METROLOGY for HYDROGEN VEHICLES

GOOD PRACTICE GUIDE:

Calibration and validation of flow meters used at HRSs for quantifying hydrogen dispensed into vehicles

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.

www.metrohyve.eu

This good practice guide was written as part of activity A1.4.8 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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Summary of recommendations

This page collects the recommendations made throughout the good practice guide. For more information about the background for the recommendations, please see the relevant sections.

Gravimetric primary standard

- The gravimetric method for field-testing of hydrogen refuelling station shows good results and achieves an expanded uncertainty of 0.3 %.
- The gravimetric method can be used for type-approval testing of hydrogen refuelling stations.
- Venting times are long and limit the number of measurements one can perform in a day.
- The evaluation of a hydrogen refuelling station takes several days with a gravimetric standard
- An alternative method to using gravimetric standards needs to be developed to reduce measuring time and therefore costs.

Master meter method vs gravimetric method

- The master meter for the field testing of hydrogen refuelling stations showed good results in the warm zone and met the requirements for a Class 4 station as defined by OIML R139 [1]. If the hydrogen refuelling station corrects for its uncertainties e.g. due to pressure differences, a Class 2 is possible. The meter has to be mounted in the hydrogen refuelling station, which would require specific permission from the station operator to modify the existing facility.
- In the cold zone, the master meter showed a large positive error (deviation >5%) and the repeatability was not as good as in the warm zone. Further tests are required to better understand the transient temperature effects on the master meter in the cold zone.

Procedures and guide for hydrogen refuelling station calibration

- Choose a master flow meter certified according to at least OIML R137 or OIML R139 if possible.
- Minimise the volume between the master flow meter and the nozzle as far as possible.
- Correct the mass error related to the process related to venting, piping and distance to delivery point.

Calibration of Coriolis flow meters with other substances than hydrogen

- Use air or nitrogen as the calibration fluid
- Calibrate the flow meter across the full range of mass flow rates at ambient temperature
- There is no need to test at a particular gas density, but inlet pressures of 40 bar or more may be required to reach the highest mass flow rates
- Determine the effect of pressure at up to 700 bar, this was done using water in the MetroHyVe project, pressures effects were insignificant for the tested flow meters
- Determine the effect of temperature at the relevant ranges, this depends on where the meter is installed and how the hydrogen refuelling station is operated

Abbreviations

APRR	-	Average Pressure Ramp Rate
CFM	-	Coriolis Mass Flow Meter
CGF	-	Compressed Gaseous Fuel
CNG	-	Compressed Natural Gas
CHSS	-	Compressed Hydrogen Storage System
DAQ	-	Data acquisition system
ESD	-	Electrostatic discharge
EUT	-	Equipment under test
HFTS	-	Hydrogen Field Test Standard
HRS	-	Hydrogen Refuelling Station
KRISS	-	Korea Research Institute of Standards and Science
MetroHyVe	-	16ENG01 EMPIR project named *Metrology for Hydrogen Vehicles*
MFM	-	Mass Flow Meter
MMQ	-	Minimum Mass Quantity
MOP	-	Maximum Operating Pressure
MPE	-	Maximum Permissible Error
NWP	-	Nominal working pressure
OIML	-	Organisation Internationale de Métrologie Légale
PVT method	-	Pressure-Volume-Temperature method
SOC	-	State of charge

1. Introduction

Europe is currently investing in a large hydrogen infrastructure, and hydrogen vehicles are now commercially available from several manufacturers. The implementation of these vehicles into the consumer market is necessary to help Europe meet the challenging targets of lowering carbon dioxide emissions. However, one metrological challenge is the accurate measurement of the amount of delivered hydrogen during fuelling from hydrogen refuelling stations (HRSs). A consequence of this challenge is that the HRS will not know how much hydrogen they have provided, and therefore cannot correctly charge the customer. The EMPIR project “Metrology for Hydrogen Vehicles” (MetroHyVe) aim to address this measurement challenge, as well as several others.

International requirements propose accuracies for meters used in HRSs, but few studies have been performed on how to test, inspect and verify such systems, both in laboratory conditions and in the field. The MetroHyVe-project is an attempt to remedy this limitation, and the first of four work packages has focused on flow metering. A large part of this work package has centred around the development of an independent, traceable, gravimetric primary standard to calibrate and verify HRs flow meters at 875 bar, in order to deliver traceability to HRSs.

Traceability was achieved by comparing the reading of a flow meter to the mass of gas collected over time in a pressure vessel on a weighing scale. The delivered mass investigated was in the range of 1 kg to 5 kg, where the latter corresponds to a full tank for light duty vehicles at a nominal working pressure (NWP) of 700 bar, corresponding to 70 MPa. Most standards and recommendations assume a Maximum Permissible Error (MPE) of 1.5 % for the flow meter and 2 % for the entire HRS. The suggested target for the gravimetric standards for flow measurement should therefore not exceed 0.3 % in order to validate against a 1.5 % MPE for the flow meters.

The aim of activity A1.4.8 was to write a good practice guide for validating hydrogen flow meters at HRSs and the type approval procedure. The guide should also include the results from tasks 1.2 (“Investigate alternative methods for type approval testing using substitute substances to hydrogen”) and 1.3 (“Investigation on the high-pressure dependence (up to 875 bar) of Coriolis mass flow meters”) and the results from all of the activities from A1.4.3-A1.4.7. The guide will thus support both HRSs and flow calibration laboratories in ensuring the stations operate using suitable accurate and fully calibrated flow meters.

In this context, JV with the support of Cesame, FORCE, METAS, NEL and RISE have used the previous results and reports from other activities in this work package to write this good practice guide. It is structured so that the main recommendations can be seen on page 4 at the beginning of the document, with the main results following in the main sections. Extended information can be found in the appendices and through the references.

In this guide, pressure is given both in the unit of bar or MPa, where 1 MPa equals 10 bar.

2. Scope

The information presented in this good practice guide is intended for HRS operators, flow calibration laboratories, flow meter manufacturers, notified bodies and people active in the field of type approval and verification of HRSs.

This guide includes a list of recommendations based on the experience collected by the project partners during the course of the MetroHyVe project. This list of recommendations is the most important part of the guide, and can be found in the beginning of the guide. Following the recommendations is a section giving the requirements for testing and validation of HRS according to the international recommendation OIML R139:2018 [1]. Then mobile primary standards and the associated measurement method are presented, as well the validation data for these standards. Extensive field-testing results using a mobile gravimetric standard form the core of the next section and give explanations on how HRS design can affect measurement results. In the course of the MetroHyVe project, the objective was also to look into ways of using substitute substances to hydrogen for testing and qualifying flow meters used in HRSs as no primary calibration facility for hydrogen flow metering exists. This alternate approach is part of the next section. Before the conclusion, a last section is devoted to uncertainties associated with the various measurement methods and their suitability for calibrating hydrogen flow meters for the hydrogen industry. This guide ends with references and appendices.

This guide is unfortunately not a guide that will answer all the questions related to hydrogen flow metering in HRSs, but it gives a general overview and the current state of the art on hydrogen flow metering in Europe.

This good practice guide applies to the calibration, validation and type approval procedure of HRSs and flow meter installed in HRSs working at nominal working pressure of 350 bar and 700 bar, with a strong focus on 700 bar, as 350 bar is more related to refuelling of heavy-duty vehicles.

Results presented in this guide have been collected in the course of the MetroHyVe project and the Fuel Cell Hydrogen – Joint Undertaking (FCH-JU) program[1].

[1] N° FCH / OP / CONTRACT 196: "Development of a Metering Protocol for Hydrogen Refueling Stations"

3. Requirements for calibration and validation of a HRS

When a hydrogen station manufacturer wishes to sell its product to a customer whose use is intended for the public, the station manufacturer must comply with the associated standards resale of energy to individuals, stated as legal metrology, to ensure reliability transaction. In 2020, there was so far no specific reference text on the sale of hydrogen through HRSs to individuals. However, there are some standards which are in use today, and which will be covered briefly in this good practice guide. These are OIML R139:2018 [1] and SAE J2601 [2]. ISO standard 19880-1 "Gaseous hydrogen - Fuelling stations" [3] will not be covered.

3.1 OIML R-139:2018 Compressed Gaseous Fuel Measuring Systems for Vehicles

OIML – Organisation Internationale de Métrologie Légale has recently revised their recommendation on compressed gas, which deals mainly with natural gas. However, in the edition published in October 2018, hydrogen has also been included such that the recommendation now includes technical constraints to the use of high-pressure hydrogen gas. The text is available on the OIML website[2], and is divided into three parts, namely

1. R139-1 - Metrological and Technical Requirements (52 pages),
2. R139-2 - Metrological controls and performance tests (63 pages),
3. R139-3 - Test Report Format (65 pages).

This OIML recommendation specifies the technical requirements and the tests to be carried out by components to obtain OIML certification. Obtaining this OIML certificate should therefore enable anyone to accept and recognize considered equipment anywhere in the world. It should be noted, however, that this document is only a recommendation, and governments and/or the certification departments of the National Metrology Institutes may request explanations of the nature of the tests carried out during this OIML certification, or further tests.

3.1.1 OIML R139-1 Metrological and technical requirements

This first section describes the elements that constitute the measurement system and therefore items that need to be tested for certification of the measuring system. Figure 1 summarizes the mandatory and optional elements of a typical compressed gaseous fuel measuring device for vehicles.

The recommendation lists all mandatory metrological requirements to obtain the OIML certification of a HRS at 700 bar, which includes, among others the MPE, the display unit of the result of the measurements, the minimum mass quantity (MMQ), and the flow rate of measurements. For the full list of requirements, see Appendix B. Although there is no metrological test rig available to perform a meter calibration for hydrogen at 700 bar at present, the recommendations states MPE for such flow meters. It is important to note that there are two accuracy classes for hydrogen, where class 4 is mainly accepted for existing HRSs and class 2 is required for new HRSs. The MPE for a type approval of a new HRS is thus 2%, according to class 2.

In addition to mandatory metrological requirements for HRSs to achieve OIML certification, the recommendation lists technical obligations and marking requirements for the measurement system. Furthermore, Annex B of OIML R139-1 details typical methods for correction of the depressurization quantity for hydrogen compressed gaseous fuel measuring systems. This depressurization leads to hydrogen loss due to venting, and describes two methods to take this vented quantity of hydrogen into account when fuelling a vehicle.

[2] https://www.oiml.org/en/files/pdf_r/r139-pe18.pdf

It is important to note that this good practice guide including Appendix B only gives an overview of the requirements in the recommendation, and the reader is referred to the full text [1].

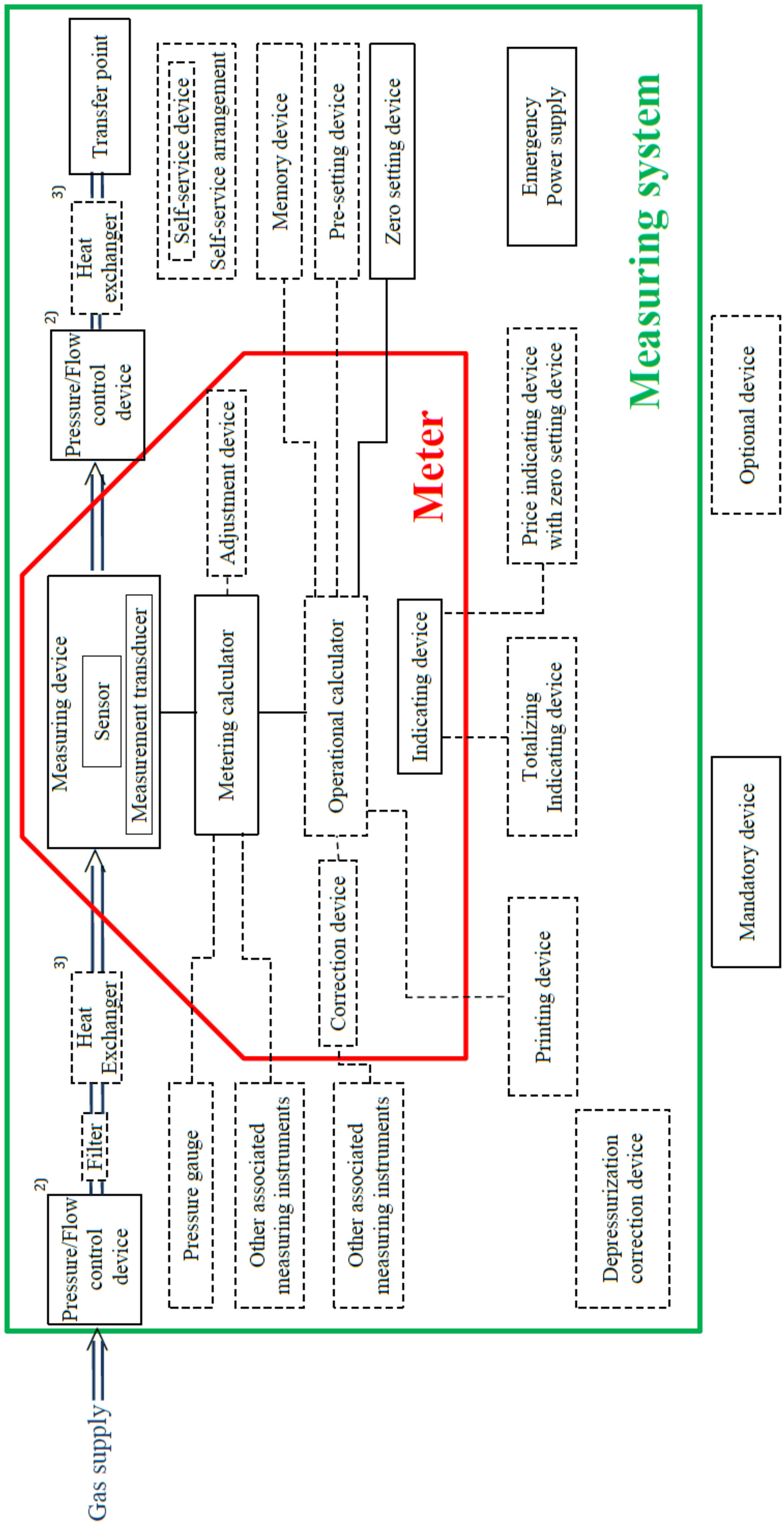

Figure 1 Constituents of a typical compressed gaseous fuel measuring system for vehicles.

3.1.2 OIML R139-2 Metrological control and performance tests

The second part of the OIML recommendation develops topics related to the metrological controls, the instrument evaluation, the type evaluation, and the initial and subsequent verifications of a HRS. For metrological controls, most of the section is devoted to the uncertainty calculations. The uncertainty requirements depend on the type of certification, and are related to the MPE of the HRS. For instrument evaluation, the recommendation details instrument specifications and meter capacity, as well as flow rate. The specific tests to be performed as part of an evaluation are detailed, and denoted as test # 4, #5 and # 7 as described in Appendix B and Table 11 to Table 13. As the tests do not need to be sequential as long as they are sufficiently documented, a suggested test sequence is # 4, # 5, # 7, # 4, # 5, # 7, # 4 , # 5. Such a disordered test sequence may minimize the testing time, for instance to allow for a full defueling overnight.

3.2 SAE J2601:2020 Fuelling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

SAE J2601 details the protocol and process limits for hydrogen fuelling of light duty vehicles as long as their total hydrogen volume capacities are greater than or equal to 49.7 litres. The process limits include fuel temperature, the maximum fuel flow rate, the rate of pressure increase, and the end pressure, and these limits are affected by factors such as ambient pressure, fuel delivery temperature and initial pressure in the fuel tank system of the vehicle. SAE established a standard fuelling protocol for many different situations based on a look-up table approach with performance targets. More information about the SAE J2601 standard can be found in Appendix C.

This standard assumes that a HRS will perform fuelling from a high pressure storage into the vehicle after successful docking and initial checks. A typical fuelling profile thus includes a connection pulse before a linear increase of pressure at the same time as the vehicle tank temperature increases. The goal of the fuelling protocols is that the main fuelling time will be 3 minutes or less for a defined set of reference parameters. These sets of parameters are thus important for the general fuelling protocol.

In addition to the general fuelling protocol, the SAE J2601 standard includes a table-based fuelling protocol. For this table-based approach, the station fuel delivery temperature, ambient temperature, compressed hydrogen storage system (CHSS) capacity category, and CHSS initial pressure to select appropriate parameters for safe and correct fuelling. A sample fuelling table can be seen in Table 15 in Appendix C.

There are several different additional classes and definitions in use for the different look-up tables. For instance, HRSs are often defined by the delivered fuel pressure class, and its fuel delivery temperature capability. Furthermore, there are four different allowable CHSS capacity categories for the table-based fuelling protocol. Each HRS may choose to implement all these different categories, or a sub-set of them. There are also two different pressure classes of hydrogen vehicles that must be accounted for.

As for OIML R139, the reader is referred to the published SAE J2601 standard rather than relying solely on this good practice guide and Appendix C for the relevant requirements.

4. Primary gravimetric hydrogen field test standard

From the perspective of an end-user, hydrogen refuelling stations look and operate in a very similar way to petrol stations, the only difference being that the delivered amount is given in kg. Vehicles are typically refuelled with precooled hydrogen gas from dispensers within 3 min to 5 min from banks of pressurized cylinders. SAE J2601 [2] establishes the protocol and process limits for hydrogen fuelling of light duty vehicles so that the vehicle storage tanks don't overheat or overfill. During a fill, temperature and pressure span wide ranges, where pressure can go from 10 bar up to a nominal working pressure of 700 bar, and hydrogen can be precooled down to -40 °C to allow short filling times. Mass flow is determined by a pressure-ramp-rate (PRR) that depend on initial pressure, available volume and temperature. We are thus far from steady conditions.

International requirements [1] propose accuracies for meters used in hydrogen refuelling stations and only very limited studies have been performed on how to test, inspect and verify such systems under laboratory conditions and in the field. Several methods for field testing dispensers are possible [4] and all require collecting the dispensed hydrogen in high-pressure vessels. In the gravimetric method, the dispensed mass is determined by weighing the amount of delivered hydrogen in a high-pressure vessel on a scale. In the Pressure-Volume-Temperature (PVT) method, the dispensed mass is determined by measuring pressure and temperature of the collected gas in a known volume and then converting to mass using the density of the gas. The third method concerns the use of a calibrated master meter.

4.1 Development of the gravimetric standards

In the course of the MetroHyVe project, the partners chose the gravimetric method because it is already an established method for field-testing of compressed natural gas (CNG) refuelling stations, delivers a result direct in mass and should capable of achieving the required expanded uncertainty of 0.3 %, which is one-fifth of the 1.5 % MPE for flow meters. The gravimetric method is also not very sensitive to pressure and temperature effects, the main uncertainty contribution comes from the weighing on the scale. In contrary, the PVT method requires an accurate volume determination as well as stable temperature and pressure readings with no drift. Master meters calibrated with hydrogen are not commercially available at this time.

Several mobile standards based on a gravimetric measurement principle have been developed in the course of this project by members from the consortium: Justervesenet, METAS and VSL have all built their own standards, while CESAME used a standard built by Air Liquide. All standards are certified for measurements in an environment with explosive atmosphere. Details to the design of the standards are given in Appendix D.

The dispensed mass into the gravimetric hydrogen field test standard (HFTS) is calculated by:

$$m_{H2} = m_2 - m_1, \quad (1)$$

where *m* is the true mass and the subscripts denote the mass of the HFTS before and after the filling, respectively. The mass indicated by the scale needs to be buoyancy corrected and for that we need the volume of the tank and of the frame.

The HFTS tank volume is a function of pressure and temperature, and is given by:

$$V_{tank} = V_0 \cdot (1 + 3 \cdot \alpha \cdot \Delta T) \cdot (1 + \lambda \cdot \Delta P), \quad (2)$$

where V_0 is the external tank volume at ambient conditions with no internal pressure , $\alpha = 2.0 \cdot 10^{-6}$ °C^{-1} is the linear thermal expansion coefficient, $\lambda = 2.2 \cdot 10^{-10}$ Pa^{-1} is the pressure expansion coefficient, and ΔT and ΔP are the difference of the temperature and pressure from the reference values, respectively. The pressure expansion coefficient has been determined experimentally during a refuelling up to 70 MPa and from manufacturer's data. The thermal and pressure expansion coefficients are very similar to values published elsewhere [4]. The correction factor for pressure differences is much larger than the correction factor for thermal expansion. As results, the thermal expansion can be completely neglected.

From Equations (1) and (2), we can now calculate the dispensed mass into the HFTS corrected for buoyancy and apparent mass reading from the scale:

$$m_{H2} = (W_2 - W_1) \cdot \left(1 - \frac{\rho_a}{\rho_N}\right) + V_0 \cdot [\rho_{air2} \cdot (1 + \lambda \Delta P_2) - \rho_{air1} \cdot (1 + \lambda \Delta P_1)] + V_{frame} \cdot (\rho_{air2} - \rho_{air1}) \, , \quad (3)$$

where W are the readings of the scale and the subscripts denote the reading before and after the filling, respectively. The factor $\left(1 - \frac{\rho_a}{\rho_N}\right)$ turns apparent mass into true mass where $\rho_a = 1.2 \, \frac{kg}{m^3}$ and $\rho_N = 8000 \, \frac{kg}{m^3}$ are the densities of air and stainless steel at reference conditions, ρ_{air} is the density of the air around the scale and the tanks before and after the fill.

To obtain a feeling for orders of magnitude, a complete fill in the METAS HFTS corresponds to 2.9 kg of hydrogen gas in the tanks at a pressure of 70 MPa. This filling yields a volume expansion of 0.92 L for each tank. Under identical ambient conditions before and after the fill, we obtain a buoyancy correction of 2.12 g (0.08% of 2.9 kg) for both tanks. The term due to the volume of the frame only plays a role if ambient conditions change during the filling process.

Laboratory tests were performed to reproduce field tests as closely as possible. The aim was to elaborate a testing procedure and practice using the HFTS before going into the field. The same procedure has then been used for the field measurements.

All laboratory measurements were performed with nitrogen gas from a bundle as a 5.5 MPa gas source to fill the HFTS. Before entering the HFTS, the gas was cooled down to -40 °C by a heat exchanger to reproduce the temperature conditions of hydrogen as delivered by a HRS. Pressure and temperature in the tanks were monitored continuously during the fill. The frame was always enclosed or partially enclosed by the housing, as the latter geometry leads to a better air circulation around the scale.

To perform the measurements, we followed several steps:

1. Disconnect all the cables and hoses from the frame, lower the HFTS onto the scale and weigh the empty HFTS, record the ambient conditions
2. Lift the HFTS from the scale, connect all sensors and measure tank pressure and temperature as well as temperature of the air in the frame
3. Connect the gas source to the HFTS inlet and fill the tanks. During the fill, all sensors are monitoring and recording data.
4. Disconnect all the cables and hoses from the frame and lower the HFTS onto the scale
5. Wait until scale reading stabilises and record value
6. Lift the HFTS from the scale and connect all sensors. Connect the vent stack and blow down the gas.

Typical results for the pressure rate and temperature profiles for a fill up to 4 MPa are shown in Figure 2. The PRR during the fill is around 1.14 MPa/min. During this period, temperature in the tanks increased due to compression heating while temperature of the tubing decreased below the freezing point of water due to the cold nitrogen gas flow. The air temperature around the scale remains constant. After the fill, all temperatures converge slowly toward the current ambient condition.

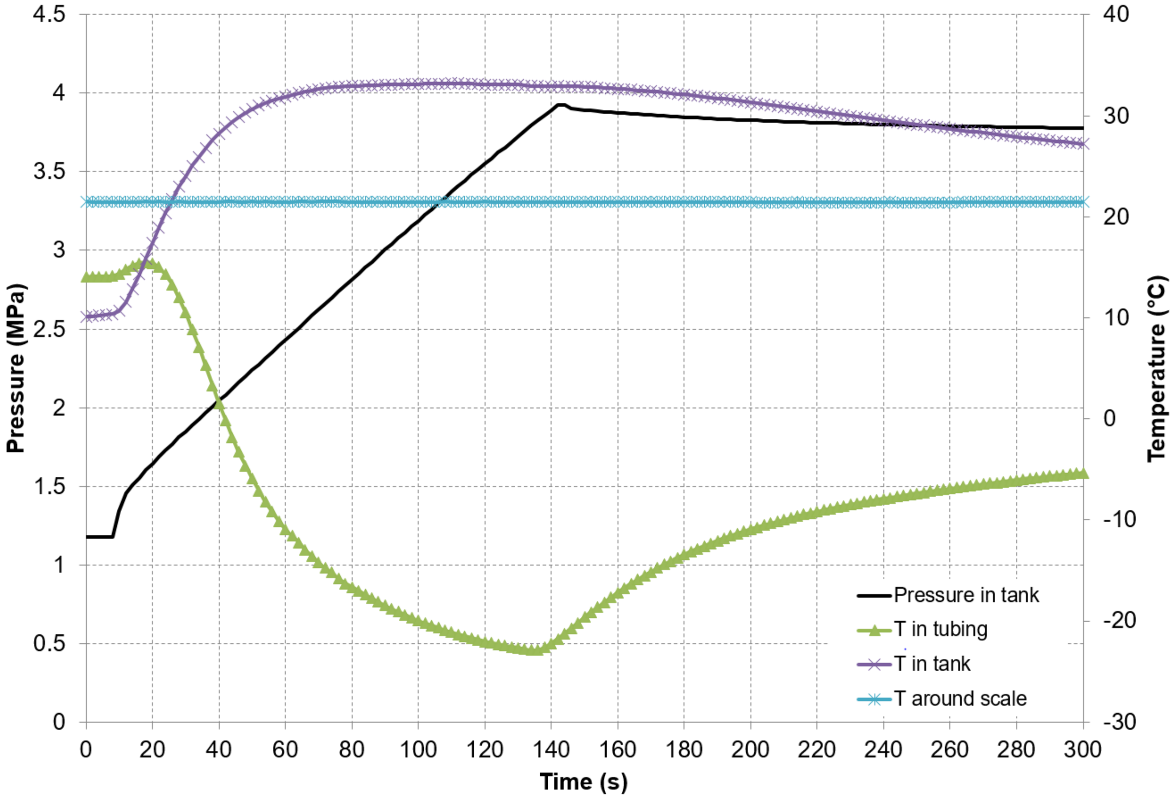

Figure 2: Pressure (in black) and temperature profiles from the HFTS during a fill, PRR = 1.14 MPa/min.

The cold gas flowing through the HFTS causes part of the humidity present around the HFTS to condense and freeze on the pipes. This quantity of ice will be weighed but should not be part of the determination of the mass of dispensed gas. This quantity of ice is by far not negligible and can amount to several grams. There are several solutions to this problem: 1) waiting for the temperature in the pipes to be above the dew point and wipe away the excess liquid with a dry cloth or 2) fill the enclosure around the scale with an inert gas to prevent any present humidity from condensing on the pipes. METAS experimented with the second method and found that it brought more unknowns related to the buoyancy correction because flooding level is not well defined and applied the first method instead by removing the melted ice after a waiting time.

4.2 Intercomparison of gravimetric standards

The gravimetric standards participated in an inter-comparison to validate the method and the claimed uncertainties of each standard. The comparison also served as preparation for handling the standards and making sure that the correct procedures are put in place. A Coriolis mass meter and its transmitter, supplied by METAS, was used as transfer standard. More detailed information can be found in the MetroHyVe report A1.4.2 [5].

The original schedule had METAS, JV, CESAME and VSL as participants. Due to damage to the Air Liquide gravimetric standard, CESAME could not participate and the VSL standard was not available yet for the comparison in the beginning of 2020. In the end, only JV and METAS participated in the comparison.

The participants used their own gravimetric standards with some additional equipment to perform the measurements. Nitrogen was used as calibration gas and was supplied by a bundle of nitrogen bottles equipped with a pressure reducing valve to limit the pressure of the incoming gas to a maximum of 50 bar. The transfer standard was then mounted in series between the nitrogen bundle and the gravimetric standard. A ball valve located before the Coriolis meter allowed for starting and stopping the nitrogen flow. Mass flow rate was adjusted using a needle valve placed after the Coriolis meter. Once flow was adjusted, opening and closing the ball valve started or stopped the measurement. A diagram of a possible setup is shown in Figure 3, which shows also a heat exchanger between the bundle and the gravimetric standard. This heat exchanger has only been added to the METAS setup after noticing that the cooling of the delivered nitrogen led to a transient temperature profile of the Coriolis meter tube and affected the repeatability of the measurements. METAS results with and without the heat exchanger are presented here. JV performed measurements without heat exchanger.

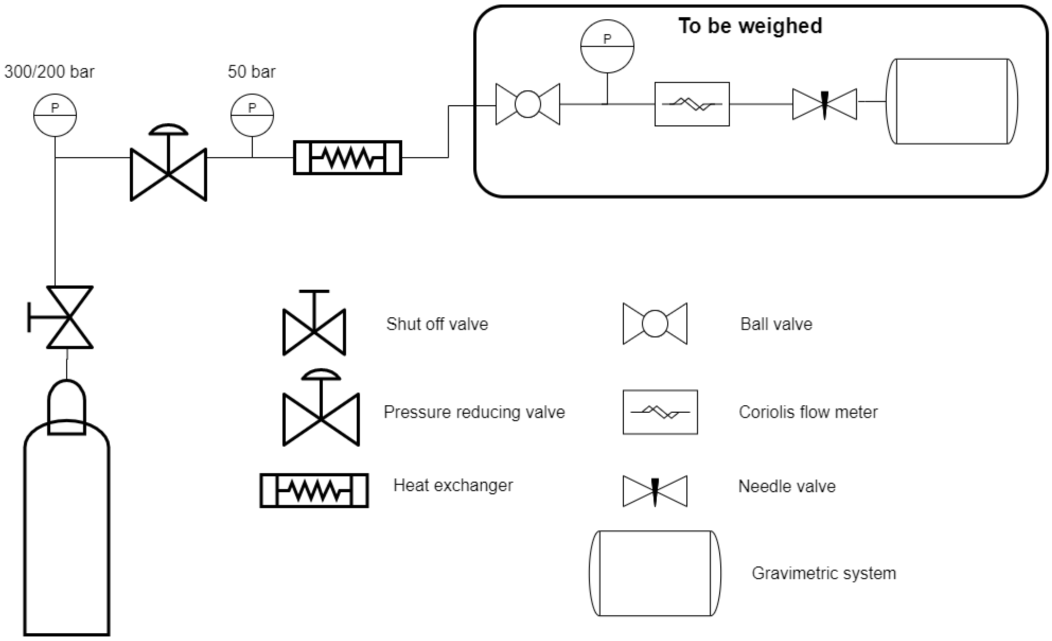

Figure 3: PID of the setup. METAS uses a 300 bar bundle, 200 bar is standard.

The measured error of the transfer standard is shown graphically in Figure 4. One notices a larger spread from the JV data compared to the METAS data. This difference is probably due to the larger temperature difference of the Coriolis meter tube between beginning and end of the filling. Indeed, the JV data show a larger and increasing difference as a function of run number, whereas the METAS temperature difference readings are rather constant. Average mass flow rates for the METAS and JV data are around 0.75 kg/min and 0.65 kg/min, respectively. Average filling times are 180 s for METAS and 320 s for JV, respectively. Filling times for JV are longer because of a larger pressure drop through the piping of their gravimetric standard and the larger volume of the high-pressure tanks on their standard.

Agreement between METAS and JV for the single measurements is reasonable; the measured error is always negative and ranges from -0.20 % to -1.15 %. Building an average from the runs for each laboratory and adding the standard deviation of the average coherently to the quoted expanded uncertainties yields the results presented in Table 1. It can be seen that the standard deviation from the JV measurements is about three times larger than the one from METAS. This increase indicates that the temperature variation of the nitrogen as it is flowing through the Coriolis meter definitely affects the repeatability of the instrument. The average errors determined by both laboratories are in excellent agreement, as indicated by the En-value, defined by

$$En = \frac{|\epsilon_{lab1} - \epsilon_{lab2}|}{\sqrt{U_{lab1} + U_{lab2}}}, \qquad (2)$$

where ϵ_{lab} is the error of the meter and U_{lab} is the expanded uncertainty of each lab, respectively. This value should be lower than 1 to have consistent results.

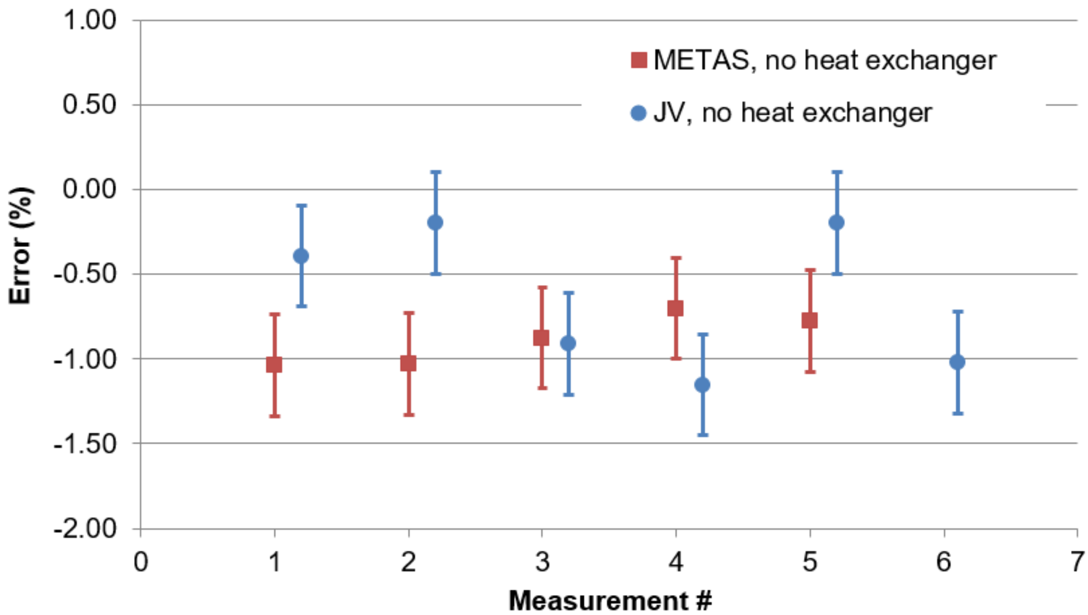

Figure 4: Error of the transfer standard for both laboratories.

Table 1: Average error for both laboratories.

	Error (%)	Standard deviation (%)	U (k=2) (%)	En value
METAS	-0.88	0.13	0.40	0.20
JV	-0.70	0.41	0.88	

It should be noted that even if one reduces the expanded uncertainty of JV by a factor of two (by reducing the standard deviation for instance), results are still largely consistent.

A comparison between the measured error with and without the heat exchanger with the METAS gravimetric standard is shown graphically in Figure 5 and summarised in Table 2. One notices an excellent agreement between both sets of measurements and a reduced spread (factor of 2) for the data taken with the heat exchanger located between the gas bundle and the transfer standard. Results are largely consistent. This clearly indicates that a heat exchanger must be used for future similar comparison measurements.

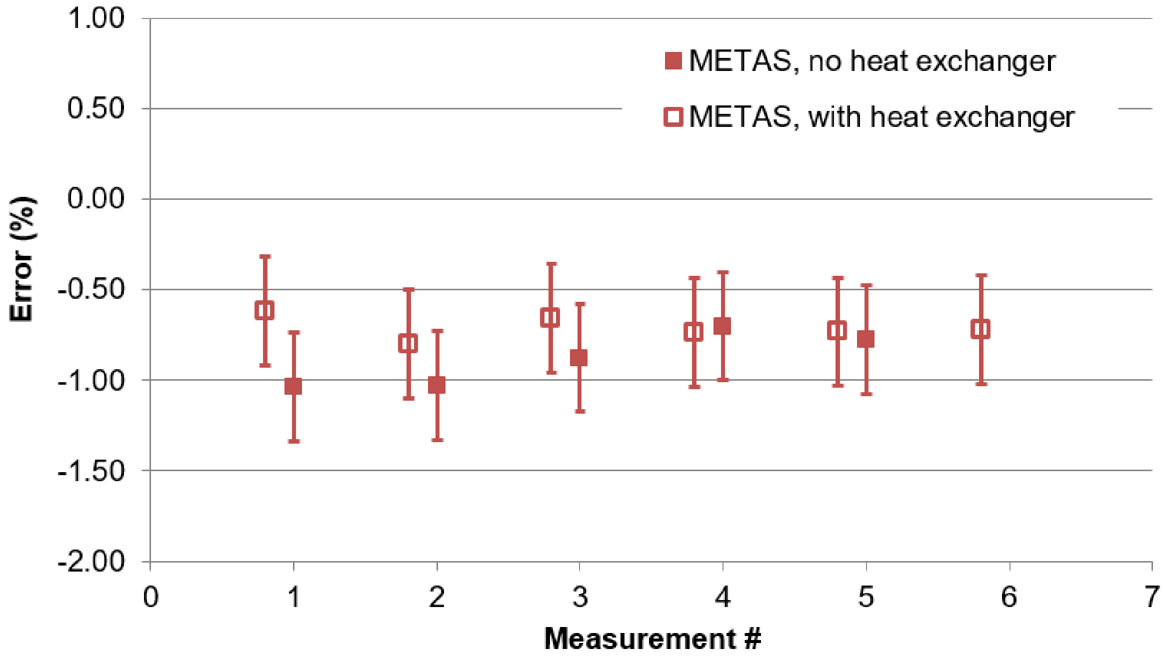

Figure 5: Error of the transfer standard with and without heat exchanger.

Table 2: METAS results with and without heat exchanger.

Run #	Error without heat exchanger (%)	Error with heat exchanger (%)
1	-1.04	-0.62
2	-1.03	-0.80
3	-0.87	-0.66
4	-0.70	-0.73
5	-0.78	-0.73
6	-	-0.72
Average (%)	-0.88	-0.71
Standard deviation (%)	0.13	0.06
Uncertainty (k=2)	0.40	0.32

4.3 Procedure for field tests

Following the comparison and laboratory measurements, field tests were conducted with the METAS HFTS at the Empa[3] hydrogen refuelling station in the same manner as the laboratory tests, except that the HFTS was filled according to SAE J2601 protocol with precooled hydrogen down to -40 °C.

Figure 6 shows the METAS HFTS mounted on a trailer next to the Empa hydrogen dispenser. The data-acquisition system (DAQ) was installed in the van and connected through the blue cables to the HFTS. The vent stack can be identified in the back. A safety cordon delimited the area.

Typical results for the pressure rate and temperature profiles for a fill up to 700 bar are shown in Figure 7. One observes a very similar behaviour to what was observed in Figure 2 under laboratory conditions with cold nitrogen. First, the pressure burst was identified to check for potential leaks before the pressure ramps up continuously up to a little more than 700 bar. The temperature in the tubing decreased immediately because of the cold hydrogen flowing in it and reached a constant value of -28°C. The temperature in the pressure vessels increased quickly during the beginning of fill up to

[3] www.empa.ch

60°C and then increases steadily to 70°C. The air temperature around the scale during the fill dropped by about 0.3°C. The exterior of the pipes and valves leading from the nozzle to the pressure tanks were covered in a thin layer of ice due to condensation of the humidity on the cold stainless steel.

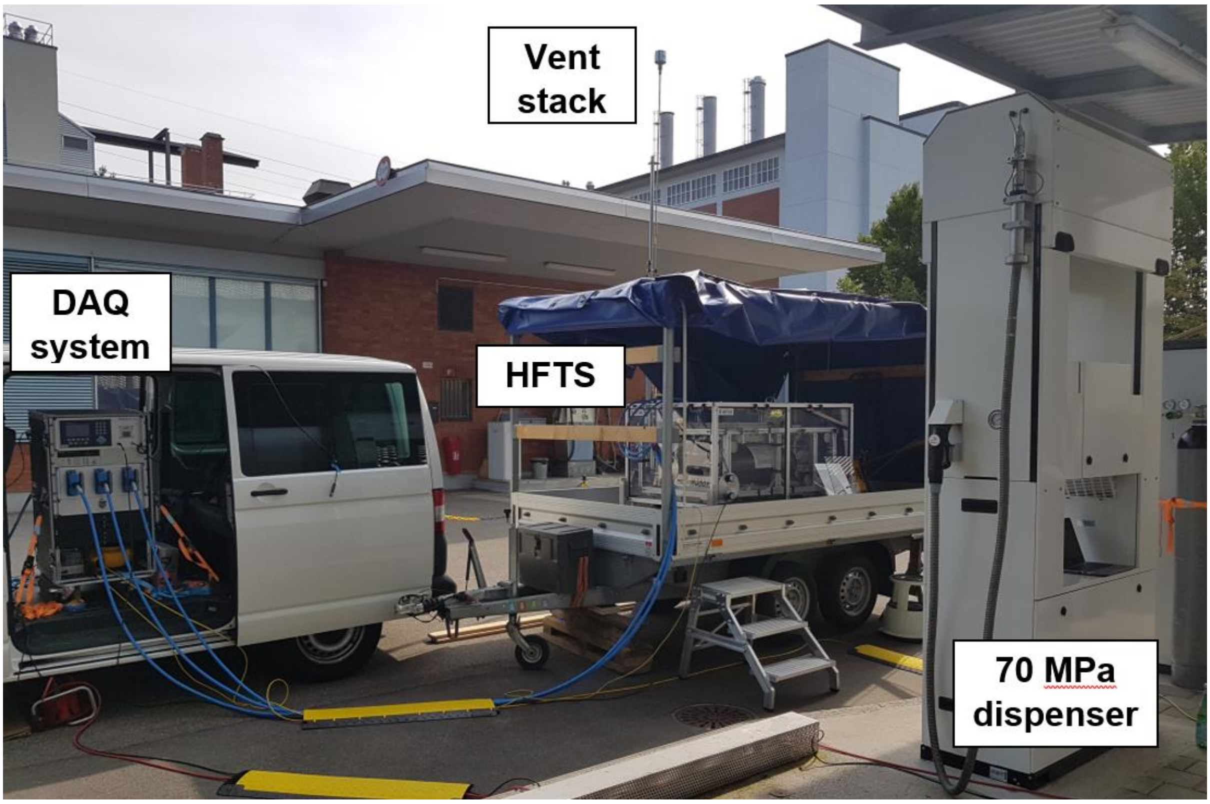

Figure 6: The HFTS at the Empa hydrogen dispenser.

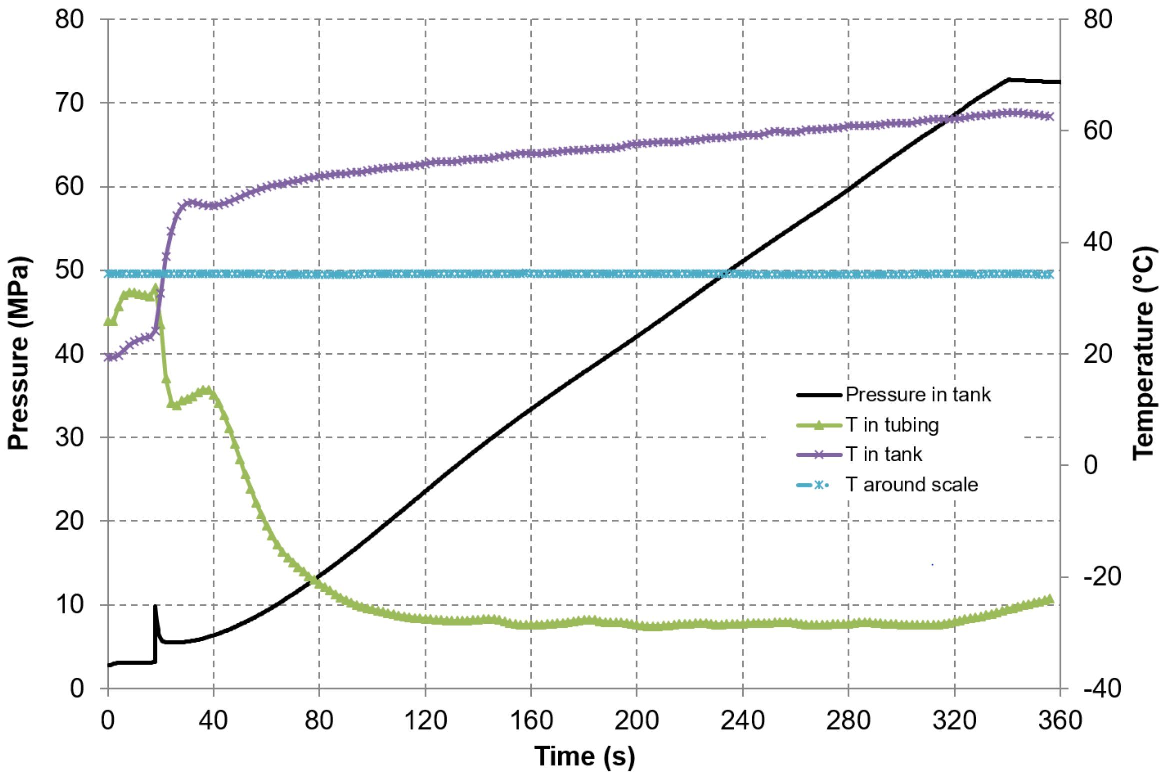

Figure 7: Pressure (in black) and temperature profiles from the HFTS during a fill with hydrogen at -35°C, with a PRR of 16 MPa/min.

During the fill and until before the weighing, the housing surrounding the scale was partially opened to allow for a better air circulation and accelerate the evaporation of the ice on the pipes. After a waiting time of about 25 minutes, the remaining humidity in the form of a thin layer of water, was removed from the pipes and valves using a dry cloth. The housing was then lowered to its lowest position and some additional time allowed the scale to stabilise. A spread in the scale indication of 1 g was confirmed by these field measurements. The high-pressure tanks were then connected to the venting stack and the tanks emptied down a residual pressure of 30 bar or 350 bar for the next fill. Venting from 700 bar down to 30 bar took about 1.25 h. A complete uncertainty budget for the gravimetric method can be found in the MetroHyVe report 1.5.4 [6] and yields an expanded uncertainty of 0.3 % (k=2) for the gravimetric method. The uncertainties of the process are further detailed in Section 7.

From the laboratory results and field-testing, the following comments and recommendations can be found:

- The gravimetric method for field-testing of HRS shows good results and achieves an expanded uncertainty of 0.3 %
- The formation of ice on the piping of the HFTS must be taken into account
- The gravimetric method can be used for type-approval testing of HRS
- Venting times are long and limit the number of measurements one can perform in a day
- The calibration of a HRS takes several days
- An alternative method to using gravimetric standards needs to be developed to reduce measuring time and therefore costs.

4.4 Master meter method (dynamic method) vs gravimetric method (static method)

One objective in the project was the assessment of the validity of using a master meter based on Coriolis mass flow meters (CFM) for the testing and calibration of HRSs.

In contrast to the verification with the gravimetric method (weighing method), the verification with a CFM (master meter method) would offer some advantages.

A possible verification of a HRS with the flow meter method would significantly reduce the effort of verification measurements by for instance the following factors:

- Significantly shorter measuring times and hence downtime for the HRS
- Significantly less equipment and installations on-site
- Significantly easier implementation (e.g. no venting of hydrogen after testing, etc.)
- More independence from external (weather) conditions (no icing, no wind effects, etc.)
- Considerably lower effort and costs for the HRS operator

The assessment in the project is based on a very limited amount of experimental field data. Data have been taken during field-testing with the METAS HFTS at the Empa HRS.

In laboratory tests, CFM could achieve uncertainties of less than 0.5 % when calibrated with water and within 0.5 % to 1 % with nitrogen under steady conditions. As seen previously, OIML R139:2018 [1] states MPE of 2% for Class 2 and 4% for a Class 4 HRS. These limits would imply that a CFM calibrated with water would achieve the needed expanded uncertainty of 1/3 MPE for a Class 2 HRS and could be used as a reference meter for verification measurements. Unfortunately, there is currently very little data on the equivalence in calibration results for Coriolis meters with water and hydrogen at pressures encountered in a typical HRS.

It can be assumed that it makes a difference at which location the master meter is installed in the HRS. The CFM can be installed either in the "hot region", which means before the heat exchanger, or after the heat exchanger in the "cold region". The meter location can have a large influence on the flow meter reading. If the CFM is installed upstream the heat exchanger, the temperature is relatively stable during the fuelling. Conversely, if the CFM is installed downstream of the heat exchanger, the meter may experience a rapid temperature variation at the beginning of the fuelling when hydrogen at ambient temperature is replaced by cooled hydrogen.

Both flow meter configurations were tested in the project at the Empa HRS. Firstly, the METAS master meter was mounted in series with the CFM and secondly, the master meter was mounted in the HFTS. The delivered mass of hydrogen was measured by the HFTS and compared to the delivered mass as displayed on the dispenser of the HRS. The METAS master meter was read out using manufacturer's software and using the value displayed in the totalizer field. This value was set to zero before each fill.

4.4.1 CFM installed in the hot region

The set-up with the master meter installed in the hot region can be seen in Figure 8. In total, seven measurements were carried out at the 70 MPa dispenser. Three full fillings, two partial fillings with low starting pressure (2 MPa) up to 35 MPa and two with medium starting pressure (35 MPa) up to 70 MPa.

Investigations were carried out on the deviations of the HRS flow meter and the METAS master meter in comparison to the gravimetric HFTS. Summarized, it has been observed that the master meter mounted in the hot region of the HRS shows good repeatability when calibrated with a HFTS.

The major concern in such a configuration is the fact that all corrections for vented quantity and piping volume need to be determined/known beforehand. Moreover, the CFM would have to be mounted in the HRS, which would require specific permission from the HRS operator to modify the existing facility and would also be time consuming.

The results seem to indicate that such installation would achieve the required accuracy for verification measurements for a Class 4 HRS. Nevertheless, more data including the corrections for vented quantity is needed to make a claim for its use in the verification of a Class 2 HRS.

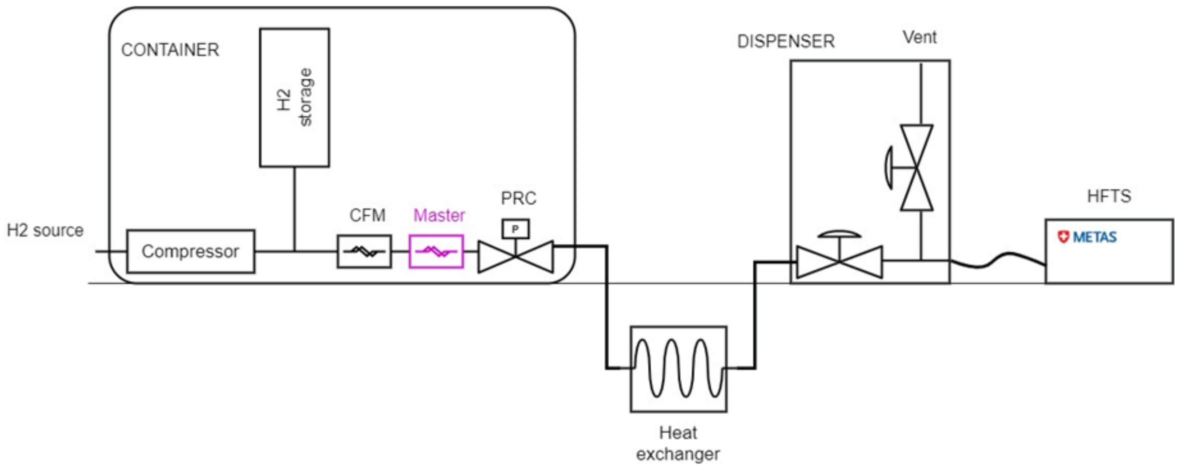

Figure 8 – Master meter installed in the hot region (before the heat exchanger) in the HRS

4.4.2 CFM installed in the cold region

The second configuration, with the master meter installed in the cold region, can be seen in Figure 9. It can be assumed that this method will likely be used for field-testing in the future as the master meter can be placed between the HRS and a vehicle or another volume representing the tank of a vehicle and no further corrections are needed.

The same seven measurements (three full fillings, four partial fillings) as for the first configuration were repeated. In contrast to previous measurements, it has been noted that the METAS master meter has a large positive deviation in all tests (deviation > 5%) and a larger spread. There is at this moment no explanation for the sudden deviation. A possible candidate could be the transient temperature influence on the flow meter and its calibration factor. In contrast to the hot region configuration, there are no error contributions from different initial and final pressures in the pipes and the vented quantity at the end of the tests.

In sum, the measurement results collected from field-testing with the master meter mounted in the cold region of the HRS have shown a wide spread and a large deviation with respect to calibration results when mounted in the hot zone of the HRS, which results in no clear conclusions. From part of the data, the required accuracy for verification measurements for a Class 4 HRS has been achieved. Nevertheless, the expanded uncertainty of the measurements varies strongly depending on the filling profile and would tend to indicate that the master meter cannot be used for verification measurements.

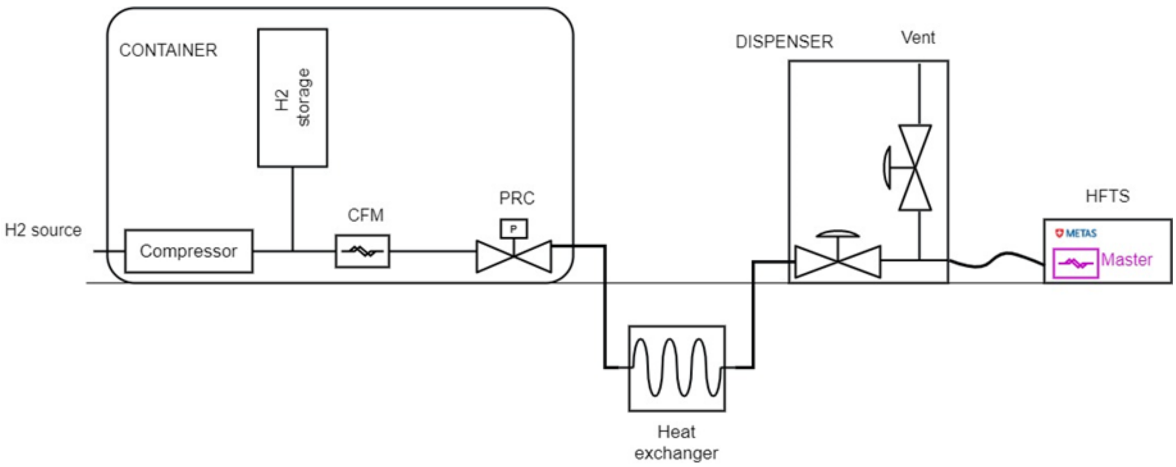

Figure 9 – Master meter installed in the hot region (after the heat exchanger) in the HFTS

From these two series of measurements, we can make the following comments:

- The METAS master meter showed good results in the warm zone (before the heat exchanger) and met the requirements for a Class 4 station as defined by OIML R139 [1]. If the HRS corrects for its uncertainties e.g. due to pressure differences, a Class 2 is possible.
- In the cold zone, the METAS master meter showed a large positive error (deviation >5%) and the repeatability was not as good as in the warm zone. Further tests are required to better understand the transient temperature behaviour in the cold zone.

More detailed information can be found in the MetroHyVe report A1.4.6 [7] and the publication of M. de Huu et al. [8].

5. Procedures and guide for HRS calibration

In this section, the HRS field tests conducted during the MetroHyVe project are detailed. The aim is to give some feedback and knowledge about how a calibration was realised. This section will include both the planning and performance of the calibration of HRSs, as well as the results of the field calibrations. Information about the selected HRSs in Europe as well as the design of the primary gravimetric HFTS utilised in the calibration can be found in Appendix D. The information in this section can also be found in a recently published article [9].

5.1 Planning for an HRS calibration

During the test campaign, the calibration procedure was more severe than what is requested in OIML R139:2018. The duration for a complete calibration was estimated to be 4 days, which is enough to perform all tests and get a good repeatability for the measurements. The main actions during the calibration procedure with the needed time are:

- the installation of the testing rig (2-3 h),
- scale verification (30 min to 1 h),
- accuracy tests (3 days), and
- de-installation (2 h).

During the 3 days of accuracy tests, it was possible to perform the test sequence as seen in Figure 10 three or four times, which adequately measures the repeatability.

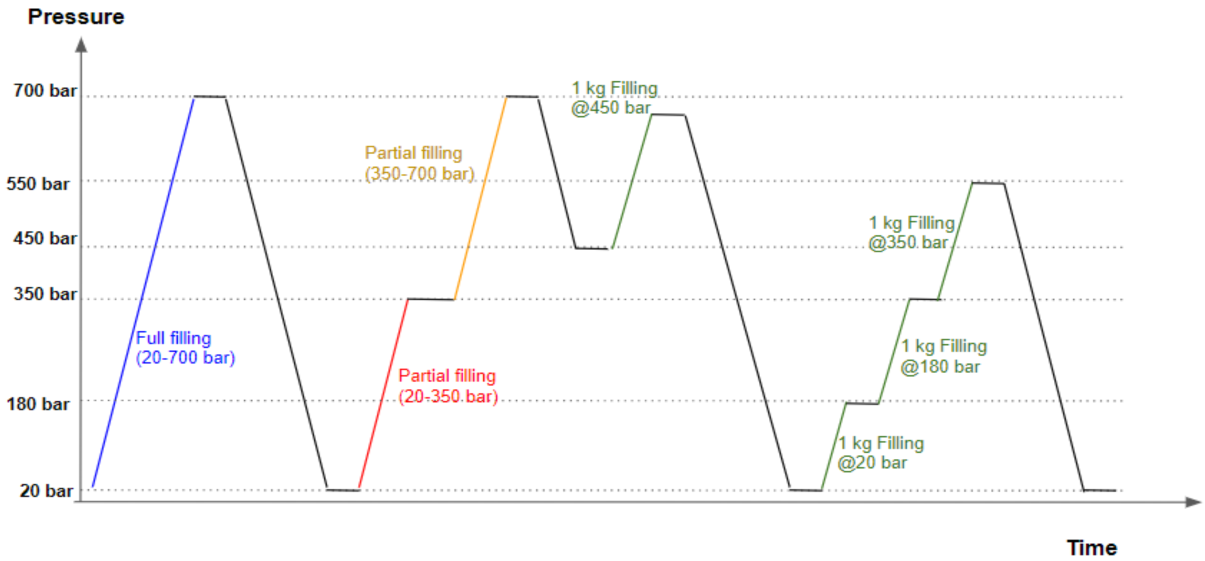

Figure 10: Sequence of full test sequence performed 3-4 times per HRS.

Note: The scale requires a warm-up time of 1h30 (minimum) to 2h after each electrical disconnection. The reading mass is not stable during the warm-up time. During the first testing week, the scale was disconnected each night. Therefore, the waiting time was 1h30 each morning to start the accuracy tests. To save some time, a solution was found with H2 Mobility to keep the scale plugged during nights. It is recommended to maintain the power of the scale during the all test duration.

Note 2: Depressurization of the tank from 700 to 20 bar takes around 2h. This duration limits the number of fuelling procedures that can be performed each day, but the depressurization rate cannot be higher in order to respect the minimum temperature inside the tank.

5.2 Scale verification for mass correction

The scale was calibrated each day of tests against reference weights of 0.5kg, 1kg or 2kg, and 20g. The type of weights applied can be seen in Figure 11. This verification was done at the full range of the scale, i.e. when the empty cylinder was already in place onto the scale. The scale deviation was recorded and hysteresis was assessed for each day. The linear regression calculated was subtracted to each mass measured the same day of the scale verification.

Figure 11: Calibrated weights handled cautiously with gloves

5.3 Description of the HRS tested

Over the seven different HRS tested, it became apparent that the HRS measuring systems can be divided into two main configurations when considering flow metering. The two main configurations are primarily associated with the knowledge and the maturity of the HRS concept. Indeed, configuration 1 is generally associated with some old HRS design, whereas configuration 2 is usually often chosen for modern and new HRS design.

- **Configuration 1**: where the Mass Flow Meter (MFM) is installed <u>in the container</u>, and not in the dispenser (see Figure 12).
    - *Advantages*: the flowmeter remains always under pressure and is exposed to stable gas temperature conditions (ambient temperature)
    - *Disadvantages*: the distance between the container and the dispenser can vary significantly (>30 meters in this experimental campaign). This long distance can generate some errors if the process is not correctly performed.

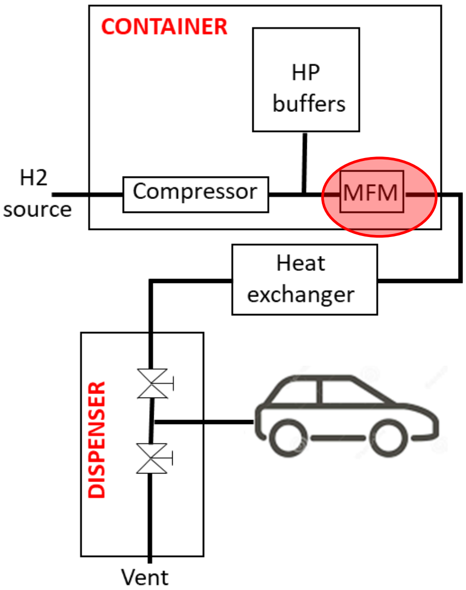

Figure 12: Illustration of configuration 1, where the MFM is located in the main container

- **Configuration 2**: where the MFM is installed in the dispenser, close to the break-away device (see Figure 13).
    - *Advantages*: The dead volume and associated error is minimized due to the short distance between the MFM and the transfer point.
    - *Disadvantages*: the flowmeter is subjected to a large variation in pressure from 10 to 875 bar, and temperatures from ambient to -40°C in less than 30 seconds, which results in more severe operating conditions.

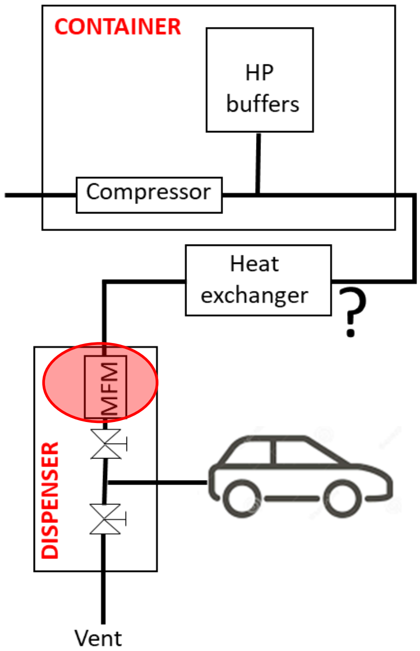

Figure 13: Illustration of configuration 2, where the MFM is located in the dispenser

5.4 Results and analysis of the HRS tests

Detailed results from the individual tests run according to Figure 10 for the seven chosen HRSs can be found in Appendix E in Figure 32 to Figure 39. From these figures, the mean value has been calculated for each station, sorted by configuration, and for each type of test. These mean values can be seen in Table 3.

The test results can be summarized as follows:

- **Configuration 1**: The same tendency was observed for all HRS of configuration 1 (***HRS 1 to 5***):
    - Very good accuracy for Full filling tests (from 20 to 700 bar): Error close to zero, and very repeatable
    - Negative deviation for Partial filling tests (from 20 bar to 350 bar)
    - Positive deviation for Partial filling tests (from 350 bar to 700 bar)
    - Variable deviation for 1 kg fillings (MMQ) depending on the initial pressure in the tank
- **Configuration 2**:
    - ***HRS 6***: After adjustment of the test results, the accuracy looks very good (close to 0% for most of tests, and < 2% for one test condition).
    - ***HRS 7***: No clear conclusion / tendency without further explanations from the HRS manufacturer on the measuring system.

Table 3: Summary table of tests results for all HRS tested, per type of tests.

	Configuration 1					Configuration 2	
	HRS1	HRS2	HRS3	HRS4	HRS5	HRS6 (*)	HRS7
Full filling 20 bar-700 bar	**-0.24%**	**0.00%**	**0.52%**	**0.00%**	**0.50%**	**0.00%**	**-0.42%**
Partial filling 20 bar–350 bar (**)	**-3.77%**	**-2.01%**	**-2.46%**	**-1.11%**	**-3.89%**	**-0.30%**	**-3.08%**
Partial filling 350 bar-700 bar	**4.13%**	**2.26%**	**0.72%**	**1.00%**	**4.58%**	**0.33%**	**-2.88%**
Filling at MMQ 450 bar-700 bar	**0.16%**	**-0.47%**	**2.02%**	**0.47%**	**4.84%**	**-0.12%**	**-5.75%**
Filling at MMQ 20 bar-180 bar (**)	**-9.94%**	**-6.26%**	**-9.95%**	**-1.74%**	**-6.75%**	**0.43%**	**-8.37%**
Filling at MMQ 180 bar-350 bar (**)	**3.36%**	**3.53%**	**-5.12%**	**0.91%**	**0.51%**	**0.74%**	**-6.32%**
Filling at MMQ 350 bar-580 bar (**)	**3.78%**	**3.59%**	**-1.07%**	**0.69%**	**4.62%**	**1.74%**	**-6.28%**

Legend: **Green value**: all values are within the limits (MPE). **Orange value**: mean value is within the limits (or very close to the limits), but some single values are out of the limits (MPE). **Red value**: all values are out of the limits (MPE). (*) single value (not mean value). (**) test out of OIML R139:2018.

Reminder: With the new version of OIML R139:2018 for HRS, accuracy class 1.5 also accuracy class 2 and 4 are allowed. Herewith for HRS the MPE for accuracy class 2 and 4 are respectively 2 and 4% for type approval, initial and subsequent verifications. For in service inspection of existing HRS the MPE increase to 3 and 5% respectively. Also, for fillings at MMQ (1 kg), the MPE is doubled. For example, for an existing HRS with accuracy class 4 during an in-service inspection, the MPE for fillings at MMQ (1 kg) is 10%. See full details in OIML R139–1:2018 paragraph 5.2.

5.4.1 Repeatability

A good repeatability was observed for most of tests. This repeatability demonstrates that the testing equipment works correctly in real conditions and on site, subjected to ambient environmental conditions which were hot temperatures during summer and moderate wind. The test bench is reliable and gives reproducible results. However, for some tests, the repeatability was lower. It is difficult to explain if this was due to the testing equipment or due to the meter itself.

Reminder: For OIML R139:2018 the requirement for the repeatability of the HRS is stated that the repeatability error shall not exceed two thirds (2/3) of the applicable MPE. This requirement is only applicable for measurand equal to or greater than 1000 scale intervals of the meter.

5.4.2 Influence of the distance between the Mass Flow Meter and the dispenser: Configuration 1

For HRS of configuration 1, a systematic deviation was observed for the partial fillings. This deviation was either positive or negative, depending on the fuelling process. For the partial filling from 20 to 350 bar, a **negative deviation** was observed such that the quantity of hydrogen delivered to the customer was higher than the quantity counted and invoiced: ***m_delivered > m_invoiced***. For the partial filling from 350 to 700 bar, a **positive deviation** was observed such that the quantity of hydrogen counted and invoiced to the customer was higher that the quantity really delivered: ***m_delivered < m_invoiced.***

When reviewing the test results, it is evident that errors observed for HRS with configuration 1 are strongly influenced by the distance between the CFM and the dispenser. This influence means that the longer the distance, and thus the bigger the volume, the bigger the errors in the flow meter. The effect of the distance between the CFM and dispenser is important both during the beginning and end of the filling process.

At the beginning of the test, the line between the MFM and the dispenser is full of hydrogen at a certain pressure, called **P1**. This situation is illustrated in Figure 14. Pressure **P1** depends on the end pressure of the previous filling, and is thus independent of the current customer. The quantity is not counted by the MFM, as it is already in the pipe at the beginning of the transaction, and is given to the customer.

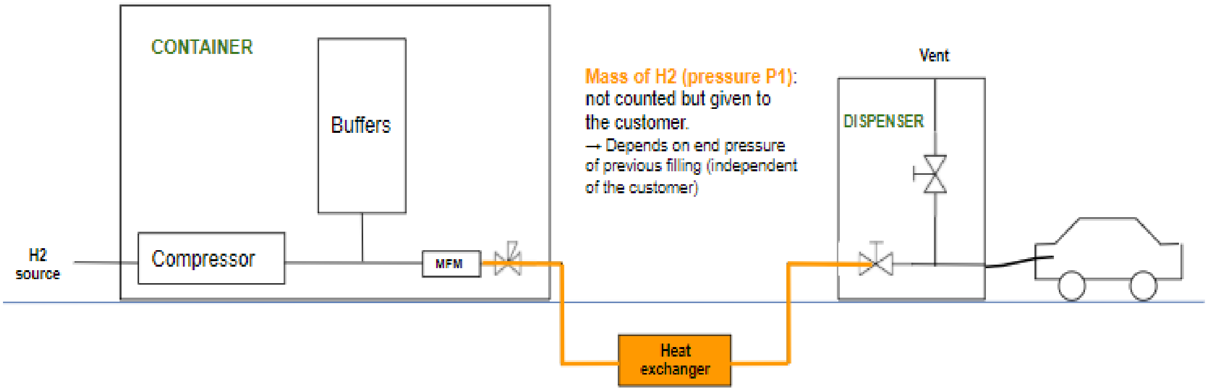

Figure 14: Schematic diagram of an HRS - situation before fuelling

At end of the test, this same line is full of hydrogen at a certain pressure, called **P2**. This situation is illustrated in Figure 15. Pressure **P2** depends on the end pressure of the ongoing filling during transaction. This end pressure is either given by the filling protocol such that it stops automatically based on the filling conditions, or stopped manually by the customer. The quantity represented by **P2** is counted by the MFM but not transferred into the customer vehicle.

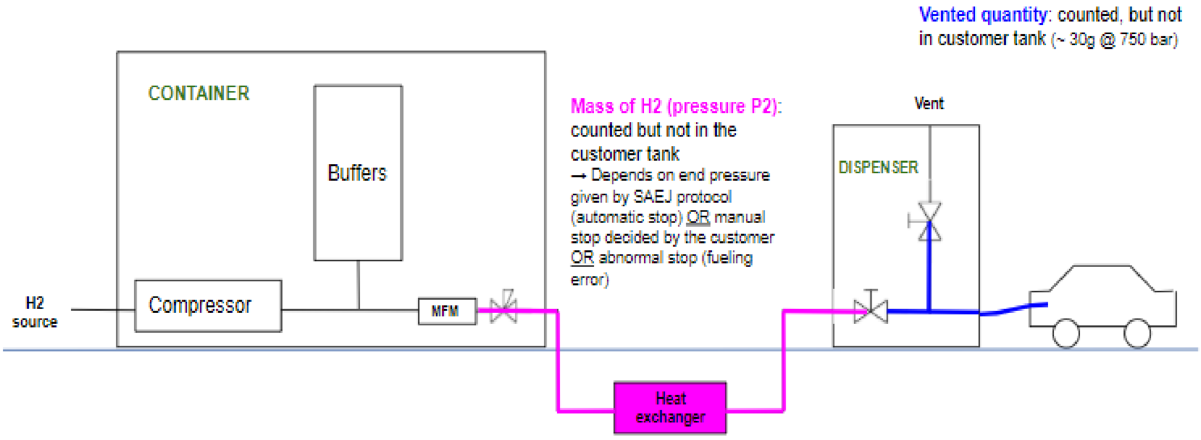

Figure 15: Schematic diagram of an HRS - situation at end of fuelling

If **P1 ~ P2**, then the customer pays exactly the quantity delivered in his tank: the quantity of hydrogen initially present in the pipe (delivered but not counted) is **replaced by the same quantity** at end of the fuelling (counted, but not delivered).

If **P1 > P2**, then the customer gets *more* hydrogen than the quantity invoiced: the quantity of hydrogen initially present in the pipe (delivered but not counted) is replaced by a ***lower*** quantity at end of the fuelling (counted, but not delivered). This situation gives a **negative deviation**.

If **P1 < P2**, then the customer gets *less* hydrogen than the quantity invoiced: the quantity of hydrogen initially present in the pipe (delivered but not counted) is replaced by a ***higher*** quantity at end of the fuelling (counted, but not delivered). This situation gives a **positive deviation**.

In Figure 10, the full sequence of tests performed can be seen with different types of tests categorized by colour. In the following list, each type of filling is described, and the state of **P1** and **P2** is detailed for each, resulting in a determination of the presence of positive or negative deviation. For all tests, P1 represents the pressure in the line between the MFM and the dispenser at the beginning of the test, which is dependent on the last type of filling performed at the HRS. P2 represents the pressure in the line between MFM and dispenser at the end of the test. It is important to note that deviations are more important for 1 kg fillings, as the reference mass is small, and the pressure difference has a greater relative influence on the delivered mass of hydrogen.

Table 4 Fillings from performed tests with their associated deviations based on pressure in the line between MFM and the dispenser at the beginning of the test (P1) and the end (P2)

Filling (colour)	**Pressures**	**P1**	**P2**	**Deviation**
Full fillings (**blue**)	From 20 to 700 bar	700	700	Close to zero (P1~P2)
Partial filling (**yellow**)	From 20 to 350 bar	700	350	Negative (P1>P2)
Partial filling (**red**)	From 350 to 700 bar	350	700	Positive (P1<P2)
Filling of 1 kg (MMQ) (**green**)	From 450 to 700 bar	700	700	Close to zero (P1~P2)
Filling of 1 kg (MMQ) (**green**)	From 20 to 180 bar	700	180	Negative (P1>P2)
Filling of 1 kg (MMQ) (**green**)	From 180 to 350 bar	180	350	Negative (P1>P2)
Filling of 1 kg (MMQ) (**green**)	From 350 to 580 bar	350	580	Negative (P1>P2)

Consequently, based on Table 3 and Table 4, it appears that **a longer distance between the delivery point and the flow meter (i.e. a larger piping volume) gives a larger error.** With accurate knowledge of the pressure and the volume of the pipe between the CFM and the nozzle, it is possible to correct the systematic error due to HRS configuration.

For the HRSs tested with configuration 1, the distance between the MFM and dispenser varies significantly. The longest distance was found for HRS 1, and was about 35 meters. HRS 5 had a medium distance of 15-20 meters, and the scatter observed on this station does not allow clear conclusions on the influence of the distance between dispenser and MFM. For HRS 2 and HRS 3, the distance between dispenser and MFM was short, about 10 meters, and as such they give lower errors than HRS 1, as seen in Table 3. This lowering of error is especially clear for MMQ fillings. The lowest error was found for HRS 4, which had a similarly short distance as HRS 2 but a smaller volume in the heat exchanger. The error of HRS 4 is low enough to be compatible with Class 2 in OIML R139:2018.

5.4.3 Influence of the distance between the Mass Flow Meter and the dispenser: Configuration 2

In the case of configuration 2 when the MFM is located in the dispenser as shown in Figure 13, the distance between the MFM and the nozzle is very small. As a result, this distance is nearly negligible, and the MFM counts exactly the quantity delivered to the vehicle without "buffer volume", except the vented quantity which must be subtracted.

This negligence is why errors were very good on HRS 6 after adjustment and close to zero whatever the type of test.

5.5 Representability of the test sequence performed in this study

The test sequence performed in this study, see Figure 16, is more complete than the tests required in OIML R139-2:2018, but also more severe. OIML R139-2:2018 request only three fillings as seen in

Figure 17, namely a full filling from 20 to 700 bar, a partial filling from 350 to 700 bar, and one MMQ filling ending at 700 bar where the pressure has to be determined from the end point. These tests are denoted as #4, #5 and #7 in the standard, respectively.

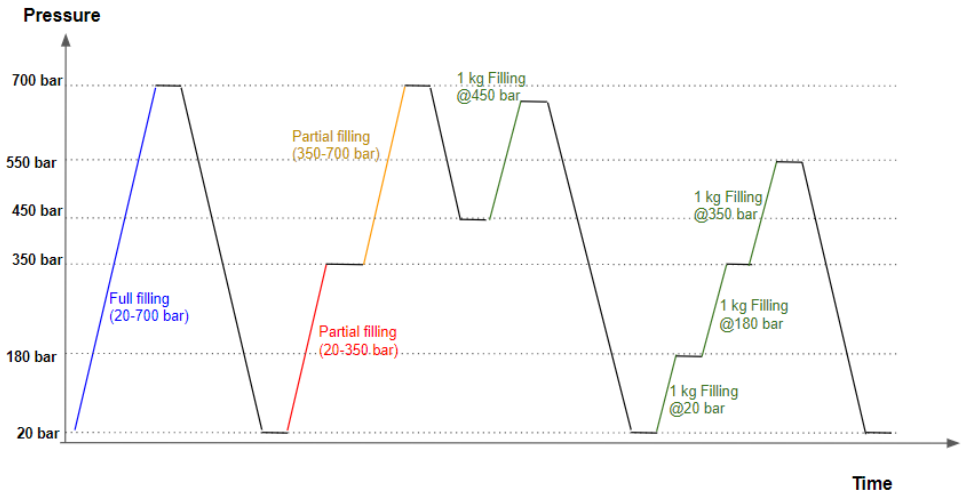

Figure 16: Full test sequence performed in this study

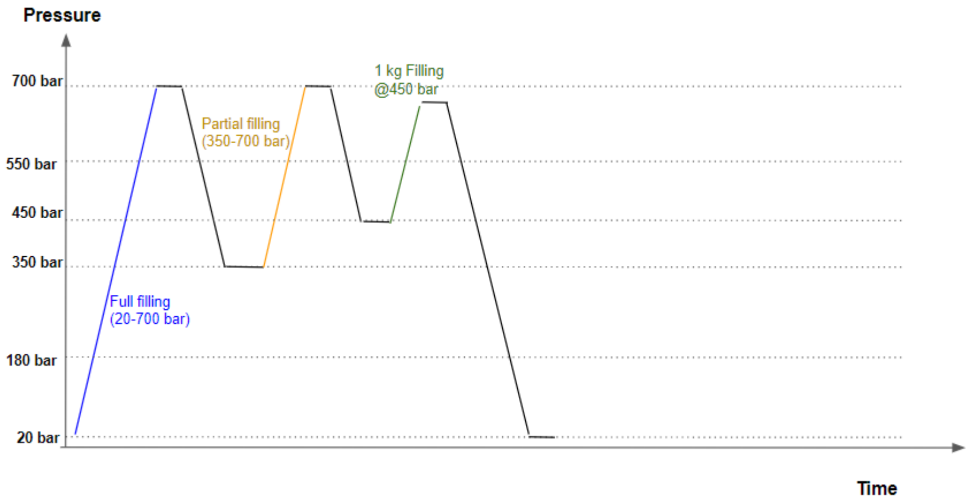

Figure 17: Test sequence requested in OIML R139-2:2018

5.5.1 Impact on test results

The three tests required by OIML R139-2:2018 have all an end filling pressure at 700 bar. If we apply the reasoning as described in the previous section, in that case the pressure in the line between the MFM and the nozzle would always be the same at beginning and end of the fuelling. So, there would always be **P1 ~ P2**, and consequently all types of tests would have errors close to zero. However, this low error needs to be verified by testing.

5.5.2 Impact on test duration

For the system supplied by Air Liquide for testing at Cesame, which uses a diaphragm for venting, the depressurization time needed to empty the tank depends on the pressure. For this system, depressurization speed is very fast at high pressures, but it decreases as much as pressure decreases. For instance, only 15 min is needed to depressurize from 700 bar to 450 bar, whereas almost 2h is needed to empty the tank from 700 bar to 20 bar. For the system utilized by METAS, however, the venting is performed with a pressure reducer, and thus the mass flow rate and pressure ramp rate are constant.

The initial pressure of each test is very important and has a high influence on the duration of the whole test campaign. For the full test sequence from Figure 16 applied in the MetroHyVe project, one day per sequence was needed to adequately perform the tests with depressurizations. For three repetitions of the sequence, at least three days were needed with a fourth day to install and uninstall the equipment. For the test sequence in Figure 17 as requested in OIML R139-2:2018, 3.5 hours per sequence is needed. As such, only one and a half day is needed to perform the test sequences from the standard three times, with an extra day for setting up and taking down the equipment.

The test duration and amount of days needed to complete the test sequences will have a strong impact on testing cost, but also on customer experience. Although the dispenser remains accessible during the tests, the drivers were asked to park in a way so that the dispenser may be accessible, perhaps negatively influencing the customer experience.

5.6 Representability of real fuelling performed by customers

In practice, it is very rare that customers stop manually the fuelling before its full completion. It is more likely that customers arrive with a half-full tank and perform a partial fuelling up to the max pressure. All fillings normally stop at 700 bar.

Based on Air Liquide statistics, 3914 refuelling were done in March and April in 3 HRSs. Among these refuellings, only 25 refuellings were manually stopped by the customer, i.e. before 700 bar). Therefore, intentional partial fillings represent only **0,64%** of all refuellings.

5.7 Recommendations to HRS manufacturers

The conclusions drawn based on test results lead us to make the following recommendations intended to HRS manufacturers:

1. Choose a MFM certified according to at least OIML R137 or OIML R139 if possible.
2. Reduce as much as possible the volume between the MFM and the nozzle.
3. Correct the mass error related to the process related to vents, piping and distances.

6. Procedures using other substances

The previous sections detailed how the overall accuracy of hydrogen dispensed at refuelling stations can be validated by field verification using either primary or secondary flow standards. These approaches are necessary to validate the refuelling station measurements under realistic operating conditions and fully account for sources of measurement inaccuracy including those related to the flow meter and otherwise (such as dead volumes and vented quantities).

Additionally, there are times where it is necessary to assess the performance of the flow meter in isolation, as opposed to the HRS as a complete measurement system. For example, when a meter is calibrated before installation at an HRS, or tested for type approval. Given that no traceable flow calibration facilities exist which can operate with hydrogen at ‘realistic’ pressure and temperature ranges (pressures up to 700 bar, temperatures -40 °C to 50°C), and that building such a facility remains economically unviable, alternative methods must be used with substitute fluids.

An alternative approach to calibration of these meters was investigated in the MetroHyVe project. This approach involved calibrating the flow meter with air at ambient temperature at mass flow rates relevant to the field conditions. The air calibrations were carried out at ambient temperature and two nominal pressures, 20 bar and 40 bar, selected to maintain gas density at either 23 kg/m^3 or 46 kg/m^3 to represent hydrogen at 350 bar or 700 bar.

Further tests were then undertaken to study the effects of temperature (-40 °C to 40 °C) and pressure (5 to 850 bar).

6.1 Choice of calibration fluid

Considering the substitute fluid used for the calibration, air or nitrogen is an obvious candidate since it is inexpensive, safe and already used by virtually every traceable gas calibration facility.

Another candidate fluid is water which fulfils a similar role in liquid calibration facilities. Since Coriolis Mass flow meters are considered relatively insensitive to changes in fluids properties, the manufacturers of the flow meters used in hydrogen refuelling stations provide the meters with a water calibration.

Data was collected in the MetroHyVe project comparing the performance of these flow meters which each fluid. The results as seen in Figure 18 showed that the meters perform better with water than nitrogen or air with the gas calibrations yielding both poorer repeatability and relatively large reproducibility uncertainty, although the average errors were fairly consistent with the water calibrations.

Whilst there does not appear to be any consistent shift towards under- or over-reading when moving from the liquid to gas calibrations, the meter performance is clearly more stable when operating with water and results from the water calibration could be considered “too optimistic” for a meter intended for use in gas service. Using nitrogen or air for the calibration should provide a more representative assessment of the likely meter performance when operated with hydrogen, although more data is required directly comparing the flow meter performance with each gas.

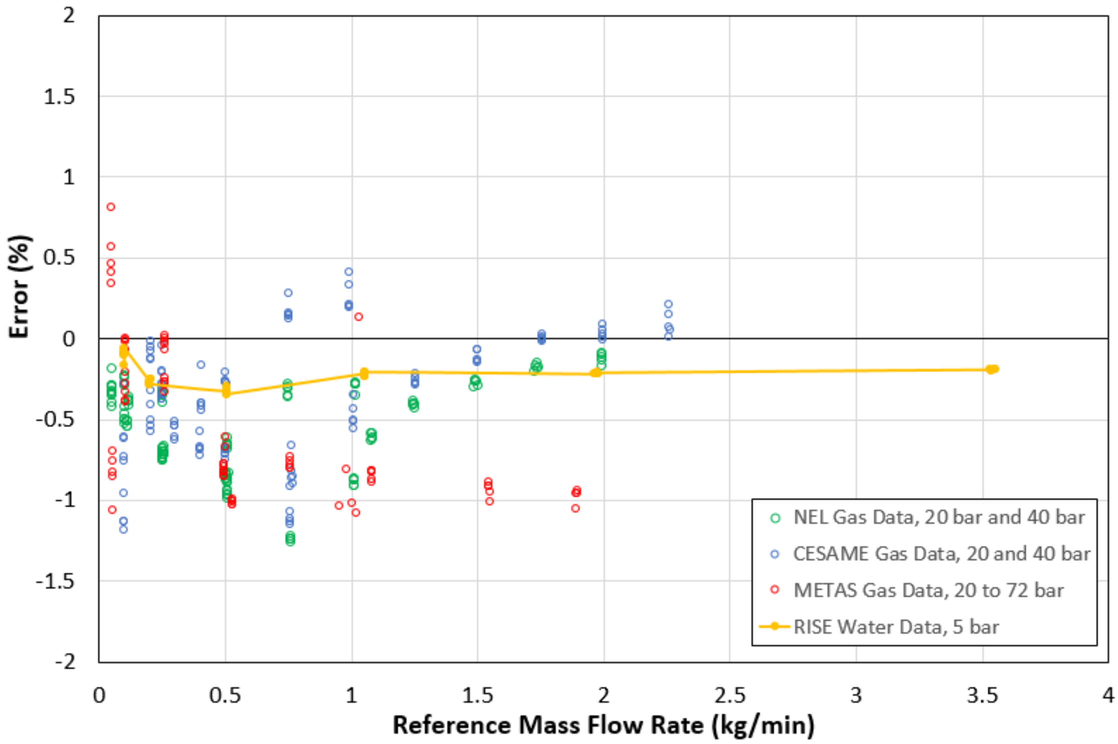

Figure 18: Comparison of results from liquid and gas tests performed as part of MetroHyVe on flow meter A.

6.2 Pressure drop and gas velocity

The flow meters used in hydrogen refuelling stations have small diameter measuring tubes which results in very high pressure drops. In an HRS, the pressure drop is relatively small compared to the supply pressure and velocity of hydrogen in the meter measuring tubes remains within acceptable ranges.

However, for calibrations with air, the pressure drop across the meter is much larger relative to the inlet pressure, and Mach numbers are greater even when testing at representative density ranges. In the MetroHyVe gas calibrations, the meter manufacturers advised a maximum flow rate of 2 kg/min at 40 bar in order to limit velocity in the measuring tubes. This advice was followed, and the calibrations at 20 bar were limited to 1 kg/min to achieve the same maximum velocity.

Additional experiments were also carried out at higher flow rates by one of the MetroHyVe project Stakeholders, the Korea Research Institute of Standards and Science (KRISS) [10]. KRISS tested a flow meter with air at flow rates up to 3.76 kg/min and pressures of 10, 20, 30 and 40 bar. The results of these tests can be seen in Figure 19, and there did not appear to be any shift in the meter performance at flow rates above 2 kg/min or pressures below 20 bar.

These results suggest that if nitrogen or air is used for calibration or type approval, it is not necessary to restrict the maximum flow rate to 2 kg/min or test at 20 bar or 40 bar to represent hydrogen at 350 bar or 700 bar. However, laboratories attempting to calibrate these meters with air at low pressure will encounter very large pressure drops and may struggle to reach the higher flow rates. In the MetroHyVe gas calibrations, at an air flow rate of 1 kg/min and 20 bar inlet pressure, the pressure drop was approximately 5 bar. Based on these figures, it would not be possible to reach the 3.6 kg/min full-scale flow rate of the meter without increasing the inlet pressure to 40 bar or more.

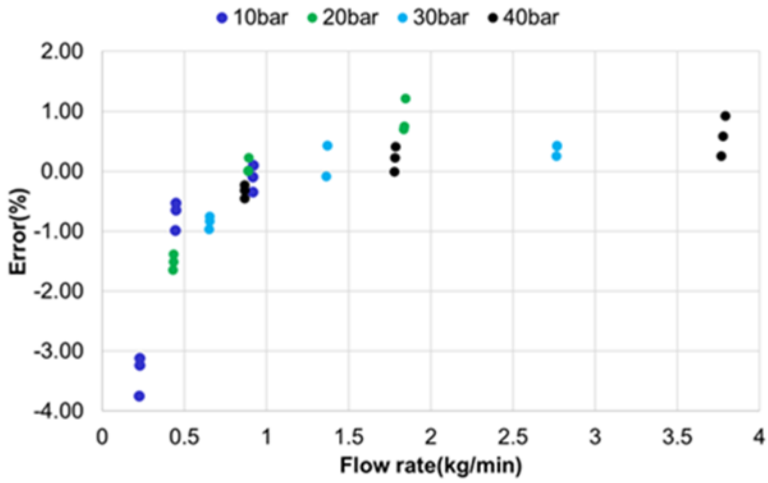

Figure 19: KRISS Test data for a CFM operated with air

6.3 Calibration Pressure and Gas Density

Although the MetroHyVe gas calibrations were carried out at two nominal pressures, additional data collected by the project partners and stakeholders covered a much wider pressure range. No influence of pressure or gas density was observed in the range from 10 bar to 86 bar.

RISE tested the same Coriolis flow meters as featured in the gas tests, at the same mass flow rates but using water. The effect of pressures up to 850 bar was studied using a newly constructed flow test facility. Two identical flow meters were installed in the test facility. The upstream meter was operated at elevated pressures while the downstream meter was maintained at atmospheric pressure. The same tests were then repeated with the upstream and downstream meters switched, in order to eliminate any systematic bias. A full description of the test apparatus, procedure and results is available in publications and reports which can be found in Appendix A.

The pressure effect was estimated at -0.0001 % per bar. Thus, based on results from the MetroHyVe experimental programme, it is not necessary to calibrate the tested flow meters at high pressure (700 bar) or at a particular density.

6.4 Calibration Temperature

The temperature effect was studied in the project with several different flow meters and over an overall temperature range from -40°C to 40°C. If sufficient time was allowed for the temperature of the meter body to stabilise, a small increase in meter errors was observed. Typical results are shown in Figure 20. At medium to high flow rates (above 0.5 kg/min), the temperature effect is minimal and all errors were within ±1.5%. At the lowest flow rates, errors increased to nearly 10%, although these flow rates were below the Qmin specified by the manufacturer.

A much larger temperature effect was observed in tests where no time was allowed for temperatures to stabilise, as shown in Figure 21. The flow meter was initially at ambient temperature and gas was introduced at -40 °C. In this case, the meter performance was erratic, with errors ranging from -15% to 5% over a period of 5 minutes. This effect is relevant to flow meters installed downstream of the heat exchanger in HRSs. In between fills, the meter body could be at ambient temperature. When refuelling begins, hydrogen will be introduced at low temperature and temperatures may not stabilise during the refuelling window.

The relevance of this temperature effect depends on where the meter is installed at an HRS and how the stations is operated. If the meter is installed upstream of the cooler, the meter body and incoming gas will not deviate significantly from ambient temperature.

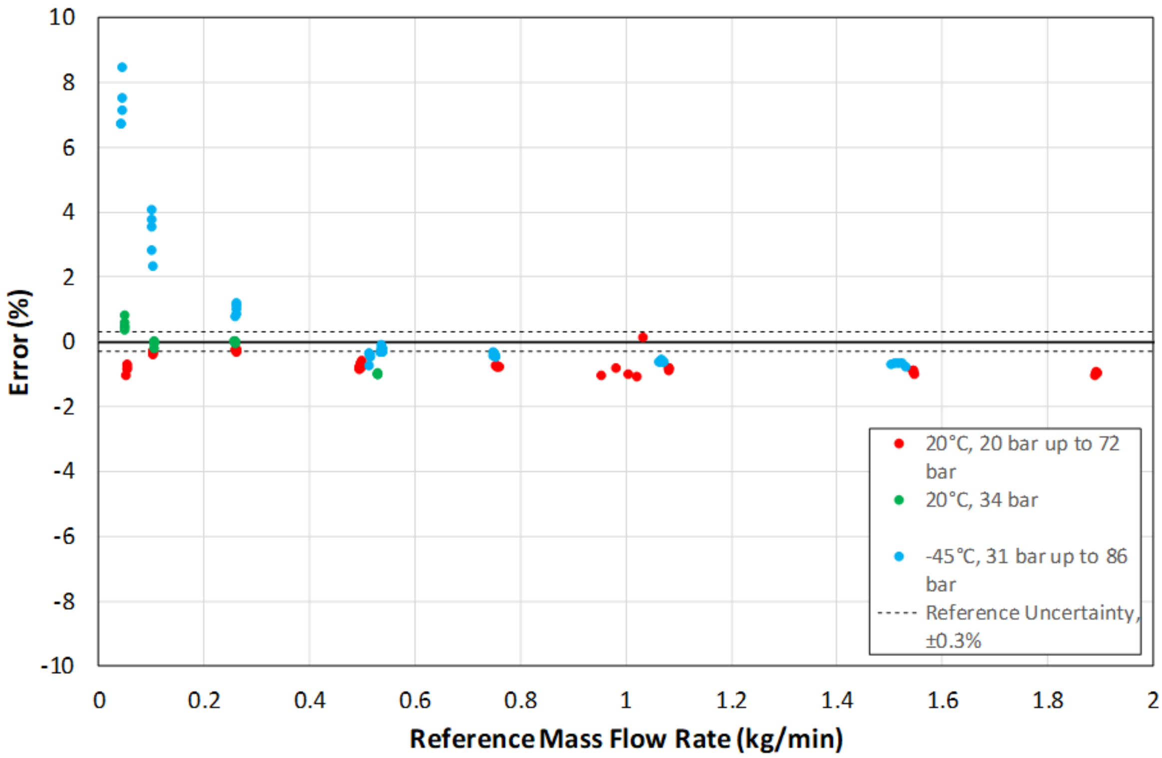

Figure 20: Results of gas testing at METAS to investigate effect of temperature. Tests performed with Meter A.

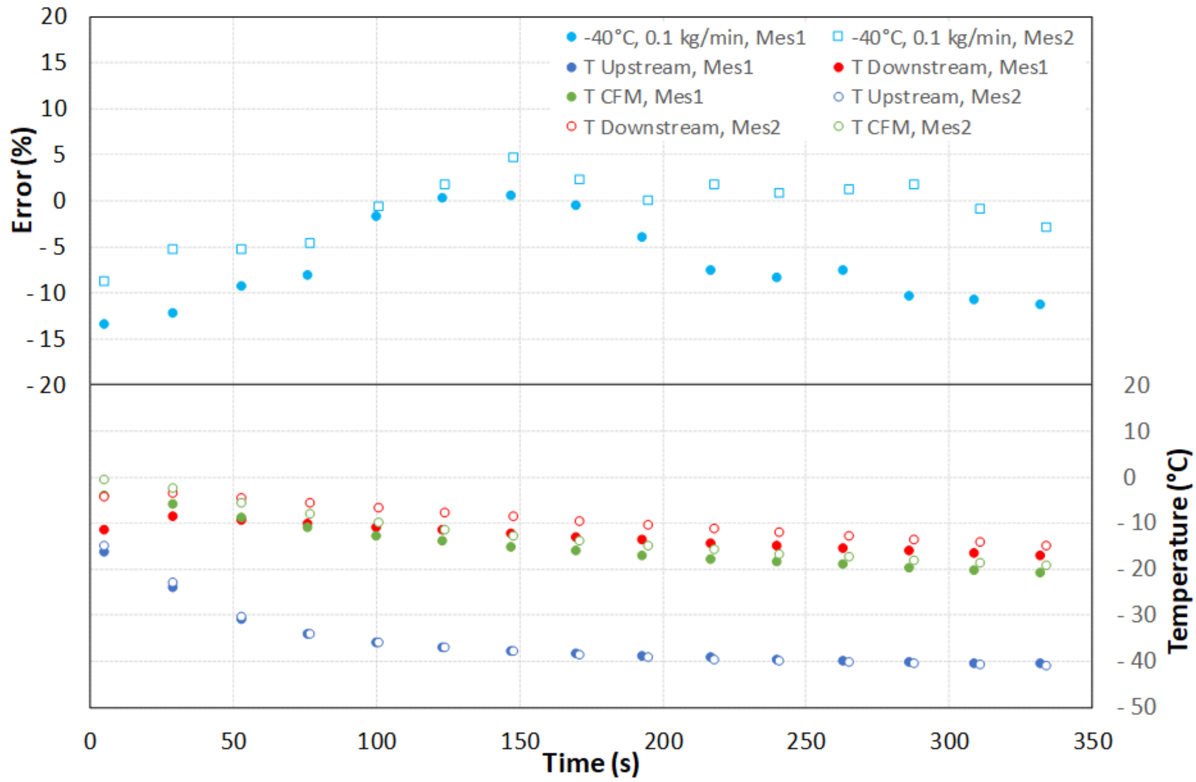

Figure 21: Results of transient testing at METAS to investigate the effect of temperature. Testing performed with Meter D at temperatures of -40°C, flow rate of 0.25 kg/min, and pressure of approximately 30 bar.

6.5 Comparison to hydrogen

To confirm the efficacy of calibration with alternative fluids, a flow meter which had been subjected to all of the above tests was then installed in a HRS and tested at field conditions. The 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
- In the METAS liquid flow laboratory using water at a pressure of 7 bar
- Against the METAS HFTS using nitrogen in a pressure range from 10 bar to 40 bar
- Against the METAS HFTS using hydrogen at a hydrogen refuelling station in the pressure range from 20 bar to 700 bar

The results from these tests are shown in Figure 22. The relevant results for hydrogen are the ones which have been corrected for the vented quantity.

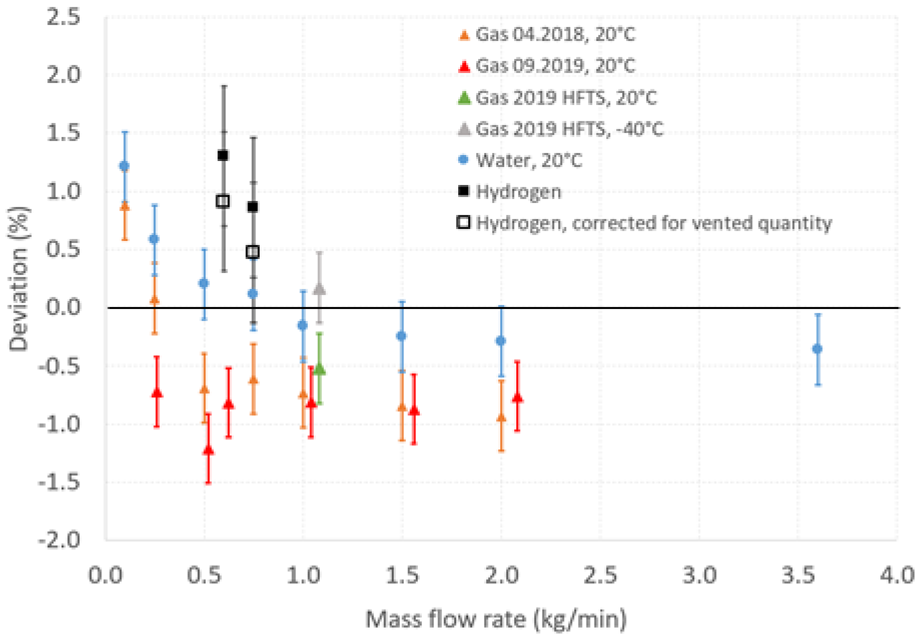

Figure 22: Comparison of results from laboratory and field testing performed by METAS as part of MetroHyVe.

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. This agreement supports the claimed measurement uncertainty of the METAS HFTS, which is ±0.3 % at 95 % confidence, 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 reference measurements 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. The flow meter was installed in the hot region of the HRS, upstream of the heat exchanger. Therefore, the meter temperature was always close to that of the incoming gas and one of the potentially largest sources of flow measurement error in a HRS was avoided. 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.

Based on the limited set of data available it cannot be concluded 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.

6.6 Overall findings

An alternative method for the calibration of flow meters used in hydrogen refuelling stations has been investigated. The important steps in this method are as follows:

- Use air or nitrogen as the calibration fluid
- Calibrate the flow meter across the full range of mass flow rates at ambient temperature
- There is no need to test at a particular gas density, but inlet pressures of 40 bar or more may be required to reach the highest mass flow rates
- Determine the effect of pressure at up to 700 bar, this was done using water in the MetroHyVe project, pressures effects were insignificant for the tested flow meters
    - This step could be skipped once enough data is available to show that pressure effects are minimal for the flow meter model
- Determine the effect of temperature at the relevant ranges, this depends on where the meter is installed and how the HRS is operated
    - Meters installed in the "hot region" upstream of the heat exchanger should only be exposed to variations in ambient temperature, the effect of temperature on meter performance should be minimal, and easy to quantify
    - Meters installed in the "cold region" downstream of the heat exchanger will be exposed to temperatures as low as -40°C. A meter which is initially at ambient temperature could experience a rapid decrease in temperature and transient effects at the beginning of refuelling, leading to very large, variable errors. These are also difficult to quantify, since the test procedure is more complex and there are more variables which can influence the meter performance.

The experiments carried out in the MetroHyVe project suggest that this approach is viable to determine the likely performance of a flow meter installed in a refuelling station. However, more data are required to determine whether there is a consistent shift in performance when a meter calibrated with nitrogen is operated with hydrogen.

7. Evaluation of the uncertainty

The MPE for the meter or complete measuring system from a HRS for type evaluation, initial or subsequent verification are given in Figure 23.

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

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 equipment under test (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 inclusion 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 %.

In the course of the MetroHyVe project, generic uncertainty budgets have been determined for utilising alternative fluids to hydrogen for calibration of CFM in the laboratory, as presented in the previous section. The detailed uncertainty budgets are available on the MetroHyVe website and in available reports.

7.1 Uncertainties when testing with alternative gases in a laboratory

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.

7.2 Uncertainties when testing with water in a laboratory

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.

7.3 Uncertainties when testing with the gravimetric approach

A generic uncertainty budget has been prepared for tests with the gravimetric primary standards. 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 situation would not correspond to reality where most vehicles tend to have tank volumes of 100 L and above.

8. Concluding remarks

This good practice report is intended for validating hydrogen flow meters at HRSs and the type approval procedure. The aim is to support both HRSs and flow calibration laboratories in ensuring the stations operate using suitable accurate and fully calibrated flow meters, and includes all important information from activities from the “Flow metering” work package of EMPIR project 16ENG04 MetroHyVe.

The good practice report started with a collection of the recommendations presented throughout the main part of the document. This main part of the document consisted of an introduction, the scope of the guide, and a brief collection of the requirements for calibration and validation of a HRS in the form of OIML R139 and SAE J2601. Then, the primary gravimetric hydrogen field standard that was developed and utilized was described, as well as its comparison to a master meter method with a Coriolis flow meter. The largest section of the main part of the good practice guide details the procedure and guide for performing a HRS calibration with the primary standard as developed through field testing. Then, calibrations and other procedures for HRSs with other substances than hydrogen were described. Last, the uncertainties obtained through the project were described for all tests performed.

Through this good practice report, readers have received state-of-the-art knowledge on the measurement of hydrogen and flow metering for light-duty vehicles in accordance with SAE J2601. A traceability chain through mass and a gravimetric primary standard has been achieved and tested, and the uncertainty obtained was below 0.3 %, which is within the recommended MPE from OIML R139. Furthermore, the readers have been introduced to a field test procedure with according results, and the discussion on the inclusion of master meter in the test procedure.

The list below repeats some of the main recommendations described in this good practice guide. Although more data is still needed, the recommendations collected in this guide gives an overview of the current status on flow metering and measurement of hydrogen.

- The gravimetric method for field-testing of hydrogen refuelling station shows good results and achieves an expanded uncertainty of 0.3 %.
- The gravimetric method can be used for type-approval testing of hydrogen refuelling stations.
- The master meter showed good results in the warm zone, but gave a large positive error in the cold zone.
- Reduce as much as possible the volume between the master flow meter and the nozzle.
- Correct the mass error related to the process related to vents, piping and distances.
- For calibration or type approval testing of the Coriolis flow meter, use air or nitrogen as a substitute for hydrogen
- Calibrate the flow meter across the full range of mass flow rates at ambient temperature
- There is no need to test at a particular gas density, but inlet pressures of 40 bar or more may be required to reach the highest mass flow rates
- Using appropriate test procedures, the influence of temperature and pressure on the meter performance can be isolated and quantified.

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.

[3] International Organization for Standardization, "19880-1 Gaseous hydrogen — Fuelling stations — Part 1: General requirements," ISO, -.

[4] J. G. Pope and J. D. Wright, "Hydrogen field test standard: Laboratory and field performance," *Flow Measurement and Instrumentation,* vol. 46, pp. 112-124, 2015.

[5] MetroHyVe report, "A1.4.2 Intercomparison of gravimetric standards," 2020.

[6] MetroHyVe report, "A1.5.4 Provision of an uncertainty budget for the gravimetric approach to calibrate flow meter at HRS," 2020.

[7] "MetroHyVe report A1.4.6 "Assessment of the Validity of the Master Meter Method compared to the Gravimetric Method for Calibration of Hydrogen Refuelling Stations"," https://www.metrohyve.eu/downloads/, 2020.

[8] M. de Huu, M. Tschannen, H. Bissig, P. Stadelmann, O. Büker , M. MacDonald, R. Maury, P. Neuvonen, H. Petter and K. Rasmussen, "Design of gravimetric primary standards for field-testing of hydrogen refuelling stations," *Flow Measurement and Instrumentation,* vol. 73, p. 101747, 2020.

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[10] M. MacDonald, M. de Huu, R. Maury and W. Kang, "Air and Nitrogen Testing of Coriolis Flow Meters Designed for Hydrogen Refuelling Stations," in *Flomeko 18th International Flow Measurement Conference*, Lisbon, 2019.

[11] L. Kirkup and R. B. Frenkel, An introduction to uncertainty in measurement: using the GUM (guide to the expression of uncertainty in measurement), Cambridge University Press, 2006.

A. Overview of reports and publications

On this page, the published reports and publications from the work and results outlined in this good practice guide can be found. These publications provide more details than this guide, and are available open access from the MetroHyVe webpage (www.metrohyve.eu). If the webpage is down or the publications are unavailable there, interested readers are free to contact one of the authors of this guide. Contact information can be found on page 1.

Reports from MetroHyVe WP1

A1.1.2: Operating conditions and uncertainty sources of a HRS

A1.4.2: Inter-comparison of gravimetric standards

A1.4.6: Assessment of the Validity of the Master Meter Method compared to the Gravimetric Method for Calibration of Hydrogen Refuelling Stations

A1.5.1: Determination of the Overall Uncertainty Budget for Utilising Alternative Gases to Hydrogen for Calibrating CMF in the Laboratory

A1.5.2: Determination of the overall uncertainty budget for utilising water for the flow calibration of CMFs in the laboratory at pressures up to 875 bar

A1.5.3: Provision of an Uncertainty Budget for the Gravimetric Approach to calibrate Flow Meters at Hydrogen Refuelling Stations

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

Published papers through the work in MetroHyVe WP1

Journal of Physics: Conference Series: 2018 1065 (9), pp 092017 - The European Research Project on Metrology for Hydrogen Vehicles – MetroHyVe. *Authors: M. de Huu, O. Büker, R. Christensen, M. MacDonald, R. Maury, M. Schrade, H.T. Petter, and P. Stadelmann*

International Journal of Hydrogen Energy: 2019 44 (35), pp.19326-19333 - Measurement challenges for hydrogen vehicle. *Authors: A. Murugan, M.de Huu, T. Bacquart, J. van Wijk, K. Arrhenius, I. te Ronde, and D. Hemfrey*

Flow Measurement and Instrumentation: 2020 73, pp. 101747 – Design of gravimetric primary standards for field testing of hydrogen refuelling stations. *Authors: M. de Huu, M. Tschannen, H. Bissig, P. Stadelmann, O. Büker, M. MacDonald, R. Maury, P. T. Neuvonen, H. T. Petter, and K. Rasmussen*

Flow Measurement and Instrumentation: 2020 74, pp. 101743 - Hydrogen refuelling station calibration with a traceable gravimetric standard. *Authors: R. Maury, C. Auclercq, C. Devilliers, M. de Huu, O. Büker, and M. MacDonald*

Flow Measurement and Instrumentation: Accepted for publication – Investigations on pressure dependence of Coriolis Mass Flow Meters used at Hydrogen Refuelling Stations. *Authors: O. Büker et al.*

Flow Measurement and Instrumentation: Submitted – Calibration of Hydrogen Coriolis Flow Meters Using Nitrogen and Air and Investigation of the Influence of Temperature on Measurement Accuracy. *Authors: M. MacDonald et al.*

B. OIML R139:2018 Compressed Gaseous Fuel Measuring Systems for Vehicles

OIML R139-1 Metrological and technical requirements

Metrological obligations for the measurement system:

This section lists all mandatory metrological requirements, in no particular order, to obtain certification according to OIML R139:2018 for a HRS at 700 bars. Requirements not related to hydrogen have not been included.

1. The results of the measures must be displayed or printed in the unit of the international system for mass (part 1 / 5.1.1).
2. The indication of the mass on the distributor's screen (display) (dispenser) must have an interval of 1×10^n, 2×10^n or 5×10^n (where n can be a positive number or negative or zero) (part 1 / 5.1.2).
3. The MPE (Maximum Permissible Error) are defined in Table 5.

Table 5: 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

There are 2 main categories in this table, the MPE for the meter itself (on the left side) and the MPE for the measuring system. There is no metrological test rig available at the moment to perform a meter calibration in hydrogen at 700 bar. This good practice guide will provide advices and knowledge about the certification of the measuring system, which includes the meter.

It is important to note that there is 2 classes for hydrogen. Class 4 will be mainly accepted for existing stations whereas class 2 shall be chosen for new HRS. As an example, the MPE during a type approval of a new HRS (class 2) is 2%.

4. In the case of the measurement of the 'smallest measurable amount', called MMQ in English (Minimum Mass Quantity) , the MPE is twice the value of the Table 5 above (part 1 / 5.2.3).

$$E_{min} = 2 \times \text{MMQ} \times R_{MPE} \text{ [g; kg]}$$

where: R_{MPE} = the maximum permissible error ratio according to 5.2.1 (in 5.2.1 expressed in percentages of the measured quantity value);

MMQ = the specified minimum measured quantity according to 5.3.2.

This relation gives Table 6, as seen below.

The MMQ has been defined as a fixed value for all hydrogen application whereas it was a function of the mass flow rate for the compressed gas fuel. It is stated in OIML R139:2018 that the maximum MMQ is **1 kg** for hydrogen.

Table 6: E_{min} values for all accuracy classes

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

5. The range of flow rate measured is limited by Q_{min} and Q_{max} and this must be specified by the manufacturer. It is therefore necessary to ensure that this range covers the full range of possibilities of the measuring system (part 1 / 5.3.1).
6. The ratio between minimum and maximum flow rate must be at least 10 (part 1 / 5.3.1.4).
7. The minimum mass of hydrogen delivered must be indicated by the manufacturer and must have a type format: 1 x 10n, 2 x 10n or 5 x 10n kg (part 1 / 5.3.2.1).
8. For any quantity of the measurand equal to or greater than 1000 scale intervals of the meter (in gram), the repeatability of the flow meter error and the measuring system must be 2/3 of the MPE (part 1 / 5.4.1). As an example, for a gram resolution for a meter, the repeatability error of the flow meter should not exceed the values in the below:

Table 7: Repeatability errors

Class	MMQ	MPE	Repeatability error	class	MMQ	MPE	Repeatability error
class 2	no	2%	1,33%	class 4	no	2%	2,67%
	yes	4%	2,67%		yes	4%	5,33%

The calculation for the repeatability error is based on this statement of OIML R139:2018: “difference between the largest and the smallest results of the several successive measurements of the same quantity carried out under the same *repeatability condition.*”

The ambient conditions of the flow meter or the measuring system can be specified. The identification plate and the instructions must indicate the limits of use (part 1 / 5.5.2).

Table 8 below details the rated operating conditions.

Table 8: Rated operating conditions

a)	High ambient temperature (T_{ah}) (1)	+30 °C, +40 °C, +55 °C, +70 °C or +85 °C (2)	Temperature range at least 40 °C
b)	Low ambient temperature (T_{al}) (1)	+5 °C, −10 °C, −25 °C, or −40 °C (2)	
c)	Temperature of the gas	As specified by the manufacturer	
d)	Pressure of the gas	As specified by the manufacturer	
e)	Relative humidity	As specified by the manufacturer (4)	
f)	Vibrations (random)	As specified by the manufacturer but normally not to exceed 10 Hz – 150 Hz, 1.6 m.s^{-2}, 0.05 m^2.s^{-3}, −3 dB/octave which is defined to be the level of vibrations related to environmental class M2, unless the manufacturer specifies higher insusceptibility levels (5) (6)	
g)	DC mains voltage/ Voltage of internal battery (3)	As specified by the manufacturer	
h)	Voltage of road vehicle battery	As specified by the manufacturer (12 ± 4)V and/or (24 ± 8)V (7)	
i)	AC mains voltage (3)	U_{nom} – 15 % to U_{nom} + 10 %	

9. The measuring system must be subjected to disturbances (electric, electromagnetic etc) to receive OIML R139:2018 certification (if items are not already individually certified OIML R139: 2018). Table 9 describes potential disruptions to be evaluated. It is available below in Table 9. These tests can be realized by the equipment manufacturers (calculator, flow meter).

Table 9: Disturbances during full operation

a)	RF electromagnetic fields	Up to 3 GHz, up to 10 V/m
b)	Common mode currents induced by RF electromagnetic fields	Up to 80 MHz, up to 3 V (e.m.f.)
c)	Bursts (transients) on AC and DC mains lines	Amplitude 1 kV, repetition rate 5 kHz
d)	Bursts (transients) on signal, data and control lines	Amplitude 0.5 kV, repetition rate 5 kHz
e)	AC mains voltage dips and short interruptions	0.5 cycles to 0 % 1 cycle to 0 % 10/12(1) cycles to 40 % 25/30(1) cycles to 70 % 250/300(1) cycles to 80 %
f)	Voltage dips, short interruptions and voltage variations on DC mains power	40 % and 70 % of the rated voltage during 0.1 s 0 % of the rated voltage during 0.01 s 85 % and 120 % of the rated voltage during 10 s
g)	Ripple on DC input power	2 % of the nominal DC voltage
(1)	For 50 Hz/ 60 Hz respectively	

10. The durability test says that the requirements in 5.5.2 and 5.7 shall be met durably. The proposed test ask that after at least 100 hours of operation at 0.8 Q_{max} , the meter shall not drift more than +/- 1% of the measured quantity.
    The durability performance criterion is the satisfactory completion of 2000 deliveries.
    For meters without moving parts, for instance Coriolis flow meters, providing documented information that show the fulfilment of the durability performance criterion is accepted. The documented information may be a life time estimation based on test results (part 1 / 5.8).

Technical obligations for the measurement system

In this paragraph are listed (without order of importance) all the technical prescriptions required to obtain OIML R139 certification: 2018 for a HRS at 700 bar.

1. The height of the numbers on the display must be 10mm or more (part 1 / 6.2.1.1).
2. The display or the number print must be divided into groups of three to facilitate the reading. Each group must be separated from space (part 1 / 6.2.1.2).
3. When the calculator is tested separately, the maximum error allowed is 0.05% (part 1 / 6.7.1).
4. Fraud protection: it should not be possible to make metrological adjustments without breaking the seals (part 1 / 6.9.1).

Marking requirements

In this paragraph related to the marking are listed all the elements information that must be included on the identification plate in order to obtain certification OIML R139: 2018 as part of a 700 bar HRS.

1. All items that have received a standard approval (debit meter, calculator, station) must have a permanent, non-transferable identification plate indicating the characteristics (part 1 / 7.1):
    a. The manufacturer's name
    b. The year of manufacture
    c. Designation/serial number
    d. The accuracy class
    e. The standard approval number and seals
    f. Serial number of the measurement set
2. The MMQ must be visible at all times on the front of the dispensing (part 1 / 7.2).
3. The following items must be given either on the identification plate or on request on the dispenser's display (part 1 / 7.3):
    a. Qmin and Qmax
    b. Maximum gas pressure in the station (Pst) (in HP buffers).
    c. Maximum vehicle pressure (Pv)
    d. Minimum gas pressure (Pmin)
    e. Maximum gas pressure in dispenser (Pmax)
    f. Type of gas used
    g. Min and Max gas temperature
    h. Min and Max ambient temperature
    i. Environmental class of the measuring system
    j. Electrical power, frequency and consumption
    k. Battery type (if necessary)
    l. Identification of the software used
    m. Type of control used (automatic, sequential)

Annex B Typical methods for correction of the depressurization quantity for hydrogen CGF measuring systems

During a vehicle filling, there is some lost hydrogen quantity at the end of the fuelling protocol. Furthermore, the hose needs to be decoupled at ambient pressure to avoid any problem, and the pressurized hydrogen must be vented to the environment.

An example of a measuring system where hydrogen loss occurs due to depressurization is shown in Figure 24.

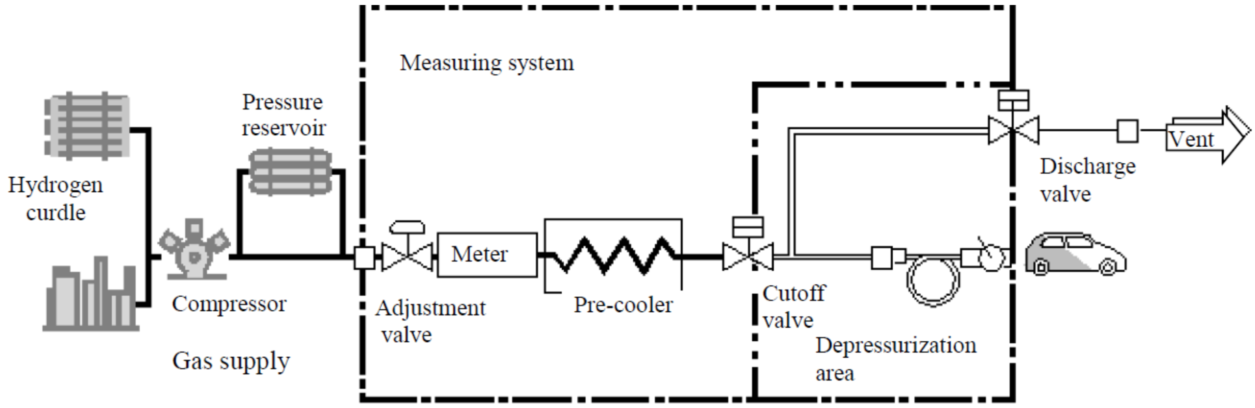

Figure 24: Schematic diagram of an example of a hydrogen dispenser

There are two proposed methods to take into account this vented quantity. The first method, A, gives a maximum value which is subtracted at the end of each refuelling, whereas the second method, B, is based on measurements for each fillings. Figure 25 shows the two options, with the equation for calculating the depressurized gas in Figure 26.

Method A	Evaluate the maximum value of the depressurized quantity as a specific value for each dispenser from the maximum hydrogen pressure and minimum temperature at the operating condition, and the volume of the depressurization area.	
Method B	Evaluate the depressurized quantity after each filling process completed;	
	B1	from the hydrogen temperature / pressure and the volume of the depressurization area.
	B2	by using a flowmeter mounted at the discharge valve.

Note 1: The volume of the depressurization area can be obtained either by calculation from the dimensions of the components of the depressurization area (the pipe length, the inner diameter of the pipe, the inner volume of the valves and so on), or by other kind of physical measurement.

Note 2: If method A is applied the correction value needs to be a settable parameter. This value of the parameter will be fixed (thus not changeable) when the system is installed.

Figure 25: Methods to take into account the vented quantity

$$C = M\sum\left(\frac{PV}{RfT}\right)$$

Where,

Where,	C :	depressurization quantity value[g]
	M :	molecular mass of hydrogen [g mol^{-1}]. The value 2.016 is applicable for measurements within the scope of this Recommendation.
	Σ :	Summation for all depressurization area
	P :	Operating pressure of hydrogen refueling station (Method A), or hydrogen pressure at the end of each refueling (Method B1) [MPa]
	V :	Volume of depressurization area [cm^3]
	R :	Gas constant [J K^{-1}mol^{-1}]. The value 8.314 46 is applicable for measurements within the scope of this Recommendation.
	f :	Compressibility factor [none]
	T :	Hydrogen temperature in the depressurization area at operating condition (Method A) or hydrogen temperature at the end of each refueling (Method B1) [K]

Figure 26 Equation from OIML R139-1 Annex B to calculate the depressurized hydrogen vented.

OIML R139-2 Metrological control and performance tests

This document develops topics such as the metrological controls, the instrument evaluation, the type evaluation, the initial verification, and the subsequent verification for a HRS. Additionally, four appendices describes the minimum test quantities for measuring systems and device, the test methods for influence quantities for Coriolis meters, and the description of selected software validation methods.

Metrological controls:

The metrological control section is devoted to the uncertainty for the measurements in 1.3. The uncertainty associated with the test method shall be taken into account in the decision on the applicability of the test method. When a test is conducted, the expanded uncertainty on the determination of errors on indications of mass shall be:

- for type evaluation less than one-fifth of the applicable MPE;
- for verifications less than one-third of the applicable MPE.

However, if the above-mentioned criteria cannot be met, the test results can be approved alternatively by reducing the applied maximum permissible errors with the excess of the uncertainties. In this case the following acceptance criteria shall be used:

- for type evaluation ±(6/5 MPE-U);
- for verifications ±(4/3 MPE-U).

Reaching a comparable confidence interval, that a meter is not outside MPE. The estimation of expanded uncertainty *U* is calculated from *Guide to the expression of uncertainty in measurement* [11] applying a coverage probability which corresponds the application of a coverage factor *k* = 2 for a normal distribution and which comprises approximately 95 % of the measurement results.

Instrument evaluation:

The measuring instrument or system shall be submitted to performance tests to determine its correct functioning under various conditions. In the paragraph 2.2.5.2 “test setup”, Table 10 as seen below is presented. This table gives the indicative values of the minimum volume (Vmin) for the test receiver (representing the vehicle fuel storage system) and the test reservoir volume (Vd) representing the refuelling station fuel storage system to be applied in the test, related to the capacity of the meter.

Table 10: Indicative values of the minimum volume for the test receiver

Test receiver volume	Meter capacity					Unit
	$Q_{max} \leq 4$	$4 < Q_{max} \leq 12$	$12 < Q_{max} \leq 30$	$30 < Q_{max} \leq 70$	$Q_{max} > 70$	kg/min
V_{min}	10	30	90[1)]	300	600	L
V_d [2)]	50	150	800	1600	2400	L

1) 50 L may be accepted provided the test receiver volume fulfills the appropriate provisions specified in this Recommendation (which require at least 1000 scale intervals).

2) The actual test reservoir volume(s) applied shall be such to ensure the flow rate drops below 120 % of Q_{min} at a point of time anywhere within the last 20 seconds of each flow test. If a sequential control device is used, this condition only applies to the highest (last) bank (see 2.2.5.2.4).

This provision does not apply where the meter or the measuring system is designed to stop the flow when the flow rate drops below Q_{min} and where the test is performed until the flow stops.

The minimum test receiver size depends on the maximum flow rate and meter capability. The maximum flow rate is given by the pressure ramp that is needed to refuel the vehicle. The pressure ramp is directly given by the SAE J2601 (see appendix 0). For most of the case, the maximum mass flow rate will be 3.6 kg/min which gives a Vmin of 30 litres. This value is relatively small and does not allow the full completion of the test program described in the next paragraphs (cf test 5 < MMQ).

For the purpose of the tests, three types of measuring systems are considered:

a) measuring systems utilizing a sequential control device of a refuelling station;
b) measuring systems that already incorporate their own sequential control device;
c) measuring systems for refuelling stations that do not utilize a sequential control device.

Up to now, the design of the HRS does not use the sequential control. It means that hydrogen is taken from one high pressure vessel to fill up the vehicle. Therefore, the test program consists of the processes detailed in Table 11 and Table 12. These tests are relevant for all compressed gas vehicles.

Table 11: Initial settings for tests on systems without sequential control

Test #	Initial state
Test 4	Initial test receiver pressure of 0 kPa or higher if so required for safety reasons Initial station storage pressure at P_{st}
Test 5	Initial test receiver pressure of 0.5 P_v Initial station storage pressure at P_{st}

Table 12: Initial settings for tests on systems with and without sequential control

Test #	Initial state
Test 7 (minimum measured quantity)	The conditions for test 3 or 6 are adapted in order to test the minimum measured quantity. For this purpose, the pressure does not have to be P_v in the test receiver at the end, but may be any pressure (as close as practical to P_v) such that the quantity of transferred gas shall be at least the minimum measured quantity.

In Table 13, a complete test program is available. It is important to note that in this test program, when hydrogen is considered, tests denoted with # 6 should be withdrawn from the test program. Furthermore, the MMQ must be done twice whereas other tests must be done 3 times. To ease the testing process, the recommendation states that tests may be performed in a random order so as to minimize the total testing time, provided that the sequence of testing is clearly recorded. This new order might for instance allow for a full defueling overnight. As an example, the sequence could thus be # 4, # 5, # 7, # 4, # 5, # 7, # 4 , # 5.

Table 13: Test program suggested in the OIML R139-2 recommendation.

Test referred to				**Applicable to meters**	**Applicable to measuring systems**
by name	**in sub clause**	**in table #**	**as test #**		
Test(s) at variable flow rate	2.2.7.1	4	0	3 times 3)	
Test(s) with adjustable sequential control 1)	2.2.7.2	5	1		3 times
Test(s) with sequential control	2.2.7.2	5	1	n/a	3 times
			2	optional, 3 times	3 times
			3	n/a	3 times
Test(s) without sequential control	2.2.7.3	6	4	3 times 2)	3 times
			5	3 times 2)	3 times
			6	n/a	3 times 2)
Test(s) on MMQ	2.2.7.4	7	7		twice 4)
Test(s) on durability	2.2.7.6	-	-	once	
Test(s) on preset function		-	-		once
Test(s) on gas influence factors	2.2.7.7	-	-	twice per influence factor	
Test(s) with flow disturbances etc.	2.2.7.8	-	-	If applicable, twice	If applicable, twice if not yet performed on meter

C. SAE J2601:2020 Fuelling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

In this Appendix, details concerning the fuelling protocols from SAE J2601 concerning hydrogen fuelled light duty vehicles are presented. It includes process limits based on several factors related to the fuelling conditions and vehicle, and establishes fuelling protocols for these different conditions based on a look-up table. This standard was latest revised in 2020.

An important factor in the performance of hydrogen fuelling is the station’s dispensing equipment cooling capability and the resultant fuel delivery temperature. There are three fuel delivery temperature categories denoted by a “T” rating: T40, T30, and T20, where T40 is the coldest. Under reference conditions, SAE J2601 has a performance target of a fuelling time of 3 minutes and a state of charge (SOC) of 95 to 100% (with communications), which can be achieved with a T40-rated dispenser. However, with higher fuel delivery temperature dispenser ratings (T30 or T20) and/or at high ambient temperatures, fuelling times may be longer.

Table 14 describes the scope of SAE J2601:2020 and potential work items for future revisions within this or other documents of the SAE J2601 series. SAE J2601 includes protocols which are applicable for two pressure classes (35 MPa and 70 MPa), three fuel delivery temperatures categories (-40 °C, -30 °C, -20 °C) and compressed hydrogen storage system sizes (total volume classification) from 49.7 to 248.6 L (35 MPa -> H35, and 70 MPa >- H70), and from 248.6 L and above (H70 only). Future versions of SAE J2601 work may incorporate warmer fuel delivery temperatures (-10 °C and ambient) and smaller total volume capacities for motorcycles and other applications.

Table 14: Scope of SAE J2601:2020

<table>
<tr><td colspan="2">Pressure Class Designation</td><td colspan="3">H35</td><td colspan="3">H70</td></tr>
<tr><td colspan="2">CHSS Capacity Range (Liters)</td><td>< 49.7</td><td>49.7 to 248.6</td><td>> 248.6</td><td>< 49.7</td><td>49.7 to 248.6</td><td>> 248.6</td></tr>
<tr><td colspan="2">CHSS Capacity Range (kg)</td><td>< 1.19</td><td>1.19 to 5.97</td><td>> 5.97</td><td>< 2.0</td><td>2.0 to 10.0</td><td>> 10.0</td></tr>
<tr><td colspan="2">CHSS Capacity Categories (nomenclature)</td><td>TBD</td><td>A, B, C</td><td>D</td><td>TBD</td><td>A, B, C</td><td>D</td></tr>
<tr><td colspan="2">Maximum Flow Rate (g/s)</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td><td>≤ 60</td></tr>
<tr><td rowspan="5">Fuel Delivery Temperature Category</td><td>T40</td><td rowspan="5">Not Included</td><td rowspan="3">Included</td><td rowspan="5" colspan="2">Not Included</td><td rowspan="3" colspan="2">Included</td></tr>
<tr><td>T30</td></tr>
<tr><td>T20</td></tr>
<tr><td>T10</td><td rowspan="2"></td><td rowspan="2" colspan="2"></td></tr>
<tr><td>Ambient</td></tr>
</table>

General fuelling protocol description

SAE J2601 establishes a gaseous hydrogen fuelling protocol for hydrogen surface vehicles with Compressed Hydrogen Storage System (CHSS) capacities between 49.7 L and 248.6 L (H35 and H70) and above 248.6 L (H70 only) and a maximum flow rate of 60 g/s. The standard assumes that a station will perform fuelling from its high pressure storage into the vehicle after successful vehicle connection and completion of initial checks. The fuelling station is responsible for controlling the fuelling process within the operating boundaries described below. Variables that affect the fuelling process include, but are not limited to:

- Ambient temperature
- Dispenser pressure class and fuel delivery temperature
- CHSS size, shape, material properties, starting temperature, and pressure
- Dispenser to vehicle pressure drop and heat transfer

A representative fuelling profile is shown below in Figure 27. The profile consists of a start-up time which begins when the nozzle is connected to the vehicle and includes a connection pressure pulse. During the start-up time, the station measures the initial CHSS pressure and CHSS capacity category and may also check for leaks. The main fuelling begins when gas starts flowing into the vehicle. During this period, the pressure rises and the temperature of the CHSS increases. The fuelling protocol should be designed such that the CHSS does not exceed the maximum operating temperature at any point during the fill. The final stage is the shutdown, which occurs after hydrogen gas has stopped flowing and ends when the nozzle can be disconnected.

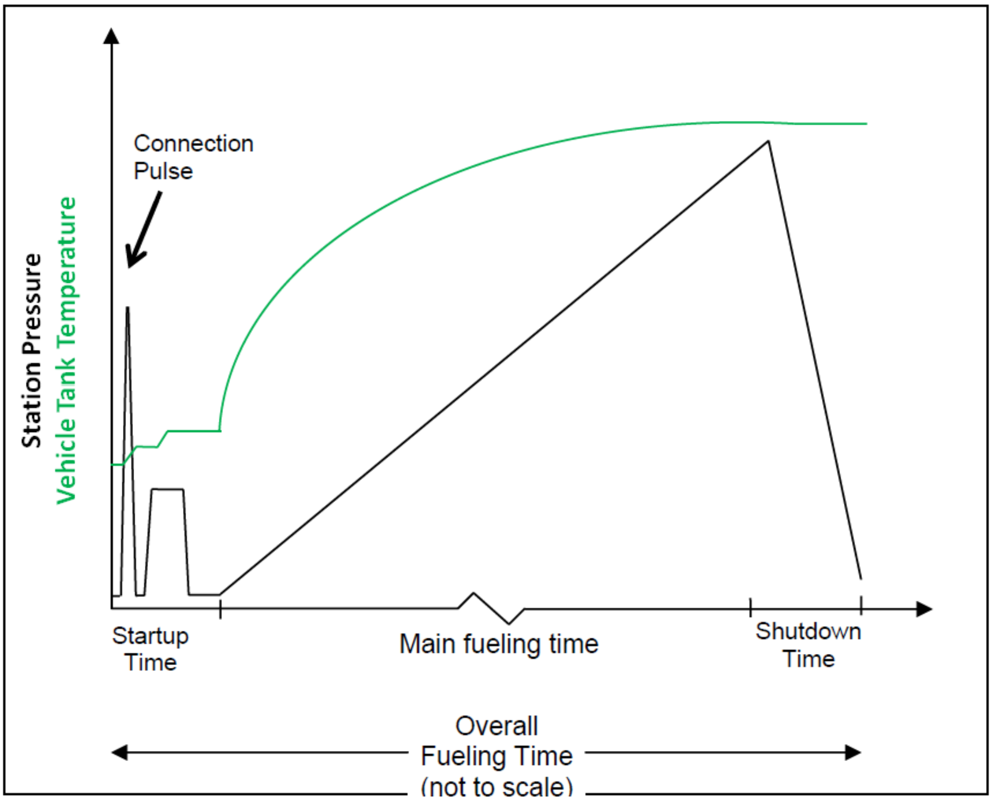

Figure 27: Representative vehicle CHSS temperature and pressure profile during a fuelling

In general, the goal of SAE J2601 is to provide a high density fuelling as fast as possible while staying within the process limits. The state of charge (SOC) target when fuelling with communications is 95 to 100% SOC under all operating conditions.

The fuelling time can vary widely depending on ambient temperature, initial CHSS pressure, size of CHSS, final SOC, and other conditions. In order to establish a fuelling time goal, the SAE team agreed to define the parameters of a "reference" fuelling:

- Communications fuelling tables
- Dispenser category = H70-T40
- Ambient temperature = 20 °C
- Initial CHSS pressure = 10 MPa
- Final SOC = 95%

Under these "reference" conditions, the goal of the fuelling protocols in SAE J2601 is that the main fuelling time is 3 minutes or less.

For a H70 CHSS, these temperature and pressure limits are -40 to 85 °C and 0.5 to 87.5 MPa, respectively. Figure 28 shows the boundaries for a H70 fuelling. The maximum CHSS gas temperature and maximum operating pressure (MOP) are fixed limits at the right (overheat) and top (overpressure) portions of the graph. The maximum density (100% SOC) provides an additional boundary.

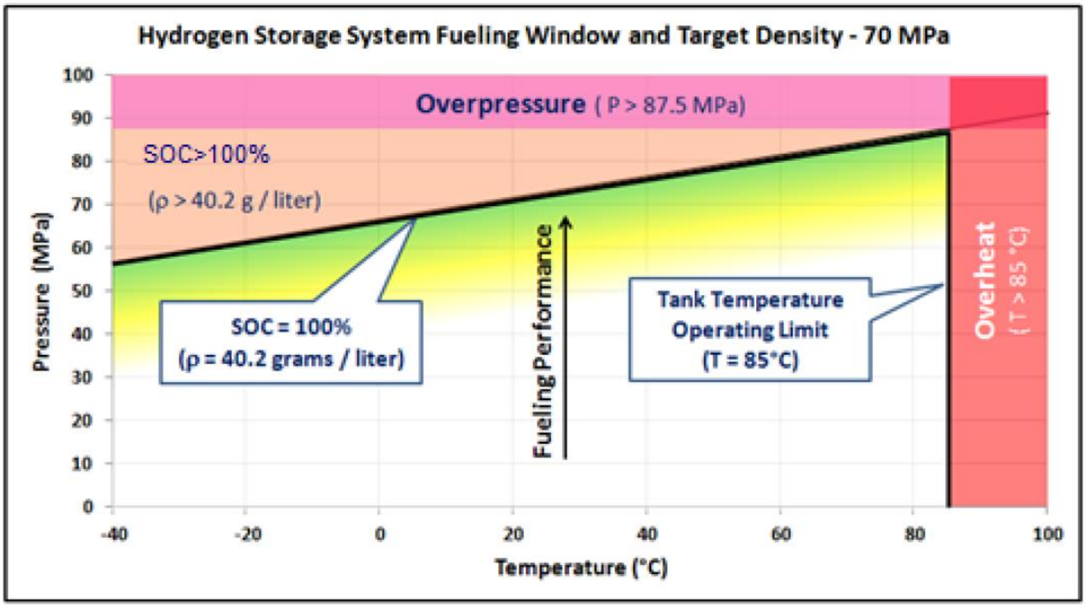

Figure 28: SAE J2601 normal H70 boundary conditions

In order to keep the CHSS within its operating boundaries (i.e., Figure 28), the station must adjust the flow of the gas depending on the full set of initial conditions. For example, if a vehicle is fuelled on a hot day, the initial CHSS temperature may be warmer, so the station must fuel more slowly to ensure the CHSS does not exceed the maximum vehicle CHSS operating temperature.

Table-based Fuelling Protocol

The table-based fuelling protocol uses the station fuel delivery temperature, ambient temperature, CHSS capacity category, and CHSS initial pressure to select appropriate fuelling parameters. Modelling has been used to develop a series of parameter look-up tables that optimize the fuelling process while ensuring that the process requirements are satisfied at all times.

The HRS selects the correct look-up table based on fuel delivery temperature, CHSS capacity category, and the absence or presence of a communications signal from the vehicle. Once the proper table is selected, the station determines the specific fuelling event parameters of average pressure ramp rate (APRR) and target pressure, based on ambient temperature and CHSS initial pressure.

For vehicles without communications, the station will fuel based on the look-up table APRR until the look-up table target pressure is reached. For vehicles with communication, the same APRR will be applied. The station may use vehicle data, including the communicated CHSS temperature, to calculate the SOC and fuel up to a pressure corresponding to an SOC of 95 to 100%.

A sample fuelling table is shown in Table 15 and the complete set of standard fuelling tables are included in an appendix of the document. It should also be noted that for any given station fuel delivery temperature, ambient temperature, and CHSS capacity category, the look-up tables provide the same APRR for both H35 and H70 fuelling (for the same CHSS volume); only the ending target pressures are different. This similarity was included to address concerns about overheating if an H70 vehicle first fuels at an H35 dispenser and then immediately has an H70 fuelling.

Table 16 illustrates the fuel delivery temperature categories per pressure classes for the table-based fuelling protocol. A station is defined by the pressure class of fuel it delivers and its fuel delivery temperature capability. For example, the fuel delivery temperature category for the range from -40 to -33 °C is designated as T40. There are three fuel delivery temperature categories, designated by T40, T30, or T20. Although a station may offer more than one combination of pressure class and fuel delivery temperature category with multiple dispensers, it is recommended that stations utilize common fuel delivery temperature.

Table 15: Sample fuelling table, CHSS Capacity Category B/H70-T40 with communications

H70-T40 Capacity Category B comm		APRR [MPa/min]	Target Pressure Ptarget [MPa]	Target Pressure Top-Off [MPa]	Top-Off-APRR [MPa/min]	Target Pressure, P_{target} [MPa]											
			Initial Tank Pressure, P_0 [MPa]														
			0,5 - 5 (no interpolation)			0,5	2	5	10	15	20	30	40	50	60	70	>70
Ambient Temperature, T_{amb} [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	5,1	78,2	87,5	2,6	see Top-Off	see Top-Off	80,8	85,7	86,8	86,5	85,8	85,0	84,0	82,7	81,1	no fueling
	45	8,1	76,3	87,5	4,0	see Top-Off	see Top-Off	81,1	86,9	86,6	86,2	85,3	84,3	83,0	81,6	79,7	no fueling
	40	11,5	73,2	87,5	5,4	see Top-Off	see Top-Off	81,1	86,9	86,4	85,9	84,7	83,5	82,0	80,3	78,3	no fueling
	35	12,4	72,9	87,5	5,6	see Top-Off	see Top-Off	81,2	86,9	86,4	85,9	84,7	83,4	81,9	80,2	78,2	no fueling
	30	15,3	70,6	87,5	6,6	see Top-Off	see Top-Off	81,0	86,8	86,3	85,6	84,3	82,8	81,2	79,4	77,2	no fueling
	25	18,5	69,0	87,4	7,2	see Top-Off	see Top-Off	81,0	86,8	86,1	85,4	83,8	82,2	80,4	78,5	76,1	no fueling
	20	21,8	67,9	87,4	7,6	see Top-Off	see Top-Off	81,2	86,8	85,9	85,1	83,3	81,5	79,6	77,5	75,1	no fueling
	10	28,0	66,3	87,4	9,0	see Top-Off	see Top-Off	81,2	86,8	85,7	84,7	82,6	80,5	78,3	76,1	73,4	no fueling
	0	28,5	no Top-Off	no Top-Off	no Top-Off	78,4	84,6	86,8	85,6	84,4	83,1	80,6	78,1	75,6	73,1	no fueling	no fueling
	-10	28,5	no Top-Off	no Top-Off	no Top-Off	82,2	87,1	86,4	85,2	84,0	82,8	80,4	77,9	75,4	72,9	no fueling	no fueling
	-20	28,5	no Top-Off	no Top-Off	no Top-Off	86,0	86,8	86,1	84,9	83,7	82,4	80,0	77,6	75,1	72,7	no fueling	no fueling
	-30	28,5	no Top-Off	no Top-Off	no Top-Off	86,8	86,5	85,7	84,5	83,3	82,1	79,6	77,2	74,9	72,5	no fueling	no fueling
	-40	28,5	no Top-Off	no Top-Off	no Top-Off	86,5	86,2	85,4	84,2	83,0	81,8	79,3	77,0	74,6	72,3	no fueling	no fueling
	<-40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 16: Fuel delivery temperature categories per pressure classes

Fuel Delivery Temperature Category		$-40\ °C \le T_{fuel} \le -33\ °C$	$-33\ °C < T_{fuel} \le -26\ °C$	$-26\ °C < T_{fuel} \le -17.5\ °C$	$-40\ °C \le T_{fuel} \le -26\ °C$	$-40\ °C \le T_{fuel} \le -17.5\ °C$
Station Designator	35 MPa NWP	H35-T40	H35-T30	H35-T20	N/A	N/A
	70 MPa NWP	H70-T40/H70-T40D	H70-T30	H70-T20	H70-T30D	H70-T20D

CHSS capacity

Table 17 contains the allowable CHSS capacity categories for the table-based fuelling protocol. The station may choose to implement all CHSS capacity categories, or may choose to implement a sub-set of the capacity categories (A, B, and C, but not D). Where a station is capable of determining the CHSS capacity using a method that is accurate to within ±15%, the CHSS capacity category can be used to select the appropriate fuelling look-up table.

Table 17: CHSS capacity categories

Pressure Class	Total Amount of Hydrogen in CHSS at 100% SOC (kg)	Water Volume of CHSS (L)	CHSS Capacity Category Identifier
H35	1.19 to 2.39	49.7 to 99.4	A
H35	2.39 to 4.18	99.4 to 174.0	B
H35	4.18 to 5.97	174.0 to 248.6	C
H70	2.00 to 4.00	49.7 to 99.4	A
H70	4.00 to 7.00	99.4 to 174.0	B
H70	7.00 to 10.00	174.0 to 248.6	C
H70	>10.00	>248.6	D

D. Hydrogen infrastructure per august 2020

As part of the MetroHyVe project, the status of the HRSs available in Europe were mapped and primary gravimetric standards were developed. In this section, the standards developed are described briefly, and the status of hydrogen infrastructure in the form of HRSs and such are presented.

Selection of HRS in Europe

The partners intended to select a representative sample of HRS in Europe, with a least a minimum of 3 Member States. Different technologies, different HRS manufacturers or different designs have been tested during the experimental campaign. Based on these criteria, seven HRSs were selected, and these have been presented in Table 18 and Figure 29. An additional criteria for the selection of HRS was the loading rate of the station, i.e. how often the station works and are in use. As such, it was mandatory that the station remained available for the customer during the whole testing week, and that the installation on site disturb as less as possible the customers to refuel their cars.

Table 18: List of HRS tested, and main characteristics

Location		**Manufacturer**	**Characteristics** especially for the metering aspect
Country	**City**		
Germany	Kamen	Manufacturer A	Design “2” design with *short* distance between the MFM (in the station) and the dispenser
	Koblenz	Manufacturer A	Design “2” design with *long* distance between the MFM (in the station) and the dispenser
	Köln airport	Manufacturer B	Compressed gas
	Hannover	Manufacturer B	Cryo Pump (cold area)
	Rostock	Manufacturer C	Compressed gas
France	Paris - Saclay (CRPS)	Manufacturer A	Design “2”
Netherlands	Rhoon (Rotterdam)	Manufacturer A	Design “1”

Figure 29: Location of the tested HRS in Europe

Pictures of the selected HRSs can be seen in the pictures below, separated by country.

Germany:

France:

Netherlands:

Design of primary gravimetric hydrogen field test standards

Through the MetroHyVe project, three primary gravimetric HFTS were developed, by METAS, JV and VSL. The one developed by METAS was used in field-testing, while the ones from JV and VSL were delayed and are scheduled for field-testing before the end of 2020. The design of all standards is very similar and only the design from the METAS HFTS will be presented here. A full description can be found in [8].

The METAS HFTS consists of two 36 L pressure tanks mounted into an aluminium frame. The tanks are type 4 cylinders (carbon fibre-reinforced epoxy with a plastic liner) with a service pressure of 70 MPa (at 15°C), corresponding to a capacity of 1.44 kg H_2 each. The nominal empty mass of each tank is 33 kg with dimensions of 320.8 mm x 910.3 mm. Figure 30 shows the HFTS in its frame resting on its aluminium base plate (1900 mm x 1000 mm), as well as surrounded by an electrostatic discharge (ESD) plastic frame. The total weight is around 400 kg. The HFTS alone weighs around 150 kg.

The HFTS is equipped with two 27 cm long Pt 100 probes inserted at one end of each tank and two digital pressure transducers with a 100 MPa range. Additional Pt 100 probes were mounted on the HFTS to monitor temperature in the tubing and around the scale. Passive pressure gauges were also mounted before the tanks. A Coriolis mass flow meter is also part of the HFTS and can be placed in series with the piping leading to the tanks for monitoring or eventual calibration purposes.

The frame is mounted on a 300 kg scale with 0.1 g resolution for gravimetric measurements. The weight of the frame can be lifted from the scale by a load removal system activated by a hand pump. The complete system (HFTS + scale) is placed on an aluminium base plate, which can be lifted with a forklift and placed into a van or on a trailer for transport.

Accompanying the HFTS is a secondary ESD plastic frame to protect the scale from the environment, a mobile DAQ with laptop and a 4 m tall stainless steel vent stack with support for venting the hydrogen gas in the field after a fill. During transport, the HFTS's load is removed from the scale and held in place by locking nuts. A detailed description of the operating instructions is part of the internal documentation of the HFTS.

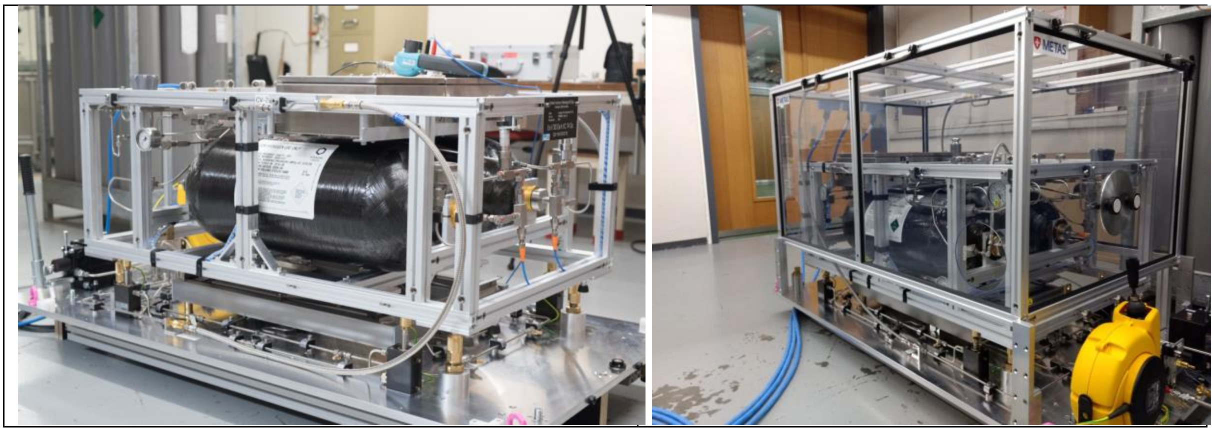

Figure 30: Left) HFTS resting on its base plate. Right) HFTS with housing partially closed. The open space between base plate and housing is 25 cm. The housing is not leak tight.

Figure 31 shows the Piping and Instrumentation Diagram (P&ID) of the HFTS. The system is composed of three lines: an inlet line connected to the hydrogen dispenser, a purge line to flush the system with N_2 and an outlet line for blowing the tanks down. The components located in the blue box are part of the frame that will be weighed on the scale. The hydrogen from the dispenser enters the HFTS through a nozzle as mounted on a car and is guided into the tanks. The gas can pass through the Coriolis mass flow meter, depending on the position of the needle valves V-4, V-1 and V-5. After filling, the tanks are emptied through a vent stack after passing through a cascade of pressure reducing valves PR-1 and PR-2 located after the needle valve V-9.

The base plate accommodates the piping for the load removal system as marked in red in Figure 31, as well as the piping for flushing and purging the tanks of all hydrogen gas before transport. Several nozzles placed around the frame allow flooding the ESD housing with an inert gas during the measurements to prevent eventual icing on the pipes. All the piping in contact with hydrogen is made of medium pressure ¼" tubing, NPT and FK series fittings and valves in 316-stainless steel.

The HFTS will store high-pressure hydrogen during field-testing and is therefore considered as equipment in an environment with explosive atmosphere (ATEX Zone 2). This puts some constraints on the design of the electrical scheme and DAQ as well as on the choice of sensors.

The temperature probes, the pressure sensors, the scale and the Coriolis mass flow meter are located in the explosive atmosphere zone and are all certified. These last two instruments are considered as non-arcing and are connected to the DAQ system through their own transmitters or readout modules. The remaining sensors are connected through terminal boxes to safety barriers located in the DAQ rack outside the ATEX Zone. An earth monitoring system guarantees that the HFTS and its DAQ system are continuously grounded with the hydrogen refuelling station to prevent electrostatic charges as ignition sources.

All cables can be plugged or unplugged from the HFTS to eliminate torqueing of the scale during weighing. The Coriolis mass flow meter is connected through a dedicated transmitter that is part of the DAQ system but read out using dedicated software from the manufacturer.

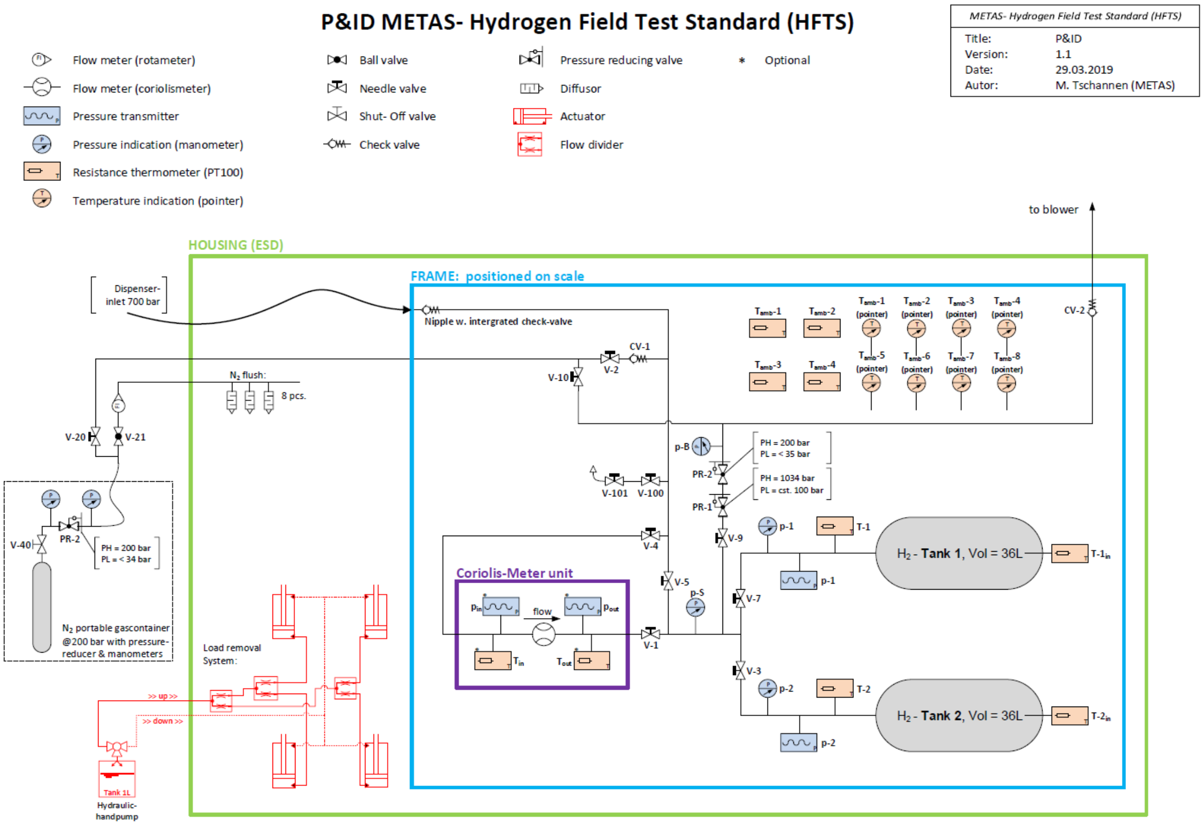

Figure 31: HFTS piping and instrumentation diagram for the METAS HFTS.

E. Full results from HRS tests at seven locations

This appendix presents the results of the accuracy tests from the procedure described in Figure 10. There are seven test series, performed on seven different HRSs with two different configurations as described in Section 5.3. Tests from 20 to 700 bar, i.e. a full filling, are represented in blue whereas partial fillings are represented in red and orange. Finally, the MMQ are in green. This colour scheme will be maintained for all the tested HRS. The results are discussed in detail in Section 5.4. Figure 32 to Figure 36 presents the hydrogen tests with the primary test benches for configuration 1 of the HRS, where the MFM is located in the main container, as shown in Figure 12. Figure 37 to Figure 39 presents the hydrogen tests for HRSs with configuration 2 as described in Figure 13, where the MFM is located in the dispenser close to the delivery point.

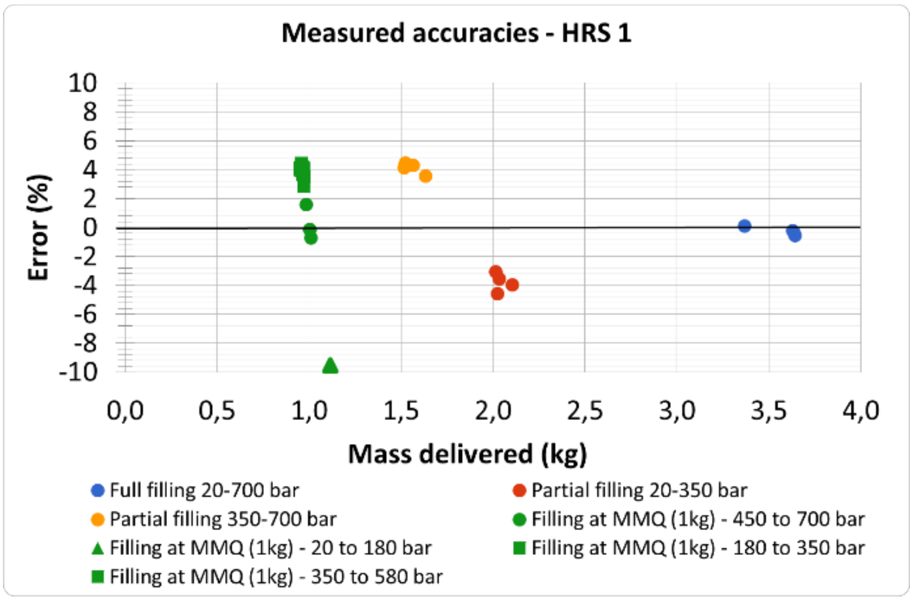

Figure 32: Results of accuracy tests in HRS 1

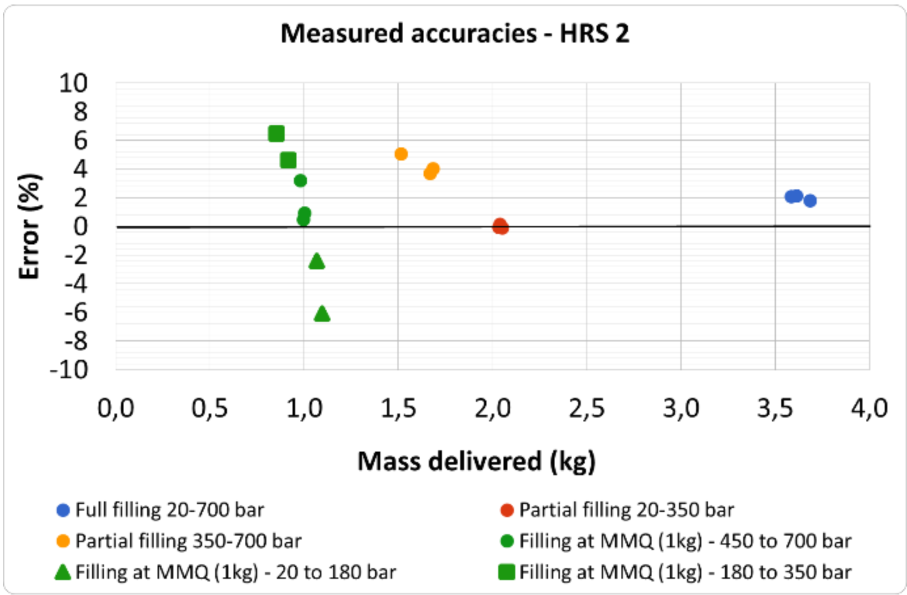

Figure 33: Results of accuracy tests in HRS 2

The results shown in Figure 33 display a positive shift in test results. According to OIML R139:2018, an adjustment is authorized on the meter to centre results on zero. This adjustment may be done with the transmitter of the flowmeter but have not yet been implemented on site. A manual correction was made to the test results afterwards, by subtracting the mean error value of full fillings tests to all results.

For Figure 35, a negative shift of 1% is observed. A manual correction was made to the test results afterwards, by subtracting the mean error value of full fillings tests to all results.

For the HRS tested in Figure 36, non-negligible scatter has been observed. However, the tendency of tests results looks similar to previous HRS.

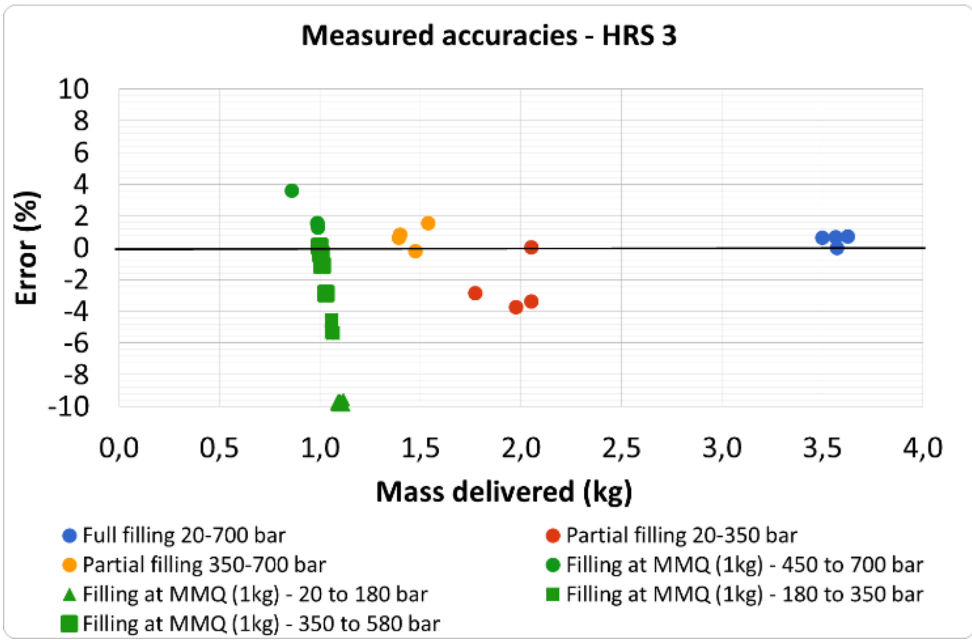

Figure 34: Results of accuracy tests in HRS 3

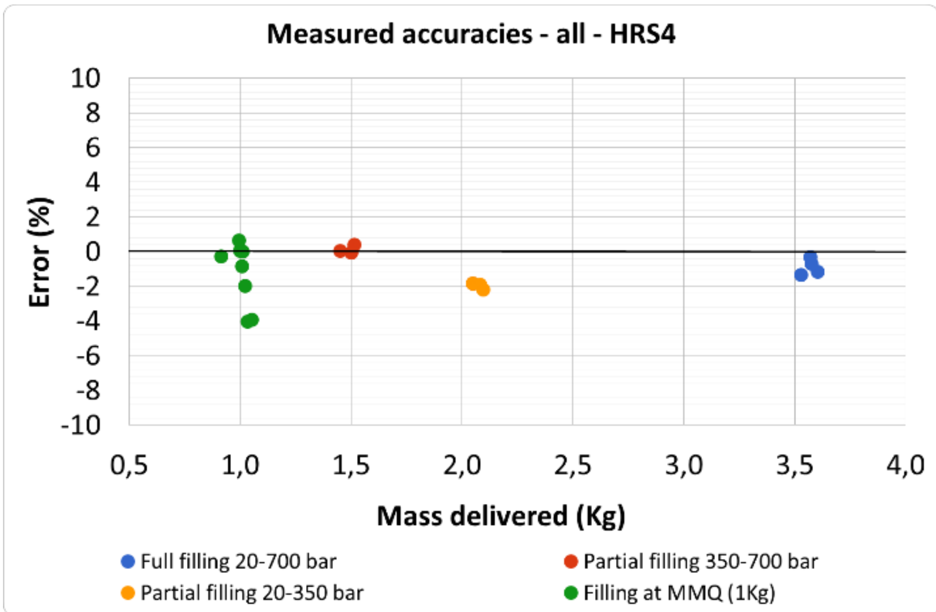

Figure 35: Results of accuracy tests in HRS 4

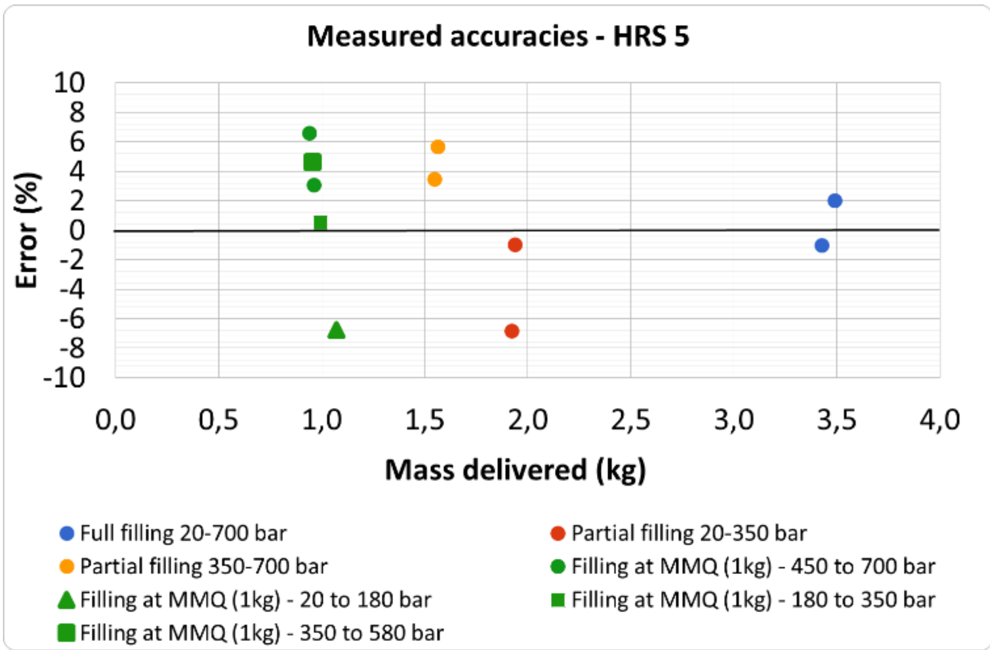

Figure 36: Results of accuracy tests in HRS 5

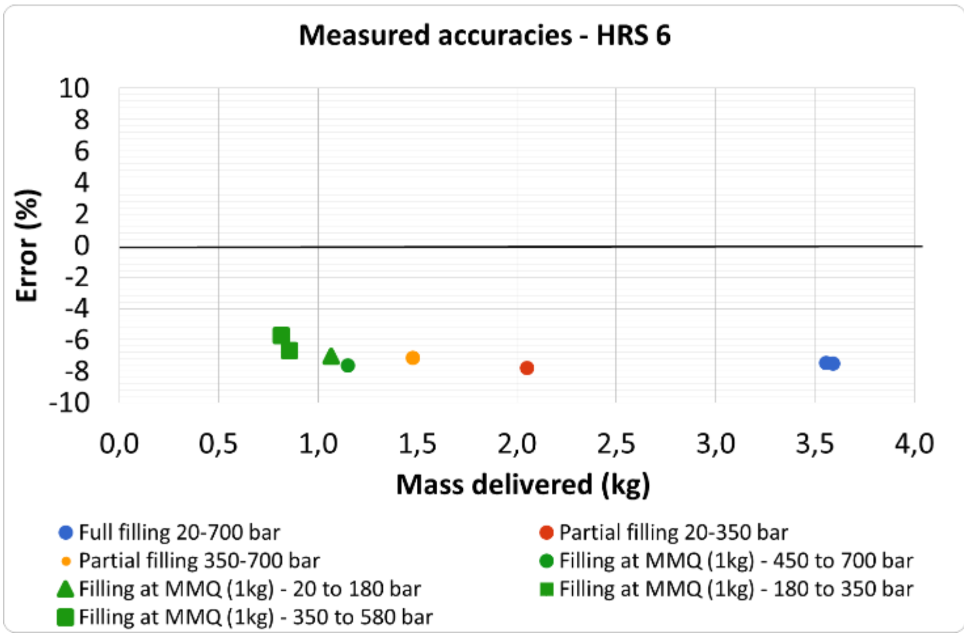

Figure 37: Results of accuracy tests in HRS 6.

For the HRS tested with results in Figure 37, a significant negative deviation was observed of around -7.5%. This error is too significant to be attributed to a simple adjustment of the CFM. It was explained afterwards by the HRS manufacturer, but no more information was given. Therefore, it has been manually corrected afterwards, to give the following results as seen in Figure 38.

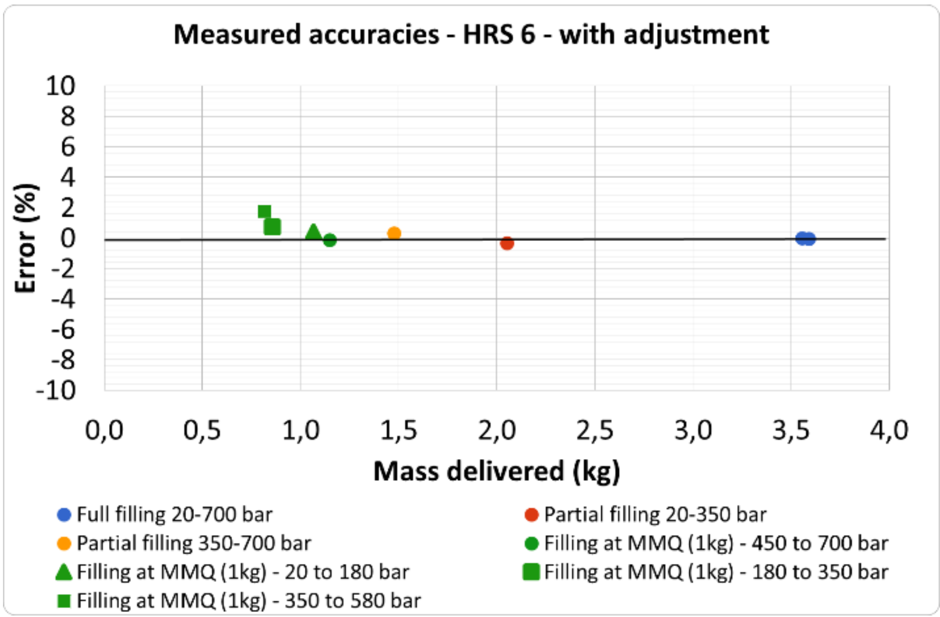

Figure 38: Results of accuracy tests in HRS 6 with adjustment.

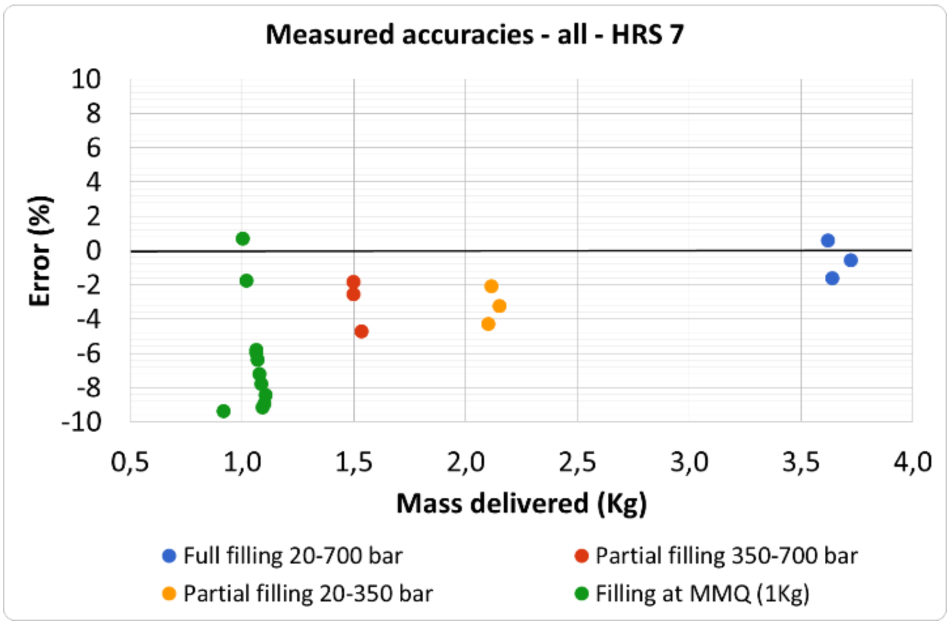

Figure 39: Results of accuracy tests in HRS 7.

For the last HRS tested, quite large repeatability errors were observed as seen in Figure 39. A constant negative deviation is noticed, with higher dispersion. Information was given by the HRS operator that a correction was made for the vented H_2 quantity, but with no more details.