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# NEW GENERATION GAS METERS BASED ON THERMAL-MASS FLOW METERS: CALIBRATION RESULTS IN TWO ACCREDITED LABORATORIES

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## ABSTRACT

This paper presents two calibration results carried out by means of two different, independent, metrological accredited laboratories, on two sample of commercial CTTMFs (*Capillary Type Thermal Mass Flowmeter*), for natural gas in domestic/residential (G4) applications. The aim of this study is to evaluate the degree of metrological agreement among different calibration results, by means of the assessment of a suitable factor (*compatibility index*, also known as *normalized error)*.

This application study is quite interesting in the field of "legal metrology", when often conformity assessment is requested in order to assure the adequate behaviour of a domestic gas meter. The two tested gas meters were calibrated in two different laboratories, each of them characterized by different values of the calibration uncertainty (also called *CMC=Calibration and Measurement Capability*, or *BMC=Best Measurement Capability*, or *Minimum Uncertainty*).

The results here reported show a satisfactory agreement between the calibrations carried out by means of two different traceable test facilities: a volumetric primary standard (bell prover) and a secondary standard (sonic nozzles).

*Keywords: Compatibility index, thermal mass flowmeter, calibration, normalized error.*

## 1. INTRODUCTION

In general, natural gas flow metering technologies are based on the following instrumentations:

1) Gas flow sensor (gas meter):

- Traditional, mechanic, *volumetric* gas meters: mainly positive-displacement types, such as diaphragm meters, rotary piston meters, etc.;
- Traditional, mechanic, non-volumetric gas meters: turbine meters, differential pressure meters;
- New technology-based meters: ultrasonic meters, thermal mass flowmeters, Coriolis meters.

2) Conversion device: auxiliary instrument for the conversion (or correction) of gas volume in function of its pressure, temperature and compressibility factor; such type of instruments are usually not required for domestic gas metering. A gas volume converter, usually is composed by (i) a pressure probe (such as a piezo-resistive sensor), (ii) a temperature probe (such as a 4-wires platinum resistance detector), (iii) an electronic unit which converts the gas volume measured/registered by the meter (gas sensor) into "reference thermodynamic conditions" (or *reference conditions*: 1.013 bar and 15°C ) through the standard formula (compliant to AGA NX19, AGA8, S-GERG):

$$V_b = \frac{p_m}{p_b} \cdot \frac{T_b}{T_m} \cdot \frac{z_b}{z_m} \cdot V_m \qquad (1)$$

where:

$V_m$ = unconverted (measured) gas volume registered by the meter (m³);

$V_b$ = converted gas volume in reference (base) conditions (Nm³);

$T_m$ = gas temperature in operating conditions (K);

$T_b$ = reference (base) temperature (15°C = 288K);
$p_m$ = gas pressure in operating conditions (bar);

$p_b$ = reference (base) pressure (1.013 bar = 1013 hPa);

$z_m$ = compressibility factor in operating conditions (-);

$z_b$= compressibility factor in reference (base) conditions (-).

The gas volume converter typically plays also function of data-storage (local data logger) and remote data-transmission through several integrated communication media and protocols.

Traditional mechanical gas meters are analogic (dynamic), and therefore they are influenced by the effects of the wear (more sensitive to performance degradation pattern).

New technology-based gas meters are usually static, smart (fully electronics or digital meters) and therefore they are typically more stable in metrological performances. In addition, mass flow metering technologies (Coriolis and thermal) do not require an external volume conversion unit, since they display directly the gas volume expressed in reference/standard thermodynamic conditions.

Accurate measurement of natural gas in commercial transactions is a crucial matter. A very significant application of gas metering is represented by the domestic (residential) volumetric meters, very popular and widespread for accounting the consumption of citizens/consumers.
The accuracy of the measurement is very important in custody transfer applications (legal metrology). The respect of the compliance with legal metrology error limits (well known as *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.

This paper presents two calibration results carried out by means of two different, independent, metrological accredited laboratories, on two sample of commercial CTTMFs (*Capillary Type Thermal Mass Flowmeter*), for natural gas in domestic/residential (G4) applications. The aim of this study is to evaluate the degree of metrological agreement among different calibration results, by means of the assessment of a suitable factor (*compatibility index*, also known as *normalized error*). This application study is quite interesting in the field of "legal metrology", when often conformity assessment is requested in order to assure the adequate behaviour of a domestic gas meter. The two tested gas meters were calibrated in two different laboratories, each of them characterized by different values of the calibration uncertainty (also called *CMC=Calibration and Measurement Capability*, or *BMC=Best Measurement Capability, or Minimum Uncertainty*).
The results here reported show a satisfactory agreement between the calibrations carried out by means of two different traceable test facilities: a volumetric primary standard (bell prover) and a secondary standard (sonic nozzles).

## 2. OPERATION PRINCIPLE OF CAPILLARY TYPE THERMAL MASS FLOWMETERS

The new generation micro-thermal mass flow sensors (such as CMOS: Complementary Metal-Oxide Semiconductor, or MEMS: micro-thermal calorimeters) are based on the cooling of a heated miniaturized object (micro heater) placed in the flow. The measurement arrangement is composed of three basic elements (Figure 1): two temperature sensors and a central micro heater; both the temperature sensors and the micro heater are controlled by a suitable electronic module.

A bypass capillary type mass flowmeter is composed of four main elements (see Figure 1):

- a bypass circuit (in which flows the capillary mass flow rate mc, in a conduit of cross-section area Ac),
- a flow sensor mounted in the bypass circuit, in which the basic elements are miniaturized, thus realizing a measurement "chip",
- an electronic circuit (microcontroller),
- a pressure dropper (laminar element), placed in the main pipe (in which flows the main mass flow rate mm, in a conduit of cross-section area $A_m$).

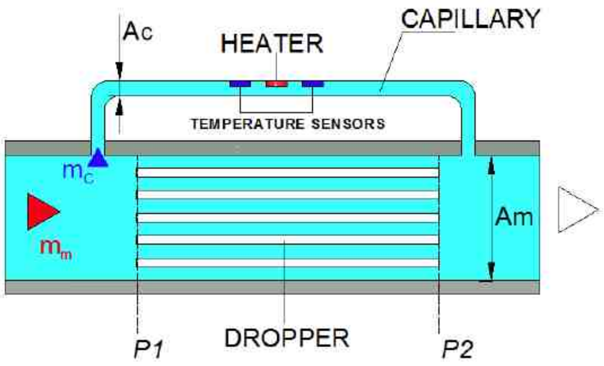


***Figure 1 – Basic elements of a by-pass capillary thermal mass flowmeter***

Gas enters the meter and is divided into two flow paths; in both the laminar flow regime is ensured: in the bypass capillary tube the laminar flow regime is ensured by the very small diameter of the capillary, and in the main tube by the pressure dropper/laminar flow element. Most of the flow ($m_m$=*main mass flow rate*) goes through the main pipe with pressure dropper: the pressure drop ($p_1$– $p_2$) forces a small fraction ($m_c$=*capillary mass flow rate*) of flow through the bypass capillary tube.

At the maximum flowrate, the pressure dropper placed in the main gas flow generates a pressure drop typically < 2 mbar. Less than 1 % (a very small amount) of the gas stream, i.e. the mass flow rate in the capillary circuit ($m_c$) is thereby forced to flow through the bypass capillary tube and over the sensor.

In the micro-thermal mass flow sensor, the temperature difference between two temperature sensors placed symmetrically upstream and downstream of the micro heater (see Figure 2) detects the passage of gas flow. If no gas is flowing over the sensor, the two thermo-elements measure the same rise in temperature (see Figure 2); if gas stream flows through the micro heater 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 exists in the form of 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 the gas flowed over the sensor-chip.

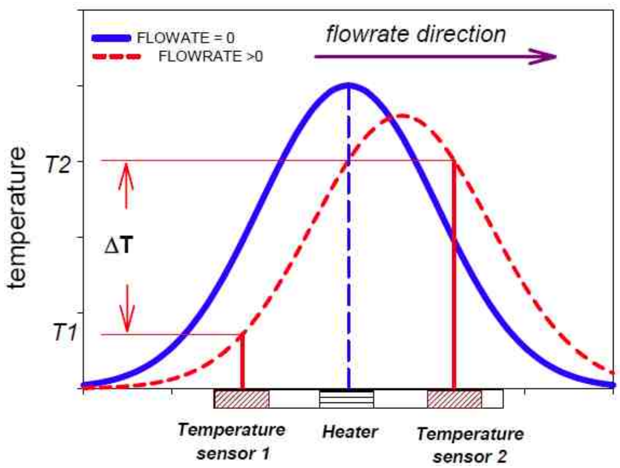


***Figure 2 – Temperature profiles in a by-pass capillary thermal mass flowmeter: with flow (dotted line) and without flow (continuous line)***

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):

$$Q_{el} = \mathrm{RI}^2 = Q_{th} = m_c c_p \Delta T \qquad (2)$$

Where:

$Q$ is the heat power produced (and measured in terms of electrical power) by the micro heater lost to the gas flow [W],

$R$ is electrical resistance [Ω],

$I$ is current intensity [A],

$m_c$ is the mass flow rate in the capillary bypass [kg/s],

$c_p$ is specific heat of the gas at constant pressure [J/(kg K)],

$\Delta T = T_2 - T_1$ is the net difference in gas temperature [K],

$T_1$ is the temperature detected by the upstream sensor [K],

$T_2$ is the temperature detected by the downstream sensor [K].

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 $\lambda$ of the gas, since the thermal diffusivity $\alpha$ of the gas is $\alpha = \lambda/(c_p \cdot \rho)$, 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).

## 3. CALIBRATION TECHNOLOGIES

Gas metering in legal metrology utilizes the meters mainly as *volume counters* (meter reading expressed in m³) rather than as volumetric flow meters (meter reading expressed in m³/s).

In the case of a thermal mass flowmeter, the gas volume - expressed at stated thermodynamic conditions: i.e. volume at *reference*, or *base* or *standard conditions* - is inferred from the measurement of the mass flow rate (by density conversion).

The *percentage error e(%)* (also called *deviation*) is defined as follows:

$$\mathrm{e}(\%) = \frac{V_{meter} - V_{ref}}{V_{ref}} \cdot 100 \qquad (3)$$

Where

$V_{meter}$ is the converted (in *base* or *standard conditions*) gas volume measured by the meter under test, [m³] (the difference between two meter readings at the beginning and at the end of the test),

$V_{ref}$ is the reference gas volume (in *base* or *standard conditions*) provided by a traceable standard, [m³].

Calibration of gas meters can be of two types:

- *primary calibration*, in which are compared the gas volume measured by the meter under test and the gas volume provided by a suitable (traceable) primary standard;
- *secondary calibration* (also called "reference - calibration"), in which are compared the gas volume measured by the meter under test and the gas volume provided by a reference (traceable) measurement system (secondary standard).

### *1.1 Primary calibration volume standard*

The *bell prover* principle of operation consists in measuring the time interval required to collect a known volume of gas at measured temperature and pressure. The bell prover typically is composed (Figure 3) by a cylindrical tank which forms an annulus filled with sealing oil. Into this annulus is placed the bell, open at the bottom and having a dome-shaped top. Its weight is nearly balanced by counterweights so that it can be raised or lowered by a small differential pressure (0.3 kPa) to collect and measure a volume of gas. A smaller counterweight is mounted on a cam so that it provides a correction for buoyancy effects as the bell immersion in the sealing liquid changes. Rollers and guide rods provide lateral stability in the bell position as it moves upwards. A control valve system provides firstly the filling of the bell by means of an air blower, and then (switching the position open/close of the valves) the gas containing in the bell flows through the meter under test for different fixed flow rate values. The accurate measurement of gas volume depends on the bell position assessment (by index), measured or in manual way (by a graduated scale) or in automatic way (by an opto-electronic systems).

Typical extended uncertainties of a primary standard bell prover range from ±0.10 to ±0.30% (with a coverage factor *k*=2, i.e. 95%);

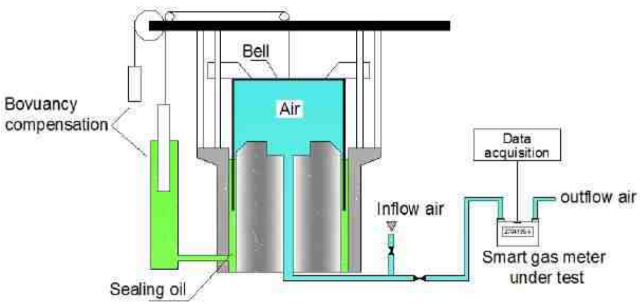


***Figure 3 – Bell prover (primary calibration) measurement scheme***

### *1.2 Secondary calibration volume standard*

A sonic nozzle is typically used as transfer standard during flowmeter calibration. The mass flow rate (in the case of sonic flow) of the gas passing through the nozzle is a function of the thermodynamic conditions upstream (inlet pressure, inlet temperature) and of the type of gas. Sonic nozzle, base the principle of measuring on a linear relationship between mass flow and the inlet pressure and temperature when the gas is flowing through the nozzle at sonic velocity. Normally, flow reaches sonic velocity when the downstream pressure is not greater than one half the upstream pressure.

The geometry of a sonic nozzle (designs and manufactures in accordance with both ASME and ISO standards) is such that the gas is accelerated along the circular arc converging section and then is expanded in a conical diverging section, which is designed for pressure recovery (Figure 4). In the throat, or minimum area point of the sonic nozzle, the gas velocity becomes equal to the speed of sound. At this point, gas velocity and density are maximized, and the mass flow rate is a function of the inlet pressure, inlet temperature, and the type of gas.

The equation characteristic of sonic nozzles is as follows:

$$\mathrm{m} = \mathrm{A}\,\mathrm{C}_d\,\mathrm{C}_c \cdot \frac{p}{\sqrt{r\,\mathrm{T}}} = \mathrm{A}\,\mathrm{C}_d\,\mathrm{C}_c \cdot \frac{p}{\sqrt{\left(\frac{R}{M}\right)\mathrm{T}}} \qquad (4)$$

where

- A is the cross section of flow at nozzle throat ($m^2$),
- M is the molar mass of the gas (kg/mol),
- m is the mass flow rate (kg/s),
- p is the upstream gas pressure, at the nozzle inlet (Pa)
- r is the ratio of the universal ideal gas constant to molar mass of the gas (J/kg K)
- R is the universal ideal gas constant (J $mol^{-1}K^{-1}$)
- T is the upstream gas temperature, at the nozzle inlet (K).
- $C_d$ discharge coefficient (-)
- $C_c$ critical flow factor

Typical extended uncertainties of a secondary standard (flow nozzle) range from ±0.30 to ±0.60% (with a coverage factor *k*=2, i.e. 95%);

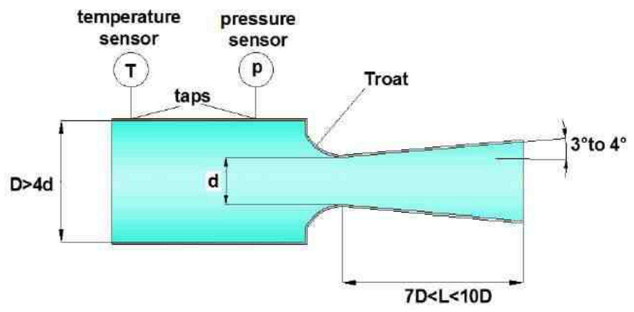


***Figure 4 – Bell prover (primary calibration) measurement scheme***

## 4. CALIBRATION AND METROLOGICAL COMPATIBILITY

The metrological characterization of a gas meter, in legal metrology applications, is carried out by means of suitable calibration. The main aim of the gas meter calibration is to determine the measurement errors, and the comparison with the Maximum Permissible Errors (MPE).

For the two tested G4 capillary type thermal mass gas meters CTTMFs (named in the following text as "meter A" and "meter B") the MPE limits are:

- ± 3% in the field $Q_{min} < Q < Q_t$ ;
- ± 1.5% in the field $Q_t \leq Q \leq Q_{max}$ ,

where $Q_t$ is the transitional flow rate that divides the flowrate range into two fields (the upper and the lower zones).

The Minimum Calibration Uncertainty (or the Best Measurement Capability, BMC) of the test facilities during the test are the following (for $k$=2):

Bell prover - primary calibration rig:

$BMC_{Lab\ 1}$ = ± 0.30% (for all the test flow rates)

Sonic nozzles – secondary calibration rig:

$BMC_{Lab\ 2}$ = ±0.60% (at the minimum test flow rate)
$BMC_{Lab\ 2}$ = ± 0.30% (at the higher flow rates)

The comparison of the calibration results is usually carried out through the *normalized error* $E_{1,2}$ (or *compatibility index*), calculated between 2 involved laboratories (for example "*Lab 1 – Primary Standard" and "Lab 2 – Secondary Standard*"):

$$E_{1,2} = \frac{\left|\bar{e}_{Lab1} - \bar{e}_{Lab2}\right|}{\sqrt{U^2_{Lab1} + U^2_{Lab2}}} \qquad (5)$$

where:

$\bar{e}_{Lab1}$ is the average percentage error (%) evaluated in the Laboratory 1 – Primary Standard, for each test gas flow rate;

$\bar{e}_{Lab2}$ is the average percentage error (%) evaluated in the Laboratory 2 – Secondary Standard, for each test gas flow rate;

$U_{Lab1}$ is the extended uncertainty (%) of the Laboratory 1 – Primary Standard

$U_{Lab2}$ is the extended uncertainty (%) of the Laboratory 2 – Secondary Standard

As concerns the average percentage error ($\bar{e}_{Lab}$) it is worth to pointing out that each Laboratory assumes 6 measurement repetitions (for each test flow rate).

The test flow rates are the following: $Q_{min}$, 0.1 $Q_{max}$, 0.2 $Q_{max}$, 0.4 $Q_{max}$, 0.7 $Q_{max}$, $Q_{max}$.

For each test flow rate, the extended uncertainty ($U_{Lab}$) of the Calibration Laboratory is defined as follows:

$$U_{Lab} = k \cdot u_{C_{Lab}}(\%) = k \cdot \left(\sqrt{u_A^2 + u_B^2}\right)_{Lab} \qquad (6)$$

where:

$u_A = \frac{s}{\sqrt{N}}$ is the type-A uncertainty (i.e. the ratio between the experimental standard deviation "$s$" of a series of 6 measurement repetitions, and the square-root of the number of repetitions N=6),

$u_B$ is the type-B uncertainty occurred during actual measurements (also called CMC o BMC),

$u_{C_{Lab}}$ is the combined standard uncertainty,

$k$ is the coverage factor, usually chosen to ensure a 95% confidence level .

$E_{n_{1,2}} \leq 1$ indicates that the metrological agreement is good (full metrological compatibility between couples of calibration measurements).

$E_{n_{1,2}} > 1$ means that the difference between the two error values determinate by different calibrations cannot be covered by the uncertainty of the same difference; in other words the two calibration results are not mutually compatible and therefore the calibration performances of the two Laboratories must be improved and "*aligned*".

| | Lab 1 - Primary Standard | | | | | |
|---|---|---|---|---|---|---|
| | Meter A | | | | | |
| | E | $u_A$ | $u_C$ | $u_B$ | k | $U_{Lab1}$ |
| **Flowrate** | % | % | % | % | | |
| $Q_{max}$ | 0.41 | 0.06 | 0.16 | 0.15 | 2.02 | 0.33 |
| $0.7Q_{max}$ | 0.68 | 0.07 | 0.16 | 0.15 | 2.03 | 0.33 |
| $0.4Q_{max}$ | 1.06 | 0.12 | 0.19 | 0.15 | 2.20 | 0.43 |
| $0.2Q_{max}$ | 0.00 | 0.06 | 0.16 | 0.15 | 2.02 | 0.33 |
| $0.1Q_{max}$ | 0.20 | 0.02 | 0.15 | 0.15 | 2.01 | 0.31 |
| $Q_{min}$ | -0.42 | 0.07 | 0.16 | 0.15 | 2.06 | 0.34 |

***Table 1 – Results of the Primary Calibration (Meter A)***

| | Lab 1 - Primary Standard | | | | | |
|---|---|---|---|---|---|---|
| | Meter B | | | | | |
| | E | $u_A$ | $u_C$ | $u_B$ | k | $U_{Lab1}$ |
| **Flowrate** | % | % | % | % | | |
| $Q_{max}$ | 0.45 | 0.13 | 0.20 | 0.15 | 2.23 | 0.44 |
| $0.7Q_{max}$ | 0.50 | 0.11 | 0.19 | 0.15 | 2.16 | 0.41 |
| $0.4Q_{max}$ | 0.70 | 0.10 | 0.18 | 0.15 | 2.11 | 0.38 |
| $0.2Q_{max}$ | -0.17 | 0.02 | 0.15 | 0.15 | 2.01 | 0.30 |
| $0.1Q_{max}$ | -0.09 | 0.03 | 0.15 | 0.15 | 2.01 | 0.31 |
| $Q_{min}$ | 0.32 | 0.05 | 0.16 | 0.15 | 2.03 | 0.32 |

***Table 2 – Results of the Primary Calibration (Meter B)***

| | Lab 2 - Secondary Standard | | | | | |
|---|---|---|---|---|---|---|
| | Meter A | | | | | |
| | E | $u_A$ | $u_C$ | $u_B$ | k | $U_{Lab1}$ |
| **Flowrate** | % | % | % | % | | |
| $Q_{max}$ | 0.33 | 0.05 | 0.16 | 0.15 | 2.02 | 0.32 |
| $0.7Q_{max}$ | 0.44 | 0.06 | 0.16 | 0.15 | 2.02 | 0.33 |
| $0.4Q_{max}$ | 0.77 | 0.03 | 0.15 | 0.15 | 2.01 | 0.31 |
| $0.2Q_{max}$ | -0.12 | 0.00 | 0.15 | 0.15 | 2.01 | 0.30 |
| $0.1Q_{max}$ | 0.15 | 0.02 | 0.15 | 0.15 | 2.01 | 0.30 |
| $Q_{min}$ | 0.56 | 0.02 | 0.30 | 0.30 | 2.01 | 0.60 |

***Table 3– Results of the Secondary Calibration (Meter A)***

| | Lab 2 - Secondary Standard | | | | | |
|---|---|---|---|---|---|---|
| | Meter B | | | | | |
| | E | $u_A$ | $u_C$ | $u_B$ | k | $U_{Lab1}$ |
| **Flowrate** | % | % | % | % | | |
| $Q_{max}$ | 0.36 | 0.05 | 0.16 | 0.15 | 2.01 | 0.32 |
| $0.7Q_{max}$ | 0.50 | 0.03 | 0.15 | 0.15 | 2.01 | 0.31 |
| $0.4Q_{max}$ | 0.57 | 0.02 | 0.15 | 0.15 | 2.01 | 0.31 |
| $0.2Q_{max}$ | -0.14 | 0.03 | 0.15 | 0.15 | 2.01 | 0.31 |
| $0.1Q_{max}$ | -0.09 | 0.01 | 0.15 | 0.15 | 2.01 | 0.30 |
| $Q_{min}$ | 0.31 | 0.01 | 0.30 | 0.30 | 2.01 | 0.60 |

***Table 4– Results of the Secondary Calibration (Meter B)***

## 5. DISCUSSION AND CONCLUSIONS

In Tables 1, 2 and 3, 4 are reported the calibration results, obtained respectively in the Primary Standard Calibration Laboratory (Lab 1) and in the Secondary Standard Calibration Laboratory (Lab 2).

In Figures 5 and 6 are shown the calibration results, plotted respect to the MPE limits.

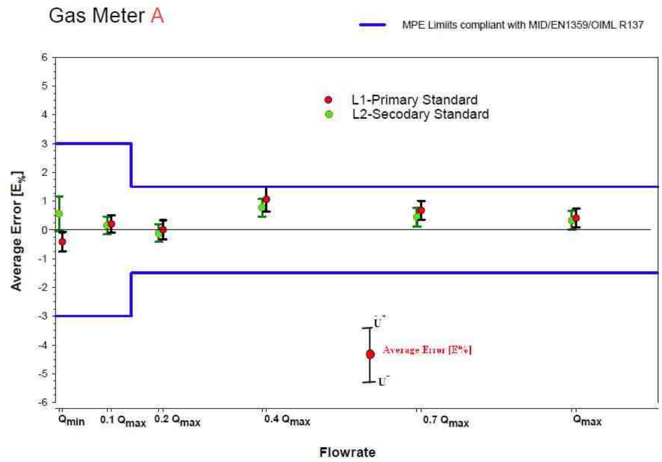


*Figure 5 – Comparison between the calibration results carried out in the two different Laboratories on the same meter A.*

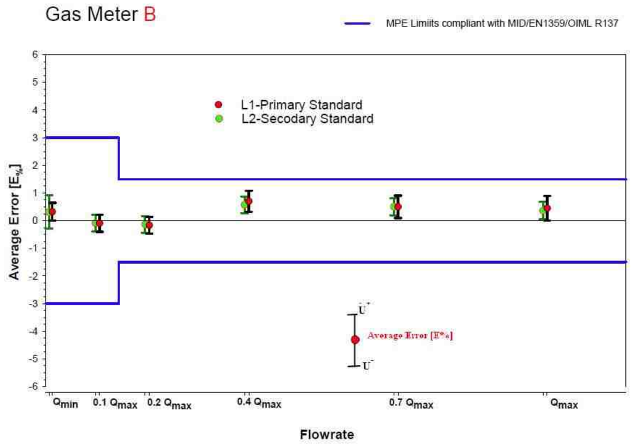


*Figure 6 – Comparison between the calibration results carried out in the two different Laboratories on the same meter A.*

In Table 3 are reported the values of the Compatibility Index between the Primary and the Secondary Calibration.

| | **Compatibility Index** | |
|---|---|---|
| | **Meter A** | **Meter B** |
| **Flowrate** | | |
| $Q_{max}$ | 0.17 | 0.16 |
| $0.7Q_{max}$ | 0.51 | 0.00 |
| $0.4Q_{max}$ | 0.55 | 0.26 |
| $0.2Q_{max}$ | 0.28 | 0.07 |
| $0.1Q_{max}$ | 0.12 | 0.01 |
| $Q_{min}$ | 1.41 | 0.02 |

*Table 5– Results of the Secondary Calibration (Meter B)*

It should be noted that the method of determination of normalized errors is based on the hypothesis that no changes of status (or of performance) of the instrument under test occur.

Possible, unavoidable, slight changes of the meter status (caused by transportation and storage condition) can affect the calibration results. In the case study here presented, the time shift in calibrations is of about 15 months. The good agreement of the calibration results is probably due to the static measurement principle of the CTTMF.

Finally, it is possible to summarize the following conclusions for the new generation of CTTMFs tested:

1) for both the tested meters the errors are within the MPE limits;
2) the two calibration results show a good (satisfactory) compatibility index;
3) the calibration results obtained in the two different test laboratories are in good agreement: such feature is particularly interesting and meaningful since the two calibration approaches are quite different: in the primary calibration rig (using the bell prover) the primary measured quantity is the gas volume and the flow rate is inferred from the test time measurement; instead in the secondary calibration rig (using critical nozzle) the primary measured quantity is the gas flow rate, and the gas volume is inferred also measuring the test time;

4) a slight misalignment is occurred only for the Meter A at the minimum flow rate (Qmin).

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