Measurement uncertainty tool for HRS dispensers

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Abstract

Verifications of hydrogen refuelling stations have shown that variations in the station design and operation can greatly influence accuracy at the dispenser, and there are sources of error unrelated to the flow meter which if uncorrected make it difficult to achieve the accuracy requirements of OIML R-139. To improve dissemination of knowledge in this area, an interactive measurement uncertainty tool has been developed which allows the user to specify a range of different station configurations and filling scenarios to estimate the resulting errors at the dispenser. This is intended to serve as a basis for HRS manufacturers to improve HRS designs with respect to billing accuracy and to assist notified bodies in understanding uncertainty contributions from an HRS and the corrections required. This paper describes the initial version of the HRS uncertainty tool, explaining the inputs required from the user, the sources of measurement uncertainty considered, how the flow meter behaviour is modelled, and which calculations are implemented.

1. Introduction

The EMPIR-funded project 16ENG01 MetroHyVe established the basis of a broad underpinning metrological infrastructure for hydrogen refuelling stations (HRS) and fuel-cell vehicles (FCEVs) in Europe. Regarding flow metrology, several partners developed primary standards for testing the amount of hydrogen delivered by the stations, which allow validation of the HRS against the requirements of the OIML R139 [1] recommendation. Additionally, extensive testing was performed on flow meters used in HRS to understand and document various influences on their performance, including pressures in the range 5 bar to 850 bar and temperatures in the range -40 °C to +40 °C.

The follow-on project 19ENG04 MetroHyVe 2 builds on this work through the development of new primary and secondary flow standards, which will both improve the existing traceability for light duty vehicles and extend it to heavy-duty applications. Knowledge developed in the project will be disseminated via guidelines and good practice guides to ensure accurate measurements and minimised uncertainty related to the design of the HRS.

A key activity is the development of a measurement uncertainty tool for hydrogen refuelling station dispensers, which would allow the user to specify a range of different HRS configurations and filling scenarios and estimate the resulting errors at the dispenser. This is intended to serve as a basis for HRS manufacturers to improve HRS designs with respect to billing accuracy and to assist notified bodies in understanding uncertainty contributions from an HRS and how to apply corrections. The need for this tool was recognised after surveying HRS operators in the first MetroHyVe project and observing that: 1) there are major differences in design between HRS, 2) certain aspects of the design can lead to large errors at the dispenser, and 3) although it is possible to apply corrections to eliminate some major sources of billing error, these corrections are not applied in many HRS. Evidence of this is provided by field verifications performed during the project [2]; measurements at seven different HRS showed that the stations studied could be categorised either as “Configuration 1” or “Configuration 2”, where the Configuration 1 stations displayed distinctive error trends dominated by uncorrected “dead volume” effects.

This paper describes the initial version of the HRS uncertainty tool, explaining the inputs required from the user, the sources of measurement uncertainty considered, how the flow meter behaviour is modelled, and which calculations are implemented.

2. Description of the measurement uncertainty tool

2.1 Overview

The uncertainty tool was developed as an MS Excel workbook. Separate sheets are used to organise the input data and calculation steps. Many of the calculations are performed at cell level, but Visual Basic for Applications (VBA) is used for the following operations:

- Formatting of user forms and results tables
- Updating the user interface when the user selects a different HRS configuration
- Selecting the appropriate fill profile data
- Calculation of hydrogen density
- Calculation of errors and measurement uncertainty associated with dead volume and vented gas

2.2 Main Contributions to Billing Error

The main output of the uncertainty tool is an estimated error range, where error refers to the difference between amount of hydrogen billed vs. the amount of hydrogen delivered by the dispenser to the vehicle tank.

A generalised schematic of a HRS is shown in Figure 1.

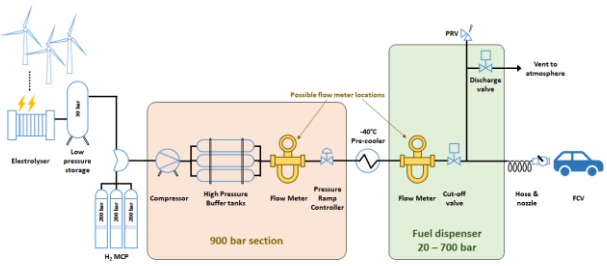


Figure 1: HRS Schematic

The three main sources of billing error can be identified with reference to the schematic:

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

Error source 1 is self-explanatory. Any inaccuracy of the flow meter directly contributes to errors in billing. Note that Coriolis meters are shown on the schematic. As far as the authors are aware, no other types of flow meter are currently used in hydrogen refuelling stations.

Error source 2 refers to the fact that for safety purposes, the dispenser hose (and other piping downstream of the cut-off valve) is vented at the end of the refuelling process. The vented hydrogen has been measured by the flow meter but not delivered to the vehicle, resulting in a billing error. Methods of correcting this error are provided in Annex B of OIML R139 [1], but there are still many HRS where no correction is applied for the vented gas.

Error source 3 is similar to source 2. It refers to the section of piping between the outlet of the flow meter and the cut-off valve in the dispenser. This contains hydrogen which has been measured by the flow meter but not delivered to the vehicle. Hydrogen contained within this "dead volume" is not vented, but the density of hydrogen can differ before and after a refuelling, resulting in the customer receiving either more or less hydrogen than they are billed for.

The relative contribution of each source of error depends on the design and operation of the HRS. Relative errors associated with the vented gas depend on dimensions of the vent piping, but also on the amount of hydrogen dispensed.

The accuracy of the flow meter is influenced by various factors including operating flow rate, temperature and pressure. As shown on the schematic, the location of the flow meter also differs between refuelling stations. Some HRS have the meter installed in the main station, upstream of the pressure ramp controller and pre-cooler, in other stations the meter is installed further downstream in the dispenser unit. The former is ideal in terms of the flow meter accuracy since the meter is maintained at ambient temperature and a high (approx. 900 bar) but consistent pressure. In the downstream location, the meter is exposed to wide pressure (approx. 20 bar to 700 bar) and temperature (approx. – 40 °C to +60 °C) ranges.

Errors attributed to the dead volume are largest when there is a significant piping volume between the meter outlet and the dispenser (e.g. meter installed further upstream), and when the current and previous HRS users refill their vehicles to different pressures (e.g. 350 bar and 700 bar).

Each of these influences is accounted for in the uncertainty tool. The following sections focus on each sheet to explain how the inputs selected by the user are used in the final calculation.

2.3 "Top Level" Sheet

This sheet allows the user to specify the configuration of the HRS and the filling sequence to be followed. It also displays the final results.

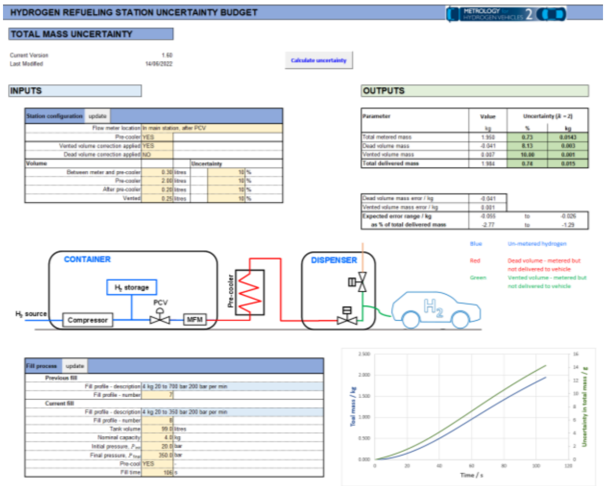


Figure 2: Screenshot of "Top Level" Sheet

The table named "Station configuration" displays the configuration settings of the HRS. Clicking the "update" button launches the user form which allows the user to change the configuration.

Under "Flow meter location", there are three options:

- In main station, before PCV
- In main station, after PCV
- In base of dispenser

Once this is specified, the schematic of the HRS is updated to show the selected flow meter location. This also determines which temperature and pressure are selected from the fill profile data to estimate the measurement uncertainty of the mass flow meter.

The user must also specify the piping volume, in litres for different sections of the HRS. The options displayed change depending on the selected flow meter location. For example, if the flow meter is located in the main station, the following volumes must be specified:

- Vented
- Between meter and pre-cooler
- Pre-cooler
- Between pre-cooler and cut-off valve in dispenser

The user also specifies the uncertainties in these volumes and whether corrections are applied for vented gas or mass change in dead volumes, or both.

The table named "Fill process" allows the user to select the fill profile followed by the current and previous users of the HRS using two drop down menus. The following information is displayed in the table:

- Fill profile description and number
- Tank volume, in litres
- Nominal capacity, in kg
- Initial pressure, in bar
- Final pressure, in bar
- Pre-cool (YES or NO)
- Fill time, in seconds

The data for each fill profile is saved to individual sheets on the Excel workbook. The user can add additional fill profiles, but the following are included already:

- 100 L tank, 20 to 700 bar, 200 bar per min
- 100 L tank, 20 to 350 bar, 200 bar per min
- 100 L tank, 350 to 700 bar, 200 bar per min
- 100 L tank, 20 to 180 bar, 200 bar per min
- 100 L tank, 180 to 350 bar, 200 bar per min
- 100 L tank, 350 to 580 bar, 200 bar per min

The "Outputs" table displays the following results which are calculated for the selected station configuration and fill profiles:

- Total metered mass, in kg
- Dead volume mass, in kg
- Vented volume mass, in kg
- Total delivered mass, in kg
- Uncertainty (k=2) in total metered mass, total mass delivered, dead volume mass and vented volume mass, in kg and as %.
- Dead volume mass error, in kg
- Vented volume mass error, in kg
- Expected error range, in kg and as % of total delivered mass

The total metered mass is calculated from the fill profile data, by integrating the mass flow rate data across the refuelling period.

The dead volume mass is calculated from the product of the piping volume and the density difference based on the current and previous fuelling profiles:

$$m_{dv} = v_{dv}(\rho_2 - \rho_1)$$

Where:

m_{dv}	=	dead volume mass, kg
v_{dv}	=	volume of piping between flow meter and cut-off valve, m^3
ρ_1	=	density of hydrogen at the end of the previous refuelling, kg/m^3
ρ_2	=	density of hydrogen at the end of the current refuelling, kg/m^3

The volume of piping is specified by the user. Density is calculated from flow profile data for temperature and pressure at the relevant locations.

To reduce the calculation time a simplified correlation has been developed for gas density, rather than using a full equation of state.

For each isotherm, the compression factor *Z*, calculated from a reference-quality formulation [3], was fitted to a virial equation in normalised density and the virial coefficients were fitted to polynomials in normalised temperature.

The correlation is valid from 5 to 900 bar between -40 and 60°C. Across its full range of validity, the correlation fits the reference data to within 0.010 %. For $T < 250$ K, the uncertainty of the reference data is 0.20 % (at $k = 2$) so the uncertainty of densities calculated from this correlation will be 0.20 % (at $k = 2$). For $T >= 250$ K, the uncertainty of the reference data is 0.04 % (at $k = 2$), so the uncertainty of densities calculated from this correlation will be 0.041 % (at $k = 2$).

The mass of vented gas is simply:

$$m_{vv} = v_{vv}(\rho_2)$$

Where:

m_{vv}	=	vented gas mass, kg
v_{vv}	=	volume of piping containing vent gas, m^3
ρ_2	=	density of hydrogen at the end of the current refuelling, kg/m^3

If the user specifies that corrections have been applied for vented gas or dead volume, then the error is reduced to value of the uncertainty.

The expected error range is a combination of the uncertainty of the flow meter and the contributions of the dead volume and vented gas. The uncertainty of the total metered mass, dead volume mass and vented volume mass are combined by quadrature summation. This results in a combined uncertainty which is symmetrical about zero. The dead volume and vented volume errors are then added by straight summation, this can introduce a noticeable asymmetry to the expected error range when the dead volume and vented gas errors are uncorrected.

The error calculation is as follows:

$$\delta m_{del} = m_{dv} + m_{vv} \pm \sqrt{(Um_{dv}^2 + Um_{vv}^2 + Um_{tot}^2)}$$

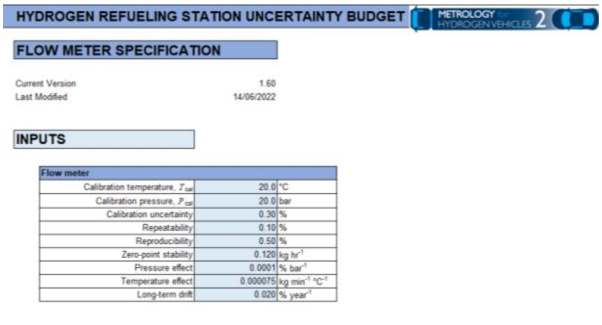
Where:

δm_{del}	=	total error in mass delivered to the vehicle tank, kg
m_{dv}	=	dead volume mass, kg
m_{vv}	=	vented gas mass, kg
Um_{tot}	=	uncertainty in total mass measured by flow meter, kg
Um_{dv}	=	uncertainty in the dead volume mass, kg
Um_{vv}	=	uncertainty in the vented volume mass, kg

The "Outputs" table is updated each time the "Calculate Uncertainty" button at the top of the sheet is clicked.

2.4 "Flow Meter" Sheet

This sheet includes a single table which displays the various factors influencing the flow meter measurement uncertainty.


HYDROGEN REFUELING STATION UNCERTAINTY BUDGET

METROLOGY HYDROGEN VEHICLES 2

FLOW METER SPECIFICATION

Current Version 1.60

Last Modified 14/06/2022

INPUTS

Flow meter		
Calibration temperature, T_{cal}	20.0	°C
Calibration pressure, P_{cal}	20.0	bar
Calibration uncertainty	0.30	%
Repeatability	0.10	%
Reproducibility	0.50	%
Zero-point stability	0.120	$kg\ hr^{-1}$
Pressure effect	0.0001	$\%\ bar^{-1}$
Temperature effect	0.000075	$kg\ min^{-1}\ °C^{-1}$
Long-term drift	0.020	$\%\ year^{-1}$

Figure 3: Screenshot of "Flow Meter" Sheet

The user has the option to input values manually, but the default values are based on experimental data for the flow meters tested in MetroHyVe 1 [4].

The parameters and their default values are as follows:

Calibration temperature: This value is used to estimate the uncertainty related to temperature effects. The default value is 20 °C.

Calibration pressure: This value is used to estimate the uncertainty related to pressure effects. The default value is 20 bar.

Calibration uncertainty: The only way to determine the base accuracy of the flow meter is to perform a flow calibration. The measurement uncertainty of the flow meter can at best only be as low as the uncertainty of the standard it is calibrated against. The default value is ±0.3%, which corresponds to the measurement uncertainty of the flow calibration facilities used in MetroHyVe 1.

Repeatability: This is a measure of how well a measuring device provides the same output when the measured parameter is held constant. The default value is ±0.1%, all the meters tested in MetroHyVe 1 achieved this figure or lower.

Reproducibility: This refers to the ability of a measuring device to provide the same output for the same measured quantity after significant changes to the location, environment, operators, measuring systems or at a significantly later time. The default value is ±0.5%, this is based on the largest shift observed for any meter tested at multiple laboratories in MetroHyVe 1.

Zero-point stability: This is a property of Coriolis mass flow meters. It is a constant offset value which is usually provided by the manufacturers. Since it is a constant value, the zero-point stability has a greater influence at low flow rates and largely determines the minimum flow rate at which the meter can provide an accurate measurement. The default value is ±0.002 kg/min, all the meters tested in MetroHyVe 1 achieved this figure or lower.

Pressure effect: Increasing the line pressure causes an increase in the stiffness of the Coriolis mass meter measuring tubes. The increased rigidity has a direct impact on the vibration behaviour of the measuring tubes and hence on the mass flow and density measurement. The pressure effect causes a relative shift which does not depend on flow rate. The default value is -0.0001% per bar. This very small value is based on observations of meters tested at up to 850 bar in MetroHyVe 1 [5].

Temperature effect: Increasing temperature leads to a decrease in stiffness in the measurement tubes and affects the density and mass flow measurement. The temperature effect is treated in a similar way to the zero-point stability, in that it is a constant which has greater influence at low flow rates. The default value is ±7.5E-5 kg/min per °C, which was based on results obtained from MetroHyVe 1 testing at stable temperatures of -40 to +40 °C. Note: The uncertainty budget only considers the effect of temperature in cases where sufficient time has been allowed for the flow meter and incoming gas to reach thermal equilibrium. In MetroHyVe 1, additional errors were observed when cold gas was suddenly introduced to meters at room temperature, but there are insufficient data to model this effect accurately.

Long-term drift: The long-term drift is the amount of change of the mass flow rate reading at the same measuring conditions over a given period of time, which is typically quoted as an annual figure. The default value is ±0.02 % per year.

2.5 "Total Mass" Sheet

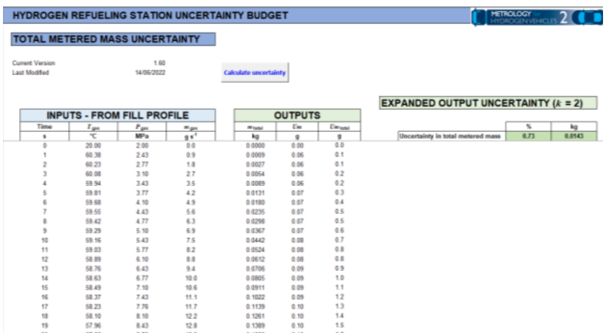


Figure 4: Screenshot of "Total Mass" Sheet

This sheet shows the data extracted from the selected fill profile which is used to calculate the uncertainty of the flow meter. The inputs are:

- Time: The timestamp from the fill profile, in one second increments
- T_{gas}: The instantaneous temperature at the flow meter for each timestamp. The calibration temperature of the meter is deducted from this value to calculate the estimated temperature effect. The flow meter location specified by the user in the "Top level" sheet determines which temperature reading is selected from the fill profile data
- P_{gas}: The instantaneous pressure at the flow meter for each timestamp. The calibration pressure of the meter is deducted from this value to calculate the estimated pressure effect. The flow meter location specified by the user in the "Top level" sheet determines which pressure reading is selected from the fill profile data.
- m_{gas}: The instantaneous mass flow rate for each timestamp. It is used to calculate uncertainty for the flow meter, since several uncertainty sources are flow-rate dependant.

The outputs are:

- m_{total}: The totalised mass of hydrogen dispensed
- U_m: The expanded uncertainty (k=2) in grams in the instantaneous mass flow rate. These values are calculated in the "Mass Flow Rate" sheet.
- $U_{m,total}$: The totalised mass uncertainty in grams.
- Uncertainty in total metered mass: The expanded uncertainty (k=2) in the totalised mass of hydrogen dispensed at the end of the filling sequence. Expressed in kg and in %. These values are also displayed in the "Top Level" sheet

2.6 "Mass Flow Rate" Sheet

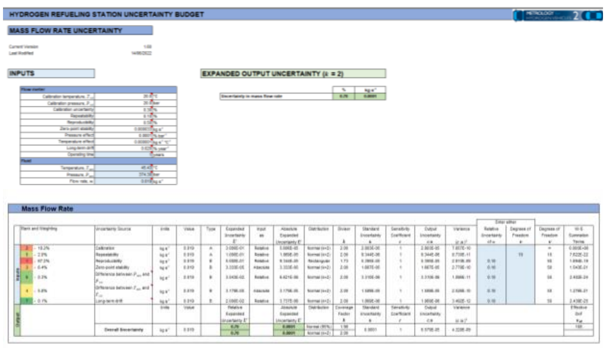


Figure 5: Screenshot of "Mass Flow Rate" Sheet

The "Inputs" table takes the component uncertainty sources from the "Flow Meter" sheet; calibration temperature, calibration pressure etc. It also has the following inputs:

- Operating time: This is used for calculation of drift uncertainty, the unit is years
- Temperature T_{gas}: The same parameter as T_{gas} on the "Total Mass" sheet.
- Pressure P_{gas}: The same parameter as P_{gas} on the "Total Mass" sheet.
- Flow rate, m: The same parameter as m_{gas} on the "Total Mass" sheet.

The "Mass Flow Rate" table shows the uncertainty budget for the flow meter, where the various component uncertainty contributions are combined to provide an expanded uncertainty (k=2) in mass flow rate. For each one second interval in the filling process, the mass flow rate, temperature and pressure at the meter are copied into the uncertainty budget to calculate the uncertainty in mass flow rate at those specific conditions. These values are then copied into the "Total Mass" sheet, where the mass flow and associated uncertainty are totalised for the refuelling period.

2.7 "Fill Profile" Sheets

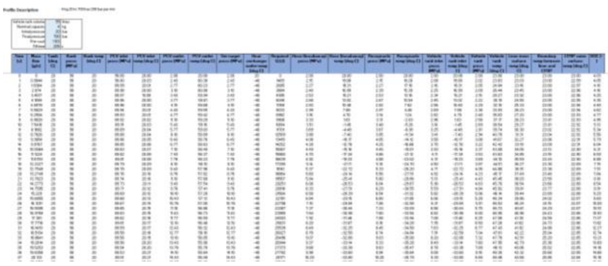


Figure 6: Screenshot of a "Fill Profile" Sheet

Billing errors at the dispenser are greatly influenced by the HRS design and operating conditions. Therefore, the uncertainty tool requires realistic fill profile data as an input. A sheet is dedicated to each fill profile, and the user can add as many as necessary. These sheets are named using the format "Fill Profile x", where x is an integer.

The following identifying information is entered by the user and used by the VBA code:

- Profile Description: The short description; it appears in the drop-down menu that allows the user to select a fill profile in the "Top Level" sheet.
- Nominal capacity: The estimated hydrogen capacity of the vessel used in the fill profile data.
- Initial Pressure: The nominal pressure at the beginning of refuelling, in bar
- Final Pressure: The nominal pressure at the end of refuelling, in bar
- Pre-cool: The user specifies whether the fill profile includes pre-cooling of the hydrogen ("YES" or "NO")
- Fill time: The total time for refuelling, in seconds

The fill profile data are then tabulated below. The H2FillS software [6] developed by NREL has been used to generate various fill profiles. Therefore, the data tables use the same format as that H2FillS exports to MS Excel. The user can add new fill profile data using other simulation software, or even real measurement data from an HRS. However, for the uncertainty tool to operate correctly, the fill profile data needs to be entered into the same table format, and at a minimum, the following cells need to be populated:

Time [s]: The timestamp for the measurements, in seconds.

Mass flow [g/s]: The instantaneous mass flow rate, in g/s.

PCV inlet press [MPa]: The instantaneous pressure upstream of the pressure control valve, in MPa. Depending on the selected HRS configuration, it may be used as a reference pressure at the meter and for calculating dead volume error.

PCV inlet temp [deg C]: The instantaneous temperature upstream of the pressure control valve, in °C. Depending on the selected HRS configuration, it may be used as a reference temperature at the meter and for calculating dead volume error.

PCV outlet press [MPa]: The instantaneous pressure downstream of the pressure control valve, in MPa. Depending on the selected HRS configuration, it may be used as a reference pressure at the meter and for calculating dead volume error.

PCV outlet temp [deg C]: The instantaneous temperature downstream of the pressure control valve, in °C. Depending on the selected HRS configuration, it may be used as a reference temperature at the meter and for calculating dead volume error.

Hose (breakaway) press [MPa]: The instantaneous pressure at the dispenser hose, in MPa. This is used for calculating the error due to vented gas. Depending on the selected HRS configuration, it may also be used as a reference pressure at the meter.

Hose (breakaway) temp [deg C]: The instantaneous temperature at the dispenser hose, in °C. This is used for calculating the error due to vented gas. Depending on the selected HRS configuration, it may also be used as a reference temperature at the meter.

Heat exchanger outlet temp [deg C]: The instantaneous temperature at the outlet of the heat exchanger, used to calculate dead volume error.

3. Limitations and further development

At the current stage of development, the uncertainty tool implements the knowledge gained from the MetroHyVe projects on the uncertainty sources within HRS dispensers and the influences on flow meter behaviour. There are however some notable limitations and areas for improvement.

The main limitation of the uncertainty tool is that it requires realistic HRS data as an input. Selecting different fill profiles is very simple, but if the user needs to simulate a different tank size or fill profile than those already available, new HRS data must be generated. If the HRS data used has errors or unrealistic trends, this will reduce the accuracy of the estimates provided by the uncertainty tool.

Considering the flow meter behaviour, all but one of the influences studied in MetroHyVe 1 has been implemented. The exception is the influence of transient temperature effects. Temperature effects have been included in the flow meter uncertainty budget, but this is based only temperature effects once thermal equilibrium is reached. Experiments were also previously carried out where the meter was initially at room temperature and gas was introduced at -40°C. In the period before thermal equilibrium was reached, the flow meter behaviour was very unstable, showing variable errors which could exceed 10% in magnitude. Unfortunately, there were not enough data to model this effect and implement it into the flow meter uncertainty budget. This effect is only relevant for one of the flow meter locations that can be selected, when the meter is in the base of the dispenser and downstream of the heat exchanger. In that case, the meter can be expected to experience rapid changes in temperature when pre-cooled hydrogen is introduced at the start of refuelling. Therefore the errors estimated by the uncertainty tool for this HRS configuration are likely to be too optimistic. This is something that will be investigated further when field verifications are performed at HRS with meters installed downstream of the pre-cooler.

Another limitation of the uncertainty tool is that a HRS configuration which is increasingly common is not represented. There are now HRS which have the meter installed in the dispenser unit, with a pre-cooler further downstream, but this option is not currently selectable. This station configuration will be added to the next revision of the HRS uncertainty tool.

Crucially, the current version of the uncertainty tool has not been validated. The authors are confident in the modelling of the flow meter behaviour since this is based on results from an extensive test programme, but the HRS error ranges estimated by the uncertainty tool have yet to be compared with measurement results from a real HRS. The tool is at least able to generate realistic looking trends. Figure 7 shows estimated error ranges for several filling conditions.

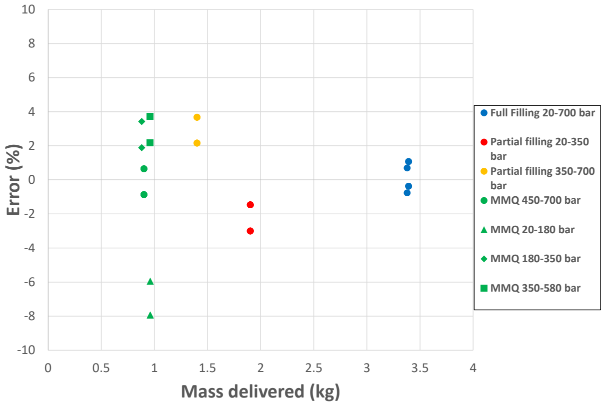


Figure 7: Estimated error ranges for sequential fills to varying pressures

The settings used are shown in Table 1.

Table 1: Configuration used for simulated sequential fills

Tank size	100 litre
Average pressure ramp rate	200 bar/min
Flow meter location	In main station, before PCV
Piping volume between meter and cut-off valve	2.5 litres
Piping volume of vented section	0.25 litres
Correction applied for vented gas?	Yes
Correction applied for dead volume?	No

The filling sequence is as shown on the legend, starting with 20 to 700 bar, then 20 to 350 bar, 350 to 700 bar etc. This is the same sequence followed in the test programme carried out by CESAME and Air Liquide during the MetroHyVe 1 project [2]. As expected, the predicted error ranges are broadly consistent with the results for “Configuration 1” stations in the field verifications. In both cases, the main error contribution comes from the dead volume effect which leads to the distinctive trend with filling sequence. A more in-depth comparison is unfortunately not possible because the piping dimensions are not known for the stations studied in the test programme.

In the remainder of the MetroHyVe 2 project, the tool will be validated with measurement data from HRS verifications using primary standards and further improvements will be made to the user interface.

However, it is anticipated that the functionality of the tool will remain largely unchanged. The final version of it will be published on the MetroHyVe 2 project website [7], links will be provided to both the Excel file and a guide for users.

4. Conclusion

A measurement uncertainty tool for hydrogen refuelling stations has been developed, with the aim to improve dissemination of knowledge about the various influences affecting accuracy at the dispenser. The tool is based on an MS Excel workbook with user forms that allow the user to specify a variety of configurations and filling profiles. Billing errors are estimated by taking into consideration the likely behaviour of the flow meter and the contribution of errors from vented gas and density changes in dead volumes. In the remainder of the MetroHyVe 2 project, the uncertainty tool will be validated using measurement data from HRS verifications. The total will be further refined, and the final version will be freely accessible from the project website

Acknowledgment

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