Global Flow Measurement Workshop
24-26 October 2023

Technical Paper

Field experience measuring hydrogen using ultrasonic flowmeters

Mark van der Zande, KROHNE
Jankees Hogendoorn, KROHNE
Dick Laan, KROHNE

1 INTRODUCTION

Hydrogen is mentioned frequently in the news as it is foreseen to play an important role in the energy transition. It is however, not new to the industry; already for decades hydrogen is applied as feedstock in the industry, for example in refineries and in the production of ammonia and methanol. The hydrogen is typically produced onsite from natural gas by steam methane reforming and is referred to as grey hydrogen since CO_2 is emitted during the production.

Hydrogen can also be produced by electrolysis of water. In case electricity from renewable energy sources is used, it is referred to as green hydrogen. When this green hydrogen is applied to replace grey hydrogen in feedstock applications it will help to decarbonize industry. Furthermore it can be used as feedstock in new industrial applications such as the production of synthetic fuels (e.g. e-diesel or e-kerosine). Alternatively, green hydrogen can be used as energy carrier for example in mobility applications and for seasonal storage of sustainable energy.

In this emerging hydrogen economy, hydrogen is produced, transported, stored and consumed by different parties. The ownership of hydrogen changes which requires custody transfer measurement of hydrogen at the transfer points. In this paper we will address some of the challenges of custody transfer measurement of hydrogen, and we will show results of the application of ultrasonic flowmeters for the measurement of hydrogen in the field and in laboratory.

2 Ultrasonic gas flowmeters for hydrogen pipelines

To enable the energy transition, hydrogen infrastructure needs to be developed. An essential part of the hydrogen value chain are transmission networks for gaseous hydrogen, connecting hydrogen production sites and import hubs to industrial clusters where hydrogen is consumed [1]. These pipeline networks show great resemblance to the existing infrastructure for the transmission of natural gas. The hydrogen transmission network will consist of newly build pipelines dedicated to hydrogen as well as repurposed natural gas pipelines where either pure hydrogen of mixtures of natural gas and hydrogen will be transported.

Analysis by European TSO's [2] indicates that the characteristics of the hydrogen pipeline network will not be much different from that of the natural gas network. European natural gas transmission pipelines are typically between 16 to 56 inches (400 to 1400mm) in diameter and operate at pressures ranging from 16 to 100barg. In distribution networks which deliver gas to end-use systems, pipeline diameters are smaller and pressures will be lower than in transmission pipelines.

Tekna
GLOBAL FLOW MEASUREMENT WORKSHOP measuring for the energy transition
NFOGM NORWEGIAN SOCIETY FOR OIL AND GAS MEASUREMENT

Custody transfer metering solutions are required to monitor, manage and account for the gas in the pipelines.

The relatively large pipe diameters in combination with pressures below 100bar, make ultrasonic flow meters very suited for the measurement of natural gas and hydrogen in pipelines[1]. The low density of hydrogen (approximately 8 times lower than for natural gas) and the high speed of sound (roughly 3 times higher than for natural gas) put some challenges on ultrasonic flow measurement of hydrogen, however, we will show in the next paragraphs, that ultrasonic flowmeters can be applied successfully to hydrogen pipelines.

3 Ultrasonic flow measurement principle

The measurement principle of the ultrasonic flowmeter is based on transit time measurement. With this method, acoustic signals are transmitted and received along a diagonal measuring path. A sound wave going downstream with the flow travels faster than a sound wave going upstream against the flow. The difference in transit time is directly proportional to the mean flow velocity of the medium. Multiplied by the inner area of the pipe, the volumetric flow can be calculated. Through the use of multiple ultrasonic paths (Figure 1), flow profile disturbances are compensated for. With this method also the speed of sound of the medium can be determined.

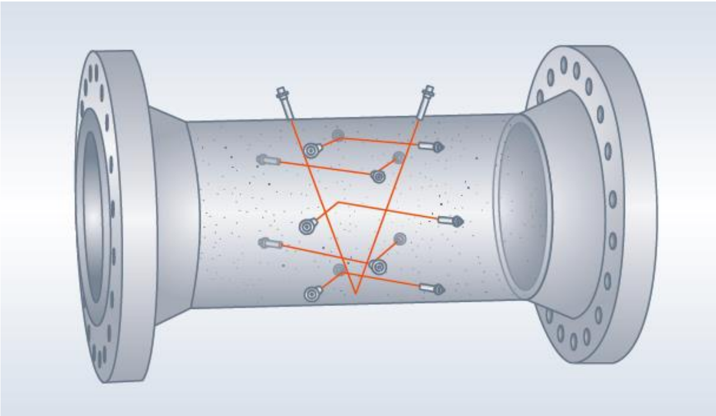

Figure 1: *Measurement paths of the ALTOSONIC V12, the ultrasonic custody transfer gas flowmeter.*

For the flow measurements presented in this paper the ALTOSONIC V12 has been applied (Figure 2). This is the ultrasonic gas flowmeter for custody transfer applications. As shown in Figure 1 the flow velocity is measured on 5 parallel horizontal planes, with reflective V-shaped paths. The middle path is diametric and there is one diagnostic vertical path. For the tests with pure hydrogen we have equipped the ALTOSONIC V12 with composite/SS transducers. Hydrogen can cause deterioration of the mechanical properties of metallic materials and alloys (e.g. ductility and fracture resistance), which is referred to as embrittlement. Therefore we selected the composite/SS transducers which have originally been designed for

[1] *It is important to note that hydrogen pipeline applications are distinctly different from hydrogen refuelling applications. For refuelling, very small diameters are applied (in the order of several mm) and very high pressures are applied (in the order of 700barg). For these refuelling applications small diameter, high pressure Coriolis mass flow meters are commonly applied.*

custody transfer measurement of natural gas and have a good compatibility with hydrogen. Furthermore, the composite transducers are very well suited for the conditions (pressure and temperature) that are typically encountered in custody transfer applications for hydrogen.

Figure 2: *ALTOSONIC V12, the ultrasonic custody transfer gas flowmeter.*

4 Lab tests on mixtures of natural gas and hydrogen

For situations where a dedicated transmission pipeline network for hydrogen is not (yet) existing and the production of hydrogen is starting up, pipeline operators are considering to mix hydrogen with the natural gas in order to (partially) decarbonize the natural gas. In these cases existing natural gas infrastructure will be applied and for that purpose it is interesting to determine how dedicated natural gas flowmeters function in case a mixture of natural gas and hydrogen needs to be measured.

In 2021 a Joint Industry Project was executed by DNV at the All-gas loop in Groningen in which 4 turbine meters, 5 custody transfer and 4 process ultrasonic flow meters were tested simultaneously. As reference system a combination of sonic nozzles, coriolis meters and turbine meters was applied. Part of the test focused on mixtures of Groningen natural gas and up to 30% of hydrogen. The details of the test and the overall results have been published two years ago [3]. KROHNE participated in these test with an 8″ ALTOSONIC V12 ultrasonic custody transfer gas flowmeter. The test have been performed at a temperature of approximately 20°C at two different pressures (16 and 32 barg) for 10 different flowrates between 16 m^3/hr to 1000m^3/hr. For each flow rate 3 measurements were performed during 100s. The reading of the flowmeter is compared to the reading of the reference system.

To assess the performance of the flowmeters for the various gas mixtures the Flow Weighted Mean Error (FWME) as defined in [4] has been determined. The results obtained with the ALTOSONIC V12 are shown in Figure 3.

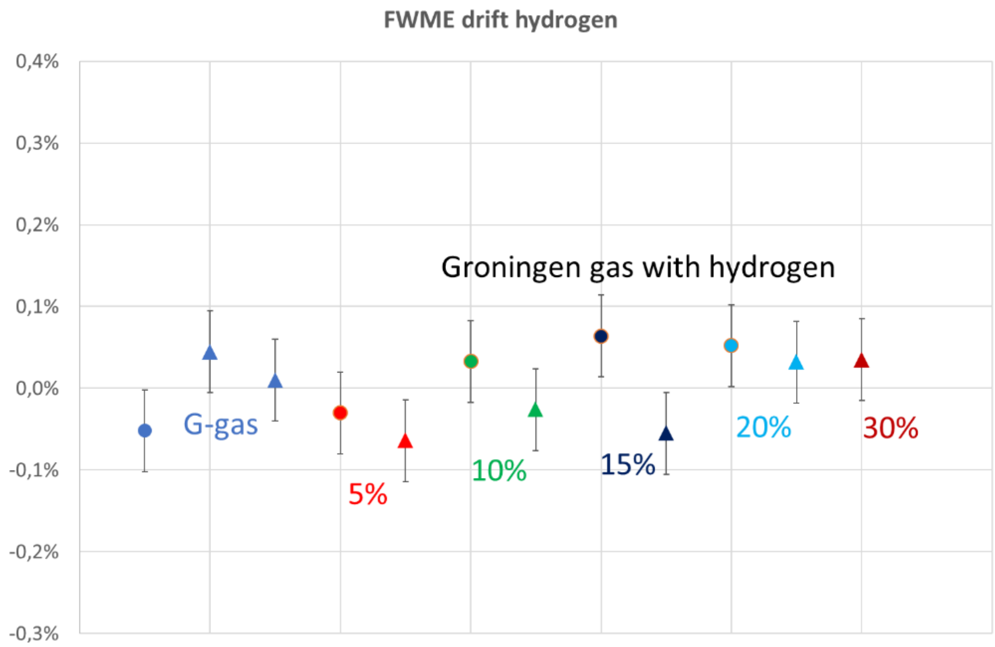

Figure 3: *Drift of the Flow Weighted Mean Error (FWME) of the ALTOSONIC V12 with gas mixtures. The dots represent the results obtained at 32bar and triangles at 16 bar. G-gas means Groningen gas and the percentages hydrogen of the gas mixtures are indicated in the text boxes below the data points.*

In Figure 3 it can be seen that the addition of hydrogen to the natural gas has no significant effect on the measurement performance of the ALTOSONIC V12 ultrasonic flowmeter; there is no significant drift of the FWME as function of the percentage of hydrogen that is mixed in to the Groningen gas. The overall FWME reproducibility of the flowmeter is about 0.10%. Note that a standard (unmodified) ALTOSONIC V12 calibrated on natural gas has been applied for the tests. This lead to the conclusion by DNV that 'no systematic drift behaviour has been assessed as compared to its transferability' and that the 'hydrogen shift is considered insignificant for all the disturbance tests done'. In other words, the flowmeter keeps its performance when in first instance it is calibrated and applied to natural gas and in a later stage hydrogen is mixed with the natural gas.

5 Field installation of ultrasonic flowmeter on hydrogen

In 2021 a field test was initiated by OGE and EVONIK to test ultrasonic flowmeters in a hydrogen distribution network. KROHNE participated with a 10" ALTOSONIC V12 ultrasonic custody transfer flow meter. At that time, there were no flow laboratories available to test and demonstrate the performance on hydrogen of such large size flowmeters. Therefore, an alternative method was applied to demonstrate the performance. To this end the flowmeters are compared against a turbine meter which was already present in the distribution network. The details of the approach and the initial results have been published in 2022 at the Global Flow Measurement Workshop [5] and the Gasmengenmessung Workshop [6].

In short, the ALTOSONIC V12 has been calibrated at Pigsar [7] on natural gas and compared to the 35 year old turbine meter. The following 3 steps were executed:

1. As a first step the ultrasonic flowmeter was **calibrated** on natural gas at Pigsar. The result is shown by the blue squares in Figure 4. It confirms that the flowmeter is within specification for the application on natural gas; over almost the entire tested range the deviation from the reference was less than 0.1%.
2. In the second step the ultrasonic flowmeter has been **compared** on natural gas to a turbine flowmeter at the same test loop of Pigsar. In this way a baseline is created of the differences in reading on natural gas between the two types of flowmeters. The result is shown by the green dots in Figure 4. For the higher flowrates the deviation fluctuates between 0.2% and 0.4%. For flowrates below 300m^3/hr the deviation increases, which can be related to the Qmin of the turbine flowmeter of 200m^3/hr.

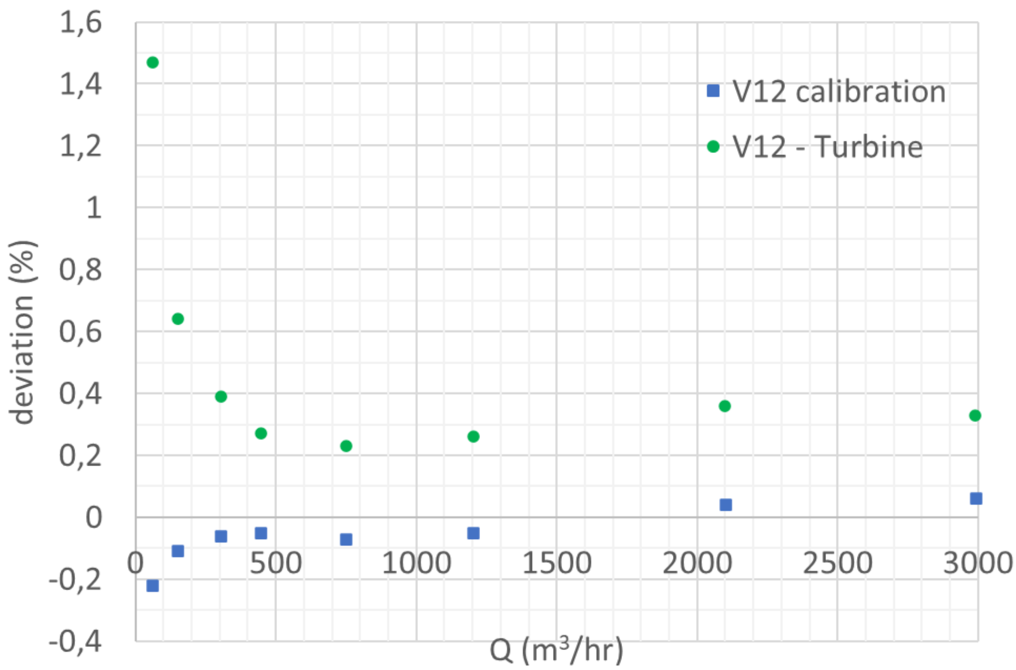

Figure 4: *Deviation (in % of the measured value) between the ALTOSONIC V12 and the reference of the Pigsar test loop (blue squares) and the deviation between the turbine meter and the V12 (green dots) as function of the flowrate. The test loop of Pigsar is operated on natural gas at 17bara.*

3. In the third and final step, the **comparison** between the two flowmeters is repeated on hydrogen in the field. The differences between the flowmeters in the field on hydrogen is compared to the differences obtained on natural gas (baseline at Pigsar). In Figure 5 the results from the field tests are shown. As explained in [5] it is important to make use of the Reynolds number to compare the test on natural gas to the tests on hydrogen.

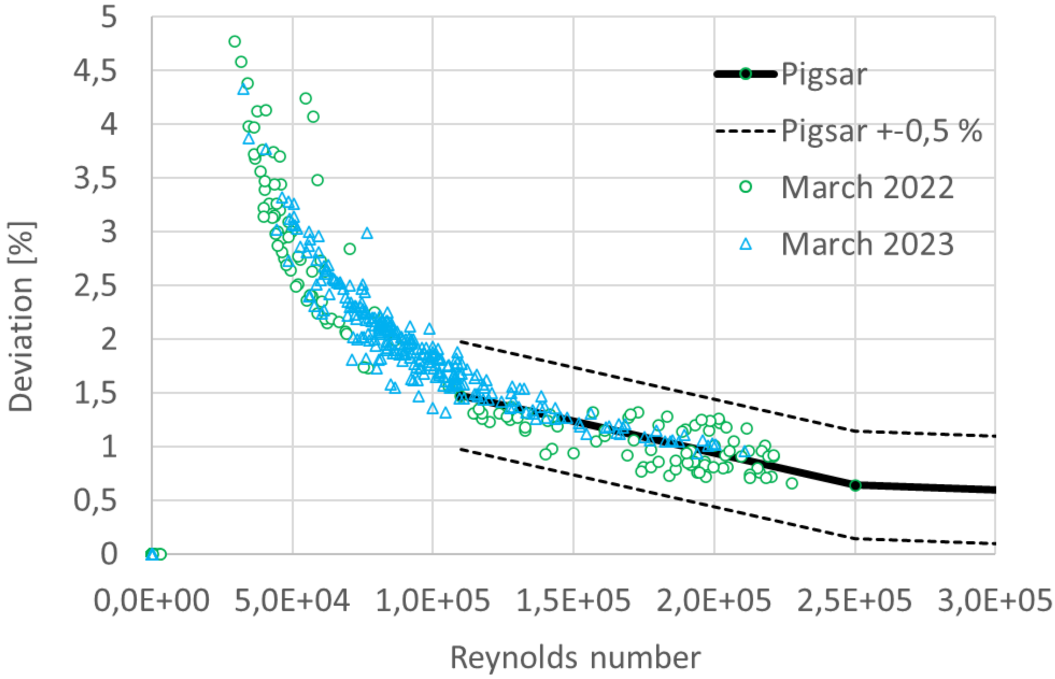

Figure 5: *Results of the field test on hydrogen. The difference (in percentage of the measured value) between the ultrasonic flowmeter and the turbine meter is plotted as function of the Reynolds number. The green circles denote the results on H_2 obtained in the field in March 2022 (hourly average) and the blue triangles represents those obtained in March 2023. The solid black line denotes the Pigsar lab results obtained on natural gas.*

As described in ref. [5] the measurements on hydrogen required optimized settings of the signal processing chain of the ultrasonic flowmeter. This is related to the low density and high speed of sound of hydrogen. At time of publication of ref. [5] only 2 weeks of valid data was available (March 16^{th} to 28^{th} 2022). This data set is represented in Figure 5 by the green circles. It can be seen that the field data follow the baseline curve obtained at Pigsar on natural gas which is considered as a satisfactory result.

In the meantime however, the flowmeter is running for more than one and a half year in the field without further updates. In Figure 5 a similar data set acquired exactly one year later (March 2023) is plotted as blue triangles. It can be seen that the data has not drifted during a period of one year and still follows the baseline curve obtained at Pigsar. This shows the robust operation and long-term stability of the ALTOSONIC V12 in this hydrogen application.

Figure 6: *The 10" ALTOSONIC V12 (150#) ultrasonic custody transfer gas flowmeter installed on site.*

6 Lab tests of ultrasonic flowmeter on hydrogen

Two years ago when the field test on hydrogen was initiated, there was no calibration facility available to test 10" flowmeters on hydrogen. In the meantime DNV has commissioned a hydrogen test facility where we have recently tested a 4" ALTOSONIC V12.

6.1 DNV hydrogen test facility

For testing the 4" ALTOSONIC V12, we utilized the hydrogen test facility at DNV in Groningen, the Netherlands [8]. In this test facility, a 4" Elster SM-RI-X G250 turbine meter serves as the reference instrument within a flow range of 20 to 400 m^3/h. This turbine meter has been calibrated using atmospheric air at PTB and at 9, 21, and 39 bar(a) with natural gas at DNV, both of which are ISO17025 accredited laboratories. Bearing friction parameters were determined through spin down curves and step rate change tests at both PTB and DNV. These measurement data were employed in the PTB turbine meter model to correct for bearing friction and gas expansion effects (if necessary), while also appropriately considering Reynolds effects. The application of this model results in a consistent error curve as function of the tested Reynolds range, spanning from 10,000 to 400,000. This error curve was subsequently applied to correct the turbine meter as a function of Reynolds number.
DNV claims an estimated uncertainty for the reference, determined by the combined factors of the residual error and calibration uncertainties of the facilities, to be in the range of 0.3% to 0.5% within the expected operational range (Re>10,000).

Figure 7: *The 4" ALTOSONIC V12 ultrasonic custody transfer gas flowmeter installed at the DNV hydrogen test facility.*

6.2 Test results of 4" ultrasonic flowmeter on hydrogen

For the test of the 4" ALTOSONIC V12 at the DNV hydrogen flow loop, the lessons learned from the field test with the 10" flowmeter (§5) have been applied. This means that the hydrogen optimized signal processing chain of the flowmeter has been implemented similar as in the field test. The 4" flow meter has been tested on the previously described test circuit (§6.1). For the measurement, a pressure of 30 bara (T=25°C) was chosen.

The results of the measurements as function of Reynolds number and volumetric flowrate are shown in Figures 8 and 9, respectively. Three repetitions have been performed for each flow rate. The standard Reynolds correction for natural gas has been applied to the measurement. Subsequently the meter factor (FWME) has been determined from the hydrogen measurements and has been applied for correction. The corrected values are shown in the graphs. The total uncertainty (k=2) due to repeatability and the uncertainty of the test circuit is indicated by the error bars. The uncertainty of the circuit is assessed to be 0.3%. As can be observed in the graphs, the uncertainty of the test circuit dominates. The obtained measurement results are consistent with previous experiences with the 4" ALTOSONIC V12 flow meter. The highest flow range is limited by the capabilities of the test circuit.

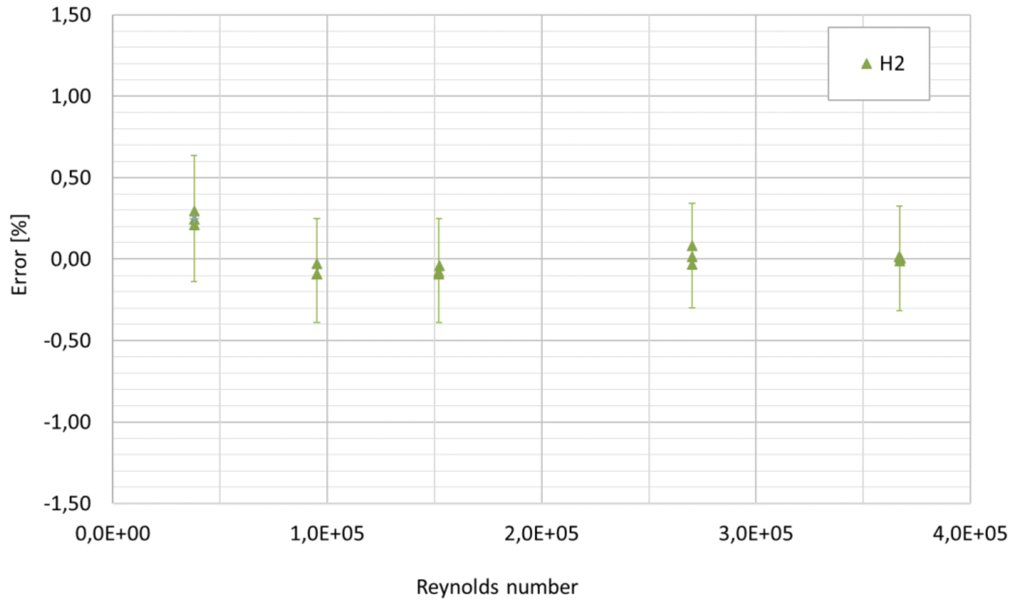

Figure 8: *Test results for hydrogen; the measurement error in [%] as a function of the Reynolds number of the 4" ALTOSONIC V12 at 30 bara (3 repetitions per flow rate). The error bars represent the total uncertainty (k=2), which is largely dominated by the uncertainty of the test circuit (a value of 0.3% has been used in the calculation).*

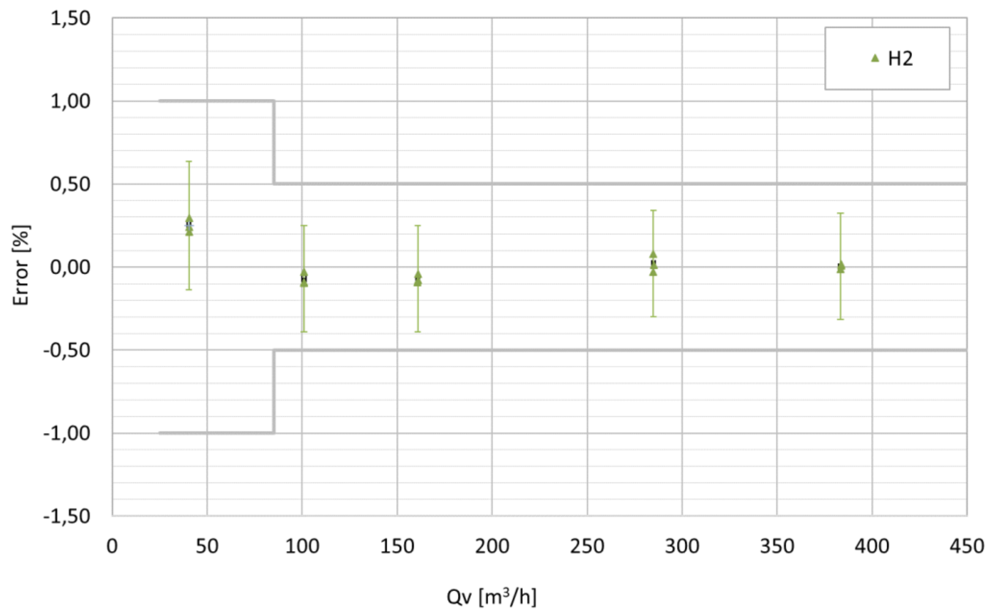

Figure 9: *Test results on hydrogen; the same data as plotted in Figure 8 is represented, only this time as function of the volumetric flowrate. The grey lines indicate the minimum and maximum allowable errors for the 4" ALTOSONIC V12.*

Analysis of the acoustic signals obtained on pure hydrogen shows that for all individual acoustic paths the signals match the expected and desired quality. This indicates that the hydrogen signal processing chain settings work well for 4″ flowmeters as well as for larger diameter (e.g. the 10″ flowmeter in §5).

The linearity of the measurement on hydrogen matches the linearity typically obtained in natural gas applications. At the lower Reynolds value, the hydrogen curve rises slightly. This is likely related to short transit times (due to the high speed of sound of hydrogen), resulting in a zero point effect.

The repeatability of the flowmeter on hydrogen is roughly in the same order as for natural gas. As indicated in the Figures 8 and 9 the three times repetition of the measurement at each flowrate does not show large deviations; the value is significantly lower that the uncertainty of the test facility

7 Summary and conclusions

Hydrogen is foreseen to play an important role in the energy transition and consequently there will be a need for transmission and distribution pipeline networks for hydrogen. In these networks custody transfer measurements are needed at the transfer points and ultrasonic measurement technology is suited for this purpose.

The ALTOSONIC V12 ultrasonic custody transfer gas flowmeter (8″) has been tested on mixtures of natural gas and hydrogen during a Joint Industry Project at DNV. The results obtained at the flow loop show that mixing up to 30% of hydrogen with natural gas does not result in any degradation of the performance of the ALTOSONIC V12. In other words, the flowmeter keeps its performance when in first instance it is calibrated and applied to natural gas and in a later stage hydrogen is mixed with the natural gas.

A 10″ version of the ALTOSONIC V12 is installed in a field test on pure hydrogen. Results obtained and lessons learned in the field test have been published in a previous paper [5]. In the current study it is shown that after one year of operation in the field the flowmeter is still performing satisfactory on pure hydrogen. At present the flowmeter is still installed and running in the field test. This shows the robust operation and long-term stability of the ALTOSONIC V12 in hydrogen applications.

A 4″ version of the ALTSONIC V12 has been tested at the hydrogen test facility of DNV. The linearity and repeatability achieved on hydrogen is very similar to the performance typically achieved on natural gas. The deviation between the reference and the of the measured values is within the allowable error for the 4″ ultrasonic flowmeter.

The low density and the high speed of sound of hydrogen put challenges on the measurements of hydrogen. As demonstrated in this paper the ALTOSONIC V12 ultrasonic gas flowmeter is able to measure accurately pure hydrogen as well as mixtures on natural gas and hydrogen. Although the flowmeter performs well on hydrogen, we continue our research to push the limits even further.

8 REFERENCES

[1] European Hydrogen Backbone (EHB), www.ehb.eu

[2] European Hydrogen Backbone report, 'how a dedicated hydrogen infrastructure can be created', July 2020. https://gasforclimate2050.eu/wp-content/uploads/2020/07/2020_European-Hydrogen-Backbone_Report.pdf

[3] H. Riezebos, JIP renewable gases; 'results on performance of turbine and ultrasonic flow meters up to 30% hydrogen and 20% CO2', paper presented at the North Sea flow Measurement workshop 2021.

[4] ISO17089-1 2010: Measurement of fluid flow in closed conduits – Ultrasonic flowmeters for gas – part 1: meters for custody transfer and allocation measurement.

[5] I. Krajcin, S. Chudoba and D. Laan; 'Comparing an ultrasonic gas flowmeter with a turbine flowmeter measuring pure hydrogen in a field situation', paper presented at the Global flow Measurement workshop 2022.

[6] I. Krajcin, S. Chudoba; 'Untersuchungen von Ultraschall- und Turbinenradgaszählern mit reinem H_2', paper presented at the Workshop Gasmengenmessung – Gasanlagen – Gastechnik, 30-31 March 2022, KCE-Akademie in Rheine.

[7] https://pigsar.de/en

[8] https://www.dnv.com/oilgas/laboratories-test-sites/technology-centre-groningen-the-netherlands/gas-technologies-ccs-hydrogen.html