Deliverable D1: Technical report on the methods used for the calibration of a Coriolis flow meter as a calibration standard under high pressure (at least 90 MPa) operating conditions, and flow rates up to 10 kg/min, with gaseous hydrogen including an uncertainty budget

DELIVERABLE D1

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<tr>
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<td>European Metrology Program for Innovation and Research</td>
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<table>
<thead>
<tr>
<th>Project name</th>
<th>Project short name</th>
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<tr>
<td>Metrology infrastructure for high-pressure gas and liquified hydrogen flows</td>
<td>MetHyInfra</td>
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<thead>
<tr>
<th>Author(s)</th>
<th>Pages</th>
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</thead>
<tbody>
<tr>
<td>Marc MacDonald NEL <a href="mailto:marc.macdonald@tuvsud.com">marc.macdonald@tuvsud.com</a></td>
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</tbody>
</table>

**Summary**

This report was written as part of activity 1.3.4 from the EMPIR Metrology infrastructure for high-pressure gas and liquified hydrogen flows (MetHyInfra) project. It describes the methods used for the calibration of a Coriolis flow meter as a calibration standard under high pressure (at least 90 MPa) operating conditions, and flow rates up to 10 kg/min, with gaseous hydrogen. The calibration results and uncertainty budget are presented as evidence for the efficacy of this approach.

**Confidentiality**

Public
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1 Introduction
The overall objective of the MetHyInfra project is to establish a metrological infrastructure which will allow the assessment and calibration of flow meters and sonic nozzles for the measurement of hydrogen flow at high pressures. WP1 aims to develop calibration methods for sonic nozzles and master meters at pressures up to 100 MPa and flow rates up to 10 kg/min. There are currently no flow testing facilities that can circulate hydrogen at those conditions, so a novel approach is taken in this project.

In Task 1.3, a master meter was mounted in a modified hydrogen refuelling station (HRS) dispenser and calibrated using a mobile gravimetric flow standard as the reference. The calibrated master meter will subsequently be used to calibrate sonic nozzles in Task 1.4.

This report describes the methods used for the calibration of a Coriolis flow meter as a calibration standard under high pressure (at least 90 MPa) operating conditions, and flow rates up to 10 kg/min, with gaseous hydrogen. The calibration results and uncertainty budget are presented as evidence for the efficacy of this approach.

2 Testing Equipment
2.1 Master Meter
There are commercially available flow meters which can operate at the conditions required for Task 1.3. Flow meters designed for use in HRS dispensers typically operate at pressures up to 100 MPa and flow rates up to 10 kg/min. Several of these meters were studied in detail in the 16ENG01 MetroHyVe project, and several measurement institutes have implemented those meters into mobile primary standards which were developed for validation of HRS dispenser accuracy. Based on this previous experience, it was decided to use a Rheonik RHM04 Coriolis belonging to METAS as the master meter for Task 1.3, this is the same meter selected as the transfer standard for the intercomparison of HRS flow standards in 19ENG04 MetroHyVe 2. The specifications are shown in Table 1.

<table>
<thead>
<tr>
<th>Specification of Coriolis Flow Meter and Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow meter type:</strong> RHM 04L GET, SN RHM-22843</td>
</tr>
<tr>
<td><strong>Transmitter:</strong> RHE 16, SN RHE-22735</td>
</tr>
<tr>
<td><strong>Manufacturer:</strong> Rheonik</td>
</tr>
<tr>
<td><strong>Flow rate range:</strong> (0.2 – 10) kg/h</td>
</tr>
<tr>
<td><strong>Pulses/kg:</strong> 10'000</td>
</tr>
<tr>
<td><strong>Connection type:</strong> Autoclave 3/8&quot; MP (9/16-18 UNF female thread)</td>
</tr>
<tr>
<td><strong>Maximum pressure rating:</strong> 1070 bar@50°C</td>
</tr>
</tbody>
</table>

Figure 1 presents the Rheonik Coriolis mass flow meter in its aluminium frame.
The flow meter had not previously been subject to a full calibration with hydrogen, however it had demonstrated favourable accuracy and measurement stability in many different operating environments and with several different fluids, including when previously installed in a hydrogen refuelling station.

A transmitter is required for power supply to and data transmission from the master meter. The meter, transmitter and cabling are shown in Table 2.
<table>
<thead>
<tr>
<th>Table 2: Flow Meter and Associated Hardware</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
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<tr>
<td><img src="image2.png" alt="Image" /></td>
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<td><img src="image3.png" alt="Image" /></td>
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<td><img src="image4.png" alt="Image" /></td>
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<td><img src="image5.png" alt="Image" /></td>
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</tbody>
</table>
2.2 Master Meter Software
The Rheonik RHM04 master meter was supplied with the proprietary Rheonik software used to communicate with the flow meter. Simple installation instructions were provided for the software and for the required drivers.

The data logging computer with the installed software connects to the transmitter via the supplied USB cable. The flow meter cable is then connected to the opposite side of the transmitter. Once the computer and flow meter are connected, the transmitter is powered on.

A screenshot of the Rheonik Dashboard software is shown in Figure 2.

![Rheonik Dashboard software](image)

Figure 2: Rheonik Dashboard software

2.3 Reference Flow Standard
A reference flow standard was required for the calibration of the Coriolis meter. The most appropriate reference flow device is a gravimetric primary standard designed for use with hydrogen refuelling stations. Several members of the MetHyInfra consortium have developed these systems and demonstrated measurement uncertainty of 0.3% (k=2) or better in mass of hydrogen. The mobile HRS flow standard built by CESAME was selected as the reference for Task 1.3. This system was chosen for its low measurement uncertainty and large collection volume. It uses two 104 litre tanks for a total collection volume of 208 L, which can store up to 9 kg of hydrogen at 70 MPa. As of September 2023, this is the largest capacity of any available HRS flow standard, which will allow higher maximum flow rates for the Coriolis meter calibration. The measurement uncertainty (k=2) in mass of hydrogen
collected is < 0.25%. Another advantage to using the CESAME flow standard is that it can be vented very quickly between fills, minimising down-time and maximising the amount of test data collected. A photo of the CESAME portable primary flow standard is shown in Figure 3.

Figure 3: CESAME Portable HRS Primary Standard
2.4 HRS Installation
To provide hydrogen at the required flow rate and pressure ranges, the master meter and reference flow standard must be connected to a hydrogen refuelling station dispenser, or a system with similar operating envelope.

The experimental hydrogen refuelling station operated by ZBT in Duisburg, Germany was selected for the master meter calibration. Unlike most HRS operators, the team at ZBT were willing to make significant modifications to the station configuration to accommodate test equipment, which is a key requirement for the calibration.

To ensure the best possible calibration, the factors affecting the Coriolis meter accuracy had to be considered. The flow meter is sensitive to various influences, particularly the operating temperature. Therefore, it was installed in the “warm region” of the refuelling station, upstream of the heat exchanger and pressure ramp controller. In this region, temperature is always near ambient and the pressure is consistently high, typically around 90 MPa. Pressure at the meter may fluctuate depending on the operating state of the refuelling station, but this particular flow meter is relatively insensitive to pressure, any fluctuations in pressure during the calibration would not introduce significant errors. The gravimetric flow standard was connected to the HRS dispenser hose, taking the place usually occupied by a vehicle. A schematic of the test installation is shown in Figure 4.

3 Test Matrix
Most flow meters are more accurate at constant flow rates and flow calibrations are normally performed at fixed flow rates covering the minimum to maximum range of the meter. This approach was not possible since the flow standard has a fixed volume and the HRS dispenser operates at variable flow rates to achieve a constant pressure ramp. A typical HRS filling profile is shown in Figure 5.
Fortunately, Coriolis meters perform well in non-steady flow, particularly in comparison to other meter types. However, like other meter types, the best accuracy is still obtained at the upper end of their flow rate ranges, with errors increasing sharply as flow rates decrease below a minimum value. There was therefore a need to calibrate the meter at various conditions with different average flow rates in order to accurately define its calibration curve as a function of operating flow rate vs. percentage error.

Previous testing of the selected meter showed that the error curve was flat for flow rates of 0.5 kg/min or above, some results for calibrations with nitrogen are shown in Figure 6.

![Figure 5: Mass flow rate as a function of time during a refuelling process.](image)

![Figure 6: Master Meter Calibration with Nitrogen](image)
During the flow meter calibration, the HRS was operated at five different pressure ramp rates, so that the flow meter could be calibrated at five different average flow rates.

The average mass flow rate during delivery to the flow standard can be estimated using

\[
\frac{dm}{dt} = \frac{V_{\text{tank}}}{\Delta t} \cdot \left( \rho_{\text{H}_2,f} - \rho_{\text{H}_2,i} \right),
\]

where \(V_{\text{tank}}\) is the tank volume, \(\Delta t\) the refuelling time and \(\rho_{\text{H}_2,x}\) the final and initial hydrogen density in the tank at the end and the beginning of the refuelling. This equation indicates that the average mass flow rate depends directly on tank volume.

The test conditions shown in Table 3 were selected based on using the CESAME flow standard, which has a total collection volume of 208 litres.

| Initial Pressure, MPa | 3 |
| Final Pressure, MPa | 70 |
| Initial density, kg/m³ | 2.44 |
| Final Density, kg/m³ | 39.7 |
| Volume of Collection vessel, L | 208 | 104 |
| Mass Collected, kg | 7.75 | 3.87 |
| Pressure Ramp Rate, MPa/min | 20 | 20 | 15 | 10 | 7.5 | 5 |
| Filling time, min | 3.35 | 3.35 | 4.47 | 6.70 | 8.93 | 13.4 |
| Average Flow Rate, kg/min | 2.31 | 1.16 | 0.87 | 0.58 | 0.43 | 0.29 |

Note that the conditions in the table were only an estimate. The maximum flow rate was calculated based on the collection volume of the CESAME flow standard, assuming that the HRS can operate with a maximum a pressure ramp rate of 20 MPa/min. In reality, the maximum pressure-ramp rate that the station can provide depends on the ambient temperature during refuelling. Fuelling tables are available in SAE J2601 [1] and give pressure ramp rates as a function of initial tank pressure and ambient temperature, as indicated in Figure 7. According to those tables, an average pressure ramp rate of 20 MPa/min will be possible as long as the ambient temperature during calibration is below 20 °C.

Rather than 2.24 kg/min, the maximum flow rate achieved was 1.84 kg/min. This figure falls short of the maximum flow rate required for the sonic nozzle calibrations in Task 1.4. It was assumed that the meter will still provide reliable measurements for flow rates above 1.84 kg/min because those flow rates are well within the flat portion of the error curve.

Each calibration point was performed twice, with the exception of the maximum flow rate which was only performed once. Ideally every point would be repeated several times to demonstrate repeatability, but this was not possible due to time constraints.
4 Measurement Procedure

4.1 Location of the Master Meter
To ensure the best stability, reliability and accuracy of the flow meter, it should be operated at stable temperatures, ideally at near ambient temperature. This was achieved by installing the meter in the warm region of the HRS, upstream of the pre-cooler. Figure 8 shows the METAS master meter installed in the warm region of the ZBT HRS, in series with the process meter of the HRS, which is located behind the master meter.
4.2 Calibration Protocol

Once the meter was installed, the following steps were followed to perform the flow calibration:

- Measure the volume of piping which is vented after refuelling. On Figure 4, this the piping after the cut-off valve and before the discharge valve and dispenser nozzle. Ensure that the HRS temperature and pressure instruments in this section are logged during all calibration points.
- Measure the piping volume between the flow meter outlet and the HRS cut-off valve and ensure that the HRS temperature and pressure instruments in this section are logged during all calibration points.
- Perform a quick leak check on the flow standard before use, it is filled with nitrogen to 3 MPa during transport, this pressure should not have dropped significantly.
- Calibrate the weigh-scale of the flow standard using reference weights.
- The flow meter is connected to the data logging PC.
- The flow meter zero procedure is performed three times. Deviations must be less than 0.2. If larger deviations are observed, this step must be repeated.
- Set the cut-off value on the meter (.0.003 kg/min).
- Connect any data transmission cables.
- Connect the HRS dispenser nozzle to the flow standard.
- Zero the totaliser of the master meter by pressing ‘Reset/Start totalizer’ on the Dashboard.
- Log the data:
  - In the menu ‘Data’, select ‘Data selection’.
  - In the sheet ‘mass flow’, select ‘MassFlowRate’ for logging.
  - In the sheet ‘Temperature measurement’, select AdcTubeMeanTemp for logging.
  - In the menu ‘Data’, select ‘Configure Data logging’ and enter a file name. Logging ‘Selected values only’ should be ticked.
  - In the menu ‘Data’, select ‘Data Logging’ ‘Data Logging On/Off’.
- Fill the flow standard to 70 MPa, the average pressure ramp rate for the station is 20 MPa/min to achieve an average mass flow rate of 2.31 kg/min. This is the first calibration point show in Table 3.
- Make a screenshot of the Dashboard of the master meter (User Interface) and save it as Meas#, where # is the measurement number.
- Record the value of the forward totalizer (from the station dispenser and the Master meter) and the tube temperature of the master meter. As soon as the filling is stopped, pressure in the tank will decrease due to temperature stabilisation.
- Disconnect the dispenser hose.
- Disconnect data transmission cables from the flow standard and wrap them around the frame.
- Take reference weight measurement once the weigh scale reading is stable. Apply calculation/corrections (e.g. for buoyancy) and report the calibration results.
- Reconnect the data transmission cables.
- Vent the system to the initial pressure required for the calibration point.
- The vent flow rate must be limited to prevent excessive cooling. The minimum safe working temperature for the tanks is -40 °C, but even at higher tank temperatures, significant moisture.

Figure 8: METAS master meter installed in warm region of the Empa HRS.
or ice formation will increase measurement uncertainty in collected mass. The researchers must aim to minimise icing and condensation on the tank surfaces and carefully remove residual moisture before weighing.

- Follow the same process to collect two repeat points at the same average mass flow rate.
- Move on to the next condition on the test matrix (Table 3).
- Vent the system to 5 MPa. Purge with nitrogen. Disconnect the dispenser nozzle and vent piping from the flow standard. Disconnect data transmission cables.

4.3 Reporting the Results

The results of the calibration provide an error curve, plotted as relative error (%) vs. mass flow rate (kg/min).

The average mass flow rate was calculated from the ratio of delivered mass measured by the reference flow standard and the elapsed time during which the mass flow measurements for the flow meter were non-zero.

\[
\dot{m}_{CMF} = \frac{m_{ref}}{t}
\]

Where \( \dot{m}_{CMF} \) is the average mass flow rate (kg/min)
\( m_{ref} \) is the delivered mass measured by the reference flow standard (kg)
\( t \) is the time period (min)

Note that corrections must be applied to the delivered mass for both the vented gas and for density changes in the piping between the flow meter and the HRS cut-off valve.

\[
m_{ref} = m_{ref0} + m_{vent} + m_{deadvol}
\]

Where \( m_{ref0} \) is the mass collected by the flow standard (kg)
\( m_{vent} \) is correction for vented hydrogen (kg)
\( m_{deadvol} \) is the correction for mass change in the dead volume (kg)

The vented gas, \( m_{vent} \), can be calculated using Method B1 in Appendix B of OIML R139 [2].

\[
m_{vent} = MW \cdot \sum P \cdot v \cdot \frac{1}{R \cdot Z \cdot T}
\]

Where \( MW \) is the molar mass (kg/mol)
\( \sum \) is the summation for relevant piping sections
\( P \) is the measured pressure (Pa)
\( v \) is the piping volume (m³)
\( T \) is the measured temperature (K)
\( R \) is the Gas constant (J/molK)
\( Z \) is the compressibility factor (dimensionless)

The dead volume correction is calculated using a similar approach, but consider both an initial and final state:
\[ m_{\text{deadvol}} = MW \cdot \left( \sum \frac{P_2 \cdot v}{Z(P_2, T_2) \cdot R \cdot T_2} - \sum \frac{P_1 \cdot v}{Z(P_1, T_1) \cdot R \cdot T_1} \right) \]

Where the subscripts 1 and 2 respectively refer to before and after the flow standard is filled.

The relative error of the master meter \( \varepsilon \) in (%) is defined as the difference between the delivered mass indicated by the flow meter and delivered mass according to the reference flow standard:

\[ \varepsilon = \frac{m_{\text{CMF}} - m_{\text{ref}}}{m_{\text{ref}}} \times 100 \]

Where \( \varepsilon \) is the relative error of the master meter (\%),

- \( m_{\text{CMF}} \) is the delivered mass indicated by the master meter (kg),
- \( m_{\text{ref}} \) is the delivered mass measured by the reference flow standard (kg).

Note that due to the nature of the calibration process, the error curve developed will plot error in totalised mass against average flow rate in unsteady flow conditions. It is assumed that although the meter is less accurate at low flow rates and vice versa, the meter accuracy does not deteriorate significantly in unsteady flow. Therefore, error in total mass determined by the flow meter is representative of error in the average flow rate for that particular calibration point, and this is approximately equal to the error that would occur if the meter was operated in steady flow conditions at that flow rate.

The error curve plotted in Task 1.3 can then be used to estimate the measurement uncertainty of the master meter when it is used as the reference for the sonic nozzle calibrations in Task 1.4.
5 Results

Figure 9 shows the initial calibration results.

The overall findings were very positive. The error “curve” for the METAS meter is essentially a flat horizontal line. Even at low flow rates, most errors were within ±0.5%. However, unusual results were observed for Run 4 and Run 7. In both cases errors were large and inconsistent with runs performed at the same flow rates. A similar shift is observed in the ZBT meter data for Run 4 and Run 7, this suggests a problem with reference measurements rather than the performance of the two flow meters.

On further investigation, the causes of these unusual results were discovered. On Run 4, the operator of the CESAME primary standard forgot to remove icing before taking weight measurements. This means that the reference weight measurement was overestimated, which appears in the results as a negative shift for both flow meters. The magnitude of over-reading was approximately 25 g, this is roughly how much icing was removed during the other runs.

With Run 7, the icing was removed correctly, the larger errors are caused by the “dead volume” effect. Since the meter was installed in the main station, upstream of the pre-cooler, there was a significant distance between the meter outlet and the CESAME primary standard. This piping is referred to as a “dead volume” and contains gas which has been measured by the flow meter but not delivered to the primary standard. For most runs, this has a negligible influence on the results, because the pressure and temperature in the dead volume did not change significantly before and after the primary standard was filled, therefore there was no significant change in the amount of hydrogen contained in the piping. Run 7 was the exception because the station was vented prior to those measurements. The initial pressure in the dead volume was only 8 MPa for Run 7, while it had been 70 MPa for all other runs.
The error introduced by this dead volume effect can be corrected by accounting for the density change in hydrogen contained in the piping:

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

Where:
- \( M_{dv} \) = dead volume mass, kg
- \( V_{dv} \) = Volume of piping between flow meter outlet and cut-off valve, m\(^3\)
- \( \rho_1 \) = density of hydrogen in dead volume before refuelling, kg/m\(^3\)
- \( \rho_2 \) = density of hydrogen in dead volume after refuelling, kg/m\(^3\)

The relevant temperature and pressure measurements from the refuelling station are shown in Table 4.

<table>
<thead>
<tr>
<th>Table 4: Inputs for calculation of dead volume correction for Run 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead volume</td>
</tr>
<tr>
<td>Initial Pressure, ( P_1 )</td>
</tr>
<tr>
<td>Initial Temperature, ( T_1 )</td>
</tr>
<tr>
<td>Initial Density, ( \rho_1 )</td>
</tr>
<tr>
<td>Final Pressure, ( P_2 )</td>
</tr>
<tr>
<td>Final Temperature, ( T_2 )</td>
</tr>
<tr>
<td>Final Density, ( \rho_2 )</td>
</tr>
<tr>
<td>Mass of hydrogen accumulated</td>
</tr>
</tbody>
</table>

The calculation yields 69.86 g of hydrogen accumulated in the dead volume. The reference mass for the calibration was therefore under-estimated by this amount, which led to the apparent over-reading of the two flow meters. The dead volume was measured by first venting the line from the master meter to the cut-off valve, which brought the pressure in the dead volume to atmospheric pressure. This dead volume was then refilled up to 72 MPa and the mass of hydrogen in the dead volume was determined using the master meter. Knowing the mass of hydrogen in the dead volume as well as temperature and pressure conditions, the volume can be calculated.
The findings are very positive and indicate that the METAS flow meter is well suited as a reference meter for the Task 1.4 calibrations, capable of achieving the target uncertainty of ±0.6% (k=2) in mass flow rate. Since the errors are only slightly larger than the uncertainty of the primary standard, it is recommended that no calibration curve should be applied to the flow meter. The meter will need to be zeroed again once installed at the Maximator test facility.
6 Uncertainty Budget

6.1 Input Uncertainty Sources

The uncertainty budget includes the following input uncertainty sources:

- **Flow standard:** This is the uncertainty in the reference mass measurements using the CESAME mobile primary standard. A value of 5 g was used, this is equal to 0.14% for a 3.5 kg fill. This is a conservative figure, CESAME have previously demonstrated that an uncertainty figure of 3 g (0.3 % for a 1 kg fill) is achievable.

- **Dead Volume:** There was a dead volume between the flow meter and flow standard. Density changes in this section introduces errors. Note that the dead volume effect is not relevant for most test conditions because the initial and final conditions were very similar (approximately 70 MPa before and after). However, the station was vented before Run 7. The initial pressure in the dead volume was only 8 MPa, when it had been approximately 70 MPa for all other runs. This required a dead volume correction of 69.86 g. An uncertainty of 4 g has been applied for the dead volume, this allows a 7% error in the final pressure measurement used to calculate the dead volume correction, or a 20 °C error in the final temperature measurement.

  This is clearly a conservative figure given that the only test point that required a dead volume correction was Run 7, and there is close agreement between Runs 6 and 7 once the correction was applied.

- **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. A value of ±0.001 kg/min is used in the uncertainty budget, based on previous measurements by METAS. The lowest average flow rate for the calibrations was 0.26 kg/min, at this flow rate, the 0.001 kg/min uncertainty is equal to 0.385 % of the mass delivered.

- **Repeatability:** This is a measure of how well a measuring device provides the same output when the measured parameter is held constant. Normally, this is estimated from the standard deviation of at least 20 repeat measurements. That was not possible in this case due to the time and cost of performing the measurements at the HRS. A figure of ±0.2% has been used, since the maximum difference in two repeat measurements during the calibrations was 0.15%. Also, it was observed that the offset between the measurements of the METAS and ZBT flow meters was consistent between repeats, varying at most by 0.19%.

- **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. This should ideally be determined by comparing flow meter calibrations in similar conditions at different laboratories or test installations, but such data was not available for the flow meter. A value of ±0.3% has been used, this is considered conservative by the partners, it is much larger than the uncertainty stated by the meter manufacturer and is the largest contributor in the uncertainty budget.
6.2 Uncertainty Budget

The structure of the uncertainty budget is shown in Table 5 below. The uncertainty sources mentioned in 6.1 are combined by quadrature summation. The overall uncertainty is expressed as a mass in kilograms, as are most of the input uncertainties and so the sensitivity coefficient is equal to 1. The exception is the zero flow, which is expressed in flow rate units, kg/min. The sensitivity coefficient in this case is equal to the test point duration in minutes, since it is the partial derivative of the output (mass) with respect to the input (mass flow rate) e.g. in the example below, the total mass of hydrogen collected was 3.5 kg, the average mass flow rate was 0.26 kg/min. Test point duration was 13.461 minutes and therefore the sensitivity coefficient for the zero flow is also 13.461.

Most of the input uncertainties are taken as a normal or Gaussian distribution (k=2), the exception is the reproducibility which is taken as a rectangular distribution (k=√3).
### Table 5: Uncertainty Budget

<table>
<thead>
<tr>
<th>Rank</th>
<th>Uncertainty Source</th>
<th>Value</th>
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<th>Absolute (units)</th>
<th>Relative (%)</th>
<th>Distribution</th>
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<th>Standard Uncertainty, $u$</th>
<th>Sensitivity Coefficient, $c$</th>
<th>Output Uncertainty, $c.u$</th>
<th>Variance, $(c.u)^2$</th>
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<td>4</td>
<td>Flow Standard</td>
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<td>kg</td>
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<td>Normal (k=2)</td>
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<td>5</td>
<td>Dead Volume</td>
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<td>0.114</td>
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<td>1</td>
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<tr>
<td>1</td>
<td>Zero-point stability</td>
<td>0.26</td>
<td>kg/min</td>
<td>0.001</td>
<td>0.385</td>
<td>Rectangular</td>
<td>2</td>
<td>0.001</td>
<td>13.461</td>
<td>0.007</td>
<td>4.530E-05</td>
</tr>
<tr>
<td>3</td>
<td>Repeatability</td>
<td>3.50</td>
<td>kg</td>
<td>0.007</td>
<td>0.200</td>
<td>Normal (k=2)</td>
<td>2</td>
<td>0.003</td>
<td>1</td>
<td>0.003</td>
<td>1.225E-05</td>
</tr>
<tr>
<td>2</td>
<td>Reproducibility</td>
<td>3.50</td>
<td>kg</td>
<td>0.010</td>
<td>0.300</td>
<td>Normal (k=2)</td>
<td>1.73</td>
<td>0.006</td>
<td>1</td>
<td>0.006</td>
<td>3.675E-05</td>
</tr>
<tr>
<td></td>
<td><strong>Overall Uncertainty</strong></td>
<td>3.50</td>
<td>kg</td>
<td>0.020</td>
<td><strong>0.584</strong></td>
<td>Normal (k=2)</td>
<td>2</td>
<td>0.010</td>
<td>1</td>
<td>0.010</td>
<td>1.045E-04</td>
</tr>
</tbody>
</table>
6.3 Output

The measurement uncertainty for each of the calibration points is shown in Table 6 below. Since several input uncertainties are absolute values, the uncertainty in delivered mass is greatest when a small quantity of hydrogen is collected. Since a minimum of 3.5 kg was collected, these sources never dominate.

The relative contribution of the zero-point stability depends on the average flow rate. At 1.84 kg/min, it has the smallest influence of any uncertainty source. At 0.26 kg/min, zero is the main uncertainty source.

For flow rates above 0.26 kg/min, the main uncertainty source is the reproducibility.

The total mass uncertainty of the flow meter ranges from 0.58% at 0.26 kg/min to 0.41% at 1.84 kg/min. This is within the target of 0.6% for the master meter calibration. Note that it was not possible to accurately define some of the uncertainty sources. In those cases, the researchers aimed to be conservative, for example by assigning a 0.3% uncertainty for reproducibility.

The fact that errors for the calibration shown in Figure 6 are all within ±0.5%, suggests that the uncertainty estimate is conservative.

Table 6: Measurement Uncertainty for each calibration point

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of H2 collected (kg)</td>
<td>6.98</td>
<td>3.57</td>
<td>3.57</td>
<td>3.59</td>
<td>3.42</td>
<td>3.47</td>
<td>3.54</td>
<td>3.51</td>
<td>3.5</td>
</tr>
<tr>
<td>Avg. flow rate (kg/min)</td>
<td>1.84</td>
<td>0.75</td>
<td>0.73</td>
<td>0.51</td>
<td>0.49</td>
<td>0.38</td>
<td>0.38</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Uncertainty of Master Meter (%) (k=2)</td>
<td>0.41</td>
<td>0.46</td>
<td>0.46</td>
<td>0.48</td>
<td>0.49</td>
<td>0.49</td>
<td>0.51</td>
<td>0.51</td>
<td>0.58</td>
</tr>
</tbody>
</table>

7 Conclusions

The aim of Task 1.3 was to calibrate a Coriolis master meter with hydrogen at pressures up to 90 MPa so that it can later be used as a master meter. The target uncertainty for the calibrated Coriolis meter was ±0.6 % (k=2). This has been achieved, the selected meter was calibrated in a modified hydrogen refuelling station dispenser using the CESAME mobile gravimetric standard as the reference.

An uncertainty budget was developed using the best available data on the meter performance and sensitivity to various uncertainty sources, this budget shows an overall mass flow uncertainty ranging from 0.41 % to 0.58 % (k=2) depending on flow rate. This is within the original uncertainty target and is considered a conservative over-estimate.

The actual calibration results show a very linear error curve for the flow meter, even at flow rates as low as 0.26 kg/min. Errors range from -0.01% to 0.39%, this suggests that there is scope to reduce the
estimated measurement uncertainty when more data is available on uncertainty sources such as reproducibility.

Given the excellent agreement between the flow meter and the reference, it was decided to apply no correction to the flow meter output when it is used in Task 1.4.
References
