METROLOGY for HYDROGEN VEHICLES

REPORT:

A1.5.5: Determination of the Overall Uncertainty Budgets of Different Calibration approaches for CFM and Assessment of their Suitability

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

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This report was written as part of activity A1.5.5 from the EMPIR Metrology for Hydrogen Vehicles (MetroHyVe) project. The three year European project commenced on 1st June 2017 and focused on providing solutions to four measurement challenges faced by the hydrogen industry (flow metering, quality assurance, quality control and sampling). For more details about this project please visit www.metrohyve.eu.

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Introduction

In the framework of the work package 1 (“Flow metering”), task 1.5 “Uncertainty budget for the type approval testing, the periodic verification and gravimetric facility” aims to identify and assess the uncertainty sources for hydrogen metering specifically for hydrogen refuelling stations.

The aim of activity A1.5.5 in this task is to provide a summary for the uncertainties achieved using the calibration approaches from A1.5.1 to A1.5.4:

- Using alternative gases to hydrogen in the laboratory
- Using water up to 875 bar in the laboratory
- Using the gravimetric approach at a HRS at 350 bar and 700 bar NWP

In this context, METAS with the support of all WP1 partners will use existing reports to assess whether these approaches are suitable for calibrating hydrogen flow meters and where the limitations of each method are. The conclusions presented in this document will only apply to Coriolis mass flow meters.

First, an introduction to the fuelling protocols used in hydrogen refuelling stations will be given because these determine the pressure, temperature and mass flow rates limits on flow metering. Then the requirements on the performances of a flow metering system from OIML R139 [1] for a hydrogen refuelling station will be summarised. The next section will present the uncertainties achieved using the calibration approaches from A1.5.1 to A1.5.4. The conclusion will assess whether these approaches are suitable for the hydrogen industry, where limitations are and if further work is needed.

SAE J2601 fuelling protocols

SAE J2601 [2] establishes the protocol and process limits for hydrogen fuelling of light duty vehicles so that the vehicle storage tanks do not overheat or overfill. This protocol is implemented in almost all HRS. There are capacity categories for the storage tanks, which correspond to (99.4 to 248.6) L for 350 bar and (49.7 to 248.6) for 700 bar. Vehicles are typically refuelled with precooled hydrogen gas from dispensers within 3 min to 5 min. The maximum mass flow rate is defined as 3.6 kg/min. Fuel delivery temperature, the maximum fuel flow rate, the rate of pressure increase and the ending pressure are all parameters that are defined by process limits. Mass flow is determined by a pressure-ramp rate (PRR) that depends on initial pressure, available volume and temperature in the vehicle's tank. At a given temperature, the smaller the tank, the smaller the mass flow rate. Typical tank sizes for light duty vehicles (cars) vary from 100 L to 150 L and can hold from 4 kg up to 6 kg of hydrogen at 700 bar, respectively. This yields an average minimum mass flow rate of $\frac{4\,kg}{5\,min} = 0.8\ kg/min$ for such tanks.

Requirements from OIML R139:2018

The Maximum Permissible Errors (MPE) for the meter or complete measuring system from a HRS for type evaluation, initial or subsequent verification are given in Figure 1.

Table 1 - MPE values

Accuracy class		MPE for the meter [in % of the measured quantity value]	MPE for the complete measuring system [in % of the measured quantity value]	
			at type evaluation, initial or subsequent verification	in-service inspection under rated operating conditions
For general application	1.5	1	1.5	2
For hydrogen only	2	1.5	2	3
	4	2	4	5

Note 4: For hydrogen the accuracy class 2 is preferred though national authorities may decide to require the accuracy class 4.

Note 5: This Recommendation does not restrict the evaluation and approval of meters and measuring systems for measuring hydrogen to just classes 2 and 4. If requested by the manufacturer, it is allowable to evaluate such a meter or system applying the accuracy class 1.5 requirements and to approve a complying instrument/system for class 1.5.

Figure 1: MPE according to OIML R139-1:2018, table 1.

The MPE applicable to the minimum measured quantity (MMQ) is twice the corresponding value as stated in Figure 1, where E_{min} is defined as the minimum specified mass deviation. The MMQ for hydrogen is 1 kg and depending on accuracy classes yields a MPE as shown in Figure 2. The magnitude of the MPE, expressed in mass, for the complete system is never less than the minimum specified deviation. For instance, a measurement during type evaluation with 1.2 kg on a Class 2 system would give a MPE of 0.024 kg. This value is lower than E_{min} = 0.04 MMQ = 0.040 kg and therefore the MPE for a measurement with 1.2 kg would have a MPE of 0.040 kg.

Table 2 - E_{min}

Accuracy class	E_{min} [g; kg]		
	for the meter	for the complete measuring system	
		at type evaluation, initial or subsequent verification	at in-service inspection
1.5	0.02 MMQ	0.03 MMQ	0.04 MMQ
2	0.03 MMQ	0.04 MMQ	0.06 MMQ
4	0.04 MMQ	0.08 MMQ	0.1 MMQ

Figure 2: MPE for the MMQ depending on accuracy class.

OIML R139-1:2018 (1.3.2) also states that the expanded uncertainty on the determination of errors on indication of mass shall be (the repeatability of the EUT shall not be included):

- < 1/5 MPE for type approval
- < 1/3 MPE for verifications

These values require taking into account any intrinsic zero point stability and resolution of the EUT. This imposes accuracy constraints on the testing equipment. As an example, testing a meter envisioned for an Accuracy Class 2 requires a testing rig with an expanded uncertainty of at most 0.3 % for type approval and 0.5 % for verifications. The same situation but for Accuracy Class 4 requires a test rig with an expanded uncertainty of 0.4 % and 0.67 % for type approval and verifications, respectively.

If these criteria cannot be met, then it is possible to reduce the applied MPE with the excess of the uncertainties, the acceptance criteria are then:

- ±(6/5 · MPE – U) for type approval
- ±(4/3 · MPE – U) for verifications

while U ≤ MPE.

For instance, if testing of an Accuracy Class 2 meter is performed on a testing rig with U=0.6 %, then the acceptance criteria for type approval are ± 1.2 % instead of ±1.5 %.

Uncertainties when testing with alternative gases in a laboratory

Based on the results of the laboratory tests from A1.2.3, a generic uncertainty budget has been prepared for three tested flow meters calibrated with air and nitrogen. This budget depends on mass flow rate due to the zero point stability of the meters and takes into account major contributions (test rig, repeatability and reproducibility, zero stability, pressure and temperature effects). The reference test rig has an expanded uncertainty of 0.3 %.

For calibrations with air or nitrogen, reproducibility is a major contribution to the uncertainty budget. Expanded uncertainties ranging from 0.77 % at 0.5 kg/min down to 0.67 % at 2 kg/min have been obtained when taking into account reproducibility. Without the latter uncertainty contribution, expanded uncertainties range from 0.51 % at 0.5 kg/min down to 0.33 % at 2 kg/min.

Uncertainties when testing with water in a laboratory

Based on the results of the laboratory tests from A1.3.1, a generic uncertainty budget has been prepared for three tested flow meters calibrated with water. This budget depends on mass flow rate due to the zero point stability of the meters and takes into account major contributions (test rig, repeatability and reproducibility, zero stability, pressure and temperature effects). The reference test rig has an expanded uncertainty of 0.1 %.

For calibrations with water, expanded uncertainties ranging from 0.42 % at 0.5 kg/min down to 0.16 % at 2 kg/min have been obtained. Repeatability with water is hardly an issue.

Uncertainties when testing with the gravimetric approach

Based on the results of the field tests from A1.4.3 and A1.4.4, a generic uncertainty budget has been prepared. This budget depends on the zero point stability of the meters and takes into account major contributions (test rig, meter resolution, zero stability and repeatability). The reference test rig has an expanded uncertainty of 3 g (0.3 % for 1 kg of hydrogen).

For calibrations with a gravimetric standard and with hydrogen, the main uncertainty contributions originate from the gravimetric standard itself as well as from the zero flow stability of the meter. In a worst-case scenario, where one considers a maximum uncertainty of 0.25 % due to zero point stability from the meter, an expanded uncertainty of 4.5 g (0.45 % for 1 kg of hydrogen) has been obtained. It should be noted that the volume of the high-pressure tanks that are part of the gravimetric standard affect the average flow rate of the meter as the mass flow rate is directly proportional to the available volume for the refuelling: the larger the tank, the larger the mass flow rate. When using a gravimetric standard with a small volume, the average mass flow rate can be in the lower part of the mass flow rate of the meter and not in favour of the meter. This would not correspond to reality where most vehicles tend to have tank volumes of 100 L and above.

Suitability of the various calibration approaches for calibration hydrogen flow meters

Based solely on the uncertainties presented for the various fluids, the method of using different fluids suggest that this approach is viable to determine the likely performance of a flow meter installed in a refuelling station.

However, the suitability of the various approaches can be only assessed if there are results for the same meter being calibrated with the different fluids. Unfortunately, only very limited data of such type are available. In the course of this project, only one meter was tested in four conditions, namely:

- In the METAS gas flow laboratory using nitrogen in a pressure range from 20 bar to 86 bar at ambient temperature
- In the METAS liquid flow laboratory using water at a pressure of 7 bar at ambient temperature
- Against the METAS gravimetric standard (Hydrogen Field Test Standard, HFTS) using nitrogen in a pressure range from 10 bar to 40 bar and at gas temperatures of 20 °C and -40 °C.
- Against the METAS HFTS using hydrogen at a hydrogen refuelling station in the pressure range from 20 bar to 700 bar and hydrogen temperature close to ambient temperature (30 °C) when entering the meter

The results from these tests are shown in Figure 3. The relevant results for hydrogen are the ones which have been corrected for the vented quantity. It should be noted that the tank volume of the METAS HFTS limited the average mass flow rate when measuring at the hydrogen refuelling station, so no data could be taken at higher mass flow rates for hydrogen.

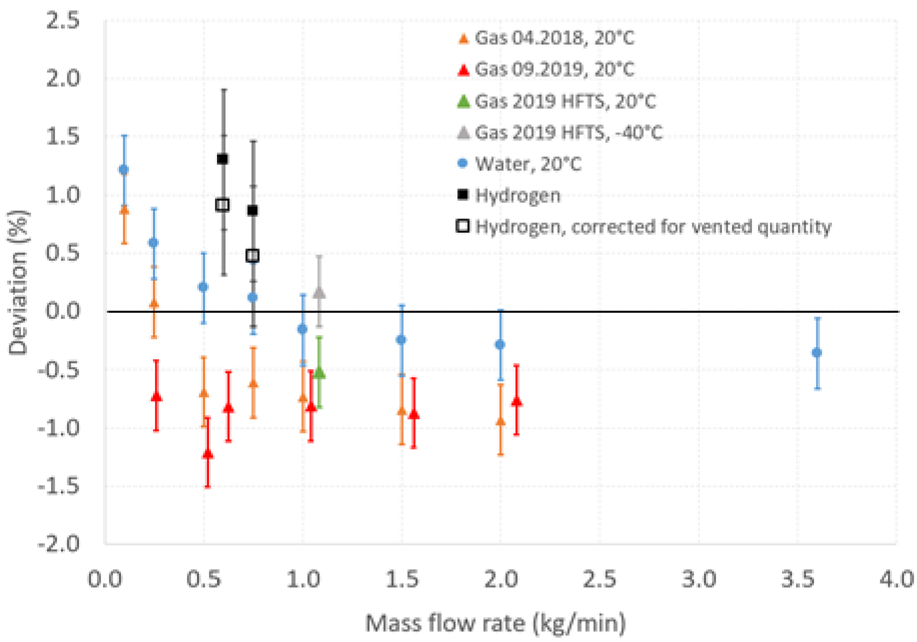

Figure 3: Comparison of results from laboratory and field testing performed by METAS as part of MetroHyVe

Regardless of the fluid tested, the test environment or the reference system used, all errors were within ±1.5 %. The smallest errors occurred for the laboratory tests with water, which were within ±0.3 % for medium to high flow rates.

There is very close agreement for all of the tests conducted with nitrogen and data is consistent. This agreement supports the claimed measurement uncertainty of the METAS HFTS, which is ±0.3 % at 95 % condfidence, and the equivalence with the gas laboratory reference flow meters.

A larger shift of approximately 1 % to 1.7 % was observed between the hydrogen and nitrogen test data compared to the hydrogen and water test data, which had a shift of approximately 0.3 % to 0.6 %. The difference between hydrogen and nitrogen data is not covered by the uncertainties of the used methods and it is unclear whether these differences can be corrected for or if nitrogen data can unambiguously be used to predict how a CFM will perform with hydrogen. Although only a limited data set is available, the linearity of the meter and consistency of results with different fluids appears to improve at higher flow rates. Test data between hydrogen and water are consistent but apply only to water or hydrogen at a steady temperature in the range 20 °C to 30°C. If the CFM is located in the cold region of the dispenser, then only testing with gas is possible to assess the characteristics of the meter.

Only a limited set of data is available and the results do not allow to conclude that the calibration approach using substitute substances to hydrogen can be used with total confidence to obtain a complete description of the characteristics of the CFM with hydrogen. More data on the equivalence of calibration results with different fluids are clearly needed.

References

[1] International Organization fo Legal Metrology, "OIML R 139 Compressed gaseous fuel measuring systems for vehicles," International Organization for Legal Metrology, 2018.

[2] SAE International, “SAE J2601-2014 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles,” SAE International, 2014.