METROLOGY for HYDROGEN VEHICLES

REPORT:

A1.5.3 & A1.5.4: Provision of an Uncertainty Budget for the Gravimetric Approach to calibrate Flow Meters at Hydrogen Refuelling Stations

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

www.metrohyve.eu

This report was written as part of activities A1.5.3 & A1.5.4 from the EMPIR Metrology for Hydrogen Vehicles (MetroHyVe) project. The three year European project commenced on 1st June 2017 and focused on providing solutions to four measurement challenges faced by the hydrogen industry (flow metering, quality assurance, quality control and sampling). For more details about this project please visit www.metrohyve.eu.

This report was written by:

Kurt Rasmussen (lead)	FORCE Technology	*ktr@force.dk*
Brian Ramsgaard	FORCE Technology	*bkra@force.dk*
Rémy Maury	Cesame Exadebit	*r.maury@cesame-exadebit.fr*
Panayotis Dimopoulos	Empa	*panayotis.dimopoulos@empa.ch*
Sigrid Rønneberg	Justervesenet	*sir@justervesenet.no*
Marc de Huu	METAS	*marc.dehuu@metas.ch*

Contents

Abbreviations

CMF	Coriolis mass flow meter
EUT	Equipment under test
HFTS	Hydrogen field test standard
HRS	Hydrogen refuelling station
MPE	Maximum permissible error
NWP	Nominal working pressure

1. Introduction

In the framework of the work package 1 ("Flow metering"), task 1.5 "Uncertainty budget for the type approval testing, the periodic verification and gravimetric facility" aims to identify and assess the uncertainty sources for hydrogen metering.

The aim of activity A1.5.3 is to provide an uncertainty budget for the field tests performed in activity A1.4.3 using the gravimetric standards developed in A1.4.1 at nominal working pressure (NWP) of 350. Likewise, the aim of activity A1.5.4 is to provide an uncertainty budget for the field tests performed in activity A1.4.4 at hydrogen refuelling stations (HRSs) with NWP of 700 bar using the gravimetric approach.

In this context, FORCE with the support from Cesame, Empa, JV and METAS have used the data collected from the field tests in order to provide an uncertainty budget, with a target of less than 4 % uncertainty, for the gravimetric approach to calibrate flow meters at HRSs dispensing hydrogen at NWP of 350 and 700 bar.

2. Relative Calibration Error

The relative calibration errors are key test results to ensure that HRSs comply with the maximum permissible error (MPE) requirements for type evaluations and verifications (1).

The relative calibration error in percent err_{H2} can be calculated by the following formula:

$$err_{H2} = \left(\frac{m_{EUT}}{m_{ref}} - 1\right) \times 100$$

where m_{EUT} is the dispensed mass on the equipment under test (EUT) which are readings of the HRS meter and m_{ref} is the dispensed mass which is calculated for the hydrogen field test standard (HFTS).

The dispensed mass on the EUT m_{EUT} can be calculated by the following formula:

$$m_{EUT} = m_{EUT2} - m_{EUT1}$$

where m_{EUT1} is the initial dispensed mass reading and m_{EUT2} is the final dispensed mass reading on the HRS.

The dispensed mass on the HFTS m_{ref} has recently been described in detail (2) and can be calculated by the following formula:

$$m_{ref} = (W_2 - W_1)\left(1 - \frac{\rho_0}{\rho_N}\right) + V_0[\rho_{air2}(1 + \lambda \Delta P_2)(1 + 3\alpha \Delta T_2) - \rho_{air1}(1 + \lambda \Delta P_1)(1 + 3\alpha \Delta T_1)] + V_{frame}(\rho_{air2} - \rho_{air1})$$

where W_1 is the initial and W_2 is the final scale reading with the mass correction factor $\left(1 - \frac{\rho_0}{\rho_N}\right)$. The buoyancy correction consists of two parts: 1) the external tank volume which is corrected for pressure and thermal expansion and 2) the frame placed on the scale.

3. Main Influence Factors

The main sources of measurement uncertainty have been considered with respect to the relative calibration error of Coriolis mass flow meters (CMFs), which are used at HRSs calibrated with gravimetric approach using the HFTS. Table 1 and Table 2 give an overview of an example measurement and the resulting uncertainty budget. The individual sources of measurement uncertainty are discussed in this section, and then presented in tabular form in the uncertainty budgets given in Table 3.

3.1. Meter Resolution

The displayed mass reading on the HRS is limited by the CMFs scale interval. This uncertainty contribution can be neglected for the initial mass reading when the HRS is equipped with a zero-setting device.

The meter resolution on a HRS is typically 1 gram.

A value of ±0.001 kg (rectangular distribution) was assigned to the uncertainty budget.

3.2. Zero-point Stability

According to uncertainty guidelines the zero-point stability of the HRSs meter also need to be taken into account in the uncertainty budget for the relative calibration error (3).

Zero point stability is a property of a CMF and corresponds to a reading offset that depends on pressure and temperature and has a greater influence at lower flow rates. It largely determines the minimum flow rate at which a CMF can provide accurate measurements.

Typical vehicle tank size is 100 liters for a NWP of 700 bar. It can hold approximately 4 kg of hydrogen, and with a typical refulling time of 5 minutes this gives an average mass flow rate of $\frac{4\,kg}{5\,min} = 0.8\,kg/min.$

In the course of these experiments, typical zero-point values of ±0.002 kg/min have been assigned. If one relates this values to the average mass flow rate value of 0.8 kg/min, this yields a maximum uncertainty of 0.25% due to zero point stability.

A value of ±0.002 kg was assigned to the uncertainty budget.

3.3. Scale Resolution

The scale reading on the HFTS is limited by the scale interval.

The scale used on a HFTS typically has a resolution of 0.1 gram.

A conservative value of ±0.001 kg was assigned to the uncertainty budget.

3.4. Scale Calibration Uncertainty

The calibration is performed to determine or verify the accuracy of the HFTSs scale, with an associated uncertainty.

A value of ±0.0005 kg was assigned to the uncertainty budget.

3.5. Scale Calibration Deviation

The deviation describes how close the reading of the meter is to its calibration curve.

A value of ±0.0005 kg was used in the uncertainty budget.

3.6. Scale Repeatability

Repeatability is a quantitative measure of how well a measuring device provides the same output when the measured parameter and conditions are held constant. Ideally, the measuring device will provide identical readings until the measured parameter is changed. However, in reality, all measuring devices will produce a spread of results to some degree.

In order to assess repeatability, the measurement conditions must be kept as consistent as possible, by following the same measurement procedure with the same operators, using the same measurement system, at the same location with the same environmental conditions. Replicated measurements should be taken over a short period of time.

The repeatability of the scale can be expressed as a relative value from the actual calibration value.

A value of ±0.0002 kg has been estimated for the uncertainty budget.

3.7. Scale Drift

The scale reading varies over time. For these measurements, a scale drift of 0.4 gram has been observed over a time of 90 minutes.

Therefore, a value of ±0.0004 kg was assigned for the uncertainty budget.

3.8. Air Density

Air density depends mainly on pressure, temperature and humidity.

It is important that the ambient conditions (e.g. heating from sunlight) are stable during tests.

The air density has been has determined with a relative uncertainty of 0.15 % (k=1) during measurements.

A value of ±0.0017 kg was assigned for the uncertainty budget.

4. Less Significant Influence Factors

Additional sources of measurement uncertainty have been included in the uncertainty budget. Their combined contribution is presumed negligible. These additional uncertainties are presented in tabular form on the uncertainty budget in Table 3, and include:

- Eccentric Loads
- External volume of tanks
- Frame volume
- Pressure transducer
- Pressure expansion coefficient
- Temperature transducer
- Linear thermal expansion coefficient

Please note that these are general considerations for the influence factors. Detailed considerations are needed for the specific field test, where the quality of the equipment in use will impact the different uncertainty contributions to the measurements.

5. Measurement Uncertainty Budget

5.1. Uncertainty budget

The uncertainty budget can be created based on the formulas for calculating the relative calibration error in section 2. The input quantities for the formulas are listed in Table 1 and the calculated output values are listed in Table 2. The uncertainty components from section 3 and 4 are listed in Table 3 and their contribution to the measurement uncertainty is summarised in the final column of Table 1.

Table 1: As an example: A typical calculation for the measurement uncertainty U(k=1) for the calibration of a HRS using HFTS gravimetric method with a nominal mass of 1.0 kg. A summary of the input values is given in this table.

input quantity		estimate		standard uncertainty		
	X_i	x_i	Unit	$u(x_i)$	Unit	contribution
Initial dispensed mass reading on EUT	m_{EUT1}	0,000	kg	0,00	%	0,0%
Final dispensed mass reading on EUT	m_{EUT2}	1,000	kg	0,21	%	86,5%
Initial scale reading	W_1	150,000	kg	0,05	%	4,4%
Final scale reading	W_2	151,000	kg	0,05	%	4,4%
Air density at reference condition	p_0	1,2	kg/m^3	0,00	%	4,47E-07
Stainless steel density at ref. conditions	p_N	8000	kg/m^3	0,00	%	4,47E-07
Hydrogen tank external volume	V_0	0,1200	m^3	0,010	%	0,19%
Frame Volume	V_{frame}	0,070	m^3	0,005	%	0,05%
Initial air density	p_{air1}	1,140	kg/m^3	0,032	%	2,1%
Final air density	p_{air2}	1,150	kg/m^3	0,033	%	2,2%
Initial pressure difference from ref. value	ΔP_1	0,10	MPa	0,000	%	3,60E-06
Final pressure difference from ref. value	ΔP_2	35,00	MPa	0,000	%	3,66E-06
Pressure expansion coefficient	λ	2,20E-04	MPa^{-1}	0,011	%	0,22%
Initial temperature difference from ref. value	ΔT_1	20,0	°C	0,000	%	2,68E-09
Final temperature difference from ref. value	ΔT_2	100,0	°C	0,000	%	2,77E-09
Linear thermal expansion coefficient	α	2,00E-06	°C^{-1}	0,000	%	8,03E-13
			(k=1)	0,22	%	100,0%

Table 2: The output values calculated from the input in Table 1.

output			
	Y	y	Unit
Dispensed mass on Equipment Under Test (EUT)	m_{EUT}	1,0000	kg
Dispensed mass on reference	m_{ref}	1,0029	kg
Relative calibration error	err_{H2}	-0,29	%
Expanded Uncertainty (k=2)	U	0,45	%

Table 3: Complete list of uncertainty sources which are summarized in Table 1.

No.	source of uncertainty (uncertainty component)	acts on imput quantity	X_i	uncertainty value a_i	Unit	% of x_i	probability distribution	divisor k	sensitivity coefficient c_i	Unit	standard uncertainty $u(x_i)$	Unit	Significance check (Contribution)
3.1	Meter resolution of 1g (not included due to zero setting)	Initial dispensed mass reading on EUT	m_{EUT1}	0	kg	-	Rectangular	1,73	-99,71	%/kg	0,00	%	0,0%
3.1	Meter resolution of 1g	Final dispensed mass reading on EUT	m_{EUT2}	0,001	kg	0,10	Rectangular	1,73	99,71	%/kg	0,06	%	6,7%
3.2	Zero flow stability	Final dispensed mass reading on EUT	m_{EUT2}	0,002	kg	0,20	Normal	1	99,71	%/kg	0,20	%	79,8%
3.3	Scale resolution of 0,1 g	Initial scale reading	W_1	0,0001	kg	6,67E-05	Rectangular	1,73	99,41	%/kg	0,01	%	0,1%
3.4	Scale calibration, uncertainty	Initial scale reading	W_1	0,0005	kg	3,33E-04	Normal	2	99,41	%/kg	0,02	%	1,2%
3.5	Scale calibration, max deviation of 0.5 g	Initial scale reading	W_1	0,0005	kg	3,33E-04	Normal	2	99,41	%/kg	0,02	%	1,2%
	Eccentric loads	Initial scale reading	W_1	0	kg	0,00E+00	Normal	1	99,41	%/kg	0,00	%	0,0%
3.6	Repeatbility	Initial scale reading	W_1	0,0002	kg	1,33E-04	Normal	1	99,41	%/kg	0,02	%	0,8%
3.7	Scale drift over 90 minutes of 0.4 g	Initial scale reading	W_1	0,0004	kg	2,67E-04	Rectangular	1,73	99,41	%/kg	0,02	%	1,1%
3.3	Scale resolution of 0,1 g	Final scale reading	W_2	0,0001	kg	6,67E-05	Rectangular	1,73	-99,41	%/kg	-0,01	%	0,1%
3.4	Scale calibration, uncertainty	Final scale reading	W_2	0,0005	kg	3,33E-04	Normal	2	-99,41	%/kg	-0,02	%	1,2%
3.5	Scale calibration, max deviation of 0.5 g	Final scale reading	W_2	0,0005	kg	3,33E-04	Normal	2	-99,41	%/kg	-0,02	%	1,2%
	Eccentric loads	Final scale reading	W_2	0	kg	0,00E+00	Normal	1	-99,41	%/kg	0,00	%	0,0%
3.6	Repeatbility	Final scale reading	W_2	0,0002	kg	1,33E-04	Normal	1	-99,41	%/kg	-0,02	%	0,8%
3.7	Scale drift over 90 minutes of 0.4 g	Final scale reading	W_2	0,0004	kg	2,67E-04	Rectangular	1,73	-99,41	%/kg	-0,02	%	1,1%
	Assigned uncertainty	Air density at reference condition	p_0	0,012	kg/m^3	1,00	Normal	1	1,24E-02	% m3/kg	0,00	%	0,0%
	Assigned uncertainty	Stainless steel density at ref. conditions	p_N	80	kg/m^3	1,00	Normal	1	1,86E-06	% m3/kg	0,00	%	0,0%
	External volme of tank has been given uncertainty (k=1) of 5 L	External tank volume	V_0	0,005	m3	4,17	Normal	1	-1,93E+00	%/m3	-0,01	%	0,2%
	The volme of the frame and attached parts, excluding tanks, that are being weighted	Frame Volume	V_{frame}	0,005	m3	7,14	Normal	1	-0,9943	%/m3	0,00	%	0,0%
3.8	Determined with uncertainty of 0,15% (k=1) during measurements	Initial air density	p_{air1}	0,0017	kg/m^3	0,15	Normal	1	18,8929	% m3/kg	0,03	%	2,1%
3.8	Determined with uncertainty of 0,15% (k=1) during measurements	Final air density	p_{air2}	0,0017	kg/m^3	0,15	Normal	1	-18,9902	% m3/kg	-0,03	%	2,2%
	Digital pressure transducer have a resolution of 2 kPa	Initial pressure difference from ref. value	ΔP_1	0,001	MPa	1,00	Rectangular	1,73	2,99E-03	%/MPa	0,00	%	0,0%
	Digital pressure transducer, long term stability of 100 kPa	Initial pressure difference from ref. value	ΔP_1	0,1	MPa	100,00	Normal	1	2,99E-03	%/MPa	0,00	%	0,0%
	Digital pressure transducer, calibration and within specification	Initial pressure difference from ref. value	ΔP_1	0,2	MPa	200,00	Normal	2	2,99E-03	%/MPa	0,00	%	0,0%
	Digital pressure transducer have a resolution of 2 kPa	Final pressure difference from ref. value	ΔP_2	0,001	MPa	0,00	Rectangular	1,73	-3,02E-03	%/MPa	0,00	%	0,0%
	Digital pressure transducer, long term stability of 100 kPa	Final pressure difference from ref. value	ΔP_2	0,1	MPa	0,29	Normal	1	-3,02E-03	%/MPa	0,00	%	0,0%
	Digital pressure transducer, calibration and within specification	Final pressure difference from ref. value	ΔP_2	0,2	MPa	0,57	Normal	2	-3,02E-03	%/MPa	0,00	%	0,0%
	Assigned uncertainty of 10% (k=1)	Pressure expansion coefficient	λ	0,0	MPa^{-1}	10,0	Normal	1	-4,79E+02	% Mpa	-0,01	%	0,2%
	Digital temperature transducer, resolution	Initial temperature difference from ref. value	ΔT_1	0,01	°C	0,05	Rectangular	1,73	8,16E-05	kg/°C	0,00	%	0,0%
	Digital temperature transducer, long term stability	Initial temperature difference from ref. value	ΔT_1	0,10	°C	0,50	Normal	1	8,16E-05	kg/°C	0,00	%	0,0%
	Digital temperature transducer, calibration	Initial temperature difference from ref. value	ΔT_1	0,20	°C	1,00	Normal	2	8,16E-05	kg/°C	0,00	%	0,0%
	Digital temperature transducer, resolution	Final temperature difference from ref. value	ΔT_2	0,01	°C	0,01	Rectangular	1,73	-8,30E-05	kg/°C	0,00	%	0,0%
	Digital temperature transducer, long term stability	Final temperature difference from ref. value	ΔT_2	0,10	°C	0,10	Normal	1	-8,30E-05	kg/°C	0,00	%	0,0%
	Digital temperature transducer, calibration	Final temperature difference from ref. value	ΔT_2	0,20	°C	0,20	Normal	2	-8,30E-05	kg/°C	0,00	%	0,0%
	Assigned uncertainty	Linear thermal expansion coefficient	α	2,00E-07	°C^{-1}	10,0	Normal	1	-4964,10	kg °C	0,00	%	0,0%
							Square of standard uncertainty $u^2(y)$				0,05	%^2	100,00%
							Standard Uncertainty $u(y)$				0,22	%	
							Expansion Coefficient k				2,00		
							Expanded Uncertainty U				0,45	%	

5.2. Measurement Uncertainty Plot

The measurement uncertainty plot summarises the results from the examples shown in Table 4 below. As seen, a significant effect is observed when the dispensed mass is small. The main contribution comes from the zero-point instability of the CMF meter on the HRS.

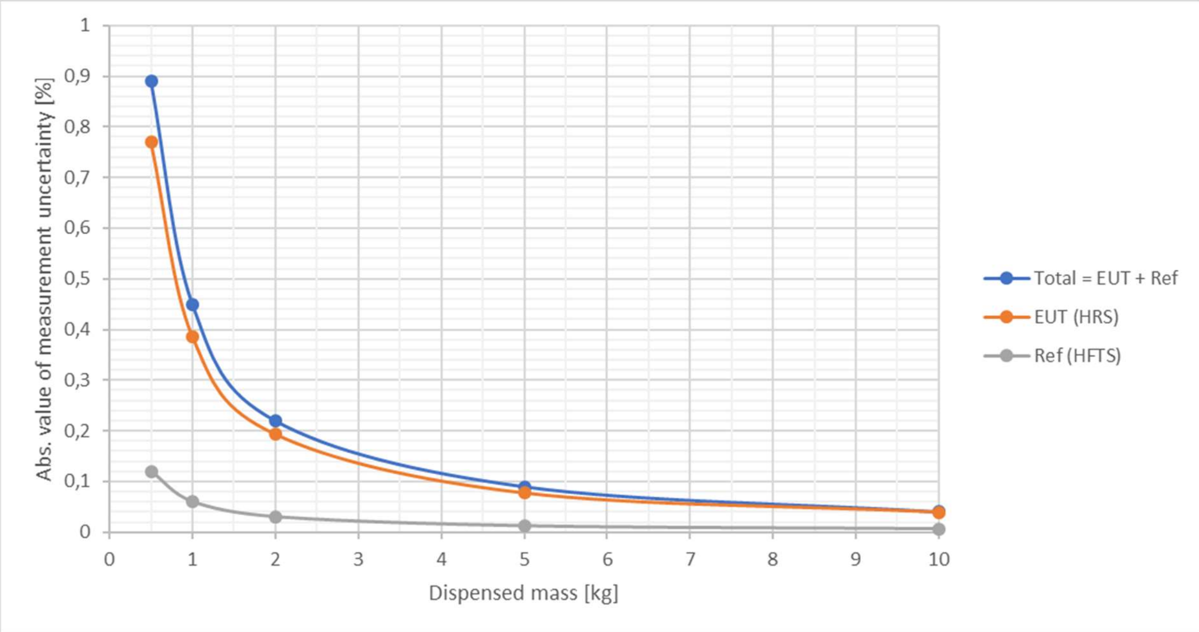

Figure 1: Measurement Uncertainty Plot U(k=2) for the examples given in Table 4.

Table 4: Examples for calculations of the measurement uncertainties U(k=2) of entire calibration curves (main contributions 3.1 to 3.8) with a focus on the effects of dispensed mass.

Dipensed mass [kg]	Absolute value of measurement uncertainty [%]
0,5	0,89
1	0,45
2	0,22
5	0,09
10	0,04

6. Sources of Measurement Uncertainty not represented in the uncertainty budget

Some potential sources of uncertainty contribution are mentioned below. These will be part of the repeatability and should be part of the expanded uncertainty budget of the gravimetric method, if they become significant contributions.

6.1. Icing and condensation

HFTS design and initial checks before testing should ensure that there is no significant contribution of icing or condensation to the uncertainty budget.

6.2. Hydrogen leaks

HFTS design and safety procedures must ensure that there are no leaks from the HFTS. As such, hydrogen leaks do not need to be added to the uncertainty budget.

6.3. Wind load on vent stack

HFTS design should ensure that there is no significant contribution, if necessary by the use of windshields or other physical barriers. Calibrations should be postponed if wind conditions contribute significantly to the calibration uncertainty.

6.4. Losses due to venting

Venting after refuelling can lead to a significant amount of hydrogen that have been measured by the HRS but not measured by the scale at the HFTS. Such venting have to be taken into account either by a correction of the dispensed mass or by an uncertainty contribution.

References

1. ***OIML R139: Compressed gaseous fuel measuring systems for vehicles Part 1: Metrological and technical requirements.*** **s.l. : International Organization of Legal Metrology, 2018.**

2. ***Design of gravimetric primary standards for field-testing of hydrogen refuelling stations.*** **M. de Huu, M. Tschannen, H. Bissig, P. Stadelmann, O. Büker, M. MacDonald, R. Maury, P.T. Neuvonen, H.T. Petter, K. Rasmussen. Flow Measurement and Instrumentation, s.l. : Elsevier, 2020, Vol. 73.**

3. ***OIML R139: Compressed gaseous fuel measuring systems for vehicles Part 2: Metrological controls and performance tests.*** **s.l. : International Organization of Legal Metrology, 2018.**