Global Flow Measurement Workshop
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Paper

Comparing an ultrasonic gas flowmeter with a turbine flowmeter measuring pure hydrogen in a field situation

Dr. Idriz Krajcin, OGE
Stefan Chudoba, Evonik
Dick Laan, KROHNE

1 Introduction; Hydrogen as an energy carrier

Ultrasonic flowmeters for custody transfer measurement have been developed and tested mainly for measurement of natural gas. With the energy transition, hydrogen is gaining momentum as an energy carrier to complement or replace natural gas. Consequently, there is a need to test the suitability of ultrasonic flowmeters for this gas. As hydrogen has different properties than natural gas (e.g. density and speed of sound) the behaviour of acoustic signals in the gas is different, which may affect the operation and performance of the ultrasonic flowmeter when applied to hydrogen.
Therefore, there is a demand for testing of flowmeters on hydrogen. Currently however, there is a lack of large scale flow laboratories for hydrogen and that is why we have agreed to test ultrasonic flowmeters in existing pipelines transporting pure hydrogen.

2 The project; test site and preparation

The project for the comparison of flowmeters on hydrogen in a field test setup was initiated by Dr. Idriz Krajcin of Open Grid Europe GmbH (OGE) [ref. 1]. The project was executed in cooperation with Mr. Stefan Chudoba of Evonik Operations GmbH [ref. 2]. The test-site is located at Industry Park Marl in Germany (figure 1).

Figure 1: *Hydrogen network of Air Liquide in Nordrhein-Westfalen. The test-site is at industry park Marl which in indicated by the red circle in the top of the map.*

Figure 2: *Hydrogen pipeline at industry park Marl.*

At the test site a pipeline is present (figure 2) with the following specifications

- Pipe diameter: DN250 (10”)
- Design pressure: PN25/DP40
- Medium: pure Hydrogen
- Operational pressure: 19 Bar
- Turbine meter: Instromet TRZ, production year: 1987
- Flow computer: Elster Z1 / table values

The pipeline provides hydrogen gas to Evonik.

For the purpose of the test, 2 different ultrasonic flowmeters have been installed directly upstream of the turbine meter in one meter run together with the necessary temperature and pressure measurements (figure 3a and b). In this paper we will only focus on the KROHNE ultrasonic flowmeter.

Figure 3a: *Meter run before installation of the UFM.*

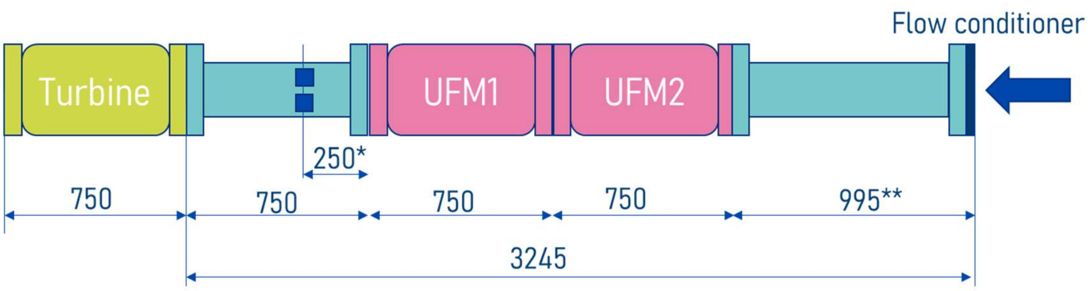

Figure 3b: *Meter run proposal including 2 ultrasonic flowmeters*

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The ultrasonic flowmeters has been calibrated at Pigsar on natural gas and compared with the turbine meter.

- The *calibration* of the ultrasonic flowmeter was executed at Pigsar to confirm that the performance of the flowmeter is within specification for the application on natural gas (figure 5).
- The *comparison* between the ultrasonic and turbine flowmeter was made at Pigsar to create a baseline of the differences in reading on natural gas between the two types of flowmeters. Especially when flowmeters are operated outside of their range (for example below Qmin of the turbine meter) deviations will occur.
- In the field test, the *comparison* between the two flowmeters is repeated, but this time on hydrogen. By comparing the differences between the flowmeters on hydrogen to the differences obtained on natural gas (baseline at Pigsar) statements can be made on the performance of the flowmeters on hydrogen.

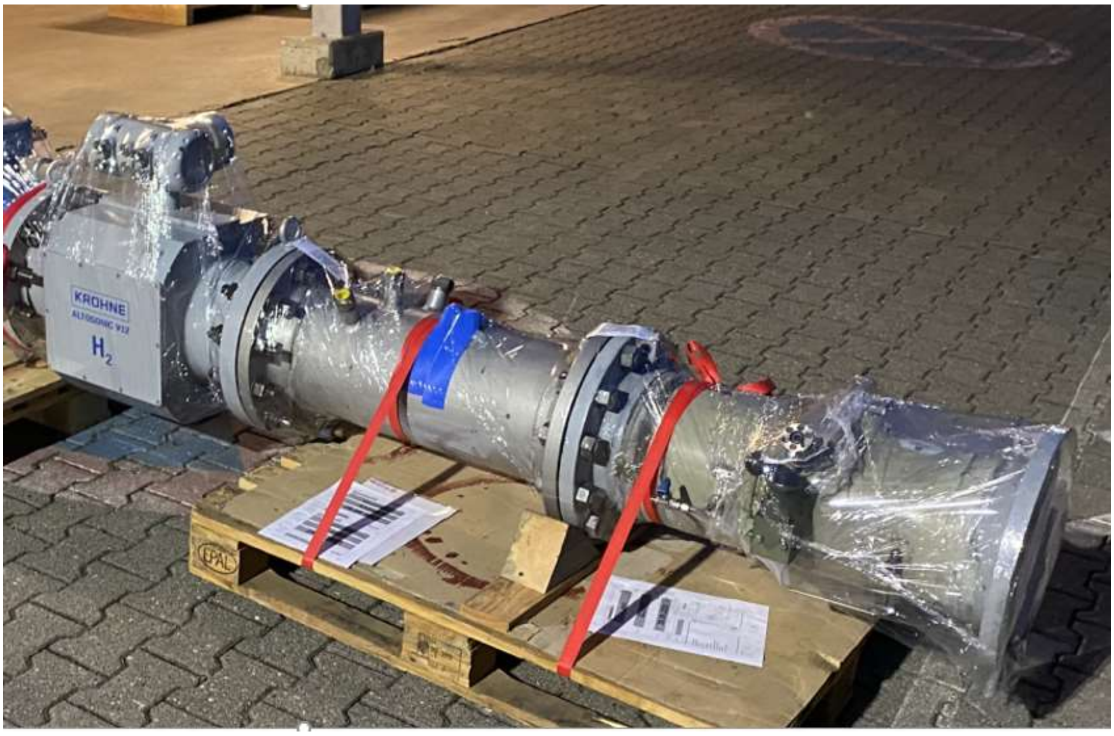

Figure 4: *The 10" ALTOSONIC V12 custody transfer gas flowmeter including meter run as supplied to Pigsar for calibration.*

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pigsar™
Operator of German National Standards
for volume of high-pressure natural gas

Calibration Certificate

Number	19549/2021
Date	2021-09-28

Applicant	Name:	Open Grid Europe GmbH
	Order no.	4510248806
Meter under test	Description:	Ultrasonic meter
	Manufacturer:	Krohne
	Type:	Altosonic V12
	Serial number:	A21047592 - forward
	Nominal size:	10"
	Range of flowrate:	50...3000 m³/h
	Rabge of calibration:	63...3000 m³/h
	Year of manufacture:	2021
	Nominal diameter of meter:	250 mm
	Nominal diameter of flange:	250 mm
	Nominal flange pressure:	PN 25 RF
Date of test	2021-09-28	

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Error Curve

Type of meter:	Ultrasonic meter	Customer:	Open Grid Europe GmbH	DN:	250 mm	p(abs):	17	bar	HF	2000,00	pulses / m³
Meter no:	A21047592 - forward	Manufacturer:	Krohne	Size:	10"	Q max:	3000	m³/h	HF	2000,00	pulses / m³
Date:	2021-09-28	Gear 1:	-			Q min:	50	m³/h	-		pulses / m³
Inspector:	Hüwener	Gear 2:	-			-		pulses / m³	-		pulses / m³

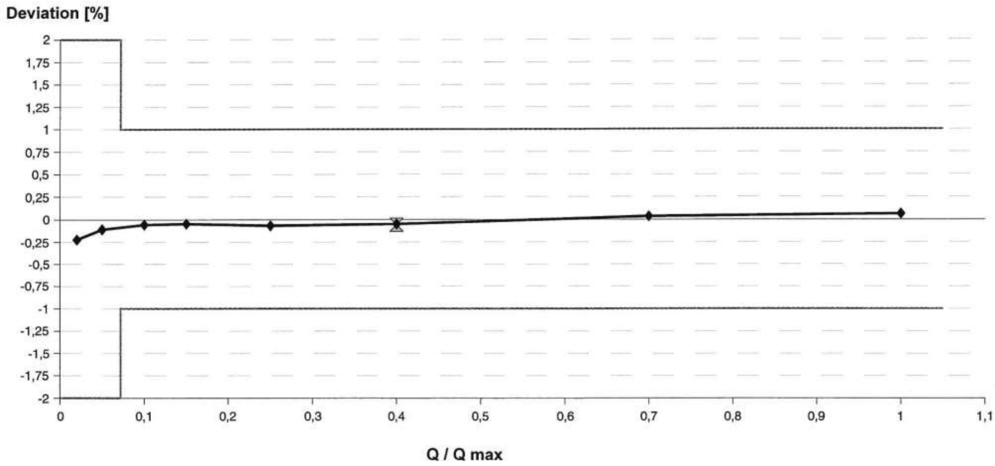

Figure 5: *The result of the calibration and verification of the ALTOSONIC V12 ultrasonic flowmeter at Pigsar. The flowmeter is well within specification on natural gas.*

3 The design of the ultrasonic flowmeter as applied at Marl.

For the field test the 10” ALTOSONIC V12 ultrasonic custody transfer gas flowmeter has been installed in the hydrogen pipeline at Marl (figure 6).

Figure 6: *The 10” ALTOSONIC V12 (150#) ultrasonic flowmeter installed on site.*

The measurement principle of the flowmeter is based on the 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 diameter of the pipe, the volumetric flow can be calculated. Through the use of multiple ultrasonic paths (figure 7), flow profile disturbances are compensated for. With this method also the speed of sound of the medium can be determined.

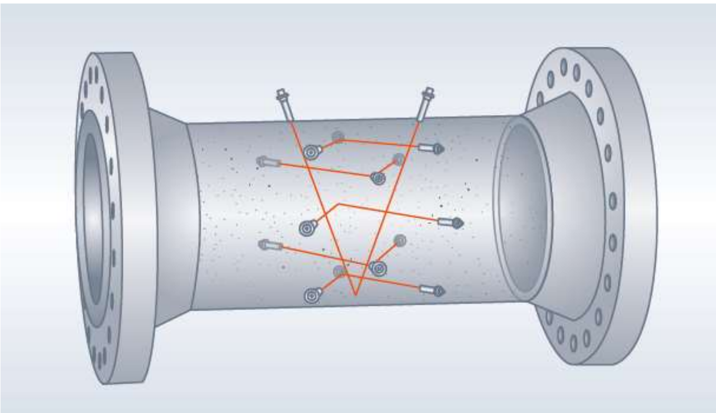

Figure 7: *Measurement paths of the ALTOSONIC V12.*

A shown in figure 7 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 field test at Marl we have equipped the ALTOSONIC V12 with the epoxy/SS transducers. This transducer has been designed for custody transfer measurement of natural gas. A main benefit of the epoxy transducer for the application on hydrogen is the robustness against hydrogen embrittlement. Hydrogen embrittlement is the hydrogen-caused deterioration of the mechanical properties (e.g. ductility and fracture resistance) of most metallic materials and alloys.
Furthermore, this transducer has a relatively large bandwidth, which means that it is possible to vary the transducer frequency. The nominal transducer frequency is 270kHz. The Epoxy transducer is very well suited for the process conditions (pressure and temperature) that are typically encountered in custody transfer applications for hydrogen.

Figure 8: *The epoxy/SS transducer.*

It should be noted that next to the epoxy/SS transducer the titanium transducer can be applied to hydrogen. This transducer has one fixed frequency as it is resonance based. This results in a high efficiency and therefore it can be applied to measure hydrogen at atmospheric pressure.
The main challenge of applying titanium to hydrogen, is to manage hydrogen embrittlement of the transducers. Therefore we only recommend titanium transducers for applications with low design pressure and low mechanical stress and in cases where the hydrogen is not pure or the process temperature is below 80°C.

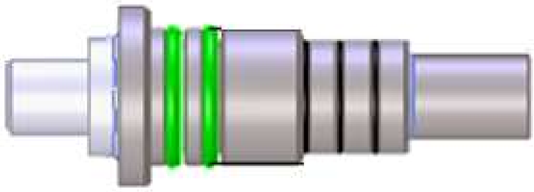

Figure 9: *The titanium transducer.*

4 Speed of sound in hydrogen

As mentioned in the previous section the speed of sound (c) can be measured by ultrasonic flowmeters. For this purpose the downstream (t_{ds}) and upstream (t_{us}) transmission time need to be known, as well as the path length (L):

$$c = \frac{L}{2}\left(\frac{1}{t_{ds}} + \frac{1}{t_{us}}\right) \tag{1}$$

The speed of sound can also be calculated based on the composition of the gas and the temperature [ref. 3]. In Table 1 the calculated speed of sound is given for various conditions.

Table 1: *The calculated speed of sound (SoS) for a pressure of 19 bar and temperature of 10°C. In the columns the results for various purity grades of hydrogen are listed. In the bottom row the effect of impurity on the calculated speed of sound is given (compared to 100% H_2).*

H_2 [mol %]	100	99.9	99.9	99.85	99.8
O_2 [mol %]	0	0.1	0	0.075	0.1
N_2 [mol %]	0	0	0.1	0.075	0.1
SoS [m/s]	1297.8	1288.2	1289.5	1284.5	1280.1
Change in SoS	0 %	-0.74 %	-0.64 %	-1.02 %	-1.36 %

What can be seen in table 1 is that the speed of sound is very sensitive to changes in the purity of the hydrogen. For example in the case of nitrogen (N_2) impurities, 0.1 mol% impurity results in 0.64% change in the speed of sound (factor 6.4). This strong dependency can be understood by considering that the speed of sound of pure hydrogen is in the range of 1300m/s whereas the speed of sound for N_2 and oxygen (O_2) is in the range of 330m/s. Consequently, the measurement of the speed of sound in an ultrasonic flowmeter can potentially be tool to monitor the purity of hydrogen.
Note that the sensitivity of speed of sound for variations in pressure and temperature is order(s) of magnitude smaller, and is taken into account in the calculation of the speed of sound.

5 Results of speed of sound measurement

The first set of field tests has been executed during a period of almost 3 months (October 13, 2021 to January 10, 2022). In figure 10 the results for speed of sound are plotted.

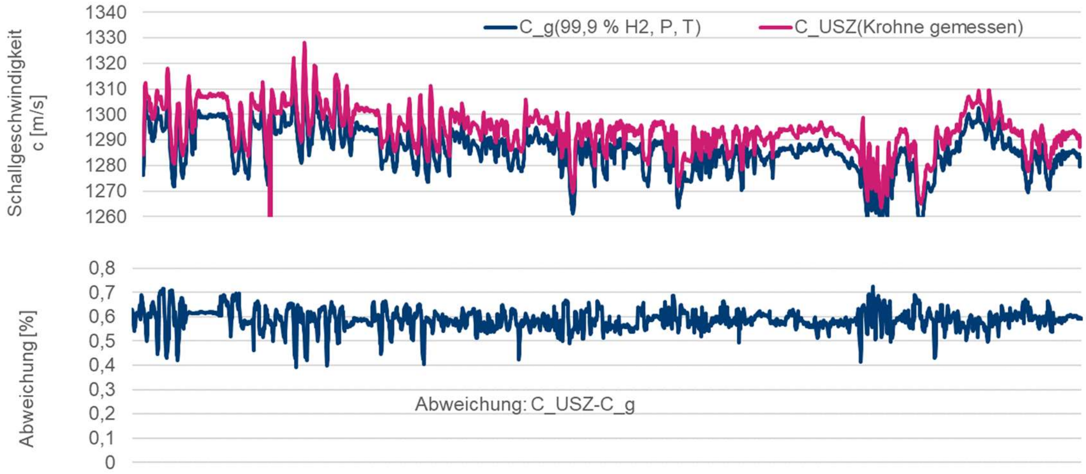

Figure 10: Top*: Speed of sound (m/s) as function of time during the 3 months test. The C_USZ curve is the measured speed of sound by the ALTOSONIC V12 and the C_g curve is the calculated speed of sound under the assumption of 0.1mol% N_2 impurity at measured pressure and temperature.* ***Bottom****: The deviation in % of the measured speed of sound versus the calculated speed of sound.*

It can be observed in figure 10 that the deviation between the calculated and measured speed of sound is on average 0.6%. To search for an explanation of this deviation, the actual gas composition has been measured (figure 11).

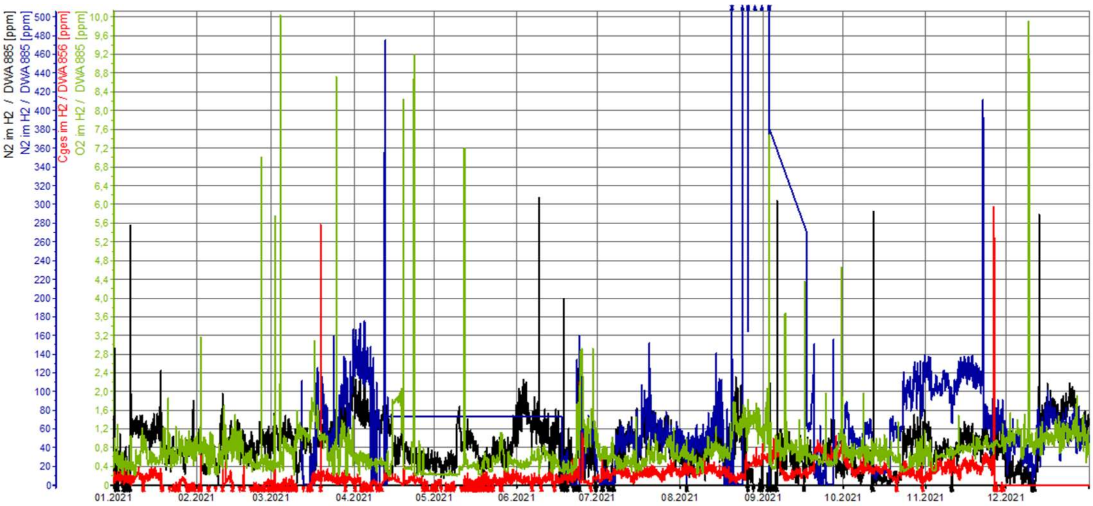

Figure 11: *The gas composition measured during 2021.The blue curve gives the N_2 concentration (ppm).*

When focusing in figure 11 on the last 3 months of 2021, the average N_2 concentration ranged between 10ppm and maximum 140ppm. This is much less than the originally assumed 0.1mol% (1000ppm). Therefore the speed of sound has been re-calculated based on a lower concentration of N_2. In figure 12 the results are plotted for an assumed concentration of 53ppm N_2.

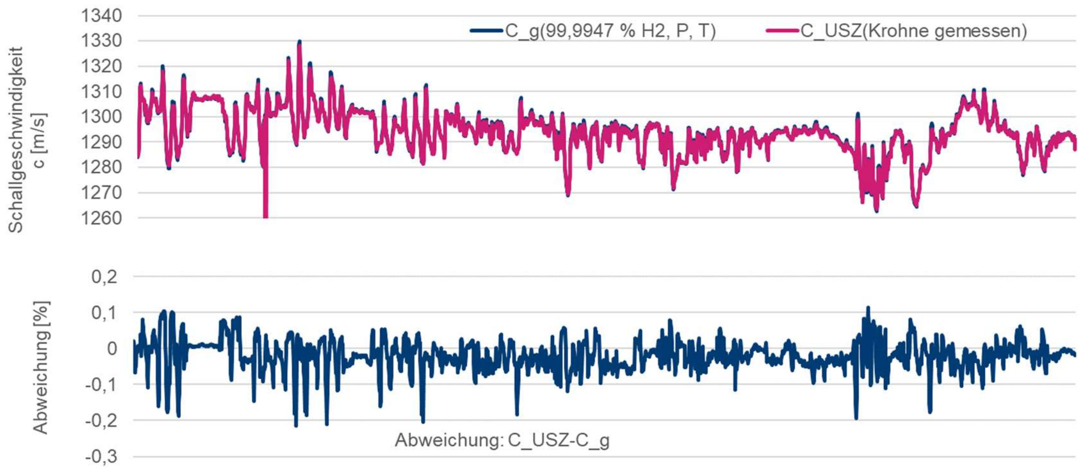

Figure 12: Top*: Speed of sound (m/s) as function of time during the 3 months test. The C_USZ curve is the measured speed of sound by the ALTOSONIC V12 and the C_g curve is the calculated speed of sound under the assumption of 53ppm N_2 impurity (0.0053mol%) at measured pressure and temperature.* ***Bottom****: The deviation in % of the measured speed of sound versus the calculated one.*

It can be observed in figure 12 that with a realistic value of N_2 impurity (53ppm), the measured speed of sound matches the calculated speed of sound.

6 Results of flow measurement

6.1 Initial results

As described in §2, the ultrasonic flowmeter has been placed in series with a turbine meter in the field test in Marl. As there is no external reference available in the field, the measured flowrates of the ultrasonic flowmeter and the turbine meter are compared. To account for the differences in process conditions, the measured actual flowrates are first converted to normal conditions.
For the turbine:

$$v_{n,Turbine} = v_{a,Turbine} \frac{P_{Turbine}\, T_n}{T_{Turbine}\, P_n} \cdot \frac{1}{K(P_{Turbine}, T_{Turbine}, x_g)} \quad (2)$$

and the ultrasonic flowmeter (UFM):

$$v_{n,UFM} = v_{a,UFM} \frac{P_{UFM}\, T_n}{T_{UFM}\, P_n} \cdot \frac{1}{K(P_{UFM}, T_{UFM}, x_g)} \quad (3)$$

Where
v = volume flow
n = normal
a = actual
K = compressibility factor
x_g = gas composition

The deviation (*DEV*) between the flowmeters has been determined as follows:

$$DEV = \frac{v_{n,UFM} - v_{n,turbine}}{v_{n,turbine}} 100\,\% \quad (4)$$

In figure 13 the flow measurement results are shown.

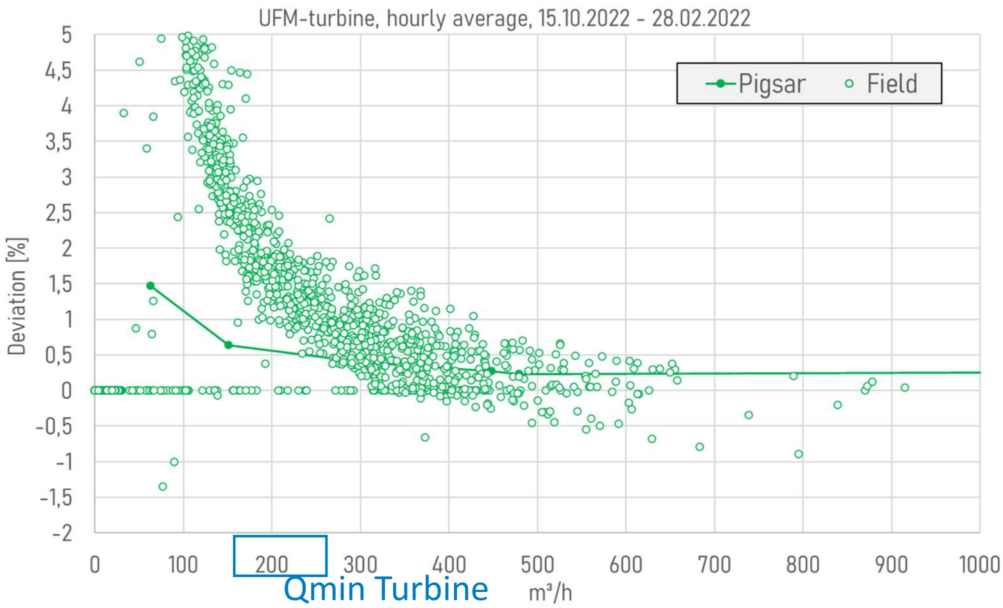

Figure 13: *The deviation (Eq. 4) between the ultrasonic flowmeter and the turbine meter plotted as function of flow rate. The circles denote the results on* H_2 *obtained in the field (hourly average) and the solid line denotes the Pigsar lab results obtained on natural gas.*

The results shown in figure 13 should be analysed in two steps.

First step is to focus on the Pigsar test results obtained on natural gas at 16bar (solid line).

- For high flowrates, the deviation between the ultrasonic flowmeter and the turbine flowmeter is stable around 0.3%. Note that the calibration report of the ultrasonic flowmeter (figure 5; obtained from the same test lab) indicates the ultrasonic flowmeter is within 0.1% of the reference for these flowrates. This proofs that the offset is caused by the turbine flowmeter.
- For lower flowrates (below 500 m^3/hr) the deviation between the ultrasonic flowmeter and the turbine meter starts to increase. Note that for the turbine meter the Qmin is 200 m^3/h and the Qmax is 4000 m^3/h. The increase in deviation can be accounted to the turbine flowmeter as it is operated close to and below its Qmin. The calibration result of the ultrasonic flowmeter (figure 5) show that the ultrasonic flowmeter is within 0.25% of the reference even at the very low flowrate of 60 m^3/hr.

The second step is to focus on the field data obtained on hydrogen (circles). Each point is an average over one hour.
A similar trend as for the natural gas tests at Pigsar can be observed; for high flowrates the deviation is small and for lower flowrates the deviation between the ultrasonic flowmeter and the turbine flowmeter starts to increase.
However, care should be taken to compare same with same; when comparing the field data obtained on hydrogen to the Pigsar lab data obtained on natural gas the comparison needs to be made based on Reynolds number (and not on flow rate).

6.2 Results versus Reynolds number

The Reynolds number is defined as :

$$Re = \frac{uL}{\nu} \tag{5}$$

Where u is the flow velocity, L is the diameter of the pipe and $\boldsymbol{\nu}$ is the kinematic viscosity.
Because of the low density of hydrogen, the kinematic viscosity of hydrogen is much higher than that of natural gas. For the process condition in our test this ratio is approximately a factor 7. As a result, for similar Reynolds numbers the flow velocity of hydrogen is approximately a factor 7 higher than for natural gas. Or the other way around, for similar flow velocities, the Reynolds number for hydrogen is approximately a factor 7 lower than for natural gas.
In figure 14 the same data as shown in figure 13 has been plotted but this time as function of Reynolds number. It can be seen that -as expected- the Pigsar natural gas data (solid line) has moved to the right compared to the hydrogen field data.

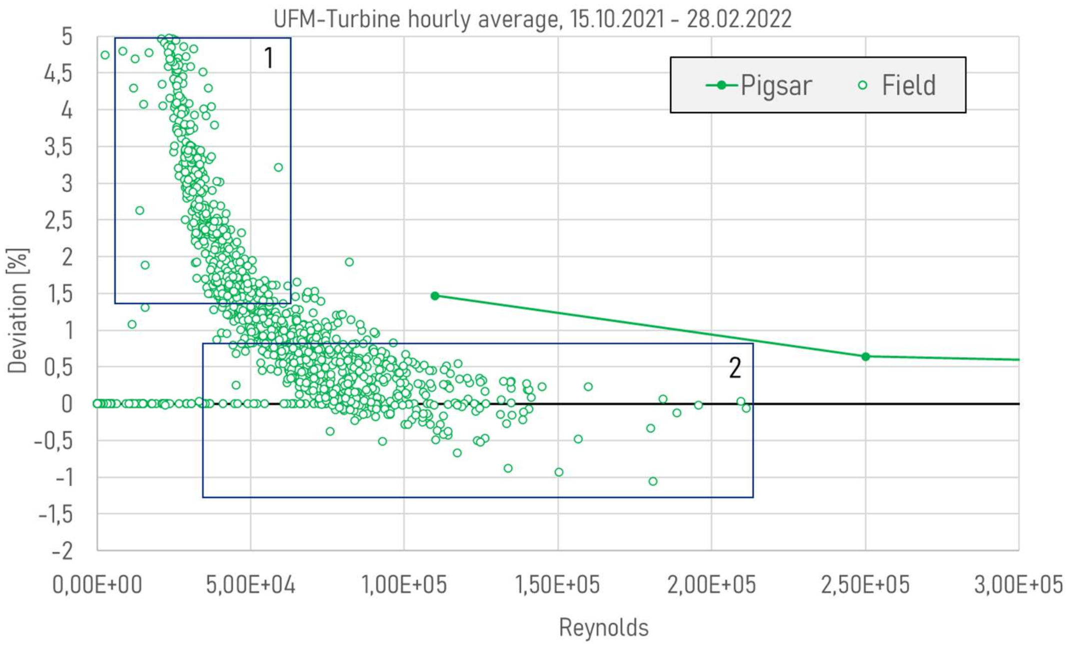

Figure 14: *The deviation (Eq. 4) between the ultrasonic flowmeter and the turbine meter plotted as function of the Reynolds number. The circles denote the results on H_2 obtained in the field (hourly average) and the solid line denotes the Pigsar lab results obtained on natural gas. The numbered boxes are explained in the text below.*

In figure 14 two boxes are displayed. Box no. 1 contains test data from the first months of testing (end of 2021). This data was all acquired at relatively low flowrates (and low Reynolds numbers). The deviation between the ultrasonic flowmeter and the turbine meter is considerable. Nevertheless, this result can be considered to be satisfactory as extrapolation the Pigsar curve to lower Reynolds numbers would results in a similar deviation. This large deviation can be understood since the turbine flowmeter is operated at significantly lower flowrates and Reynolds numbers than tested on natural gas (far below Qmin) and therefore the turbine flowmeter is suspected to be responsible for the large deviation.

In box no.2 test data acquired early 2022 is shown. For these tests the flowrates (and Reynolds numbers) were higher. The Reynolds numbers for the high flowrate field data on hydrogen are matching the Reynolds numbers for low flowrate natural gas (Pigsar) data. Therefore, it is expected that the deviation between the ultrasonic flowmeter and the turbine meter is similar for both tests. However it can be seen that field data (green circles) lay below the test lab data (solid line). This was not expected and required a deeper analysis of the flow measurement obtained with the ultrasonic flowmeter.

6.3 Optimisation of the settings of the ultrasonic flowmeter

As described in §6.2, the initial results from the field required a deeper analysis of the measurement signal of the ultrasonic flowmeter. In figure 15 a snapshot of the measured transducer signal is shown.

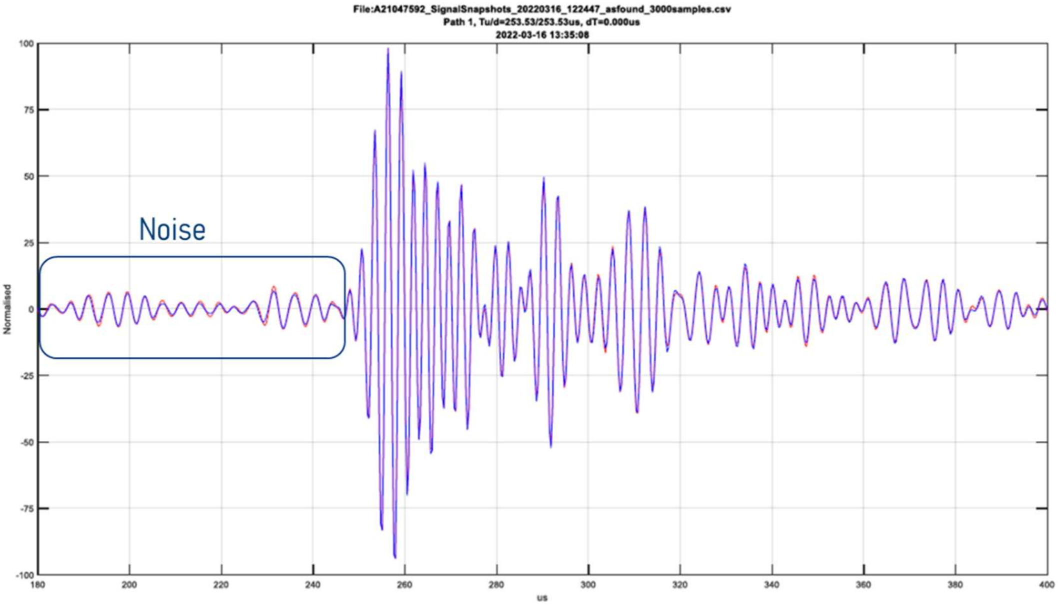

Figure 15: *Snapshot of the ultrasonic transducer signal in hydrogen prior to optimisation. On the vertical axis the amplitude is given in arbitrary units. and on the horizontal axis the time is given in microseconds (us).*

The acoustic signal as plotted in figure 15 shows a considerable noise prior to the arrival of the expected signal. This noise is caused by crosstalk; unwanted signals travelling through the pipe wall reach the opposite transducer faster than the desired signal travelling through the gas. Note that for natural gas applications this noise due to crosstalk is not present (due to a different density and speed of sound). The nature of this crosstalk noise is such, that it can be reduced by adjustment of filter settings and by adjustment of the ultrasonic transducer frequency. After this optimisation the transducer signal has been analysed again (figure 16).

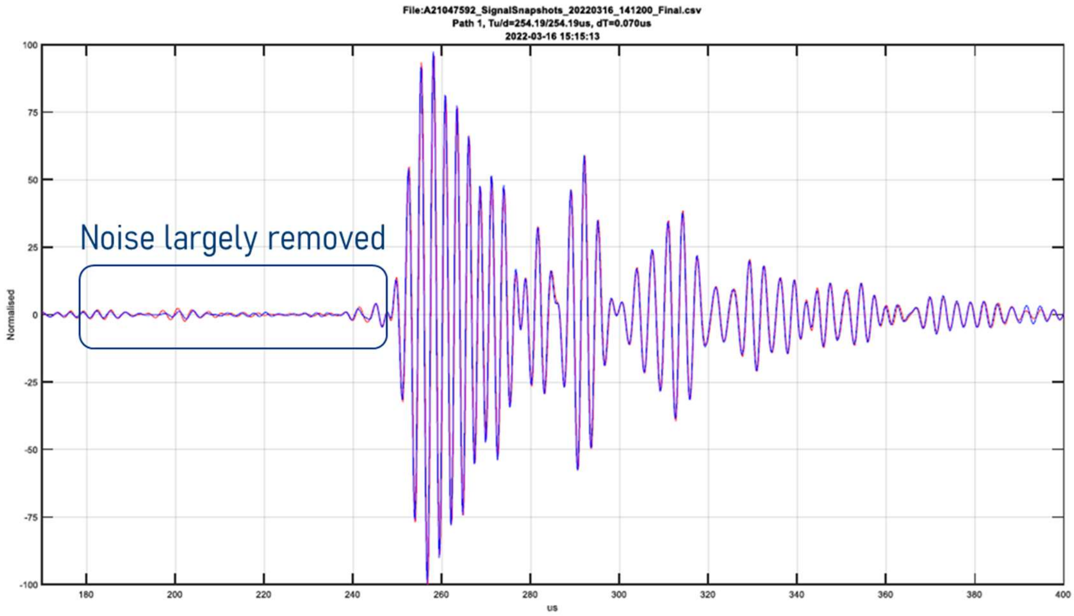

Figure 16: *Snapshot of the ultrasonic transducer signal in hydrogen after optimisation of the settings (filter and frequency) for hydrogen applications.*

As can be seen in figure 16, the optimisation has largely removed the noise from the acoustic signal. The expected result of this optimisation is an improvement in the measured flowrate and a reduction in scatter of the measurement.

6.4 flow measurement results after optimisation

With the optimised setting of the ultrasonic flowmeter the field tests continued in March 2022. The results obtained with the optimised settings are shown in figure 17.

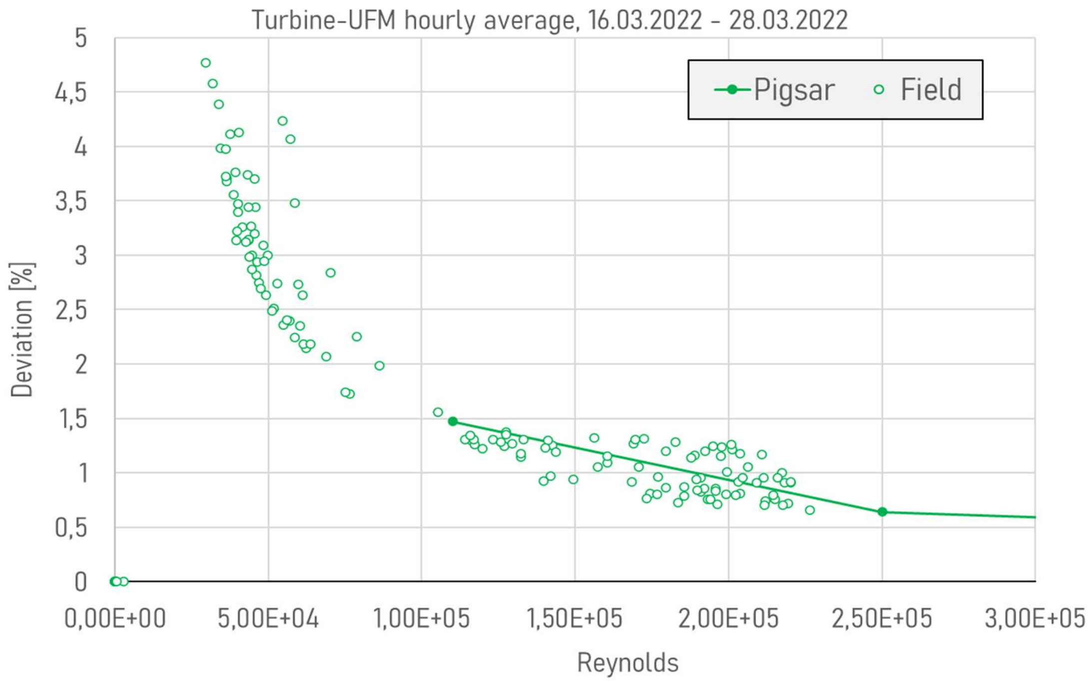

Figure 17: *Results after optimisation of the settings of the ultrasonic flowmeter. The deviation (Eq. 4) between the ultrasonic flowmeter and the turbine meter is plotted as function of the Reynolds number. The circles denote the results on* H_2 *obtained in the field (hourly average) and the solid line denotes the Pigsar lab results obtained on natural gas.*

The results in figure 17 clearly show the positive effect of the optimised filter and frequency settings. For Reynolds number roughly between $1 \cdot 10^5$ and $2 \cdot 10^5$ the deviation on hydrogen between the ultrasonic flowmeter and the turbine flowmeter follow the trend line as measured at Pigsar for natural gas. Also the scatter in the data is largely reduced.
For Reynolds numbers below $1 \cdot 10^5$ the measured deviation is in line with the extrapolated trend measured on natural gas at Pigsar. Together with the calibration results of the ultrasonic flowmeter on natural gas (figure 5), this leads to the conclusion that also for the lower flowrates the performance of the ultrasonic flowmeter on hydrogen is satisfactory.

With the optimised filter and frequency settings the speed of sound has been measured. First assessment shows a slight impact on the measured speed of sound of around 0.5%. The high speed of sound of hydrogen (1330m/s) results in very short transit times compared to natural gas and therefore the measurement is sensitive to small deviations in delay time settings of the flowmeter. This effect is currently under further investigation.

Also the impact of the optimised filter and frequency settings on the calibration of the flowmeter has been assessed. For this purpose a 4" ALTOSONIC V12 ultrasonic flow meter has been calibrated at Force on natural gas. The flowmeter has been calibrated twice; first with the original settings, and in a second run with the optimised hydrogen settings. The results are shown in figure 18. It can be seen that the deviation between the two calibration is less than 0.2%.

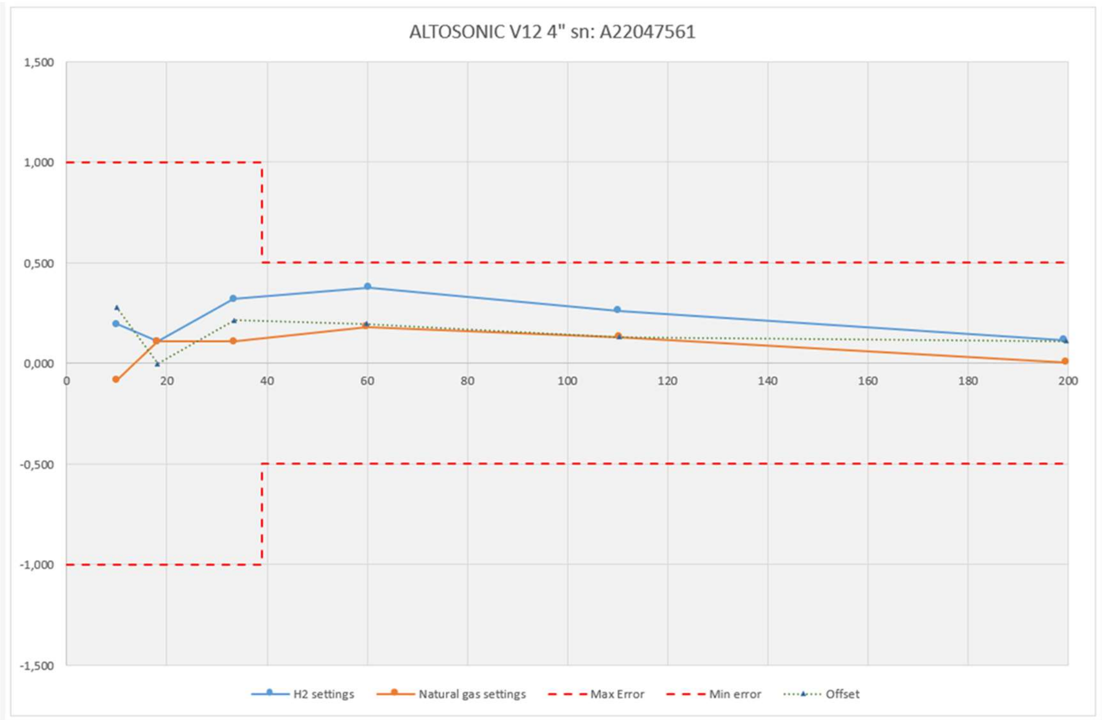

Figure 18: *Results of the calibration of a 4" ALTOSONIC V12 on natural gas at Pigsar. The orange line represents the calibration at standard settings and the blue line represents the results for modified 'hydrogen' settings.*

7 Summary and conclusions

Hydrogen is foreseen to play an important role in the energy transition and custody transfer measurement of hydrogen will be needed. Therefore OGE and Evonik proceeded to do a field test with custody transfer ultrasonic flow meters.

KROHNE has participated in the test with a 10" ALTOSONIC V12 custody transfer ultrasonic gas flowmeter. The flowmeter has been calibrated on natural gas at Pigsar. In the field the flowmeter is measuring hydrogen and compared to a turbine flowmeter.

The speed of sound of gases can be measured with the ultrasonic flowmeter. The speed of sound in hydrogen is very sensitive to small amounts of impurities. Results from the field test on hydrogen show that the speed of sound measurement in a ultrasonic flowmeter may provide a method to monitor the purity of hydrogen.

To improve the quantification of impurity level detection methods and procedures for dry calibration and field operation are being worked out in detail with users, the PTB and manufacturers.

For comparing the performance of flowmeters on natural gas to the performance on hydrogen it is needed to take the Reynolds number into account. For equal flow rates the Reynolds number is approximately a factor 7 lower for hydrogen.

The comparison between the ultrasonic flowmeter and the turbine flowmeter in the field test on hydrogen show a deviation that is similar to what was observed during the verification tests on natural gas at Pigsar (figure 17), which is a satisfactory result.

The analysis of the results of the field test have resulted in optimised settings of the ultrasonic flowmeter (filter and transducer frequency) for hydrogen applications. The lessons learned from the field test will be applied in further development of the ultrasonic flowmeter for hydrogen applications.

8 References

1. OGE is one of Europe's leading gas transmission system operators (https://oge.net/en).

2. Evonik is one of the world's leading specialty chemicals companies. (https://corporate.evonik.com/en)

3. AGA10 or AGA 8 / GERG2008 / ISO 20765 can be used for calculation of speed of sound.