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Extending the functionality of the METAS primary standard in gas flow

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Abstract

METAS is the Swiss national metrology institute. Its laboratory for flow operates several primary standards for liquid and gas flow, among which two piston provers with BIPM-registered CMC entries in the range (0.1 to 300) L/min. To extend their functionality, additional working modes have been implemented in the data-acquisition software that allow almost endless measurement possibilities over the flow range (0.002 to 300) L/min. With the current extension of functionalities, all types of flow meters, from critical nozzles to laminar flow elements can now be calibrated under various configurations.

In this paper, we will present the changes that have been made to the design, as well as commissioning and validation results with various types of flow meters. The increase in flow rate range towards very low values brings pressure and temperature stability consideration into account that are being treated and presented here. Finally, results from a METAS internal bilateral comparison are presented and show an excellent agreement between two primary standards.

1. Introduction

METAS is the Swiss national metrology institute and operates, among its many standards, two piston provers as BIPM-registered primary standards [1] for gas flow rate in the range (0.1 to 300) L/min at ambient conditions with an uncertainty of 0.067 % (k=2). Due to their current design, these standards could only be operated in a blow down mode with a maximum upstream pressure of 3 kPa above ambient pressure. Instruments that need a larger upstream pressure or with a larger pressure drop could not be calibrated on these piston provers.

To overcome these limitations and extend their functionality to the calibration of all types of gas flow meters, the working mode of the piston provers has been increased from a simple blow down mode to three additional modes. The facility offers now almost endless measurement options and an increased measuring range. In this paper, we will present the design and elements that have been added to the existing system, as well as commissioning and validation results with various types of flow meters that could not be calibrated before. With the extension of gas flow rate range to a much lower range, the uncertainty budget had to be revised to take into account relevant effects due to the new functioning mode of the piston provers, especially gas density changes in the piping and cylinder of the piston prover during measurements. We also performed an internal comparison with the other primary standard for gas flow with BIPM-registered CMCs using molblocs as transfer standards.

2. Measurement possibilities of the piston provers before the functionality extension

The measurement principle of the piston provers is based on the displacement of gas from a closed cylinder by a piston of known geometry. The volume flow at any point can be calculated using the law of conservation of mass. Volume flow can be converted to any reference conditions using the equation of state for ideal gases. Traceability is assured through length (dimension of the piston, displacement) and time (start and stop of measurement).

The METAS piston provers are shown in Figure 1, the 6.5 L prover on the left and the 180 L prover on the right. Both instruments are located in a climate-controlled room.

Figure 1: The METAS piston provers, on the left the 6.5 L piston, on the right the 180 L piston.

Data-acquisition is performed through commercial hardware and in-house written software. Motors with a high dynamic range with intelligent axis controllers move the pistons and allow a high degree of automation of the measuring system. Time-critical signals are processed directly on a Field Programmable Gate Array (FPGA) with 40 MHz cycle time, this eliminates variable latency due to the operating system and allow fast pulse sequences (e.g. quadrature encoder or Device Unter Test signals, DUT) to be analysed on board.

Before the functionality extension, the provers could only be operated in a blow down mode, where previously sucked-in laboratory air was pressed through the piston cylinder and the DUT, finally into the atmosphere. The process in indicated in Figure 2 where one can identify the piston moving downward and pressing out the air from the cylinder through the DUT and into the atmosphere. Pressure drop across the DUT is limited 3 kPa.

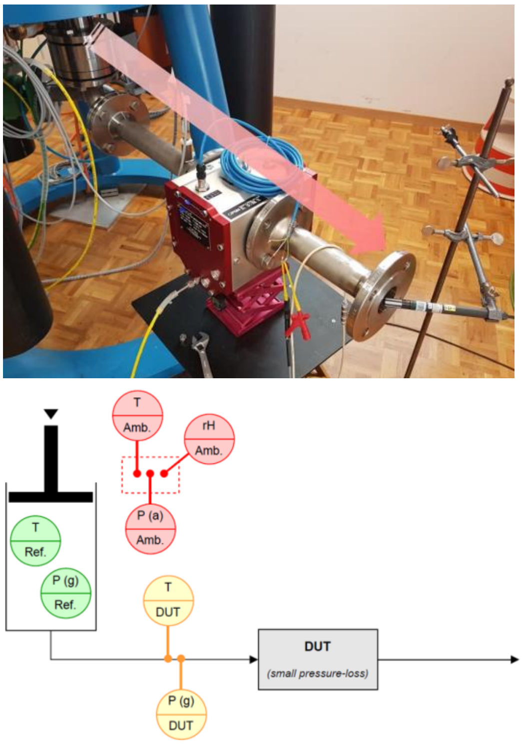

Figure 2: Blow down mode: flow direction is indicated by the arrow in the top of the figure. i.e from the cylinder chamber into the DUT.

In this measuring mode, the piston provers are used for calibrating instruments with small pressure low like positive displacement meters, turbines meters and some types of calorimetric meters.

3. Improvements and pressure-regulated mode

After some minor hardware changes related to safety and major software modifications, the piston provers can now be used, in addition to the blow down mode, in three different modes. Depending on the selected setup and the used test gas, different user options are available for density and volume calculation:

i. When using air, the CIPM-2007 formula [2] is applied. It enables the direct determination of mass flow. Optionally, relative humidity can be fixed to any value, if required.
ii. When using gases other than air (inert and non-explosive), the generally valid equation of state for ideal gases is used (using density ratios, mass flow rate cannot be directly computed)

The improvements brought to the piston provers lead to an increase in flow rate range to much lower values. This is solely due to a better characterisation of the motor of the smaller piston prover. The 180 L was characterised in depth several years ago after replacement of the motor and it was noticed that its new motor had a configurable dynamic range up to 1:40000. Since both pistons use motors of the same type, a similar range could be obtained with the 6.5 L piston, which lead to an extension of the minimum flow rate from 100 mL/min down to 1.4 mL/min. This flow rate value corresponds to the minimum configured movement speed of the piston.

3.1 Pulling in ambient air

Similar to the blow down mode, it is now possible to pull in air, i.e. laboratory air is aspirated into the cylinder chamber through the DUT by the piston movement, as indicated in Figure 3 where one can see that the piston is moving upward and therefore forcing laboratory air through the DUT into the cylinder chamber.

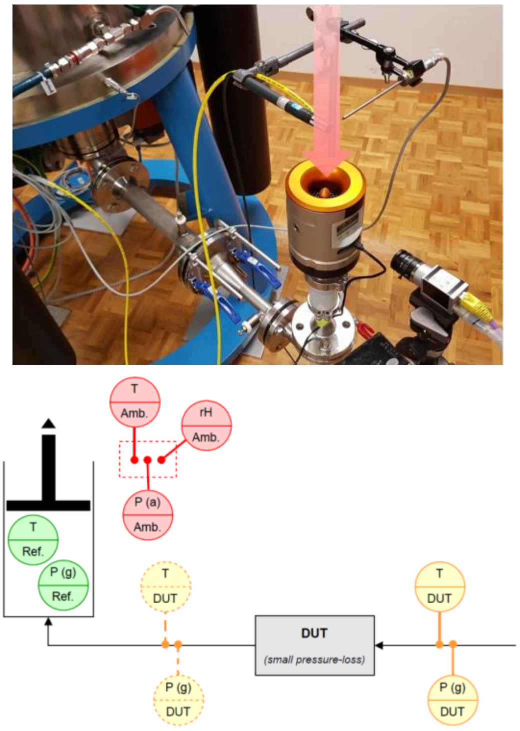

Figure 3: Suck in mode: flow direction is indicated by the arrow in the top of the figure, i.e. from the DUT into the cylinder chamber.

The advantage of this measuring mode is that there is no pressure drop before the DUT. It is particularly adapted for calibrating air samplers that work by sucking in air.

3.2 Pressure-regulated modes

The piston provers can finally be operated in a pressure-controlled mode. The driving speed of the piston is then controlled by a PID loop in such a way that the pressure of the gas in the cylinder chamber is at a defined constant level. The width of the pressure control window is ± 2 Pa.

In such a mode, the following options are available:

i. Selection of the pressure measuring point (reference of DUT).
ii. Regulation of the gas pressure to an absolute value, resp. the ambient pressure that was present at the beginning of the measurement (uncoupling of weather effects).
iii. Regulation of the gas pressure to any relative value.

Gas flow direction can be from the cylinder chamber to the DUT, as shown schematically in Figure 4. A typical application would be the calibration of critical nozzles working close to or at atmospheric conditions. A vacuum pump located downstream of the nozzle generates the pressure difference to put the nozzle in a choked flow mode and the PID control loop moves the piston downwards to maintain a constant pressure in the cylinder chamber.

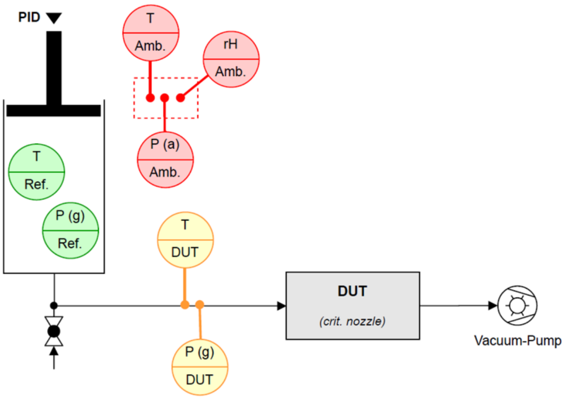

Figure 4: Pressure-regulated source: laboratory air is fed through the DUT to a lower pressure level.

Gas flow direction can also be from the DUT into the cylinder chamber, as shown schematically in Figure 5. Test gas is introduced from a higher-pressure level (typically a pressure cylinder) through the DUT into the cylinder chamber. This is by far the most versatile measurement mode.

Typical applications would be the calibration of any type of flow meter that requires an upstream pressure above atmospheric pressure like molblocs (laminar flow elements), mass flow controllers, critical nozzles or gas flow calibrators.

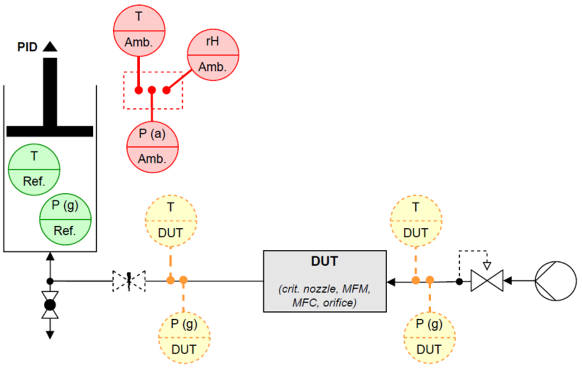

Figure 5: Pressure-regulated sink: test gas is fed into the cylinder chamber from a higher pressure level.

4. Validation measurements

An extensive set of validation measurements were carried out and only a short summary will be presented here. Test meters were a G16 rotary meter, a couple of molblocs and several critical nozzles. All meters had been stored in the laboratory for at least 48 h for acclimatisation.

Test parameters were measuring time (identical to measuring volume), uncoupling of weather effects and selection of measuring point for pressure. The molbocs were used at an upstream pressure of 3000 kPa and flow rate was calculated to reference conditions (0 °C and 1013.25 hPa).

Measurement results for the G16 rotary meter are shown in Figure 6 where the deviation of the meter against the reference flow rate as determined by the 6.5 L piston prover is indicated for different measurement modes and conditions.

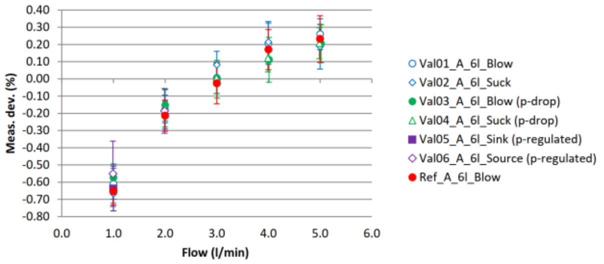

Figure 6: Deviation of the G16 rotary meter under various measurement conditions.

There is an excellent agreement between all the different modes. The red data points represent the reference values obtained in a blow down mode.

The molbocs were previously calibrated using another METAS primary standards for gas flow rates with BIPM-registered CMCs in the range (3 to 100) mL/min with an uncertainty of 0.15 % to confirm the new measuring range down to 2 mL/min.

Measurement results from both primary standards for a flow rate of 2 mL/min are presented in Figure 7. The red data represents the measured deviation by the primary standard with BIPM CMCs while the remaining points are from the 6.5 L piston prover functioning as a pressure-regulated sink. The full triangles are the mean values from five measurements, while the open triangles are the individual measurements. Measuring volume was 30 mL.

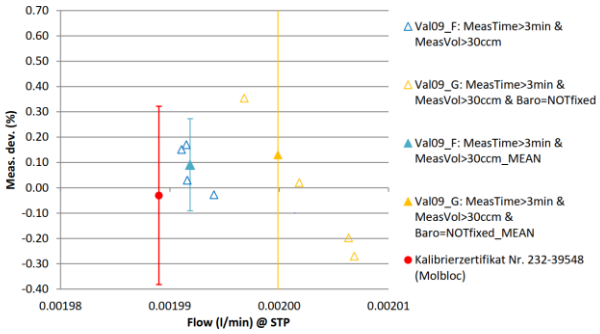

Figure 7: Comparison between CMC traceable results (in red) and results obtained with the 6.5 L piston prover under different measuring conditions for a flow rate of 2 mL/min.

The mention "Baro=NOTfixed" indicates that the pressure regulation with respect to atmospheric conditions was not active and applies to the yellow data points. This is relevant because the pressure inside the cylinder chamber is measured using a differential pressure sensor relative to atmospheric pressure, thus affected by changes of ambient pressure conditions. For the blue data points, the pressure regulation maintained a constant pressure drop with respect to the atmospheric pressure. The effect is visible by the fact that the individual measurements for the yellow points show more spread than for the blue points because atmospheric pressure conditions changed during the measurements and the regulation loop did not correct for it for the yellow points.

The agreement between both primary standards is excellent and applies to the complete measuring range from (2 to 100) mL/min.

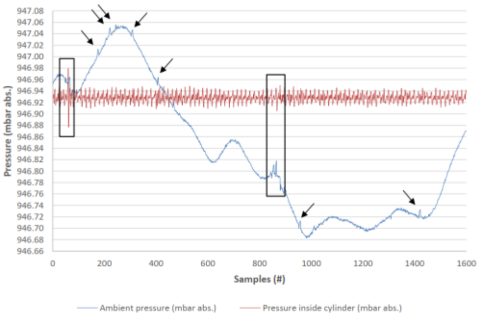

Figure 8: Time evolution over 30 minutes of atmospheric pressure conditions (in blue) and the regulated pressure (in red).

To better understand the effect of the regulation with respect to atmospheric pressure, Figure 8 shows a recording at a flow rate of 5 mL/min of the atmospheric pressure (in blue) over 30 minutes while the red curve shows the stability of the pressure regulation as it tries to maintain identical pressure drop conditions with respect to the start of the measurement. The spikes in the black blocks are pressure perturbations due to people actioning the door and accessing or leaving the laboratory. The regulated pressure has a bandwidth of ± 2 Pa.

5. Dead volume effect (virtual leaks)

The dead volume V_{dead} is therefore flow dependent. Typical values used for the validation measurements are shown in Table 1. It is immediately obvious that for small flow rate, the dead volume is always larger than the measuring volume and that any instability in temperature or pressure will affect the density of the gas in the dead volume during measurements. We name this contribution to the measurements a virtual leak.

Table 1: Dead and measuring volume as a function of flow rate

Volume flow (mL/min)	Dead volume V_{dead} (mL)	Measuring volume (mL)
2	620 + 1 + 1 = 622	30
10	620 + 1 + 5 = 626	50
50	620 + 20 + 25 = 665	500
500	620 + 50 + 250 = 920	1500

5.1 Managing virtual leaks

Several methods can be applied to manage the contribution of virtual leaks. The most obvious one is to limit the size of dead volume but this is not always possible, especially for small flow rates. Regulating the pressure inside the cylinder chamber to an absolute value to decouple it from atmospheric pressure is also an option. This method is easy to implement and mandatory if long measuring times are used. In this case, increasing pressure difference between cylinder chamber and atmospheric pressure could lead to real leaks.

Another method would be to consider a constant dead volume and determine its contribution to the uncertainty budget. This is in our case a realistic approach because the most important component from the dead volume comes from the volume of the cylinder chamber when the piston is in its lowest position. The variable components due to variable parts of piping can then be estimated properly for the uncertainty budget. One could also determine the dead volume before the measurements for the current configuration and calculate the contribution from this virtual leak. This would be a cumbersome and time-consuming task. Finally, limiting changes in gas temperature during measurements would also greatly contribute. This can be achieved by using metallic piping, let the system stabilise thermally and, if needed, add heat exchangers.

For our piston provers, we applied several methods listed above: decoupling the atmospheric contribution, consider a constant dead volume and use metalling piping with small passive heat exchangers.

5.2 Temperature effect on virtual leaks

We measured the maximum temperature difference in the dead volume directly at the entrance of the cylinder chamber of the piston prover and recorded a maximum difference of $\Delta T = 0.02\ K$. Using Equation 2

$$\Delta V_{leak} = V_{dead} \cdot \left(\frac{273.15 + \Delta T}{273.15} - 1\right) \qquad (2)$$

one can determine the change in volume from the dead volume resulting from this temperature change. Finally, the contribution to the measured deviation of the DUT can be computed from Equation 3

$$E_T = \frac{\Delta V_{leak}}{V_{meas}} \qquad (3)$$

where V_{meas} is the measurement volume.
Results for some flow rates are presented in Table 2 and it is immediately apparent that the contribution from virtual leaks is flow dependent and has the largest contribution at the lowest flow rates.Table 1

Table 2: Contribution to virtual leaks from temperature variations

Volume flow (mL/min)	**Measuring volume (mL)**	**E_T (%)**
2	30	0.15
10	50	0.09
50	500	0.01
500	1500	0.01

Values presented are maximum values, typical of a rectangular distribution. The effect of virtual leaks due to temperature can be limited by increasing the measuring volume, under the assumption that the maximal temperature variation is constant.

5.3 Pressure effect on virtual leaks

We measured the maximum pressure difference in the dead volume directly at the entrance of the cylinder chamber of the piston prover. When pressure regulation is decoupled from atmospheric pressure, the regulated pressure has a bandwidth of ± 2 Pa. When decoupling is not active, changes in atmospheric pressure directly affect the pressure reading from the cylinder volume and thus the measurement results, Changes of several Pa/min are possible, as can be seen in Figure 8. In a similar fashion to temperature, we can now estimate the contribution on dead volume from pressure variations.

Table 3: Contribution to virtual leaks from pressure variations

Volume flow (mL/min)	**Measuring volume (mL)**	***Decoupling active***	***Decoupling inactive***	***Δp (Pa)***
		***E_T* (%)**	***E_T* (%)**	
2	30	0.05	-0.043	2
10	50	0.03	0.060	-3
50	500	0.01	-	-
500	1500	0.01	-	-

Results for some flow rates are presented in Table 3 when decoupling is active or inactive, respectively. The last column indicates the maximum observed change in atmospheric pressure during measurements. It should be noted that weather conditions were very stable during the data-taking days.

In all cases, pressure regulation with decoupling will be used for measurements to ensure the smallest contribution from pressure variations. One notices that virtual leaks originating from pressure variations are three times smaller than contributions from temperature variations.

6. Conclusion

In this paper, we presented new functionalities of the METAS piston provers. Software modifications and minor hardware changes allow both pistons to run in a so called pressure-regulated mode and massively extend their measurement capabilities. As a by-product, the flow rate range could be greatly increased toward smaller flow rates down to 2 mL/min. It is now possible to calibrate all types of flow meters, irrespective of upstream or downstream pressure limits.
An extensive set of validation measurements has been carried using various types of flow meters and has demonstrated the versatility of the piston provers. A METAS internal comparison with another primary standard with BIPM-registered CMCs yielded an excellent agreement over the flow range (2 to 100) mL/min. A planned bilateral comparison with a primary standard from another national metrology institute will serve as evidence to extend the existing CMCs to lower flow rates. The METAS piston provers are available for commercial calibrations using all types of non-explosive gases except helium.

References

[1] BIPM, CMC repository, www.bipm.org/kcdb
[2] Picard A. et al., "Revised formula for the density of moist air (CIPM-2007)", *Metrologia*, **45**, 149-155, 2008