

Hydrogen refuelling station calibration with a traceable gravimetric standard

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Abstract

Of all alternatives to gasoline fuels, hydrogen offers the greatest long-term potential to radically reduce many problems inherent in transportation fuel use. Hydrogen vehicles have zero tailpipe emissions and are very efficient. If it is made from renewable sources, nuclear power, or fossil sources with carbon emissions captured and sequestered, hydrogen use on a global scale could produce nearly zero greenhouse gas emissions and greatly reduce emissions of air pollutants. The aim of this work is to realise a traceability chain for hydrogen flow metering in the range typical for fuelling application in a wide pressure range with pressures up to 875 bar (for Hydrogen Refuelling Station HRS with Nominal Working Pressure of 700 bar) and temperature changes from -40 °C (pre-cooling) to 85 °C (maximum allowed vehicle tank temperature) in accordance with the worldwide accepted standard SAE J2601. Several HRS have been tested in Europe (France, Netherlands and Germany) and the results show a good repeatability for all tests. This demonstrates that the testing equipment works well in real conditions. Depending on the configuration of installation, some systematic errors have been detected and explained. Errors observed for the stations of Configuration 1 can be explained by the difference of pressure, at beginning and end of the fuelling, in the piping between the CFM and the dispenser: the longer the distance, the bigger the errors. For Configuration 2, as this distance is very short, the error is negligible.

1. Introduction

We observe air quality issues in our cities. It is not only about CO₂ but also about NO_x, SO_x and particulate matter. These are much smaller particles that enter the bloodstream and are at the root of the cause of many deceases in big urban agglomerations. It is therefore important to tackle one of the main causes of these issues at city but also rural level: the transport sector.

Amongst the major objectives of the European Union, the decarbonization of transportation has a significant role. Reducing transport related greenhouse gases emissions through both Energy efficiency improvements and increased usage of Clean Alternative technologies (powertrain, fuels) is considered as critical. With 25% of the GHG emissions attributable to transport, and the requirement to reduce them by 95% by 2050, there is no other way than to opt for massive electrification of transport, spurred by introduction of renewables, including both battery electric vehicles and fuel cell electric vehicles which complement each other.

Without efficient electric power drive systems such as fuel cells the long-term climate goals cannot be achieved.

Of all alternatives to gasoline fuels, hydrogen offers the greatest long-term potential to radically reduce many problems inherent in transportation fuel use. For example, hydrogen could enhance energy security and reduce dependence on imported oil, since it can be made by water electrolysis from various primary energy sources, including natural gas, coal, biomass, and wastes, and renewables. Also, hydrogen vehicles have zero tailpipe emissions and are very efficient. If it is made from renewable sources, nuclear power, or fossil sources with carbon emissions captured and sequestered, hydrogen use on a global scale could produce nearly zero greenhouse gas emissions and greatly reduce emissions of air pollutants.

In many countries, there is increasing support for the development of a large hydrogen infrastructure as a measure to reduce greenhouse gas emissions. This includes a network of hydrogen refuelling stations (HRS), which is necessary to enable the

widespread adoption of hydrogen fuel cell vehicles. However, the industry faces the dilemma that they are required to meet measurement requirements set by legislation that cannot currently be followed due to the lack of available methods and standards. In the EMPIR Metrology for Hydrogen Vehicles (MetroHyVe) project, this is addressed through the development of gravimetric standards for field verification; as well as an investigation into the use of substitute fluids for laboratory calibration of flow meters.

The aim of this work is to realise a traceability chain for hydrogen flow metering in the range typical for fuelling application in a wide pressure range with pressures up to 875 bar (for HRS with NWP of 700 bar) and temperature changes from -40 °C (pre-cooling) to 85 °C (maximum allowed vehicle tank temperature) in accordance with the worldwide accepted standard SAE J2601 [1].

2. Basic operating principle of a HRS station

2.1 Basic principle and listing of the component

The refuelling station system boundary starts at the hydrogen supply source and ends with the inlet to the vehicle's tank. The hydrogen can be supplied to a refuelling station in either gaseous or liquid form. The components that are part of the refuelling station vary and are dictated by the physical form of supplied hydrogen (i.e., gaseous or liquid) and the working pressure of the vehicle's tank. Most automakers have agreed to adopt a 700bar vehicle storage system. The primary goal of a refuelling station is to refuel vehicles to a 100% state of charge (SOC) throughout the station's daily operations.

The hydrogen station is usually composed of a low-pressure storage (200bar), a low-mid pressure compressor, some mid/high pressure storage, a booster compression for high pressure, a precooling and dispensing device. All these components are shown in Figure 1 below.

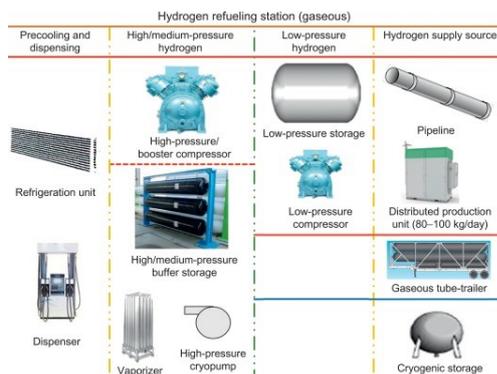


Figure 1: Hydrogen refuelling station components.
FLOMEKO 2019, Lisbon, Portugal

The OIML R139 [2] describes a Hydrogen Refuelling Station as a measuring system which should include at least:

- meter;
- pressure and/or flow control device;
- emergency power supply;
- transfer point;
- gas piping;
- zero-setting device.

The Figure 2 (from OIML R139 [*]) shows the constituents of a typical compressed fuel measuring system for vehicles.

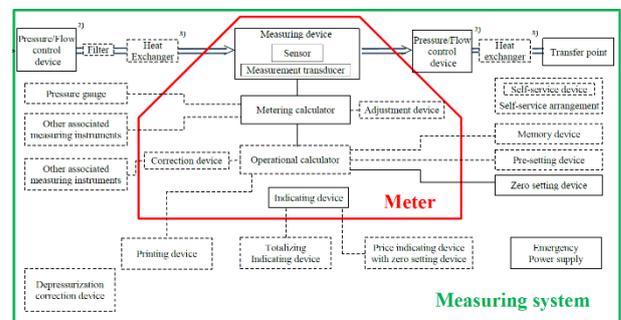


Figure 2: Constituents of a typical compressed gaseous fuel measuring system for vehicles.

The measuring system may also be provided with the following other ancillary and additional devices:

- calculator;
- associated measuring instruments;
- pressure gauge;
- digital indicating device;
- self-service arrangement;
- pre-setting device;
- memory device;
- price indicating device;
- printing device;
- heat exchanging device
- other ancillary and additional devices.

The “devices” listed above can be designated as a “typical” configuration of a measuring system.

2.2 Potential sources of error in the mass measurement

Within the framework of the EMPIR project (METROHYVE), an extensive list of uncertainty sources and measurement errors will be given and sorted out by their influence on the calculation of the hydrogen mass displayed by the dispenser (see Table 1).

Table 1: List of potential uncertainty sources and their impact on the uncertainty budget

Main Uncertainty Sources	
Mass flow rate from Coriolis meter	1
Pressure measurements (in particular those closest to flow meter/dead volume/fuel transfer point) Pressure measurements may be used for pressure corrections to the flow meter and for calculating the density of hydrogen in the dead volume to allow the mass to be determined.	2
Temperature measurements (in particular those closest to flow meter/dead volume/fuel transfer point) Temperature measurements may be used for temperature corrections to the flow meter and for calculating the density of hydrogen in the dead volume to allow the mass to be determined.	3
Depressurisation of fuel hose & dead volume connecting volume between flow meter and fuel nozzle (generally in hose)	4
Position of flow meter (this will affect the dead volume)	5
Hydrogen density equation	6
System repeatability	7
System reproducibility	8
Minimum Measurable Quantity	9

Explanation on each source:

1-Mass flow rate from Coriolis flow meter:

The rapid variation in temperatures / pressure can affect stress and torsion on the meter and might modify the meter accuracy / performance.

- The CFM manual (tested) states that the temperature variation shall be no more than 1°C per second.
- During the pulse initial phase, literature suggests large errors can be expected. Is the pulse measurable for the CFM?

The zero adjustment must be done once before type approval or periodic verification but how reliable is it if conditions evolve significantly?

2-pressure measurements:

A pressure measurement will be required for 'dead volume' gas density calculations and correction. Literature suggests that drift of the pressure sensors can be a significant issue.

3-Temperature measurements:

A temperature measurement will be required for 'dead volume' gas density calculations.

4-Depressurisation of fuel hose & dead volume:

Dead volume is the volume between the flow meter and the point of transfer into the vehicle (fuel nozzle at the end of the hose mainly). The mass dispensed into a vehicle is the mass measured by the flow meter minus the mass in the dead volume (generally refuelling hose) at the end of a fill (assuming there was no gas mass in the dead volume to begin with). If hydrogen was present in the dead volume at the start of the fill, the mass dispensed into a vehicle is the mass measured by the flow meter minus the difference in mass in the dead volume at the end of the fill and start of the fill. The design of the system shall ensure that the measured quantity is delivered. Figure 3 shows what is usually vented in a HRS.

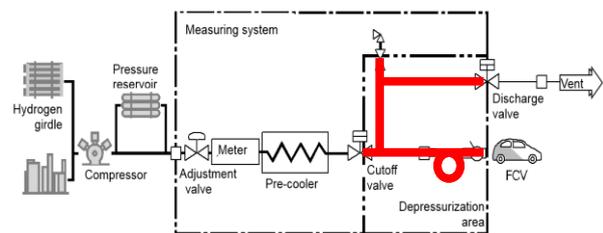


Figure 3: Depressurization in a HRS

The size of the dead volume is therefore required. As a rough approximation, for an 8mm inner diameter (typical 9/16" medium pressure tubing ID) hose that is 5m long, the maximum mass of hydrogen in the dead volume should be approximately 10g (assuming a gas density of ~40 kg/m³ at 700 bar and 20 °C). The depressurization takes also into account the piping length from the hose to the flow meter.

It has been reported by end users that the vented quantity is generally between 10g and 50g. Since storage masses for cars generally vary from 1 kg (being the minimum quantity) to 5 kg. Fill masses are therefore likely within this range, the dead volume mass can correspond up to 1% of the tank's mass capacity.

As mentioned, pressure and temperature measurements close to the dead volume are required to calculate the density, and therefore the mass of hydrogen in the dead volume. Uncertainty in this could therefore be a significant contributor to the overall uncertainty.

5-Position of the meter:

Flow meter position is important as the further away it is from the point of transfer into the vehicle, the larger the mass of hydrogen that is measured by the flow meter that is not actually dispensed into the vehicle (dead volume).

The meter location can have a large influence if it is mounted before or after the heat exchanger. Depending of the position, the flow meter can have a relatively stable temperature during the fuelling in the warm area (before the heat exchanger) or experience a rapid temperature variation at the beginning of the fuelling when hydrogen at ambient temperature is replaced by cooled hydrogen after it went through the heat exchanger. In both case, pressure variations are always present.

3. Test protocol for HRS calibration (on-site) and primary gravimetric standard (by Air Liquide).

3.1 Definition of the testing protocol based on the OIML R139 requirements

This work has been done within the framework of two European project: the METROHYVE project (Empir EURAMET) and the FCH-JU program (N° FCH / OP / CONTRACT 196: "Development of a Metering Protocol for Hydrogen Refuelling Stations").

The objective of this study is to define, in agreement with European national metrological institutes, a structured approach for accelerating the certification of metering systems for HRS in Europe. This certification is required for invoicing hydrogen at Hydrogen refuelling Stations (HRS) to the public. In the European countries where the roll-out of the hydrogen infrastructure has started (for instance, in Germany), the authorities require a prompt implementation of metering systems compliant with national regulation; without such certified metering systems, the construction of new stations could be stopped in the coming years.

For this reason, it was critical to define a temporary certification process for HRS before a revised version of OIML R139 is issued. Even if this revision was expected for beginning of 2019, it will take time to change the legislation in each European country.

For accuracy tests, it has been decided to perform a new test on-site. The tests are more severe than

the proposed tests in the OIML R139 since it is requested to perform:

1. Full filings: 20-700 bar → 2 times
2. Partial filings 20-350 bar → 1 time
3. Partial filings 350-700 bar → 1 time
4. Filing at Minimal Measured Quantity (MMQ = 1 kg) → 4 times with several initial pressures.

The acceptance criteria are the following for this test campaign:

1. Class 2 for future station (i.e. MPE=2% and 4% at MMQ)
2. Class 4 for existing station (i.e. MPE=4% and 8% at MMQ).

The Figure 4 presents the test protocol

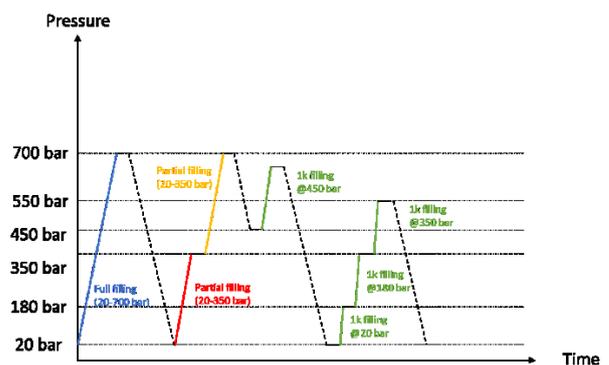


Figure 4: Test protocol

This test protocol should be repeated at least three times to assess the repeatability of the measurements.

3.2 Description of the primary gravimetric standard

The primary standard has been developed by Air Liquide with the support of LNE-LADG. Air Liquide received a PTB certification for the "Usage for the conformity assessment and verification for legal metrology purposes".

The gravimetric calibration device is measuring standard which is designed as a compact, mobile reference measuring system. This standard serves for measuring the amount of hydrogen filled into a tank at hydrogen refuelling stations according to the SAE J2601 protocol.

The primary standard consists in a hydrogen tank (type IV) with an inner volume of 104 L which is mounted on a frame. The mass of the tank including

the mass of the frame for mounting the vessel, the piping and gas containing devices (valves, manometer etc.) can be measured before and after the filling process with the installed precision scale (Mettler PKB989-CC150).

This enable the determination of the mass difference and hence the amount of fuel gas. The balance is carried out with explosion protection measures (ATEX zone 2).

For protection against wind forces and the influences connected with them, the primary standard is installed in a vehicle trailer with closable openings inclusive a massive and openable trailer roof. For different steps of operation, the roof and the openings may be used. A pneumatic lifting device serves for applying and removing the load onto the precision scale. This allows installing the balance below the frame with the vessel at the place of use as well as removing the scale for transport.

The Figure 5 presents two pictures of the primary standard developed by Air Liquide (in collaboration with LNE-LADG).



Figure 5: Pictures of the reference measuring system for hydrogen refuelling station

The primary standard measures the mass difference of a vessel before and after the filling by a hydrogen refuelling station. At the beginning of the measurements, this means before the first filling, the precision balance may be tarred. Else the mass of the empty tank including frame may be addressed before the measurements. The results are given in kg. The resolution of the display is 0,2 g.

The standard allows to use either nitrogen or hydrogen from 20 to 875 bar. The gas temperature range should be maintained between -40 and 40°C.

3.3 Uncertainty budget assessment of the primary gravimetric standard

In the OIML R139, there is two class of maximum permissible error defined, class 2 and class 4. The MPE for the measuring system are 2 and 4% respectively. The MPE are doubled at the MMQ.

An uncertainty budget assessment of the primary standard has been carried out by LNE-LADG, PTB and NMi certin for different mass of hydrogen (from 1kg to 4 kg). The main uncertainty sources have been identified as the following:

- Buoyancy (stability of air density at the beginning of the fuelling, vessel expansion)
- Short time drift of the scale (temperature effect, wind)
- Water condensation
- Repeatability of measurements
- Connection / disconnection influence
- Non-linearity of the scale
- Zero stability after depressurization



The primary standard is under the requirements (1/5 of MPE) for all the range of hydrogen mass for a class 1.5.

4. Results from on-site measurements with the primary traceable gravimetric standards.

In this chapter, the description of the experiments in several hydrogen refuelling stations will be detailed.

4.1 Selection of HRS

The purpose was to involve a statistically significant sample of HRS in Europe, representing a minimum of 3 members States. This has been transferred to 3 main requirements for the selection.

1. All technologies and / or specificities should be tested
2. HRS from different manufacturers in Europe
3. HRS in operation in minimum three different countries of the EU.

Based on these criteria, the following HRS were selected (see Table 2 below).

Table 2: List of HRS tested in the protocol and main characteristics

LOCATION		CHARACTERISTICS
Country	City	
Germany	HRS1	Short distance between CFM (in the station) and the dispenser
	HRS2	long distance between CFM (in the station) and the dispenser
	HRS3	Compressed gas
	HRS4	Cryo pump (cold area)
	HRS5	Compressed gas (CFM in dispenser)
France	HRS6	--
Netherlands	HRS7	--

The Figure 6 presents the different hydrogen station environment.



Figure 6: Pictures of HRS tested in the program

4.2 Description of testing protocol for each HRS

The time needed to perform the protocol is approximatively 4 days. The first day, 2 or 3 hours are needed to the installation of the primary standard and the hydrogen venting system. The trailer must not move for the whole test campaign to avoid any levelling adjustment. The Hydrogen Refuelling Station must be accessible for car filings. The scale must be powered up for 1h30 before starting any measurements.

The calibration of the scale is done each day with reference weight (30 minutes) by following the procedure detailed below (see Figure 7).

- Check zero-point stability during 5 min
- Put the balance below the frame (and fix it)
- 1/ Check the resolution with the 20g weight: it must be exactly the value (a deviation of +/- 0,2g is accepted)

2/ Check the sensitivity with reference weight: 0,5Kg or 1Kg (depending on the MMQ value, 2Kg / 4Kg. At least two times for each weight. Compare the results with the mass. Maximum deviation shall be inside 1/5 of the uncertainty budget (in grams). Check hysteresis:

- ◆ Put 0,5Kg (or 1Kg), then remove
- ◆ Put 2Kg, then remove
- ◆ Put 4Kg, then remove
- ◆ Put 4Kg again, then remove
- ◆ Put 2 Kg, then remove
- ◆ Put 0,5Kg (or 1Kg), then remove
- ◆ Put 0,5Kg (or 1Kg) again, then remove



Figure 7: Calibrated weights handled cautiously with gloves

This verification was done at the full range of the scale, i.e. when the empty cylinder was already in place onto the scale. Scale deviation was recorded and removed to the mass measurement for each day. The linear regression calculated (see Figure 8) is subtracted to each mass measured the same day of the scale verification.

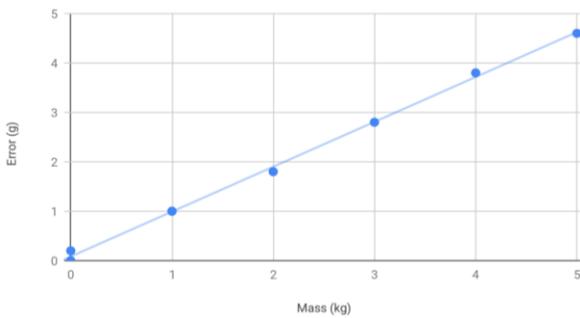


Figure 8: Example of scale deviation

4.3 Description of HRS configuration

Over the 7 HRS tested, it came out that HRS measuring systems can be divided into two main configurations:

- Configuration 1: where the CFM is installed in the container, and not in the dispenser (see Figure 9).

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 generates some errors.

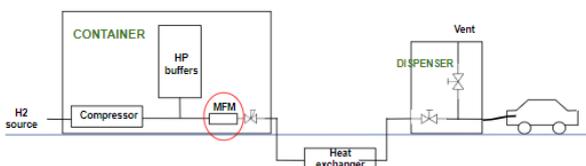


Figure 9: Illustration of configuration 1, where the CFM is located in the main container

- Configuration 2: where the CFM is installed in the dispenser, close to the break-away device (see Figure 10).

Advantages: The error is minimized due to the short distance between the CFM and the transfer point.

Disadvantages: the flowmeter is subjected to big variation of pressure (from 0 to 875 bar) and temperature (from ambient to -40°C in less than 30 seconds) → *more severe operating conditions.*

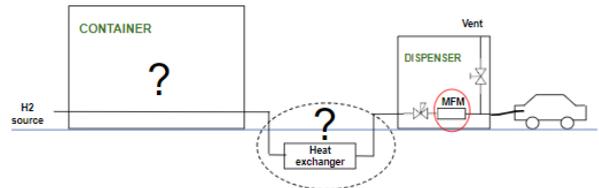


Figure 10: illustration of configuration 2, where the CFM is located in the dispenser

4.4 Results for accuracy tests – configuration 1 (HRS 1 to 5)

The Figure 11 to Figure 15 present the summary of all the tests realized in the week (see Figure 4 for reminder).

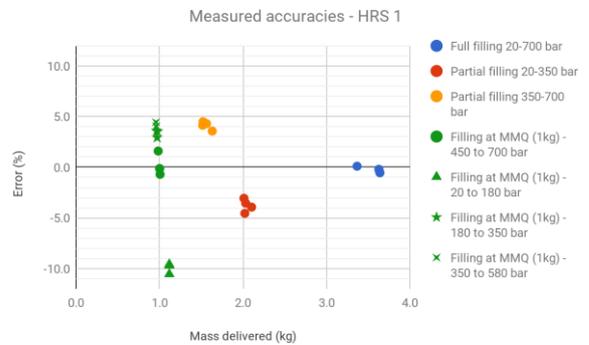


Figure 11: Results of accuracy tests in HR1.

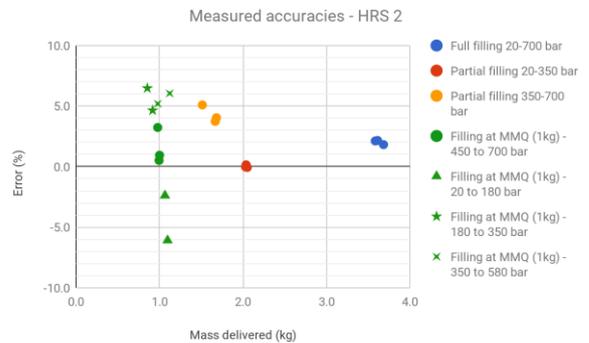


Figure 12: Results of accuracy tests in HR2.

These results show a positive shift of test results. According to OIML R139, an adjustment is authorized on the meter to center results around 0. This adjustment could be done with the transmitter of the flowmeter but has not been implemented yet on site. A manual correction was brought to the test results afterwards, by subtracting the mean error value of full fillings tests to all results.

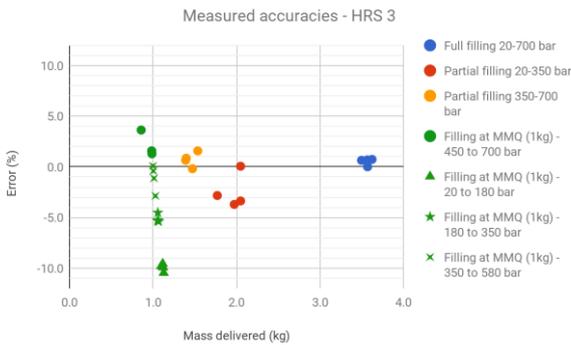


Figure 13: Results of accuracy tests in HR3.

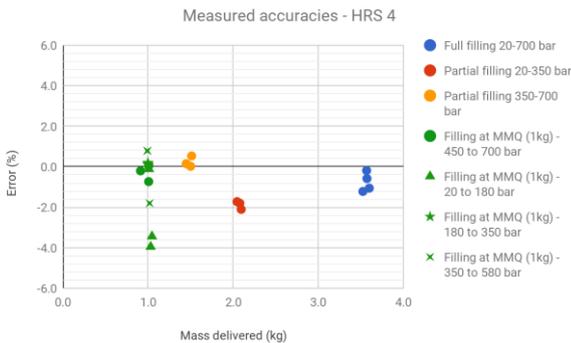


Figure 14: Results of accuracy tests in HR4.

Here again, a negative shift of 1% is observed. A manual correction was brought to the test results afterwards, by subtracting the mean error value of Full fillings tests to all results.

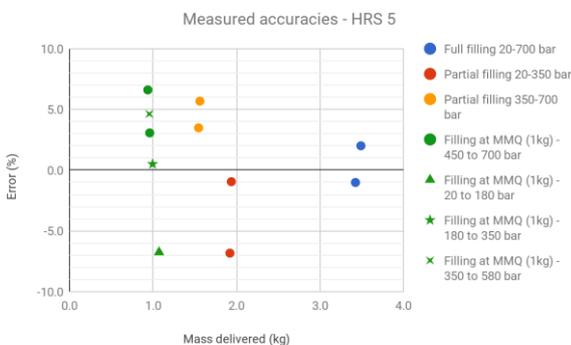


Figure 15: Results of accuracy tests in HR5.

A non-negligible scatter has been observed on this station. But the tendency of tests results looks similar to previous HRS.

4.5 Results for accuracy tests – configuration 2 (HRS 6 to 7)

The to present the summary of all the tests realized in the week (see Figure 4 for reminder).

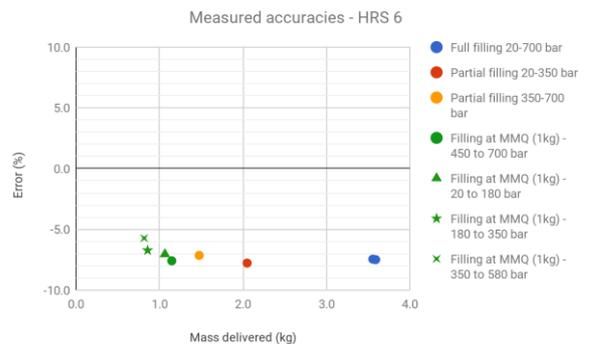


Figure 16: Results of accuracy tests in HR6.

In this case, a significant negative deviation was observed (around -7,5%). This error is too significant to be attributed to a simple adjustment of the CFM. It has been explained afterwards by the HRS manufacturer, but no more information was given. Therefore, it has been manually corrected afterwards, to give the following results

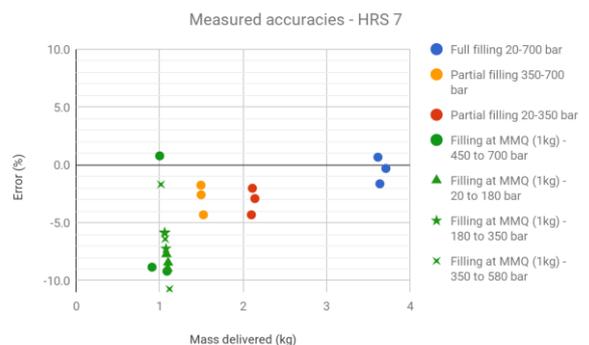


Figure 17: Results of accuracy tests in HR7.

Pretty large repeatability errors have been observed in that case (more dispersion). A constant negative deviation is noticed. Information was given by the HRS operator that a correction is done for the vented H2 quantity, but with no more details.

4.6 Analysis of the accuracy tests

From all the figures presented in the section 4.5, the mean value has been calculated for each station and for each type of tests (see below).

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

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

Tests results can be summarized as follow:

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 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.

Reminder:

With the new version of OIML R139:2018 for HRS besides 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 existing HRS (in service inspection), the MPE are respectively 3 and 5 %. For fillings at MMQ (1 kg), the MPE is twice the mentioned MPE. 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.

4.7 Explanation of the accuracy tests results: influence of distance between CFM and dispenser

Configuration 1:

For HRS of Configuration 1, a systematic deviation (either positive or negative) was observed for partial fillings:

Partial filling - from 20 to 350 bar:

Negative deviation means that the quantity of hydrogen delivered to the customer is higher than the quantity invoiced (i.e. counted): **$m_{delivered} > m_{invoiced}$**

Partial filling - from 350 to 700 bar:

Positive deviation means that the quantity of hydrogen invoiced to the customer (i.e. counted) is higher than the quantity really delivered: **$m_{delivered} < m_{invoiced}$**

In analyzing in more details, the test results, it comes out that errors observed for HRS (**Configuration 1**) can be explained by the distance between the CFM and the dispenser: the longer the distance (i.e. bigger the volume), the bigger the errors.

Indeed, at beginning of the test, the line between the CFM and the dispenser is full of hydrogen at a certain pressure, called **P1** (see Figure 18).

- This pressure depends on the end pressure of the previous filling (independent of the customer).
- This quantity is not counted by the CFM (because already in the pipe at beginning of the transaction) and given to the customer.

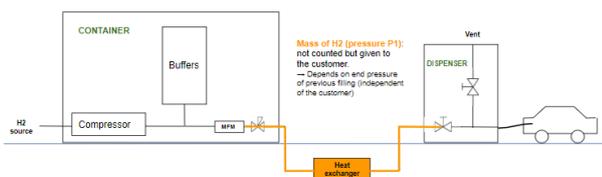


Figure 18: Schematic diagram of a HRS – situation before fuelling

At end of the test, this same line is full of hydrogen at a certain pressure, called **P2** (see Figure 19).

- This pressure depends on the end pressure of the ongoing filling (during transaction): end pressure is given by the filling protocol (and depends on filling conditions - AUTOMATIC stop). But the customer can at any time stop the filling by himself (STOP button).
- This quantity is counted by the CFM but not transferred into the customer vehicle.

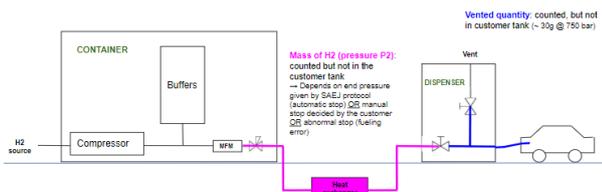


Figure 19: Schematic diagram of a HRS – situation at the end of fuelling

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) → **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) → **Positive deviation**.

Application to the tests performed:

Full fillings (from 20 to 700 bar):

- These tests were performed right after the previous filling which ended at 700 bar. So, pressure in the line between CFM and dispenser is around 700 bar (**P1**)
- End pressure was around 700 bar. So, pressure in the line between CFM and dispenser is around 700 bar (**P2**)
- So **P1 ~ P2**. That is why the found error is **close to zero**.

Partial filling (from 20 to 350 bar):

- These tests were performed right after the previous filling which ended at 700 bar. So, pressure in the line between CFM and dispenser is around 700 bar (**P1**)
- End pressure was around 350 bar. So, pressure in the line between CFM and dispenser is around 350 bar (**P2**)
- So **P1 > P2**. That is why the found error is **negative**.

Partial filling (from 350 to 700 bar):

- These tests were performed right after the previous filling which ended at 350 bar. So, pressure in the line between CFM and dispenser is around 350 bar (**P1**)

- End pressure was around 700 bar. So, pressure in the line between CFM and dispenser is around 700 bar (P2)
- So $P1 < P2$. That is why the found error is **positive**.

Filling of 1 kg (MMQ) (from 450 to 700 bar):

- These tests were performed right after the previous filling which ended at 700 bar. So, pressure in the line between CFM and dispenser is around 700 bar (P1)
- End pressure was around 700 bar. So, pressure in the line between CFM and dispenser is around 700 bar (P2)
- So $P1 \sim P2$. That is why the found error **close to zero**.

Filling of 1 kg (MMQ) (from 20 to 180 bar):

- These tests were performed right after the previous filling which ended at 700 bar. So, pressure in the line between CFM and dispenser is around 700 bar (P1)
- End pressure was around 180 bar. So, pressure in the line between CFM and dispenser is around 180 bar (P2)
- So $P1 > P2$. That is why the found error is **negative**.

Note: deviations are much important for 1 kg fillings, as the reference mass is small.

Filling of 1 kg (MMQ) (from 180 to 350 bar):

- These tests were performed right after the previous filling which ended at 180 bar. So, pressure in the line between CFM and dispenser is around 180 bar (P1)
- End pressure was around 350 bar. So, pressure in the line between CFM and dispenser is around 350 bar (P2)
- So $P1 < P2$. That is why the found error is **negative**.

Filling of 1 kg (MMQ) (from 350 to 580 bar):

- These tests were performed right after the previous filling which ended at 350 bar. So, pressure in the line between CFM and dispenser is around 350 bar (P1)
- End pressure was around 580 bar. So, pressure in the line between CFM and dispenser is around 580 bar (P2)

- So $P1 < P2$. That is why the found error is **negative**.

By consequent, it appears that **the longer the distance (i.e. the bigger the volume), the bigger the errors**. Knowing precisely the pressure and the volume of the pipe between the CFM and the nozzle, it must be possible to correct the systematic error due to HRS configuration.

Configuration 2:

In case of **Configuration 2** (when the CFM is located in the dispenser), the distance between the CFM and the nozzle is very small (almost negligible): the CFM counts exactly the quantity delivered to the vehicle (no “buffer volume” as in Configuration 1), except the vented quantity which must be subtracted.

That is why errors were very good on HRS 6 (after adjustment), and close to zero whatever the type of test.



7. Conclusion

Test results are presented in this report. For Configuration 1, it showed mainly:

- A very good accuracy for Full filling tests (from 20 to 700 bar): Error close to zero, and very repeatable
- A negative deviation for Partial filling tests (from 20 bar to 350 bar): around -2 to -4%
- A positive deviation for Partial filling tests (from 350 bar to 700 bar): around +2 to 4%
- A variable deviation for 1 kg fillings (MMQ) depending on the initial pressure in the tank: Error close to zero from some of them, and error up to -10% in specific test conditions.

For Configuration 2, accuracy looked much better, especially for one HRS which showed found errors close to zero, whatever the type of test performs.

Based on these results, the following conclusions can be drawn:

- A good repeatability was observed for all tests. This demonstrates that the testing equipment works well in real conditions.
- Errors observed for the stations of Configuration 1 can be explained by the difference of pressure, at beginning and end of the fueling, in the piping between the CFM and the dispenser: the longer the distance, the bigger the errors. For Configuration 2, as this distance is very short, the error is negligible.

8. Acknowledgement

“The information and views set out in this report are those of the author(s) and do not necessarily reflect the official opinion of the FCH 2 JU. The FCH 2 JU does not guarantee the accuracy of the data included in this study. Neither the FCH 2 JU nor any person acting on the FCH 2 JU’s behalf may be held responsible for the use which may be made of the information contained therein.”

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