Deliverable D2

Recommendations for verification periods of HRS including guidelines on how to ensure accurate measurements and minimised uncertainty due to HRS design

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Authors: Bernhard Rotter, Alexander Wiener, Rémy Maury, Marc MacDonald, Marc de Huu, Edvardas Venslovas

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Report on Recommendations for verification periods of HRS including guidelines on how to ensure accurate measurements and minimised uncertainty due to HRS design	
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Author(s) **Bernhard Rotter** BEV-PTP **Alexander Wiener** BEV-PTP **Rémy Maury** CESAME **Marc MacDonald** NEL **Marc de Huu** METAS **Edvardas Venslovas** JV	**Pages** 13 pages

Summary

This report was written as part of activity 1.5.3 from the EMPIR Metrology for Hydrogen Vehicles 2 (MetroHyVe2) project. The three-year European project commenced on 1st August 2020 and focused on providing solutions to four measurement challenges faced by the hydrogen industry (flow metering, quality assurance, quality control, sampling and fuel cell stack testing). For more details about this project please visit https://www.sintef.no/projectweb/metrohyve-2/.

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Contents

1 Introduction

Commercial hydrogen refuelling stations (HRS) are still a rather new phenomenon. In Europe there are only a few hundred hydrogen stations while the total number of petrol stations is around 100'000. Hence the metrological and technical experience with HRS is still rather limited. In the following report we try to bring some light into the question of verification period and present guidelines on how to ensure accurate measurements and minimise uncertainty due to HRS design – taking from international examples, the situation in different European countries as well as technical and metrological data from MetroHyVe 2 as well as other projects.

2 OIML R139

Currently there is one regulation by the International Organization of Legal Metrology (OIML) which is applicable to HRS. OIML R 139 [1] is an international recommendation on "Compressed gaseous fuel measuring systems for vehicles" and originates back to 2007 when its main focus was on the application of compressed natural gas (CNG). In the first revision in 2014 hydrogen applications were first mentioned (part 2 section 6.1.3) but no adaptions for hydrogen were made.

> "Note: Specifications for hydrogen applications may be significantly different from those for CNG." [2]

HRS were at that time still more in the stage of research and there were no testing facilities available in Europe for certifying flow meters to OIML R139. As the number of commercial used hydrogen refuelling increased (Germany, France) the need for a revision came up. In the meantime, sales of H_2 were tolerated by the authorities [3].

A second revision was done in 2018. This OIML R139-2018 revision (which is the latest revision) brought the following changes for hydrogen:

- two new accuracy classes 2 and 4: Class 4 may be used for older types but class 2 should be used as the preferred one for new HRS
- MPE (Maximum Permissible Error): 2% for class 2, 4% for class 4, MPE is twice at MMQ
- MMQ is 1 kg for hydrogen (independent of the delivered quantity)
- No need for Durability tests if the meter is a Coriolis meter

For detailed explanation of MPE see section 2.1.1 and 2.1.2 in Deliverable D1 of MetroHyVe 2. In the following we will describe test procedures for type evaluation as well as initial and subsequent verifications and what is the current recommendation on verification periods.

2.1 Test procedures

OIML R139 describes the testing procedures in part 2 of the document. It deals with tests for type evaluation, initial and subsequent verifications. As most HRS designs have no sequential control over banks the most useful tests are presented in table 6 and 7 in part 2. In these tables an initial pressure in the test receiver is denoted. The end pressure of all the tests shall be P_v (the maximum allowed fill pressure) as this is the typical way of refuelling hydrogen. These tests can be referred to as full fills (Test 4), half fills (Test 5) and MMQ fills (Test 7). The formulation of the tests and the required accuracy of the test equipment imply that a gravimetric primary standard has to be used.

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 1: Initial settings for tests on systems without sequential control (see OIML R139-2 table 6)

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.

Table 2: Initial settings for tests on systems with and without sequential control (see OIML R139-2 table 7)

2.1.1 Test for type evaluation

Tests for type evaluation are listed in table 3. From all the tests, only a few are achievable with HRS. That especially is the case for tests applicable to meters as they usually cannot be taken out of a station.

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

Not achievable with H2

Note 1: Provided that the sequence of testing is clearly recorded, tests may be performed in a random order so as to minimize the total testing time and, for example, to allow for a full defueling overnight.
Note 2: Tests are mandatory unless otherwise specified (in the applicable subclause).

Footnotes:
1) Test at extreme (pressure) adjustment limits.
2) Test is not applicable for hydrogen CGF measurement systems.
3) For hydrogen CGF measurement systems the individual quantity values measured shall preferably be more than 1 kg. If this appears not feasible the test shall be executed applying 2 instead of 3 filling phases.
4) This test is mandatory, when not yet covered by the test(s) at variable flow rate (Test # 0).

Table 3: Test program (see OIML R139-2 table 9). Blue highlighted tests are usually not achievable with HRS, red boxes mark the important tests.

About the number and order of these tests needed for type evaluation it is stated:

3.5.3 Measuring systems specific for hydrogen fuel

3.5.3.1 Tests 4 and 5 shall be performed at least three times on the complete system and test 7 shall be performed at least twice. Each individual error shall not exceed the MPEs specified in R 139-1, 5.2 for the measuring system.

3.5.3.2 Preferably each test is performed consecutively under the same condition or all of the tests are performed in a cyclic consecutive order (e.g. in the sequence # 4, # 5, # 7, # 4, # 5, # 7, # 4, # 5). For Test 4 and Test 5, the requirement on repeatability specified in R 139-1, 5.4 shall be fulfilled.

5.4 Repeatability
For any quantity of the measurand equal to or greater than 1000 scale intervals of the meter, the repeatability error of the meter and of the measuring system shall not exceed two thirds (2/3) of the applicable MPE.

2.1.2 Tests for verifications

For verifications (initial as well as subsequent) three different methods are mentioned, albeit for hydrogen "4.6.7 Alternative procedure for hydrogen CGF measuring systems" is the most useful. A cyclical test of three full fills, three half fills and two MMQ is to be performed.

4.6.7 Alternative procedure for hydrogen CGF measuring systems

4.6.7.1 For hydrogen CGF measuring systems the tests can be performed on-site. Either a gravimetric method or master meter method should be used. The tests can be performed at ambient temperature.

4.6.7.2 Tests 4 and 5 shall be performed at least three times on the complete system and test 7 shall be performed at least twice. Each individual error shall not exceed the MPEs specified in R 139-1, 5.2 for the measuring system.

4.6.7.3 Preferably each test is performed consecutively under the same condition or all of the tests are performed in a cyclic consecutive order (e.g. in the sequence # 4, # 5, # 7, # 4, # 5, # 7, # 4, # 5). For Test 4 and Test 5, the requirement on repeatability specified in R 139-1, 5.4 shall be fulfilled.

For CNG the preferred procedure is described in 4.6.5. It is mentioned, that alternatively, the more practical procedure specified in 4.6.6 may be applied (for CNG as well as H_2):

4.6.6 Alternative procedure

- The tests are performed in conditions available in the refueling station, provided that, if applicable, the bank pressures shall be such that refueling into the specified test cylinders will cause the activation of all stages of the operation of the sequential control device.
- Tests sufficiently representing the real conditions of use are performed. In general, this condition is fulfilled when following the sequence:
    - o filling the test receiver from empty to P_v;
    - o venting the test receiver to a pressure of 0.5 P_v ;
    - o re-filling the test receiver from 0.5 P_v to P_v .
- This sequence provides two metrological results to be compared with the MPEs. Each applicable test is performed at least twice and as far as necessary to fulfill the requirement in the first paragraph of this sub clause.

- Each individual error shall fulfill the requirement on MPEs specified in R 139-1, 5.2.3.

2.1.3 Verification Period

With regard to verification periods, it states (part 2 chapter 5) that

"For countries having a system of mandatory subsequent verification, an interval between verifications not exceeding 5 years is suggested. If during type evaluation the meter has not been subjected to the

> durability test as specified in 2.2.7.6, it is suggested to set the interval between the initial verification and the first subsequent verification not to exceed a 2 years' time period."

The durability test is only necessary for meters with internal moving parts and not for others like the most commonly used type of mass flow meters – Coriolis meter. But then documented information showing the fulfilment of the durability performance criterion is needed (part 1 section 5.8.2). So, from the standpoint of the OIML Recommendation a verification interval of less than 2 years is advised.

3 Current situation

Currently most countries have no legal requirements for testing HRS. When they perform field-testing, most stick to the OIML R139 with its various methods. OIML R139 would also be the starting point for setting up of national regulations for HRS. European countries however put little effort in developing national regulations since it is expected or hoped that HRS will be part of an updated Measurement Instrument Directive.

3.1 Europe

3.1.1 Austria

At the moment there are no hydrogen specific regulations for legal metrology. Hydrogen refuelling stations are only covered by the "Maß- und Eichgesetz" (Metrology Act), but there is currently no "Eichvorschrift" (regulation governing specific measurement devices) for hydrogen refuelling stations. The currently existing HRS in Austria have a two-year verification period which was determined in their type approval certificate. The testing procedure used for type verification as well as initial verification is 3 full fills, 3 half fills and 2 MMQ fills. For subsequent verifications the number can be reduced to 2 full fills, 2 half fills and 2 MMQ fills.

3.1.2 France

The French government represented by "La DM" ("Division de la Métrologie") has regulated that all verifications have to be carried out with three full fills, three half fills and three MMQ fills. The verification period is one year.

3.1.3 Norway

In Norway, there are no regulations for legal metrology that covers on shore measurement activity of hydrogen in gaseous state. Any regulation related to metrology for "on shore" will be the responsibility of Justervesenet as the national regulator for metrology, the notified body according to MID and NAWI, and responsible for any in-field verification of meters under legal control.

In general, there are no established requirements at this time for the sale or custody transfer for flow meters that measure gas in gaseous state. Therefore, there are no requirements for the subsequent verification interval. Justervesenet is planning to send a proposal for a regulation that will cover some points about measurement of gas in gaseous state in 2023.

The Norwegian regulations for flow measurement of liquids and for weights comes from European harmonized directives. Any potentially new regulations for flow measurement of gas in gaseous state, applying to compressed gas for vehicles, will be based on international normative documents, for instance OIML. It is unlikely that any proposed regulation will have stricter requirements than what the normative documents suggest, due to the estimated low technological readiness level.

The most likely method of legal inspection of HRS will be inspection of the internal quality system. Justervesenet might, for instance, inspect that the internal quality system is appropriately handled and complied with.

3.1.4 Switzerland

Hydrogen refuelling stations are currently not regulated from a metrological point of view in Switzerland. It would be the responsibility of METAS to write the ordinance that would regulate HRS metrologically. A new regulation would most certainly rely heavily on requirements for OIML R139:2018. Initial verification and subsequent verification would be performed using field-testing.

3.1.5 UK

No UK regulations are currently in place for H_2.

3.2 Americas

3.2.1 USA

After Japan, South Korea, China and Germany, the United States are the biggest provider of HRSs. Currently almost all the Hydrogen refuelling stations in the United States are located in California. The verification period is determined by the California Code of Regulations. According to Title 4, Division 9, Chapter 3, Article 1 Inspection Frequencies Hydrogen Gas-Measuring Device are to be inspected (which includes the testing of the device) every year.

3.3 Asia

3.3.1 Japan

Japan has gained a lot of experience in field-testing. The used methods are based on the guideline G0002 "Operating guideline for Hydrogen metering control" developed by "The Association of Hydrogen Supply and Utilization Technology" HySUT in 2018 as well as the Japanese Industry Standard JIS B8576 (2016). They both had a key influence for the revision of OIML R139 in 2018. The method described allows a maximum permissible error of 10 % and uses a verification procedure consisting of one full fill and at least one but usually three MMQ fills (1 kg). A verification period of two years is in use, however if two consecutive verification results are within 5 % the period can be extended to three years. [4]

3.3.2 South Korea

South Korea has just started with field-testing. A procedure consisting of 3 full fills, 3 half fills and 3 MMQ fills is currently used for initial verifications. As this is more in research status, they have not decided yet on how to perform subsequent verifications or what interval to use.

4 Challenges in field-testing and Guidelines

4.1 Different HRS designs

In Europe there are a number of different Hydrogen refuelling station operators as well as manufacturers. In general, the current industry standard for hydrogen refuelling is SAE J2601 [5]. It covers different refuelling options for light duty gaseous hydrogen surface vehicles. On one hand there are different pressure options. The industry standards at the moment are 350 bar and 700 bar. Currently the most common design in Europe is the 700 bar dispenser for light duty vehicles. 350 bar is more common for heavy-duty vehicles. For the 700 bar dispenser, hydrogen is usually pre-cooled (down to -40 °C in the climate region of central Europe). This is done in order to avoid overheating the tanks due to the heat of the compression of hydrogen.

Individual dispensers don't only vary by pressure, but also by flow range. There are at the moment two versions of 350 bar dispensers. On one hand there are the 350 bar dispensers for light-duty vehicles (mainly passenger cars) on the other hand there are 350 bar dispensers for heavy duty-vehicles. Light-duty, low-flow dispensers are limited according SAE J 2601/1 to 60 g/s. Heavy-duty, high-flow dispenser are limited to 120 g/s.

The most important difference in design (at least from a metrological point of view) of hydrogen refuelling stations is in the varying position of the mass flow meter. In older HRS the mass flow meters are often located closer to the storage tanks, thus far away from the dispensing point, while in the newer HRS the mass flow meters are typically located directly in the dispenser, before or after the heat exchanger.

4.2 Difficulties

Considering a typical HRS, the main sources of measurement errors are:

1. Accuracy of the flow meter
2. Gas vented at the end of a refuelling
3. Density changes in dead volume

Available (Coriolis) flow meters are capable of meeting the accuracy requirements [6]. However, during field-testing, large errors could be observed that could be related to the HRS design when corrections are not applied [7]. These errors can be explained by the location of the meter.

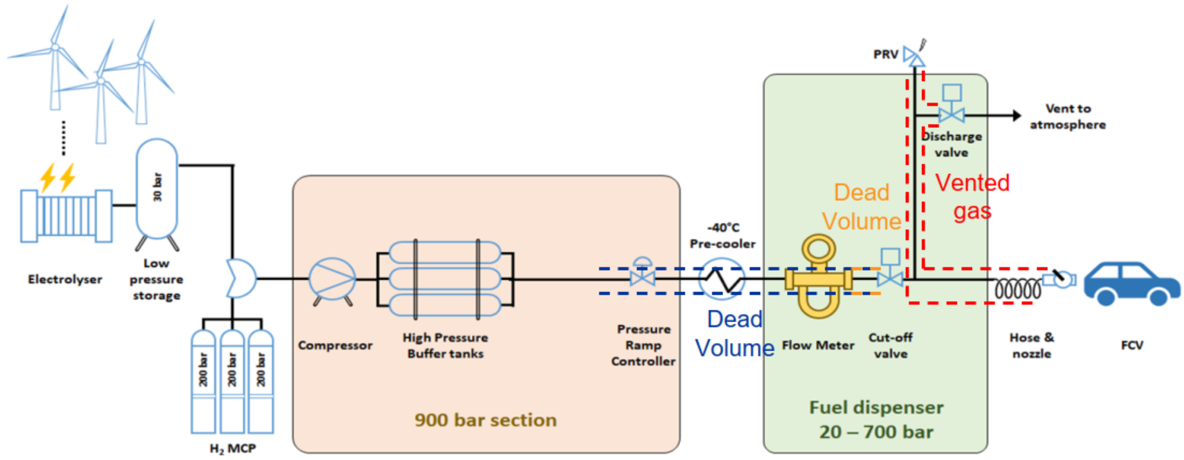

Figure 1 shows the layout of a typical hydrogen refuelling station. The process meter of the HRS can be located either in the dispenser, where it is then very close to the delivery point, or in the container containing the high-pressure buffer tanks. For the former location, the meter can be mounted either before or after the heat exchanger when pre-cooling of the hydrogen is required. When in the container, the process meter is then far away from the delivery point (up to 50 m) and so called 'dead volume' effects play an important role and can lead to a misunderstanding of the process meter's readings.

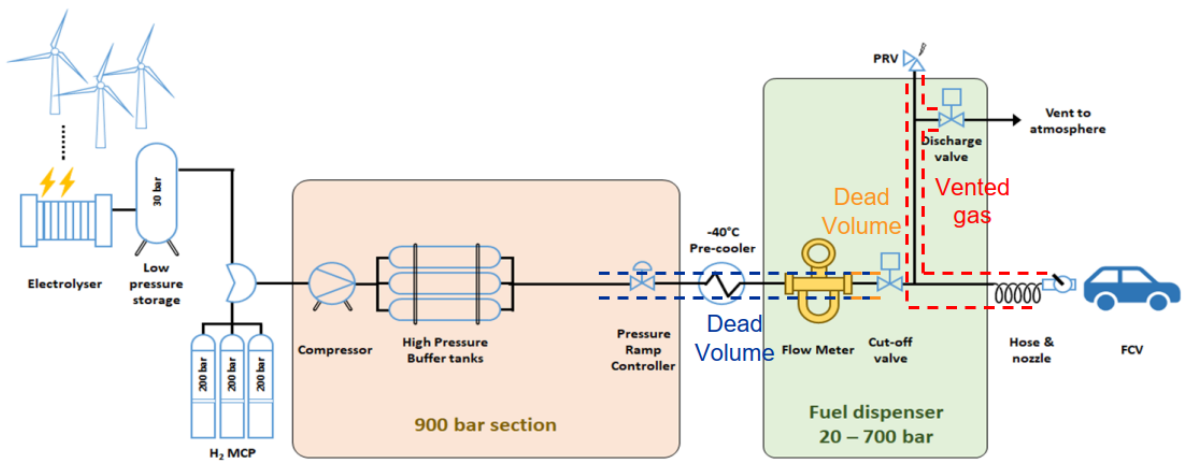

Figure 1: Typical scheme of a modern HRS [8]

Indeed, as shown in Figure 2, the piping of the HRS can de divided into several sections.

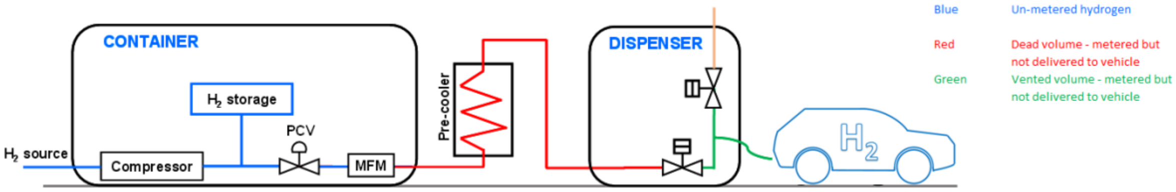

Figure 2: Piping sections with un-metered and metered hydrogen.

It is assumed that the meter is located in the container. The blue part is un-metered hydrogen, which is obviously not delivered; the red part contains hydrogen that was metered but not delivered, the green part is the venting quantity that was metered but not delivered. This last quantity is never delivered to the vehicle. The hydrogen in the red section of piping can vary depending on the final pressure of the last refuelling. It can happen that not the same amount of hydrogen is replaced and this leads to an error that is not caused by the meter but by the design of the HRS. This dead-volume effect is very small if the process meter in located directly in the dispenser, before or after the heat exchanger.

This dead-volume effect was clearly demonstrated from field-studies carried out within the frame of an FCH-JU project [7] which showed that when dead-volume effects are not taken into account this can lead to an error in the magnitude well over MPE. Figure 3 (left) shows a real measurement of a HRS with the flow meter located before the pressure ramp controller. Full fills show almost no error but partial fillings have significant errors. Such behaviour is typical if the dead volume is large and no corrections are applied. During MetroHyVe 2 an Uncertainty Model was developed [9] helping HRS manufacturers and notified bodies to understand uncertainty contributions from different HRS designs and the required corrections as well as uncertainty estimates. Figure 3 (right) shows a simulation of the real situation. The good match confirms the validity of the model and the necessity for corrections of dead-volume effects. Newer stations tend to have a design with the meter mounted in the dispenser. Hence the influence of dead volume is minimised.

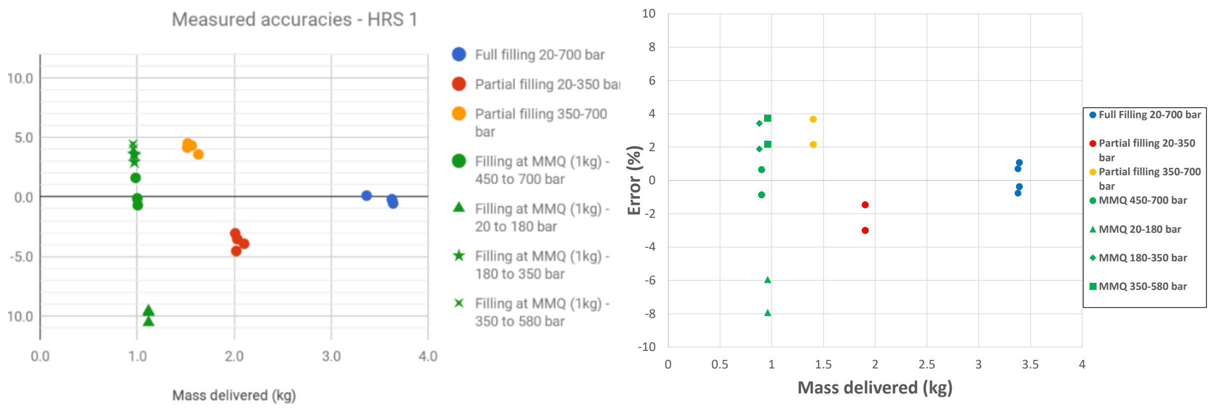

Figure 3: Left) Real measurement [7]. Right) Simulation result using the uncertainty model [9]

OIML R139 suggests that as part of the type approval tests, the meter should be tested alone. This however cannot be done as the meter cannot be removed from the station and sent to a lab as there is no lab which can calibrate an 875 bar hydrogen flow. Moreover, such an approach would neither account for transient temperature effects on the meter (if it is located downstream of the heat exchanger), nor for volume effects like vented quantities and dead volumes, or check if the meter is zeroed correctly. This means that measuring the meter alone is not sufficient for verifying a HRS. Therefore, field-testing of HRS is a necessity.

4.3 Guidelines for field-testing of Hydrogen Refuelling stations

There are two options available for field-testing depending on the required accuracy. Type approval requires the use of gravimetric primary standards. Periodic verification could use either primary standards or secondary standards as the accuracy requirements are more accommodating. Gravimetric primary standards are the most basic measuring devices as they directly compare a refuelled amount of hydrogen to calibrated mass weights. In 2020 only a few of such systems, which could be used for light duty vehicles, were available in Europe, some of which are described in literature [3], [10]. In the meantime (2023) several primary standards were developed by several NMIs. They tend to have larger storage capacities (around 6 kg) to also match the typical tank sizes of newer hydrogen cars. In general, they consist of hydrogen tanks that are weighted before and after a fill on a precise weighing scale. There are several operational challenges to achieving the requirement measurement accuracy

A graphical representation of typical challenges is given in Figure 4. The impact of wind can be minimised up to a certain level using an external shell to protect the weighing system.

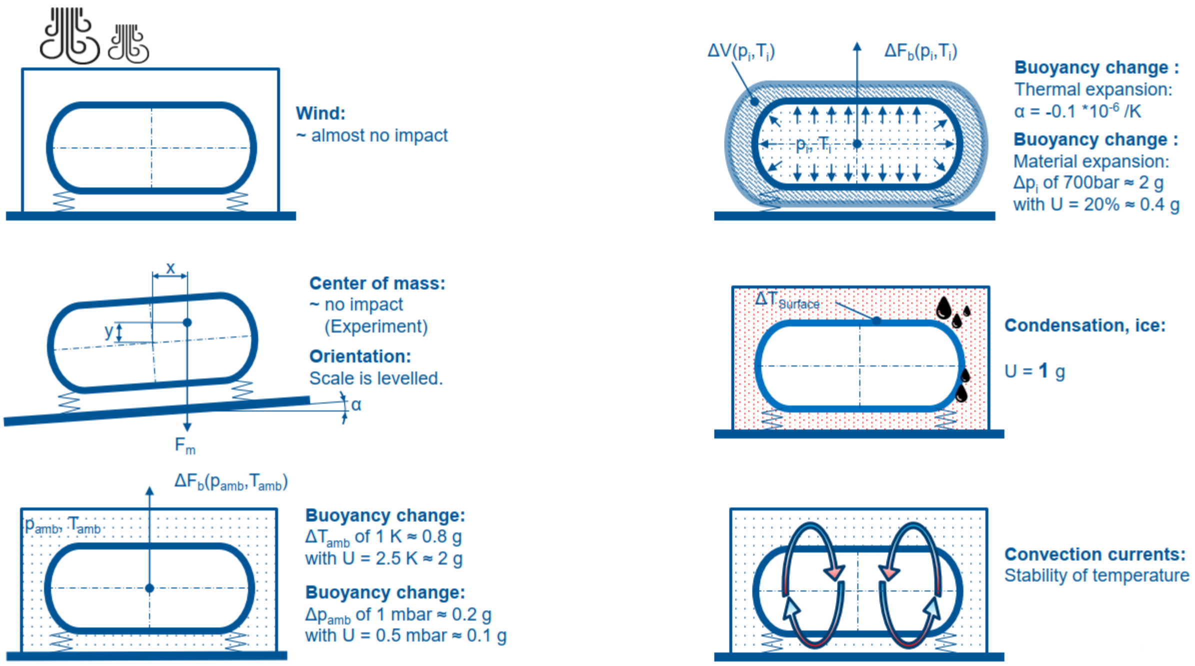

Figure 4: Graphical illustration of typical challenges in field-testing with mobile primary standards

A complete model equation including buoyancy corrections can look like [10]:

$$m_{H_2} = (W_2 - W_1).\left(1 - \frac{\rho_a}{\rho_N}\right) + V_0[\rho_{air2}(1 + \lambda\Delta P_2) - \rho_{air1}(1 + \lambda\Delta P_1)] + V_{frame}.(\rho_{air2} - \rho_{air1})$$

Where:

W_1, W_2: initial and final mass readings from the balance

The factor $\left(1 - \frac{\rho_a}{\rho_N}\right)$ turns apparent mass into true mass, ρ_a = 1,2 kg/m^3 and ρ_N = 8000 kg/m^3

ρ_{air1}, ρ_{air2}: air density calculations based on environmental sensor readings

λ: pressure coefficient for the tank

P_1, P_2: tank initial and final pressures

V_0 : volume of the external tank(s) volume(s) at zero internal pressure

V_{frame}: volume of HFTS frame, instrumentation, tubing and fittings

Condensation or icing on the piping of the primary standard when using pre-cooled hydrogen can lead to measurement errors. The same applies to venting the tanks after a refuelling, if the venting rate is too high, then condensation or icing can form on the tanks.

Moreover, the system has to be shielded from ambient influences like wind (movement) and sun (temperature). This is why it is useful to place the system within a closed trailer and if possible, even a temperature control system should be considered as it will help a lot stabilising convection currents within the system. Of course, the system has to be levelled to reduce errors due to centre of mass.

In addition, the system must fulfil safety requirement (national regulations for explosion safety and pressure equipment). For venting the hydrogen, a safe location near the dispenser has to be found.

Although primary standards measure more accurately with a lower uncertainty, they also have their limitations. The biggest issue is that measurements with these devices are very time consuming. This is because the venting of the filled tanks has to be done very careful providing low pressure rates not to damage the type 4 tanks. This can lead to a total time of 1,5 hours for venting, depending on the design of the primary standard. As there is no possibility to refill the hydrogen to the station this is also a big waste not only in terms of money but also in terms of energy demand needed for production of the hydrogen.

Existing primary standards have similar hydrogen capacities as light-duty vehicles (cars), approximately 4 to 6 kg of hydrogen at 700 bar. When refilled at a HRS, filling times and mass flow rates are the same as for cars. This is not the case for heavy-duty vehicles (trucks). These vehicles store typically more than 30 kg of hydrogen at 350 bar with collection volumes of more than 1000 L. Light-duty primary standards have 100 L to 200 L collection vessels and would therefore sample the process meter at much lower flow rates and would not be a representative test of the station.

In the course of this project, two primary standards for heavy duty were developed and are described in D1 [11].

The most promising solution for field verifications are secondary standards, which have higher uncertainty, but allow much faster verifications. They consist of a calibrated Coriolis flow meter which is put between the dispenser and a vehicle or dummy tanks. Secondary standards are calibrated by primary standards directly at a refuelling station under realistic conditions. One important benefit of using a vehicle is that the infrared communication protocol defined in SAE J2601 [5] would be used by the HRS. Hence the HRS follows the appropriate filling profile which is also applied when refuelling vehicles. Without infrared communication the HRS uses a filling profile with higher safety margins that can lead to a lower maximum fill pressure.

In the course of this project, one secondary standard was built and tested by CESAME [11].

5 Recommendations

5.1 Results of MetroHyVe2

Monitoring of HRS with different designs over a 24-month period was the goal of activity 1.5.1 of this project. Although only two participating institutes, METAS and CESAME, had a functioning primary standard ready 12 month after the beginning of the project little data is available. Two different types of HRS were monitored: a 350 bar (without pre-cooling) dispenser and a 700 bar (with pre-cooling) dispenser. In both stations, the mass flow meters were located in the dispenser but upstream of the heat exchanger. Data from field testing over several months are shown in Figure 5. Each point represents a full fill.

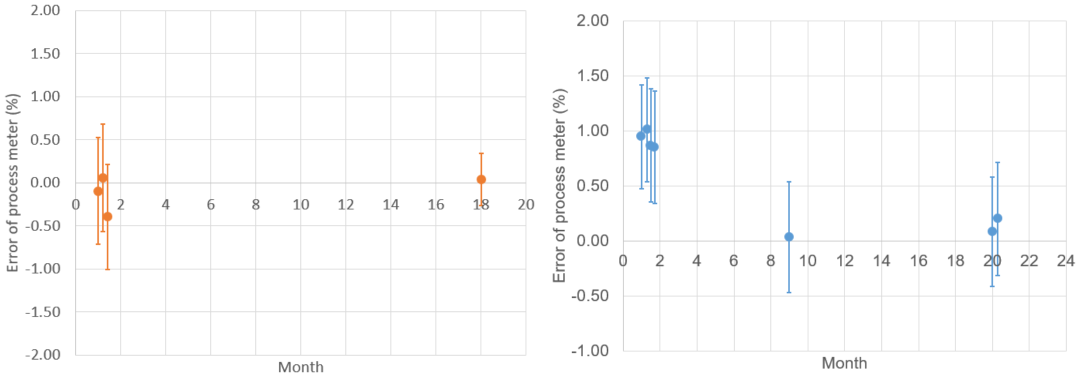

Figure 5: Results from Field-testing of a 350 bar station (left) and a 700 bar station (right)

Results from the 350 bar station show no significant changes within 17 month of observation. All measurements are well within MPE. Results from the 700 bar station are a bit different as they show a slight positive deviation at the beginning which goes to almost zero after 8 month where it settles. It should be mentioned that both stations are not used very frequently. Nevertheless, the deviations are always within MPE.

5.2 Recommendations on verification period

All in all, it is not possible to give a precise recommendation on the verification period due to the scarce data. Combining our obtained data with other results (type approval measurements and initial verifications) we find a verification period of two years still very reasonable. Field data from Japan also point in this direction [4]. This is due to the stable behaviour of Coriolis meters and the improvements in HRS design over time.

5.3 Discussion about verification procedure

Regarding on how to perform the verifications we see different approaches across the world. Some are testing very strict using a full test procedure as described in 4.6.7 of OIML R139-2, others do a reduced set of tests.

One should differentiate between initial verification and subsequent verification. We find the procedure as described in 4.6.7 (3 full fills, 3 half fills and 2 MMQ fills) very reasonable for type evaluation and initial verification. These tests aim at verifying the station's design and correct building. For subsequent verifications we think a more practical approach should be used. That means reducing the total number of tests as data show that repeatability is not the main issue and also tests are very time consuming. One possibility would be using procedure 4.6.6 as the preferred method for subsequent tests and would mean omitting the MMQ test. This might be arguable because it is rare that a consumer will buy such a low amount of hydrogen. On the other hand, MMQ is a rather quick test because of a short venting time. However, another combination like 2 full fills and 2 MMQ might be an option. Moreover, the availability of secondary standards (master meters) will change the testing a lot.

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