Metrology infrastructure for high-pressure gas and liquified hydrogen flows

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Abstract

This paper gives an overview of "The Joint Research Project (JRP) 20IND11 “Metrology infrastructure for high-pressure gas and liquified hydrogen flows” (MetHyInfra) ", the challenges to tackle and the strategy to deal with these challenges. It will outline how this project will lead to a state of art for hydrogen quantity measurement. The paper is connected to four other FLOMEKO submissions, which deal with the latest outputs from the project.

1. Introduction

The key message of the Paris Agreement [1] is to limit global warming to well below 2 K compared to pre-industrial levels. This led to different strategies and roadmaps worldwide. What all these plans have in common is that they name hydrogen as part of the solution and as a key technology for a greener future and a clean energy transition. For example, the European Green Deal [2] includes a hydrogen strategy with the goal of installing 40 GW of renewable hydrogen electrolysers in Europe by 2030. A production capacity of up to 8 Mt of hydrogen is expected by 2035 [3]. To meet this demand for hydrogen, hydrogen must be imported from another 40 GW of electrolysers installed by Europe's neighbours. Against the background of the war in Ukraine, the gas supply in Europe is being reassessed in terms of alternatives such as LNG and hydrogen and a renewed focus on liquefied energy gases and hydrogen can be expected. Based on these Green Deal plans and current political realities, the industry and the associated measurement technology must become "hydrogen-ready" even faster. The needs of the industry have already been identified in discussions with the most important stakeholders from the hydrogen industry (hydrogen producers, station operators, car manufacturers and standardization bodies). Due to the need for an efficient use of storage capacities, hydrogen must be stored under high pressure or in the liquid phase. Hence, the key metrological challenges are named, that need to be addressed to foster the growth of the hydrogen market.

2. Metrology infrastructure for high-pressure gas and liquified hydrogen flows

The EMPIR project "Metrology infrastructure for high-pressure gas and liquefied hydrogen flows" (MetHyInfra) aims to create traceability options for a large number of applications in the field of hydrogen measurement. The focus here is on high-pressure applications up to 100 MPa and the measurement of liquid hydrogen, which represent the states of highest energy density. To tackle this holistic approach the work is split up in four technical work packages.

2.1 High pressure hydrogen flow metering standards

The main goal of bringing traceability will be reached be promoting the use of critical flow venturi nozzles (CFVN) as transfer reference over full range of high-pressure gaseous hydrogen applications. Because there is a lack of calibration service in this range. As only for the range of low pressure (<1 MPa) and for dispensers at refuelling stations calibration service is available.
CFVNs are very stable secondary standards used as reference in many laboratories. So far, their response to hydrogen, especially above 10 MPa, has not been extensively studied and reference data linking the low-pressure to the high-pressure range (0.5 MPa to 100 MPa) are lacking.
For this purpose, a test setup corresponding to the ATEX and PED specifications will be set up and a reference standard suitable for traceability must be identified. For the latter, it is planned to connect a Coriolis flow meter under high-pressure conditions to the SI unit system via a gravimetric primary standard (see Figure 1).

Figure 1: Gravimetric primary standard (design and built by METAS)

Such a method is well known from previous projects [5]. With the Coriolis meter as a reference standard, CFVNs are then calibrated in the next step. For this purpose, nozzles and nozzle holders (see Figure 2) were designed and built for high- and low-pressure flow measurement of hydrogen. Particular attention is paid to safety restrictions. For the investigations planned in work packages one and two, 12 nozzle designs were manufactured. The nozzles differ in shape (cylindrical and toroidal), throat diameter and roughness (see Table 1).

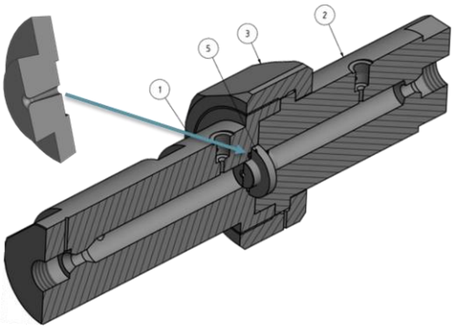

Figure 2: High pressure nozzle holder (design and built by EP Ehrler Prüftechnik Engineering)

Table 1: variety of nozzles

set	Number of CFVN	diameter		roughness Ra [µm]			shape	
		1 mm	2 mm	<0.1	0.4<…<0.6	0.9<…<1.1	Cylin-drical	toriod
A	12	X	X	X	X	X	X	X
B	2	X		X			X	X

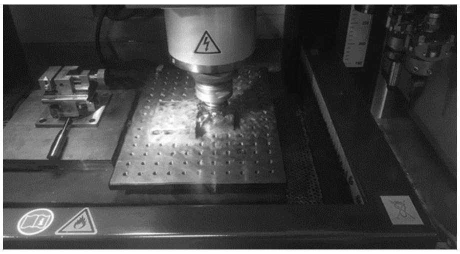

Figure 3: Nozzle production by electro-erosion machining

For the manufacturing process electro erosion was chosen to build out the different levels of roughness. The two sets of nozzles are dedicated to be used in different purposes. One set (Set B) consisting of two nozzles is used for high pressure measurements, while the second set (Set A) containing all twelve nozzle designs is used for the remaining measurements carried out in work package two. More details about the strategy behind the design of sets of CFVN is shown in another paper from the MetHyInfra project [6].

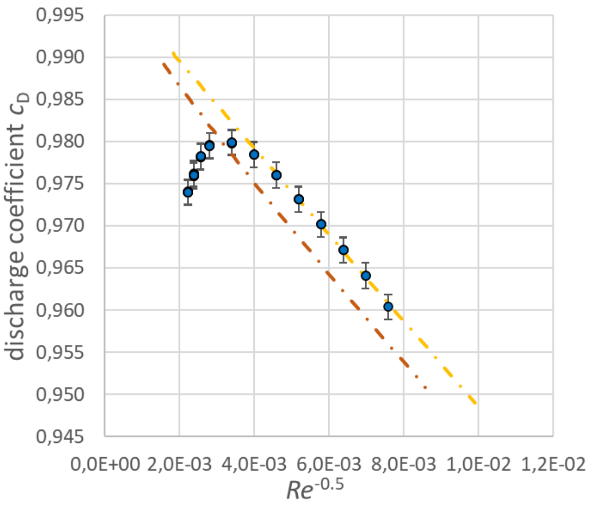

Figure 4: First test on the nozzle

These nozzles are first subjected to a metrological study of the nozzle characteristic with air or nitrogen to evaluate the quality of the manufacturing process regarding the made specification for each nozzle and to ensure that their low-pressure properties are sufficiently known before the measurements are carried out with high-pressure hydrogen. Figure 4 shows a first simple pre-check of the nozzle. The brown line shows an ideal nozzle according to ISO 9300 [7], while the yellow line is a fit to the test data. This gives first impression of the effect caused by the variety of nozzle designs.

Since there are currently no test benches with traceable standards capable of performing the calibration of a nozzle directly with high-pressure hydrogen, an alternative method had to be developed. During the MetroHyVe [8] project, it was shown that Coriolis meters mounted in the hot area of a hydrogen filling station can achieve good repeatability by being calibrated against a gravimetric standard. The same procedure cannot be used to calibrate nozzles because the mass flow of a hydrogen station does not meet the stability criteria. Therefore, part of an existing hydrogen station is to be modified by sending the high-pressure hydrogen through a dedicated line instead of through a dispenser, which contains pressure regulators, valves, a Coriolis meter, and heat exchangers to make measurements. The effluent hydrogen is collected in a gravimetric standard, which is used to calibrate the Coriolis meter at different flow rates and a pressure of 700 bar. The volume of the tanks in the gravimetric standard defines the maximum achievable flow rate, but it is not assumed that the Coriolis meter can be calibrated over its full range. However, it is well known that the calibration curve of a Coriolis meter is linear above 20% of full scale and extrapolation is possible.

In a further step, the nozzles in the previously described line for high-pressure measurements in the range from 10 MPa to over 80 MPa can then be calibrated in series with the previously returned Coriolis meter, which will serve as a reference.

2.2 Alternative fluids for assessing the discharge coefficient on toroidal and cylindrical CFVNs

The second work package is dedicated to the transferability of measurement results to other media, i.e., a transfer of the measurement behaviour from a test medium other than hydrogen to a measurement with hydrogen is to be examined. Ultimately, an alternative to direct calibration with hydrogen should be found. For this purpose, a set of nozzles (set A from work package one), is calibrated as part of an interlaboratory comparison on existing high-pressure test benches (with established CMC entries) (participants are shown in Figure 5). Before going to the interlaboratory comparison an initial study is carried out by comparing discharge coefficient between toroidal nozzles at low pressure (up to 0.7 MPa) to define suitable gases for the interlaboratory comparison. The results of this initial study can be found in a paper from the MetHyInfra project [9].

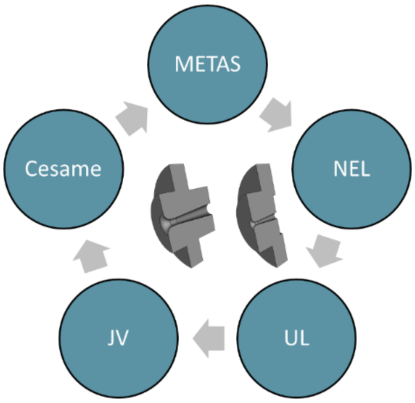

Figure 5: Participating institutes of the intercomparison

In order to be able to make further statements about the transferability, the inner geometry of the nozzle is analysed, since the flow rate mainly depends on the nozzle geometry and the surface roughness in addition to the medium. Here, various methods for geometric measurement are to be considered in order to obtain parameters such as diameter, concentricity, roughness and profile shape. The aim is to obtain an accurate assessment of surface roughness and nozzle shape by defining a standardized method that will be validated by the partners.

Figure 6 shows the throat section from a toroidal CFVN. Overall, it shows a good accordance to the ISO 9300 limited be the capability of the manufacturing process.

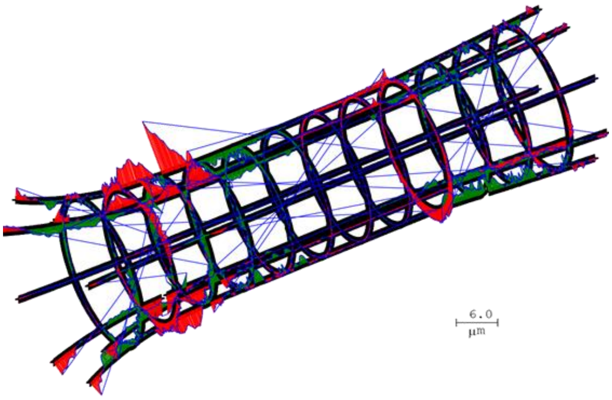

Figure 6: Dimensional calibration of CFVN (by METAS)

Equally important for the calibration of nozzles is the knowledge of the parameter C* (critical flow factor). As available equations of state were not based on high pressure hydrogen data in the required range, there is a need for an equation of state with low uncertainties for the range of interest.

By determining the virial coefficients, an equation of state for hydrogen for the high-pressure range is to be adapted, from which the parameter C* is calculated. To create the equation of state, experimental data from sound velocity measurements in hydrogen at pressures of up to 100 MPa are in progress. Figure 7 shows the test setup for the speed of sound measurement. This equation of state is to be implemented both for the high-pressure measurement in work package one and in the Computational Fluid Dynamics (CFD) model in work package three. Which makes these two approaches, real measurement and CFD simulation, comparable.

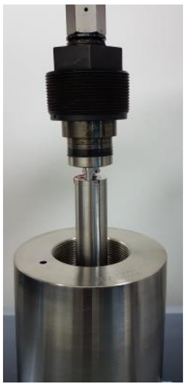

Figure 7: ultrasonic cell and high-pressure vessel (Imperial College London)

2.3 Development of a CFD model in OpenFOAM for high pressure hydrogen flows

The aim of the third work package is the development of a computational fluid dynamics (CFD) model in OpenFOAM for high-pressure hydrogen flows in critically flow venturi nozzles. Due to the planned pressure range of up to 100 MPa, the physical properties of the gas change significantly and real gas effects become more important. These are to be implemented in a suitable CFD model. Here, the roughness of the nozzle surfaces and the non-adiabatic walls in transonic flows are considered. On the basis of the dimensional calibration, digital images of the actually measured nozzles are also developed, which are incorporated into the model. The results of the measurements from the first work package are also to be compared with the simulation results via the implementation of the new equation of state.

More details on the first results and the chosen approach can be found CFD paper of MetHyInfra [10], where the computational domain of the cylindrical nozzle (shown in Figure 8) are explained.

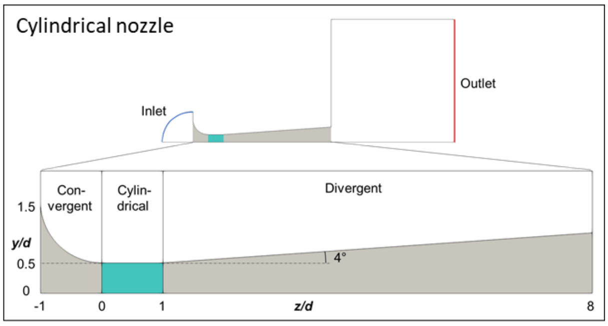

Figure 8: Geometrical model of a cylindrical critical flow venturi nozzle according to ISO 9300

2.4 Transfer standards and methods for the SI-traceable measurement of gas and liquefied hydrogen flows

The fourth work package is divided into two topics. In the first part, a traceable measuring device for flow rates up to 4 kg/h and for pressures up to 30 bar (gaseous) is set up. This includes the development of suitable primary standards for calibrating critical flow venturi nozzles to be used as transfer standards and the identification of suitable reference standards for hydrogen flow measurement. These primary standards will be proven, and the calibration of critical nozzles defined with work instructions.

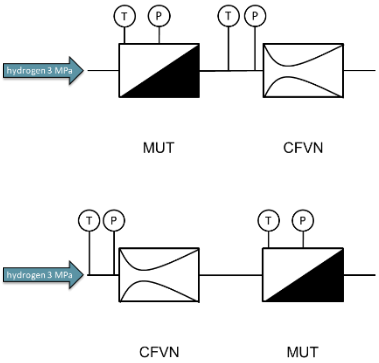

Figure 9: Calibration of meter under test (MUT) upstream or downstream of the critical flow venturi nozzle

Figure 9 shows the proposed setup. For testing at up to 3 MPa, the flow meters would be installed upstream of the reference critical flow nozzle. For testing at 0.1 MPa the test meters would be installed downstream of the reference critical flow nozzle.

The second part is devoted to determining the measurement uncertainty for the flow measurement of liquid hydrogen. In this context, the experience that was generated during the calibration of meters with other liquefied gases should also be used. The aim of the project is to reduce the uncertainties in hydrogen flow measurement to 0.3% to 0.8%. To achieve this goal, a thorough assessment of the current measurement uncertainties is performed. This knowledge is then included in a practical part, in which measurements traced back to the SI are carried out at flow rates in the range of 1000 to 5000 kg/h for a DN25-DN50 measuring section and 4 kg/h for a DN3 meter (see Figure 10) can be realized.

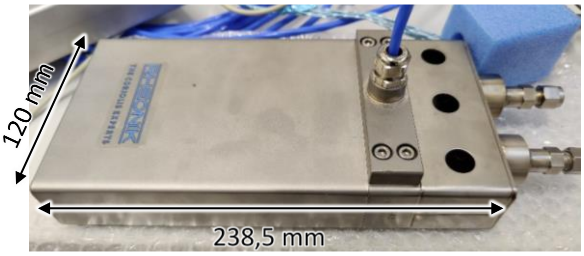

Figure 10: Coriolis Flow Meter DN3 (by Rheonik)

Here, a three-pronged approach for traceable flow measurement of liquefied hydrogen using flow calibration facilities is applied: (I) assessing the transferability of water and liquefied natural gas (LNG) calibrations to liquefied hydrogen conditions (see Figure 11);

Figure 11: LNG calibration and test facility (VSL) [11]

(II) To evaluate the transferability of calibrations using water, liquefied nitrogen and liquefied helium in the vaporization process to liquefied hydrogen conditions (see Figure 12);

Figure 12: Vaporisation test rig (provided by KIT[1] and used at PTB)

(III) novel cryogenic laser Doppler velocimetry (LDV) adapted to liquid hydrogen flow application, which can be used either as a primary standard or as a secondary standard for liquid hydrogen flow measurements (see Figure 13).

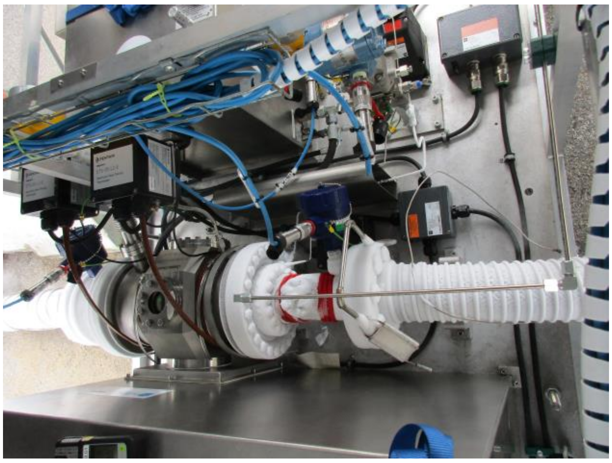

Figure 13: LDV standard for traceable cryogenic measurement (design and built by Cesame®) [12]

More details on the three approaches and the challenges of transferability of a water calibration is shown in another paper of MetHyInfra [13].
In addition, the conversion from "para" to "normal" hydrogen (25% para + 75% ortho) is considered and shown in a good practise guide.

3. Conclusion

In view of the very dynamic development in hydrogen technologies and the accelerated market ramp-up, metrology must also position itself accordingly. In the area of flow, the use of hydrogen and here in particular of regeneratively produced hydrogen as a process gas and as an energy carrier has become the focus of many applications. However, in order to ensure a metrologically verified quantity measurement of hydrogen, both for the low to high gaseous hydrogen pressure range and liquid hydrogen, research and development work is required in addition to the establishment of appropriate traceability chains in order to cover the wide range of operating conditions to obtain valid statements on the measurement accuracy and measurement stability of the meters used. The projects presented addresses this need by providing reliable data, infrastructure, procedures, and normative contributions.
As shown, the project deals extensively with the research of nozzles and nozzle properties. Measurement campaigns are run over a wide range of pressure, which examine the influence of roughness and consider the comparability with other media. This is supported by the geometric measurement and the establishment of a validated equation of state, which is based on experimental data. In addition, further insights into the understanding of the flow physics inside the nozzle are generated via CFD. This leads to the availability of measuring systems and methods for SI traceable calibration of CFVNs and other flow meters at total pressures to almost 100 MPa.
For liquid hydrogen an uncertainty budget will be given and on the site of traceability a level of 0.3 % to 0.8 % is targeted. Three approaches were shown, which cover a wide range of flow rates and will lead to better understanding of the challenges and transferability to liquid hydrogen from other media.
These project outcomes will establish a higher level of trust among end-users (consumers). Those methods will ensure traceable measurements, which is important to achieve a higher share of hydrogen in total energy consumption.

Latest result can be found on the projects website [14].

4. Acknowledgements

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