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CALIBRATION PROCEDURES AND UNCERTAINTY ANALYSIS FOR A THERMAL MASS GAS FLOWMETER OF A NEW GENERATION

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ABSTRACT

This paper deals with the differences between traditional and new technology gas meters, and focuses specifically on the calibration procedure and uncertainty evaluation of CTTMFs (Capillary Type Thermal Mass Flow Meter). In particular, measurements performed on a sample set of commercial CTTMFs for natural gas in domestic/residential (G4) applications allowed to evaluate the modifications to calibration procedures required by the new generation, digital, gas flow meters. Indeed, traditionally natural gas is metered by means of volumetric measurement techniques, while the modern, static gas flow meters (thermal and ultrasonic ones) are based on electronic flow sensors. This implies that the gas volume through the meter is measured by sampling the flow rate at selected time points and integrating the flow rate in time. The measurement time becomes therefore an important parameter, thus requiring a thorough rethinking of the calibration procedure. In order to analyse the effects of the various parameters, a series of ad-hoc calibrations were performed. Specifically, one set of calibrations was performed with constant totalized volume, while the other required a constant measurement time. In order to highlight the novelties that will have to be implemented in ordinary calibration procedures to get the best of the new technologies, the two procedures as performed on a sample set CTTMFs will be compared; the theoretical (generic) evaluation of the associated uncertainty will also be presented. Measurements were carried out at the test facility of INRIM, the Italian National Metrology Institute,

1. Nomenclature

Symbol	Quantity	Unit SI
c_p	specific thermal heat at constant pressure	kJ kg^{-1}K^{-1}
$\dot{m}$	mass flowrate	kg s^{-1}
Q	heat power	W
R	electric resistance	Ohm
T	Temperature	K
A	Cross section	m^2
a	diffusivity	m^2 s^{-1}
V	measured gas volume	L
$\dot{V}$	Volume flowrate	L min^{-1}

Greek letters

ρ	gas density	kg m^{-3}
λ	thermal conducibility	Wm^{-1}K^{-1}

Subscripts

th	thermal
el	electrical
0	reference state
c	capillary
m	meter

Keywords: smart gas meter; calibration; flowmeter.

1. INTRODUCTION

The use of natural gas as a fuel has been commonplace in most industrial countries for decades now, and the market for this commodity has a value of several billion Euros worldwide [1]. The advantages of this kind of fuel are its extreme facility of transportation, widespread distribution of reserves, ease of use, essentially no solid residual after the burn. Applications range from very small kitchen burners to large industrial boilers, including water heaters for large thermoelectric power stations.

Of course, such a wide range of applications implies an equally wide range of flow rates at the final customer; such flow rates must be measured as accurately as possible for the correct invoicing.

Instruments for the measurement of the flown volume of gas (gas meters) are thus present at every end-user connection point, in addition to the ones used across the distribution lines for monitoring and cross-checking, and the ones used for the international trade between producing countries and user countries.

Traditional end-user instruments are based on a mechanical measurement principle, called volumetric positive displacement technology. Several practical developments were introduced during the years, but the measurement principle of these instruments, which presently represent the large majority of the installed units, is still based on a measurement of a fixed (determined) volume, which is cyclically filled and emptied. This technology, although improved (e.g. using suitable material, such as composite, and new manufacturing techniques) and consolidated, intrinsically

suffers from two major drawbacks, i.e. the aging of the moving parts (wear and mechanical deterioration) and the sensitivity of the measurement to the ambient conditions.

The respect of the compliance with legal metrology error limits (usually called Maximum Permissible Error = MPE) guarantees the correctness of commercial transactions: legal metrology ensures the quality and credibility of measurements that are used directly in regulation and in areas of commerce. In order to assess and ensure the metrological reliability of gas meters, they are initially verified at the manufacturer, then in most Countries are subject to further periodical verifications. The full and deep characterization of meters (metrological reliability) is performed by an experimental activity called ''calibration'', in which errors, standard deviations, uncertainties and confidence levels are determined [2-8].

The calibration procedures are based on the comparison, for a same quantity (measurand: quantity intended to be measured; International Vocabulary of Metrology, item 2.3), of the metering values provided by the meter under test and the values provided by a suitable (traceable) measurement standard.

In the field of legal metrology, the conformity assessment of a meter is called verification [9]: it consists in a periodic (at fixed intervals) calibration of the meter, carried out in an accredited laboratory (in conformity with the stated legal requirements).

In the field of industrial or scientific metrology, instead, the assessment of the meter's reliability is called metrological confirmation [10]: it consists in a periodic calibration of the metering instrument in order to assess the match of the meter's performance with the needed requirements for specific use (for example the conformity to ISO 9000 quality assurance standards).

In recent years, new laws and the European directive 2012/27/EU [11], have introduced the concept of *smart meter*, with the aim of improving the invoicing process and of providing more services to the end user, such as the real-time transmission of measurement data to the distributor [12-14] .

Gas meter producers readily answered the call; essentially two approaches were taken. The first approach was to patch once more the old technology, by adding temperature probes to the measuring volume and operating a correction on the measured volume via computation. The alternative was to develop new concepts of gas meters, based on more up-to-date, digital and static technologies. One of these is the thermal mass meter; a complete description of the principle will be given in par. 2. The main advantage of this technique is that the quantity actually measured is the mass flow rate, which allows to overcome the problem of the temperature volume correction [15]. These instruments are based on a totally different approach with respect to the volumetric positive displacement technology,therefore the calibration and verification process shall have to take into account such difference[16-18].

In the present paper we shall analyse the implications on the calibration procedures of the technological innovations recently introduced, showing that, although the general process remains the same, some fine tuning is necessary in order to get the best of such innovations. The specific example of meters for domestic/residential applications (G4 gas meters) will be studied, but of course the same general principles will remain valid also for other sizes. The main technical

adaptation are a direct consequence of the new static measurement principles (see Par. 2) as opposed to the full mechanical dynamic flowmeters adopted to date.

Indeed, traditionally natural gas is metered by means of volumetric measurement techniques, while the modern, static gas flow meters (thermal and ultrasonic ones) are based on electronic flow sensors. This implies that the gas volume through the meter is measured by sampling the flow rate at selected time points and integrating the flow rate in time. The measurement time becomes therefore an important parameter, thus requiring a thorough rethinking of the calibration procedure. In order to analyse the effects of the various parameters, a series of ad-hoc calibrations were performed. Specifically, one set of calibrations was performed with constant totalized volume, while the other required a constant measurement time.

The implications of the aforementioned technological differences on the calibration and conformity assessment of gas meters will be analysed, together with a theoretical (generic) evaluation of the uncertainty associated to the different types of flow metering technologies. Measurements were carried out at the test facility of INRIM, the Italian National Metrology Institute.

2. MEASURING PRINCIPLE OF THERMAL MASS METER

The CTTMFs (Capillary Type Thermal Mass Flowmeters) are based on a MEMS micro-thermal mass flow sensors built using CMOS technology. The sensor is composed of a central micro heater and two temperature sensors placed symmetrically upstream and downstream of the micro heater, both the heater and the sensors are controlled by a suitable electronic module.

Gas enters the meter and is divided into two flow paths - main flow and capillary sensing path - in both of which laminar flow regime is ensured (in the capillary tube because of the very small diameter, and in the main tube by means of a pressure dropper/laminar flow element). Figure 1 displays a schematic of the overall arrangement of the meter.

The micro-thermal mass flow sensor is positioned within the capillary as shown in Figure 1.

The measurement principle is based on the analysis of the modifications to the heat exchange between the heater and the sensors due to the flow in the capillary: when no gas is flowing over the sensor, the two thermo-elements measure the same rise in temperature (see Figure 2, symmetrical curve). Conversely, when gas flows through the capillary the temperature symmetry is disturbed, and the asymmetry can be expressed as a temperature difference between the two temperature sensors (see Figure 2). This temperature difference signal, which is measured as a voltage difference (thermopile), is processed in the analogue part of the sensor chip and then digitalized in the digital part. This measurement signal (voltage difference) is proportional to the mass flowrate of gas over the sensor-chip.

Basically, the micro-thermal mass flow sensor uses the thermal properties of the gas to directly measure the mass flow rate (considering the electric power supply, Q_{el}, provided to the micro heater as being equal to the thermal power, Q_{th}, generated by the Joule's effect (RI^2) and lost to the gas flow by means of forced convective heat transfer (see ISO 14511:2001): $Q_{el} = RI^2 = Q_{th} = m_c c_p \Delta T$. The sensor chip detects the mass flow rate in the capillary tube (m_c): if the flow regime is laminar in both the circuits (the capillary one and the main one) the ratio m_c/m_m (mass flow rate in the capillary circuit/mass flow rate in the main pipe) is constant (typically equal to the ratio between the cross section areas A_c/A_m). The sensor uses the basic principle that each gas molecule has the

specific ability to pick up heat (forced convective heat transfer). This property, called the specific heat for a constant pressure (c_p), directly relates to the mass and physical structure of the molecule and can be determined experimentally. The physical structure of molecules varies widely from gas to gas, as does the specific heat, c_p, which varies depending on the gas composition and temperature (for a gas with a "real" behaviour, not ideal gas). Changes in c_p also imply changes in the thermal conductivity λ of the gas, since the thermal diffusivity a of the gas is a = $\lambda/(c_p.\rho)$, where ρ is the gas density.

The gas sensitivity (or gas identification/recognition) represents a crucial feature for the measurement reliability. Nowadays, the new and improved generations of CTTMF are able to sense gas composition, providing possible corrections to all current gas families (compliant to EN 437:2009).

It is important to observe that, since the sensor is directly sensitive to the mass flow, the meter will not require temperature and pressure sensors since the mass can be directly converted to corresponding volume at the established thermodynamic conditions.

2.1.MEASUREMENT AND SAMPLING

In order to reduce battery consumption, measurements are not carried out continuously; on the contrary, the flow is evaluated at discrete time intervals $\Delta\theta$ (sampling), i.e. a sampling is performed. The meters calibrated in this work perform acquisitions of the mass flowrate every 0.4 seconds when *calibration mode* (also called *test mode*) is set, every 2 seconds in *operation mode*. The totalized gas volume is obtained by summing the discrete product (flowrate * sampling time Δt). For each sample, the volume passed through the meter $V_{m,sample}$ is calculated by multiplying the mass flowrate "$\dot{m}$" measured as before described during the sample time by the reciprocal density "$1/\rho_0$" (where ρ_0 is the gas density at reference conditions) and by the time sampling interval "Δt" : $V_{m,sample} = \dot{m}_i/\rho_0 \cdot \Delta t_i$; the total volume is the sum of the samples: $V_m = \sum_i \dot{m}_i/\rho_0 \cdot \Delta t_i$.

The CTTMF meter resolution depends on the flowrate sensitivity of the sensor and the sampling time. Typically, the sensitivity of a thermal mass flow meter is extremely high, in the order of 10^{-3} L. This high resolution implies that the minimum calibration volume is significantly reduced as compared to a traditional diaphragm gas meter: this implies that the calibration volume influence on the measurement calibration error/uncertainty is significantly reduced, but on the other hand for the CTTMFs the sampling time is crucial to curtail the measurement error. In Figure 3 the behavior of the gas flow profile at the startup of the meter is represented together with the CTTMF sampling points. It can be observed that the flow integration with the trapezoidal rule leads to an error in the computation of the measured volume, which depends on the final flow rate and the steepness of the growing ramp. Of course, a similar situation will be present at the shutdown. Notice that this uncertainty contribution can be avoided in calibration by starting the measurements once the steady state is reached; on the other hand, this contribution will also be present in the field applications.

Similarly, Figure 4 represents the behavior during the (nominal) steady state functioning. Again, due to the finite time resolution, the integration causes an error in measurement. This contribution can be minimized by increasing the number of samplings (and therefore the total calibration time) since the various contribution will cancel each other.

3. CALIBRATION AND MEASUREMENT UNCERTANTIES

3.1. Comparison between static vs. positive displacement techniques uncertainty analysis

In order to highlight the basic differences expected in the behaviour of the different types of meters, an uncertainty analysis of the CTTMF and of the positive displacement gas meters was performed; the full computations are reported in Appendix A.

The quantity considered is the totalized volume measured by the meter, V_m; of course, developing the expression for this quantity leads to different formulations, due to the fact that the measurement principles of the two meters are radically different. Notice, that in both cases a reference density is required for the determination of the measured volume, although for different reasons[1],but this value is immaterial in the evaluation of the uncertainty since it is determined through assigned (and therefore univocally defined) values of thermodynamic conditions and thermodynamic constants[2]; on the other hand, the measured quantities are radically different: the CTTMF employs the instant flow rate and the time interval, while the constant displacement meter requires the unit volume and the actual thermodynamic conditions. This difference translates quickly in a completely different uncertainty evaluation. Indeed, when developing the calculations, (see appendix A), it comes out that the uncertainty on the measured volume in the case of the CTTMF depends on the relative uncertainty on the measured mass flow rate and on the time interval, while in the case of the positive displacement meter the relevant quantities are the internal volume of the meter and the actual thermodynamic conditions. In addition, in both cases the overall uncertainty depends on N, the number of samplings, but it has to be noticed that this value has different meanings – and different values – in the two cases: indeed, while for the CTTMF N is the number of acquisitions from the sensor (and is therefore connected to the total *time* of acquisition), for the positive displacement meter N is the number of cycles, and is therefore connected to the total measurement *volume*. Since the time interval is quite small, it is possible in the case of the CTTMF to raise the value of N easily (a one-minute calibration implies 150 samplings with a typical time interval of 0.4 seconds), while the typical value for N is of the order of 10 to 50 with typical positive displacement meters; it is therefore possible to reduce the final uncertainty with little effort.

Another important observation is that, in the CTTMF, the uncertainty on the time interval is very small[3] with respect to the other uncertainty sources, therefore the only uncertainty source of importance is the measured flow rate. The uncertainty of this quantity is relatively small and most of all can be considered as quite stable, since the mass flow sensor is not subject to wear or other mechanical processes; also, it is quite protected within the meter, therefore it can be expected to perform almost in design conditions throughout the life of the instrument. On the other hand, the positive displacement involves at least three major uncertainty sources, namely the uncertainty on

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[1] In the case of the CTTMF, the reference density is required to convert the measured mass to volume, while in the case of the positive displacement meter this quantity allows to convert the measured volume to the reference volume through the measured to reference density ratio.
[2] Actually, the gas constant and the gas molar mass involve an uncertainty, but its value is so small that it can be neglected.
[3] The Δt_i is provided by a clock, and even low-quality clocks can easily provide uncertainties better than 0.01 %.

the volume (subject to mechanical stresses, therefore to wear), the uncertainty on the pressure measurement and the one on the temperature measurement.

In conclusion, the main result of relevance to the present paper of the uncertainty analysis is that the parameter of importance in the calibration of the CTTMF is the measurement time (since an increase in this parameter increases the value of *N*), as opposed to the classical positive displacement meter where the parameter of importance was the total measured volume. This fact has several implications in the definition of a correct calibration procedure. First of all, the prescriptions will have to be on the minimum calibration time, which will be the same for all flow rates; this has the additional implications of making it much easier to forecast the required total time of calibration. On the other hand, for the higher flow rates this will lead to an increase in the total volume required to complete the calibration, but this is hardly a problem with modern reference facilities. Another implication is that the measurement uncertainties will tend to be lower, and the reduction of the meter uncertainty will increase the importance of the calibration facility uncertainty on the final result uncertainty. This will of course lead to a requirement for improvement in the calibration facilities and procedures, and possibly to an ultimate reduction in the prescriptions on acceptable uncertainties of the meters, which in turn will mean fairer billing for the final user.

4. TEST FACILITY AND PROCEDURE

The test facility employed for taking the measurements was INRIM's test rig BELLGAS. This facility is used for the definition of the Italian National Standard of gas flow rate in the flow range between 1 L/min and 120 L/min.

The test rig is a modified American Standards bell prover with a nominal volume of 160 L. The baseline instrument was modified at INRIM during the '80s and '90s to boost its accuracy and data monitoring. To reach this aim, the main improvements were the following:

- replacement of the bell cap, which was substituted by a brass flat top provided with fittings for the insertion of a Pt100 thermal sensor.

- modification of the reading system, which is now constituted by an encoder connected to the bell cap through a steel ribbon; the encoder has a resolution of 360000 steps per rotation and allows a volume resolution of about 0.6 mL per step;

- addition of vertical guides provided with low friction bearings to avoid bell oscillations;

- hydrostatic pull compensation by a weight suspended on an involute-of-circle device;

- control of the gas entrance/exit through pneumatic valves controlled by an electronic device;

With this set of improvements, the test rig can now measure volumes and flow rates in the said flow rate range with an uncertainty of 0.12% or better for differential volumes larger than 20 L.

The test rig was calibrated with a gravimetric method, using an oil substitution procedure.

4.1. Test procedure

The procedure employed for taking the measurement is a modification of the standard INRIM procedure for gas meter calibration.

In particular, three CTTMFs were connected in series downstream of the bell prover, which functioned in this case as the gas source. The bell was loaded with a constant load, which produced an internal pressure of about 800 Pa, and the flow rate was regulated using the bell exit valve. Leaks were checked by closing the exit of the last meter in the series, then opening full the bell valve and monitoring the bell vertical position through the encoder reading while checking that the internal pressure remained at the set value. After a transient of stabilization, it was observed that the encoder reading was stable to within 1 step/minute; recalling now that the volume corresponding to 1 encoder step is of about 0.6 mL, it can be stated that leaks, if present, influence the measurement by less than this quantity.

To perform measurements, the bell is filled with ambient dry air through the dedicated fan, then the inlet is closed and the exit valve is opened enough to provide the selected flow. The flow is checked on the bell reading display and, when it reaches stability, readings are launched (almost) simultaneously on the bell control device and on the gas meters software. In the normal procedure, the flow is stopped after at least 20 L have been delivered and at least 1 minute has elapsed since these parameters allow guaranteeing the stated uncertainty of the bell measurements. For the measurements described here, timings and volumes were selected differently with the aim of analyzing the effects of these parameters on the meter performance. Of course, these variations also influence the bell uncertainty, which was recomputed for every measurement according to the complete uncertainty analysis.

The meters under test were a set of 3 CTTMF meters, G4 sized (full scale flowrate of 6 m^3/h), model *Domusnext^{TM}*, produced by the Company MeterSIT.

First of all, a baseline (steady state, 3 repetitions, 8 nominal flow rates: 1%-5%-10%-20%-30%-50%-75%-100% of Full Scale Reading) calibration was carried out for each of the meters.

To analize the effects of sampling times on the CTTMF meter calibration, further measurements were then performed for different acquisition time periods at some of the baseline calibration nominal flow rates (1-5-10-20 L/min); the flow rates were selected so that they allowed to attain at least 5 minutes of continuous and stable measurements and therefore to build a solid (representative) set of comparison data. The complete matrix of flow/time points is reported in Table 1.

In the Appendix B, data from all three tested meters were collected and reduced for each point in the matrix ; such data were then used for the analysis reported in the following.

5. RESULTS AND DISCUSSION

Results are presented in terms of average percentage deviation of the meter, $E\% = \sum_{i=1}^{3} \frac{e\%}{3}$ where: $e_{\%} = \frac{V_m - V_{ref}}{V_{ref}} \cdot 100$ and V_m and V_{ref} are respectively the volume measured from meter under test and the reference meter. In particular, in the Figure 5 the data were plotted with the measurement flowrate as parameter, instead in Figure 6 the data were plotted with the measurement measurement time as parameter. The calibration curves for all meters, as showed in Figure 5, are full satisfactory with a good repeatability (see appendix B). All calibration points are within MPE

limits and the values of the experimental standard deviation are always less than 0.45 for low flowrate (Q<Qt) and less than 0.3 for high flowrate except for a few calibration points (see appendix B). The exception in repeatability could be due at not appropriate ratio between the gas volume passed through the meter under test and the number of samples.

Figure 6 reports the relative percentage error of measurement in function of flowrate, for different time acquisition. It can be seen that then percentage errors decrease as the number of sampling increases. Also in this case, the tested meters show to be a good measurement repeatability (MSD less than 1%). Btesides, it can be observed that the results are essentially the same independent of the flow rate, which also means independent of the delivered volume. Consider now the 1 min acquisition time data; for the 1L/min rate, this means a delivered volume of 1 L, while e.g. at 20 L/min the delivered volume would be 20 L. Now, it can be seen that the data dispersion (indicative of the measurement uncertainty) is essentially the same for the two extreme cases, in contrast with what would happen with traditional diaphragm meters for which the expectation is of a much larger dispersion at the lowest volumes. This indicates that the delivered volume is not an issue in the calibration of CTTMFs, while the number of samples might be. Therefore, as also shown by the uncertainty analysis (par. 3.1), the leading parameter in this type of measurement is the measurement time calibration in opposition of what happens with diaphragm gas meter where the total gas volume is more important.

6. CONCLUSIONS

This paper focuses on the implications of the innovative measurement principle of CTTMF gas meters on the procedures to be adopted for the calibration of such meters. In particular, the uncertainty balance of calibration for this type of meters was analysed and compared to the equivalent balance relative to the traditional diaphragm gas meters. A set of calibrations performed on a set of meters was also presented to support the computations.

The main result of the study is that the leading parameter in CTTMF calibration is the sampling time, in contrast to the delivered volume which is to be considered for the traditional meters. This result indicates that a review of the calibration procedures is required for the correct quality assessment of the new generation gas meters. In particular, the measurement acceptability parameter will have to be based on the measurement time instead of the measurement volume. Results presented here suggest that the minimum calibration time could be of the order of 1 minute, which would imply a significant reduction of overall calibration times, with important consequences on the productivity and economic assessment of calibration laboratories.

Another important feature of CTTMF meters, which will be the object of future work, lies in their increased accuracy with respect to traditional meters. Such increased accuracy leads to a lower uncertainty, which in turn poses more pressing requirements on the process of laboratory alignment, with the aim of maintaining *calibration compatibility* between laboratories.

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APPENDIX A: UNCERTAINTY CALCULATION

Thermal mass meter uncertainty calculation

The model equation for the total measured volume in the case of the CTTMF is:

$$V_m = \sum_{i=1}^{N} V_i = \sum_{i=1}^{N} \frac{\dot{m}_i}{\rho_0} \cdot \Delta t_i$$

Where V_m is the total volume measured by the meter and $\frac{\dot{m}_i}{\rho_0} \cdot \Delta t_i$ is the volume measured in a single time interval expressed as a function of the flow rate which, we recall, is the quantity actually sensed. The uncertainty on the total volume can therefore be expressed as:

$$u^2(V_m) = \sum_{i=1}^{N} u^2(V_i) = \sum_{i=1}^{N} u^2 \left(\frac{\dot{m}_i}{\rho_0} \cdot \Delta t_i \right)$$

And, developing this formulation to obtain the dependency on the various quantities:

$$u^2(V_i) = \left(\frac{\partial \frac{\dot{m}_i}{\rho_0} \cdot \Delta t_i}{\partial \dot{m}_i} \right)^2 u^2(\dot{m}_i) + \left(\frac{\partial \frac{\dot{m}_i}{\rho_0} \cdot \Delta t_i}{\partial \rho_0} \right)^2 u^2(\rho_0) + \left(\frac{\partial \frac{\dot{m}_i}{\rho_0} \cdot \Delta t_i}{\partial \Delta t_i} \right)^2 u^2(\Delta t_i)$$

Since ρ_0 is a reference value, it is not affected by measurement uncertainty, therefore:

$$u^2(V_i) = \left(\frac{\Delta t_i}{\rho_0} \right)^2 u^2(\dot{m}_i) + \left(\frac{\dot{m}_i}{\rho_0} \right)^2 u^2(\Delta t_i)$$

$$u^2(V_m) = \sum_{i=1}^{N} u^2 \left(\frac{\dot{m}_i}{\rho_0} \cdot \Delta t_i \right) = \sum_{i=1}^{N} \left(\frac{\Delta t_i}{\rho_0} \right)^2 u^2(\dot{m}_i) + \sum_{i=1}^{N} \left(\frac{\dot{m}_i}{\rho_0} \right)^2 u^2(\Delta t_i)$$

$$\sum_{i=1}^{N} \left(\frac{\Delta t_i}{\rho_0} \right)^2 u^2(\dot{m}_i) = \left(\frac{\Delta t_i}{\rho_0} \right)^2 \sum_{i=1}^{N} u^2(\dot{m}_i) = \left(\frac{\Delta t_i}{\rho_0} \right)^2 N \cdot u^2(\dot{m}_i)$$

$$\sum_{i=1}^{N} \left(\frac{\dot{m}_i}{\rho_0} \right)^2 u^2(\Delta t_i) = \frac{u^2(\Delta t_i)}{\rho_0^2} \sum_{i=1}^{N} \dot{m}_i^2$$

$$u^2(V_m) = \left(\frac{\Delta t_i}{\rho_0} \right)^2 N \cdot u^2(\dot{m}_i) + \frac{u^2(\Delta t_i)}{\rho_0^2} \sum_{i=1}^{N} \dot{m}_i^2$$

Assuming that the instant flow rates are always the same, the summation reduces to::

$$\sum_{i=1}^{N} \dot{m}_i^2 = N \cdot \dot{m}_i^2$$

Hence:

$$u^2(V_m) = \left(\frac{\Delta t_i}{\rho_0}\right)^2 N \cdot u^2(\dot{m}_i) + \frac{u^2(\Delta t_i)}{\rho_0^2} N \cdot \dot{m}_i^2$$

Converting to relative uncertainty, considering that: $V_m = N \cdot V_i$ and recalling the formulation for V_i :

$$\frac{u^2(V_m)}{V_m^2} = \frac{1}{N \cdot V_i^2} \left[\left(\frac{\Delta t_i}{\rho_0}\right)^2 \cdot u^2(\dot{m}_i) + \frac{u^2(\Delta t_i)}{\rho_0^2} \cdot \dot{m}_i^2\right]$$

$$\frac{u^2(V_m)}{V_m^2} = \frac{1}{N} \left[\frac{u^2(\dot{m}_i)}{\dot{m}_i^2} + \frac{u^2(\Delta t_i)}{\Delta t_i^2}\right]$$

Positive displacement gas meter uncertainty calculation

The model equation for the total measured volume in this case is:

$$V_m = \sum_{i=1}^{N} \frac{\rho_i V_i}{\rho_0}$$

$$u^2(V_m) = \sum_{i=1}^{N} u^2\left(\frac{\rho_i V_i}{\rho_0}\right)$$

So that:

$$u^2(V_m) = \sum_{i=1}^{N} u^2\left(\frac{\rho_i V_i}{\rho_0}\right) = \sum_{i=1}^{N} \left(\frac{\rho_i}{\rho_0}\right)^2 u^2(V_i) + \sum_{i=1}^{N} \left(\frac{V_i}{\rho_0}\right)^2 u^2(\rho_i) + \sum_{i=1}^{N} \left(\frac{\rho_i V_i}{\rho_0^2}\right)^2 u^2(\rho_0)$$

Again, ρ_0 is a reference value not affected by measurement uncertainty, therefore:

$$u^2(V_m) = \sum_{i=1}^{N} \left(\frac{\rho_i}{\rho_0}\right)^2 \left(\frac{V_i}{V_i}\right)^2 u^2(V_i) + \sum_{i=1}^{N} \left(\frac{V_i}{\rho_0}\right)^2 \left(\frac{\rho_i}{\rho_i}\right)^2 u^2(\rho_i)$$

$$u^2(V_m) = \sum_{i=1}^{N} \left(\frac{V_s}{V_i}\right)^2 u^2(V_i) + \sum_{i=1}^{N} V_s^2 \left(\frac{1}{\rho_i}\right)^2 u^2(\rho_i)$$

$$\left(\frac{1}{\rho_i}\right)^2 u^2(\rho_i) = \left(\frac{1}{T_i}\right)^2 u^2(T_i) + \left(\frac{1}{p_i}\right)^2 u^2(p_i)$$

$$u^2(V_m) = \sum_{i=1}^{N} \left(\frac{V_s}{V_i}\right)^2 u^2(V_i) + \sum_{i=1}^{N} V_s^{\ 2} \left(\frac{1}{T_i}\right)^2 u^2(T_i) + \sum_{i=1}^{N} V_s^{\ 2} \left(\frac{1}{p_i}\right)^2 u^2(p_i)$$

$$u^2(V_{sm}) = \sum_{i=1}^{N} \left(\frac{V_s}{V_i}\right)^2 u^2(V_i) + \sum_{i=1}^{N} V_s^{\ 2} \left(\frac{1}{T_i}\right)^2 u^2(T_i) + \sum_{i=1}^{N} V_s^{\ 2} \left(\frac{1}{p_i}\right)^2 u^2(p_i)$$

$$\frac{u^2(V_s)}{V_m^{\ 2}} = \frac{V_s^{\ 2} N}{V_m^{\ 2}} \left[\left(\frac{1}{V_i}\right)^2 u^2(V_i) + \left(\frac{1}{T_i}\right)^2 u^2(T_i) + \left(\frac{1}{p_i}\right)^2 u^2(p_i) \right]$$

$$\frac{V_s^{\ 2}}{V_m^{\ 2}} = \frac{1}{N^2}$$

$$\frac{u^2(V_s)}{V_m^{\ 2}} = \frac{1}{N} \left[\left(\frac{1}{V_i}\right)^2 u^2(V_i) + \left(\frac{1}{T_i}\right)^2 u^2(T_i) + \left(\frac{1}{p_i}\right)^2 u^2(p_i) \right]$$

APPENDIX B: CALIBRATION RESULTS

Meter #12935				
1L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	127	1.04	2.84	0.35
3	364	3.04	1.32	0.73
5	646	5.32	1.29	0.22
10	1237	10.14	1.21	0.15
20	2430	19.93	0.81	0.32
5 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	117	5.04	-0.39	0.55
3	356	14.49	0.50	0.32
5	618	24.70	0.41	0.13
10	1218	48.26	0.33	0.17
20	2467	96.74	0.22	0.07
10 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	119	10.22	0.23	0.48
3	388	31.10	-0.01	0.20
5	607	48.25	0.15	0.14
10	1219	96.57	0.06	0.06
20 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	120	20.61	0.27	0.16
3	361	58.30	0.12	0.05
5	603	97.11	-0.06	0.09
RPE=Relative Percentage Error; MSD=Mean Standard Deviation				

Meter # 13198				
1L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	129	1.10	-2.01	0.56
3	369	3.14	-1.76	0.26
5	649	5.49	-1.85	0.40
10	1226	10.47	-1.95	0.07
20	2422	20.54	-2.20	0.19
5 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	121	4.98	0.70	0.13
3	359	14.53	0.23	0.16
5	616	24.78	0.09	0.03
10	1221	48.38	0.09	0.14
20	2463	97.02	-0.08	0.08
10 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	120	10.18	0.62	0.15
3	385	31.03	0.20	0.03
5	607	48.24	0.17	0.11
10	1225	96.61	0.03	0.03
20 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	122	20.64	0.11	0.19
3	360	58.37	0.01	0.08
5	606	97.03	0.03	0.05
RPE=Relative Percentage Error; MSD=Mean Standard Deviation				

Meter # 13344				
1L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	133	1.10	-2.79	0.09
3	375	3.14	-1.90	0.29
5	656	5.48	-1.78	0.09
10	1248	10.41	-1.37	0.14
20	2455	20.42	-1.62	0.19
5 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	118	4.99	0.56	0.25
3	360	14.51	0.36	0.05
5	616	24.70	0.42	0.07
10	1231	48.27	0.30	0.11
20	2475	96.68	0.27	0.05
10 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	121	10.21	0.34	0.11
3	389	31.06	0.10	0.06
5	603	48.33	0.00	0.10
10	1221	96.70	-0.07	0.02
20 L/min				
t/min	#Sample	Volume/L	RPE%	MSD%
1	120	20.71	-0.22	0.11
3	360	58.45	-0.14	0.09
5	614	97.14	-0.09	0.05
RPE=Relative Percentage Error; MSD=Mean Standard Deviation				
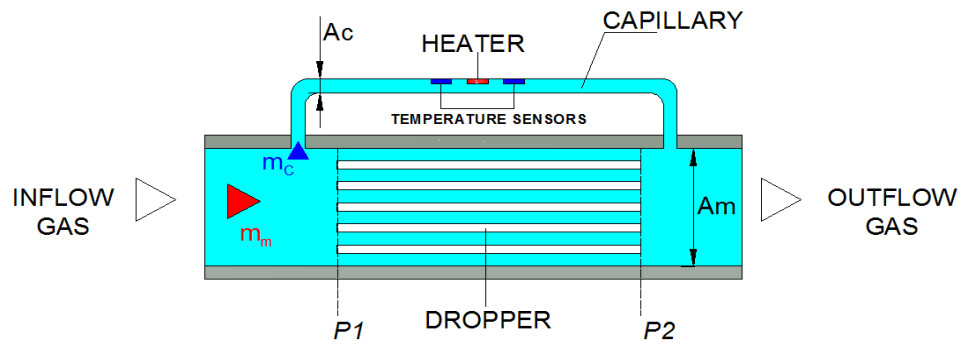
Figure1

Figure 1 - Basic elements of a by-pass capillary thermal mass flowmeter.
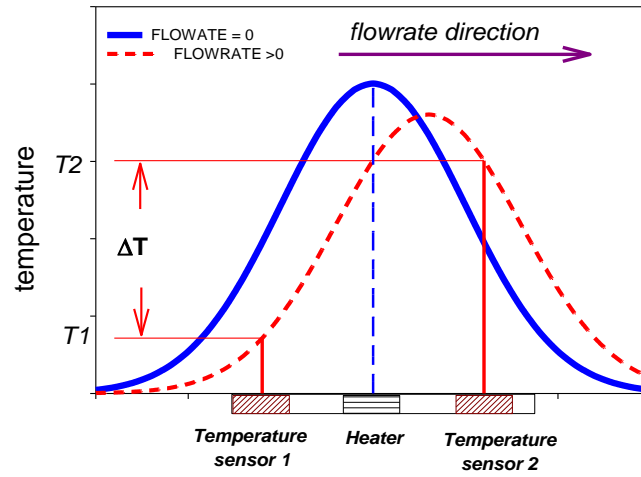
Figure 2 – Measurement principle of a by-pass capillary thermal mass flowmeter.
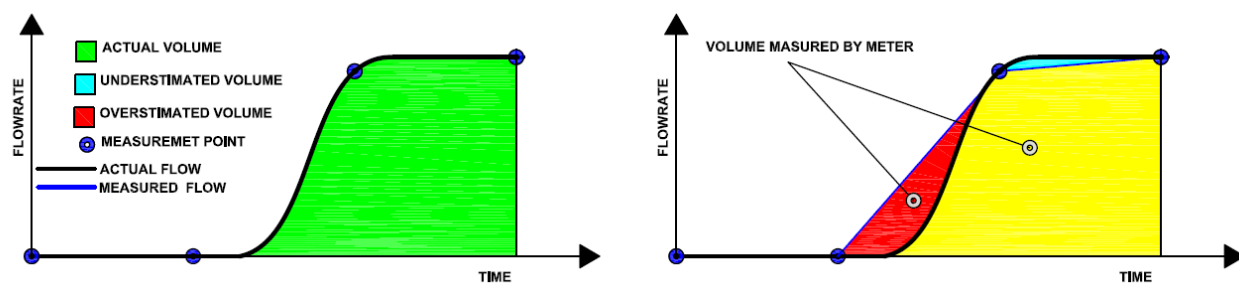
Figure3

Figure 3 - Gas flow profile at the startup of the meter with the measurement point (sampling points). It can be observed an error in the computation of the measured volume.
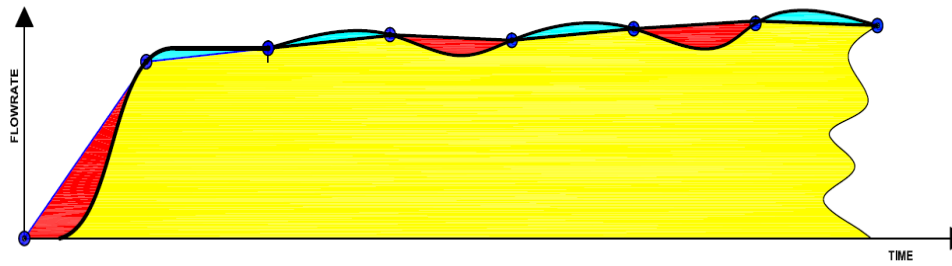
Figure4

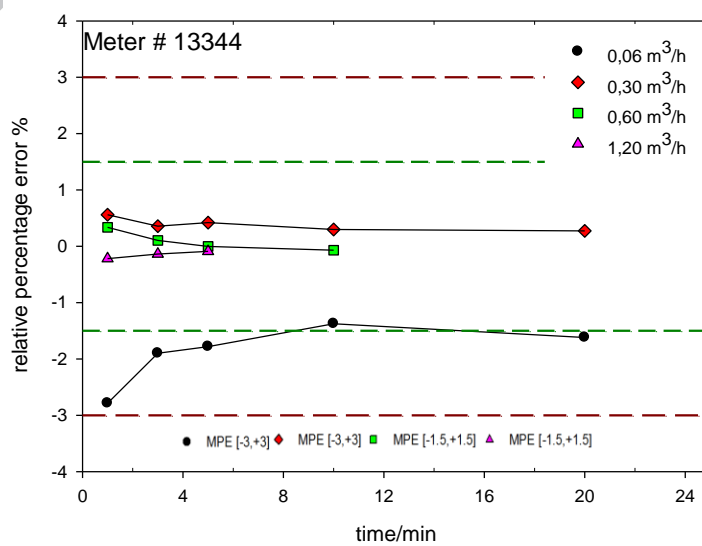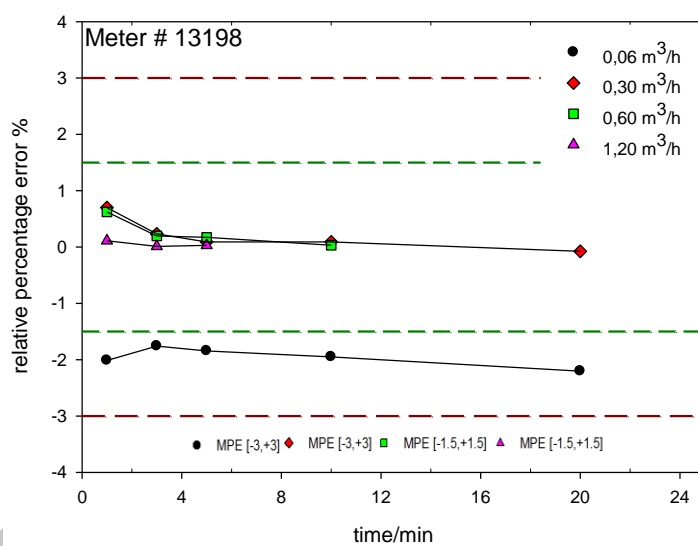*Figure 4 - Computation of the delivered volume during the (nominally) steady state functioning.*
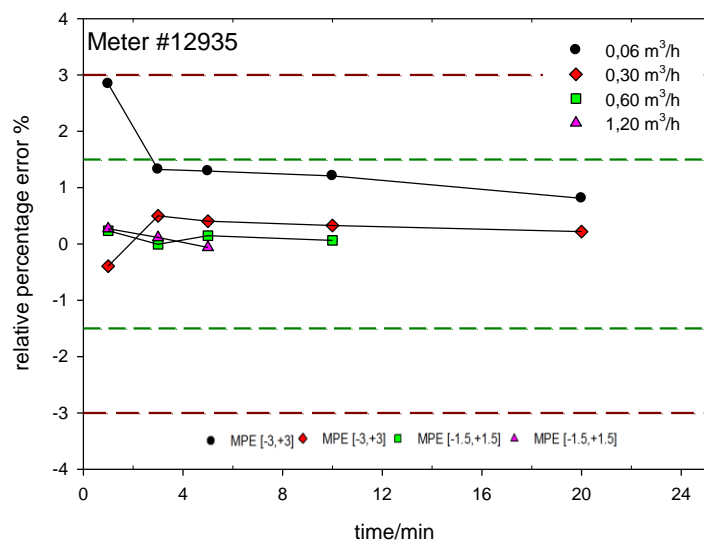
Figure5

Figure 5- Results of calibration test in terms of Relative Percentage Errors (RPE).
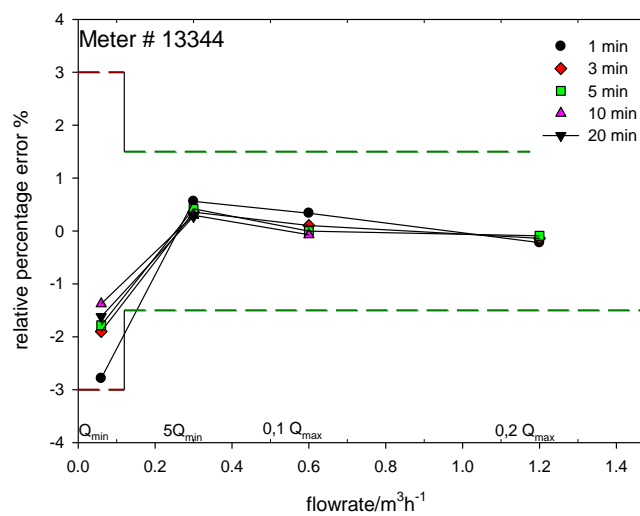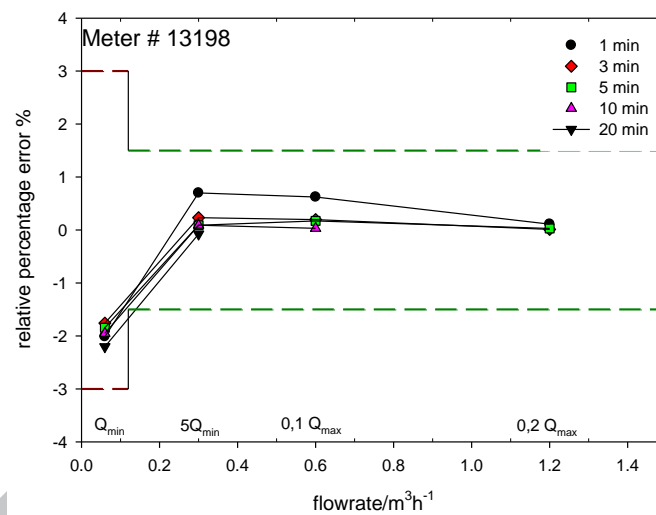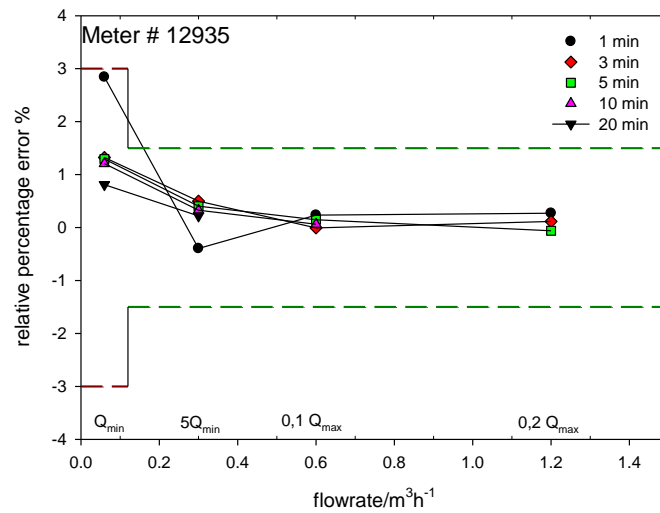
Figure6

Figure 6- Results of calibration test in terms of Relative Percentage Errors (RPE), in function of flowrate passed through the meter.

Tab.1- Tests carried out

Flowrate/m³h⁻¹	Time/min				
	1	3	5	10	20
0.06	✔	✔	✔	✔	✔
0.3	✔	✔	✔	✔	✔
0.6	✔	✔	✔	✔	
1.2	✔	✔	✔		

Highlights

- Different calibration procedures on a sample set of commercial Capillary Thermal Mass Flow Meter for natural gas
- Analysis of influence of sampling time on measurement accuracy
- Measurement uncertainties comparison between diaphragm and thermal mass gas meter