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A novel calibration of the Large Piston Prover at INRIM

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Abstract

INRIM realizes its flow rate standard using three distinct facilities, aimed at measuring different flow rate ranges; in particular, for the larger flow range (10-2600 L/min) a piston of 1000 mm nominal diameter and 1200 mm nominal stroke is used. The traceability of the standard is obtained through dimensional calibration of the piston, regarding both the piston size and its stroke.
The first calibration of the machine was performed at its initial installation. Even if most of the relevant documentation about this first calibration is not available, INRIM realized a procedure similar to the old one and performed measurements to renovate the first facility calibration. The present paper will dedicate special attention to the description of the measurement chain used for the calibration of the piston in its own siege. Moreover, the method for the transfer of traceability from the length standard to the measurement of the piston diameter will be discussed; it should be noted that the dimensional study is not completed yet, because the first set of measurements described in the present work, evidenced the criticalities of the procedure adopted in the past. For this aim, a further measurement campaign will be carried out in order to minimize the uncertainty associated to the dimensional measurement of the piston and of its displacement. Finally, the results of first dimensional evaluation will be presented alongside.

1. Introduction

Measurement of gas flow rates is a field whose importance is growing due to the need for accurate calibration of mass flow meters with various FSR (Full Scale Range), that have an increasingly wide field of application (*e.g.* for dynamical gas mixing, aerospace applications, etc.).

For intermediate flow ranges, a robust and reliable technology is the piston prover volumetric method, since it allows to provide a carefully controlled flow of gas; its accurate measurement requires a reliable and precise knowledge of the relationship between delivered volume and piston movement, the possibility to precisely measure the gas temperature and pressure, and the possibility of using high purity gases for the tests.

INRIM has operated the MEGAS bell prover for several years now [1]. This test rig allows measurements of flow rates lower ranging between 1 and 2400 L/min with uncertainties of the order of 0.05% due to several technological features which include a very accurate piston machining, reduced movement friction, accurate measurement of the piston movement and of the gas thermodynamic conditions, and temperature stabilization of the ambient. Though, the main requirement for the measurement is still an accurate calibration of the volume of the piston as a function of its movement, which can be obtained through measurement of the local diameter; in this paper, the dimensional method employed at INRIM for this task is described alongside with the presentation of results obtained during the last measurements.

2. MEGAS design and capabilities

2.1 MEGAS design

The MEGAS test rig (Figure 1) was designed as a high-performance piston prover for gas flow; within volumetric calibration machines, the piston prover design is intrinsically more accurate than the bell prover design since it requires an accurate machining of the exterior diameter of a piston instead of the interior diameter of a bell and allows therefore lower uncertainties. Of course, this is true provided all other terms of the uncertainty budget are kept low enough. The prover here described includes a stainless steel hollow piston with nominal diameter of 1 m and nominal length of 1.6 m, which moves within a cylindrical chamber also built in stainless steel; the system is provided with a pressure probe allowing the measurement of its internal pressure and twelve platinum resistance thermometers (PT100), placed on the inner wall of the cylinder at different heights in order to measure

the average temperature of the test gas inside the machine and to detect possible vertical thermal gradients. The piston is moved by a screw (10 mm pitch) actuated by an electrical motor controlled by a digital driver and connected to a gear box with variable ratio; it is thus possible to obtain a wide range of stably controlled piston speeds.
The measurement of the gas flow is performed by measuring the movement of the piston by a high resolution encoder (18000 steps per revolution) and the flow time by a quartz clock. The gas flow is then obtained by means of the mass equation balance. This method computes the gas flow by evaluating the initial mass of gas present inside the cylinder (which can be obtained from the initial thermodynamic conditions and an evaluation of the initial volume) and the final mass of gas (obtained from the final thermodynamic conditions and the final volume). The method thus implicitly keeps into account the variations of thermodynamic conditions. More importantly, it can be shown that, if the variations of thermodynamic conditions are not large, the sensitivity coefficient of the uncertainty associated to the initial volume is very small, therefore it is not required to have an accurate evaluation of this quantity; on the other hand, the accuracy on the volume variation is one of the main components in the determination of the final uncertainty, therefore all details of the machine were designed with the aim of increasing this accuracy. In particular, the piston was carefully machined to have a shape very close to a perfect cylinder and the thickness of its wall is large enough to ensure a very high rigidity, thus a remarkable stability, as will be shown in the results section. Additionally, the distance between the piston and the inner walls of the chamber is of 40 mm to reduce the dead volume.
In order to reduce temperature variations, the test rig is placed within a temperature-conditioned room where the temperature is stable within 0.1 K (during a typical measurement time) and with small vertical temperature gradients. The ambient pressure and the relative humidity of the room are monitored by means of a TESTO instrument.

2.2 MEGAS capabilities

The test rig presented in subsection 2.1 has a maximum flow rate capability of 2400 L/min (which corresponds to 144 m^3/h), which can be obtained by completing a full stroke of the piston in 30 s, while the minimum flow rate that can be obtained is of the order of 1 L/min. The uncertainty of the flow rate, evaluated based on the previous calibration of the system, is of 0.05%.
The machine in its present status can work as a gas provider running at constant speed, although future developments of the motor control system are forecast to render it possible to work as a gas acceptor and to run at variable speed to maintain constant pressure inside the cylinder in order to expand its calibration possibilities

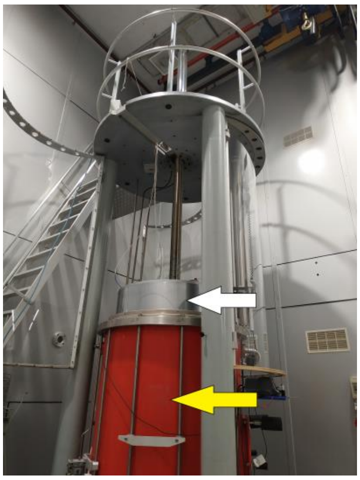

Figure 1: MEGAS; the piston (yellow arrow) and the chamber (withe arrow).

3. MEGAS calibration procedure

The MEGAS calibration takes into account the geometrical characteristics of the MEGAS piston, the displacement and the translation time of piston inside the MEGAS chamber (see Figure 1).
The total volume of the piston has to be evaluated in order to compute the mean volume variation during the piston translation. The piston is not removable from the chamber, and its sizes of about 1 m of diameter and 1.6 m of length do not allow its geometrical evaluation by means of the measurement facilities allowable at INRIM (as for example the Coordinate Measurement Machine property of the Institute). For these two reasons the relevant geometrical characteristics of the piston were evaluated in situ.
A linear encoder system was used for the diameter evaluation whereas the vertical translation of the piston was measured by a traceable interfero-meter. The two system and their placement are described in detail in the following section.

An appropriately designed bar (Figure 2), traceable to the length standard, was used as a reference for the piston diameter measurement. The reference bar is made of stainless steel with two parallel faces at the tips and a nominal length of 1 m; the rectangular faces are machined to reduce the surface roughness and to grant an accurate parallelism between each other. The body of the bar is designed to allow its positioning on the top of the piston taking into account the footprint of the central screw. The bar length is traceable to the length standard by means of a calibration report. According to the calibration report, the bar length was evaluated in two different positions on the tip faces: in the central point of the rectangular faces and in a peripheral position. For the current measurements the mean vale of the two calibrated lengths has been considered:

$\bar{l}_{ref}$ = 999.255 mm ± 5 µm.

Figure 2: The reference bar and an enlargement showing the tip face.

The evaluation process of the piston diameter consists in the dimensional scanning of six couple of generatrices positioned at an angle of 30° from each other and a seventh couple of generatices (Ref) positioned as shown in Figure 3. This test configuration has been repeated according to the first calibration procedure conducted on the MEGAS in order to compare present results with those obtained in the past.

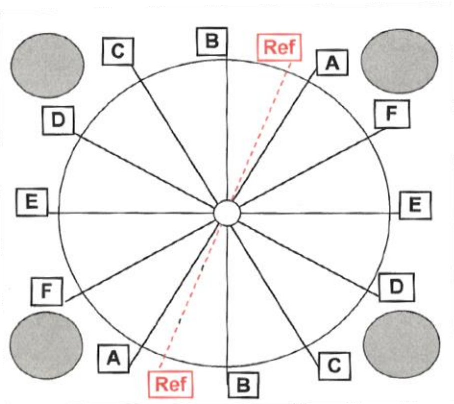

Figure 3: sketch of the top view of the piston. Letters indicate the seven positions investigated. Notice that the Ref (in red) indicates the last configuration investigated and not the reference bar.

The scanning procedure was conducted with two calibrated linear encoders positioned as described in section 4. A platinum resistance thermometer (PRT) was positioned on the reference bar in order to monitor the thermal conditions of the bar reference during scanning measures.

The piston is about 1.6 m long and the two end-of-strokes of the piston run cover 1.3 m of total length. For the diameter evaluation a portion of the piston height, called *working length*, of about 0.8 m centred with respect to the middle section of the piston, has been considered.

The piston displacement has been evaluated by means of an interferometer aligned to the piston axis. The acquisition of the interferometer was synchronous with that of the linear encoder system. The interferometer setup and its positioning is described in section 4.

The measurement procedure followed for the seven couple of generatrices is the following:

The linear encoders are positioned in the configuration A according to the scheme shown in Figure 3.

The piston is positioned in its lower position and the reference bar is placed on top of the piston; after an appropriate waiting time for thermal effect stabilization caused by the operator intervention, the linear encoders are set on the reference parallel tip faces (see Figure 4). The initial reference value Δl_{ref1} is thus acquired, then the piston is positioned at its lower end-of-stoke and the scanning procedure of the first couple of generatrices started. The piston is stopped at its higher end-of-stroke and the scanning procedure is repeated downward.

The generatrix scanning (upward and downward) is thus repeated six times obtaining seven repetitions totally. Finally the final reference value Δl_{ref2} is acquired again by the two linear encoder on the reference bar that was kept in the same position for the whole scanning procedure. The acquisition of this last reference value complete the scanning procedure of one couple of generatices.

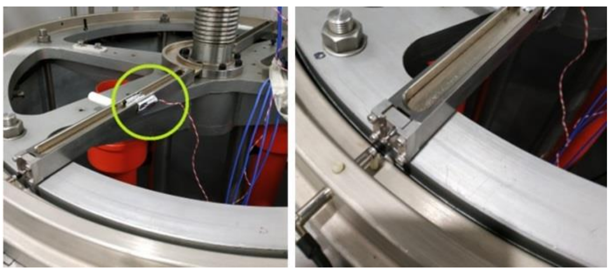

Figure 4: on the left: reference bar placed on the top of the piston and PRT on the reference bar (green circle); on the right: linear encoder positioned on a reference tip face.

At the end of the first scan (configuration A), the linear encoders are rotated around the piston axis according to the proposed scheme (Fig. 4) and the scanning procedure is repeated for the remaining six positions (B, C, D, E, F and Ref).

The acquisition of the interferometer, measuring the piston displacement, was set synchronous with the linear encoder system. Ambient conditions (pressure, temperature and humidity) have been acquired during the whole measurement campaign in order to evaluate the proper correction for air refractivity.

The analyses of measures are described in results subsection 5.

4. Measurement chain for calibration

Details of the measurement chains designed for the MEGAS calibration are described in this subsection in order to detail the measuring procedure in the previous section.

4.1 linear encoder system

Two linear encoders TESATRONIC TT60 have been used to evaluate the mean value of the piston diameter. The TT60 measurement range is 5 mm with a resolution of 0.1 μm. A stainless steel ring was opportunely designed to place the two linear encoder in correspondence to the piston diameter (Figure 5).

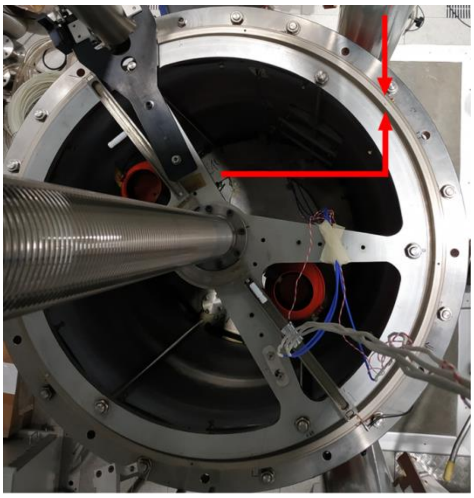

Figure 5: red arrows indicate the ring for the linear encoder positioning.

The ring is placed on the O-ring between the chamber and the piston after removing a ring made of Teflon for dust protection. The ring is transversally holed in order to insert the two linear encoder steams in correspondence to a ring diameter. The steams are thus locked to the ring structure by means of two clamping grains made of Teflon (Figure 4).

For this first measurement campaign the ring has not been fixed during the scanning procedure but it is expected to consider the use of a fixing system for future measures. The linear encoders were positioned in the seven configurations described in the previous section (Figure 3) by turning the ring around the piston axis.

The measure of each couple of generatrices was conducted at a piston speed of about 6.5 mm/s; the acquisition time for every generatrix was about 197 s, corresponding to 1295 output samples.

4.2 interferometer

An AGILENT 5518A interferometer was placed under the MEGAS chamber on the floor (Figure 6). The laser alignment was difficult because, in spite what happens usually, it was not possible to move the corner cube (CC), which was fixed to the piston bottom surface inside the MEGAS chamber. As a consequence of this measurement system configuration, the alignment of the Laser to the movement axis had to be performed with two mirrors (M1 and M2), with a not favourable optical leverage. The alignment was checked with a four-quadrant detectors in order to keep the cosine error below 10^{-8}. The interferometer acquisition was synchronous with the linear encoder system resulting in about 1 output sample every millimetre of piston stroke.

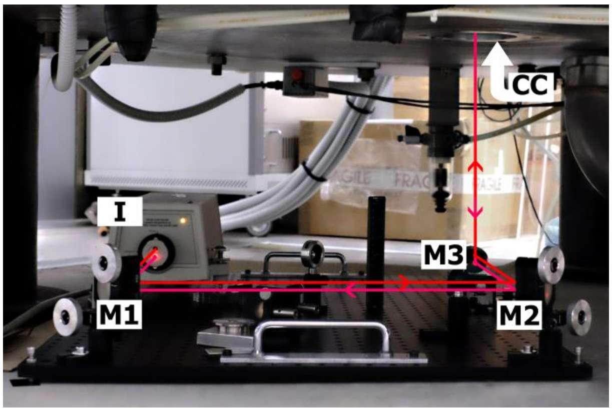

Figure 6: red arrows indicate the laser path. I: interferometer: M1, M2, M3: mirrors; CC: corner cube positioned on the piston (not visible in figure).

4.3 thermometric sensors

The temperature of the piston was measured by placing four platinum resistance thermometers (PRT - Pt100 1/3 Din) inside it.

Four PRTs have been positioned in the inner surface of the piston in correspondence of the two generatrices A (fig. 4) and in particular: one

thermometer was placed in the middle of a generatrix, whereas three thermometers are placed respectively in the centre and about 0.5 upward and 0.5 m downward with respect to the centre of the specular generatrix. This thermometer placement allowed to evaluate thermal stability over time and to monitor the temperature gradient along the axis and the central diameter of the piston.
A fifth additional PRT has been placed on the reference bar to evaluate its thermal stability (Figure 3).
All PRTs are connected to a KEITHLEY 6 ½ Digit digital multimeter mod. 2700 via a 20-channel scanner card. This thermometric chain was calibrated at INRiM, in a range from 18 °C to 22 °C with a final expanded uncertainty of 0.01 °C.
The commercial software ExcelLink by KEITHLEY was used for acquisition. Every thermometer temperature has been acquired in series during all the scanning procedure every 2 seconds.
In addition to these five thermometers, placed specially for MEGAS facility calibration, twelve PT100 calibrated probes, are placed on the inner surface of the chamber containing the piston at different heights. This last thermometric chain is a permanent component of the MEGAS measurement chain and it is used to monitor the temperature gradients of the test gas inside the facility and to detect vertical thermal gradients in the piston chamber.

5. Measurement results

In this section the first measurement results are shown.
First, the linear encoders measures have been analysed for the evaluation of the pistons diameter as a function of the generatrices.
The following Equation (1) has been applied:

$$d_{i\,(genA)} = \Delta l_{i(genA)} - \bar{l}_{ref(genA)} + \bar{l}_{ref} \qquad (1)$$

Where:
$\boldsymbol{d_{i\,(genA)}}$ is the i-th diameter with linear encoders positioned in the A configuration (generatrix A, Figure 3).
$\boldsymbol{\Delta l_{i(genA)}}$ is the i-th linear encoders output (generatrix A).
$\boldsymbol{\bar{l}_{ref(genA)}}$ is the mean value of Δl_{ref1} and Δl_{ref2} (see section 3)
$\boldsymbol{\bar{l}_{ref}}$ is the calibrated mean length of the reference bar (see section 3).

The equation 1 is representative for the case of linear encoder in the configuration A (Figure 3); the same equation is used for all the seven configurations (A, B, C, D , E, F and Ref.)
Then the mean diameters of the piston, taking into account the seven couple of generatrices scanned seven times each, has been evaluated; the resulting curve trends are shown in Figure 7.

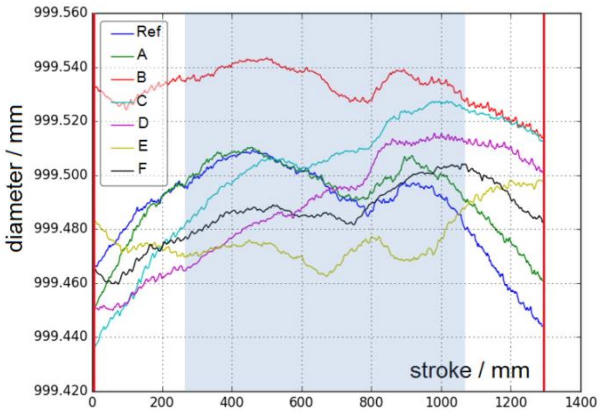

Figure 7: mean diameters as a function of the seven generatrices. Red lines: end-of-strokes; blue zone: working length.

The less regular trend evidenced by the acquisition at the ends of the piston are out of the working zone, therefore the higher dispersion of the curves in these zones does not contribute to the mean diameters dispersion. Taking into account the working zone (between 265 mm to 1063 mm in Figure 7) the mean diameter curves show a dispersion of vales between 999.46 mm to 999.54 mm. This result shows a larger dispersion with respect to the first MEGAS calibration [1], when a dispersion between 999.50 mm to 999.53 mm at 20 °C in a working length of 1 m was found.
In Table 1 the mean values of each diameter curves as a function of the generatrix positions are shown.

Table 1: diameters mean vales and associated standard deviations as a function of generatrices.

Generatrix	stroke		working length	
	Mean / mm	σ / mm	Mean / mm	σ / mm
Ref	999.489	0.016	999.498	0.007
A	999.492	0.014	999.501	0.005
B	999.532	0.007	999.536	0.005
C	999.501	0.024	999.508	0.012
D	999.489	0.021	999.493	0.015
E	999.477	0.009	999.472	0.005
F	999.486	0.011	999.489	0.007

As a final evaluation, the mean diameter of the piston has been computed taking into account all the repeated acquisition along the seven generatrices. Table 2 summarizes this last result.

Table 2: mean diameter of the piston as a function of the investigated zone.

	Mean / mm	σ / mm
stroke	999.495	0.024
working length	999.500	0.021

The PRT on the bar evidenced a temperature variation of the order of 0.05 K. The same order of temperature variation was registered by the four PRT placed on the inner surface of the piston. Taking into account the coefficient of thermal expansion of stainless steel (of the order of 10 ppm/K) and the acquired temperature variations, it is reasonable to neglect the thermal expansion of the reference bar and of the piston in the final mean diameter computation.

As regards the piston displacement measure, a mean displacement of the piston has been evaluated to be (0.5555 ± 0.0006) μm/step.

Figure 8 and Figure 9 show, respectively, the displacement of the piston as acquired by the interferometer between two consecutive sampling points (corresponding to 1 mm), and a closer view of the first 100 points, showing a periodic variation with a period equal to the 10 mm screw pitch.

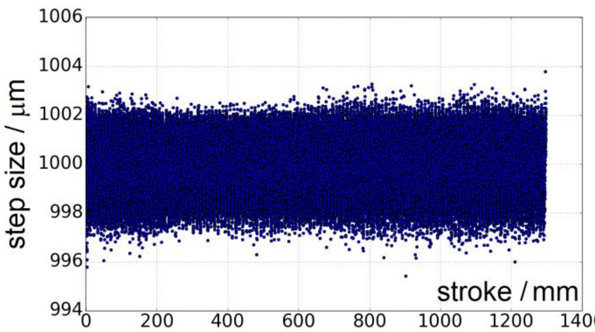

Figure 8: displacement between two consecutive interferometer sampling points.

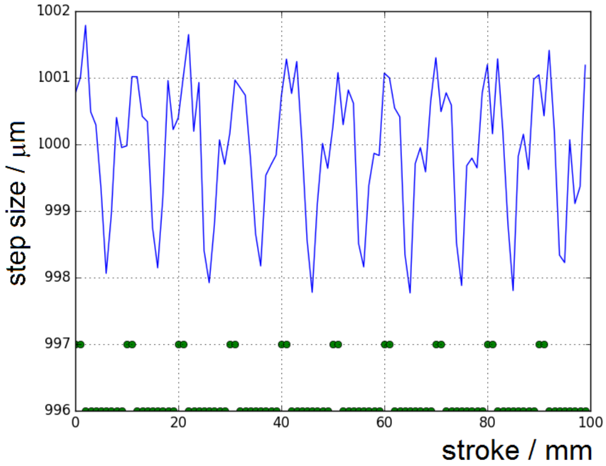

Figure 9: close-up of Figure 8.

We anticipate the result of the mean volume increment obtainable by moving the piston by one single step:
V_{step} = (4.358 ± 0.005)×10^{-7} m^3/step,
corresponding to (0.4358 ± 0.0005) mL/step.

6. Conclusion

The dimensional investigation of the test volume at the MEGAS confirmed the values of the previous calibration and, at the same time, evidenced some criticality in the measurements procedure. The measures of piston diameters and displacements will be repeated. In particular, the displacement evaluation need to be investigated more deeply as this measure influences the volume uncertainty budget considerably. A review of the interior piston structure could be evaluated in order to reduce the dispersion of displacement measures and will be discussed in a future work.

References

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