

21GRD05 Met4H2

D3 - Gas flow metering using national standards and gas mixtures containing hydrogen

Organisation name of the lead participant for the deliverable:  
Justervesenet

Due date of the deliverable: 30<sup>th</sup> of September 2025

Actual submission date of the deliverable: 5<sup>th</sup> of November 2025

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**Confidentiality Status:** PU - Public, fully open

**Deliverable Cover Sheet**

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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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## Gas flow metering using national standards and gas mixtures containing hydrogen

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**Keywords:** intercomparison, hydrogen, gas meter, gas mixtures, impurities

## Abstract

We present the first European intercomparison of primary flow measurement standards with hydrogen-enriched natural gas (up to 20 % hydrogen) and natural gas with pressure up to 60 bar and volume flow rates in the range (5 to 160) m<sup>3</sup>/h. We describe the principles of operation of the primary standards and present the transfer standards, a rotary meter and an ultrasonic meter, used for the intercomparison. In many instances, the overlap between the different laboratories is satisfactory, but the collected results are limited and do not allow to make advanced conclusions. In addition, we investigate the effect of nitrogen impurities (2 % in volume) on the performance of low pressure gas meters for pure hydrogen using newly developed measurement standards. We present the methods and results of this investigation. We show that nitrogen impurities affect volume flow measurements of an ultrasonic meter but seem to have little effect on a thermal mass flow meter. The paper explores future potentials and challenges in international intercomparisons involving hydrogen blends, and highlights key issues and solutions with hydrogen gas metering in the presence of impurities.

## 1 Introduction

Driven by the European Union's goal to reduce greenhouse gas emissions by 55 % by 2030 [1], European countries are collaborating to introduce hydrogen into gas grids [2]. However, the introduction of hydrogen into natural gas grids possesses significant challenges. One of these challenges concerns the aspect of flow metrology, with potential issues arising both in hydrogen-enriched natural gas (HENG) and "pure hydrogen" (i.e. close to 100 % hydrogen) [3]. Due to the unique properties of hydrogen (e.g. low density, low viscosity, high speed of sound), HENG can have substantially different properties than regular natural gas, which may affect the performance of gas flow meters. Conversely, small fractions of other gases in nominally pure hydrogen can have large effects on gas properties. Hence, flow meters used for natural gas may behave differently when used with HENG, and flow meters used for measuring flow hydrogen may behave differently when levels of impurities, such as nitrogen and methane, increase, or even worse, fluctuate. These questions are relevant to the flow metering in both transmission grids (high pressure, high flow rates) and distribution grids (low pressure, low flow rates), including domestic gas meters.

In recent years, a number of (European) projects (e.g. [4, 5, 6, 7] have investigated the performance of flow meters, both of HENG and pure hydrogen [8, 9, 10, 11, 12, 13, 14]. In the case of natural gas, the traceability chains of flow calibration facilities with relevance to transmission

**Table 1.** Technical data: meters used for intercomparison

	Ultrasonic meter	Rotary meter
Flow range (m <sup>3</sup> /h)	2.5 to 200	0.8 to 160
Min. pressure (bar)	5	1
Max pressure (bar)	98	101.2
Participants	VSL, FORCE	VSL, FORCE, CESAME

grids, are compared on a regular basis, and in some cases the reference levels are even harmonized [15], ensuring fair custody trade and billing. Due to the novelty of using HENG in national measurement standards however, the European traceability chains for HENG have not been compared directly. Additionally, although a few flow facilities for calibrating domestic gas meters with pure hydrogen exist, so far only grade 4.0 hydrogen (purity > 99.99 %) is used for testing, and the effect of relatively large mole fractions of impurities (e.g., 0.5 % - 2 % which is conformed with grade A hydrogen [16]) may occur in European hydrogen gas distribution grids, is not known.

The work presented in this paper is part of the Met4H2 project[17]. In this project, the state of the art in metering HENG and hydrogen was advanced by developing measurement standards to enable calibration and validation of flow metering equipment under actual conditions (pressure, temperature), used to accurately quantify flow rates of hydrogen (including blended hydrogen) through the hydrogen supply chain, and to facilitate compliance with respect to e.g., OIML R137 [18], OIML R140 [19], and the EU Measurement Instruments Directive [20].

The experimental work is presented into two independent parts: the intercomparison with natural gas and HENG (up to 20 % hydrogen), and the gas meter tests using hydrogen with impurities with up to 2 % impurities.

## 2 Intercomparison

The study is carried out from May 2024 to August 2025. One NMI (National Metrology Institutes) and two DIs (Designated Institutes) were participating: VSL National Metrology Institute (the Netherlands, called VSL), FORCE Technology (Denmark, called FORCE) and CESAME-EXADEBIT (France, called CESAME). Two natural gas flow meters with different measuring principles were selected: an ultrasonic and a rotary flow meter. The national standards used are piston provers at FORCE and VSL and a pVTt (pressure Volume Temperature time) system at CESAME. The objective of the comparison was to document experimental evidence of the behaviour of gas meters when used with HENG for different pressure and flow regimes and compare the results between the three institutions. Natural gas is called NG, and the mixture of 20 % hydrogen and 80 % NG is called HENG.

VSL was the coordinating laboratory. The two meters (Table 1) circulate according to this calendar: first at VSL, then at FORCE, then back at VSL; finally the rotary meter was sent to CESAME. The meters must return to the pilot lab to assess the drift. Experiments are conducted with different flow rates, pressures and gases (detailed in Annex, Table 3). Gases used included HENG, NG and air. The temperature remains ambient. The participating laboratories followed their own procedures to perform measurements. The experimental flow rates should match the designated ones as closely as possible, at least within  $\pm 5$  %. The results were not disclosed until the end of the measurements of the last participant to ensure the reliability of the intercomparison.

The intercomparison was customized to match the capabilities of the flow facilities available at the participants' institutes. This step included involving both large-scale and small-scale facilities, where large-scale is considered having flow rates of (5 to 200) m<sup>3</sup>/h at pressures of (8 to 60) bar and small scale was defined with maximum flow rates of up to 16 m<sup>3</sup>/h. Both parts of the intercomparison were performed at ambient temperatures, aiming for an expanded uncertainty lower than 0.5 %. The task includes a selection of relevant gas meters to be collected in a transfer standard package, which was circulated among the participants. Each gas meter was calibrated by at least two separate facilities.

### 2.1 Instruments

During the preparation of the project, gas meters suitable for this comparison were investigated. In the end, the following two gas meters were selected: a volumetric rotary meter DELTA S-FLOW G100 DN50 (Figure 1, called "rotary meter") and an ultrasonic meter based on velocity transit time principle FLOWSIC550, dimension 2 inches (Figure 2, called "ultrasonic meter").



**Figure 1.** Rotary piston gas meter DELTA-S-FLOW G100 DN50



**Figure 2.** Ultrasonic meter FLOWSIC550 2 inches

## 2.2 Calibration procedure

Both gas meters were tested at gas temperatures ranging from 8 °C to 22 °C under the conditions listed in Annex, Table 3.

For the rotary gas meter, the measured error was compensated for temperature according to the following formula:

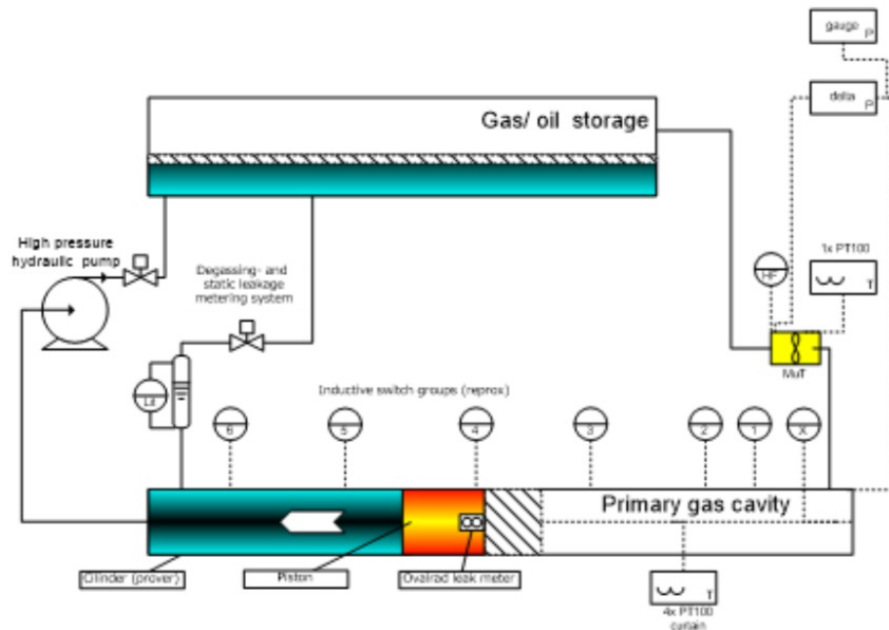
$$E_t = E_m + \beta(T - T_{ref})$$

where  $E_t$  is the error of the gas meter used for final evaluation (%),  $E_m$  is the error of the gas meter measured during the test (%),  $\beta=0.0069$  %/°C is the temperature coefficient (accounting for the expansion of flow meter elements with temperature),  $T$  is the temperature measured at the gas meter during the test (°C) and  $T_{ref}$  is set at 20 °C. At each flow rate the accuracy test was repeated at least 3 times.

The following parameters were recorded during the tests or calculated afterwards (MUT: Meter Under Test):

- Test gas
- Date
- Nominal flow rate (m<sup>3</sup>/h)
- Average temperature (°C)
- Average pressure (bar)
- Real flow at MUT (m<sup>3</sup>/h)
- Indicated flow MUT (m<sup>3</sup>/h)
- Error of the meter (%)
- Reynolds number (-)
- Average indicated flow (m<sup>3</sup>/h)
- Average error of the meter (%)
- Standard deviation of the mean (%)
- Uncertainty of measurement U(k=2) (%)

The error of the meter is the difference between the volume indicated by the meter and the volume which has flowed through the meter, divided by the later value.



**Figure 3.** Test facility at VSL - Schematic view

$$E = 100 \cdot \frac{(Q_i - Q_c)}{Q_c}$$

where  $E$  is the error of the meter (%),  $Q_i$  is the indicated flow rate by the meter ( $\text{m}^3$ ) and  $Q_c$  is the real flow rate which has flowed through the meter ( $\text{m}^3$ ).

### 2.3 Test facilities

**2.3.1 VSL, the Netherlands** VSL participated in this comparison using their primary standard for natural gas flow known as gas-oil piston prover (GOPP). The working principle is based on the displacement of a piston acting as a gas-oil separator. The piston travels at a maximum speed of 0.2 m/s through a cylinder of approximately 60 cm in diameter. A speed-controlled centrifugal pump generates an oil flow that moves the piston with a uniform velocity inside the measuring cylinder, passing sensors indicating discrete volumes. The oil & gas container at the top side of the configuration works also like a displacement system and the gas is forced towards the open outlet of the top container and flows back into the measuring cylinder. Figure 3 shows a schematic view of the system and Figure 4 a picture with a MUT (meter under test).

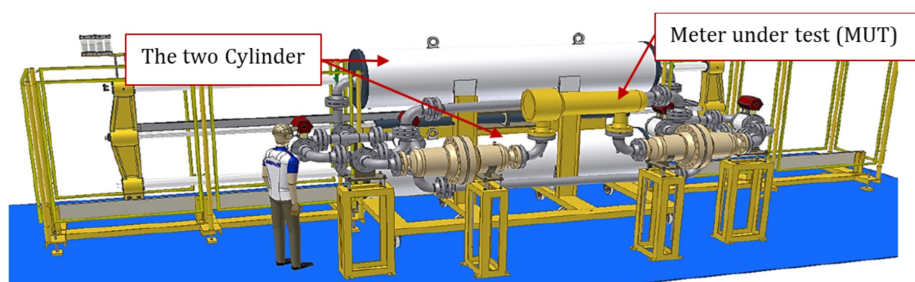
During the gas transport from the container to the cylinder, the mounted gas-meter will indicate a passed actual volume of gas that is compared to the known volume of the displaced piston. It is a process with two strokes: after the active measuring stroke (piston moves to the left end) the pump will be stopped, valves around the pump will be switched to reverse the flow direction of the oil and the pump is restarted, pushing the piston back to its starting position. Proximity switches take care of the comparison process.

The HF (high frequency) pulses coming from the MUT are compared with the reference LF (low frequency) pulses of the passed volumes of the primary cylinder. The GOPP has a flow-range from  $5 \text{ m}^3/\text{h}$  to  $230 \text{ m}^3/\text{h}$  at actual gas flow conditions with uncertainties from 0.29 % to 0.06 % ( $k = 2$ ), operating up to 63 bar(g). The system is designed for calibrations of 4-inch reference meters and has a direct relation to the SI-units meter and second.

**2.3.2 FORCE, Denmark** The piston prover principle used at FORCE is not strictly identical to the VSL system: the movement of both pistons is hydraulically controlled at the same time using a double-acting cylinder approximately 0.66 m in diameter. As the piston moves, the gas volume is displaced from one side of the cylinder to the other through the piping system and the meter under test (MUT). The diameters of the two cylinders are well known, and the piston's travel distance is measured during the calibration of a meter under test (MUT). This allows the reference volume to be calculated. After correcting the reference volume for temperature and pressure, it can be



**Figure 4.** Test facility at VSL with the rotary meter at the meter-under-test position, with a part of the prover tube in the background



**Figure 5.** Piston Prover – Primary Gas Calibration Laboratory at FORCE. The two white-colored cylinders represent the piston prover units.

compared with the volume indicated by the MUT. The resulting error can then be determined and corrected.

Figure 5 shows a schematic view of the piston prover, and Figure 6 a picture of the actual system

Cylinder diameter, piston rods and measuring of the length movement are calibrated with traceability according to the International Meter Convention (SI Metric Unit).

The system can be used with the following gases:  $N_2$ , NG,  $CO_2$ , HENG, Air, and Non-corrosive gases. The prover diameter is 0.66 m and it can calibrate devices up to 4", expandable to 6". The flow rate ranges from 2 to 400  $m^3/h$ , and the pressure ranges from 1 to 66 bar (abs). The uncertainty according to CMC (Calibration and Measurement Capabilities) ranges from 0.13 % (low flow rates) to 0.07 % (high flow rates), for  $k=2$ ; given that the gas composition differs from pure natural gas, an uncertainty of 0.15 % is chosen for the experiment to account for potential variability. The test temperature is  $20\text{ }^\circ\text{C} \pm 5\text{ }^\circ\text{C}$ .

**2.3.3 CESAME, France** The laboratory CESAME-EXADEBIT used its testing equipment based on the pVTt method (Pressure, Volume, Temperature, Time).

A pVTt-system is a primary gas flow standard used by several national metrology institutes and other laboratories for several decades. The CESAME-EXADEBIT's standard consists of pressurised bottles as a flow source, 4 collection tanks with 3 different volumes (50 L, 2 x 100 L and 400 L), a vacuum pump, pressure and temperature sensors, and a critical flow Venturi nozzle. Figure 7 shows a picture of the pVTt system at CESAME.

The flow rate ranges from 0.4 to 34 kg/h, the pressure from 1 to 70 bar. The operating temperature ranges from 15 to 65  $^\circ\text{C}$ , ideally 20  $^\circ\text{C}$ . The gases which can be used are: hydrogen,



**Figure 6.** Testing of the ultrasonic meter at FORCE



**Figure 7.** Test facility at CESAME

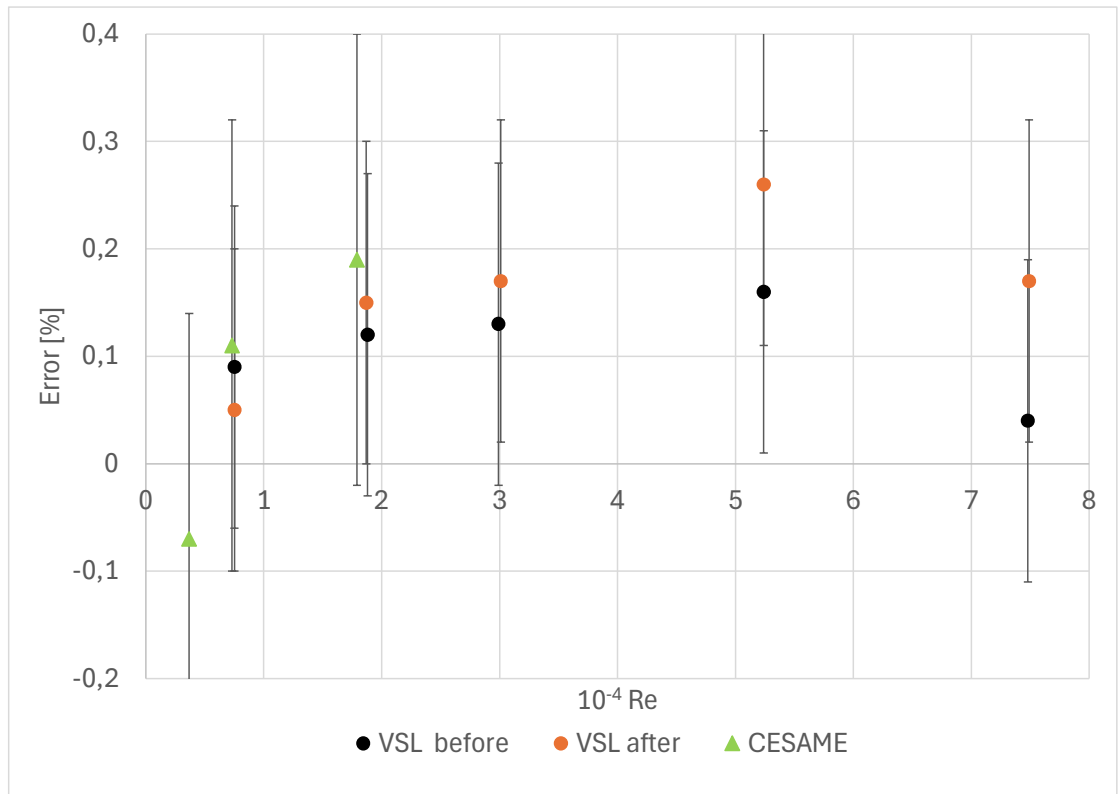
hydrogen/methane, methane, nitrogen, and air. The nozzle diameter can range from 0.2 to 5 mm, all geometries possible. The target uncertainty ( $k=2$ ) is 0.15 % on the value of the discharge coefficient ( $C_d$ ).

#### *2.4 Stability of the meters*

During the project the Rotary meter was tested twice in the pilot laboratory (VSL): once at the start of the project (called “VSL before”), and once after VSL and FORCE had performed the high-pressure measurements, but before CESAME performed their measurements (called “VSL after”). Results are presented in Annex, Table 4.

The estimated standard uncertainty caused by the stability (reproducibility) of the rotary meter is 0.08 %. In this case, a uniform distribution between minimal value and maximal value is assumed. The maximum value of the "difference" was 0.13 % and the estimated uncertainty was obtained by dividing this value by the square root of 3 (rectangular distribution assumed).

During the project the ultrasonic meter was tested twice in the pilot laboratory (VSL). The results are presented in Annex, Table 5. The estimated standard uncertainty caused by the reproducibility of the ultrasonic gas meter is 0.50 %. Compared to the base uncertainties reported by the participating laboratories, this reproducibility-related uncertainty is very high. It is



**Figure 8.** Reynolds analysis – rotary meter, air, 1 atm

important to note that the reproducibility test was conducted with air at ambient pressure, conditions which are not within operating standards of the meter. Thus, the experimental results cannot be exploited as intercomparison results and are displayed for research purposes.

## 2.5 Results

All numerical data are displayed in Annex, from Table 6 to 14.

**2.5.1 Air at atmospheric pressure, rotary meter** Figure 8 shows a graphical representation of the results. There is a very good overlap between the two labs despite the drift.

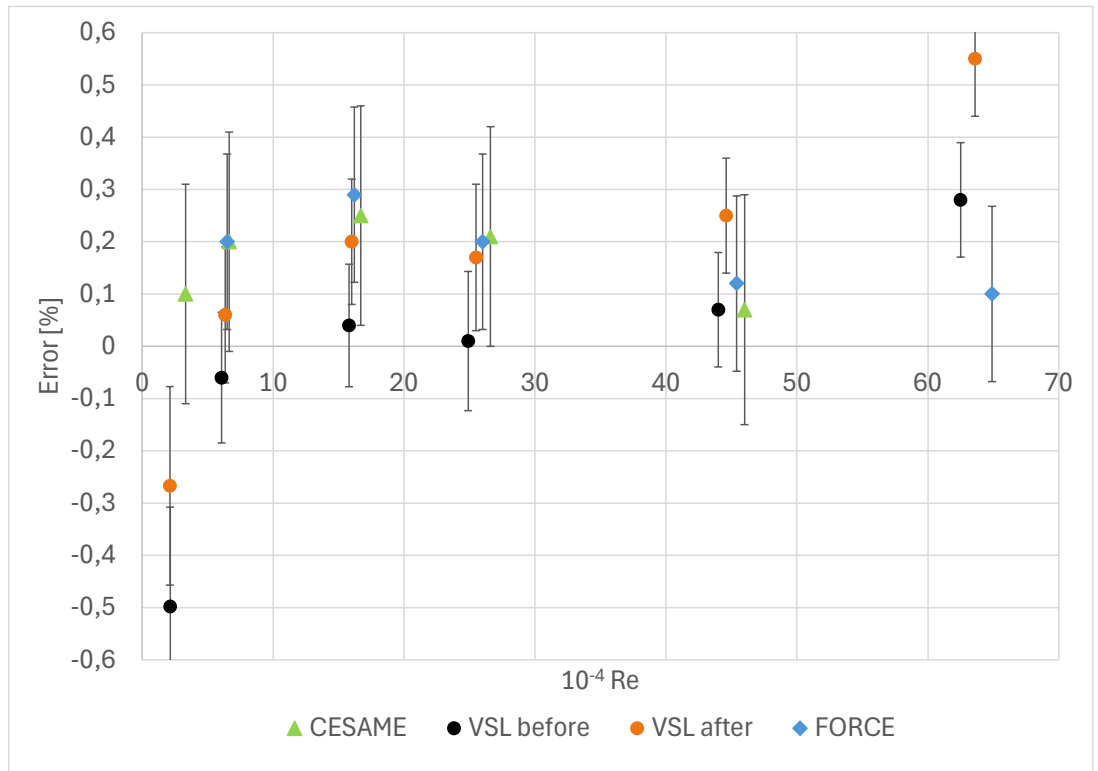
**2.5.2 Natural gas at 8 bar, rotary meter** Figure 9 shows a graphical representation of the results. We can notice a drift from both experiments run at VSL. The results overlap except at the highest Reynolds numbers.

**2.5.3 Natural gas enriched with 20 % of hydrogen at 8 bar, rotary meter** Figure 10 shows a graphical representation of the results. For that case, the drift is less significant and the results overlap except for the extreme Reynolds number values.

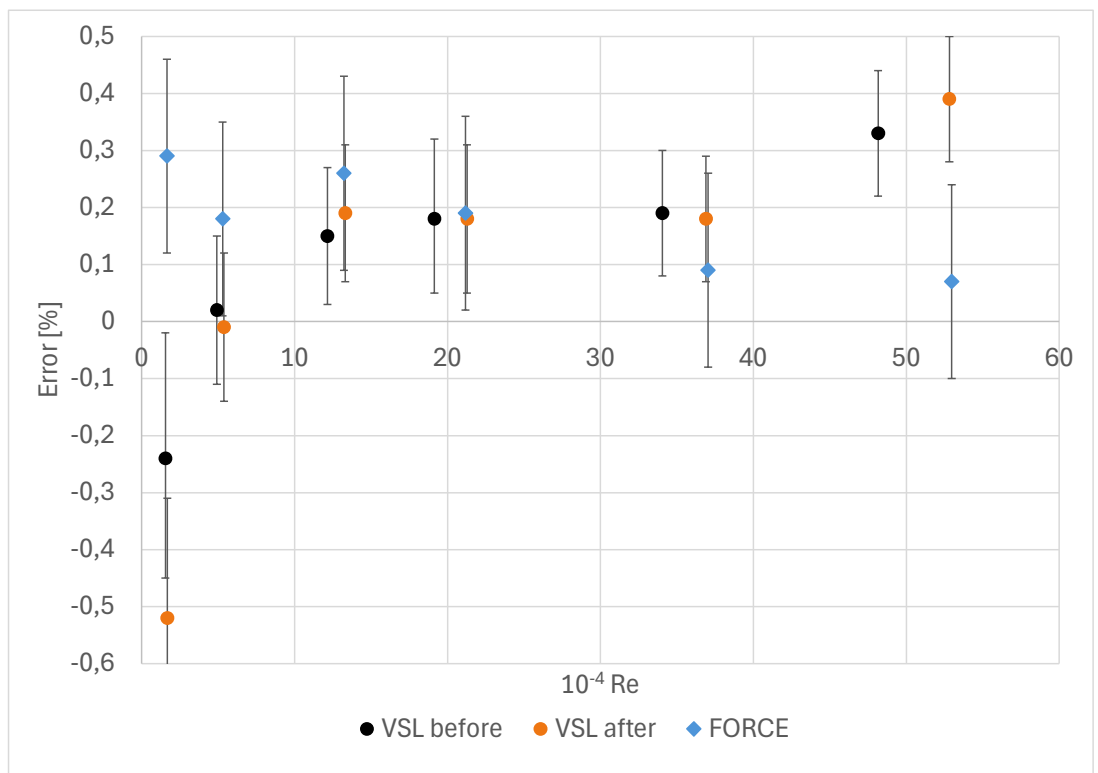
**2.5.4 Natural gas at 60 bar, rotary meter** Figure 11 shows a graphical representation of the results. For this experiment, there is a good overlap along the Reynolds number range.

**2.5.5 Natural gas enriched with 20 % of hydrogen at 60 bar, rotary meter** Figure 12 shows a graphical representation of the results. The general overlap between the two laboratories is good except for one point around slightly below  $Re = 10^6$ .

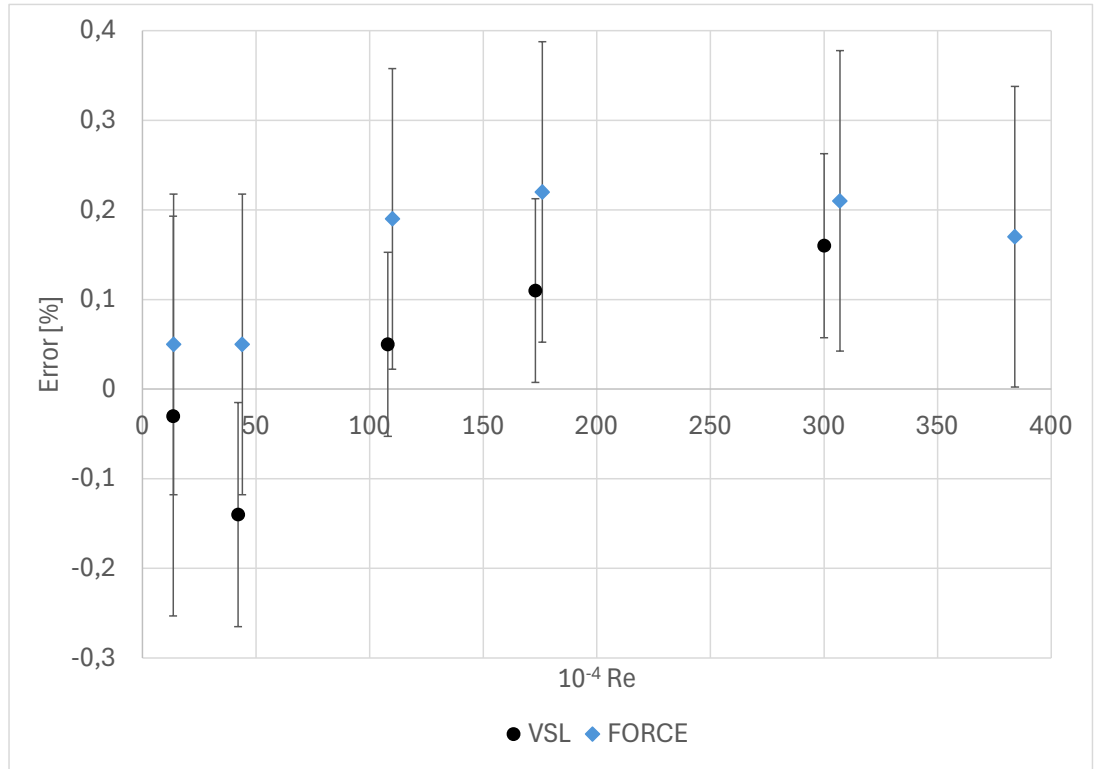
**2.5.6 Natural gas at 8 bar, ultrasonic meter** Figure 13 shows a graphical representation of the results. The overlap is very good at low Reynolds number but the results drift when the Reynolds number is increasing.



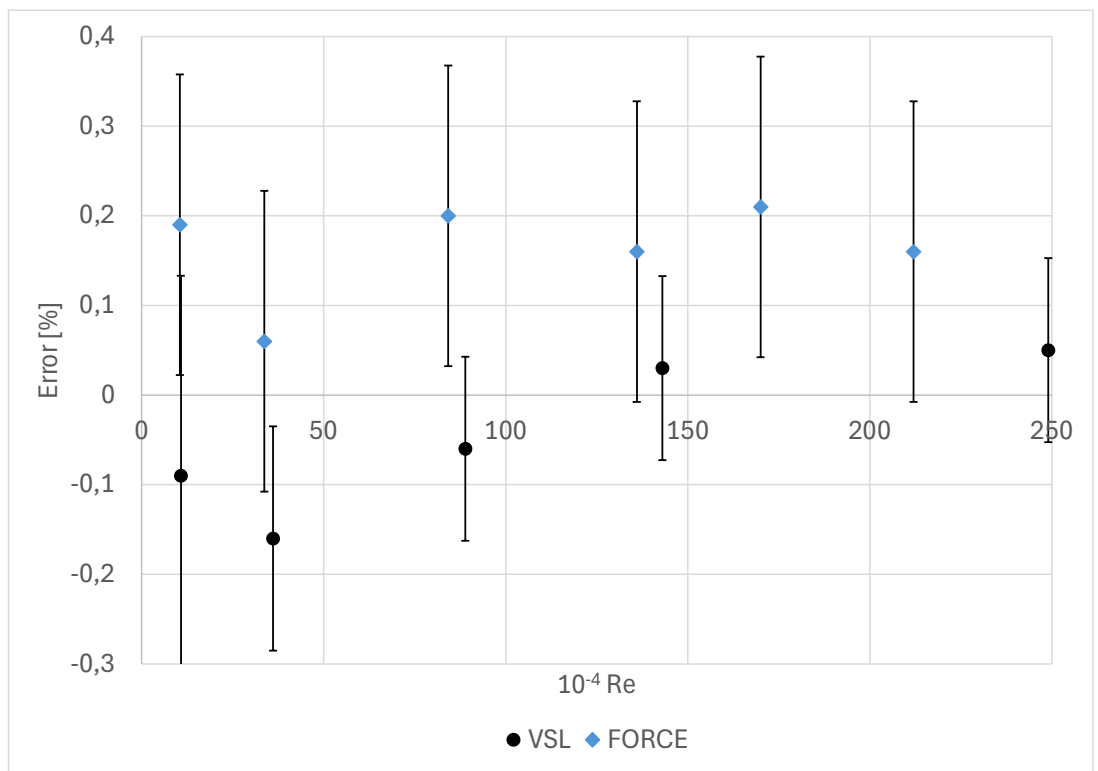
**Figure 9.** Reynolds analysis – Rotary meter, NG (air for CESAME), 8 bar (g)



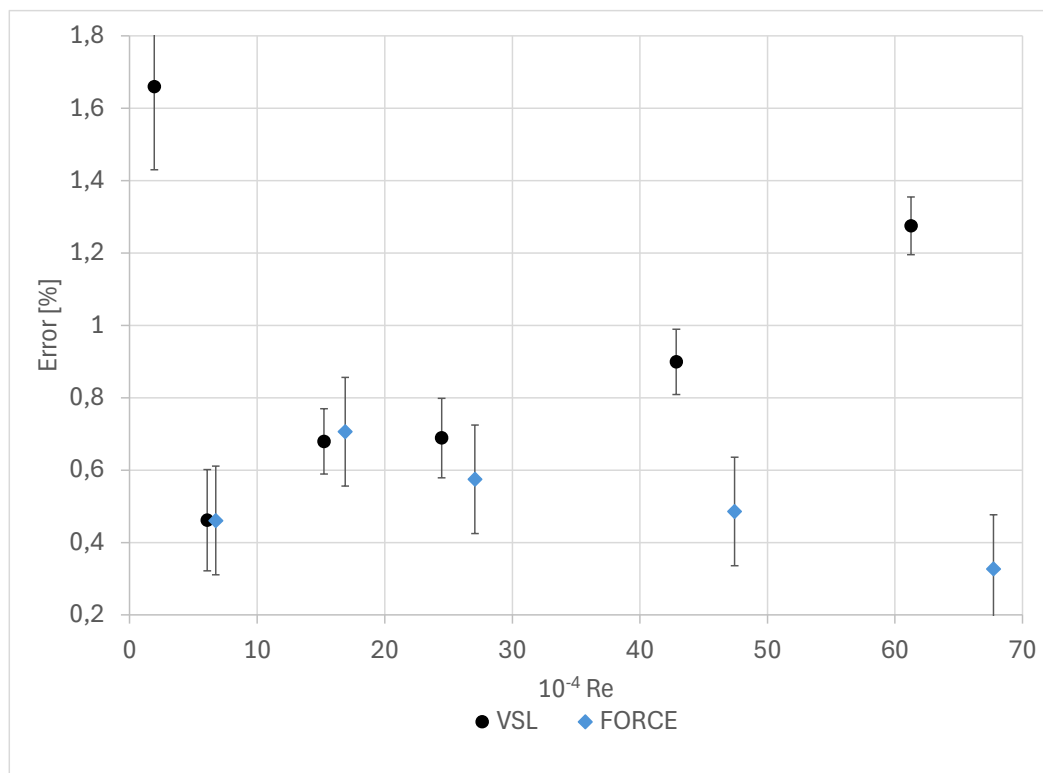
**Figure 10.** Reynolds analysis – Rotary meter, HENG, 8 bar (g)



**Figure 11.** Reynolds analysis – Rotary meter, NG, 60 bar (g)



**Figure 12.** Reynolds analysis – Rotary meter, HENG, 60 bar (g)



**Figure 13.** Reynolds analysis – Ultrasonic meter, NG, 8 bar (g)

*2.5.7 Natural gas enriched with 20 % of hydrogen at 8 bar, ultrasonic meter* Figure 14 shows a graphical representation of the results. There is no overlap at low Reynolds number, it gets better at higher Reynolds number.

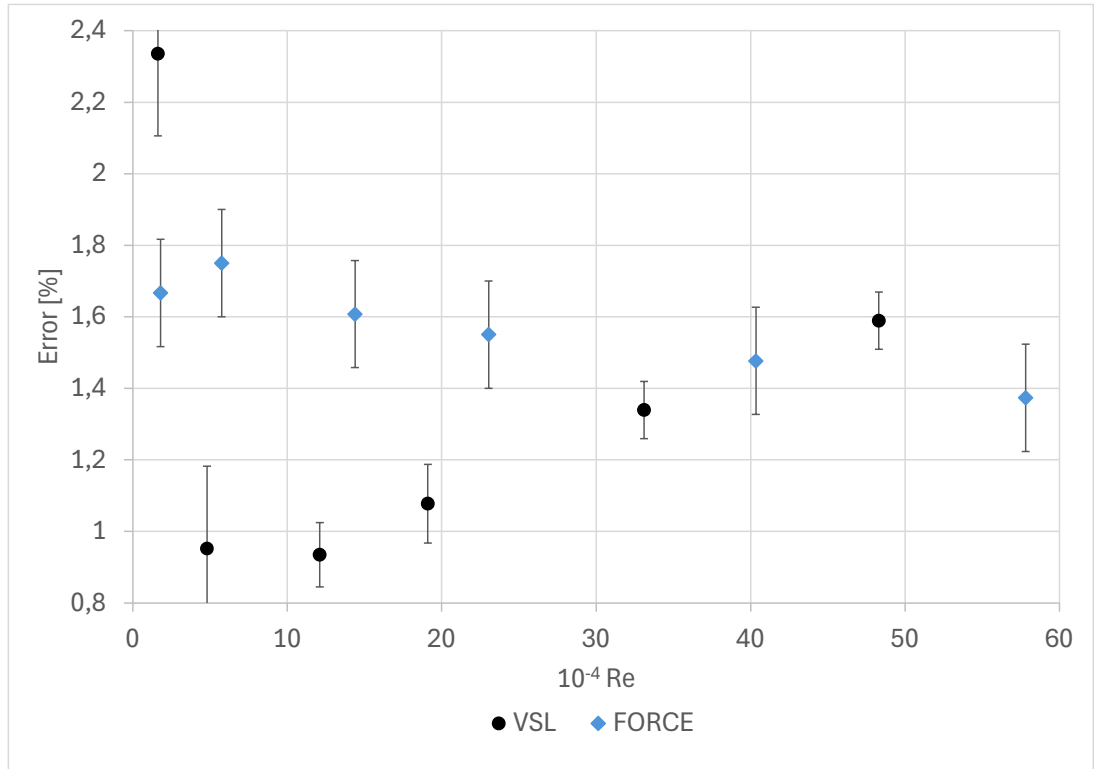
*2.5.8 Natural gas at 60 bar, ultrasonic meter* Figure 15 shows a graphical representation of the results. The results overlap only at the lowest flow rate.

*2.5.9 Natural gas enriched with 20 % of hydrogen at 60 bar, ultrasonic meter* Figure 16 shows a graphical representation of the results. The results do not overlap at all.

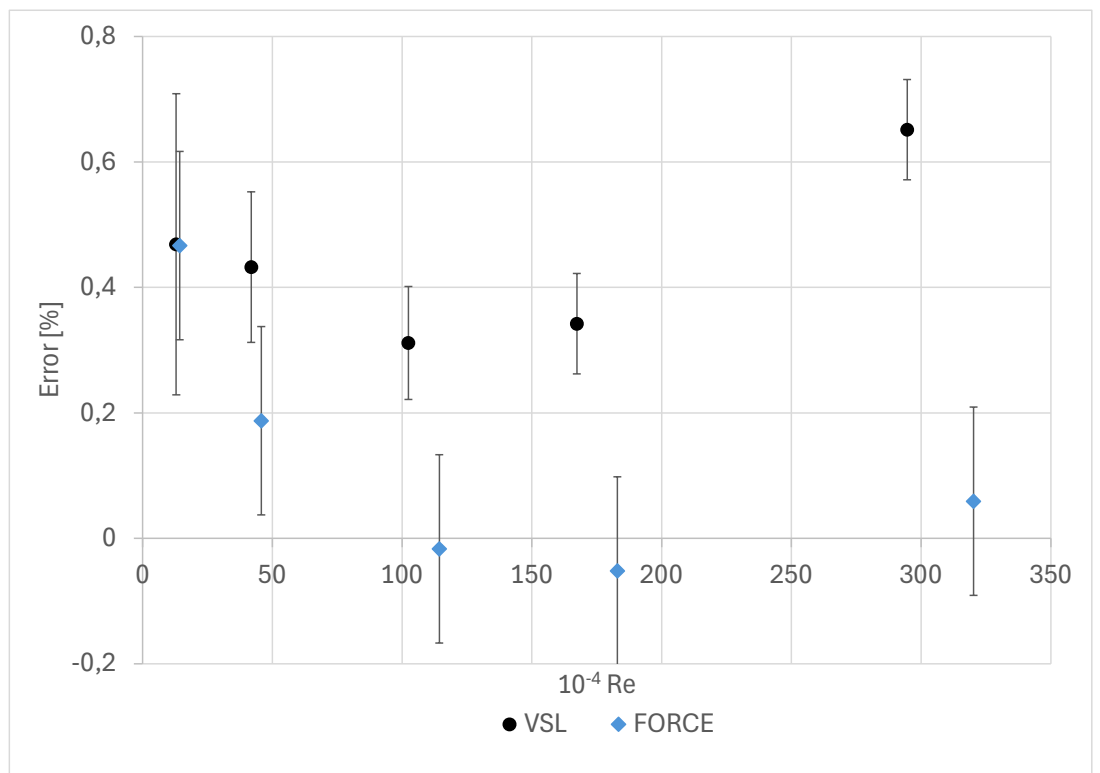
## 2.6 Intercomparison with NG and HENG: discussion

This comparison was not a registered EURAMET/CIPM comparison and has a significant R&D character. The agreement between the results from different laboratories is reasonably good for the rotary meter, however, some discrepancies can also be observed. Concerning the ultrasonic meter, due to its instability, discrepancies were expected, and some overlapping occurs anyway; the overlapping would be very good if the drift from the meter (indicated in Annex) was included in the calculation, but the intercomparison would be inconclusive anyway due to the instability. The potential reasons for these discrepancies could be:

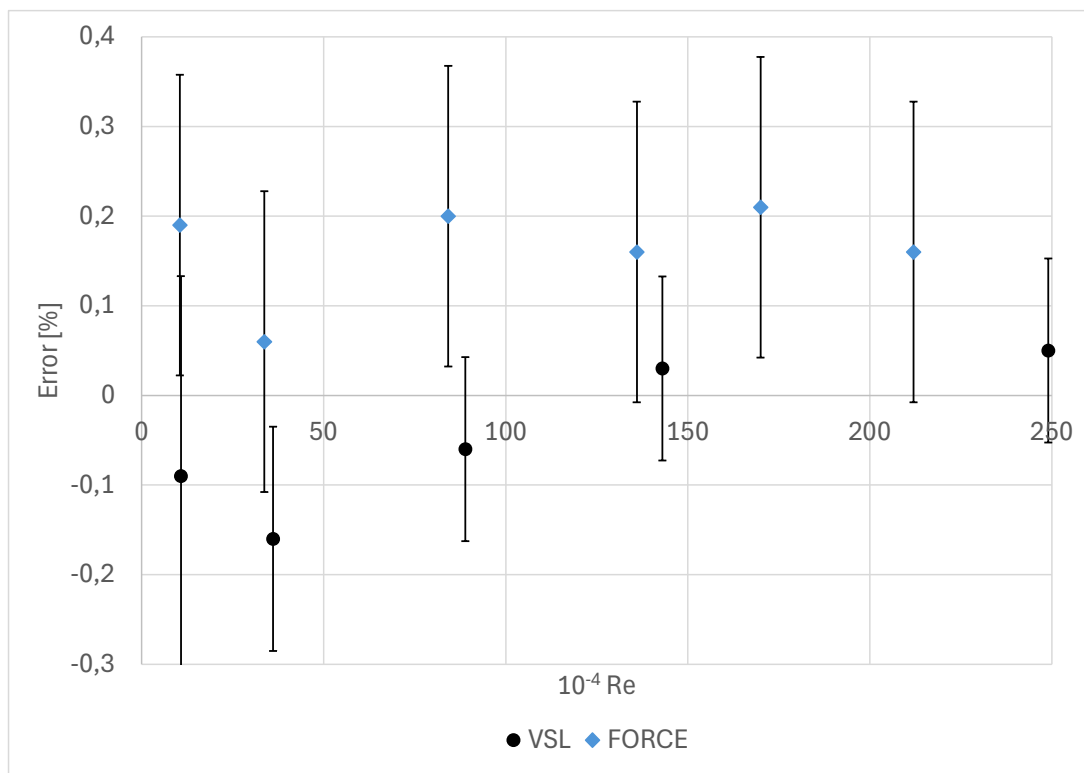
- Temperature effects: in some laboratories, the temperature of the facility is not controlled. Hence, the temperature range during calibrations is (8 to 22) °C. Although a temperature correction was applied for the rotary meter, there may be additional effects not covered by this first-order correction. Temperature effects can also be significant for the ultrasonic meter, but the main effects are covered by the built-in corrections. No additional corrections were applied.
- Gas composition effects: The natural gas in Denmark and the Netherlands differs greatly in composition, with the former having a larger density. Consequently, although the experiments are performed at the same nominal flow rate, the Reynolds numbers can differ significantly, which may cause differences in the reported error of the meter. In addition, both VSL and FORCE aimed at having 20 % hydrogen for the HENG tests, but due to operational



**Figure 14.** Reynolds analysis – Ultrasonic meter, HENG, 8 bar (g)



**Figure 15.** Reynolds analysis – Ultrasonic meter, NG, 60 bar (g)



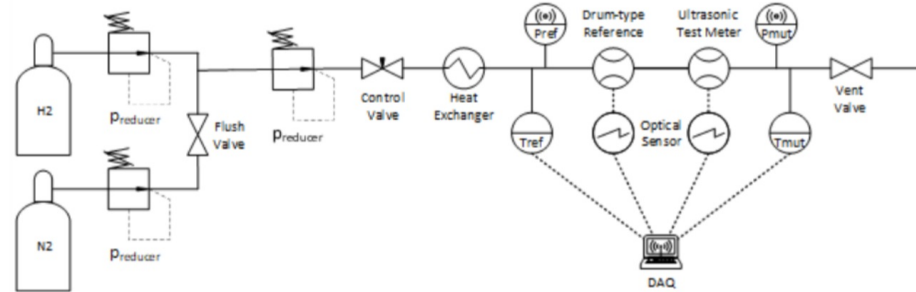
**Figure 16.** Reynolds analysis – Ultrasonic meter, HENG, 60 bar (g)

reasons could not control this perfectly. The hydrogen content measured at VSL was 19.7 % at 8 bar and 17.2 % at 60 bar. At FORCE, the hydrogen content for the ultrasonic meter was 14.0 % at 8 bar and 15.7 % at 60 bar. For the rotary meter, it was 18.0 % at 8 bar and 20.0 % at 60 bar. This yields to additional differences in Reynolds number.

- Pressure effects: due to operational reasons there were some mild differences in actual pressure of the calibrations. For example, VSL calibrated the rotary meter at 58 bar with natural gas while FORCE measured at 61 bar. Both the error of rotary meters and ultrasonic meters are affected to some extent by pressure levels.
- Novelty of the tests: neither FORCE nor VSL had any experience with testing ultrasonic flow meters on their piston provers, which was challenging due to the relatively short stroke of the piston provers combined with the characteristics of the ultrasonic flow meter (delays in pulse output). In addition, there were significant differences in piping configuration, which could affect the ultrasonic flow meter. The stability of the experimental setups is then not guaranteed.
- Stability of the flow meters: as described previously, the stability of the flow meters is relatively poor compared to the CMC's of the participating laboratories. This is especially true for the ultrasonic meter. An analysis according to "Criterion 'D'" [21] was not performed due to time limitations, but would potentially yield inconclusive results, meaning that the stability of the flow meters may not have been sufficient to confirm the participants' CMC values.
- The ultrasonic flow meter was a natural gas meter and as such the addition of hydrogen had a significant experimental nature.
- The VSL piston prover was designed for 4" rotary meters of a specific type, and this intercomparison is the first comparison with this piston prover using smaller meter diameters.
- The rotary meter was a relatively new meter, and the overall increase in measurement error (meter indicates more after the comparison, cf. the "VSL after" results above) seems to be consistent with the theory that the bearings start running more smoothly after an initial run-in period.

**Table 2.** Technical data: meters tested for domestic gas meters test. Both meters are configured for hydrogen.

	Ultrasonic meter 2	Thermal mass meter
Flow range	0.4 to 15 m <sup>3</sup> /h	1.0 to 4 kg/h
Accuracy class	1.5	Not specified
Participant	VSL	NEL

**Figure 17.** Schematic of the measurement setup at VSL

### 3 Domestic gas meters

This section presents test results from two different meters calibrated with pure hydrogen and a mixture of 98 % hydrogen and 2 % nitrogen. One NMI and one DI participated: VSL, and TÜV SÜD National Engineering Laboratory (United Kingdom, called NEL). The results for the hydrogen blends are compared with those for pure hydrogen to determine whether the presence of impurities up to 2 % by volume significantly alters the performance of the meters.

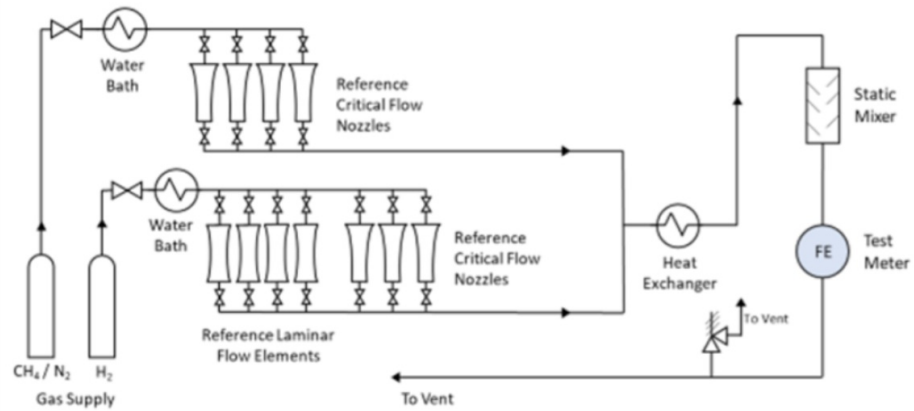
#### 3.1 Meters tested

Two meters with different measurement principle were procured for the test measurements: one thermal mass meter, and one ultrasonic meter (called ultrasonic meter 2 to avoid confusion with the former one used for the intercomparison). Both meters were configured to measure hydrogen. Their characteristics are shown in Table 2.

#### 3.2 Testing facilities

**3.2.1 VSL test facility** The ultrasonic meter 2 was tested at VSL using their domestic calibration facility. The complete setup was moved outside of the main building in a container so that measurement with explosive gases could be performed. Figure 17 shows a schematic representation of the test facility. Gas cylinders are used as gas sources. Before entering the test section, the gas passes through a passive heat exchanger to stabilise temperature. A wet drum-type gas meter from Ritter (TG50-1.4571-PE-e) with an internal volume of 50 L and filled with Diala S4 ZX-I mineral oil was used as reference meter. Flow was adjusted using a control valve located upstream of the reference meter. The ultrasonic meter 2 was mounted downstream of the reference meter. Ambient conditions were monitored. Gas pressure and temperature were measured upstream of the reference meter and downstream of the test meter, as can be seen in Figure 17. The reference flow rate is corrected for pressure and temperature conditions at the test meter. Measurements are done with a read-out of every single complete revolution of the reference meter using an optical sensor that is triggered by the dial in the front of the drum-type gas meter. The pulse output from the test meter was used and set to 1000 pulses/m<sup>3</sup>.

**3.2.2 NEL test facility** The thermal mass flow meter was tested at NEL using their domestic gas meter facility. Figure 18 shows a schematic representation of the test facility. Pressure bottles were used as gas sources. Before entering the test section, the gas passed through a passive heat exchanger to stabilize temperature. The reference flow rate is from reference Critical Flow Venturi Nozzles (CFVN), which is then corrected for pressure and temperature conditions at the test meter. Gas passes through a heat exchanger before entering the test section. Pressure is measured upstream of the test meter and temperature is measured downstream. Gas is vented in the atmosphere. The test meter was read out using its dedicated software from the manufacturer via RS-232 digital communications. The final output of the software was in L/min.



**Figure 18.** Schematic of the measurement setup at NEL

### 3.3 Results

Each laboratory provided the results with the reference flow rate at the test meter, the flow as measured by the test meter, the associated error of the test meter and pressure and temperature conditions. All numerical data are displayed in Annex.

**3.3.1 Ultrasonic meter 2** The results presented below are the average of three repetitions at each flow rate. The expanded uncertainty of the measurements is of the order of 1 %, except for the point at the lowest flow rate for pure nitrogen (2.5 %). Repeatability is of the order of 0.1 %. DUT stands for Device Under Test (test meter).

For the measurements with pure hydrogen and hydrogen with nitrogen as impurity, there is an important gas temperature difference (from 2.14°C up to 7.51°C) between the reference meter and the test meter at flow rates above 6 m<sup>3</sup>/h, indicating that the measurements were not performed under stable gas temperature conditions. The reason for this is that the passive heat exchanger was too small in diameter. At higher flow rates, part of the gas expansion occurs after the heat exchanger, causing the gas to cool down significantly (despite the negative Joule-Thompson coefficient of hydrogen gas). This most probably affected the absolute value of the flow measurement, particularly the calculation of the reference flow rate at the test meter. We are interested in how measurements with hydrogen blends compare to pure hydrogen for such type of meter. The temperature difference for pure hydrogen and the hydrogen blend share similar features, which means that the difference in error is still a good indicator for the response of the meter to pure hydrogen and the current hydrogen blend.

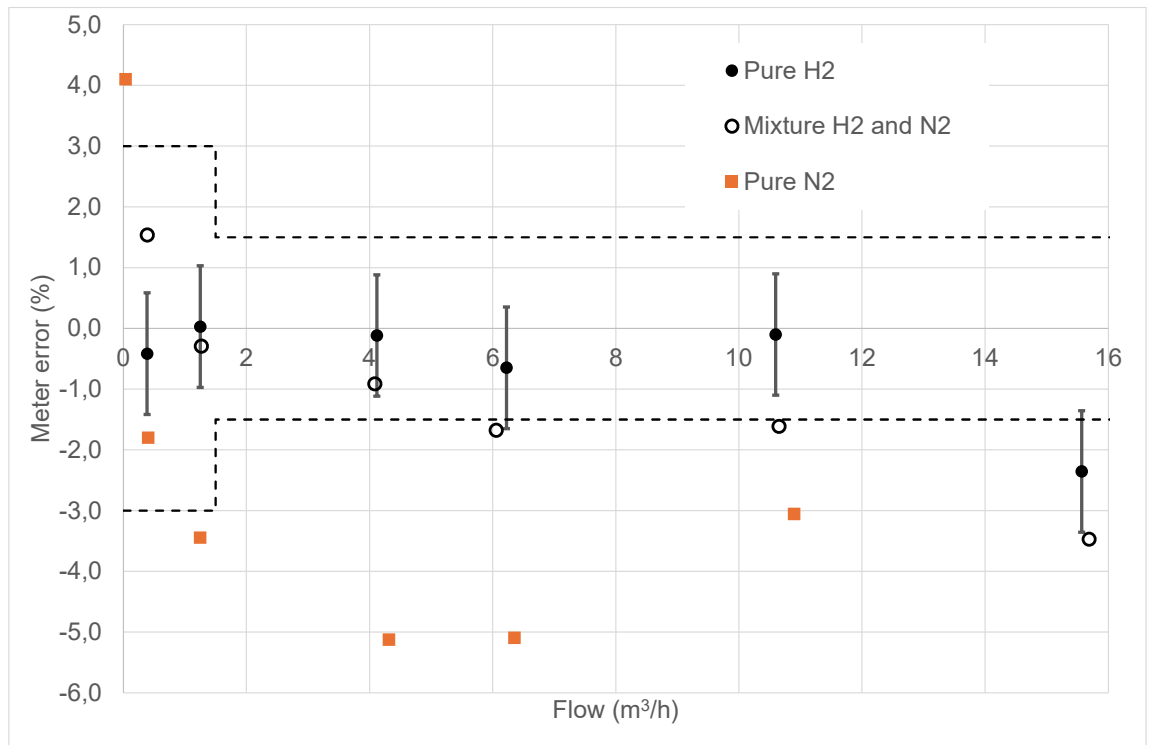
One notices also that the gage pressure at the test meter is negative for the two lowest flow rates with hydrogen. This is probably due to a bad zeroing of the pressure sensor. The potential effect on the measurement error is small (0.05 %).

The errors of the ultrasonic meter 2 as a function of flow rate for all three gases are shown graphically in Figure 19, the dotted lines represent the Maximum Permissible Error for a Class 1.5 meter with a transition flow rate at 1.5 m<sup>3</sup>/h. Only the error bars for hydrogen are shown for better readability and to give a sense of scale.

It is immediately apparent that the meter was not configured for nitrogen, which explains why the error of the test meter lies outside the MPE (Maximum Permissible Error) band. These results will not be discussed any further and we will focus on the results with hydrogen.

The measurement results for pure hydrogen are within a range of -0.65 % and 0.03 %, well within the MPE band, except for the highest flow rate, where the error is -2.35 %. This last point could be due to the not ideal temperature conditions as the other points show a relatively constant error.

The measurement results for hydrogen blended with 2 % nitrogen are within a range of 1.54 % and -3.47 % and the errors present a linear trend as a function of flow rate. The errors at the lower flow rates (< 6 m<sup>3</sup>/h) are within the MPE limits. The data seems to indicate an offset with respect to the pure hydrogen data. One should keep in mind that the measurement results of ultrasonic meters depend on the speed of sound and thus the density of the gas. Blending 2 % of nitrogen with hydrogen yields an increase in density of 25 % compared to pure hydrogen. This can likely affect the reading of an ultrasonic meter that has been configured for pure hydrogen.



**Figure 19.** Measurement results for the ultrasonic meter 2

**3.3.2 Thermal mass flow meter** The results presented below (Figure 20) are the average of three repeats at each flow rate. The expanded uncertainty of the measurements is of the order of 0.5 %, the repeatability is below 0.1 %. DUT stands for Device Under Test (test meter).

The errors of the thermal mass flow meter as a function of flow rate for both gases are shown graphically in Figure 20. The MPE limits are not shown because the thermal mass flow meter that was tested was not a meter typically used for domestic metering. The manufacturer specifies an accuracy of  $\pm 0.5$  %. Like for the ultrasonic meter, only the error bars for pure hydrogen are shown for better readability and to give a sense of scale

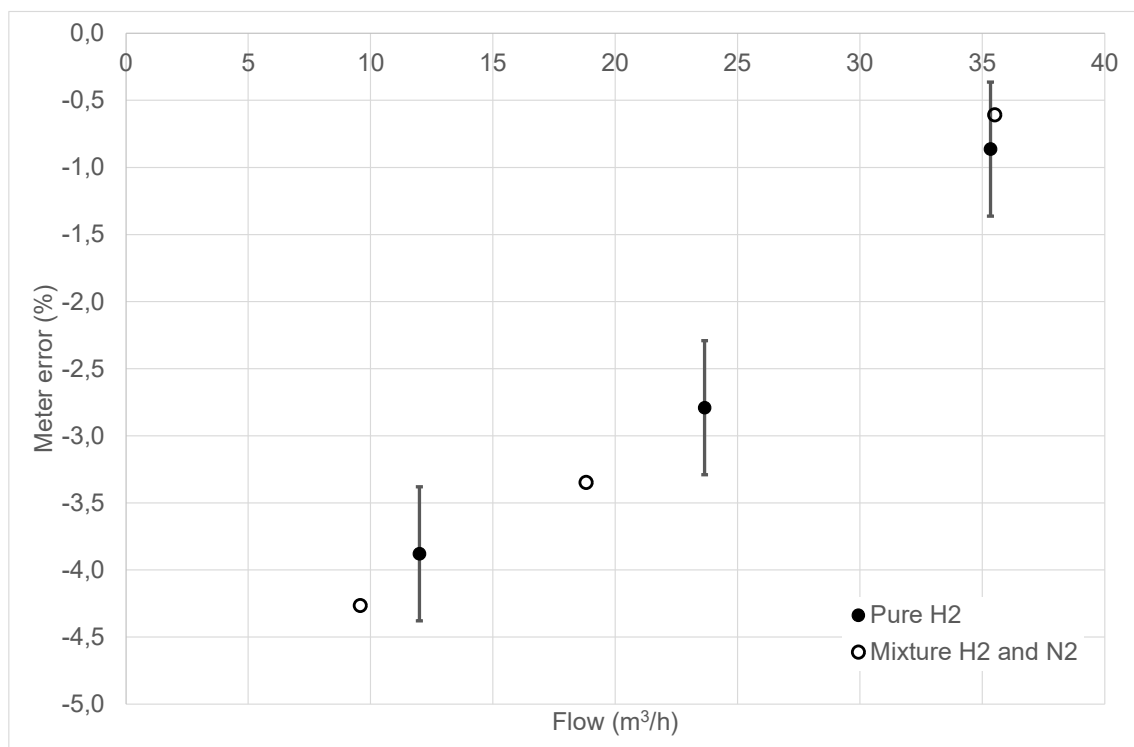
The measurement results for both gases show an identical trend with a clear flow-dependent error. There is hardly any difference between both gases because they have very similar molar heat capacities at constant pressure under the condition of the experiments (room temperature, both gases are diatomic). The presence of impurities at up to 2 % do not seem to affect significantly the reading of the meter in volume flow, however the chemical profile of the impurity is critically important. Indeed, diatomic gases are more likely going to match the molar heat capacity of hydrogen; one could expect more effect from impurities with different molar heat capacities such as methane.

There seems however to be a problem with the linearisation of the error curve of the meter. The meter has the smallest error between -0.86 % and -0.61 % at the highest flow rate of 35 m<sup>3</sup>/h. The error changes to around -4 % at 10 m<sup>3</sup>/h with a clear linear trend.

**3.3.3 Tests with pure hydrogen and hydrogen with impurities: discussion** Two meters with different measurement principles were measured using pure hydrogen and hydrogen blended with 2 % nitrogen (in volume). Volume flow was measured for both devices. Measurement results for an ultrasonic meter that was configured for measuring pure hydrogen show that impurities up to 2 % in volume affect the reading of the meter in a linear way as a function of flow rate. Measurement results for a thermal mass flow meter that was configured for measuring pure hydrogen show that impurities up to 2 % in volume hardly affect the reading of the meter in volume flow.

The main observations of this experiments are:

- The accuracy of the ultrasonic meter, originally designed for pure hydrogen, is significantly disturbed by the impurities. The impurities increase the density of the mixture by 25 %, it



**Figure 20.** Measurement results for the thermal mass flow meter

may explain the difference.

- When using a thermal mass meter, the impurities do not seem to affect the accuracy of the volume flow rate measurement. It can be explained by the similar heat capacity at constant pressure for both hydrogen and nitrogen (used as impurity). However, the meter error was large at lower flow rates even with pure hydrogen, so results must be interpreted carefully. In addition, for impurities with significantly different molar heat capacities (typically non-diatomic gases such as methane), larger differences could be expected.

Thermal flow meters may be more suitable than ultrasonic meters to measure hydrogen flows susceptible to be polluted by impurities, however more measurements should be conducted, with different gases and meter technologies, to confirm or disprove this hypothesis.

#### 4 Conclusion

This study was built around an intercomparison to check the similarity of outputs between several laboratories when gas meters were tested with natural gas mixed with hydrogen; to which an additional study with two gas meters tested with hydrogen with impurities was added. Thus, gas meters were tested with hydrogen, both diluted in natural gas (intercomparison) and at purities level of 98 % and 100 % (test with domestic meters).

The intercomparison provided results from at least two (FORCE and VSL), and in some cases three laboratories (CESAME in addition). Therefore, data and information that could lead to more general conclusions are limited. A rotary meter and an ultrasonic meter were tested. Participants underlined that they did not have much experience in testing ultrasonic gas meters. The ultrasonic gas meter used was designed for measuring natural gas and the reproducibility under test conditions was limited, and therefore its measurement uncertainty is high; this leads to unconvincing results concerning the intercomparison. The rotary gas meter also showed some drift during testing, likely because it was a new and not completely run-in. Furthermore, measurements were carried out at different temperatures, pressures, and the composition of the gas used also differed. In general, the overlap between the different laboratories is sufficient for the rotary meter, supporting their CMC claims; concerning the ultrasonic meter, the overlap is very good if the large instability of the meter is included in the uncertainty. However, advanced conclusions are difficult to draw without more measurement data.

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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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One key insight gained from this comparison is that the tested rotary gas meter exhibits significantly less variation across different pressures and gas compositions when compared to the ultrasonic gas meter tested. In addition, the test setup appears to influence meter behaviour, suggesting dynamic effects that may warrant further investigation.

Concerning the test of two domestic gas meter with pure hydrogen and hydrogen with impurities: the thermal mass meter seems less sensitive to presences of nitrogen, likely due to the similar molar heat capacity between hydrogen and nitrogen; on the other hand, the ultrasonic meters seems to be influence, likely due to the change in density when adding impurities. Additional experiments with other impurities and meter technologies are recommended.

The results of both experiments show promising results: there is no evidence that blending up to 20 % (molar) of hydrogen with natural gas will prevent a successful intercomparison between laboratories; and accuracy of rotary meter and thermal mass meters used with hydrogen may not be disturbed by impurities. For ultrasonic meter the results show some dependance on test medium when they are operated outside their specified medium range. Further measurements with similar and different meter technologies are necessary before concluding about the relevance of one technology on another.

### Acknowledgments

The project 21GRD05 Met4H2 has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States. The authors would like to acknowledge the help and support of Kurt Rasmussen (FORCE), Hamidou Soumaré (CESAME), Edvardas Venslovas (Justervesenet), Bernhard Rötter (BEV, Austria), Hugo Bissig (METAS), Søren Heide Lambertsen (FORCE) and the high-pressure team (VSL).

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- Marcel Workamp: conceptualization, data curation, investigation, resources, methodology, validation, visualization, original draft, review and editing
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## References

- [1] European Commission and Directorate-General for Communication. *The European Green Deal – Delivering the EU’s 2030 climate targets*. Publications Office of the European Union, 2023.
- [2] The european hydrogen backbone. <https://ehb.eu>, 2025. Accessed: 2025-07-08.
- [3] Arul Murugan, Oluwafemi Omoniyi, Emma Richardson, Marcel Workamp, and Annarita Baldan. Vision for a european metrology network for energy gases. *Environmental Research: Infrastructure and Sustainability*, 2(1):012003, 2022.
- [4] Metrology for decarbonising the gas grid, decarb. <https://www.decargrid.eu/>, 2025. Accessed: 2025-07-09.
- [5] Flow metering of renewable gases, newgasmet. <https://newgasmet.eu/>, 2025. Accessed: 2025-07-09.
- [6] New methods of testing for measurement of natural gas and hydrogen mixtures, thoth2. <https://thoth2.eu/>, 2025. Accessed: 2025-07-09.
- [7] Metrology infrastructure for high-pressure gas and liquified hydrogen flows, methyinfra. <https://www.methyinfra.ptb.de/the-project/>, 2025. Accessed: 2025-07-09.
- [8] Marc MacDonald, Dale Anderson, Rainer Kramer, Matthias Weyhe, Daniel Schumann, Hans-Benjamin Böckler, Marcel Workamp, and Menne Schakel. Conformity assessment of domestic and commercial gas meters for usage with hydrogen enriched natural gas and pure hydrogen. *Flow Measurement and Instrumentation*, 97:102594, 2024.
- [9] Marcel Workamp and Menne Schakel. Effect of hydrogen admixture on the accuracy of a rotary flow meter. *Global Flow Measurement Workshop 2022*, 2022.
- [10] Marcel Workamp, Arjan de Kater, Wouter Stiphout, and Pieter Pinson. Performance testing of gas flow meters with renewable energy gases. *Measurement: Sensors*, 38:101552, 2025. Proceedings of the XXIV IMEKO World Congress.
- [11] Matteo Robino, Salvatore Fici, Alessandro Guzzini, Marco Pellegrini, Cesare Saccani, Remy Maury, Hamidou Soumare, Ludovico Mazzocco, Pawel Kulaga, Adrian Dudek, Monika Gajec, Jadwiga Holewa-Rataj, Diana Enescu, Denis Smorgon, Rezvaneh Nobakht, Rugiada Cuccaro, Andrea Gaiardo, Matteo Valt, Matteo Testi, and Ruben Bartali. Development of testing protocols for the measurement of pure and blended hydrogen in natural gas grids: An outlook from the thoth2 project. *Measurement: Sensors*, 38:101610, 2025. Proceedings of the XXIV IMEKO World Congress.
- [12] Masataka Matsuda, Yuya Takakura, Yuji Nakabayashi, and Toshihiro Morioka. Ultrasonic gas flow and concentration measurement in hydrogen and nitrogen gas mixtures. *Measurement: Sensors*, 38:101535, 2025.
- [13] Aleksandr Andreev, Eric Starke, Toralf Dietz, Martin Oberlander, and Moritz Siegried. Practical experience, challenges and solutions at testing and calibrating of hydrogen ultrasonic flow meters. *Global Flow Measurement Workshop 2024*, 2024.
- [14] Gabriele Chinello, Arjan de Kater, Mahdi Sadri, Jorge Modrego, Dennis van Putten, Wouter Stiphout, Marcel Workamp, and Dale Anderson. Calibration facilities and test results for gas network hydrogen and hydrogen enriched natural gas flow meters. *International Journal of Hydrogen Energy*, 160:150431, 2025.
- [15] EuReGa consortium. European reference for gas. <https://www.euramet.org/research-innovation/search-research-projects/details/project/eurega-1>, 2025. Accessed: 2025-07-09.
- [16] Hydrogen fuel quality — product specification. International Standard ISO 14687:2025, 2025. 2nd edition.
- [17] Metrology for the hydrogen supply chain, met4h2. <https://met4h2.eu/>, 2025. Accessed: 2025-07-09.
- [18] Gas meters, 2012. OIML R137:2012.

- [19] Measuring systems for gaseous fuel, 2007. OIML R140:2007.
- [20] Directive 2014/32/eu of the european parliament and of the council of 26 february 2014 on the harmonisation of the laws of the member states relating to the making available on the market of measuring instruments (recast), 2014. Applicable from 20 April 2016.
- [21] John Wright, Blaza Toman, Bodo Mickan, Gerd Wübbeler, Olha Bodnar, and Clemens Elster. Transfer standard uncertainty can cause inconclusive inter-laboratory comparisons. *Metrologia*, 53(6):1243, oct 2016.

## Annex

**Table 3.** Experimental conditions for the intercomparison: gas tested (Air, NG or HENG) depending on meters, flow rates, pressure and institution

Meter	Pressure	Institution	Flow rates (m <sup>3</sup> /h)			
			Low*	16, 40	64, 112	160
Rotary Meter	1 atm	VSL (bef.+aft.)		Air		
	8 bar	VSL (bef.+aft.)	Air	NG, HENG		
		FORCE CESAME	HENG	Air	NG, HENG	
60 bar	VSL, FORCE**	NG, HENG				
Ultrasonic meter	8 bar	VSL	NG, HENG			
	60 bar	FORCE	HENG	NG, HENG		
		VSL, FORCE	NG, HENG			

\*: 5 m<sup>3</sup>/h for VSL and FORCE, 8 m<sup>3</sup>/h for CESAME

\*\* : FORCE ran this test at 80 and 100 instead of 112 m<sup>3</sup>/h for HENG; and in addition at 140 m<sup>3</sup>/h for NG.

**Table 4.** Stability of the Rotary meter. Tests realized in March 2024 and March 2025 at VSL under atmospheric pressure

Flow rate (m <sup>3</sup> /h)	Error of the meter (March 24, %)	Error of the meter (March 2025, %)	Difference (%)
16	0.09	0.05	-0.04
40	0.12	0.15	0.03
64	0.13	0.17	0.04
112	0.16	0.26	0.10
160	0.04	0.17	0.13

**Table 5.** Stability of the ultrasonic meter. Tests realized in April 2024 and March 2025 at VSL under atmospheric pressure

Flow rate (m <sup>3</sup> /h)	Error of the meter (March 24, %)	Error of the meter (March 2025, %)	Difference (%)
16	1.11	1.99	0.88
40	1.79	1.74	-0.05
64	1.58	1.73	0.15
112	0.43	0.64	0.21
160	0.05	0.28	0.23

**Table 6.** Numerical results for the rotary meter tested with air at 1 atm

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)
VSL before	0.7523	0.09	0.15	VSL after	0.7519	0.05	0.15
	1.878	0.12	0.15		1.871	0.15	0.15
	2.995	0.13	0.15		3.006	0.17	0.15
	5.235	0.16	0.15		5.240	0.26	0.15
	7.477	0.04	0.15		7.487	0.17	0.15
Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)				
CESAME	0.3673	-0.07	0.21				
	0.7316	0.11	0.21				
	1.792	-0.19	0.21				

**Table 7.** Numerical results for the rotary meter tested with NG (air for CESAME) at 8 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)
VSL before	2.132	-0.57	0.19	VSL after	2.119	-0.32	0.19
	6.072	-0.06	0.13		6.342	0.06	0.13
	15.76	0.04	0.12		16.02	0.20	0.12
	24.90	0.01	0.13		25.54	0.17	0.14
	43.97	0.07	0.11		44.59	0.25	0.11
	62.50	0.28	0.11		63.63	0.55	0.11
Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)
FORCE	6.490	0.20	0.17	CESAME	3.306	0.10	0.21
	16.22	0.29	0.17		6.645	0.20	0.21
	25.96	0.20	0.17		16.67	0.25	0.21
	45.42	0.12	0.17		26.65	0.21	0.21
	64.91	0.10	0.17		46.01	0.07	0.22

**Table 8.** Numerical results for the rotary meter tested with HENG at 8 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)
VSL before	1.553	-0.24	0.22	VSL after	1.689	-0.52	0.21
	4.920	0.02	0.13		5.389	-0.01	0.13
	12.15	0.15	0.12		13.32	0.19	0.12
	19.14	0.18	0.14		21.28	0.18	0.13
	34.04	0.19	0.11		36.90	0.18	0.11
	48.16	0.33	0.11		52.81	0.39	0.11
Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)				
FORCE	1.636	0.29	0.17				
	5.237	0.18	0.17				
	13.09	0.26	0.17				
	20.95	0.19	0.17				
	36.70	0.09	0.17				
	52.50	0.07	0.17				

**Table 9.** Numerical results for the rotary meter tested with NG at 60 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)
VSL	13.47	-0.03	0.22	FORCE	13.73	0.05	0.17
	42.14	-0.14	0.13		43.92	0.05	0.17
	107.8	0.05	0.12		109.8	0.19	0.17
	173.0	0.11	0.14		175.6	0.22	0.17
	299.6	0.16	0.11		307.2	0.21	0.17
				384.4	0.17	0.17	

**Table 10.** Numerical results for the rotary meter tested with HENG at 60 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)
VSL	10.81	-0.09	0.22	FORCE	10.52	0.19	0.17
	36.14	-0.16	0.13		33.68	0.06	0.17
	88.87	-0.06	0.10		84.19	0.20	0.17
	143.2	0.03	0.10		135.9	0.16	0.17
	249.4	0.05	0.10		169.8	0.21	0.17
				212.4	0.16	0.17	

**Table 11.** Numerical results for the ultrasonic meter tested with NG at 8 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
VSL	1.937	1.67	0.56	0.23
	6.079	0.46	0.53	0.14
	15.23	0.68	0.52	0.09
	24.45	0.69	0.52	0.11
	42.85	0.90	0.52	0.09
	61.25	1.28	0.51	0.08
Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
FORCE	6.758	0.46	0.53	0.15
	16.90	0.71	0.53	0.15
	27.08	0.57	0.53	0.15
	47.42	0.49	0.53	0.15
	67.58	0.46	0.53	0.15

**Table 12.** Numerical results for the ultrasonic meter tested with HENG at 8 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
VSL	1.616	2.34	0.56	0.23
	4.800	0.95	0.56	0.23
	12.06	0.93	0.52	0.09
	19.14	1.09	0.52	0.11
	33.07	1.34	0.51	0.08
	48.27	1.59	0.51	0.08
Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
FORCE	1.791	1.67	0.53	0.15
	5.747	1.75	0.53	0.15
	14.38	1.61	0.53	0.15
	23.04	1.55	0.53	0.15
	40.34	1.48	0.53	0.15
	57.82	1.37	0.53	0.15

**Table 13.** Numerical results for the ultrasonic meter tested with NG at 60 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
VSL	12.94	0.47	0.56	0.24
	41.87	0.43	0.52	0.12
	102.4	0.31	0.52	0.09
	167.3	0.34	0.52	0.08
	294.6	0.65	0.51	0.08
Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
FORCE	14.30	0.47	0.53	0.15
	45.75	0.19	0.53	0.15
	114.4	-0.02	0.53	0.15
	182.9	-0.05	0.53	0.15
	320.2	0.06	0.53	0.15

**Table 14.** Numerical results for the ultrasonic meter tested with HENG at 60 bar

Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
VSL	11.81	0.98	0.65	0.40
	36.45	0.80	0.52	0.16
	88.94	0.75	0.52	0.07
	143.3	0.73	0.52	0.07
	252.1	1.00	0.51	0.08
Laboratory	Re (x10e-4)	Error (%)	Uncertainty (k=2, %)	Base uncert. (k=2, %)
FORCE	11.33	1.80	0.53	0.15
	36.22	1.56	0.53	0.15
	90.49	1.32	0.53	0.15
	144.9	1.25	0.53	0.15
	253.4	1.35	0.53	0.15

**Table 15.** Numerical results for the ultrasonic meter 2 tested with pure hydrogen, 98 % hydrogen and 2 % nitrogen (hydrogen with impur.), and pure nitrogen

Gas	Reference volume flow rate (m <sup>3</sup> /h)	Error (%)	Gage pressure at the meter (Pa)	T <sub>DUT</sub> (°C)
Pure hydrogen	15.57	-2.35	243	18.97
	-0.10	0.80	113	18.81
	6.223	-0.65	41	18.96
	4.118	-0.12	16	19.15
	1.249	0.03	-8	19.74
	0.386	-0.42	-13	21.13
Hydrogen with impur.	15.69	-3.47	301	22.89
	10.65	-1.61	144	18.52
	6.056	-1.68	49	20.30
	4.085	-0.91	20	18.54
	1.268	-0.29	-6	23.75
	0.3869	1.54	-12	20.75
Pure nitrogen	10.89	-3.05	904	12.81
	6.029	-5.09	348	16.57
	4.312	-5.12	183	16.48
	1.247	-3.44	33	17.14
	0.403	-1.80	14	22.11
	0.036	4.10	15	20.53

**Table 16.** Numerical results for the thermal mass meter tested with pure hydrogen, and: 98 % hydrogen and 2 % nitrogen (hydrogen with impur.)

Gas	Reference volume flow rate (m <sup>3</sup> /h)	Error (%)	Gage pressure at the meter (hPa)	$T_{DUT}$ (°C)
Pure hydrogen	35.33	-0.86	83.26	22.18
	23.65	44.74	44.74	22.41
	11.99	-3.88	17.30	22.49
Hydrogen with impur.	35.50	-0.61	99.10	22.66
	18.80	-3.35	36.87	22.69
	9.574	-4.27	14.61	22.72