21GRD05 Met4H2

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Contents

1 Introduction

The overall objective of the Met4H2 research project is to provide new and improved standards for safe hydrogen applications, flow measurement, hydrogen quality assessment and custody transfer. A significant part of the project is focused on flow measurement. The objective is to collect and analyze data on flow measurements of hydrogen and gas mixtures containing hydrogen along the entire hydrogen supply chain; and to design a traceability strategy for large-scale hydrogen flow metering, to facilitate compliance with respect to e.g., OIML R137, OIML R140, and the Measurement Instruments Directive.

This technical report presents the findings of an effort in the Met4H2 project to produce a traceability chain for hydrogen flow metering. Relevant flow metering points and requirements for fiscal metering points were found by surveying stakeholders involved in large-scale hydrogen applications.

A route for traceability is suggested. It involves the operation of newly developed primary standards to calibrate Critical Flow Venturi Nozzles (CFVN). The primary standards that are suggested are of the pVTt type, for which a concept study and a cost estimate is provided. The CFVNs are then combined in an array to bootstrap to larger flow rate ranges, detailed in an experimental protocol. The array allows for calibration of master meters.

Calibrations of CFVN with hydrogen gas were performed. Early results show that the discharge coefficient curve for hydrogen closely follows that of air, and both are within the uncertainty of the laboratory.

2 Traceability chain based on stakeholder needs

2.1 Introduction

The aim of this chapter is to design a European metrological traceability chain based on the needs identified from a survey of relevant stakeholders involved in high-flow hydrogen applications. That survey was performed earlier in the project. The traceability chain contains relevant calibration points for required fiscal flow metering and identifies needs for new flow measurement facilities. The targeted flow rates are above 0.2 kg/min (approx. 134 Nm3/h[1]). At least three options for the traceability chain are discussed,

1) Primary standards.

2) Combination of several small sonic nozzles calibrated with hydrogen.

3) Large nozzles calibrated with air, assuming hydrogen equivalence.

This chapter includes the definition of large and small nozzles, with the assumption that small nozzles can be calibrated directly with primary standards while large nozzles require flow rates that are too large to be calibrated with hydrogen directly.

2.2 Primary standard

A primary standard is the highest level in the traceability chain and is traceable to the International System of Units (SI) which ensures unidirectional and accurate measurement for all types of measurements including length, mass, temperature and time. In this context, it applies to the piston prover and pVTt system. The SI is coordinated by the BIPM (International Bureau of Weights and Measures).

2.2.1 Piston Prover

The Piston Prover is a primary gas flow standard that is traceable to the SI. It comprises a cylindrical chamber with a known volume. Inside the chamber, a piston moves, pushing the gas. By comparing the measured volume from the piston prover with flow meter reading, flow meter deviation can be calculated.

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[1] Unit for volumetric flow rate of air or gas at a temperature of 0 °C and pressure of 101,3 kPa, expressed in cubic metres per hour, Normal Cubic Metres Per Hour (Nm3/h) | Oil and Gas Drilling Glossary | IADCLexicon.org

2.2.2 pVTt

pVTt stands for Pressure, Volume, Temperature and Time. The pVTt system measurement accuracy depends on these four quantities and the compressibility factor Z. Similarly to the piston prover, it serves as a primary gas flow standard traceable to the SI.

A pVTt system contains a constant volume tank (CVT) where gas flow is diverted. Initially, the gas flows through the device under test (DUT) and eventually reaches the CVT.

2.3 Calibration of CFVN

The gas flows through the throat of a Critical Flow Venturi Nozzle (CFVN), whose diameter is known. As the gas passes through the narrow throat, its velocity increases to the speed of sound. By measuring the upstream pressure and the temperature, and by knowing the diameter of the throat and the thermodynamic properties of the gas, the flow rate can be determined.

Nowadays, master meters are typically calibrated against a traceable primary standard or another calibrated master meter with traceability. The objective of this project is to establish a traceability chain by employing Critical Flow Verification Nozzles (CFVNs) for the calibration of larger master meters.

2.4 Bootstrapping Calibration to higher flow

Bootstrapping is a well-known method for calibrating larger flow meters using smaller traceable flow meters. By adding more calibrated flow meters in parallel, higher flow rates can be achieved, allowing for the calibration of larger flow meters. However, the addition of more meters also introduces higher uncertainty. Nevertheless, the uncertainty remains very low at the CFVN. Figure 1 illustrates how bootstrapping can be applied with CFVN.

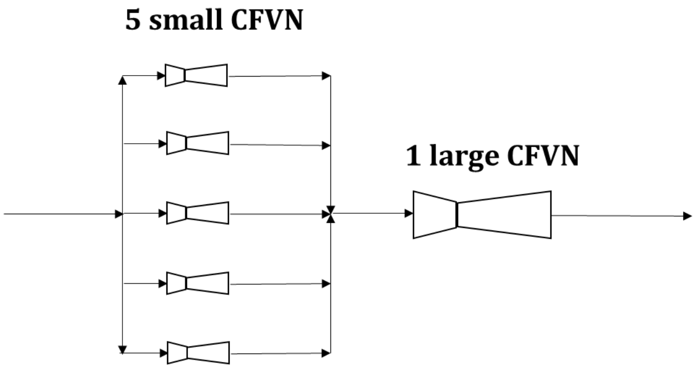


Figure 1: Bootstrapping with five small CFVNs in parallel

2.5 Definition for small or large CFVN

We define small CFVNs as those which may be calibrated by a primary standard. After investigating primary calibration facilities, as shown in Table 3 below, the maximum flow rate which may be achieved is 20 kg/h. This initial calibration serves as the basis for calibrating larger CFVNs, which can subsequently be used to calibrate master meters.

The initial step involves calibrating all small CFVNs against a primary standard. It is desirable to minimize bootstrapping steps, as this will reduce the uncertainty of the calibration's accuracy. When you have a meter or CFVN in a bootstrap, each component has a small uncertainty from the SI metric system; by reducing the amount of meters, the overall uncertainty decreases.

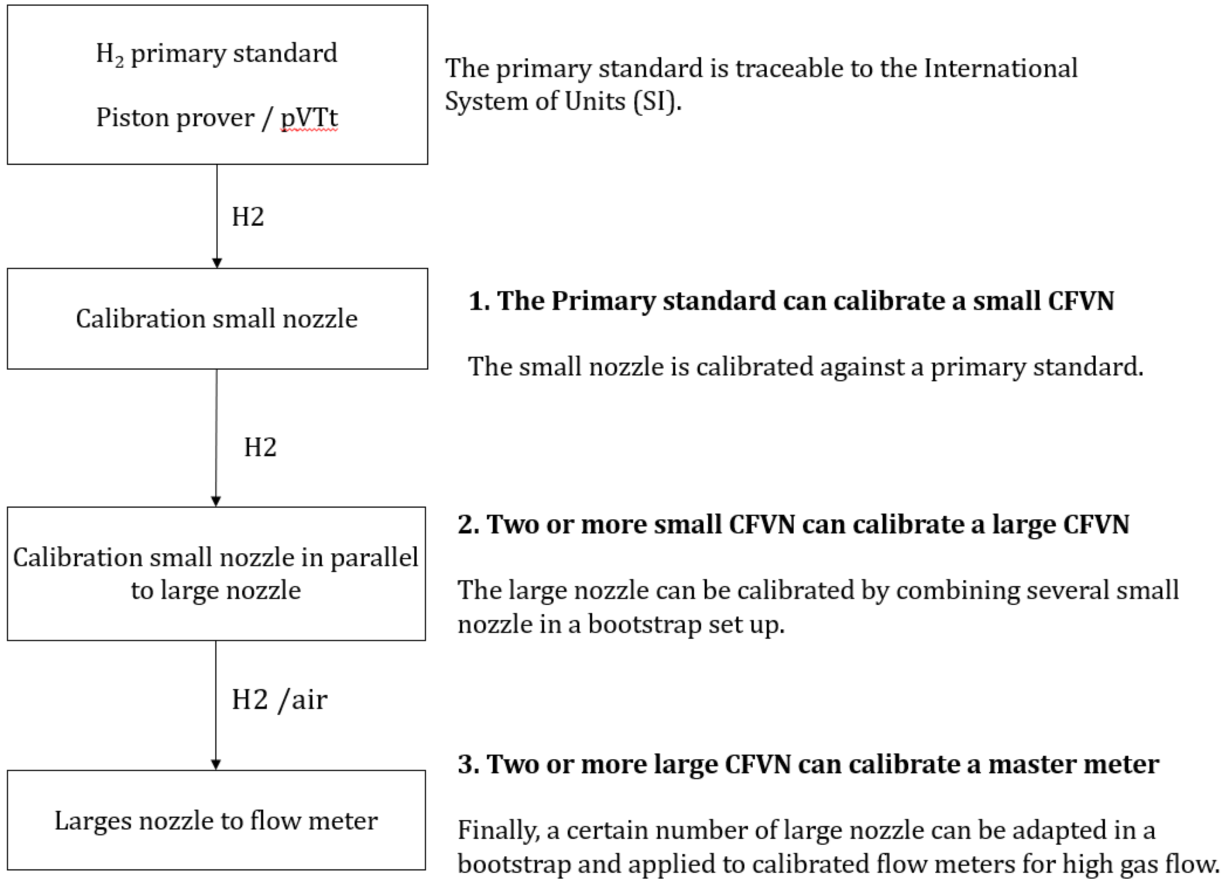
Thus, it is preferable to have the highest possible flows through the small calibrated CFVN.

Large CFVNs are defined as those which cannot be directly calibrated by a primary standard, and which may require a combination of small CFVNs in parallel to calibrate. For example, larger CFVNs with flow rates up to 120 kg/h can be calibrated from either six small CFVNs operating at 20 kg/h or twelve small CFVNs operating at 10 kg/h.

For Hydrogen Flow	Max Flow [kg/h]	Max Flow [Nm3/h]
Small nozzle	20	220
Large nozzle	120	1 350

Table 1: Definition of large and small nozzle for hydrogen flow. Nm^3/h is rounded.

2.6 Traceability chain draft in EU



The primary standard is traceable to the International System of Units (SI).

1. The Primary standard can calibrate a small CFVN

The small nozzle is calibrated against a primary standard.

2. Two or more small CFVN can calibrate a large CFVN

The large nozzle can be calibrated by combining several small nozzle in a bootstrap set up.

3. Two or more large CFVN can calibrate a master meter

Finally, a certain number of large nozzle can be adapted in a bootstrap and applied to calibrated flow meters for high gas flow.

2.7 Calibrating CFVNs using a Hydrogen Primary Standards

To achieve the highest traceability to the International System of Units (SI), the first step is to have a primary standard.

Primary calibration facilities for hydrogen flow which can give input to the European traceability chain are shown in Table 2[2].

The second step in the traceability chain is to calibrate individual small CFVNs against a primary standard, with hydrogen flow up to 20 kg/h, and to determine the discharge coefficient of each nozzle for various Reynolds numbers by covering its entire operational range within a specific pressure range. Small nozzles are currently defined as those calibrated by a primary standard, up to 20 kg/h. Future improvements in primary standards may potentially lead to a revision of this numerical threshold.

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[2] A number of institutes have been asked about their primary facility in a survey. Responses from this survey are illustrated in this table.

The following European primary facilities are or will be able to calibrate a small CFVN at a flow from 0.75 kg/h to 20 kg/h:

Institute	**Up to [kg/h]** (Hydrogen)	**Traceable to primary** (Hydrogen)
NEL (TÜV SÜD)	8	pVTt
University of Ljubljana	0.75	Piston Prover
CESAME	20	pVTt

Table 2: Institutes with small CFVN test facility

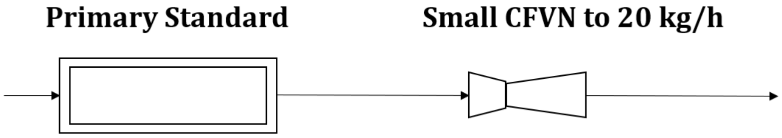

Figure 2: Primary Standard calibration of a single small nozzle.

The third step in the traceability chain is to calibrate a large CFVN on a bench with small nozzles operating in a bootstrap setup, thereby activating a higher hydrogen flow for calibrating large CFVNs up to 120 kg/h, as shown in Figure 3. Just as for small nozzles, the numerical threshold may be changed in the future.

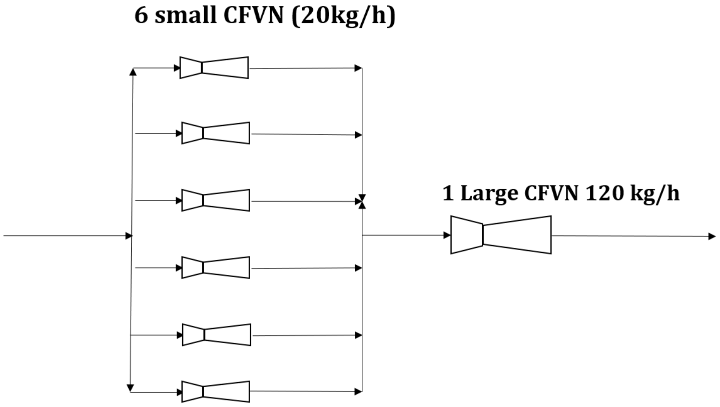

Figure 3: Calibration of a single larger nozzle by bootstrapping small CFVNs.

2.8 Master Meters

The final step is to calibrate a master meter. A certain number of large nozzles can be adapted in a bootstrap setup and applied to calibrate Master Meters for high hydrogen flow. These can be calibrated with another gas like air or hydrogen, see Figure 4. Currently, the institutes that can perform calibration with hydrogen, traceable to air or natural gas, are listed in Table 3.

Institution	**Up to [kg/h]** (Hydrogen)	**Traceable to ?**
RMA	4 405	Hydrogen: Nozzles from PTB, meter
DNV	1350	Air and Natural Gas: Turbine meter

Table 3: Institutes with facilities for calibration of Master Meters from hydrogen or air.

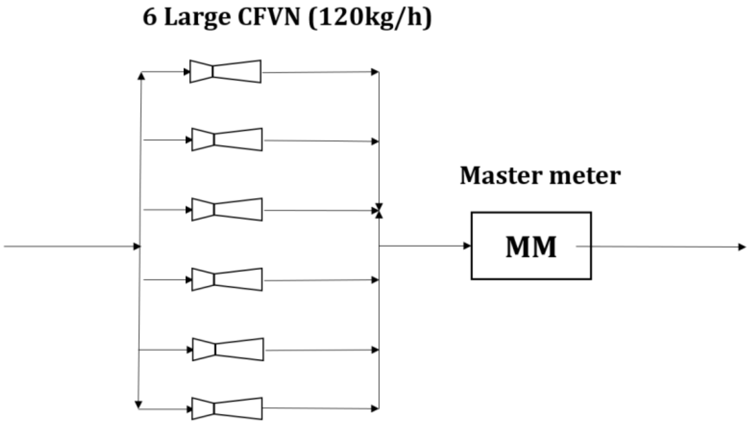

Figure 4: Calibration of a Master Meter by bootstrapping large CFVNs

2.9 Summary from the stakeholder survey

The survey of the stakeholders that was conducted has helped to gather information regarding the requirements of the industry for calibration facilities. The investigation has identified key points which are summarized here.

The focus of the survey was to gather the response of Transmission System Operators (TSOs) and major companies in the hydrogen business. The stakeholders who responded to the survey were generally involved with hydrogen transport. Other common involvements were hydrogen production and hydrogen storage. A few respondents were involved in hydrogen end use and hydrogen retail.

The pipe flow demands of the stakeholders are generally evenly distributed. However, there was slightly more demand for flow ranges above 250 Nm^3/h, up to 25 000 Nm^3/h (0°C, 1.01325 bar(a)). Table 4 below illustrates the distribution of flow demand across the flow categories from the survey, including definitions of the flow calibration equipment.

q [Nm^3/h]		$\dot{m}$ [kg/h]			Answer	[% of Response]	Calibrations device
0 to	25	0	to	2	5	29	Small CFVN
25 to	250	2	to	20	7	41	Small CFVN
250 to	1 350	20	to	120	12	71	Large CFVN
1 350 to	2 500	120	to	230	12	71	Master Meter
2 500 to	25 000	230	to	2 250	12	71	Master Meter
25 000 to	250 000	2 250	to	22 500	9	53	Master Meter

Table 4: The flow demands from the survey include the definition of calibration equipment (CFVN). The mass flow is rounded, and the percentage is based on the responses from 17 participants.

When it comes to the temperature ranges,the range from 0 to 20 °C has most replies (15 out of 18 responses), followed by the temperature range from 20 to 40 °C (11 out of 18 responses). For more details see Table 5.

T [°C]	Answer	[% of Response]
Cryogenic to -40	0	0
-40 to 0	4	22
0 to 20	15	83
20 to 40	11	61
> 40	5	28

Table 5: The demand for the temperature is based on the A2.4.2 survey. Based on 18 responses.

The survey also maps the pressure ranges which are relevant according to the industry. Pressures from 10 to 200 bar(g) are the most commonly quoted., Table 6 illustrates the responses distribution.

p [bar(g)]	Answer [% of Response]	
< 2	3	17
2 to 10	6	33
10 to 50	12	67
50 to 200	12	67
> 200	4	22

Table 6: The demand for the pressure is based on the A2.4.2 survey.Based on 18 responses.

Figure 5 illustrates the relationship between the various stakeholders' demands in relation to pressure and flow.

To enhance understanding and provide a clearer overview of the survey's demands for flow and pressure ranges, all company requirements are considered in Table 4. This allows a comprehensive understanding of the requirements across different companies.

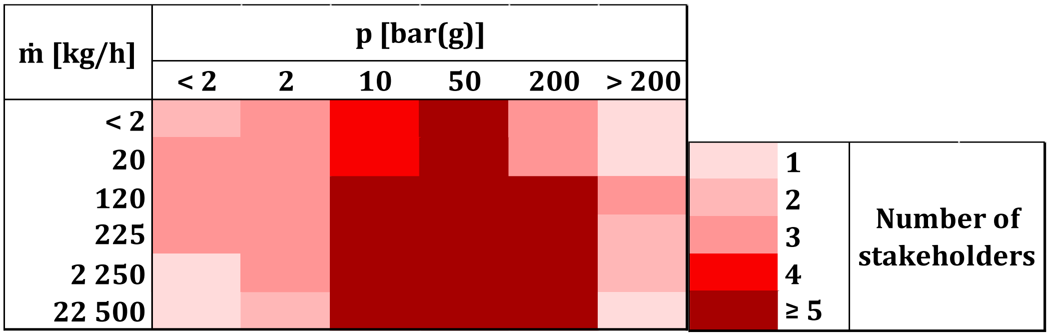

Figure 5: Pressure and flow demands from the stakeholders according to the survey of the stakeholders, together with the number of responses.

The industry requirements for meter accuracy are illustrated in Table 7, along with the entire distribution of industry responses.

Accuracy [%]	Answer	[% of Response]
< 0.5	9	56
0.5 to 1	9	56
1 to 2	3	19
2 to 5	2	13
> 5	2	13

Table 7: The demand for the meter's accuracy is based on the the survey of the stakeholders. Based on 16 responses.

2.10 Summary and Evaluation of EU Facilities Compared to Survey Demand

The need for hydrogen calibration facilities in Europa is widespread, as indicated by the survey discussed above. The results are presented in Table 8 in gray color.

The red filter indicates the test area with the highest demands according to the survey. However, this represents only the participants in the survey.

The hydrogen flow facilities across Europe are indicated with the green color, this is also roughly illustrated in Table 8. Generally, these facilities can calibrate at 20°C ±5°C.

Table 8 shows the gaps across the flow rate range and pressure rate range.

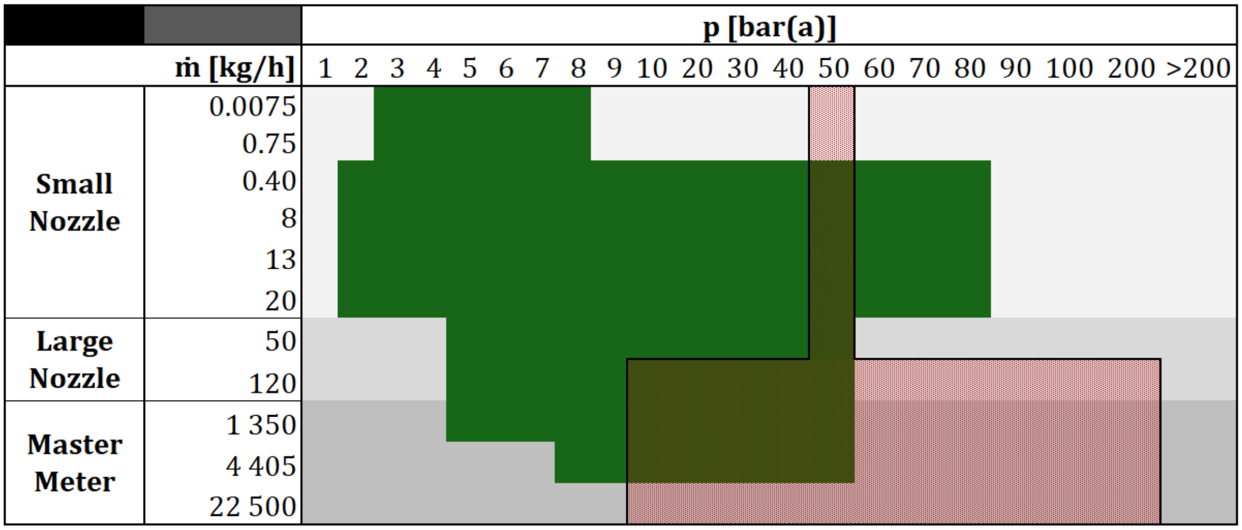

Table 8: The Surveys demands for flow, and the summarize of the upcoming and operational European hydrogen facility for flow calibration in 2024.

Definition of the colors:

🟩 Existing calibration facilities for hydrogen.

▨ Demands with most response for calibration according to the survey.

□ Survey demands for flow.

Table 9 provides more detailed information about the companies' hydrogen flow facilities in Europe.

Calibration facility	Min Flow [kg/h]	Max Flow [kg/h]	Pressure [bar(a)]	Tempera-ture [°C]	Traceability to/ Reference master meter	Pressure	Pressure unit
Ljubljanas universitet	0.0075	0.75	1 - 7	20	Piston Prover	1 -7	bar(a)
TÜV SÜD NEL	0.035	3	0	20	pVTt	3 - 5	bar(a)
CESAME	0.4	20	2 - 81	20	pVTt	1	bar(g)
DNV HyFLG flow loop specifications	7.0	1 350	5 - 40	20	Master Meter NG and Air	5 - 40	bar(a)
RMA	5	4 405	5 - 51	15	Nozzle Master Meter	8 - 51	bar(a)

Table 9: Upcoming and operational European hydrogen facility for flow calibration from 2024.

For more details on each of the mentioned facilities, refer to

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Annex A, European calibration facilities for hydrogen.

2.11 Conclusion

Hydrogen flow meter test facilities are being actively being developed. However, the survey results show that the current testing infrastructure does not fully meet the growing demand, revealing a noticeable gap. This may lead to the need for building additional test facilities or exploring whether alternative media could serve as suitable substitutes for hydrogen in calibration processes.

3 Concept study on the design of a primary standard to provide traceability to large-scale hydrogen transportation

3.1 Introduction

This chapter provides a concept study for the design of a primary standard and is based on design specifications from existing primary standards (CESAME) or under construction (METAS, NEL) using the pressure-volume-temperature and time (pVTt) method. The design of these three primary standards started during 20IND11 MetHyInfra. The standard from CESAME could be completed during the course of this project and is used as a primary standard in the traceability chain as defined in 23IND05 H2FlowTrace (1). The concept study for the design presented here will mainly be based on the design of the METAS standard. This document does not provide a detailed discussion on the operation of the pVTt standard nor does it give details on the risk assessment of the Ex-zones (hazardous area). A detailed description of the pVTt method with its accompanying uncertainty budget can be found in (2).

The primary standard is designed to provide traceability to large-scale hydrogen transportation as determined in the survey of the stakeholder needs and to serve as metrological basis for the traceability chain proposed in the previous chapter. The concept design includes a suitable technological solution for realizing sufficiently low uncertainties and a cost estimate.

This document starts with the presentation of the traceability chain, followed by a short description of the pVTt method before moving on to the design section of a primary standard. A cost estimate will be presented at the end.

3.2 Traceability chain

A traceability chain was proposed in the previous chapter and its schematic is presented in Table 10. CFVN stands for Critical Flow Venturi Nozzle. The project protocol of 23 IND05 H2FlowTrace provides most of the input to this section.

Table 10: Schematic of the traceability chain from the previous chapter.

Stage	Standard	Calibrated device	Flow and pressure range	Target expanded uncertainty of calibrated device
1	Primary (pVTt)	Six CFVN (Set A)	up to 20 kg/h (0.1 to 5.1) MPa	0.15 %
2	Nozzles Set A	Six CFVN (Set B)	up to 120 kg/h up to 3.3 MPa	0.20 %
3	Nozzles Set B	Four master meters	up to 720 kg/h up to 6.2 MPa	0.30 %

The traceability chain starts with a primary standard used to calibrate a set of six CFVN (Set A) with hydrogen over a pressure range (0.1 to 5.1) MPa. The target expanded uncertainty of each CFVN is expected to be 0.15 % with a maximum flow rate of 20 kg/h. In a second stage, combinations of the CFVN from Set A are positioned upstream of a single CFVN from another set of six larger CFVN (set B) to calibrate it with hydrogen up to 120 kg/h. The target expanded uncertainty of each CFVN of set B is expected to be 0.20 %. In a final stage, combinations of the CFVN from Set B are used to calibrate a skid comprising four master meters up to 720 kg/h at 6.2 MPa. Please be advised that the individual steps may vary depending on the laboratory facilities. Consequently, both the flow size proportions and the number of sonic nozzles may differ.

3.3 The pVTt method

Standards using the pVTt method are primary gas flow standards as they allow the collection of an amount of gas over a measured time interval under known pressure and temperature conditions in a known volume.

A calibration rig based on the pVTt method is shown schematically in Figure 6. It consists of a gas source, a test section where pressure and temperature conditions are stable and continuously monitored, a system for diverting gas flow into a known volume and determining the collection time. Flow can be diverted into the collecting volume by a set of valves. The concept is to generate stable flow conditions in the test section and then divert flow to a collection volume for a certain time. Given the known collection volume and time, as well as initial and final pressure and temperature conditions in the collection volume, one can determine the collected mass and finally the average mass flow rate using the time information. A CFVN isolates the test section from downstream pressure variations when gas is collected.

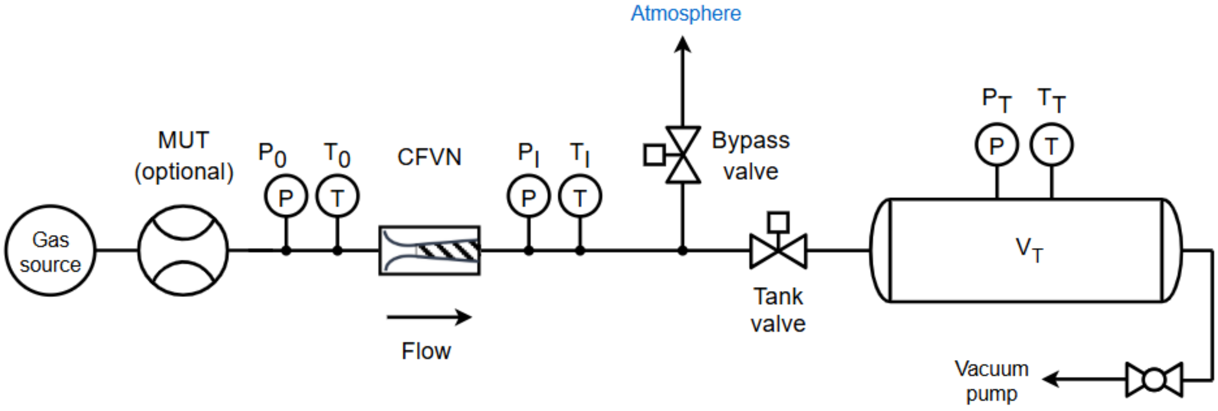

Figure 6: Schematic of a calibration test rig using the pVTt method.

The principle of operation is the following:

1. Start with the tank valve closed and the bypass valve open

2. Evacuate the collecting volume V_T using a vacuum pump to create known initial pressure and temperature conditions in the collecting volume (tank or collection of tanks) to determine the initial density and therefore the initial mass of gas in V_T.
3. Establish a stable flow.
4. Close the bypass valve and start the timer.
5. When the bypass valve is fully closed, open the tank valve so that gas is collected in V_T.
6. During collection time, record pressure and temperature in the test section until a predetermined pressure in V_T is reached.
7. Close the tank valve and stop the timer.
8. Open the bypass valve and wait for pressure and temperature in V_T to stabilise to determine the final density.

In between steps 4 and 5, the bypass valve is closing and gas will accumulate in the piping between the CFVN and the tank valve. As soon as the tank valve opens, this accumulated gas mass will be collected in V_T. The same applies in between steps 7 and 8 but in this case, the accumulated gas mass will not end in V_T. This part of piping downstream from the CFVN and both valves is called the inventory volume V_I and is normally smaller by orders of magnitude to V_T. This inventory volume must be determined. Pressure and temperature conditions in the inventory volume must be recorded in the intermediate state where both valves are closed to properly establish a mass balance.

The mass balance for the collecting volume and the inventory volume between initial and final conditions can be written as follows:

$$\Delta m = (m_{T,final} - m_{T,initial}) + \ (m_{I,final} - m_{I,initial}) \tag{1}$$

where $m_{T,final}$ and $m_{T,initial}$ are the final and initial mass in the collecting volume V_T and $m_{I,final}$ and $m_{I,initial}$ are the final and initial mass in the inventory volume V_I.

Assuming that V_T and V_I do not change between initial and final conditions, one gets from equ. (1)

$$\Delta m = V_T \cdot (\rho_{T,final} - \rho_{T,initial}) + \ V_I \cdot (\rho_{I,final} - \rho_{I,initial}) \tag{2}$$

where $\rho_{T,final}$ and $\rho_{T,initial}$ are the final and initial gas densities in the collecting volume V_T and $\rho_{I,final}$ and $\rho_{I,initial}$ are the final and initial gas densities in the inventory volume V_I.

One can finally derive equ. (3), which expresses the average mass flow rate during the collection time.

$$\dot{m} = \frac{V_T \cdot (\rho_{T,final} - \rho_{T,initial}) + \ V_I \cdot (\rho_{I,final} - \rho_{I,initial})}{t_{final} - t_{inital}} \tag{3}$$

3.4 Design of pVTt standard

This section focuses on the dimensioning and metrological requirements of the various pieces of equipment of the pVTt standard.

3.4.1 Dimensioning of the collecting volume

The minimum measuring time is an important factor for the dimensioning of the collecting volume. The largest volume is needed at the maximum flow rate and low pressure. One can calculate the needed collecting volume using equ. (3) and neglecting the inventory volume. For the sake of simplicity, the initial density in the collecting volume is set to 0.0 kg/m3. One ends up with a simplified version of equ. (3) that only contains the tank volume, the final density and the collecting time in equ. (4).

$$\dot{m} = \frac{V_T \cdot \rho_{T,final}}{t_{collecting}} \tag{4}$$

This yields for the volume as a function of mass flow rate equ. (5).

$$V_T = \frac{\dot{m} \cdot t_{collecting}}{\rho_{T,final}} \tag{5}$$

The CFVN needs to be in choked mode during the collecting time, meaning that the back pressure ratio (BPR, ratio between outlet and inlet pressure at the nozzle) needs to be at most 0.5. For small nozzles (< 5 mm) and depending on the ratio between the CFVN throat nozzle and upstream piping, this BPR can increase to 0.8 but should always be confirmed experimentally.

The primary standard maximum flow rate with hydrogen is 20 kg/h (5.56 g/s). Estimates of collecting time per 100 L of collecting volume are presented in Table 11 for various BPR and an inlet pressure of 100 kPa. The density of hydrogen is calculated considering a temperature of 20 °C and using the equation provided by NIST (3).

Table 11: Collecting time estimate per 100 L of collecting volume for different final densities.

BPR	final pressure in the collecting volume	H_2 density	Collecting time / 100 L at maximum flow rate
0.5	50 kPa	41.3 g/m^3	0.74 s
0.8	80 kPa	66.1 g/m^3	1.01 s

A conservative BPR of 0.5 and a minimum collecting time of 10 s yield a collecting volume of 1346 L. This would only apply if one were to limit the inlet pressure to 100 kPa. Increasing inlet pressure will decrease the required collecting volume. The CESAME, METAS and NEL standards all have very similar collecting volumes of around 650 L, implying that the CFVN would have to be calibrated at a higher inlet pressure to reach 20 kg/h.

The collecting volume is best divided over several tanks, so that flow range and measuring time can be optimised. The METAS standard has a complete collecting volume of 660 L distributed over three 200 L tanks (200 cm in length), one 50 L tank (45 cm in length) and one 10 L tank (20 cm in length). All tanks are cylindrical, made of stainless steel and have a pressure rating of 10 MPa. Each tank can be used separately to collect the gas. Wall thickness varies from 6 mm to 8 mm, depending on tank volume.

3.4.2 Dimensioning of the piping

Converting the maximum flow rate of 20 kg/h in volumetric flow at 1 bar and 20 °C for hydrogen yields 242 m^3/h (0.067 m^3/s). One can calculate the gas speed as a function of piping diameter.

Various scenarios are presented in Table 1213). Inner piping diameters are taken from stainless steel tubing data from the company Swagelok (www.swagelok.com). The pressure rating of the tubing is at least 20 MPa. The speed of sound in hydrogen at 1 bar and 20 °C is approximated to 1300 m/s.

Table 12: Gas speed as a function of piping diameter for hydrogen at 1 bar and 20 °C.

Piping diameter	Inner diameter	Sectional area	Gas speed	Gas speed
½"	10.21 mm	8.19e-5 m^2	818 m/s	0.63 · speed of sound
¾"	15.75 mm	1.948e-4 m^2	344 m/s	0.26 · speed of sound
1"	21.18 mm	3.52e-4 m^2	190 m/s	0.15 · speed of sound

Piping should have at least a diameter of ¾".

3.4.3 Dimensioning of the water bath

The density of the gas in the collecting and inventory volumes is one of the most important sources of uncertainty. It depends on pressure and temperature of the gas. When evacuating the tank, the density in the tank will be very small and its uncertainty contribution can be considered negligible for our current analysis. This is not the case after the tank has been filled because the compression of the gas will lead to an increase in gas temperature that would require a long time to reach thermal (and obviously pressure) equilibrium.

To reduce this waiting time, the collecting volume is mounted on a frame and immersed in a water bath. The METAS bath is rectangular in shape with dimensions 284 cm x 114 cm and height of 112 cm. To limit the temperature gradient in the bath, the water can either be circulated or stirred. If a circulation system is used, water at the bottom, where it is coldest, is pumped through an external heat exchanger and injected again in the upper water layer. The uniformity and stability of the water temperature are important and are monitored using temperature sensors placed in the bath at various water depths.

For the METAS standard, temperature sensors (Pt100) are inserted in every tank to measure the gas temperature in the tank after a fill (before the fill, the pressure in the tanks is too small and the temperature sensor will not measure the gas temperature correctly). The sensors reach up to the middle of the smaller tanks and only 45 cm into the 200 L tanks. The 50 L tank is equipped with two sensors mounted at different height positions in the tank to measure any potential thermal stratification. Two additional sensors (Pt100) are immersed in the water (top and bottom) to measure the temperature gradient. These latter sensors can be moved to measure the temperature distribution in the tank when the water is circulating and its temperature being controlled.

After a filling process, the gas temperature in the tanks should be in equilibrium with the water temperature because of heat conduction. For the METAS standard, readings over hours from the temperature sensors in the tanks and the water were all within ± 20 mK of their mean.

3.4.4 Pressure and temperature sensors

As the sensors are intended to be used in a potentially hazardous area, they must be in the right equipment categories for use in the relevant ATEX zones. For the METAS standard, part of the standard is considered to be in an ATEX Zone 2 (explosive atmosphere not likely to occur in normal operation and only for very short durations). To ease the procurement process, all pressure and temperature sensors in the METAS standard are Ex-classified.

Pressure is measured in the upstream part of the test section in the inventory volume when both valves are closed, and in the collecting volume using various Keller Serie 33 X Ei sensors with full scale ranges from 0.1 MPa to 10 MPa. The manufacturer specifies an uncertainty of 0.02 % of full scale. All sensors were calibrated against METAS standards that confirmed easily the claimed uncertainty.

Temperature is measured in the upstream part of the test section, in the inventory volume when both valves are closed, in the various tanks and the water bath. All sensors are Pt100 and were calibrated simultaneously (to have the same zero) in a temperature bath against a reference sensor. The calibration uncertainty for all sensors is 20 mK.

3.4.5 Uncertainty requirements

The expected expanded uncertainty of the primary standard is 0.15 %. From equ. (3), one can already consider the main contributors to the uncertainty budget, namely the collecting volume V_T, the inventory volume V_I and the gas densities during the initial and final situation. The contribution from the collecting time is small if this time is taken as long enough and will be neglected here.

This section gives uncertainty estimates for the main contributing factors to see if an expanded uncertainty of 0.15 % can be achieved.

Collecting volumes can be best calibrated using a gravimetric method. Typical uncertainties (k=1) for such calibrations range from 80 ppm to 200 ppm.

Inventory volume can be best determined using a mixture of 3 D models of the piping that have been confirmed by a gravimetric method. The uncertainty of the inventory volume is not a major contribution.

The determination of gas density relies on pressure and temperature measurements, as well as gas composition and the equation for the calculation of the density. The NIST equation (3) quotes an uncertainty of 0.04 %. Considering a hydrogen quality of 5.0, the difference in density between pure hydrogen and 5.0 quality is 0.012 %. Considering an uncertainty in pressure of 0.02 % of full scale and 0.025 °C in temperature yields an uncertainty in the density determination of 0.05 % at 0.1 MPa. Adding all values quadratically gives an uncertainty of 0.065 %.

The difference in gas quantity in the inventory volume when both valves are closed when diverting flow to the tanks or to the exhaust is the quantity that needs to be determined. The estimation of the amount of hydrogen in the inventory volume is complicated because pressure and temperature conditions are not stable. The pressure and temperature sensors will lag with respect to the real conditions. This analysis goes beyond the scope of this report and the reader is directed to Reference (2) for thorough explanations.

The determination of hydrogen density represents in this simple analysis the most important contribution to the uncertainty budget. This implies that the uncertainties on pressure and temperature measurements need to be minimised if one is aiming for an expanded uncertainty of 0.15 %.

3.5 Safety considerations

This section provides a non-exhaustive list of safety considerations to take into account when designing and building a flow test rig for gaseous hydrogen.

- Hydrogen-specific hazards (flammability, explosivity, rapid dispersion, embrittlement, permeation)
- Pressure-related safety (pressure rating, pressure relief devices, pressure monitoring, isolation and lockout)
- Material and component selection (piping and tubing, fittings and valves, seals and gaskets, sensors and instrumentation certified for hydrogen)
- Ventilation and containment (continuous mechanical ventilation, dedicated hydrogen exhaust ducts, fume hood around high risk zones)
- Detection and alarm systems (fixed hydrogen detectors, portable detectors, alarm hierarchy)
- Electrical and grounding considerations (explosion proof, bonding and grounding of piping and vessels, isolated power supplies)
- Operational procedures (purging, continuous pressure and leak monitoring, depressurisation at shutdown, maintenance, emergency response)
- Training and documentation (personal training, standard operating procedures, safety data sheets, regulatory compliance records)

3.6 Cost estimate

In this section, a cost estimate of the building blocks of a primary standard is provided. It is partially based on the current development costs of the METAS standard. This estimate must be taken with caution as prices can vary significantly depending on country and final quality. The cost estimate below includes:

- the equipment of the primary standard (piping and instrumentation)
- safety equipment related to the ATEX Zone and the required ventilation system

It does not include

- certification costs (ATEX, PED, any other)
- building transformations
- training

Item	Price per item / €	Quantity	Total price / €
Pressure tanks	8000	5	40000
Pressure sensors	1000	8	8000
Temperature sensors	250	10	2500

Pressure regulators	2500	3	7500
Safety valve	3000	1	3000
Valves (hand operated)	500	15	7500
Frame for tanks	5000	1	5000
Tubing and fittings	30000	1	30000
Piping to gas source	25000	1	25000
Vacuum pump	8000	1	8000
Gas source installation (safety)	10000	1	10000
Water bath	10000	1	10000
Safety barriers (ATEX)	400	18	7200
Safety connector box (ATEX)	4000	2	8000
Hydrogen sensor	1500	2	3000
Hydrogen warning system	5000	1	5000
Heat exchanger (gas)[3]	4000	1	4000
Heat exchanger (water)	4000	1	4000
Water circulation in bath	2500	1	2500
Ventilation system (ATEX)	15000	1	15000
Data acquistion system	10000	1	10000
Various			20000
TOTAL			235200

The estimated cost (without labour hours) amounts to 235 k€ approximately.

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[3] Heat exchanger dimensioned for operation with H2 gas. For other gases, prices will differ.

4 Experimental Protocol for Combining Multiple Nozzles to Achieve Traceability for High Flow Rate Hydrogen Metering

4.1 Introduction

This chapter aims to develop an experimental protocol for achieving traceability in high-flow hydrogen metering by combining multiple smaller nozzles. The approach builds on traceability chain option (2) from chapter 3 and is led by NEL with support from Cesame, FORCE, and METAS. The protocol will establish the number and size of nozzles required, calibration procedures, and key operational considerations for ensuring measurement accuracy.

4.2 Objectives

- Define a method for combining smaller nozzles to achieve metrological traceability in high-flow hydrogen metering.
- Determine the required number of nozzles based on flow rate and uncertainty constraints.
- Establish calibration procedures and data validation techniques.
- Develop a standardised process to maintain measurement accuracy and consistency.

4.3 Methodology

4.3.1 Selection of Nozzles

- Determine the nozzle size (throat diameter) that is needed based on target flow rate, pressure ranges, temperature, and hydrogen properties under test conditions. The nozzle size can be calculated using the equations provided in ISO 9300 (4). To achieve this, Equation 7 (see Section 4.5) needs to be re-rewritten for the throat area, A*. Then the throat diameter can be calculated from A*. As an example, an array of six identical toroidal nozzles of 1.6 mm throat diameter and calibrated up to 20 kg/h (at approximately 44 bar and 20 °C upstream conditions) could be used to achieve the maximum total flowrate of 120 kg/h.
- When the nozzle sizes are determined, they can then be fabricated in either toroidal or cylindrical shape in accordance with the specifications of ISO 9300 (4).
    - Define criteria for nozzle selection, including material compatibility and technical specifications such as pressure range and flow capacity. Fulfil ISO 9300 (4) requirements, as much as possible. ISO 9300 (4) standard provides guidelines on various aspects of nozzle fabrication such as materials, surface finish and geometry.
    - The material should have good workability with regard to the surface, be non-corrosive, resistant to hydrogen embrittlement and have known thermal expansion behaviour. There is useful information on the design and fabrication of nozzles for hydrogen applications in the output report of Activity 1.1.1 of MetHyInfra (5). The aforementioned report suggests using stainless steel of type 1.4404 (X2CrNiMo17-12-2) for its desirable properties such as polishability, good machinability, good

corrosion resistance (molybdenum addition), suitability for low and high temperatures up to 550 ° C.

- To measure the throat diameter of the nozzles, it is recommended to follow a Good Practice Guide, such as the one produced in MetHyInfra (6).

4.3.2 Nozzle Combination Strategy

- Determine the number of nozzles needed to reach the desired flow rate. This can be achieved by using Equation 1, if nozzles are equally sized. Otherwise, the sum of the maximum flowrate of nozzles should be used to determine the number and combination of the required nozzles to achieve the desired total mass flowrate. The size of each nozzle should be chosen considering the available calibration capability (see Section 4.3.3 and Table 13). The number of nozzles should ideally be minimised to reduce the total uncertainty.

$$N = \frac{\dot{M}}{\dot{m}_{max}} \qquad (6)$$

where N is the number of nozzles required, $\dot{M}$ is the desired total mass flow rate (kg/s), and $\dot{m}_{max}$ is the maximum calibrated flow rate of a single nozzle (kg/s). The combination of the small nozzles can later (i.e. after calibration) be used to test larger nozzles. Based on the definitions in chapter 3, a small nozzle and a large nozzle have a maximum flow rate of up to 20 kg/h and 120 kg/h, respectively. Currently the capability for calibrating small nozzles up to 20 kg/h is being developed at CESAME, as shown in Table 13. Several calibrated small nozzles can therefore be combined to test larger nozzles and the larger nozzles can then be combined similarly to test even larger flow measurement devices. This will eventually establish traceability for a flow measurement device with a desirable large flow rate. For more information on this refer chapter 3 (7). Figure 7, which has been taken from Section 4.3 of this report, shows an example of a parallel arrangement of six CVFNs and a large CVFN that is being tested against them.

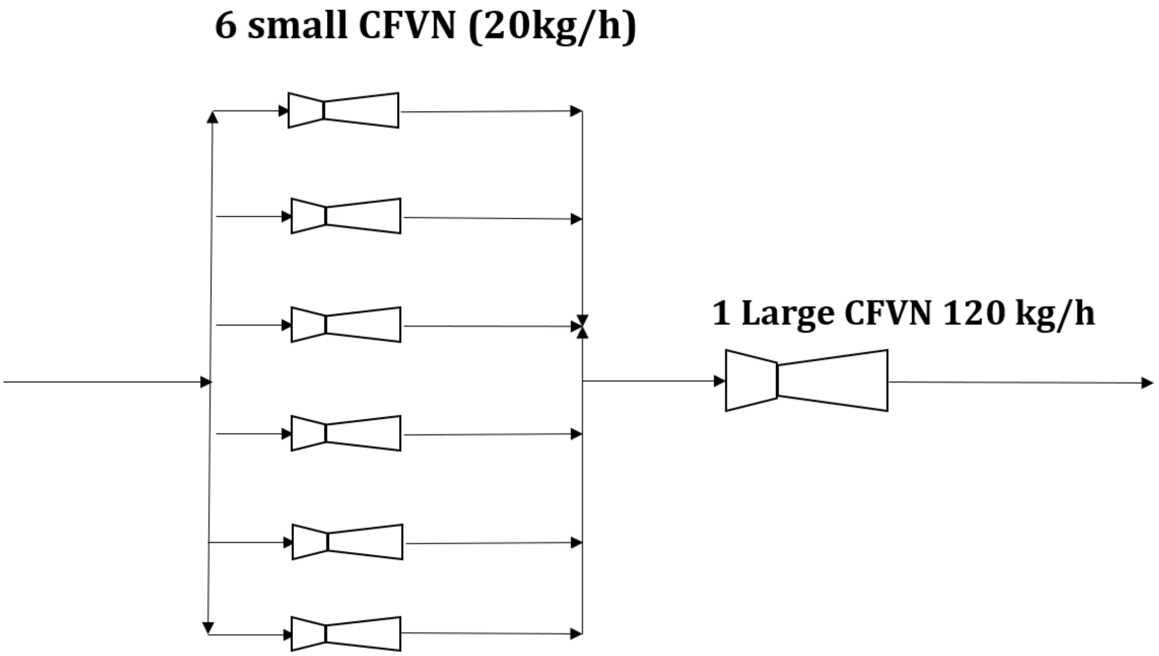

Figure 7: A schematic of a parallel arrangement for 6 CVFNs (7)

- Determine an optimal configuration for arranging multiple nozzles in parallel. Below is a list of suggested actions you could take to achieve this:
    - Ensure proper installation of nozzles by following the guidelines of ISO 9300. Nozzles can be installed in a pipe configuration (a pipe of circular cross-section with a diameter ratio of the throat to inlet conduit, β, ≦ 0.25) or a chamber configuration (a large volume-chamber or plenum- upstream the nozzle with β being effectively zero). The pipe configuration can only contain a single nozzle and should meet the requirements of Sections 9.2 (pipe configuration) and 9.1.2 to 9.1.7 (pressure measurements, temperature measurements, etc) of ISO 9300. The chamber configuration can have multiple nozzles in a cluster and should meet the requirements of Sections 9.3 (chamber configuration) and 9.1.2 to 9.1.7 of ISO 9300. It is also recommended to use the literature and the prior experience of relevant organisations in the design and assembly process.
    - Minimise interference between nozzles by optimising spacing and orientation. This can prevent aerodynamic interference such as shock waves or turbulence, which can distort individual nozzle performance. The aim is to ensure each nozzle functions independently and within specification. ISO 9300 only provides installation guidelines/requirements for a single CFVN. However, guidelines on CFVN array installations could be found in the literature. When building a CFVN array, the nozzle spacing (i.e. distance between the centres of two adjacent nozzles) should be kept at

least 4.36 times of the throat diameter, and preferably larger (8). Also placing any nozzles closer than one spacing length to the pipe wall should be avoided (when nozzles are on the same flange) (9) .

- Ensure structural integrity and maintain precise alignment for long-term operation. This is necessary to prevent mechanical deformation, vibration-induced shifts, or alignment drift over time because of repeated use under varying pressure and temperature conditions. Make sure to consider this in the design, material and component selection and construction phases. Periodic inspections and recalibration should be scheduled to detect any degradation or misalignment.
- Design for scalability, allowing modification of nozzle configurations for different flow rates. Such a design can provide flexibility in case future calibration or testing needs involve out of range flow rates. Without scalability, the entire setup would require redesign or reconstruction.
- Make required adjustments or validate the setup through experimental measurements, comparing actual flow rates with expected values. The aim is to assess the accuracy and consistency of the flow rates produced by the nozzle array and to detect any anomalies such as unexpected pressure drops, non-uniform flow distribution, or flow instability. This should be done by operating the nozzle array under controlled conditions when the array is assembled, measuring the output flow rates and other parameters such as pressure using calibrated reference instruments, and comparing them to the calculated or simulated values.

4.3.3 Calibration and Traceability

- Establish traceability for individual nozzles using primary hydrogen standards. The existing primary calibration facilities for hydrogen flow include pVTt (Pressure, Volume, Temperature, and Time) systems and piston provers, which are traceable to SI units. Notable European facilities capable of calibrating small CFVNs include TÜV SÜD National engineering Laboratory (NEL) with a pVTt system, CESAME with a pVTt system, and the University of Ljubljana using a piston prover (Please see Table 13 and Reference (7) for more details). Moreover, METAS is developing a primary standard for the calibration of CFVNs with hydrogen which is expected to be ready in 2026. Among these facilities, the pVTt facility at CESAME has the largest capacity and can cover flow rates up to 20 kg/h, which is the maximum flowrate for a small nozzle based on the definitions in Reference (7).
- Calibrating small nozzles is the first step of establishing traceability for larger nozzles or other flow measurement devices. The small nozzles are calibrated against a primary standard with a fixed collection volume, whereas, in the second step after bootstrapping the small calibrated nozzles, each large nozzle is calibrated at steady flow conditions in series with the array of parallel small nozzles (see Figure 7). Subsequently, larger calibrated nozzles could be used in a similar setup to calibrate even larger flow measurement devices and establish traceability.

Table 13: Existing and Under Development Primary Standards capable of calibrating small CVFNs with hydrogen (7)

Institute	**Calibration Method**	**Max Flow (kg/h)**
NEL (TÜV SÜD)	pVTt System	8
CESAME	pVTt System	20
Univ. of Ljubljana	Piston Prover	0.75
METAS	pVTt System	15

4.4 Data Analysis and Uncertainty Estimation

- Quantify measurement uncertainty by considering different factors such as temperature and pressure fluctuations and gas compressibility (See the next section for equations).
- Implement statistical analysis techniques to assess the repeatability of measurements. (Equation 11)
- If possible, compare results with those of high-flow hydrogen metering facilities. For more information about these facilities, see Reference (7).

4.5 Equations

The mass flow rate ($\dot{m}$) through a single sonic nozzle is calculated using the standard critical flow equation according to ISO 9300 (4):

$$\dot{m} = C_d A^* P_0 \sqrt{\frac{\gamma}{RT_0}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (7)$$

where:

- C_d is the discharge coefficient (dimensionless),
- A^* is the nozzle throat area (m^2),
- γ is the specific heat ratio (dimensionless),
- P_0 is the stagnation pressure (Pa),
- R is the specific gas constant for hydrogen (4124 J/kg·K),
- T_0 is the stagnation temperature (K).

For multiple nozzles arranged in parallel, the total mass flow rate ($\dot{m}_{total}$) is the summation of individual nozzle flow rates:

$$\dot{m}_{total} = \sum_{i=1}^{n} \dot{m}_i \qquad (8)$$

where $\dot{m}_i$ is the mass flow rate through the ith nozzle.

The combined uncertainty $u_c\left(\dot{m}_{total}\right)$ for the total mass flow rate is determined by propagating individual measurement uncertainties:

$$u_c\left(\dot{m}_{total}\right) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial \dot{m}_{total}}{\partial x_i} u(x_i)\right)^2} \qquad (9)$$

where:

- x_i represent individual input parameters $(C_d, A^*, P_0, T_0, \gamma)$,
- $u(x_i)$ are their associated standard uncertainties.

Sensitivity coefficients $\frac{\partial \dot{m}_{total}}{\partial x_i}$ are calculated analytically by differentiating the mass flow rate equation with respect to each parameter. For instance, the sensitivity coefficient for pressure P_0 is:

$$\frac{\partial \dot{m}}{\partial P_0} = C_d A^* \sqrt{\frac{\gamma}{RT_0}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (10)$$

Repeatability of flow measurements is quantified through the standard deviation of repeated experiments under constant conditions, u_{rep} (see Reference (10)):

$$u_{rep}\left(\dot{m}\right) = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(\dot{m}_j - \bar{\dot{m}}\right)^2} \qquad (11)$$

where $\dot{m}_j$ is the jth measured flow rate and $\bar{\dot{m}}$ is the mean value from N measurements.

The expanded uncertainty U is given by:

$$U = k \cdot u_c\left(\dot{m}_{total}\right) \qquad (12)$$

where k is the coverage factor, typically set to 2 for approximately 95% confidence.

More details on equations for a CVFN and uncertainty calculations can be found in ISO 9300 (4) and GUM (11), respectively.

4.6 Documentation and Reporting

- Compile findings into a comprehensive report detailing the experimental setup, methodology, results, and recommendations.

4.7 Conclusion

This protocol provides a structured approach to achieving traceability in high-flow hydrogen metering using multiple sonic nozzles. By validating this methodology experimentally, the project aims to establish a reliable reference framework that can be adopted by industry and standardisation bodies.

5 Large nozzles calibrated assuming hydrogen equivalence

5.1 Introduction

Two nozzles were calibrated with both hydrogen gas and with air by Cesame using their novel pVTt system. The purpose was to estimate the experimental applicability of calibrating with air and assuming a hydrogen equivalence, as well as investigating the flow range equivalence for larger nozzles without direct calibration. Previous nozzle calibrations with hydrogen gas have been limited to the laminar boundary later regime (12); this was extended to also include the turbulent boundary layer regime.

The nozzles were picked from the nozzle set that was produced in the Joint Research Project MetHyInfra (13). In that project, the nozzles were extensively tested by the partners and thus have historical data of interest. Most of the partners tested the nozzles either with nitrogen gas or air, but they were also tested with helium and hydrogen in the laminar flow regime (nozzle SN10).

5.2 Theory

The theoretical mass flow rate, $q_{m,th}$, through an ideal CFVN is defined as

$$q_{m,th} = \frac{A_{nt}\, C^*\, p_0}{\sqrt{\left(\frac{R}{M}\right) T_0}}$$

Where A_{nt} is the area of the throat of the nozzle [m^2], C^* is the critical flow function [-], p_0 is the stagnation pressure [Pa], R is the specific gas constant, and T_0 is the stagnation temperature [K], assuming one-dimensional isentropic flow of a gas.

The Reynolds number is defined as

$$Re = \frac{4\, q_m}{\pi\, d\, \eta_0}$$

Where η_0 is the dynamic viscosity of the fluid at stagnation conditions.

The discharge coefficient is defined in ISO9300 (4) as

$$C_d = \frac{q_m}{q_{m,th}}$$

Where q_m is the mass flow rate. The discharge coefficient is thus a ratio between the mass flow rate and the theoretical mass flow rate.

5.3 Test setup

The nozzles that were selected were both of toroidal geometry, as defined in ISO 9300 (4), and with a nominal throat diameter of 1 mm and 2 mm. The nozzles were part of a set of 14 manufactured in a previous project with the specific intent of being used for hydrogen measurement (14). The set of nozzles had a surface finish with three different levels of roughness; the two selected nozzles were of the roughest finish. The material of the nozzles was of stainless steel, type 1.4404 and grade 316 L.

The nozzles were from a previous project dimensionally characterized with a Coordinate Measuring Machine (CMM), with the results shown in Table 14 (13).

Table 14: Dimensional properties of the nozzles calibrated with hydrogen and air.

ID	Diameter (nominal)	Diameter (CMM)	Roughness
SN10	1 mm	0.993393 mm ± 0.005782 mm	0.9 µm < Ra < 1.1 µm
SN12	2 mm	1.994517 mm ± 0.002745 mm	0.9 µm < Ra < 1.1 µm

The nozzles were calibrated using the novel Cesame pVTt standard.

5.4 Results

Results are shown in Figure 10 and Figure 11.

The results are overlaid the previous measurements performed in MetHyInfra. More details about those measurements are available in Reference (15). Measurements for the 1 mm nozzle were performed with nitrogen (METAS, NEL, UL), dry air (Cesame), helium (UL) or hydrogen (UL). Measurements for the 2 mm nozzle were performed with the same fluids, except for helium and hydrogen.

The measurement results of Cesame are generally in good agreement with their previous measurements, despite being performed with a different type of test bench. Previous calibration of the CFVNs were performed with a reference set of CFVN. The largest difference between the two comes at the highest flow rates.

The measurements have good overlap with previous measurements in MetHyInfra.

It is observed that the measurements with hydrogen and air are within the measurement uncertainty band of the laboratory at almost all points. In general, the discharge coefficient is larger when calibrating with hydrogen than air.

The SN10 CFVN was measured at 5 different flow rates with air (0.00129 kg/s, 0.00270 kg/s, 0.00397 kg/s, 0.00529 kg/s and 0.00659 kg/s) and 4 different flow rates with hydrogen gas (0.000806 kg/s, 0.00137 kg/s, 0.00203 kg/s and 0.00268 kg/s). The SN12 was measured at 4 different flow rates with air (0.00288 kg/s, 0.00569 kg/s, 0.0121 kg/s and 0.0236 kg/s) and 5 different flow rates with hydrogen gas (0.00046 kg/s, 0.000597 kg/s, 0.00149 kg/s, 0.00307 kg/s and 0.00451 kg/s). 3 repetitions were performed at each measuring point.

The nominal pressure at which the CFVNs were measured were

- For SN10: Air, 7 to 35 bar(a); hydrogen, 16 to 56 bar(a).

- For SN12: Air, 3 to 30 bar(a); hydrogen, 2 to 24 bar(a).

The CFVNs were tested against collection tanks (2 tanks of 100 L each) of 200 L. The system was controlled with LabView.

The calibration of the nozzles was performed with two different gases: hydrogen gas (100%, see table below) and dry air (unknown to date). The hydrogen gas was provided in compressed gas cylinders, located outside the laboratory. The dry air was provided by the laboratory.

The average temperature of the hydrogen was around 20°C, but for air it was not well-controlled, the averages of the values for the flow points are dispersed. There is a small heat exchanger with a pump in the system, which is not efficient when used with air, as it is designed for hydrogen and nitrogen. The interval of acceptable range of temperature difference is 2 °C. For air, the temperature repeats well but is not controlled by heat exchanger.

The Sutherland formula was used for the calculation of the viscosity of both hydrogen and air.

A diagram of the test setup is shown in Figure 8. The operation of the test bench is identical to the procedure described in the previous Section 3.3. The system was evacuated before every measurement with the vacuum pump.

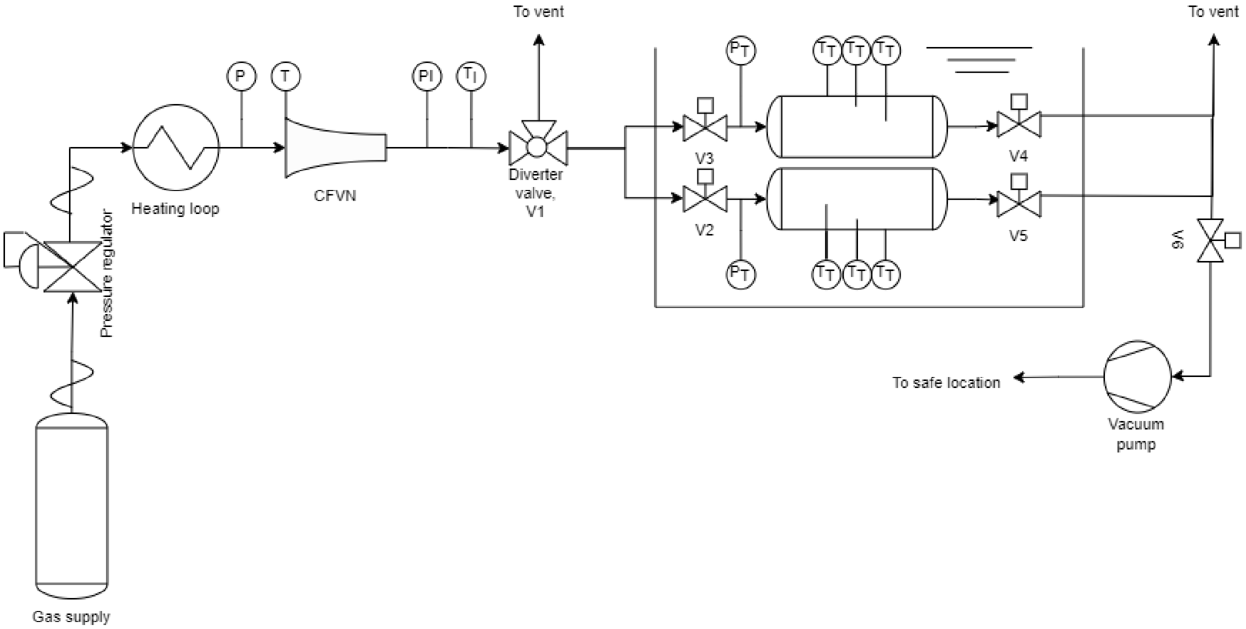

Figure 8: Diagram of the test setup.

A picture of the test setup is shown in Figure 9.

Figure 9: Test setup in the laboratory.

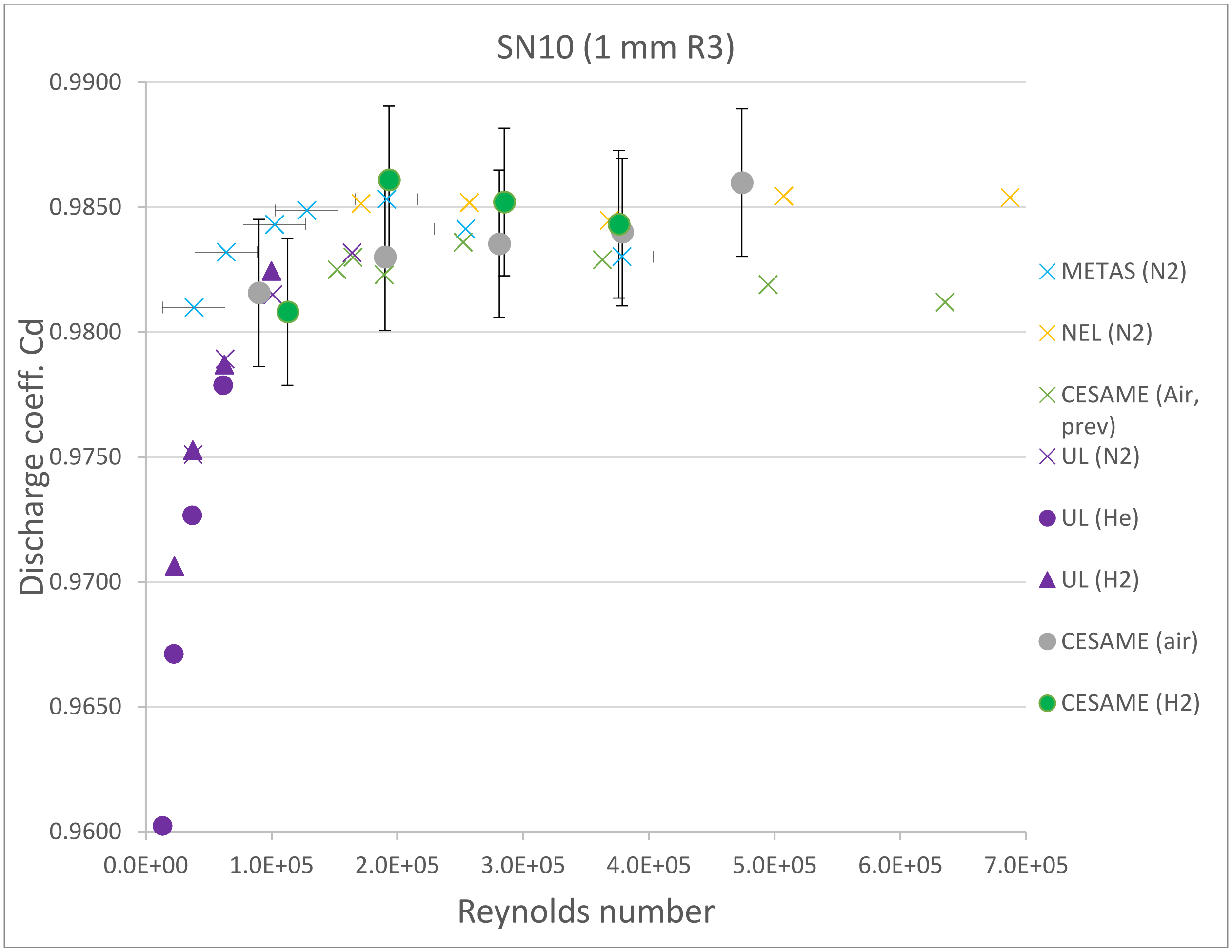

Figure 10: Results for the 1 mm nozzle (in filled dots, with uncertainty bars). The error bars indicate the measurement uncertainty (k=2) of ±0.3 %. Previous results from the MetHyInfra project are also included (X-shaped: nitrogen or air; dots: helium; triangles: hydrogen). The previous measurement uncertainties are at the level ±0.2 % to ±0.3 % but are not shown for clarity.

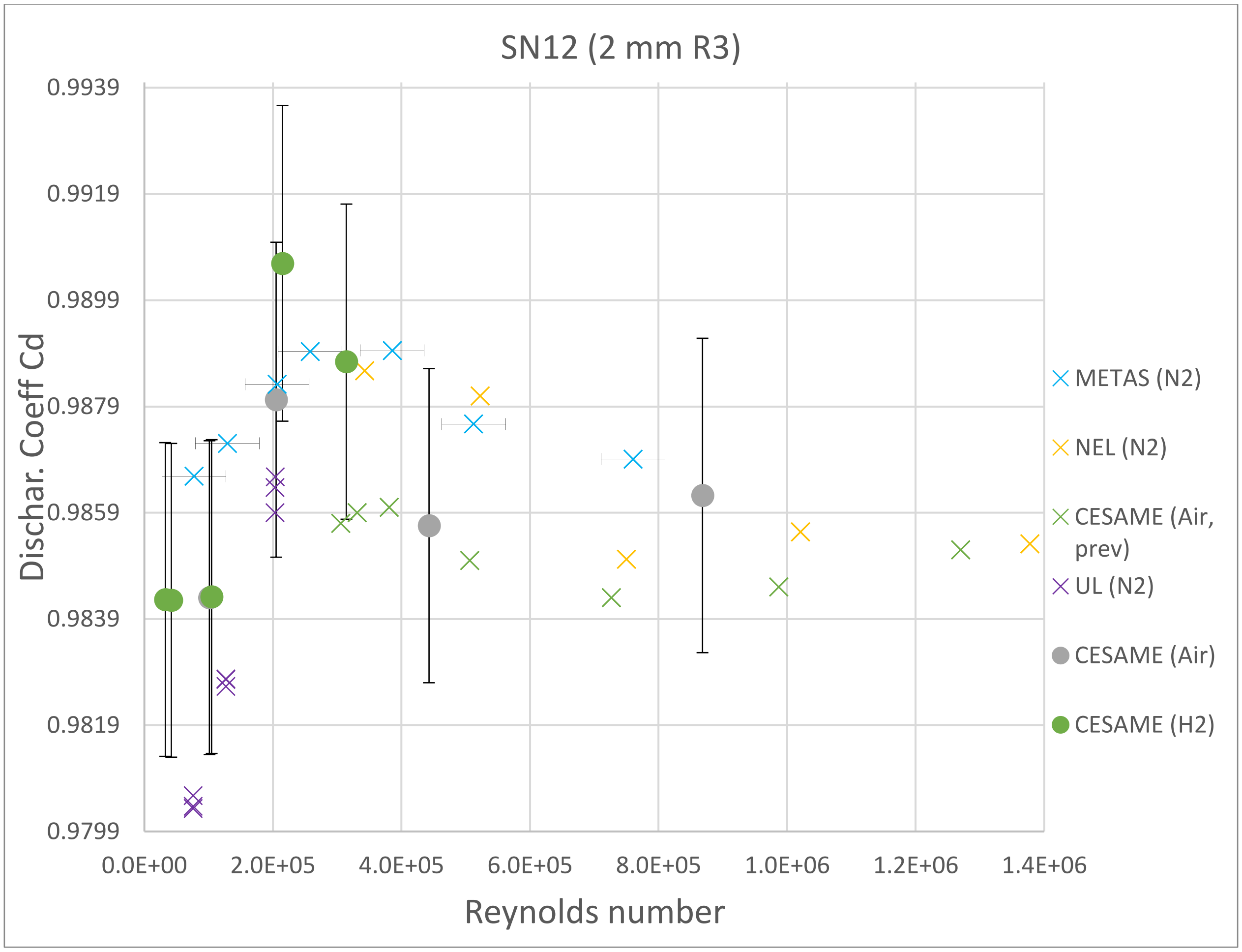

Figure 11: Results for the 2 mm nozzle (in filled dots). The error bars indicate the measurement uncertainty (k=2) of ±0.3 %. Previous results from the MetHyInfra project are also included (X-shaped). The previous measurement uncertainties are at the level ±0.2 % to ±0.3 % but are not shown for clarity.

5.5 Discussion

As the method is based on measuring pressures and temperatures in a pre-calibrated volume filled with gas for a certain period of time through a nozzle with specific upstream pressure and temperature, we estimated the uncertainty by taking the following factors into account:

- Filling time (s)
- Pre-calibrated volume (m^3)
- Real gas factor
- Upstream pressure
- Upstream temperature

- Initial pressure
- Initial temperature
- Compressibility factor
- Final pressure
- Final temperature
- Gas constant R
- Molar mass

Among these factors, those that have the greatest influence on overall uncertainty, based on our experience, and which have been taken into account in the estimate, are as follows:

- Pressures
- Temperatures
- Mass flow
- Filling time

The new measurements have a good overlap with previous measurements, despite being performed with a different standard. It was performed with the novel pVTt standard at Cesame. Previous laboratories have calibrated the nozzles with either reference nozzles (Cesame, NEL) or piston provers (UL, METAS).

The previous hydrogen data from UL for SN10 may be compared to the new hydrogen data that was obtained. This is shown in Figure 12. The agreement, at Reynolds number 10^5, the point which is closest to matching both laboratories, is good and within the laboratory uncertainty.

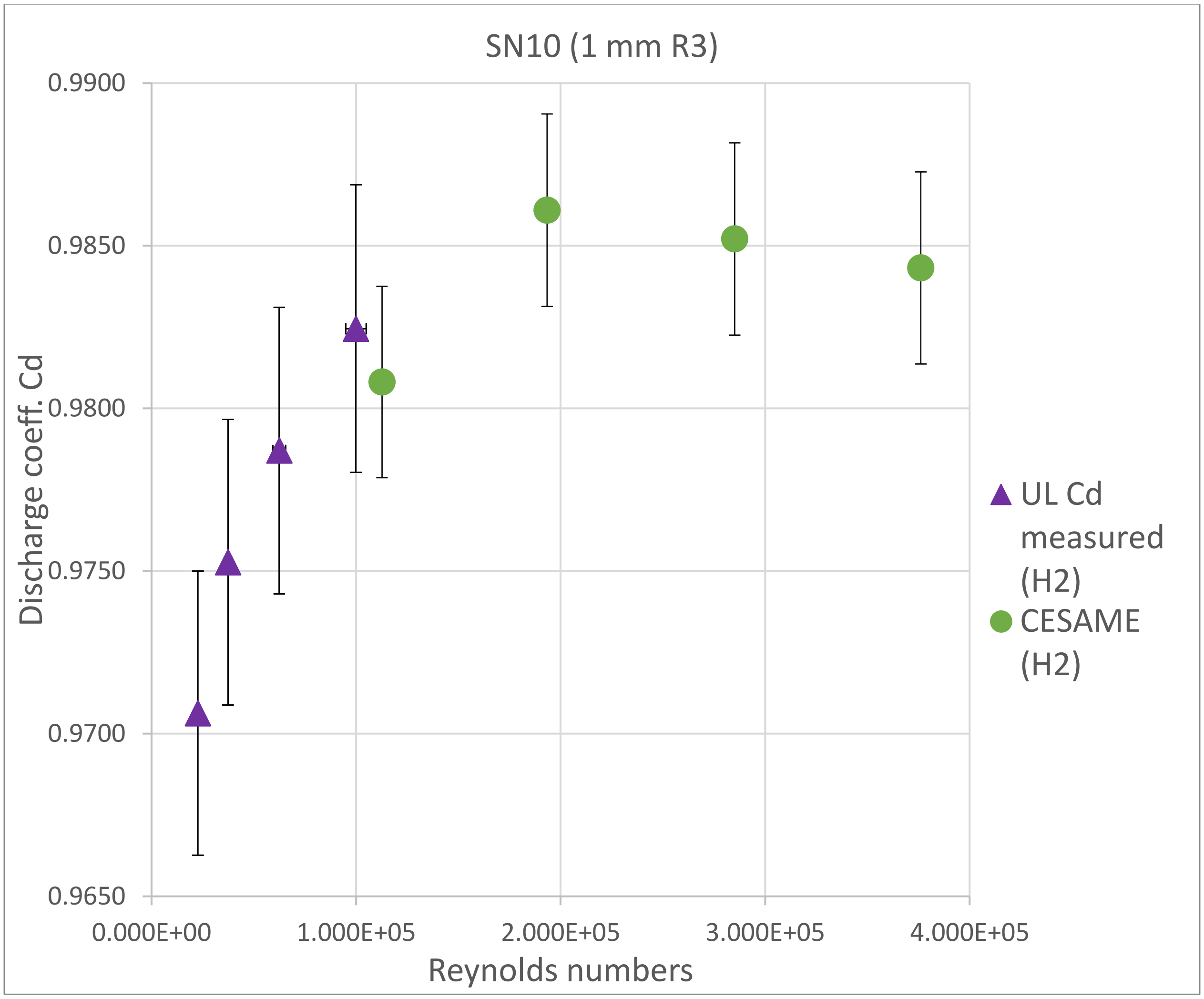

Figure 12: Zoomed in comparison between hydrogen measurements in this project (in green filled circles) and from the previous MetHyInfra project (in purple triangles). UL uncertainty: ±0.45 % (k=2), and with an additional uncertainty in pressure.

5.6 Conclusion

Two small CFVNs were calibrated with both hydrogen and air using a pVTt primary standard. Results indicate that the two CFVNs calibrated with hydrogen gas have a similar calibration curve compared to air, that is within the laboratory uncertainty. This remained true also for the transitional and turbulent boundary layer regime. The hydrogen measurements seem to have a slightly higher discharge coefficient in general than air, but more research is needed to quantify the effect. This shows that a pVTt type standard may be used to calibrate CFVNs with hydrogen gas.

6 Summary and conclusion

The following conclusions are drawn from this work:

- Hydrogen flow meter test facilities are being actively being developed. Survey results show that the current testing infrastructure does not fully meet the growing demand and that there is a noticeable gap. This may lead to the need for building additional test facilities or exploring whether alternative media could serve as suitable substitutes for hydrogen in calibration processes.
- This protocol provides a structured approach to achieving traceability in high-flow hydrogen metering using multiple sonic nozzles. By validating this methodology experimentally, the project aims to establish a reliable reference framework that can be adopted by industry and standardisation bodies.
- Two small CFVNs were calibrated with both hydrogen and air using a pVTt primary standard. Results indicate that the two CFVNs calibrated with hydrogen gas have a similar calibration curve compared to air, that is within the laboratory uncertainty. This remained true also for the transitional and turbulent boundary layer regime. The hydrogen measurements seem to have a slightly higher discharge coefficient in general than air, but more research is needed to quantify the effect. This shows that a pVTt type standard may be used to calibrate CFVNs with hydrogen gas.

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Annex A, European calibration facilities for hydrogen

TÜV SÜD NEL

NEL’s Domestic Gas Metering Facility (DGMF) includes nozzles that can calibrate meters with hydrogen, methane, and nitrogen, using small flow rates ranging from 0.035 kg/h to 3.7 kg/h (for hydrogen), 0.100 kg/h to 47.0 kg/h (for methane), and 0.143 kg/h to 52.3 kg/h (for nitrogen).

NEL is currently relying on dry air calibrations across the operational Reynolds number range, assuming fluid transferability for nitrogen and hydrogen based on existing experimental evidence. An additional uncertainty term has been added for methane as there is a lack of experimental evidence in this area.

Additionally, they achieve traceability from CEESI (US) which has traceability to a primary standard at NIST (pVTt).

NEL is currently developing its own hydrogen primary test facility (16) where in future nozzles will be calibrated against pVTt tanks.

Company	Min Flow	Max Flow	Pressure	Temperature	Pipe Diameter	Nozzle size
	[kg/h]	[kg/h]	[bar(g)]	[°C]	[inch]	[mm]
NEL	0.035		3 – 15	20	1”	0.011
NEL	0.16	0.74	3 – 15	20	1”	0.022
NEL		3.17	3 – 15	20	1”	0.044

Uncertainty: ±0.33…±0.51 % (k = 2)
Traceability: pVTt system
Gas composition: The nozzle can as well be used to methane or nitrogen beside hydrogen.

Table 15 TÜV SÜD NEL hydrogen DGMF test facility (16).

Justervesenet (JV)

Justervesenet is currently in the process of acquiring a primary standard for the calibration of CFVN nozzles and gas meters, it **is expected to be ready in 2026**. The emphasis will be first on establishing a primary standard, the separate facility for testing hydrogen with nozzles as references could come later. The first aim is to achieve an uncertainty of 0.3 % (k=2), with an expectation that further improvements and experience may reduce the uncertainty (17) *and* (18).

Company	Min Flow	Max Flow	Pressure	Temperature	Pipe Diameter	Nozzle size
	[Sm^{3*}/h]	**[Sm^{3}/h]**	**[bar(g)]**	**[°C]**	**[inch]**	**[mm]**
JV	1	94	5 to 60	20 ±5	1	0.5 to 2

JV hopes to achieve a min flow at 0.1 Sm^{3}/h at 5 bar(g).

Uncertainty: ±0.3 % (k = 2).

Traceability: pVTt system.

Gas composition: The nozzle may also be calibrated with methane or nitrogen in addition to hydrogen in ranges from 0-100%.

* **Sm^{3}**: SI unit for volumetric flow rate of air or gas at a temperature of 0 °C and pressure of 101,3 kPa, expressed in cubic metres per hour

Table 16 JV hydrogen CFVN test facility (18) and (17).

University of Ljubljana (UL)

University of Ljubljana (UL) can calibrate CFVN up to 50 l/min, by using their piston prover with an uncertainty of 0.15 % (k = 2). All components in the calibrations system are connected to the PC using the control program released in the LabVIEW programming environment. The program enabled the control of the pressure at the input of the CFVNs and the storage of all necessary data for further processing.

Beside the uncertainty for the piston prover, the uncertainty for the pressure measurement is 0.02 % MV or 80 Pa (k = 2) and the temperature measurement uncertainty is 0.2 °C (k = 2) measured at the gas inlet manifold of the CFVNs.

Over the next two years, UL expects to expand their piston prover up to 1500 l/min. (19).

Company	**Flow**	**Pressure**	**Temperature**	**Nozzle size**
	[l/min]	**[bar(a)]**	**[°C]**	**[mm]**
UL	50	1 to 7	20±5	0.175 – 1
Uncertainty: 0.15 % (k=2) Traceability: Piston prover to 50 l/min Gas composition: The nozzle can as well be used to calibrate methane or nitrogen beside hydrogen from 0-100%.				

Table 17 The table illustrate UL hydrogen CFVN test facility (19).

CESAME EXADEBIT

CESAME is establishing a nozzle flow calibration facility to calibrate CFVN for hydrogen. The minimum flow rate is 0.4 kg/h and can reach a maximum flow of 20 kg/h. The system operates at pressures ranging from 1 bar gauge (bar(g)) up to 80 bar(g). Traceability is achieved through a volumetric system using pVTt.

In the coming months after August 2024, CESAME expects to calibrate DN15 meters at ambient pressure with a flow rate of 0.4 to 20 kg/h (20).

Company	Min Flow	Max Flow	Pressure	Temperature	Pipe Diameter	Nozzle size
	[kg/h]	[kg/h]	[bar(g)]	[°C]	[DN]	[mm]
CESAME pVTt system	0.4	20	1	20	15	1-5
CESAME Nozzle test rig	0.4	20	Up to 80	20	15	1-5
Uncertainty: the aim is ±0.3 % Traceability: pVTt system, volumetric Gas composition: hydrogen and any mixture						

Table 18 The table illustrates CESAME hydrogen CFVN test facility (20)

METAS

METAS is currently building a nozzle flow calibration facility to calibrate CFVN for hydrogen. The minimum flow rate is 0.1 kg/h and can reach a maximum flow of 15 kg/h. The system operates at pressures ranging from 1 bar gauge (bar(g)) up to 40 bar(g). Traceability is achieved through a volumetric system using pVTt.

In the coming months, METAS are expected to finalize and start commissioning the new test rig.

Company	Min Flow	Max Flow	Pressure	Temperature	Pipe Diameter	Nozzle size
	[kg/h]	[kg/h]	[bar(g)]	[°C]	[inch]	[mm]
METAS	0.1	15	Up to 40	20	¾”	1-5
Uncertainty: the aim is ±0.3 % Traceability: pVTt system, volumetric Gas composition: hydrogen and any mixture						

Table 19 The table illustrates METAS hydrogen CFVN test facility.

DNV

Company	Min Flow	Max Flow	Pressure	Temperature	Pipe Diameter	Nozzle size
	[kg/h]	**[kg/h]**	**[bar(a)]**	**[°C]**	**[inch]**	**[mm]**
DNV	7	1350	5 to 40	20 ±5	1” to 6”	n.a
Uncertainty: the aim is ±0.3% high Re and ±0.5% low Re Traceability: The turbine meter is traceable to NG and air from FORCE and PTB (Reynolds curve + bearing friction compensation according the PTB turbine meter model). Gas composition: hydrogen and any mixture Meter type: USM, Turbine, Rotor, dP, Coriolis						

Table 20 The table illustrate DNV hydrogen CFVN test facility (21), (22).

RMA

The information about RMA’s hydrogen test facility is from their homepage.

The flow rate is calculated using a temperature of 15°C, with the lowest flow occurring at the lowest pressure and the highest flow at the highest pressure.

Company	Min Flow	Max Flow	Pressure	Temperature	Pipe Diameter
	[kg/h]	**[kg/h]**	**[bar(a)]**	**]°C [**	**[DN]**
RMA	3	4 405	8 to 51		50 to 300
Uncertainty: the aim is ±0.2% to 0.3 % Traceability: PTB (media?) Gas composition: hydrogen Meter type: USM, Turbine, Rotor, dP, Coriolis					

Table 21 The table illustrate RMA hydrogen CFVN test facility (23)