FLOMEKO 2022

Establish traceability for liquefied hydrogen flow measurements

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Abstract

The EU aims to be climate-neutral by 2050 and usage of liquid hydrogen (LH2) for transportation is expected to grow fast. With the expected uptake, traceability in custody transfer is required. Existing metrological infrastructure can be used to provide traceability with basic calibrations performed typically under ambient conditions. However, due to the very challenging LH2 process conditions, with temperatures as low as 20 K, there is a need to determine the flow measurement uncertainty at these process conditions. Within the Joint Research Project (JRP) 20IND11 “Metrology infrastructure for high-pressure gas and liquified hydrogen flows” (MetHyInfra) [1], traceability for liquefied hydrogen flow measurements is developed by a three-pronged approach: (I) assessment of transferability of water and LNG calibrations to LH2 conditions; (II) cryogenic Laser Doppler Velocimetry (LDV) adapted to LH2 flow applications; (III) assessment of transferability of water, liquefied nitrogen, and liquefied helium calibrations in the vaporisation method to LH2 conditions. In this paper the initial MetHyInfra project results are presented comprising: (I) description of LH2 flow meters, water and LNG calibration results, analytical model prediction statements of uncertainty at LH2 conditions when calibration is performed under ambient conditions, finite element numerical modelling analysis of various thermal effects affecting CFMs at LH2 conditions, (II) design modifications of cryogenic LDV to ensure operability at LH2 conditions, (III) description of the vaporisation standard. It was found that obtaining a definite quantitative number of liquefied hydrogen flow measurement uncertainty from the analytical model is challenging for a variety of reasons.

1. Introduction

The EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal [1] and in line with the EU’s commitment to global climate action under the Paris Agreement (COP21). The hydrogen strategy for a climate neutral Europe [2] identifies liquid hydrogen as a means of energy transport to reach the Green Deal objective. The usage of liquefied hydrogen (LH2) is growing fast, and transportation sectors are pushing towards this solution (aircraft, liquefied hydrogen carriers, trains). With the expected uptake, traceability in LH2 custody transfer will be required to support reliable and consistent measurement.

Due to the absence of traceable calibration facilities using LH2 as calibration medium, it is not currently possible to provide traceable calibrations of LH2 flow meters directly on LH2. In flow measurement it is then typical to provide traceability by a calibration with an alternative fluid. An example is the widespread acceptance of calibrating a flow meter with air for use on gases other than air (see gas meter standards [3], [4]). Since fluid properties and process conditions in the actual application are different from those during calibration, a discussion arises on the degree of transferability of the calibration to the conditions in which the flow meter is used, and the extent to which alternative fluid calibrations lead to additional measurement uncertainty in the application (see e.g., [5], [6] for the Liquefied Natural Gas (LNG) flow meter application or [7] for a discussion on effects from temperature, pressure, and fluid viscosity on Coriolis Flow Meters (CFMs)). Logically, two approaches can be followed in an attempt to resolve the discussion. Either calibration facilities under actual process conditions are being developed to establish calibration results and to compare them with the alternative fluid calibration result, or physical models are developed and proven to yield valid extrapolation of alternative fluid calibrations to process conditions.

Within the Joint Research Project (JRP) 20IND11 “Metrology infrastructure for high-pressure gas and liquified hydrogen flows” (MetHyInfra) [8], traceability for liquefied hydrogen flow measurements is developed by a three-pronged approach: (I) assessment of transferability of water and LNG calibrations to LH2 conditions; (II) cryogenic Laser Doppler Velocimetry (LDV) adapted to LH2 flow applications; (III) assessment of transferability of water, liquefied nitrogen, and liquefied helium calibrations in the vaporisation method to LH2 conditions. For the first method, an analytical model of a CFM is developed based on existing literature to calculate the uncertainty from influencing variables such as temperature, pressure, material properties, fluid properties, and tube design. Model predictions are compared to alternative fluid calibrations of the CFM to obtain an extrapolated uncertainty for liquefied hydrogen conditions. The second method (based on cryogenic LDV) is based on the LDV-technique, which is made suitable for cryogenic conditions. It was successfully applied in providing traceability to LNG flow already [9]. Its design was recently modified to ensure operation at LH2 conditions, at temperatures as low as 20 K. Due to its measurement principle, it can be used either as a primary standard or as a secondary standard for LH2 flow measurements. The first two methods are applicable to flow rates in the range of 1000 kg/h – 5000 kg/h (DN25 – DN50). For the third method (based on vaporisation), a much smaller flow rate is considered, with a maximum of 4 kg/h (DN3). Here, the mass reading of a CFM measuring a fluid flow in liquid state is compared to the vaporised mass flow reading measured by a traceably calibrated laminar flow element of the fluid in gaseous state.

In this paper the initial MetHyInfra project results are presented comprising: (I) description of LH2 flow meters, water and LNG calibration results of a 2” turbine and a 2” “U-tube” CFM, analytical model prediction statements of uncertainty at LH2 conditions when calibration is performed under ambient conditions, finite element numerical modelling analysis of various thermal effects affecting CFMs at LH2 conditions, (II) design modifications of cryogenic LDV to ensure operability at LH2 conditions, (III) description of the vaporisation standard. The alternative fluid calibration error of the CFM on LNG falls within the OIML R117 [10] guideline accuracy class 1.5 % range, implying a maximum permissible error (MPE) of 1.0 % for the meter. It was found that obtaining a definite quantitative number of liquefied hydrogen flow measurement uncertainty from the analytical model is challenging for a variety of reasons. The research project aims to deliver traceability for liquefied hydrogen flow measurement at a level between 0.3 % to 0.8 %, hence further improvements will be targeted.

2. LH2 flow meters

Two commercially available liquefied hydrogen flow meters (turbine meter – TrigasDM and Coriolis meter) were secured and calibrated with water and LNG.

2.1 LH2 turbine flow meter alternative fluid calibration

Figure 1 shows a 2” LH2 turbine flow meter as it was installed during an alternative calibration on LNG. The flow meter was not insulated.

Figure 1: TrigasDM turbine LH2 flow meter installed in VSL’s LNG calibration and test facility [11].

Figure 2 shows the water and LNG calibration results of the LH2 turbine flow meter. Calibrations were performed in VSL’s traceable calibration facilities for water and LNG [11] . The K-factor is at about 64 on water and ranges from about 61 to about 64 on LNG (for a broader Reynolds range).

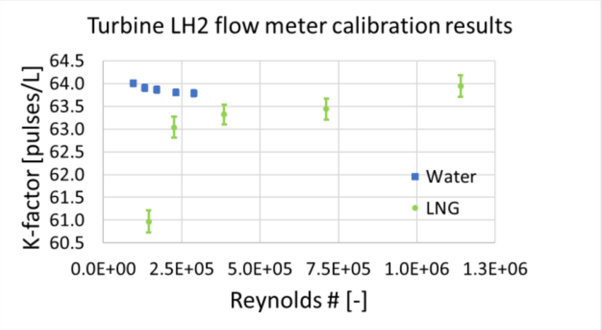


Figure 2: LH2 turbine flow meter alternative fluid calibration results obtained in VSL’s traceable calibration facilities. Calibration uncertainty is indicated by the error (uncertainty, *k* = 2) bars. For the water calibration, these bars are smaller than the symbols.

2.2 Coriolis flow meter alternative fluid calibration

LH2 CFMs are commercially available. Figure 3 shows the water and LNG calibration results of the CFM (2” “U-tube” shape). The meter error is at about 0 % on water and at about -0.4 % on LNG. The flow meter was insulated during calibration on LNG.

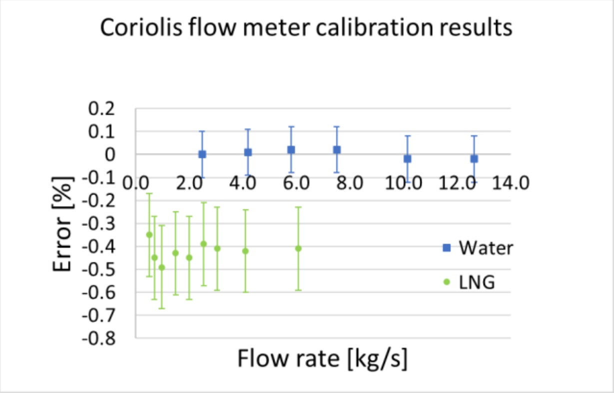
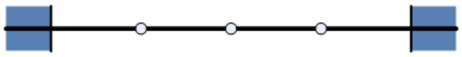


Figure 3: CFM alternative fluid calibration results obtained in VSL’s traceable calibration facilities. Calibration uncertainty is indicated by the error (uncertainty, *k* = 2) bars.

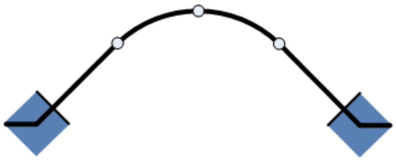
3. Analytical and finite element modelling of CFM uncertainty in LH2 conditions

A Type B uncertainty estimation (see [12], [13] for Type B definition and estimation) of CFM measurements is difficult. Although all CFMs use the same physical principle to measure the mass flow rate, there is no analytical equation for the flow that is valid for all the CFM designs. For example, it is known that the Young's modulus influences the measurement result. While Poisson’s ratio is also important for a U-tube CFM [14] it plays no significant role for a straight tube CFM [15]. This means that the flow through CFMs of other shapes, such as the delta shape, could in principle obey other equations and be influenced by other factors. An analytical estimate of measurement uncertainty based on such equations will therefore inevitably differ from flow meter shape to shape, and the U-tube CFM is likely to have larger uncertainties than the straight tube due to the additional uncertainty in the Poisson’s ratio. The limited availability of data is also a challenge for a Type B estimation of measurement uncertainty at cryogenic temperatures. We have found only one publicly available data set on the elastic properties of stainless steel 304, 310 and 316 at cryogenic temperatures [16], and the associated uncertainty is quite large (on the order of 1 % to 2 %, depending on quantity and steel type). In addition, the uncertainties were not reported according to currently applicable standards (e.g., the GUM [12]), so that questions remain on how the uncertainty budget was obtained in the first place. The uncertainty contributions due to other factors, such as pressure, are secondary compared to the uncertainty of the measured data for the elastic properties of the steel. We used a numerical finite element method (FEM) model of CFMs, based on the Timoshenko beam model of the tube and the one-dimensional model of the fluid flow, to analyse the internal tensile forces for three CFM shapes. This enables to investigate how the sensitivity of the CFMs changes with temperature.

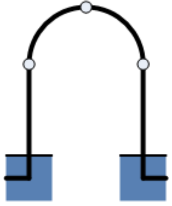
The FEM model considers fixed boundary conditions at the connection of the tube to the supporting structure and temperature-dependent material properties of stainless steel 316 using empirical models for the elastic and shear moduli from [14], which are originally based on data from [16], and for the thermal strain from the NIST website [17], which rely on data from [18]. Each simulation consists of three steps: (i) static analysis, where the static centrifugal force acting on curved sections and the virtual external force of thermal expansion are taken into account and the resulting static internal axial forces and/or deflections are calculated; (ii) modal analysis, where the natural frequencies of the tube are calculated; and (iii) harmonic analysis, where the corresponding phase differences are calculated. The flow sensitivity of the CFM is defined as the ratio between the time difference and the mass flow rate, where the time difference is equal to the phase difference divided by the angular natural frequency. The simulations presented in this paper were performed for three different designs of the measuring tube shown in Figure 4, discretised into 400 elements along the tube length. Input data for the LH2 flow rate is as follows: mass flow rate of 0.1 kg/s, density at 71 kg/m^3, temperature at 20 K; pressure effects were not taken into account.



(a) Straight tube



(b) Arc tube



(c) U-tube

Figure 4: Simulated designs of the measuring tubes (tube dimensions at 293 K: length 600 mm, internal diameter 20 mm, thickness 1 mm, tube material: stainless steel 316).

Figure 5 shows the simulation results for the static internal tensile force along the tube length due to a temperature change from ambient conditions (293 K) to LH2 conditions (20 K). The average value of the internal force is about 37 N, 527 N and 40900 N for the U-tube, Arc tube and straight tube designs, respectively. For the curved tubes, the tensile force varies along the tube length, with the largest values occurring in curved sections.

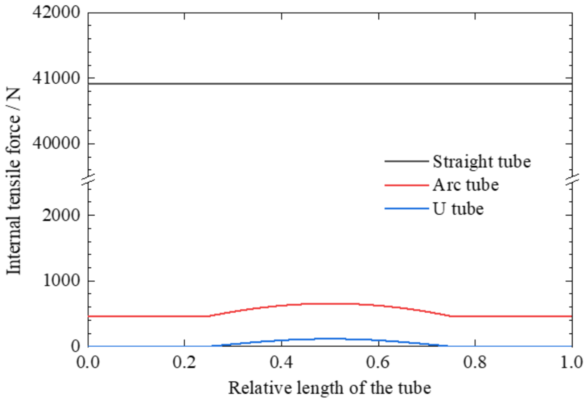


Figure 5: Variation of the static internal tensile force along the tube length for three different designs of the measuring tube due to temperature change from 293 K to 20 K.

Figure 6 shows the simulation results for the relative effects of a temperature change from 293 K to 20 K for the flow sensitivity corresponding to the natural frequency of the first out-of-plane bending mode. In the case of the U-tube, most of the temperature effect is attributed to variations of the elastic modulus. For example, if the correction takes into account that the flow sensitivity is inversely proportional to the elastic modulus, the related temperature effect decreases from -6.6 % to -0.3 %. If the elastic-modulus correction is considered for the Arc tube and the straight tube, the remaining temperature effects on the flow sensitivity are -0.6 % and -19.7 %, respectively. In general, this residual temperature effect is a combination of the effects of temperature variations in Poisson's ratio, thermal contraction in the radial and axial directions, and the effects of internal tensile force. The latter is very significant in the straight tube design, which is modelled with fully constrained boundary conditions and consequently with zero axial contraction of the tube.

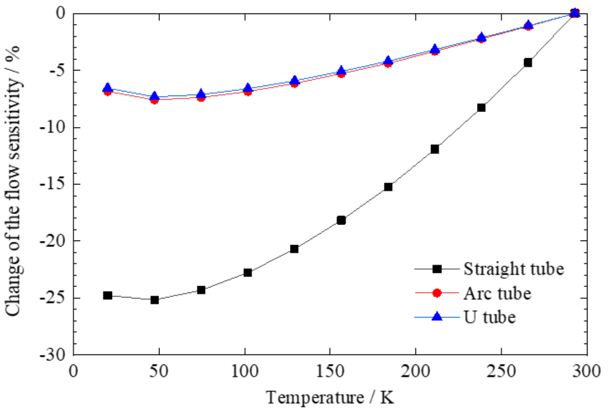


Figure 6: Relative temperature effect on flow sensitivity for three different designs of the measuring tube.

4. Cryogenic Laser Doppler Velocimetry standard: liquefied hydrogen ready

The "Référence en Débitmétrie Cryogénique Laser" (in French), abbreviated as RDCL, is a novel dynamic cryogenic flow standard. The traceability is realized via velocity measurements (length and time). Figure 7 shows a schematic of the cryogenic standard. The principle and main details are provided in Maury et al. [9].

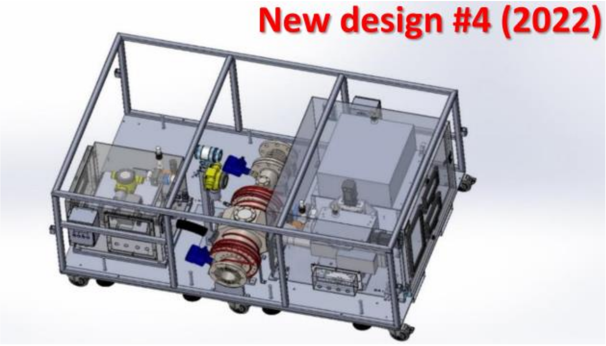


Figure 7: LDV standard for traceable cryogenic measurement (design and built by Cesame®)

The inner centre part, which consists of a flow meter, has been redesigned to be LH2 ready. Indeed, the shrinking will be considerably higher with LH2 (temperatures as low as 20 K) compared to LNG (temperatures as low as 110 K), for which it was made suitable already [9]. New features have been implemented to take care of the thermal constraint, limiting the heat conductibility while maintaining a good level of vacuum. All the equipment will be ATEX-rated for LH2. Furthermore, the inlet has been changed to be vacuum insulated to avoid regasification upstream the measuring section. Note that the LDV technique requires a monophasic flow (liquid or gas).

5. LH2 traceability by the vaporisation method

Another approach to bring traceability to liquified gases is the vaporisation method. The setup which was kindly provided by KIT[1] is shown in Figure 8 and is designed for a maximum flow rate of 4 kg/h. Here the meter under test is installed in a vacuum isolated pipe (2 in the picture) to measure the quantity of a cryogenic liquid. For this setup a CFM is chosen as meter under test. Then the medium is vaporised (3 in the picture). The reference is in atmospheric conditions in the gaseous phase. A panel with 5 different sized laminar flow elements (4 in the picture) ensures the traceability to the International System of Units (SI) for different flow rates. This way the CFM behaviour given by the water calibration done by the manufacturer can be compared to cryogenic conditions. The utilised liquified gases (nitrogen, helium) are supplied from cryogenic storage vessels and will be injected to the setup at the inlet (1 in the picture). To reuse the helium, the exhaust gas will be transferred back to the helium liquefier after collection in a balloon (5 in the picture).

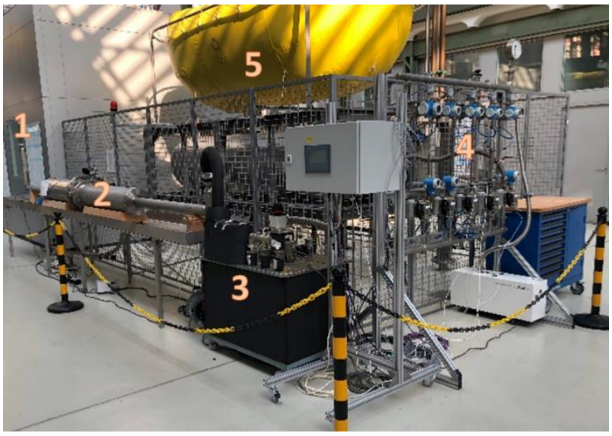


Figure 8: Picture of the vaporisation test rig

Due to explosion safety reasons a test with liquified hydrogen is not possible. To emulate the operation conditions, liquified nitrogen and liquified helium will be used as alternative fluids covering the temperature range of interest. The materials used for the construction of the CFM by the manufacturer are compatible for the use with hydrogen and are the same as for liquified helium. It is expected that the metering behaviour is mostly influenced by the stiffness of the installed pipes inside of the CFM. The stiffness itself is depending on the material, dimensions and temperature. Furthermore, the results will be relevantly affected by the quality of the zero compensation. Particularly because in the given application the meter will work at the lower end of its range. It is expected that boil off effects in the cryogenic liquid can be an issue in these tests.

6. Discussion and conclusions

Figure 2 and Figure 3 show that a calibration result on water can be different than a calibration result on LNG. The results were plotted in terms of the physical parameter that is commonly believed to describe the meter behaviour (Reynolds number for a turbine meter, mass flow rate for a Coriolis meter). This suggests that extrapolating alternative fluid calibrations to LH2 cryogenic conditions is not necessarily straightforward.

The alternative fluid calibration error of the CFM on LNG falls within the OIML R117 [10] guideline accuracy class 1.5 % range, implying a maximum permissible error (MPE) of 1.0 % for the meter. This percentage in turn requires an uncertainty at a level of one-fifth (for type approval) or one-third (for verifications) of the 1.0 % MPE (for LNG). The uncertainty (k = 2) for the CFM LNG calibration result is at about 0.2 % (c.f., Figure 3). It can be interpreted that delivering calibration and measurement uncertainty at this level (0.2 %) for LH2 conditions, with temperatures as low as 20 K, will be challenging, let alone when it is reduced as a consequence of stricter accuracy limits.

It was found that obtaining a definite quantitative number of liquefied hydrogen flow measurement uncertainty from the analytical model is challenging for a variety of reasons: (i) it relies on literature uncertainty claims made prior to the current guidelines on expressing uncertainty (e.g., the GUM [12]), (ii) only one publicly available data set on the elastic properties of stainless steel is available from literature, (iii) the associated uncertainty of this significantly contributing parameter to the overall uncertainty is quite large (on the order of 1 % to 2 %), and (iv) there is no analytical equation for the flow that is valid for all the CFM designs.

Modifications were made to the cryogenic LDV standard to enable traceable measurement at LH2 conditions. The modifications are related to the need for proper insulation at much lower temperatures for LH2 with respect to liquid nitrogen or LNG.

In the vaporisation method, the traceability is provided in the gas phase by laminar flow elements while the meter under test measures in the liquid phase.

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At the time of writing, no calibration results are available for the cryogenic LDV standard nor for the vaporisation method setup.

The research project aims to deliver traceability for liquefied hydrogen flow measurement at a level between 0.3 % to 0.8 %, for flow rates in range 1000 kg/h – 5000 kg/h or at a maximum of 4 kg/h (DN3; vaporisation method), hence further improvements will be targeted.

Acknowledgements

This work was supported through the Joint Research Project “Metrology infrastructure for high-pressure gas and liquified hydrogen flows”. This project 20IND11 MetHyInfra has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. This project has received funding from the Ministry of Economic Affairs and Climate Policy of the Netherlands.

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