METROLOGY for HYDROGEN VEHICLES

REPORT:

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

EMPIR EURAMET

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 report was written as part of activity A1.4.6 from the EMPIR Metrology for Hydrogen Vehicles (MetroHyVe) project. The three-year European project commenced on 1st June 2017 and focused on providing solutions to four measurement challenges faced by the hydrogen industry (flow metering, quality assurance, quality control and sampling). For more details about this project please visit www.metrohyve.eu.

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Introduction

Work package 1 of the “Metrology for Hydrogen Vehicles” Joint Research Project aims to establish a traceability chain for hydrogen flow metering in fuel cell vehicle refuelling applications. Several portable gravimetric flow standards will be developed in the project, which will allow calibration and verification of flow meters directly at hydrogen refuelling stations (HRSs) in the field. Another option that will be investigated is the use of master meters for verifications in the field.

This report provides an assessment of the validity of using a master meter based on Coriolis Flow Meters (CFM) for the testing and calibration of hydrogen refuelling stations. This assessment is based on a very limited amount of experimental field data. Data have been taken during field-testing with the METAS Hydrogen Field Test Standard (HFTS) at the Empa hydrogen refuelling station (HRS).

Testing with a Master Meter: Overall Findings

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. OIML R139:2018 gives Maximum Permissible Errors (MPE) of 2 % for Class 2 and 4 % for a Class 4 HRS. This 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 very little data on the equivalence in calibration results for Coriolis meters with water and hydrogen at pressures encountered in a HRS.

Master meter mounted in the hot region

A master meter mounted in the hot region of the HRS that has been calibrated with a gravimetric system at the same HRS shows good repeatability. Results seem to indicate that such a master meter would achieve the required accuracy for verification measurements for a Class 4 HRS. More data are needed to make a claim for its use in the verification of a Class 2 HRS.

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 meter 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.

Master meter mounted in the cold region

The measurement results collected from field-testing with the master meter mounted in the cold region of the HRS showed too much spread and a large deviation with respect to calibration results when mounted in the hot zone of the HRS, therefore no clear conclusions can be taken. From some part of the data, the required accuracy for verification measurements for a Class 4 HRS has been achieved. More data are clearly needed. 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.

Description of the HRS measuring system at Empa

In this section, the operating principle of the HRS at Empa and potential uncertainty sources of the measuring system are explained. Figure 1 shows a simplified schematic of the HRS. Generally, the HRS consists of a compressor, H_2 buffer storage cylinder, a heat exchanger and a dispenser. At the Empa station, the CFM of the dispenser is mounted upstream of the heat exchanger and therefore has a relatively stable temperature condition during a refuelling process.

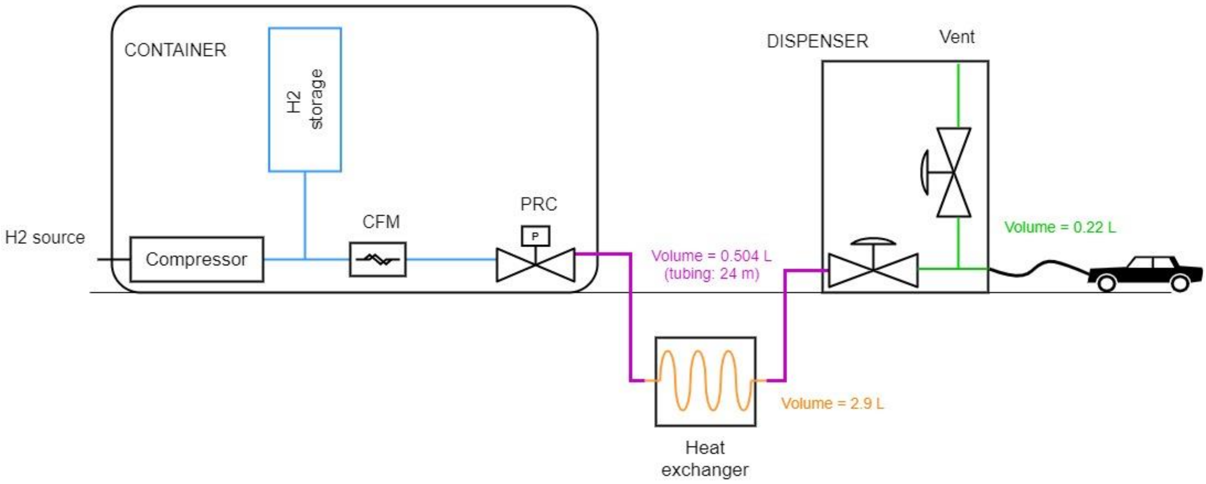

Figure 1: Schematic of the HRS measuring system at Empa, the volumes of the connecting pipes located after the CFM are indicated.

The mass of hydrogen delivered to a vehicle is the mass of hydrogen measured by the CFM minus the vented quantity (marked green in Figure 1) at the end of a fill and minus the possible mass difference of hydrogen stored in the pipes between the flow meter and dispenser (marked purple and orange) before and after refuelling due to final pressure differences between two sequential fills. To correct for the associated uncertainties, the size of the different volumes were determined.

Figure 2 shows the calculated vented quantity at the Empa station as a function of pressure at minimum temperature conditions of -40 °C. Depending on the filling pressure reached, the vented quantity can be up to 10 grams. This corresponds to 1 % of the minimum measured quantity (MMQ) that is set to 1 kg in the current OIML version (2018) [1].

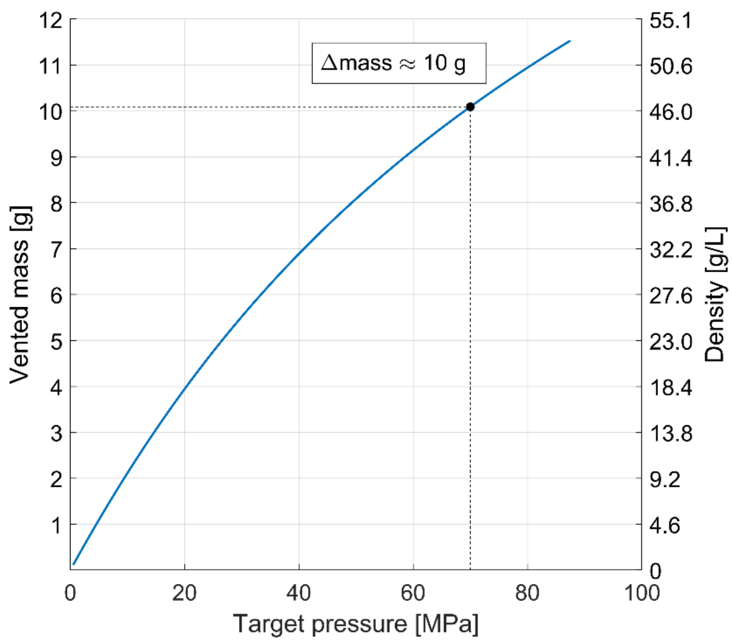

Figure 2: Vented quantity at the Empa station

Another uncertainty contribution is due to hydrogen in the piping between the flow meter and the dispenser, since pressure in these pipes may be different before and after refuelling and therefore could lead to different quantities of hydrogen stored in the pipes and having passed the flow meter. A larger pressure after refuelling, for example, implies that a certain amount of hydrogen passed the flow meter but did not enter the vehicle tank. In the event that the customer manually stops the refuelling or an error occurs during the process, the filling pressure reached can lie well below the initial pipe pressure, such that more hydrogen is delivered than invoiced. Figure 3 shows the calculated difference in measured mass depending on the filling pressure reached with an initial pipe pressure of 70 MPa.

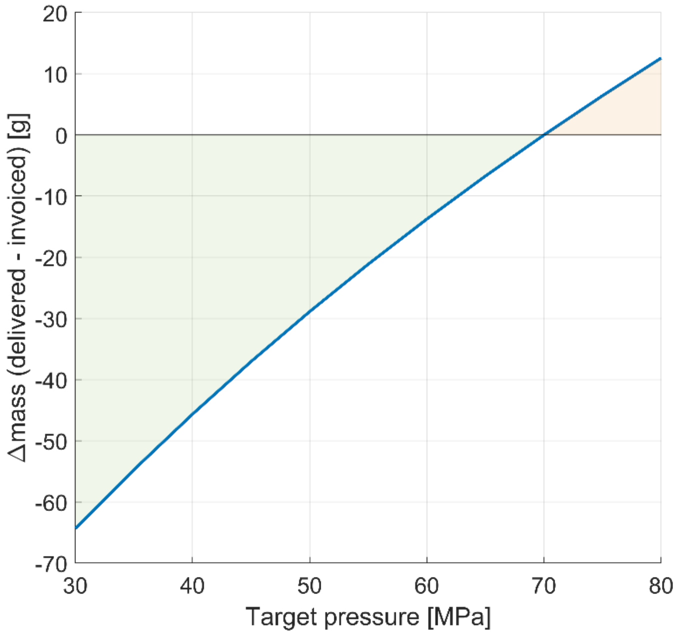

Figure 3: Uncertainty contribution of the volume between flow meter and dispenser. The initial pipe pressure was assumed to be 70 MPa

Depending on the final filling pressure, the volume between flow meter and dispenser can be a significant contributor to the overall uncertainty and can amount to tens of grams.

In the following graphs, a typical refuelling process is plotted to explain the operating principle of the station. Figure 4 shows in a) the total mass and flow rate and in b) the temperature and pressure profiles as measured by the Empa station during a refill.

a)

b)

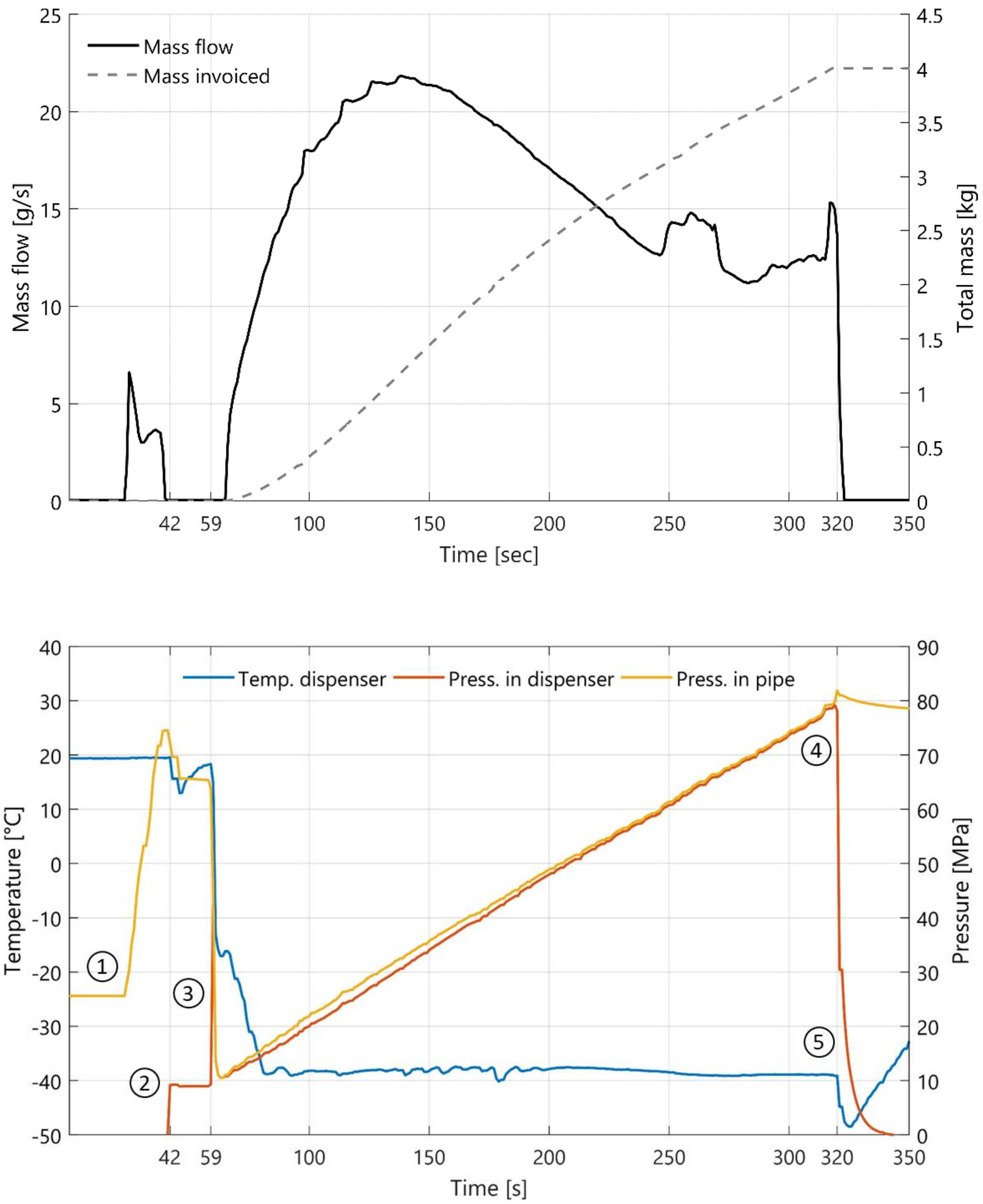

Figure 4: Temperature, pressure and mass flow profile as measured by the refuelling station for a typical hydrogen refuelling

At first (position 1 in figure b) the station brings the pipe pressure (in yellow) to 70 MPa. Note that the station measures the mass flow needed to fill the pipes, but does not charge for it. This is an important measure to avoid potential errors of the measuring system. Before the main refuelling starts, the pressure in the dispenser (in orange) is increased at t = 42 s (position 2) to reach vehicle tank pressure level. This allows the dispenser control to determine initial vehicle tank pressure, which is then compared to the value communicated via infrared or replaces the latter if it is a refuelling without communication. The pressure is maintained at this level for around 17 s to check for possible leaks in the joints and fuelling lines to the vehicle. As the main refuelling starts at t = 59 s (position 3), a sharp pressure peak is apparent. Subsequently the pressure in the dispenser rises linearly. At the end of the refuelling process at t = 320 s (position 4) the remaining hydrogen in the refuelling hose connecting HRS and vehicle is vented to the atmosphere as can be seen by the dispenser pressure curve falling to zero. The complete refuelling process takes approximately four to five minutes.

Further, it can be seen that the hydrogen is cooled during refuelling. As the main refuelling starts, the temperature measured in the dispenser decreases rapidly to -33 °C and is then kept constant in the range from -40 °C to -33 °C. This corresponds to the T40 category of the SAE J2601 fuelling protocol [2]. At the end (position 5), during the venting of the hydrogen in the dispenser, the cooling effect due to isentropic expansion is visible.

Description of the METAS HFTS

The METAS HFTS, shown in Figure 5, consists of two high-pressure tanks horizontally mounted on a frame that can be lowered on a scale for weighing the amount of delivered high-pressure hydrogen in the tanks. The hydrogen is horizontally injected in each tank through a one-hole axial injector with 3 mm internal diameter. It has been shown (Hytransfer project, www.hytransfer.eu) that such dimensions of the injector prevent temperature stratification in a 36 L tank. Several valves, dedicated piping, pressure and temperature sensors and a Coriolis mass flow meter are also mounted on the frame. The hydrogen stored in the tanks after weighing can be vented in the atmosphere through a blower mounted on a 4 m mast and connected to the tanks through a pressure-reducing valve.

Figure 5: Left) METAS HFTS, Right) METAS HFTS during field-testing

Each tank of the HFTS is equipped with a pressure (up to 1000 bar abs) and temperature (Pt100 IEC 4 4-L) sensor for monitoring and logging purposes. Temperature in the tanks is measured by a Pt100 (6 mm diameter, 270 mm in length) mounted in each tank. The temperature probe is mounted opposite the injection point and terminates at approximately 1/3 of the tank length. The temperature around the frame in the housing is indicated by several temperature indicators and Pt100 probes also logged.

An electronics rack houses the display of the scale, a sensor to monitor ambient conditions (air pressure, temperature and humidity), the data-acquisition system for the various sensors and the scale, and has a common ground with the HFTS and the HRS. A complete description of the HFTS can be found in [4].

The two different configurations tested

Two different configurations were tested. In the first week, the METAS master meter was mounted in series with the CFM of the filling station and in the second week, the master meter was on the HFTS. Figure 6 schematically shows the measurement setup at Empa for both weeks.

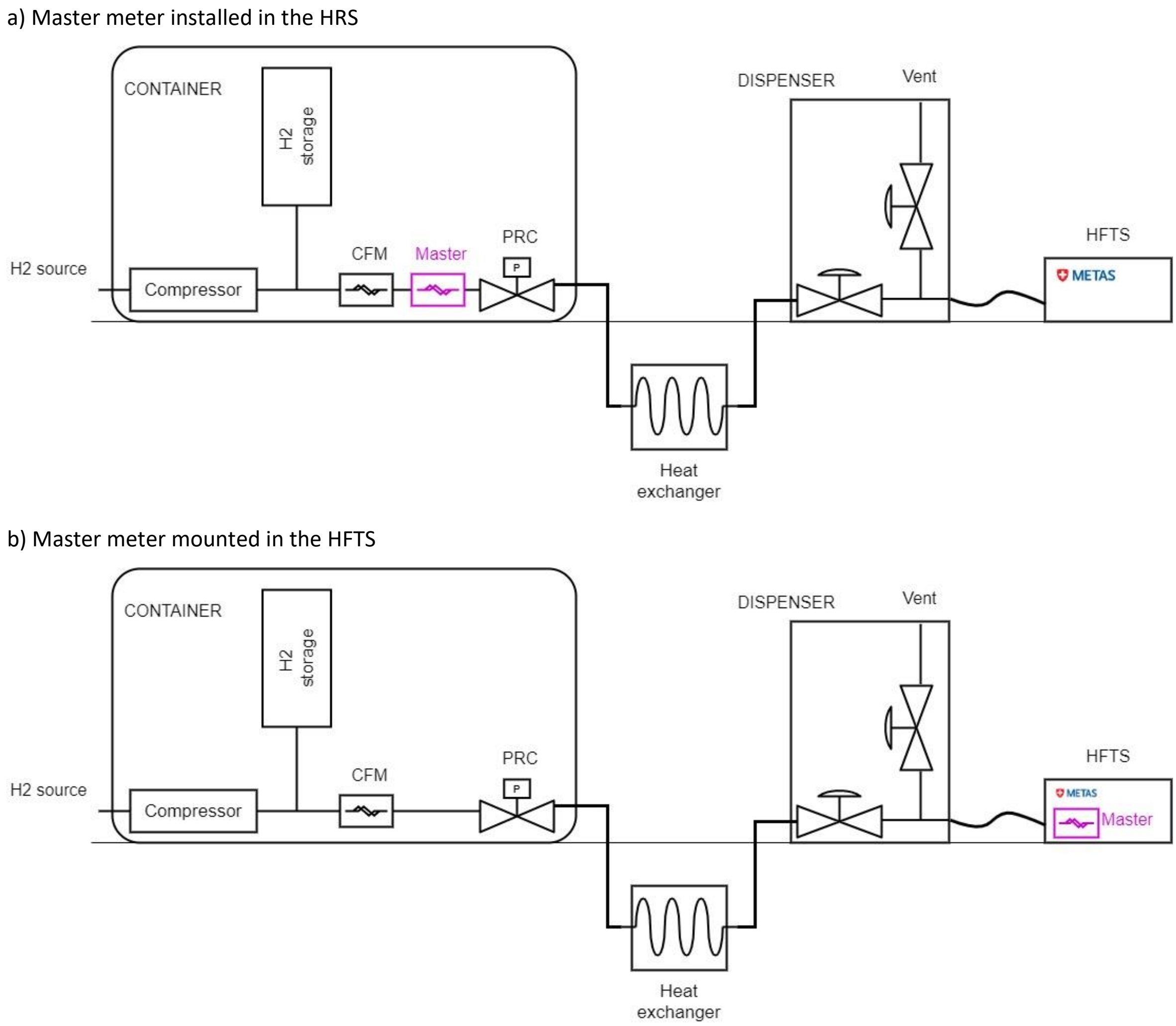

Figure 6: Tested configurations at the refuelling station at Empa

Figure 7 shows the station control panel before (left) and after (right) installation of the METAS master meter. Note that the flow meter is placed before the pressure ramp controller (PRC) when it was installed in the HRS.

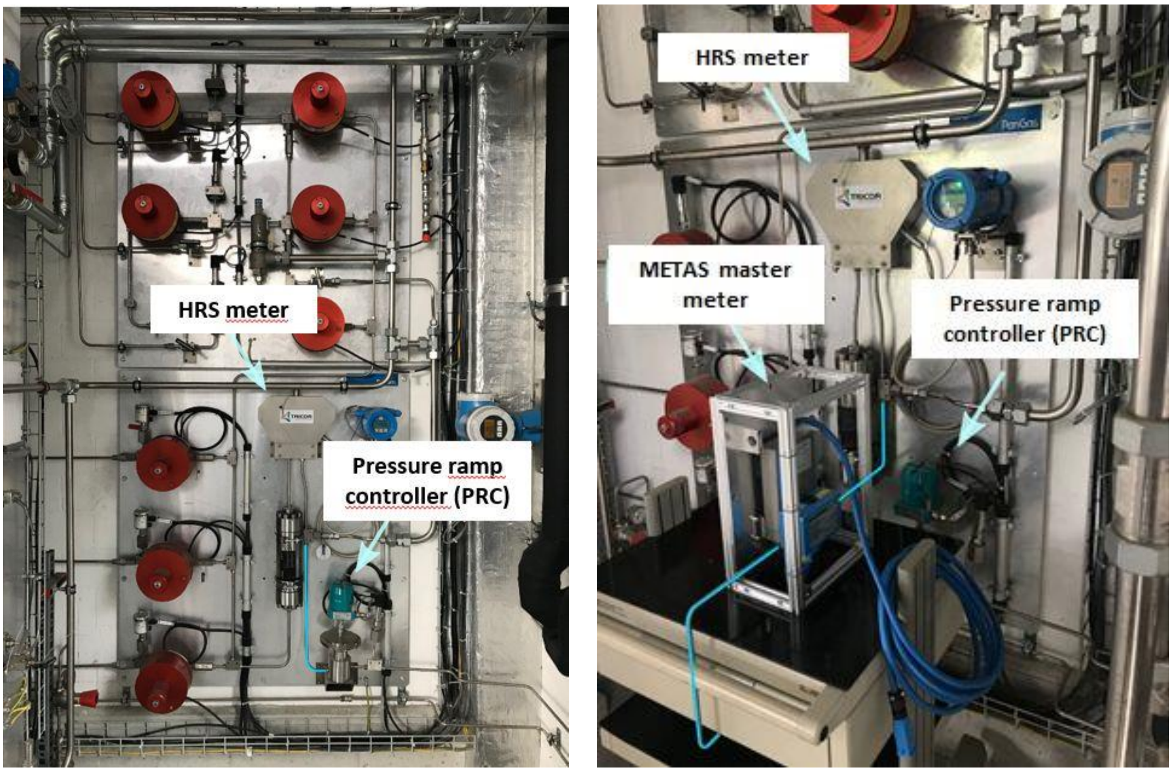

Figure 7: Left) before installation of the Master meter CFM. Right) after the installation of the Master meter

The meter location can have a large influence on its readings, depending on whether it is mounted before or after the heat exchanger. If installed in the warm area (before the heat exchanger), the flow meter can have a relatively stable temperature during the fuelling. Conversely, if 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. In both cases, pressure variations are always present.

Results

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 manufactuer's software and using the value displayed in the totalizer field. This value was set to zero before each fill.

Master meter installed in HRS

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 . For the measurements in the first week, the METAS master meter was placed in series to the station flow meter.

Figure 8 shows the deviation of the flow meter from the HRS and the METAS master meter compared to the HFTS. The initial and final pressure in the tanks are also indicated below the dispensed mass. A full fill corresponds to (2 to 70) MPa and partial fillings correspond to (2 to 35) MPa or (35 to 70) MPa.

The HRS flow meter shows a significant negative deviation for both partial fillings, while a deviation between -3 % to 5 % was observed for the full fillings. The repeatability of the tests, in particular for the full filling, was rather poor and can't be explained by the uncertainty of the station design alone, and is therefore attributed to the flow meter.

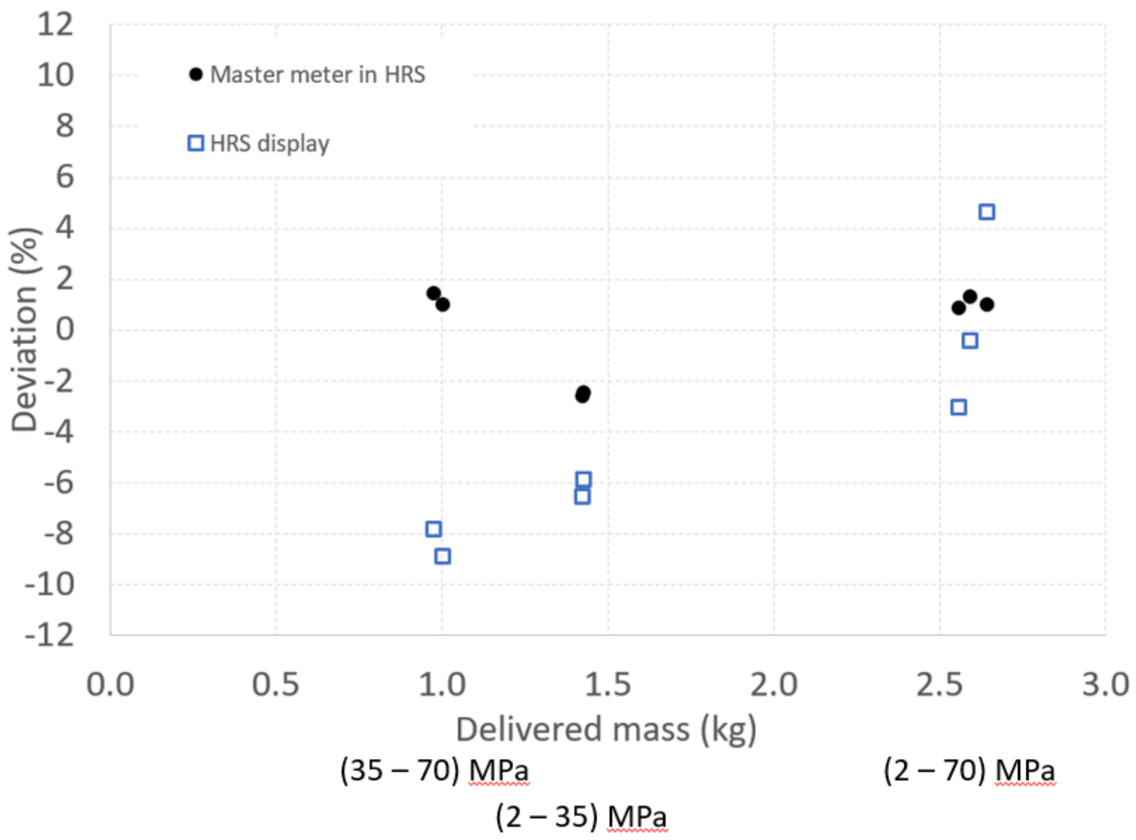

Figure 8: Deviation of the HRS meter and the METAS master meter with respect to the HFTS. Both flow meters are mounted in series at the same location in the HRS before the heat exchanger

The METAS master meter shows for the full and partial fillings with a target pressure of 70 MPa, a slight positive error. This can be explained by the vented quantity at the end of each refuelling, which was counted by the flow meter but did not enter the customer's tank and was therefore not measured by the HFTS. As previously mentioned, depending on the final filling pressure, the vented quantity at the Empa station can be up to 10 grams. Note that the nominal pressure in the pipes before and after refuelling is similar, which means that the uncertainty contribution of the volume between flow meter and dispenser is minimal because the same quantity of hydrogen has been replaced before and after the fill in the piping volume after the flow meters.

For the partial filling from 2 to 35 MPa, the error is negative. This can be explained as the refuelling was manually stopped early at a filling pressure of 35 MPa and that hydrogen in the pipe volume at 70 MPa has been replaced by hydrogen at 35 MPa. A lower pipe pressure after refuelling implies that more hydrogen is delivered than invoiced. In this case, the difference is close to 50 g (hydrogen that was delivered to the HFTS but not measured by the flow meter). This result is in line with the findings of a recent FCH-JU study [3]. Overall, the METAS master meter showed good repeatability (0.23 % for full fills).

Figure 9 shows the deviation of the METAS master meter compared to the HFTS, taking into account the vented quantity and the contribution of the volume between flow meter and dispenser when the final pressure is not 70 MPa. After correction, the measured mass is in good agreement with the HFTS and even meets the requirement for a Class 2 station as defined by OIML R139 [1].

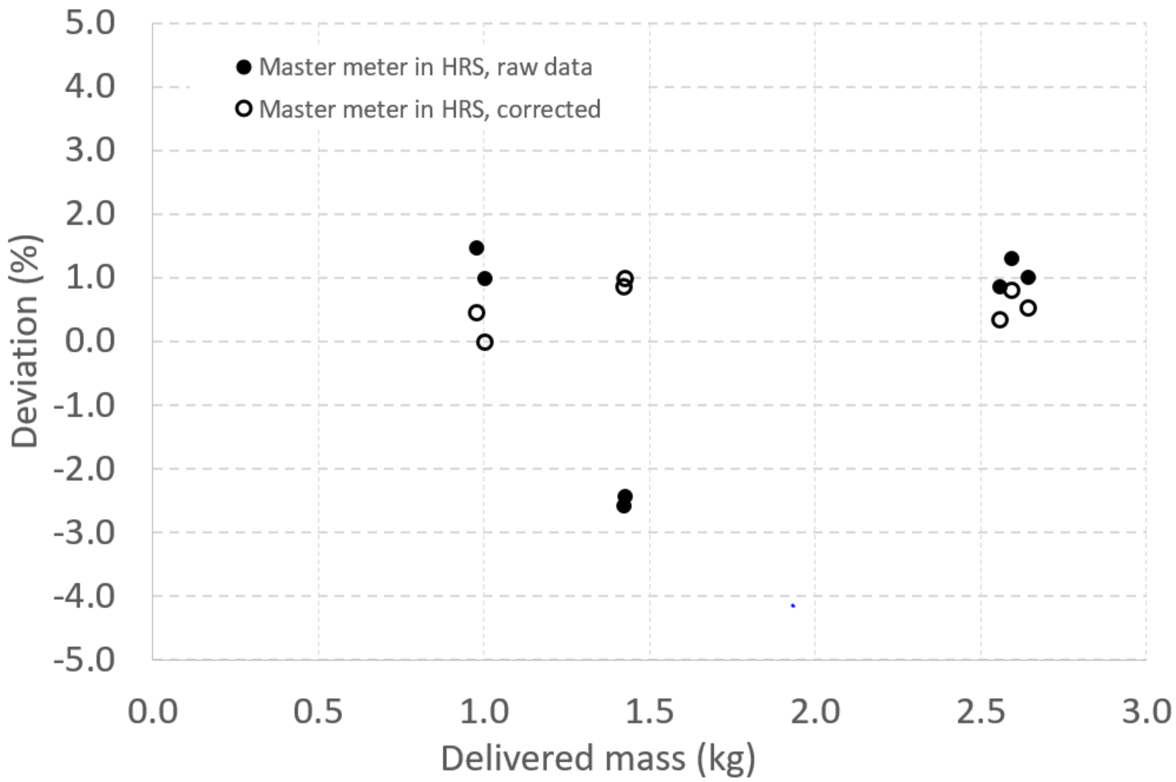

Figure 9: Deviation of the METAS master meter with respect to the HFTS, with and without correction for vented quantity and difference in initial and final pipe pressure.

Table 1 summarizes the mean values and standard deviations of the performed tests, as well as calibration results with water and nitrogen at 20 °C fluid temperature under steady conditions. Note that for the HFTS, the partial filling from 35 to 70 MPa corresponds to the MMQ measurement. The expanded uncertainty of the HFTS measurements is 0.3%. The expanded uncertainty of the measurements varies strongly depending on the filling profile and indicate a possible minimum of 0.37 % when the measurements show excellent repeatability. The calibration with water is in better agreement with the hydrogen data than the calibration with nitrogen.

Table 1: Accuracy of the METAS master meter mounted in the HRS

MEAN VALUES	**Master meter**	**Master meter** *(corrected)*	**Standard deviation**	**Uncertainty (k=2)**	**HFTS**
Full filling 2-70 MPa	***1.06 %***	***0.56 %***	***0.23 %***	***0.55 %***	*2.597 kg*
Partial filling 2-35 MPa	***-2.51 %***	***0.94 %***	***0.10 %***	***0.37 %***	*1.425 kg*
Partial filling 35-70 MPa	***1.23 %***	***0.21 %***	***0.34 %***	***0.75 %***	*0.989 kg*
Calibration with water (20 °C)	***0.16 %***	-	-	-	-
Calibration with nitrogen (20 °C)	***-0.60 %***	-	-	-	-

Master meter installed in the HFTS

In the second week of measurement, the same seven measurements were repeated. The only difference is that the METAS master meter was placed in the cold zone (after heat exchanger) and was part of the HFTS.

Figure 10 shows the mass flow rate and tubing temperature profile recorded by the master meter in the HFTS during a refuelling. The first peak for the mass flow rate is due to the leak check from the HRS. One notices that some hydrogen is already delivered (in this case, approximatively 30 g) and that the flow meter is able to record it. The refuelling then starts properly and one observes a transient behavior of mass flow rate and tubing temperature. After approximately 100 s, the tubing temperature is constant and one observes a stabilization of the mass flow rate. The changing temperature is due to the cold hydrogen at -35 °C entering the flow meter that is at ambient temperature (33.8 °C in this case). The average mass flow rate is around 0.5 kg/min. The small ripples in mass flow rate are induced by the master meter transmitter and represent a defect of the transmitter. This does not alter the absolute value of the measurement, only the stability of the reading. This has been verified in the laboratory under controlled conditions. The faulty transmitter showed a zero point stability of 10 g/min but a correct absolute reading. After replacing the transmitter, we observed the same deviations when testing with nitrogen but a much better zero point stability and repeatability of the measurements.

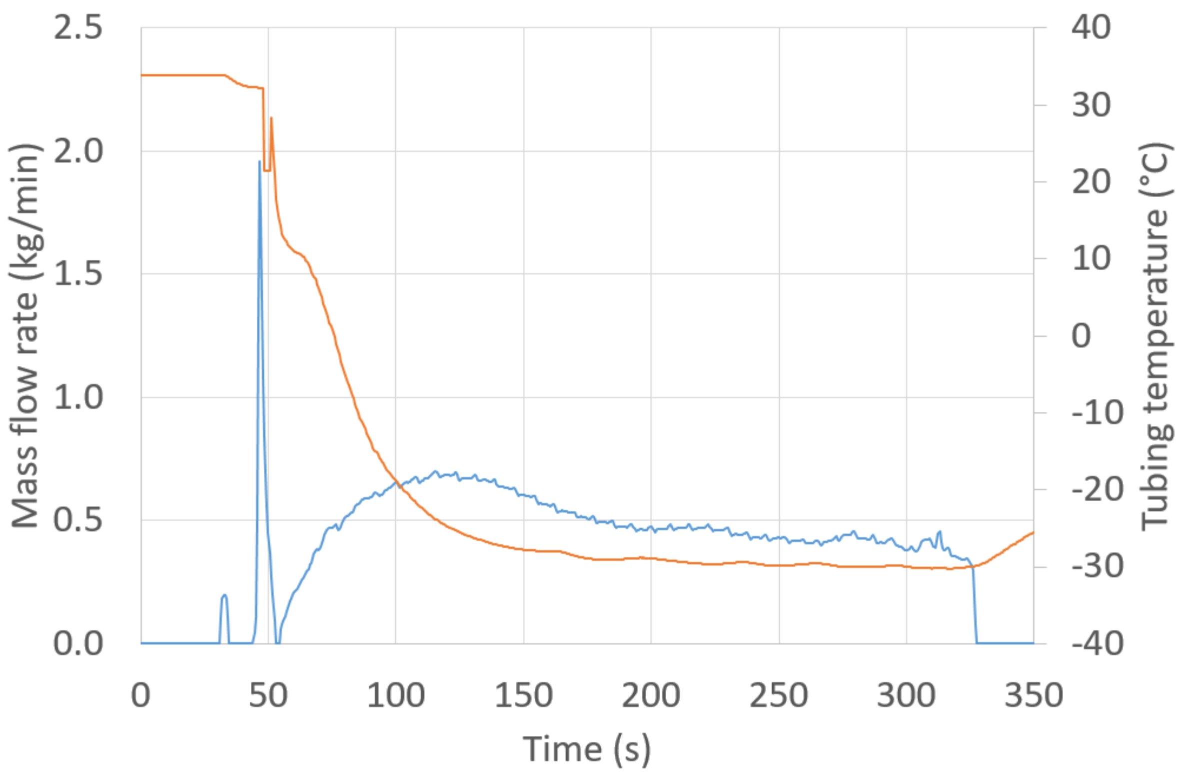

Figure 10: Mass flow rate (in blue) and tubing temperature profiles from the METAS master meter during a refuelling.

Figure 11 shows the deviation of the flow meter in the HRS and the METAS master meter, the latter mounted on the HFTS, compared to the HFTS. The data from the HRS flow meter from the previous week's measurements is also shown and gives an indication of the repeatability of the HRS flow meter. As before, the HRS flow meter has poor repeatability and shows a negative error in all tests. For the partial filling from (2 to 35) MPa, an error of down to -10 % was observed. No correction for vented quantity has been applied.

In contrast to previous measurements, the METAS master meter has a large positive deviation in all tests (deviation > 5 %) and a larger spread than during the first week. It should be noted that the full fills have been performed over 2 days. 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. More data need to be collected. There is no contribution from different initial and final pressures in the pipes. The vented quantity is not measured by the master meter with this configuration.

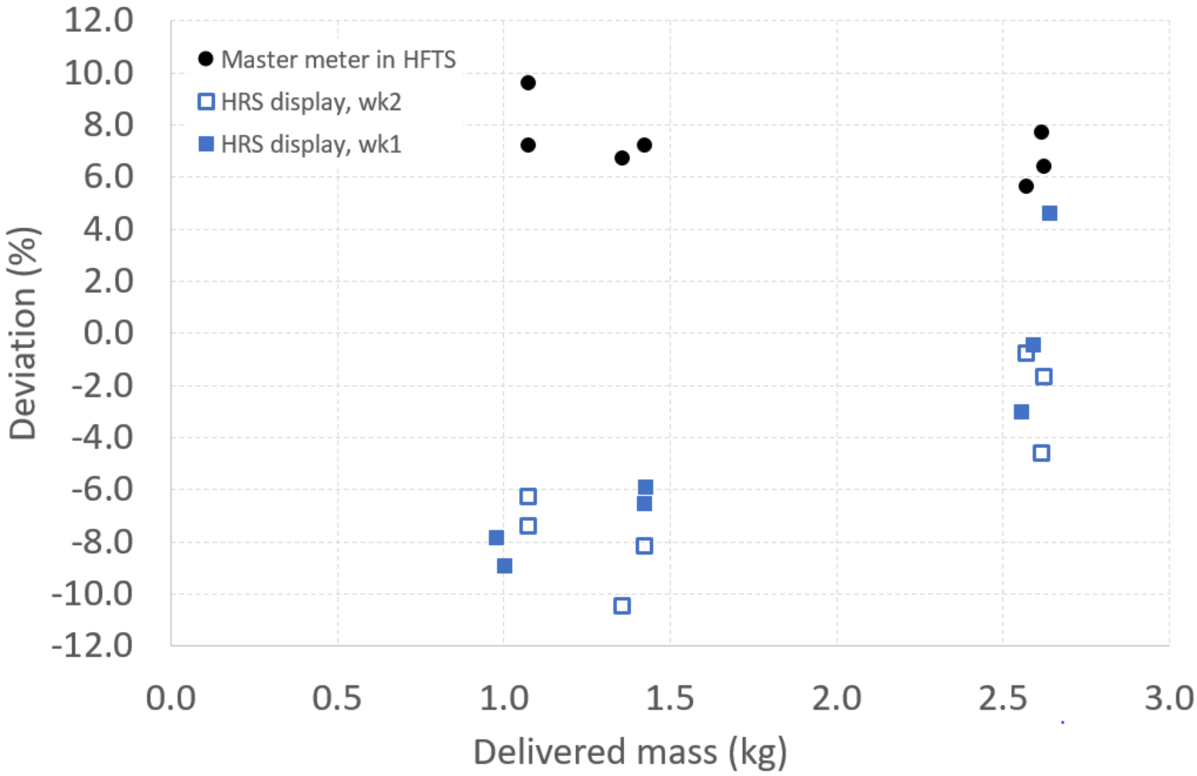

Figure 11: Deviation of the HRS meter and the METAS master meter with respect to the HFTS. The METAS master meter is mounted in the cold zone, after the heat exchanger, on the HFTS.

Table 2 summarizes the mean values and standard deviations of the performed tests with the master meter. The expanded uncertainty of the HFTS measurements is 0.3 %. No obvious effects due to different pressure in the pipes before and after refuelling are observed, as expected. 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.

Table 2: Accuracy of the METAS master meter mounted in the HFTS

MEAN VALUES	**Master meter**	**Standard deviation**	**Uncertainty (k=2)**	**HFTS**
Full filling 2-70 MPa	***6.61 %***	***1.05 %***	***2.13 %***	*2.775 kg*
Partial filling 2-35 MPa	***6.98 %***	***0.34 %***	***0.75 %***	*1.389 kg*
Partial filling 35-70 MPa	***8.42 %***	***1.70 %***	***3.42 %***	*1.073 kg*

Improvements and conclusions

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

- The station flow meter, although positioned in the warm zone, showed poor repeatability and large deviations that cannot be explained by uncertainties in station design.
- Based on these observations, it is mandatory to change the CFM of the station to meet the requirements for a Class 4 station.
- 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 due to pressure differences, a Class 2 is possible.
- In the cold zone, the METAS master meter showed a large positive error (error>5%) and the repeatability was not as good as in the warm zone. Further tests are required to better understand the transient temperature behavior in the cold zone.

Bibliography

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