Publishable Summary for 20IND11 MetHyInfra
Metrology infrastructure for high-pressure gas and liquified hydrogen flows

Overview

The EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. This goal is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement. This European Green Deal provides a roadmap to promote efficient use of resources, restore biodiversity and cut pollution. To achieve this goal, certain actions are required, including investments in environmentally friendly technologies such as hydrogen. This project is the first large-scale industry project that will provide the necessary metrological infrastructure (and traceability) required to address the measurement challenges that are currently faced by the hydrogen industry. This will support growth in several sectors (mobility, fuel cells, liquified hydrogen). The aim of this project is to ensure measurement traceability in the hydrogen distribution chain. Therefore, Critical Flow Venturi Nozzles (CFVN) will be established as standards for use with high pressure gas and a traceability route for liquified hydrogen will be created. Without these measures, verifiable measurements are not possible, and hydrogen will not be accepted as an environmentally friendly fuel.

Need

The European Green Deal includes a hydrogen strategy with the aim of installing 40 GW of renewable hydrogen electrolysers in Europe by 2030. By 2035, a production capacity of up to 8 Mt of hydrogen is expected. To meet the demand for hydrogen it will be necessary to import hydrogen from another 40 GW of electrolysers installed by Europe's neighbours. Germany, for example, has entered a partnership with Morocco to develop an industrial plant to export green hydrogen to Germany. In addition to these plans, there are numerous hydrogen strategies and roadmaps at national and international level around the world. What all these plans have in common is that they consider hydrogen as part of the solution and as a key technology for a greener future and a clean energy transition. Against the background of the war in Ukraine, gas supply in Europe is in many ways being reassessed regarding alternatives such as Liquefied Natural Gas (LNG) and hydrogen, and a renewed shift in focus from natural gas from Russia to liquefied energy gases and hydrogen can be expected. Based on these Green Deal plans and current political realities, the industry, and the associated metrology need to be "hydrogen-ready" even faster. The needs of the industry have already been identified in discussions with the key stakeholders from the hydrogen industry (hydrogen producers, station operators, car manufacturers and standardisation bodies). Regarding the need for high energy storage capacities, hydrogen needs to be stored at high pressure or in the liquid phase. This results in the main technical measurement challenges that need to be addressed in order to foster the growth of the hydrogen market.

- At present it is not possible to provide calibration services for pure hydrogen at high pressure (> 1 MPa) to the industry, except for dispensers at refuelling stations, although meters are available for use with hydrogen at 100 MPa. The convener of ISO/TC 30/SC 2/WG 19 indicated a need for "flow metering technologies of high-pressure gas". The first published results for high-pressure nozzle calibrations show that ISO 9300 is not applicable for hydrogen with sufficient accuracy as no uncertainty value is given. An adequate database of nozzle calibrations with hydrogen is needed. This emphasises the need to develop calibration methods and a traceability chain. The experimental work will be limited to 90 MPa, rather than 100 MPa, for safety reasons, but the results will be extrapolated up to 100 MPa. This need will be addressed using Critical Flow Venturi Nozzles (objective 1).
- Critical Flow Venturi Nozzles are very stable secondary standards, which are used in many laboratories as reference flow meters. Unfortunately, their response to hydrogen, especially above

1 MPa, has not been widely investigated and crucial reference data to connect low to high-pressure calibrations are missing. This needs to be investigated (objective 2).

- For a complete view of the flow physics inside the nozzle, a Computational Fluid Dynamics (CFD) model is needed, which takes into account the most relevant real gas effects (objective 3).
- The number of hydrogen cars is increasing in Europe and fuel cell consumption needs to be accurately measured. However, the infrastructure is not currently available for such metrological measurements (up to 2.5 MPa and 4 kg/h). This will be addressed by creating a primary standard for the requested conditions (objective 4).
- The use of liquified hydrogen is growing rapidly and new sectors are aiming to use this liquid fuel (e.g., aircraft, liquified hydrogen carriers, trains). As hydrogen is becoming a large volume transport fuel, the liquefaction process is also becoming a good candidate for cost reduction and increased efficiency. Indeed, it is expected that liquified hydrogen will become important as a fuel for big and frequently used vehicles, with alternatives to (gaseous) hydrogen vehicle storage solutions being required. Traceability is not available yet, which is a problem for international hydrogen producers and distributors because without traceability, there can be no consistency or trust in the measurement of liquid hydrogen. Solutions are needed for testing flow meters with liquified hydrogen and for a traceability route (objective 4).

Objectives

The overall objective of this project is to establish a metrological infrastructure which will allow the assessment and calibration of flow meters for the measurement of hydrogen flow at high pressures ($p_{\max}$ up to 100 MPa).

The specific objectives of the project are:

1. To develop and investigate methods for the calibration of Critical Flow Venturi Nozzles (CFVNs) and master meters to be used as primary calibration standards for gaseous hydrogen at high pressure ($p_{\max}$ = 100 MPa) and flow rates up to 10 kg/min. To enhance the methods available for air and inert gases (N_2) to be used with hydrogen (e.g., gravimetric method). This includes a comparison of nozzle calibration results, and the determination and validation of uncertainty budgets.
2. To study CFVNs and perform dimensional characterisation. To develop and optimise an equation of state (EoS) for the foreseen pressure (100 MPa) range. To test toroidal and cylindrical CFVNs with different size and surface roughness, using alternative fluids up to 3.6 kg/min and to assess the feasibility of using alternative methods / fluids to perform hydrogen flow meter calibrations with CFVNs and to analyse nozzle behaviour (e.g., discharge coefficient) in comparison with the dependencies described in ISO 9300. To contribute amendments and restrictions, related to the use of nozzles with hydrogen, for possible inclusion in ISO 9300.
3. To evaluate the applicability of currently available models for nozzle flow and to develop a CFD model in OpenFOAM for high pressure (100 MPa) hydrogen flows through CFVNs, which takes relevant real gas effects into account. Furthermore, rough CFVN surfaces as well as non-adiabatic CFVN walls will be considered in this model.
4. To design and develop primary standards for use in the calibration of CFVNs and a rig for testing the suitability of master meters for use under medium pressure (i.e., $p_{\max}$ = 3 MPa; $Q_{N,max}$ = 4 kg/h or about 100 kW fuel cell power) gaseous hydrogen flow conditions. To quantify the SI-traceable uncertainty of liquefied hydrogen flow measurement using alternative fluid calibrations under medium pressure conditions (i.e., vaporisation method: $p_{\max}$ = 0.4 MPa, $Q_{N,max}$ = 4 kg/h; other methods: $p_{\max}$ = 1 MPa, $Q_{N,max}$ = 5000 kg/h). To assess the performance of potential master meters, such as Coriolis flow meters, ultrasonic and differential pressure devices, in the previously stated conditions. This project aims to improve the liquid hydrogen flow measurement uncertainty to 0.3 % to 0.8 %.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (calibration laboratories, NMIs, DIs), standards developing organisations (ISO 9300, ISO 5167) and end users (hydrogen industry e.g., mobility, fuel cell, grid, industry, storage and generation).

Progress beyond the state of the art

CFVNs are widely used and constitute a standardised and accepted method for measuring the flow rate of inert gases (e.g., air, N2...). The nozzle behaviour for high pressure (up to 100 MPa) hydrogen is not fully known. This project will design and build a safe, reliable nozzle holder and several nozzles for high pressure measurement up to 100 MPa. In addition, it will develop a metrological framework for performing hydrogen CFVN calibrations with a master meter technique at high pressure (up to 100 MPa), which is calibrated by a gravimetric standard. The results will be reported to ISO/TC 30 for inclusion in a possible revision of the ISO 9300 standard “Measurement of gas flow by means of critical flow Venturi nozzles”.

Study of CFVNs including nozzle behaviour and dimensional characterisations

The prediction for nozzle behaviour in ISO 9300 needs an equation of state (EoS) to calculate the critical flow factor C*. For hydrogen, the given EoSs are derived from a small experimental database in the range of interest. This project will focus on testing the applicability of the ISO 9300 models for the measurement of hydrogen flow by using a modified and improved equation of state (EoS) for hydrogen at high pressures (up to 100 MPa). The modification and the improvement of the EoS will be based on new experimental data to have the best information about the hydrogen properties in the range of interest.

Calibration with hydrogen is an expensive procedure. An inter-comparison with alternative fluids (air, nitrogen, helium) will be realised using a set of CFVNs in order to determine the dependencies of the fluid properties (C^*, C_d at low pressure) in comparison with the high-pressure hydrogen measurements from objective 1.

CFD model for high pressure hydrogen flows through CFVNs

It is expected that, in the pressure range above 10 MPa, real gas effects will be more dominant inside the nozzle. For a better understanding of the flow physics of high-pressure hydrogen inside the nozzle this project will develop a nozzle model that takes the most important influences of real gas effects into account, up to 100 MPa, including CFVN wall roughness and heat transfer. The data generated by dimensional characterisation will be transformed into the parameters of a CFD-applicable computer model of the physical process, which will be elaborated and documented. With such a link between the dimensional data of a real nozzle and the CFD results of its computer model, a well-defined procedure for the dry calibration of nozzles will be possible. Furthermore, efficient parameter studies will be performed, based on a validated CFD models, to identify the most significant parameters influencing the flow behaviour through CFVNs.

Development of primary standards for the traceable calibration of CFVNs and liquefied hydrogen flow measurement, and a test rig for master meters

The automotive industry has a standard (ISO 23828 “Fuel cell road vehicles - Energy consumption measurement - Vehicles fuelled with compressed hydrogen”) for performing the calibration of fuel cell consumption, but there are no metrological services available to realise these calibrations. This project will build new primary standards for CFVN calibration with hydrogen. A comparison will be made between different types of potentially suitable gaseous hydrogen flow meters in a test rig comprising the calibrated CFVN to provide traceability for flows pertinent to the fuel cell application. A new calibration service will be provided, as a first step towards a full CMC claim, for the calibration of liquefied hydrogen flow meters (Coriolis, USM, differential pressure) at pressures up to 1 MPa.

The liquid hydrogen flow measurement uncertainty is estimated to be in the order of 1 % to 2 % due to unknown effects of the fluid’s temperature on the meter, the lack of available calibration results, and the need for the development of liquefied hydrogen flow meters. Primary and transfer standards for liquefied hydrogen measurements are not available. This project will develop a primary and/or transfer standard for liquefied hydrogen flow measurement with a target uncertainty between 0.3 % and 0.8 %.

This project will also improve the liquid hydrogen flow measurement uncertainty (target 0.3 % to 0.8 %) through the establishment of primary and/or transfer standards for liquefied hydrogen flow measurement. Flow measurements will be undertaken at the flow rates and pressures that are relevant for application in liquefied hydrogen truck unloading (Q_{max} = 5000 kg/h and p_{max} = 1 MPa).

Results

Objective 1: To develop and investigate methods for the calibration of Critical Flow Venturi Nozzles (CFVNs) and master meters to be used as primary calibration standards for gaseous hydrogen at high pressure (p_{max} = 100 MPa) and flow rates up to 10 kg/min. To enhance the methods available for air and inert gases

(N2) to be used with hydrogen (e.g., gravimetric method). This includes a comparison of nozzle calibration results, and the determination and validation of uncertainty budgets.

The design of the nozzles and dedicated nozzle holders has been done. A first characterisation is completed.

The design of the flow line for the calibration of the CFVN up to 90 MPa using a Coriolis flow meter as reference meter has been finalised. Sourcing the components lead to postponing the high-pressure calibration campaign, which will start beginning of 2024.The Coriolis meter that will be used as reference meter for the calibration of the CFVN up to 90 MPa was calibrated successfully with a gravimetric standard over a flow range from 0.25 kg/min up to 1.84 kg/min with an expanded uncertainty of less than 0.6 % at a hydrogen refuelling station.

Objective 2: To study CFVNs and perform dimensional characterisation. To develop and optimise an equation of state (EoS) for the foreseen pressure (100 MPa) range. To test toroidal and cylindrical CFVNs with different size and surface roughness, using alternative fluids up to 3.6 kg/min and to assess the feasibility of using alternative methods / fluids to perform hydrogen flow meter calibrations with CFVNs and to analyse nozzle behaviour (e.g., discharge coefficient) in comparison with the dependencies described in ISO 9300. To contribute amendments and restrictions, related to the use of nozzles with hydrogen, for possible inclusion in ISO 9300.

The dimensional characterization of the nozzles was performed, and a Good practice guide on the dimensional characterisation of sonic nozzles (CFVNs) with different size, shape and surface roughness'(link) was published.

The laboratory comparison of CFVNs has started and is on schedule. A protocol for was written for the comparison and the participating laboratories are now performing calibrations in the selected Reynolds number range. The first round of tests has indicated that some unexpected behaviour occurred with some small nozzles. At least two laboratories are performing consistency checks before publishing the final results of this comparison. The CV curves have a canonical shape following the ISO9300 curves.

A large database on single phase experimental data for normal hydrogen has been produced. It gathers topics on homogeneous density, thermal virial coefficients, vapor pressure and speed of sound and isobaric heat capacity. New measurements of the speed of sound in hydrogen at temperatures between 0 and 50°C, with pressures up to 100 MPa, have been completed. The new measurements have been used to better fit the new equation of state for high pressure hydrogen.

The virial coefficient experiments have started and they should confirm the coefficient that are currently used in the new equation of state. The final results are expected before March 2024.

Objective 3: To evaluate the applicability of currently available models for nozzle flow and to develop a CFD model in OpenFOAM for high pressure (100 MPa) hydrogen flows through CFVNs, which takes relevant real gas effects into account. Furthermore, rough CFVN surfaces as well as non-adiabatic CFVN walls will be considered in this model.

A baseline model for the flow of air (modelled as ideal gas) through the two nozzle types that are present in the ISO 9300 standard has been implemented in OpenFOAM. Two different turbulence models, namely the k-omega shear stress transport (SST) turbulence model and the gamma-Re_{theta} transitional model, have been investigated. A comparison of the resulting C_D value with corresponding experimental data shows good agreement for both models in the laminar ($Re \leq 1e5$) and turbulent ($Re > 1e6$) regions. In the transitional region, however, the predictions with the gamma-Re_{theta} model are much closer to experimental data than the ones obtained with the SST model. Hence, this model seems to be a good starting point for further investigations.

New correlations for the thermophysical properties of hydrogen in the pressure and temperature range relevant to the project have been developed and implemented into OpenFOAM. The newly implemented real gas model has been validated in the numerical simulation of a CFVN. Comparison with previously available real gas models shows not only better accordance with experimental data but also slightly faster computation times.

Furthermore, the influence of non-ideal nozzle shapes and rough walls was investigated in the numerical model. A script that transforms the measured shape of nozzles to a computational mesh for the CFD simulation has been developed. The roughness of the wall can additionally be modelled by respective parameters in the CFD model.

Currently, the influence of non-adiabatic walls on the resulting flow field is investigated. For this, different wall temperatures are prescribed in the region of the nozzle throat. Corresponding experiments have been performed to be able to validate the results of the CFD simulations.

Objective 4: To design and develop primary standards for use in the calibration of CFVNs and a rig for testing the suitability of master meters for use under medium pressure (i.e., p_{max} = 3 MPa; $Q_{N,max}$ = 4 kg/h gaseous hydrogen flow conditions. To quantify the SI-traceable uncertainty of liquefied hydrogen flow measurement using alternative fluid calibrations under medium pressure conditions (vaporisation method: p_{max} = 0.4 MPa, $Q_{N,max}$ = 4 kg/h; other methods: p_{max} = 1 MPa, $Q_{N,max}$ = 5000 kg/h). To assess the performance of potential master meters, in the stated conditions.

The design of the gaseous hydrogen flow measurement test setup, in which traceability will be obtained from CFVNs, was completed ($p_{\max}$ = 3 MPa; $Q_{N,max}$ = 4 kg/h). Partners developing primary standards for CFVN calibrations (with, at least, $p_{\max}$ = 3 MPa; $Q_{N,max}$ = 4 kg/h) decided on adopting the pressure, volume, temperature and time (pVTt) method and started commissioning of (parts of) the standards. Traceability development for liquified hydrogen progressed as follows. A liquified flow measurement uncertainty study applicable to Coriolis flow meters was completed and the findings were publicized as a project report (link). A literature study on the conversion of para to normal hydrogen was completed and a good practice guide on ensuring complete conversion from para to normal hydrogen of vaporized liquified hydrogen was published as “PTB Bericht” (PTB-Report) (link). Flow meters able to measure under liquified hydrogen conditions were secured and calibrated on alternative fluids such as water and LNG. A successful liquefied hydrogen flow experiment was performed, reaching flow rates up to 3000 kg/h. Turbine meters were placed in series with a Coriolis flow meter that was calibrated with alternative fluids. A test rig for the implementation of the vaporization method (anticipated maximum flow rate up to 4 kg/h) was constructed and commissioned with liquid nitrogen. Liquid nitrogen and liquid helium experiments were performed where a Coriolis flow Meter, measuring in the liquid phase, was calibrated against laminar flow element references, measuring in the gaseous phase The cryogenic Laser Doppler Velocity flow meter design was modified to ensure its operability under liquified hydrogen conditions.

Impact

Thus far, the consortium participated in 26 events to present the project’s objectives, such as the International Metrology Congress (CIM), EURAMET TC-Flow, Global Flow Measurement Workshop (GFMW 2022) and at some national events (e.g. Germany and France). The project presented five contributions at the prestigious 19th International Flow Measurement Conference (FLOMEKO 2022) and three scientific journal papers have been published.

Impact on industrial and other user communities

The results will significantly improve the availability of measurement systems and methods for the SI traceable calibration of CFVNs and other flow meters at total pressures up to 100 MPa. Traceable flow standards, particularly CFVNs, will be made available to accredited calibration laboratories, test rig companies and to the R&D departments of flow meter manufacturers.

The implementation of the CFD code is carried out in OpenFOAM so that it can be taken over by any interested stakeholder. The code will include all essential parts, including tutorials for implementation. The CFD results will provide a complex spatial and temporal view of the flow field (which would otherwise be invisible for experimental investigation) and can contribute significantly to the analysis and understanding of flow phenomena inside CFVNs (ISO 9300). An optimised CFD solver can also extend the set of experimental data for a wide range of specific geometrical parameters and physical properties. In combination with other results from this project, a proper CFD model will lead to a ‘dry calibration’ of CFVNs.

The experimental speed of sound data will provide the required validation to assess the quality of the equation of state. This will facilitate an immediate reduction in the uncertainty of the CFVNs for high pressure hydrogen flow measurement and will be fundamental to the hydrogen flow measurement science.

Calibration laboratories and companies building calibration facilities currently rely on CFVN calibrations with air, natural gas, or other alternative fluids. This project will acquire the knowledge needed to assess the transferability of nozzles calibrated with alternative fluids to nozzles used with hydrogen and will provide primary standards for the direct calibration of nozzles operating with hydrogen. This will have positive effects by reducing the cost of recalibration.

This project will provide two new calibration services for the calibration of liquefied hydrogen flow meters (Coriolis, ultrasonic meter, differential pressure) at pressures up to 1 MPa, and flow rates up to 5000 kg/h. These services can be used directly by instrument manufacturers, already associated with the project (several stakeholders/partners linked to the project), aerospace research institutes, and by liquefied hydrogen trailer companies for which these flow rates are of interest. These services and the availability of high-pressure CFVN hydrogen calibration, will be a cornerstone for verifiable measurements and for trustworthy trade of gaseous hydrogen.

The outcomes of this project will be disseminated to calibration laboratories and industrial stakeholders, such as flow meter manufacturers, by organising workshops and presenting the project results at conferences and in scientific journals. Workshops for collaborators and stakeholders will be organised as part of the project. Knowledge will also be disseminated to end users through training courses and an advisory group consisting of industrial stakeholders will be established to meet regularly to exchange information with the consortium to ensure that the project delivers relevant results and information to end users. The involvement of industrial partners in the project will also help to tailor the project to the needs of the industry.

The two workshops on CFVNs and the cryogenic flow measurement training had first impact on industry. The next results of the project will be published in several reports, which will be finalised soon. The project has an active website where public documents such as presentations from the workshops or latest publishable summary are now available to the public. Two reports relating to the liquified hydrogen flow measurement activities were made available. To address the social media the project runs a LinkedIn profile, where latest information and highlights are posted.

Impact on the metrology and scientific communities

Methods for the metrological analysis of measurement systems for very high pressure gaseous and liquified hydrogen will be developed. Based on these project results, the NMIs/DIs will be able to establish new capabilities and skills in the field of calibration at their institutions. Calibration data will be generated for a range of nozzles, which will contribute to research on nozzle flow physics, in particular for very high Reynolds numbers as the measurement will be performed in a new level of high pressure. In addition, NMIs/DIs will be able to better understand the behaviour of CFVNs with hydrogen at high pressure, and this will have an impact by providing input to the most important uncertainty contributions, which in turn are used to reduce calibration uncertainty. Based on the project results, a recommended approach to ensure traceability in the range up to 100 MPa using CFVNs will be derived. This will benefit calibration laboratories as they will be able to uptake a verified method for traceable high-pressure hydrogen calibration.

Calibration with alternative fluids will also impact calibration laboratories as they will be able to use these methods to establish calibration procedures and traceability for hydrogen with their existing infrastructure. The metrological and scientific community will benefit as they will have a new opportunity for cross correlation to the high-pressure region, and they will be able to establish new traceability and uncertainty calculation methods.

Fundamental scientific insights into the physics of hydrogen flow in nozzles will be gained, comprising a better understanding of the Joule-Thomson effect as well as the pressure and temperature dependence of the isentropic exponent. The development of a CFD modelling approach will improve simulation results by including real gas effects. The results will initiate further scientific activities, and these will strongly contribute to hydrogen flow measurement science.

The availability of a validated equation of state for hydrogen, based on experimental data with a traceable uncertainty assessment, will enable the traceable conversion from mass to volume using a well-defined, highly accurate density. This will lead to a lower overall flow measurement uncertainty. This has the potential to lead to highly cited publications.

A robust infrastructure for the calibration of CFVNs with hydrogen (Q_{max} = 4 kg/h), will be provided by the development of primary standards and the performance of an intercomparison. Meter types, which are suitable for the measurement of hydrogen gas flow, and their (dis)advantages in this application, will be identified.

The flow measurement uncertainty of liquified hydrogen is currently unknown/unquantified, but it is estimated to be on the order of 1 % to 2 % (k = 2). The activities of this project on liquefied hydrogen flow measurement will contribute to reducing this measurement uncertainty (target 0.3 % to 0.8 %, k = 2). SI-traceable liquefied hydrogen flow measurement methods and/or standards will result from this project (1000 kg/h – 5000 kg/h flow rates, and p_{max} = 1 MPa).

The first impact on the metrological and scientific communities is expected later this year. The project had one CIM2023 contribution and five contributions during the internationally renowned flow metrology conference FLOMEKO 2022. A paper on the development, implementation and validation of a reference data-based real gas model for hydrogen is currently under revision for the "International Journal of Hydrogen Energy" (IJHE).

Impact on relevant standards

This experienced consortium will provide input to several national and international committees dealing with hydrogen in general and with hydrogen flow metering in particular. Several partners already have strong links with the relevant committees (ISO, OIML, CEN, WELMEC) and working groups. Significant early-stage input is anticipated to working group ISO/TC30 related to ISO 9300 (Measurement of gas flow by means of CFVN), ISO 10790 (Measurement of fluid flow in closed conduits - Guidance to the selection, installation and use of Coriolis flow meters (mass flow, density, and volume flow measurements)) and ISO 5167 (Measurement of fluid flow by means of differential pressure devices). Calibration data for hydrogen gas flow will be provided to be considered for use in the update of the ISO 9300 standard. In addition, the project results will drive improvements in liquefied hydrogen flow measurement techniques that can serve either as possible input to update ISO 21903:2020 or as starting point for a new work item on liquefied hydrogen flow metering, addressing the calibration and installation requirements under ISO/TC 28.

As soon as results are available it will be forwarded to the standards committee and the project will offer a presentation and discussion on the results. As a good example, several standards development organisations (SDOs), such as ISO/TC 28, CEN/TC 268, CEN 234, ISO/TC 22 SC 37, CEN CLC JTC06, ISO/TC 197 and ISO/TC 30 SC 2 were invited to the stakeholder meeting at RISE to hear about the progress of the project. Several members of these SDOs accepted the invitation.

Longer-term economic, social, and environmental impacts

The hydrogen strategy for a climate-neutral Europe is a pillar of the European Green Deal. It offers a solution to decarbonise industrial processes and economic sectors where reducing carbon emissions is both urgent and difficult to achieve. In the longer term, this project will establish the necessary metrological infrastructure to decarbonise automotive and industrial sectors through hydrogen, and to enable the large-scale transport of energy in the form of liquefied hydrogen.

The efficiency of products and processes can be improved by providing reliable flow and quantity measurements. For some applications, hydrogen may lead to CO_2-free processes, e.g., the replacement of coke by hydrogen in steel production. The process control and the acceptance of hydrogen as an alternative fuel will be improved by reducing the uncertainties of the measurement devices.

As hydrogen fuel cell vehicles only emit water vapour, the exhaust gas is fully safe from a health perspective. However, conventional petrol and diesel engines can produce harmful levels of carbon monoxide, nitrogen oxides and particles, and in addition large amounts of carbon dioxide. In the longer term, this project will support the acceptance of hydrogen vehicles by the market, allowing consumers to opt for a vehicle that produces safe levels of emissions.

Just like electricity, hydrogen is an energy vector which can only be produced from other sources of energy like wind, solar radiation, biogas, or fossil fuels. It can be stored easily in a gaseous and liquified state, the latter one permitting a very high energy density which makes it very interesting for the transport sector. For some applications like steel production, gaseous hydrogen can be used directly as a process gas. During the development of a hydrogen-based economy, fossil fuels may be used in parallel which will allow a smooth reduction in fossil energy usage. The market launch of hydrogen has been fast. There are several strategies for hydrogen use, which each need to be investigated for their overall efficiency. An enduring evaluation requires an accurate determination of hydrogen quantities and flow rates, which this project will help to provide.

List of publications

1. Gregor Bobovnik, Bodo Mickan, Peter Sambol, Rémy Maury, and Jože Kutin, (2023) Investigation of the discharge coefficient in the laminar boundary layer regime of critical flow Venturi nozzles calibrated with different gases including hydrogen. *Measurement*, Volume 217. https://doi.org/10.1016/j.measurement.2023.113134.
2. Carsten Wedler and J. P. Martin Trusler, (2023) Speed of Sound Measurements in Helium at Pressures from 15 to 100 MPa and Temperatures from 273 to 373 K. *J. Chem. Eng. Data* 68, 6, 1305–1312. https://doi.org/10.1021/acs.jced.3c00083

3. Sebastian Weiss, Jiri Polansky, Markus Bär, Kilian Oberleithner, and Sonja Schmelter, (2023) Derivation and validation of a reference data-based real gas model for hydrogen. *International Journal of Hydrogen Energy*, Volume 48, Issue 61. https://doi.org/10.1016/j.ijhydene.2023.03.073.

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 June 2021, 36 months	
Coordinator: Hans-Benjamin Böckler, PTB Tel: +49 531 592 1335 E-mail: hans-benjamin.boeckler@ptb.de Project website address: https://www.methyinfra.ptb.de/		
Internal Funded Partners: 1. PTB, Germany 2. Cesame, France 3. JV, Norway 4. METAS, Switzerland 5. NEL, United Kingdom 6. RISE, Sweden 7. VSL, Netherlands	External Funded Partners: 8. EP-E, Germany 9. ESI, Czech Republic 10. IC, United Kingdom 11. ITS, Germany 12. MH, Germany 13. RUB, Germany 14. UL, Slovenia	Unfunded Partners: 15. BHT, Netherlands 16. DNV, Netherlands
RMG01: JV, Norway (Employing organisation); NEL, United Kingdom (Guestworking organisation)		