FINAL DELIVERABLE

Date: 30/04/2019
Author: C. DEVILLIERS / Air Liquide

D2.2 - Test campaign on existing HRS & Dissemination of results

Abstract:

This document is the final deliverable of Tasks 2 & 3 of the tender N° FCH / OP / CONTRACT 196: “Development of a Metering Protocol for Hydrogen Refueling Stations”.

In Task 2, a test campaign was organized on several HRS in Europe, to apply the testing protocol defined in Task 1. This protocol requires mainly to perform different accuracy tests, in order to determine the error of the complete measuring system (i.e. from the mass flow meter to the nozzle) in real fueling conditions. Seven HRS have been selected to fulfill the requirements specified in the tender.
Tests results obtained are presented in this deliverable, and conclusions are proposed to explain the errors observed.

In the frame of Task 3, results and conclusions have been widely presented to additional Metrology Institutes than those involved in Task 1, in order to get their adhesion on the testing proposed protocol.

All the work performed in Tasks 2 & 3 and associated outcomes / conclusions are reported here.

Résumé:

Ce document est le livrable final des Tâches 2 & 3 de l’étude N° FCH / OP / CONTRACT 196: “Développement d’un protocole de comptage pour les stations de remplissages hydrogène”.

Dans la Tâche 2, une campagne d’essai a été organisée sur plusieurs stations de remplissage hydrogène en Europe, pour appliquer le protocole définit dans la Tâche 1. Ce protocole nécessite de réaliser plusieurs essais d’exactitude, avec pour objectif de déterminer les erreurs de l’ensemble de la chaîne de mesurage (i.e. du débitmètre jusqu’au pistolet) dans des conditions réelles de remplissage. Sept stations ont été sélectionnées pour satisfaire les exigences spécifiées dans l’étude.
Les résultats d’essais obtenus sont présentés dans ce livrable, ainsi que les conclusions permettant d’expliquer les erreurs observées.

Dans le cadre de la Tâche 3, les résultats d’essais et conclusions ont été largement présentés à d’autres instituts de métrologie que ceux impliqués dans la Tâche 1, dans le but d’obtenir leur adhésion au protocole de test proposé.

Tout le travail réalisé dans les Tâches 2 & 3 et les résultats / conclusions de l’étude sont présentées dans ce livrable.

PDF ISBN: 978-92-9246-338-0 doi: 10.2843/21565 EG-01-20-045-EN-N

Table of contents

1 List of abbreviations

Here is a list of the different abbreviations frequently used in this document.

HRS	Hydrogen Refueling Station	**MID**	Measurement Instrument Directive
OIML	"Organisation Internationale de Métrologie Légale" (International organization of Legal metrology)	**WELMEC**	Western European Legal Metrology Cooperation
MPE	Maximal Permissible Error	**MFM**	Mass Flow Meter
MMQ	Minimal Measured Quantity	**EMC**	Electromagnetic compatibility

2 Publishable executive summary

English version:

This deliverable presents the test results obtained in Task 2 of the tender N° FCH / OP / CONTRACT 196: "Development of a Metering Protocol for Hydrogen Refueling Stations". In this Task, several HRS have been selected to implement the testing protocol proposed in Task 1, for the certification of hydrogen measuring systems.

In this report, the results of accuracy tests performed on site are presented for the seven HRS tested. These tests were performed using the reference test bench developed by Air Liquide, and approved by PTB / LNE / NMi Certin according to OIML R139:2014 requirements (uncertainty < 1/5 * MPE = 0,3%). This test campaign was the first opportunity to use the testing equipment on site in real conditions, i.e. submitted to various environmental conditions (hot and cold temperature, moderate wind speed). This test bench showed good performances and a high reliability in the measurements.
Tests were performed under the supervision of third parties to attest the appropriate use of the test bench as described in the approval certificate:

- CESAME Exadebit was present during the whole duration of the test campaign,
- a representative of the National Metrology Institute of the country in which the station is installed, also attended the tests for one or two days.

It came out that accuracy test results depend on the configuration of the measuring system. Two configurations were identified:

- Configuration 1 where the flow meter is located in the compressor container (i.e. far away from the transfer point),
- Configuration 2 where the flow meter is located directly in the dispenser (i.e. close from the transfer point).

<u>Configuration 1</u>:
Results showed a very good accuracy, with deviations of ± 0,5 %, for full fillings (from 20 to 700 bar) on the five HRS tested with Configuration 1. The deviations were much bigger for partial fillings (20-350 bar and 350-700 bar), respectively around -2 to -4% and +2 to +4% more or less. These results are acceptable according to OIML R139:2018 in which higher accuracy classes have been defined for HRS (class 2 and 4 instead of class 1.5) and wider Maximum Permissible Errors (MPE) are allowed for measuring systems already in operation (MPE for in-service inspection). However, even if a class 4 is defined in OIML R139:2018, the accuracy class required for HRS is decided by each national authority: it is not compulsory that a class 4 will be accepted by the national authorities; it might be that a class 2 will be required for existing HRS also.
Then several fillings at Minimum measured Quantity (MMQ =1 kg) have been performed: some of them showed very good accuracy (deviation close to 0%), whereas some other deviations showed up to -10%, depending on the starting pressure.

It seems that deviations are due to the difference of pressure in the pipe between the MFM and the nozzle, at the beginning and end of the fueling:

- The higher the difference of pressure in the line between the MFM and the nozzle (at the beginning and end of the fueling), the higher the deviation.

- When pressure in the pipe is identical at beginning and end of the fueling, then the error is close to 0% (for example: full fillings)
- The longer the distance (volume) between the mass flow meter and the nozzle, the bigger the error.

Configuration 2:
Only two HRS with configuration 2 were tested. Deviations were smaller for this configuration. One HRS showed errors close to zero whatever the type of test performed (full filling / partial filling / MMQ filling). The other HRS showed bigger errors with a large scatter of data, but remains within the MPE authorized for a Class 4. It is difficult to determine precisely where this scattering comes from (meter / HRS configuration / testing device?)

The test results and conclusions were presented to different National Metrology Institutes in Europe, in the frame of Task 3, during several web-meetings held in November 2018 and January 2019. Representatives from CMI (Czech Republic), CEM (Spain) and the Belgium authorities attended.
Contact was made also with partners of the MetroHyVe project (Work Package 1 - dedicated to Hydrogen Flow Metering in HRS). Representatives from METAS/EMPA (Switzerland), RISE (Sweden), FORCE (Denmark), JV (Norway), TÜV NEL (United Kingdom) and VSL (Netherlands) attended

The final face-to-face meeting of Task 3 took place on March 20th, 2019 in FCH-JU facilities in Brussels. The objective was to share results and conclusions of the study with many Metrology Institutes in Europe (see list of participants in §6.3), and get their adhesion to apply the testing protocol as defined in Task 1.

French version:

Ce livrable présente les résultats obtenus lors de la Tâche 2 de l'étude n° FCH / OP / CONTRACT 196: "Développement d'un protocole de comptage pour les stations de remplissages hydrogène". Dans cette tâche, plusieurs station de remplissage hydrogène ont été sélectionnées pour appliquer le protocole d'essais proposé dans la tâche 1 pour la certification des ensembles de mesurage hydrogène.

Dans ce rapport final, les résultats des essais d'exactitude réalisés sur site sont présentés, pour les sept stations H2 testées. Ces tests sont réalisés en utilisant le banc de test de référence développé par Air Liquide et approuvé par la PTB / le LNE / le NMi Certin, selon les exigences de l'OIML R139:2014 (incertitude < 1/5 * MPE = 0,3%). Cette campagne d'essais fut la première occasion d'utiliser ce moyen de tests sur site en conditions réelles, i.e. soumis à des conditions environnementales variées (températures élevées en été et basses en hiver, vitesse du vent modérée).
Une bonne performance du moyen de test a été démontrée, ainsi qu'une très bonne fiabilité des mesures réalisées.
Les essais ont été réalisés sous la supervision de parties tierces pour attester la bonne utilisation du banc de tests selon les exigences spécifiées dans le certificat d'approbation:
- CESAME Exadebit était présent durant toute la durée de la campagne d'essais,
- Une personne de l'Institut National de Métrologie dans lequel la station est installée, a participé aux essais durant 1 ou 2 jours.

Il en ressort que les résultats dépendent de la configuration de l'ensemble de mesurage. Deux configurations sont identifiées :
- Configuration 1 où le débitmètre est situé dans le container (c-a-d loin du point de transfert),

- Configuration 2 où le débitmètre est situé directement dans le dispenser (c-a-d proche du point de transfert).

Configuration 1:
Les essais d'exactitude ont montré de très bons résultats, avec des erreurs de ± 0,5 % pour des remplissages complets (de 20 à 700 bar) pour les trois stations testées. Les erreurs obtenues étaient plus élevées pour les remplissages partiels : comprise entre -2 et -4 % environ pour les remplissages de 20 à 350 bar, et +2 et +4 % environ pour les remplissages de 350 à 700 bar. Ces résultats sont acceptables selon l'OIML R139:2018 dans laquelle des classes d'exactitude plus élevées ont été définies pour les stations hydrogène (classe 2 et 4 au lieu d'une classe 1,5) et de plus grandes erreurs maximales tolérées (EMT) sont autorisées pour les ensembles de mesurages déjà en opérations (EMT pour les inspections en services). Puis, plusieurs remplissages à la quantité minimale mesurée (=1 kg) ont été réalisés : certains d'entre eux montrent de très bonnes précisions (erreur proche de 0%), alors que d'autres montrent des erreurs les plus importantes (jusqu'à -10%), selon la pression initiale.

Il semble que les erreurs obtenues sont due à la différence de pression dans la tuyauterie (entre le débitmètre et le pistolet) au début et à la fin du remplissage :

- Plus la différence de pression entre la pression initiale et la pression finale est élevée, plus l'erreur est importante:
    - Quand la pression de la tuyauterie est identique en début et en fin de plein, alors l'erreur est proche de 0% (par exemple : remplissages complets)
- Plus la distance (donc le volume) entre le débitmètre et le pistolet est importante, plus l'erreur est élevée.

Configuration 2:
Seules deux stations de la configuration 2 ont été testées. Les erreurs obtenues semblent meilleures pour cette configuration. Une station a montré des erreurs proche de zéro quelque soit le type d'essai réalisé (remplissage complet / partiel / à la quantité minimale). L'autre station a montré des erreurs plus importantes avec beaucoup de dispersion, tout en restant dans les erreurs maximales tolérées pour une Classe 4. Il est difficile de dire si cette dispersion vient du débitmètre, de la configuration de la station ou du moyen de test.

Les résultats d'essais, ainsi que les conclusions ont été présentés à différents instituts de métrologie en Europe dans le cadre de la tâche 3, lors de conférences téléphoniques organisées en novembre 2018 et janvier 2019. Des personnes du CMI (République Tchèque), du CEM (Espagne) et des Autorités belges ont participé.
Un contact a été établit également avec les partenaires du projet MetroHyVe (Work Package 1 - dédié à la débitmétrie Hydrogène dans les stations H2), où des personnes de METAS/EMPA (Suisse), RISE (Suède), FORCE (Danemark), JV (Norvège), TÜV NEL (Royaume-Uni) and VSL (Pays-Bas) ont participé.

La réunion finale de la tâche 3 s'est tenue le 20 mars 2019, dans les locaux du FCH-JU à Bruxelles. L'objectif était de partager les résultats et conclusions avec plusieurs Instituts de Métrologie en Europe, et de recevoir leur adhésion pour appliquer le protocole d'essais défini dans la tâche 1.

3 Scope and objectives

The objective of this study is to define, in agreement with European national Metrology Institutes, a structured approach for accelerating the certification of metering systems for HRS in Europe. This certification is required for invoicing hydrogen at Hydrogen refueling Stations (HRS) to the general 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. The new version of OIML R139 was issued at the end of 2018; however, it will take time to change the legislation in each European country accordingly. Therefore a temporary solution is needed to ensure compliance of existing and future HRS with respect to legal aspects. This is the main objective of the tender: FCH / OP / CONTRACT 189 "Development of a Metering Protocol for hydrogen refueling Stations".
It must be noticed that the certification process proposed here must be validated ahead with the National Authority of the country where the dispenser is installed. It must be considered as guidelines for both manufacturers and authorities to validate dispensers installed before implementation of official regulation for H2 dispensers.

The testing protocol and acceptance criteria were defined in **Task 1**, with the participation of three European Metrology Institutes: PTB (Germany) / LNE (France) / NMi Certin (Netherlands). Purpose was to ensure equivalence with OIML R139:2018 requirements. This protocol is defined and explained in detail in Deliverable "D1.1 - Final deliverable Task 1 (Vfinal)_with abstract", available on the FCH-JU website: https://www.fch.europa.eu/publications (publication of October 4th, 2018). The main outcomes of Task 1 are recalled in *Chapter 4*.

The objective of **Task 2** was to implement this protocol on several Hydrogen Refueling Stations (HRS) in Europe. It consists of performing mainly different accuracy tests, using the reference test bench developed by Air Liquide and approved by PTB / LNE / NMi Certin according to OIML R139-2014 requirements (uncertainty < 0,3%). This deliverable presents in *Chapter 5*:

- The organization of the test campaign: criteria of selection of several HRS, planning, constraints on site;
- The description of the three first HRS tested in Task 2: model of Mass Flow meter used and location in the station;
- The results of accuracy tests obtained for the three first HRS tested;
- And the preliminary conclusions, based on above-mentioned results.

Finally, it was expected in **Task 3** to convince five other Metrology Institutes in Europe, of implementing the proposed protocol. For that, contact was made with several National Institutes / Authorities, but also with the members of the MetroHyVe project, whose one work package is dedicated to the metering of Hydrogen in Refueling Stations. Conclusions of Task 3 are given in *Chapter 6*.

4 Reminder on outcomes of Task 1

In order to establish a testing protocol for the certification of Hydrogen Refueling Station (HRS) in waiting for the revised version of OIML R139, the following reasoning was followed:

- Main components of the measuring system (calculator and meter) must fulfill the requirements of OIML R139:2014;
- However, most of them are not approved according to OIML R139:2014, but according to the previous version of OIML R139 (2007 for example) or according to different standards (R117-1 for liquid meters for example);
- Therefore deviations to OIML R139:2014 for these components (in their certified version) have been evaluated for each category of tests required for the Type Approval:
    - Electromagnetic compatibility (EMC)
    - Environment testing (climatic test, humidity, etc).
    - Accuracy tests
    - Gas temperature accuracy tests
    - Durability tests
    - Software (WELMEC 7.2)

Based on the results of the aforementioned evaluation, a proposal was made to require, or not, new or additional tests. This evaluation has been done:

- for future stations that will be installed according to this protocol (before the revised version of OIML R139 is issued), on the one hand;
- for existing stations already installed and in operation in Europe, on the other hand.

The testing protocol and associated requirements are summarized in Table 1 below:

		Calculating & indicating device		**Measurement transducer (electronics) & Measurement sensor**	
		Certified according to: **OIML R117-1:2007** or **OIML R139:2007**	Certified according to: **OIML R117-2:2014** or **OIML R139:2014**	Certified according to: **OIML R117-1:2007** or **OIML R139:2007** or **OIML R137:2012**	Certified according to: **OIML R117-2:2014** or **OIML R139:2014**
Type approval tests	EMC	**2** (**3**)	**3**	**2** (**3**)	**3**
	Environment testing (climatic test, humidity)	**3**		**3**	
	Mechanical test (vibration)	**3** if M1		**3** if M1	
	Accuracy test	**3**		**1**	
	Accuracy gas temperature tests	**3**		**4**	
	Software (WELMEC 7.2)	**4**	**3**	**4**	**3**
	Durability test	**3**		**4** (**3**)	
Initial verification	Adjustment on site	**1**		**1**	

Table 1: Summary table of the proposed testing protocol

How to read this table?
For the calculator and the meter, choose the column corresponding to its actual certification. Then for each category of tests, refer to the legend below:

- **1 = Complete new tests**
- **2 = Additional test required**
- **3 = No test required**
- **4 = No test required, but under conditions**

Remark: This table applies for *future stations* that will be certified according to this protocol, but also to *existing stations*. When requirements differ between future and existing stations, the number specified into brackets applies to existing stations.

Remark 2: Table 1 above is a visual summary. For details, please refer to the corresponding deliverable “D1.1 - Final deliverable Task 1 (Vfinal)_with abstract”, available on the FCH-JU website: https://www.fch.europa.eu/publications (publication of October 4th, 2018).

5 Test campaign on existing HRS (Task 2)

5.1 Organization of the test campaign

5.1.1 Selection of HRS

The tender specifications mentioned the following requirements for the selection of HRS to be tested: "*This should involve a statistically significant sample of HRS in Europe, representing a minimum of 3 Member States*". This requirement has been translated into three specific criteria:

1. All technologies and/or specificities should be tested
2. HRS from different manufacturers in Europe: Air Liquide, Linde and H2 Logic (NEL)
3. HRS in operation in a minimum of three different countries of the European Union

Based on these criteria, the following HRS were selected (see Table 2 and Figure 1 below):

LOCATION		**START-UP DATE**	**TECHNOLOGY PROVIDER**	**OPERATOR**	**CHARACTERISTICS (especially for metering aspects**
Country	**City**				
Germany	Kamen	May 2017	Air Liquide	H2M	AL G2 design with short distance between the MFM (in the station) and the dispenser
	Koblenz	June 2017	Air Liquide	H2M	AL G2 design with long distance between the MFM (in the station) and the dispenser
	Köln airport	Oct. 2017	Linde	H2M	Compressed gas
	Hannover	July 2018	Linde	H2M	Liquid
	Rostock	Dec. 2016	NEL - H2 Logic	H2M	Compressed gas
France	Paris - Saclay (CRPS)	Oct. 2017	Air Liquide	Air Liquide (ALAB)	FCH2-JU funded project: H2ME1: G2 design
Netherlands	Rhoon (Rotterdam)	Apr. 2016	Air Liquide	Air Liquide (ALAB)	AL G1 design

Table 2: List of HRS tested in Task 2, and main characteristics

The technology for each HRS manufacturer is explained in details in Chapter **§5.1.3**.

Another criteria for the selection of HRS was the loading rate of the station. It was mandatory that:

1/ the station remains available for the customer during the whole testing week,

2/ the installation on site disturb as little as possible the customers to refuel their cars.

That is why we have chosen, in agreement with H2 Mobility, HRS with a low loading rate (few fillings per month).

Figure 1: Map of HRS tested in Task 2

Here are some pictures of the different HRS listed above:

Germany:

AL station - Kamen


AL station - Koblenz

Linde - Cologne

Linde - Hannover

NEL station - Rostock

France:

Netherlands:

AL station - Paris (Saclay)

AL station - Rotterdam (Rhoon)

For confidentiality issues, the results presented hereafter will refer to HRS1 / HRS2 / … / HRS7. Numbering does not correspond to the order of HRS presented above.

5.1.2 Planning

The first HRS (Kamen) was tested end of July 2018 (W30). Then tests were spread over 9 months.

The time needed to perform all tests was in agreement with the estimation done. Here is the standard planning to test perform the test program defined in Task 1:

- Installation: 2-3 h
- Scale verification: 30 min to 1 h
- Accuracy tests : 3 days (see details below)
- De-installation: 2 h

In total 4 days were enough to perform all tests, and get a good repeatability.

Note: The scale requires a warm-up time of 1h30 (minimum) to 2h after each electrical disconnection. During the first testing week, the scale was disconnected each night. So waiting time was needed for 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.

Note 2: Depressurization of the tank from 700 to 20 bar takes around 1h45. This limits a lot the number of fuelings that can be performed each day, but the depressurization rate cannot be higher in order to respect the minimum temperature inside the tank.

During the 3 days, it was possible to perform 3 to 4 times the following test sequence (see Figure 2), to get a good idea of the repeatability:

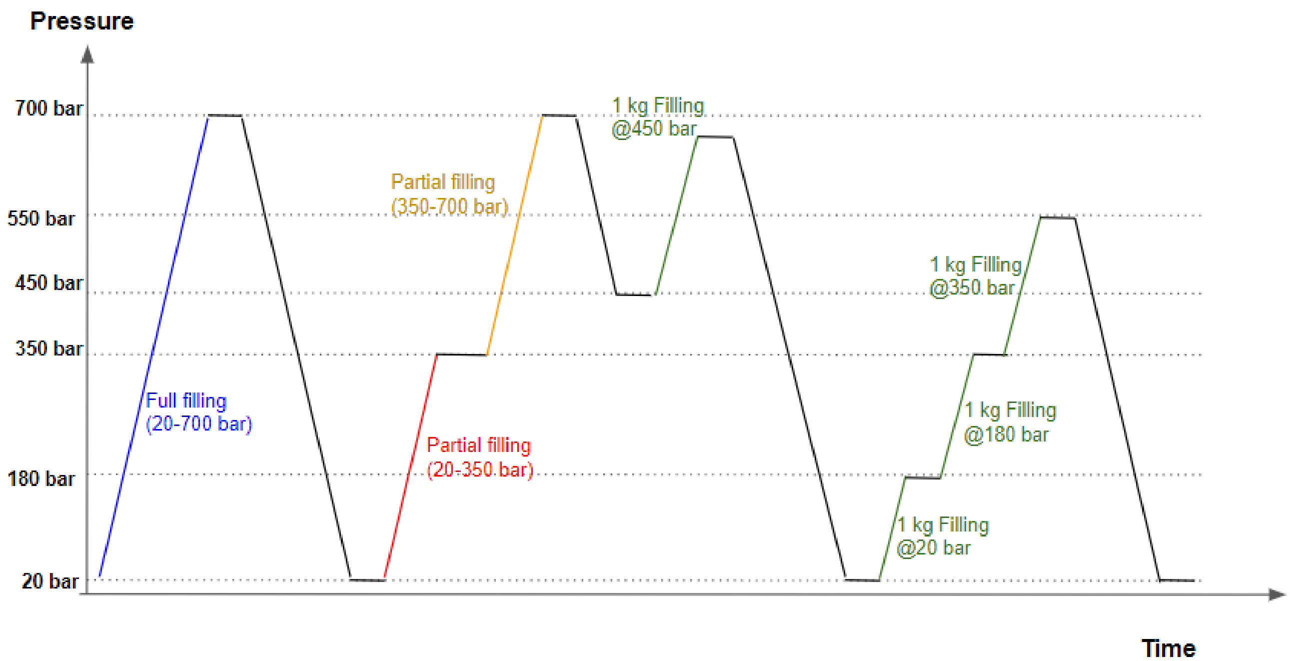

Figure 2: Sequence of tests performed 3-4 times per HRS

5.1.3 Scale verification for mass correction

Each day of test, the scale was verified using reference weights of 1 kg / 2 kg / 2 kg (see Figure 3). 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 subtracted from the mass measurement for each day. The linear regression calculated (see Figure 4) is subtracted to each mass measured the same day of the scale verification.

Figure 3: Calibrated weights handled cautiously with gloves

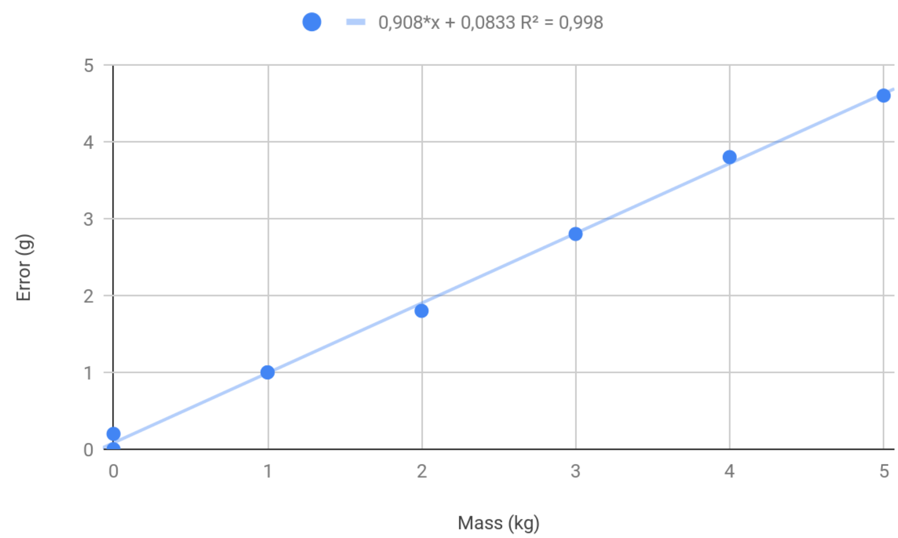

Figure 4: Example of scale deviation

5.1.4 Constraints and needs on site

The main constraint was the site configuration. Indeed, we had to adapt the installation of the trailer considering:

- The way vehicles move around the dispenser (dispenser must remain accessible for customers, and the test bench cannot be moved once installed)
- Solar radiations: avoid as much as possible direct solar radiation onto the tank/scale.

<u>In Cologne</u>: possibility to approach the dispenser in going backwards, manoeuvre mandatory. One H2 vehicle came to refuel during the week.

Figure 4: Installation at Cologne HRS

5.2 Description of HRS tested

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

- **Configuration 1**: where the MFM is installed <u>in the container</u>, and not in the dispenser (see Figure 6).
    - *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 (see Chapter 5.5.3)

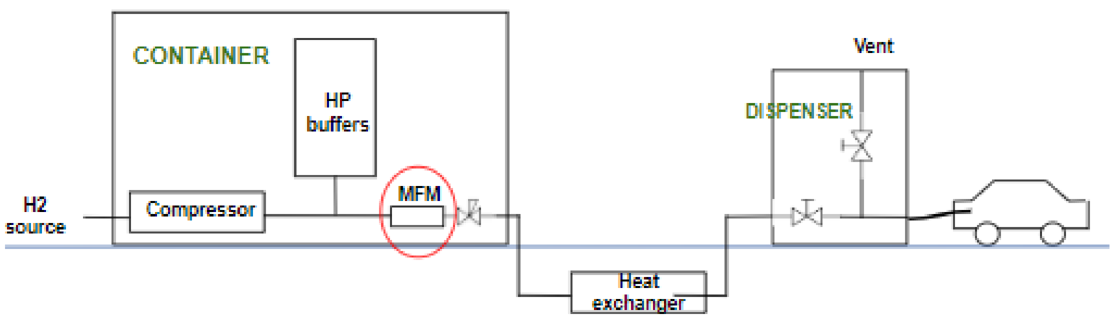

Figure 6: Illustration of Configuration 1, where the MFM is located in the main container

This configuration applies for five HRS over the seven HRS tested.

- **Configuration 2**: where the MFM is installed <u>in the dispenser</u>, close to the break-away device (see Figure 7).
    - *Advantages*: The error is minimized due to the short distance between the MFM and the transfer point (see Chapter 5.5.3)
    - *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.

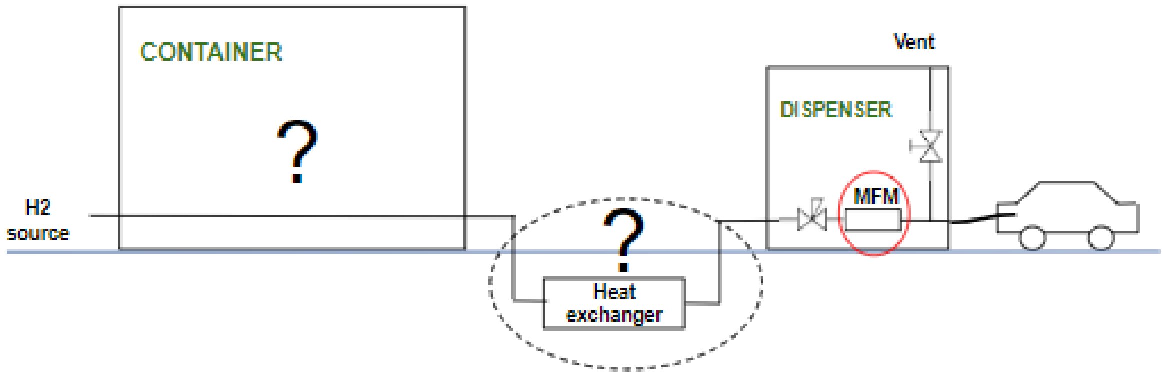

Figure 7: Illustration of Configuration 2, where the MFM is located in the dispenser

This configuration applies for two HRS over the seven HRS tested.

Various model of MFM were tested over the seven HRS:

- Rheonik: **RHM04 + RHE 12 (or RHE07c)**
- KEM Küeppers: **TCHM0450 + TCE8000**
- Heinrichs: **TM SH + UMC4**

5.3 Results obtained for accuracy tests

5.3.1 Configuration 1 (HRS 1 to 5)

- HRS 1:

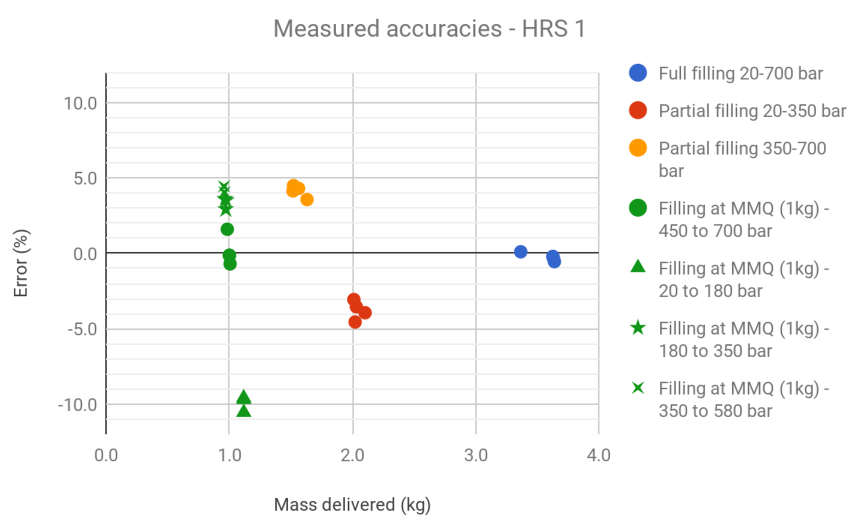

Figure 8: Results of accuracy tests in HRS 1

- HRS 2:

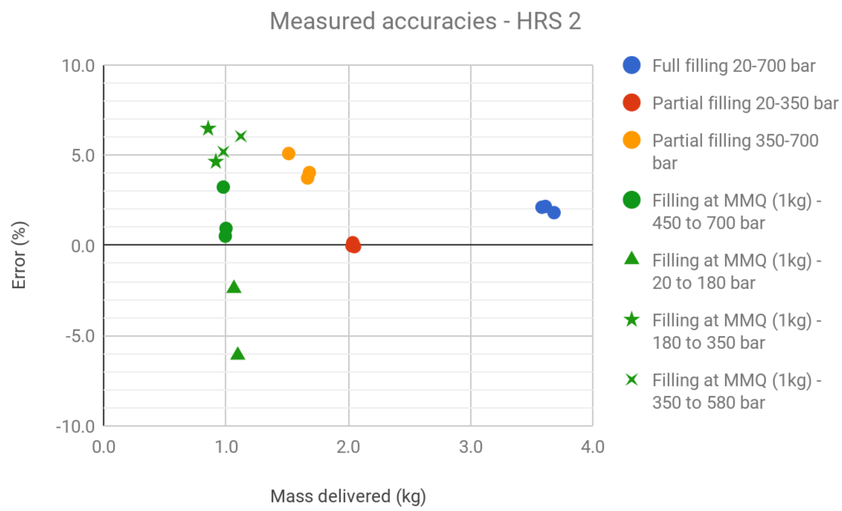

Figure 9: Results of accuracy tests in HRS 2

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.

This leads to the following results (see Figure 10):

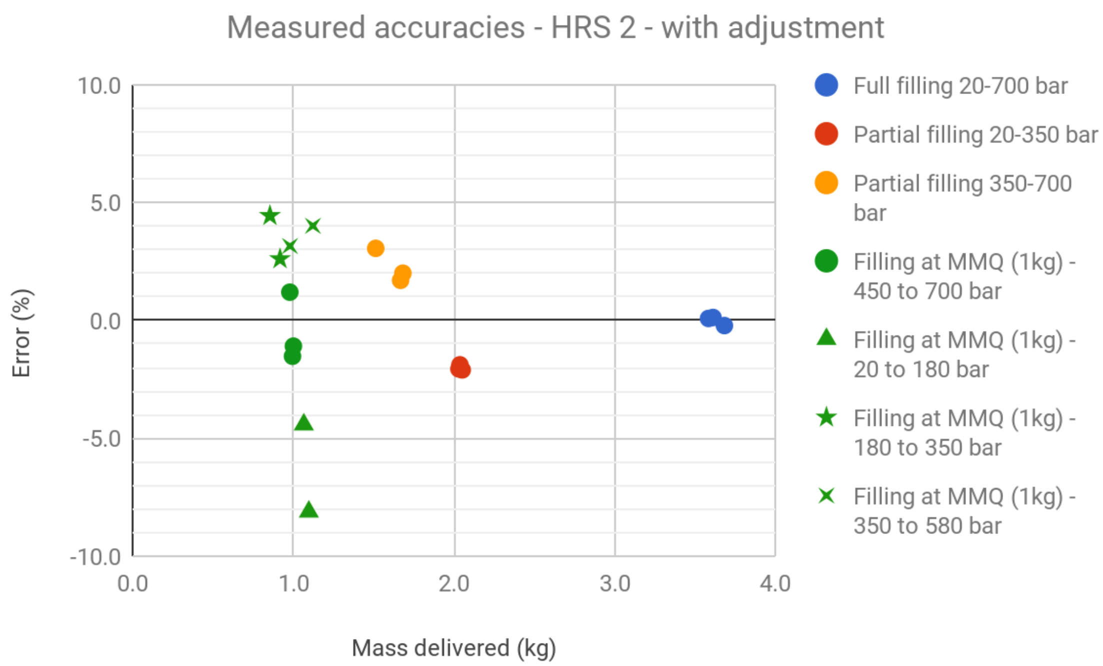

Figure 10: Results of accuracy tests in HRS2, after adjustment

- <u>HRS 3:</u>

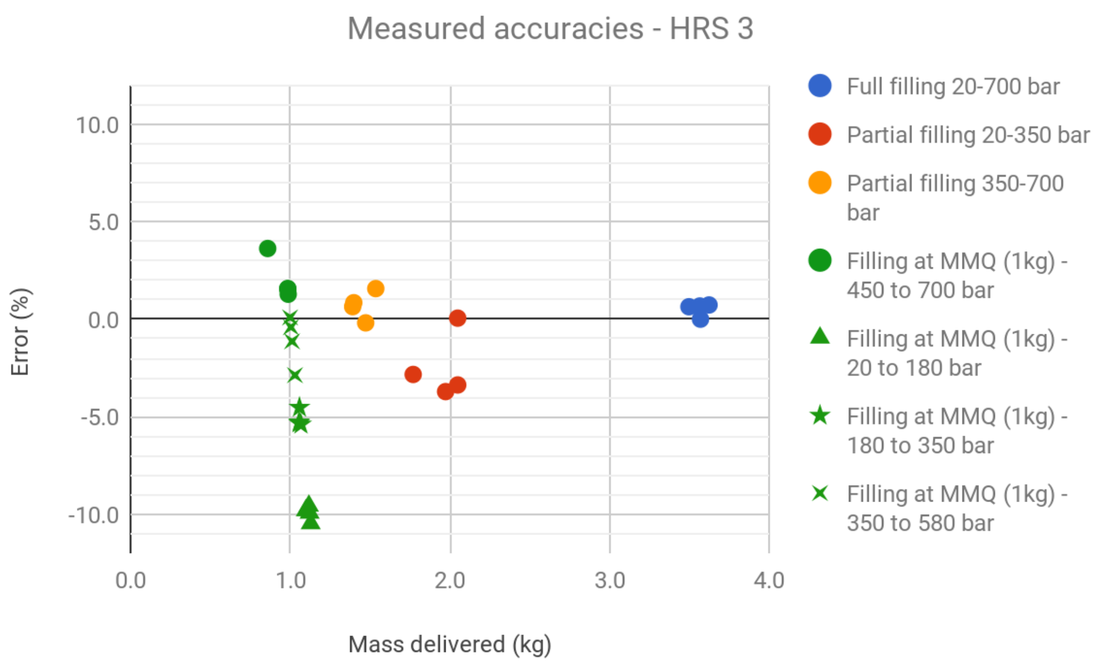

Figure 11: Results of accuracy tests in HRS 3

- <u>HRS 4:</u>

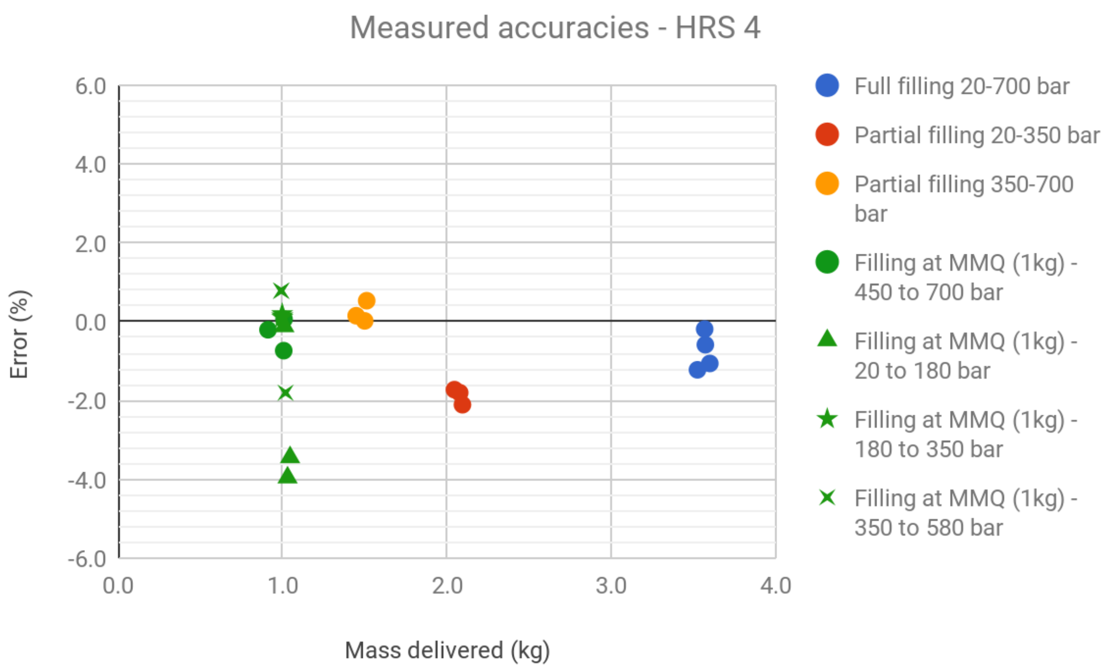

Figure 12: Results of accuracy tests in HRS 4

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.

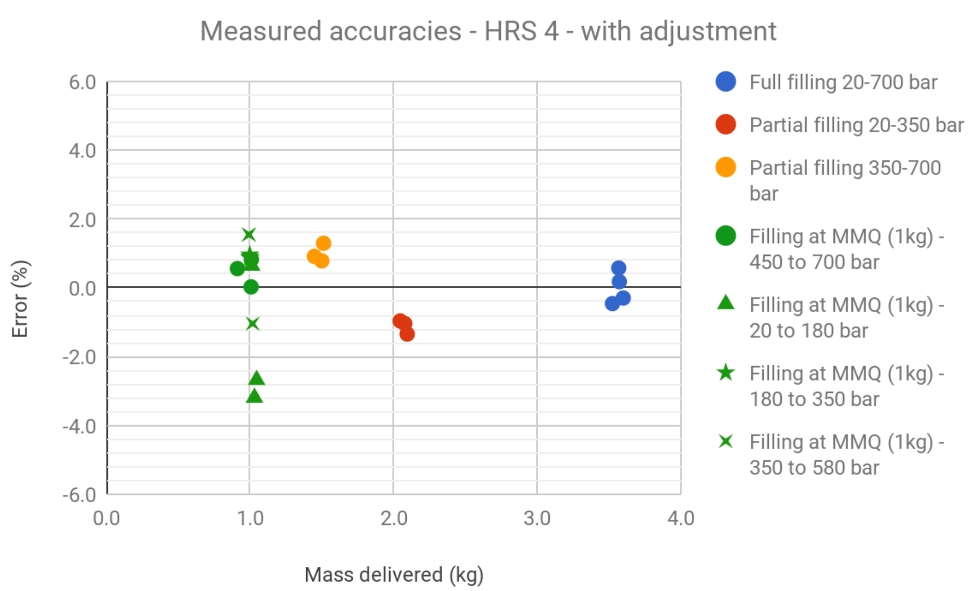

Figure 13: Results of accuracy tests in HRS 4, after adjustment

- <u>HRS 5:</u>

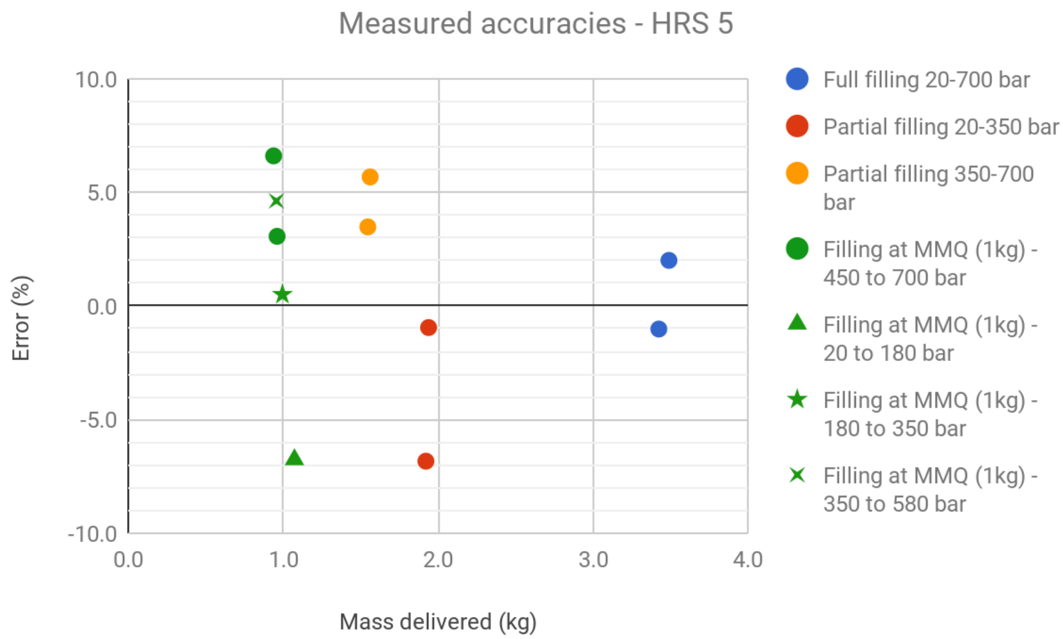

Figure 14: Results of accuracy tests in HRS 5

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

5.3.2 Configuration 2 (HRS 6 & 7)

- <u>HRS 6:</u>

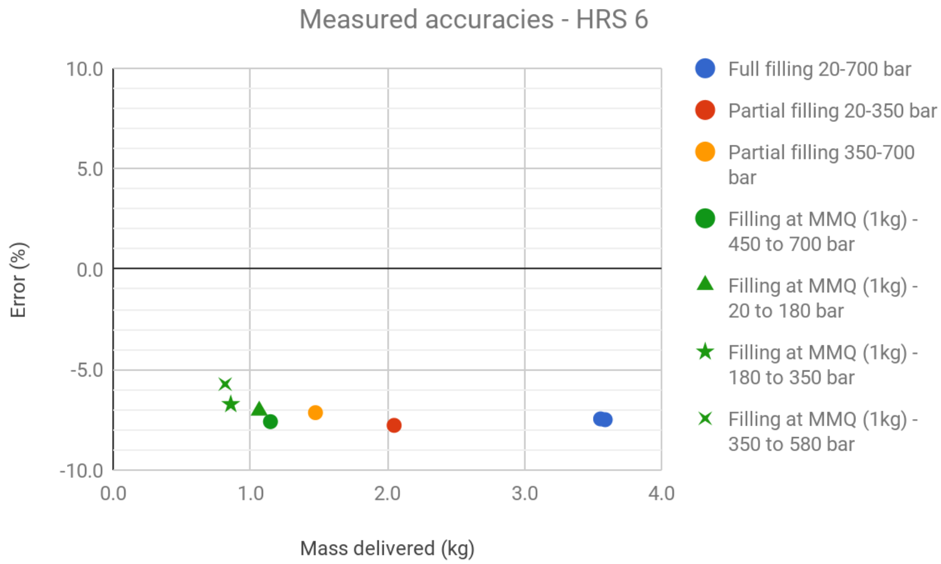

Figure 15: Results of accuracy tests in HRS 6

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 MFM. 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 (see Figure 16)

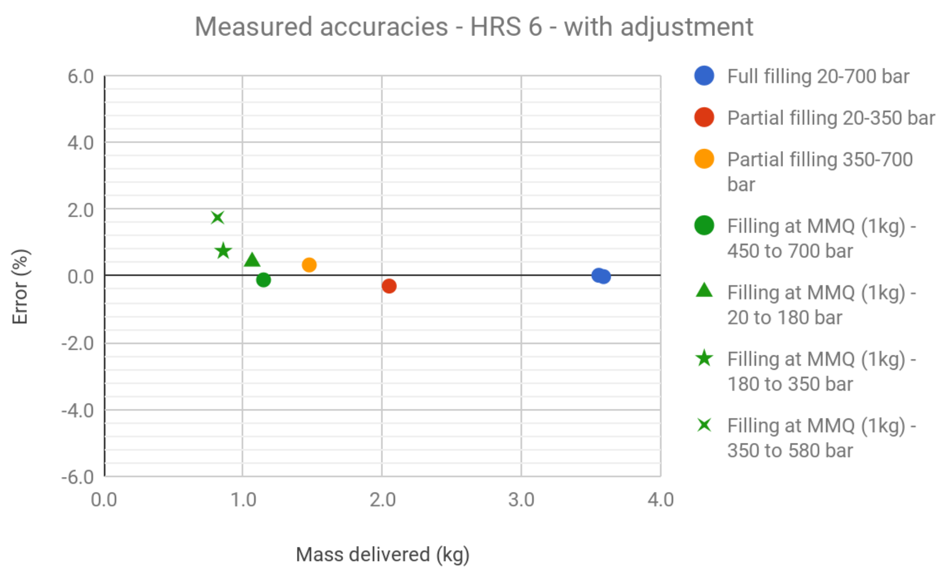

Figure 16: Results of accuracy tests in HRS 6, after adjustment

- <u>HRS 7:</u>

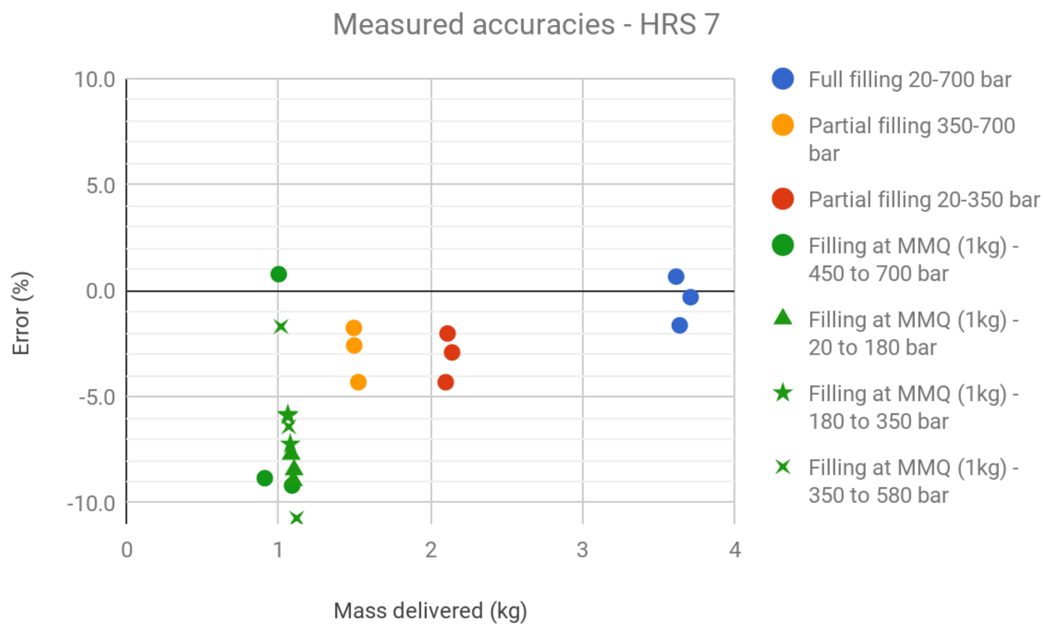

Figure 17: Results of accuracy tests in HRS 7

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.
Consequently, it is difficult to clearly conclude on accuracy for this HRS.

5.4 Synthesis of test results

A mean value has been calculated for each station and for each type of tests (see Table 3):

	CONFIGURATION 1					CONFIGURATION 2	
	HRS 1	**HRS 2** *(based on adjusted values)*	**HRS 3**	**HRS 4** *(based on adjusted values)*	**HRS 5**	**HRS 6**	**HRS 7**
Full fillings 20-700 bar	**-0,24%**	**0,00%**	**0,52%**	**0,00%**	**0,50%**	***0,00%***	**-0,42%**
Partial fillings 20-350 bar (*)	**-3,77%**	**-2,01%**	**-2,46%**	**-1,11%**	**-3,89%**	***-0,30%*** (*)	**-3,08%**
Partial fillings 350-700 bar	**4,13%**	**2,26%**	**0,72%**	**1,00%**	**4,58%**	***0,33%*** (*)	**-2,88%**

Filling at MMQ 450 to 700 bar	0,16%	-0,47%	2,02%	0,47%	4,84%	*-0,12%* (*)	-5,75%
Filling at MMQ 20 to 180 bar (*)	-9,94%	-6,26%	-9,95%	-1,74%	-6,75% (*)	*0,43%* (*)	-8,37%
Filling at MMQ 180 to 350 bar (*)	3,36%	3,53%	-5,12%	0,91%	0,51% (*)	*0,74%* (*)	-6,32%
Filling at MMQ 350 to 580 bar (*)	3,78%	3,59%	-1,07%	0,69%	4,62% (*)	*1,74%* (*)	-6,28%

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

Legend:
- **Green value** : all values are within the limits (MPE), considering a Class 4.
- **Orange value**: mean value is within the limits (or very close to the limits), but some single values are out of the limits (MPE), considering a Class 4.
- **Red value**: all values are out of the limits (MPE), considering a Class 4.
- (*) 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 appears to be very high (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 examination, initial verifications 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.

5.5 Explanations

5.5.1 Repeatability

A good repeatability was observed for most of the tests. This demonstrates that the testing equipment works perfectly in real conditions: on site, subjected to ambient environmental conditions (hot temperatures during summer, moderate wind). The test bench is reliable and gives reproducible results.
For some tests, the repeatability was not so good. It is difficult to say 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 is only applicable for measurand equal to or greater than 1000 scale intervals of the meter and for successive measurements of the same quantity carried out under the same repeatability condition. Achieving the same repeatability condition during testing in the field is difficult to achieve.

5.5.2 Type of flowmeter

Over the seven HRS tested:
- five were equipped with a Rheonik MFM (RHM04 + RHE12 or RHE07c)
- one was equipped with a KEM MFM (TCHM0450 + TCE8001)
- and one was equipped with a Heinrichs MFM (TM SM + UMC4).

The Rheonik meter was used in both configurations (1 & 2), whereas the KEM meter was tested in Configuration 1 only and the Heinrichs meter was tested in Configuration 2 only.

The good results for Full fillings for all HRS demonstrate that the three meters perform well in general (good overall repeatability, low error). For HRS with bad repeatability, investigation must be done to determine if it comes from the meter itself or from the complete measuring system.

5.5.3 Influence of distance between MFM 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***

An in-depth analysis of test results reveals that errors observed for HRS of ***Configuration 1*** can be explained by the distance between the MFM and the dispenser: the longer the distance (i.e. the bigger the volume), the bigger the errors.

- At beginning of the test, the line between the MFM 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 MFM (because it is already in the pipe at the beginning of the transaction) and given to the customer.

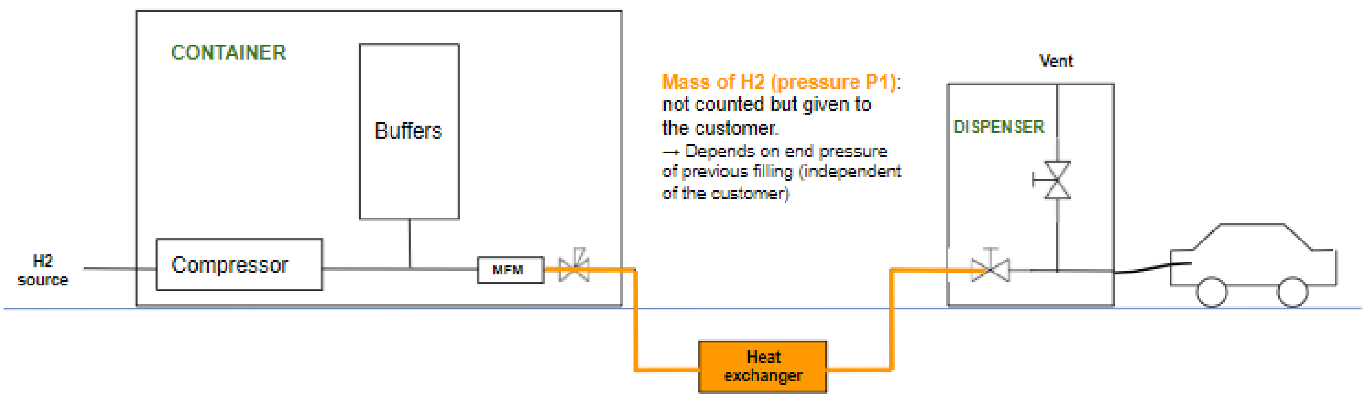

Figure 18: Schematic diagram of a HRS - situation before fueling

- At the 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 MFM but not transferred into the customer vehicle.

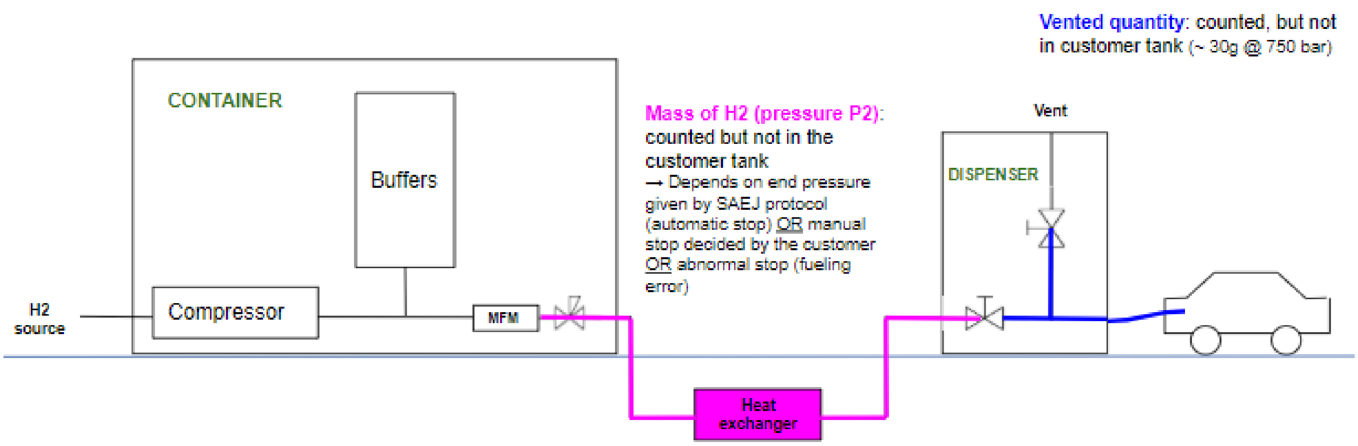

Figure 19: Schematic diagram of a HRS - situation at end of fueling

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 fueling (counted, but not delivered).

If **P1** > **P2**, then the customer get *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 fueling (counted, but not delivered) → Negative deviation.

If **P1** < **P2**, then the customer get *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 fueling (counted, but not delivered) → Positive deviation.

<u>Application to the tests performed:</u>

- **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 MFM and dispenser is around 700 bar (P1)
  - End pressure was around 700 bar. So pressure in the line between MFM and dispenser is around 700 bar (P2)
  - So **P1** ~ **P2**. That is why the deviation 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 MFM and dispenser is around 700 bar (P1)
    - End pressure was around 350 bar. So pressure in the line between MFM and dispenser is around 350 bar (P2)
    - So **P1 > P2**. That is why the deviation 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 MFM and dispenser is around 350 bar (P1)
    - End pressure was around 700 bar. So pressure in the line between MFM and dispenser is around 700 bar (P2)
    - So **P1 < P2**. That is why the deviation 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 MFM and dispenser is around 700 bar (P1)
    - End pressure was around 700 bar. So pressure in the line between MFM and dispenser is around 700 bar (P2)
    - So **P1 ~ P2**. That is why the deviation **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 MFM and dispenser is around 700 bar (P1)
    - End pressure was around 180 bar. So pressure in the line between MFM and dispenser is around 180 bar (P2)
    - So **P1 > P2**. That is why the deviation is ***negative***.

Note: deviations are more 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 MFM and dispenser is around 180 bar (P1)
    - End pressure was around 350 bar. So pressure in the line between MFM and dispenser is around 350 bar (P2)
    - So **P1 < P2**. That is why the deviation 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 MFM and dispenser is around 350 bar (P1)
    - End pressure was around 580 bar. So pressure in the line between MFM and dispenser is around 580 bar (P2)
    - So **P1 < P2**. That is why the deviation is ***negative***.

As a result, it appears that **the longer the distance (i.e. the bigger the volume), the bigger the errors**. For example:

- d_HRS 1 ≈ 35 m (long distance)
- d_HRS 2 ≈ d_HRS 3 ≈ 10 m (short distance). That is why errors are lower than HRS 1, especially for MMQ fillings.
- d_HRS 4 ≈ similar to HRS 2 (short distance), but the volume in the Heat Exchanger is much smaller. This explains why errors are compatible with a Class 2.
- d_HRS 5 ≈ 15-20 m (medium distance). The scatter observed on this station cannot allow to clearly conclude on the influence of the distance MFM - nozzle.

Knowing precisely the pressure and the volume of the pipe between the MFM 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 MFM is located in the dispenser), the distance between the MFM and the nozzle is very small (almost negligible): the MFM 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.

5.5.4 Influence of vibrations

For each HRS tested, CESAME Exadebit installed (when accessible) an ATEX accelerometer on (or at the vicinity) of the Coriolis flow meter (see Figure 20) to detect if vibrations could modify the accuracy of measurements. The purpose is to ensure that vibrations coming from the compressors (when the MFM is installed in the compressor container) do not affect the flow meter accuracy.

Figure 20 : ATEX accelerometer

Characteristics of the accelerometer:

- Measured quantity: vibrations on the MFM
- Sensor: accelerometer
- Model: CTC AC932-1A
- Range: 1 to 15 000 Hz
- Resolution: 50 mV/g
- Signal processing: conditioner output +/-10 Vcc with variable gains
- Acquisition system: NI USB-6002

Example of data recorded during car refueling (see Figure 21):

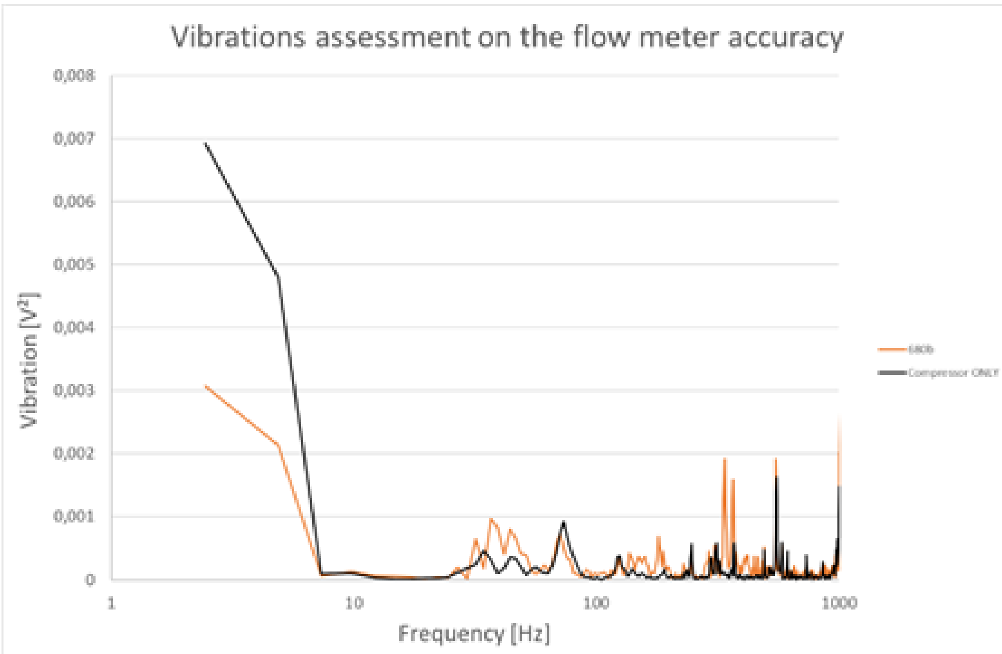

Figure 21 : Vibrations assessment on the CFM - HR2

During filling, the MFM does not encounter any large vibrations. When the compressor was running, the related frequencies remained low (below 10 Hz). No bias has been found regarding vibration perturbations in this study.

5.6 Discussions

Representativity of the test sequence performed in this study

The test sequence performed in this study (see Figure 22) is more complete than the tests required in OIML R139-2:2018 (Figure 23), but also more severe.

Reminder: OIML R139-2:2018 request to perform only three fillings :

- One Full filling from 20 to 700 bar (**Test #4**)
- One partial filling from 350 to 700 bar (**Test #5**)

- One MMQ filling ending at 700 bar (initial pressure to be determined so that MMQ filling stops around 700 bar) (**Test #7**)

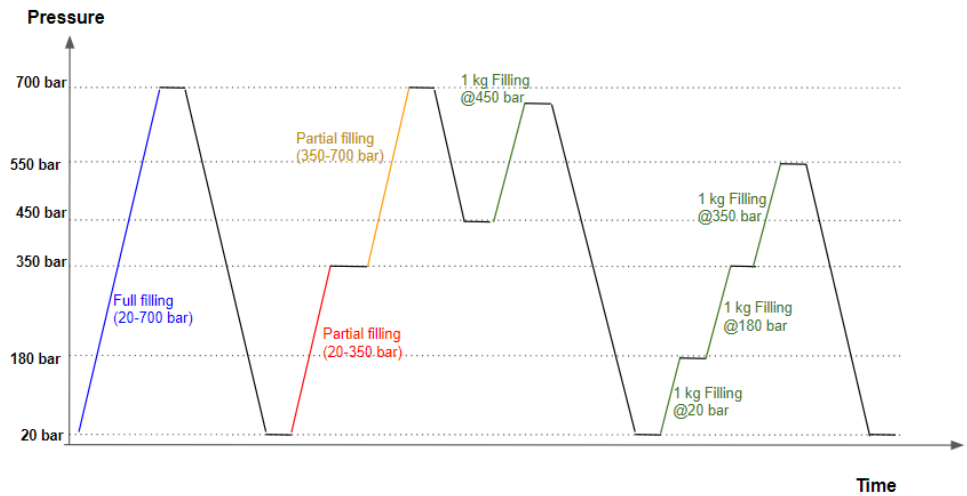

Figure 22: Full test sequence performed in this study

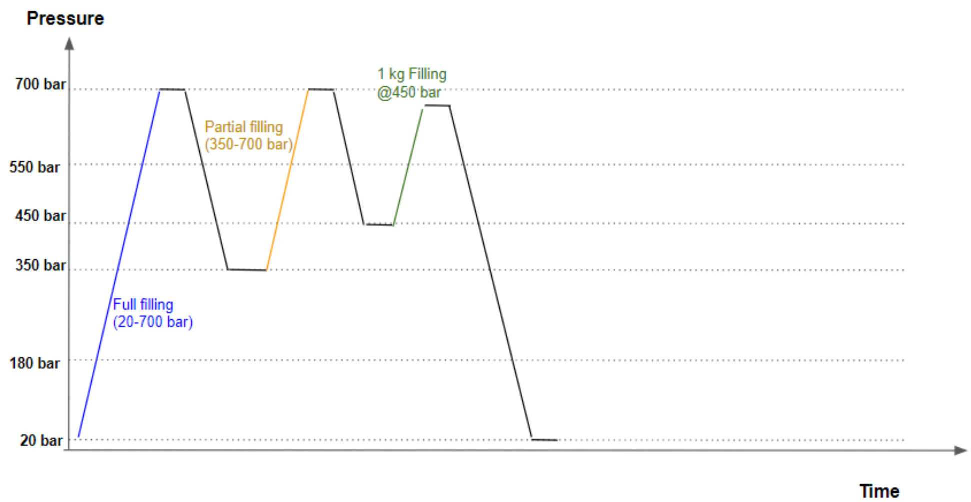

Figure 23: Test sequence requested in OIML R139-2:2018

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 Chapter 5.5.3, 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 fueling. So we would always have **P1** ~ **P2**, and consequently errors would be close to zero for all types of test (to be fully demonstrated by testing).

Impact on test duration

The depressurization time needed to empty the tank depends on the pressure: the depressurization speed is very fast at high pressure, but it decreases as much as pressure decreases. For example: only 15 minutes are needed to depressurize from 700 bar to 450 bar (and let's say around 20 minutes to depressurize down to 350 bar), whereas almost 2 h is needed to empty the tank from 700 bar to 20 bar only.
So the initial pressure of each test is very important and has a high influence on the duration of the whole test campaign.

- *Time needed to perform the full test sequence*: **1 day per sequence**. So at least 3 days were needed to perform three times the full test sequence. With the installation and uninstallation time of the testing equipment, 4 days are needed in total.

- *Estimated time to perform test sequence as requested by OIML R139-2:2018*: **3,5h per sequence**. So 1 ½ day only would be needed for perform three times the test sequences requested in OIML R139-2:2018. With the installation and uninstallation time of the testing equipment, 2 ½ days are needed in total.

This will have a strong impact on testing cost, but also on customers experience. Indeed, during the tests, the dispenser remains accessible, but drivers are asked to manoeuvre in order to be able to access the dispenser. So the shorter the test duration, the better the customer experience.

Representativity of real fuelings performed by customers

In practise, it is very rare that customers stop manually the fueling before its full completion. It is more likely that customers arrives with a half-full tank and perform a partial fueling up to the maximum pressure. So all fillings stopped at 700 bar.

Some figures:
Based on our statistics, 3914 refuelings were done in March and April (over three HRS). Among these refuellings, only 25 refuelings were manually stopped by the customer before the end of the fueling (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 R137:2012 or OIML R139:2018 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 (vent, piping length)

6 Dissemination to other NMIs (Task 3)

6.1 Identification of potential participants in Task 3

Contact was made at beginning of this Task with people identified at end of Task 1 in order to organize the different meetings along Task 3.
Among the different metrology institutes / authorities identified, one of them declined the invitation: BEV from Austria due to a lack of resources to participate in this project.
A new contact person was identify in CEM / Spain, and answered positively to the invitations.

Organization / country	**Name of the contact person**	**Member of the MetroHyVe project**	**Comments**
CMI / Czech republic	Klenovský Pavel / Miroslava Benkova		
Belgium	Marc Wouters		
BEV / Austria	Ulrike Fuchs / Karin Bittner-Rohrhofer / Petra Milota		Interested in the topic, but no resources for further actions in the project
CEM / Spain	Teresa Lopez / Teresa Fernandez / Maria Sanchez		
METAS & EMPA / Switzerland	Marc de Huu / Patrick Stadelmann	**X**	
RISE / Sweden	Oliver Büker	**X**	
FORCE / Denmark	Lars Poder	**X**	
JV / Norway	Henning Kolbjornsen	**X**	
NEL / United Kingdom	Marc MacDonald	**X**	
VSL / Netherlands	Harm Petter	**X**	

Table 4: Contacts in different European Metrology Institutes

Some contacts were made also by Carlos Navas (FCH-JU) to identify people from Italy and Austria:

- **Italy**: *Italian Institute of Technology (IIT)*: Thomas KLAUSER and Walter HUBER. No answer.

- **Austria**: *Federal Ministry for Sustainability and Tourism (BMNT)* and *Austrian Ministry for Transport, Innovation and Technology (BMVIT)*: Maria BAIERL and Theodor ZILLNER respectively. No answer.

6.2 Web meetings

The kick-off meeting was organized on **November 26th, 2018** as a web-meeting. Participants were:

- Partners of the project: PTB / LNE / NMi Certin / CESAME
- Participants of Task 3: CMI / CEM / Belgium

Unfortunately members of the MetroHyVe project were not available, as they had the 18M progress meeting of the project. So it was decided to organize a dedicated meeting with them, on January 10th, 2019.

Then a progress meeting was organized on **January 31st, 2019** as a web-meeting. Participants were:

- Partners of the project: PTB / LNE / NMi Certin / CESAME
- Participants of Task 3: CMI / CEM / Belgium / FORCE / EMPA

For the kick-off meeting, presentation was focused on: the testing protocol for the certification of Hydrogen Refueling Station (HRS) as defined in Task 1, as well as the results obtained on the three first HRS tested (Task 2).
For the progress meeting in January, it has been updated with the latest results obtained from the test campaign.

The material of the presentation was distributed right after the meeting to all participants. No particular feedback or comment was received from the audience. The content of the presentation was substantial and participant needed time to assimilate the results and proposed approach.

6.3 Final face-to-face meeting

For the final meeting of this study, it was decided to organize a face-to-face meeting in Brussels at FCH-JU premises. It took place on **March 20th, 2019**. Despite a large diffusion of the invitation, participants were:

- Partners of the project: PTB / LNE / NMi Certin / CESAME
- Participants of Task 3: CMI / CEM (remotely) / METAS / EMPA

Several people from the European Commission and the FCH-JU were also present.

During this meeting, the testing protocol was explained again in details to all participants. Then focus was done on the test campaign and results obtained so far, with associated explanations and conclusions.
Time was given for discussions at the end with all participants.

People acknowledged the quality of this study performed and the knowledge developed with the test campaign. It was difficult to get the formal agreement of each participant to apply the testing protocol in their respective country, because the final decision is in the scope of each National Authority, based on each national legislation.

At end of this seminar, a discussion took place between all participants about the need and potential benefits to include Hydrogen dispensers in the scope of the European Directive, named MID 2014/32/EU (Measuring Instruments Directive).
For measurement instruments covered by MID, the WELMEC organization is responsible for harmonization of MID implementation at a European level. As Hydrogen dispensers are not covered by MID, it is difficult to get this as an official topic on the working program for one of the instrument specific WELMEC groups. Such extensive topics should be introduced to the WELMEC Committee and could be added to the work program of the instrument specific WELMEC group after approval of the WELMEC Committee.

In order to accelerate discussions with WELMEC committee and check the possibility to include Hydrogen dispenser to the MID, it was suggested to initiate a cross-check table to demonstrate that hydrogen dispensers certified according to OIML R139:2018 fulfills the requirement of the MID, at least for essential requirements (MID Annex I).

For example, the cross-check table for petrol fuel dispenser is given below:
https://www.welmec.org/documents/corresponding-tables/ct-005/

However, before starting such a work, WELMEC committee and the Working Group for Measuring Instruments must agree with this approach. So it is recommended to contact them first, to get their opinion.

By experience, a strong argument must be presented to demonstrate the necessity to include hydrogen dispenser in the scope of MID. One example could be that a national certificate is not accepted as it is in other european countries (against the principle of free movement of products in Europe). Up to now, no such difficulties have been encountered yet. So this request might be difficult to be accepted with no actual feedbacks or difficulties raised.

Note: the last revision of the Measuring Instrument Directive has was issued in 2014, and a *statu quo* with respect to the previous version of 2004 was agreed (meaning that no changes / change of scope were needed in the MID).

7 Milestones

Several milestones are expected at end of Task 2 & 3. Below is the list of milestones and the status of each of them (Table 5):

Milestone number	Milestone name	Passed / Failed	Justification
M2.1	Support of presentation to be updated with test results on a regular basis, throughout Task 2.	Passed	A presentation with all test results was prepared for the progress meeting on October 26th, 2018 in Brussels. This material has been completed with results and conclusions after each HRS tested. It has been shared with many people for dissemination, especially participants involved in Task 3.
M3.1	Meeting with the 5 NMIs involved in Task 3	Passed	Done on : - November 26th, 2018 with **CMI (Czech Republic), CEM (Spain), and Belgium authorities**. - January 10th, 2019 with members of the MetroHyVe projects were several Metrology Institutes are involved: **METAS / Empa (Switzerland), RISE (Sweden), JV (Norway), FORCE (Denmark), NEL (UK), CESAME (France), VSL (the Netherlands)** - January 31st, 2019 with same participants as mentionned above: **CMI (Czech Republic), CEM (Spain), Belgium authorities, FORCE (Denmark), EMPA (Switzerland).**
M3.2	Formal agreement from all institutes involved for application in their respective country	Partially passed	Final face-to-face meeting hold on **March 20th, 2019**. It was difficult to get the formal agreement of each participant to apply the testing protocol in their respective country, because the final decision is in the scope of each National Authority, based on each national legislation.

Table 5: Status of milestones associated to Tasks 2 & 3

8 Conclusions

A test campaign fulfilling all criteria specified in the tender has been organized. This test campaign aimed at applying the testing protocol as specified in Task 1, which consists mainly in performing several accuracy tests in various conditions (initial and final pressure in the tank).

Constraints linked to the availability of the stations were taken into account, so that the station can remain available for the customer during the whole test campaign.
Seven HRS have been tested in total. Five of them were equipped with a Rheonik RHM04 flow meter, one was equipped with a KEM Kueppers TCHM 0450 flow meter and another one was equipped with a Heinrichs TM SH flow meter. Two different configurations of the measuring system were identified:

- Configuration 1 where the MFM is located in the container, far away from the dispenser (nozzle = transfer point).
- Configuration 2 where the MFM is located directly in the dispenser, close from the transfer point.

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 deviations close to zero, whatever the type of test perform.

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 perfectly in real conditions. The test bench is reliable and gives reproducible results.
- 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 MFM and the dispenser: the longer the distance, the bigger the errors. For Configuration 2, as this distance is very short, the error is negligible.

Results obtained were shared with the German Authorities (Eichämter) and the Dutch market surveillance (Agentschap Telecom), which was very appreciated.

In parallel, several dissemination meetings were organized in the frame of Task 3, with people from different National Institutes / Authorities in Europe than those involved in Task 1: Spain, Czech Republic and Belgium. A specific web-meeting was organized with the members of the MetroHyVe project (WP1 dedicated to hydrogen flow metering in HRS) to disseminate widely the results and conclusions, and get feedbacks from different experts in gaseous flow metering.
A final face-to-face meeting was organized at FCH-JU premises on March 20th with all stakeholder in Europe. A good support was obtained from all participants, but the final decision to apply the testing protocol remain in the hands of each National Authority in Europe.

This tender has been finished at end of April 2019.