", September 1994.

[3] ASME/ANSI MFC-7M-1987 "Measurement of Gas Flow by Means of Critical Flow Venturi Nozzles".

[4] Michael Bair, "The Dissemination Of Gravimetric Gas Flow Measurements Through an LFE Calibration Chain", August 1999.

[5] Charles Britton, Richard Caron and Thomas Kegel, "The Critical Flow Function, C*, for Humid Air", 1198 ASME Fluids Engineering Division Summer Meeting FEDSM'98, June 1998.

UNCERTAINTY TABLES

molbloc-L (LFE) Full modelization, low pressure or single pressure 1E1 through 1E4

Typical Flow Measurement Uncertainty:
± 0.2 % of reading or 0.02 % full scale whichever is greater with molbox1
± 0.5 % of reading or 0.05 % full scale whichever is greater with molbox RFM
± 0.5 % of reading or 0.0025 % full scale whichever is greater with molbox RFM-M

Variable or Parameter	Type Unc	molbox-1 A350k	molbox-1 A700k	molbox RFM	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading	% of reading
absolute pressure	L1	0.007	0.013	0.072	0.072
differential pressure	L2	0.013	0.016	0.073	0.073
pressure model	L3	0.050	0.050	0.050	0.050
molbox resistance	L4	0.016	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005	0.005
molbloc-L linearity	L6	0.050	0.050	0.050	0.050
ref uncertainty	L7	0.050	0.050	0.050	0.050
molbloc-L stability	L8	0.018	0.018	0.018	0.018
Cg determination	L9	0.025	0.025	0.025	0.025

COMBINED		0.095 % of rdg + 0.0035 %FS	0.096 % of rdg + 0.0050 %FS	0.139 % of rdg +0.02 %FS	0.139 % of rdg + 0.0006 %FS
COMBINED & EXPANDED FOR (K=2)		0.19 % of rdg + 0.007 %FS	0.19 % of rdg + 0.010 %FS	0.28% of rdg + 0.04 %FS	0.28 % of rdg + 0.001 %FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS	Pa / %FS
Differential pressure	L2	1.8	2.5	10.6	0.3
Nom FS DP = 50 kPa	----------	0.0035 %	0.0050 %	0.021 %	0.0006 %

molbloc-L (LFE) Full modelization, low pressure or single pressure 3E4

Typical Flow Measurement Uncertainty:
± 0.3 % of reading or 0.03 % full scale whichever is greater with molbox1
± 0.5 % of reading or 0.05 % full scale whichever is greater with molbox RFM
± 0.5 % of reading or 0.0025 % full scale whichever is greater with molbox RFM-M

Variable or Parameter	Type Unc	molbox-1 A350k	molbox-1 A700k	molbox RFM	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading	% of reading
absolute pressure	L1	0.007	0.013	0.072	0.072
differential pressure	L2	0.013	0.016	0.073	0.073
pressure model	L3	0.050	0.050	0.050	0.050
molbox resistance	L4	0.016	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005	0.005
molbloc-L linearity	L6	0.100	0.100	0.100	0.100
ref uncertainty	L7	0.050	0.050	0.050	0.050
molbloc-L stability	L8	0.018	0.018	0.018	0.018
Cg determination	L9	0.025	0.025	0.025	0.025

COMBINED		0.128 % of rdg + 0.0035 %FS	0.128 % of rdg + 0.0050 %FS	0.164 % of rdg + 0.02 %FS	0.164 % of rdg + 0.0006 %FS
COMBINED & EXPANDED FOR (K=2)		0.26 % of rdg + 0.007 %FS	0.26 % of rdg + 0.010 %FS	0.33 % of rdg + 0.04 %FS	0.33 % of rdg + 0.001 %FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS	Pa / %FS
Differential pressure	L2	1.8	2.5	10.6	0.3
Nom FS DP = 50 kPa	----------	0.0035 %	0.0050 %	0.021 %	0.0006 %

molbloc-L (LFE) **Full modelization, low pressure or single pressure 1E5**

Typical Flow Measurement Uncertainty: ± 0.5 % of reading or 0.125 % full scale whichever is greater with molbox1
± 0.5 % of reading or 0.025 % full scale whichever is greater with molbox RFM-M
not used with molbox RFM

Variable or Parameter	Type Unc	molbox-1 A350k	molbox-1 A700k	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading
absolute pressure	L1	0.007	0.013	0.072
differential pressure	L2	0.013	0.016	0.073
pressure model	L3	0.050	0.050	0.050
molbox resistance	L4	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005
molbloc-L linearity	L6	0.125	0.125	0.125
ref uncertainty	L7	0.075	0.075	0.075
molbloc-L stability	L8	0.018	0.018	0.018
Cg determination	L9	0.100	0.100	0.100

COMBINED		0.190 % of rdg + 0.0035 % FS	0.190 % of rdg + 0.005 % FS	0.21 % of rdg + 0.006 % FS
COMBINED & EXPANDED FOR (K=2)		0.38 % of rdg + 0.007 % FS	0.38 % of rdg + 0.01 % FS	0.43 % of rdg + 0.012 % FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS
Differential pressure	L2	1.8	2.5	0.3
Nom FS DP = 5 kPa	----------	0.0035 %	0.0050 %	0.006 %

molbloc-L (LFE) **Full modelization, high pressure or single pressure 1E1 through 3E4**

Typical Flow Measurement Uncertainty: ± 0.2 % of reading or 0.02 % full scale whichever is greater with molbox1
± 0.5 % of reading or 0.05 % full scale whichever is greater with molbox RFM
± 0.5 % of reading or 0.0025 % full scale whichever is greater with molbox RFM-M
not applicable to molbox-1 A350k or 1E5 molbloc

Variable or Parameter	Type Unc	molbox-1 A700k	molbox RFM	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading
absolute pressure	L1	0.007	0.039	0.039
differential pressure	L2	0.023	0.073	0.073
pressure model	L3	0.050	0.050	0.050
molbox resistance	L4	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005
molbloc-L linearity	L6	0.050	0.050	0.050
ref uncertainty	L7	0.050	0.050	0.050
molbloc-L stability	L8	0.018	0.018	0.018
Cg determination	L9	0.025	0.025	0.025

COMBINED		0.096 % of rdg +0.005 %FS	0.125 % of rdg + 0.021 %FS	0.125 % of rdg + 0.0006 %FS
COMBINED & EXPANDED FOR (K=2)		0.19 % of rdg + 0.01 %FS	0.25 % of rdg + 0.04 %FS	0.25 % of rdg + 0.001 %FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS
Differential pressure	L2	2.5	10.6	0.3
Nom FS DP = 50 kPa	----------	0.0050 %	0.0212 %	0.0006 %

molbloc-L (LFE) **Full modelization, downstream 1E1 through 1E4**

Typical Flow Measurement Uncertainty: ± 0.2 % of reading or 0.02 % full scale whichever is greater with molbox1
± 0.5 % of reading or 0.05 % full scale whichever is greater with molbox RFM
± 0.5 % of reading or 0.0025 % full scale whichever is greater with molbox RFM-M

Variable or Parameter	Type Unc	molbox-1 A350k	molbox-1 A700k	molbox RFM	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading	% of reading
absolute pressure	L1	0.012	0.023	0.139	0.139
differential pressure	L2	0.010	0.013	0.046	0.046
pressure model	L3	0.050	0.050	0.050	0.050
molbox resistance	L4	0.016	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005	0.005
molbloc-L linearity	L6	0.050	0.050	0.050	0.050
ref uncertainty	L7	0.050	0.050	0.050	0.050
molbloc-L stability	L8	0.018	0.018	0.018	0.018
Cg determination	L9	0.010	0.010	0.010	0.010

COMBINED		0.092 % of rdg + 0.0020 %FS	0.094 % of rdg + 0.0028 %FS	0.172 % of rdg + 0.01 %FS	0.172 % of rdg + 0.0003 %FS
COMBINED & EXPANDED FOR (K=2)		0.18 % of rdg + 0.004 %FS	0.19 % of rdg + 0.006 %FS	0.34 % of rdg + 0.02 %FS	0.34 % of rdg + 0.0007 %FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS	Pa / %FS
Differential pressure	L2	1.8	2.5	10.6	0.3
Nom FS DP = 90 kPa	----------	0.0020 %	0.0028 %	0.012 %	0.0003 %

molbloc-L (LFE) **Full modelization, downstream 3E4**

Typical Flow Measurement Uncertainty: ± 0.3 % of reading or 0.03 % full scale whichever is greater with molbox1
± 0.5 % of reading or 0.05 % full scale whichever is greater with molbox RFM
± 0.5 % of reading or 0.0025 % full scale whichever is greater with molbox RFM-M

Variable or Parameter	Type Unc	molbox-1 A350k	molbox-1 A700k	molbox RFM	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading	% of reading
absolute pressure	L1	0.012	0.023	0.139	0.139
differential pressure	L2	0.010	0.013	0.046	0.046
pressure model	L3	0.050	0.050	0.050	0.050
molbox resistance	L4	0.016	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005	0.005
molbloc-L linearity	L6	0.120	0.120	0.120	0.120
ref uncertainty	L7	0.050	0.050	0.050	0.050
molbloc-L stability	L8	0.018	0.018	0.018	0.018
Cg determination	L9	0.010	0.010	0.010	0.010

COMBINED		0.143 % of rdg + 0.0020 %FS	0.144 % of rdg + 0.0028 %FS	0.204 % of rdg + 0.01 %FS	0.204 % of rdg + 0.0003 %FS
COMBINED & EXPANDED FOR (K=2)		0.29 % of rdg + 0.004 %FS	0.29 % of rdg + 0.006 %FS	0.41 % of rdg + 0.02 %FS	0.41 % of rdg + 0.0007 %FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS	Pa / %FS
Differential pressure	L2	1.8	2.5	10.6	0.3
Nom FS DP = 90 kPa	----------	0.0020 %	0.0028 %	0.012 %	0.0003 %

molbloc-L (LFE) **Full modelization, downstream 1E5**

Typical Flow Measurement Uncertainty: ± 0.5 % of reading or 0.125 % full scale whichever is greater with molbox1
± 0.5 % of reading or 0.025 % full scale whichever is greater with molbox RFM-M
not used with molbox RFM

Variable or Parameter	Type Unc	molbox-1 A350k	molbox-1 A700k	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading
absolute pressure	L1	0.012	0.023	0.139
differential pressure	L2	0.010	0.013	0.046
pressure model	L3	0.050	0.050	0.050
molbox resistance	L4	0.016	0.016	0.016
PRT linearity	L5	0.005	0.005	0.005
molbloc-L linearity	L6	0.125	0.125	0.125
ref uncertainty	L7	0.075	0.075	0.075
molbloc-L stability	L8	0.018	0.018	0.018
Cg determination	L9	0.050	0.050	0.050

COMBINED		0.165 % of rdg + 0.020 %FS	0.166 % of rdg + 0.028 %FS	0.220 % of rdg + 0.003 %FS
COMBINED & EXPANDED FOR (K=2)		0.33 % of rdg + 0.04 %FS	0.33 % of rdg + 0.06 %FS	0.44 % of rdg + 0.007 %FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS
Differential Pressure	L2	1.8	2.5	0.3
Nom FS DP = 9 kPa	----------	0.020 %	0.028 %	0.003 %

molbloc-S (CFN) **All ranges, 20 to 200 kPa or 50 to 500 kPa**

Typical Flow Measurement Uncertainty: ± 0.2 % of reading from 10 to 100 % with molbox1
± 0.5 % of reading from 10 to 100 % with RFM

Variable or Parameter	Type Unc	molbox-1 A350k	molbox-1 A700k	molbox RFM	molbox RFM-M
(relative unc's)	----------	% of reading	% of reading	% of reading	% of reading
molbox resistance	S2	0.004	0.004	0.004	0.004
Throat area	S3	0.002	0.002	0.002	0.002
molbloc-S linearity	S4	0.025	0.025	0.025	0.025
reference flow	S5	0.060	0.060	0.060	0.060
molbloc-S stability	S6	0.006	0.006	0.006	0.006
discharge coefficient	S7	0.013	0.013	0.013	0.013
COMBINED		0.067 % of rdg + 0.006 % FS	0.067 % of rdg + 0.006 % FS	0.067 % of rdg + 0.025 % FS	0.067 % of rdg + 0.025 % FS
COMBINED & EXPANDED FOR (K=2)		0.13 % of rdg + 0.01 % FS	0.13 % of rdg + 0.01 % FS	0.13 % of rdg +0.05 % FS	0.13 % of rdg + 0.05 % FS
(absolute Unc's)	----------	Pa / %FS	Pa / %FS	Pa / %FS	Pa / %FS
Absolute pressure	S2	0.006	0.006	0.025	0.025

NOTES