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Technical Paper

Challenges in non-invasive clamp-on flow measurement of hydrogen – experiences from the field and laboratory

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1 Introduction

In the scenarios of the energy transition, hydrogen plays a central role: For the decarbonization of electricity and heat generation as well as other industrial processes, hydrogen is intended to be used as a fuel in the future. In addition, hydrogen produced from renewable energy sources will be injected into existing natural gas networks.

Pilot projects in the field of adapting existing infrastructure and the development of entirely new systems for the transport and storage of pure hydrogen as well as hydrogen mixtures are already underway, and many more are in the planning stages. The main interest initially lies in ensuring pipeline integrity through materials science testing of pipes and fittings. However, the switch to hydrogen also has enormous impacts on the flow measurement technology used.

Currently, ultrasonic clamp-on flow meters (USCO) are often used for operational measurements in the existing high-pressure natural gas infrastructure, such as the transport network or in underground natural gas storage. Since their installation does not require opening the pipeline, they are ideally suited for retrofitting as well as for flow measurement of potentially hazardous media. The following sections will highlight the particularities of flow measurements with hydrogen and what experiences have already been made in the laboratory and in practice.

Hydrogen as a fluid in USCO measurements

Sound velocity and density are two important state properties of hydrogen, which can be directly derived from the molar mass and are exceptionally different compared to, for example, air or natural gas.

Key parameters of various process gases compared at 60 bar and 20°C:

Gas	mol weight [g/mol]	sound speed [m/s]	density [kg/m³]	impedance [kg/(m² s)]	compressibility	HHV [kWh/Nm³]	Ex approval
H_2	2.02	1355	5	6.5E3	1.036	3.54	IIC
Air	28.96	354	72	2.6E4	0.9872	-	-
NG (Ggas)	16.84	419	47	2.0E4	0.8883	11.11	IIA/IIB

The acoustic impedance, defined as ρ*c (where ρ is the density and c is the speed of sound), is critical for the clamp-on measurement principle. Acoustic waves need to propagate from the emitting piezo into the metal pipe wall (with an impedance of approximately 2.5E7 kg/(m²s)), and from there into the process fluid, and then back into the metal pipe wall and to the receiving piezo. Overcoming the insertion impedance between the metal pipe wall and the process fluid is particularly challenging with hydrogen compared to other gases. This leads to a requirement for a minimum fluid pressure that is about three times higher than that for natural gas. An advantage of hydrogen over natural gas is the absence of reachable internal degrees of freedom for rotation and vibration in the molecules, so no additional molecular damping of the ultrasound is observed. Depending on the pipe size and the frequency of the sound transducers, this can also lead to similar requirements for the minimum pressure.

For explosion protection, there is a stricter requirement with gas group IIC than, for example, with natural gas. Similarly, there is an extensive discussion about the specific requirements of hydrogen regarding the pipe material. One objective is to use as large a portion of the existing pipeline transport infrastructure as possible for hydrogen. This discussion is irrelevant for USCO.

The energy content per volume (Higher Heating Value HHV) is about three times smaller for hydrogen than for natural gas. If an equivalent amount of energy as NG is to be transferred, either the pressure could be increased or the flow rate. The discussions about materials, see above, argue against increasing the pressure. An increase in the flow rate is an advantage for clamp-on with hydrogen compared to other process gases. The beam blow-off and thus signal distortion is less critical because the speed of sound is much higher. This significantly higher speed of sound means that for optimal measurement results, the positions of the sound transducers on the pipe wall must be changed for hydrogen measurements.

In summary, there are no special design guidelines for clamp-on measurement technology for hydrogen measurements. Even before the buzzword *Green Hydrogen* became popular, USCO was successfully used to measure the flow of gaseous hydrogen as a process fluid in refineries or chemical plants.

The experiences gathered over an extended period are now being examined more systematically through experiments in the laboratory and in the field, which will be reported on in the following chapters.

Calibration of USCO, transferability and special considerations

Some current pilot and research projects on the topic of hydrogen flow measurement are addressing the question: How well can a calibration be transferred to the process fluid hydrogen? This is a very important issue, especially for billing-capable measurement systems. Common and widespread calibration fluids include air, nitrogen, methane, natural gas, and of course water and various liquid hydrocarbons.

The FLUXUS USCO measurement system is not calibrated with a process fluid; rather, the calibration of the transmitter and ultrasonic transducers is performed separately and independently from each other in a patented process. For this purpose, the signal transit time measurement of the transmitter is calibrated with synthetic signals.

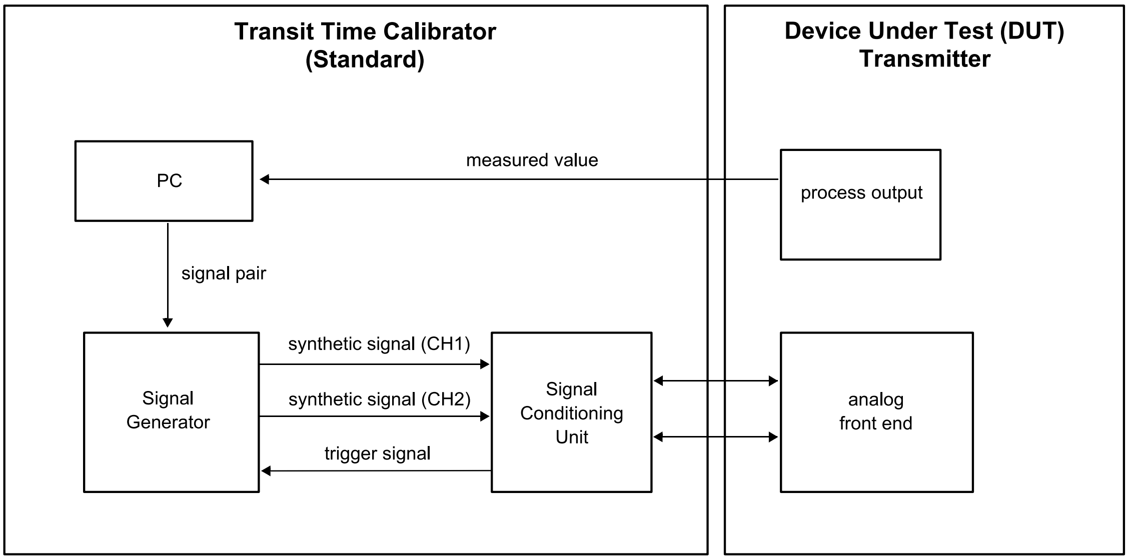


Figure 1 Calibration of transmitter with synthetic signals

The measuring effect in a flow measurement using the transit-time difference method is created by the different path lengths in the upstream wedge of the forward and return signals. For the factory calibration of the ultrasonic transducers used, a method is employed that also does without the use of real flowing fluids.

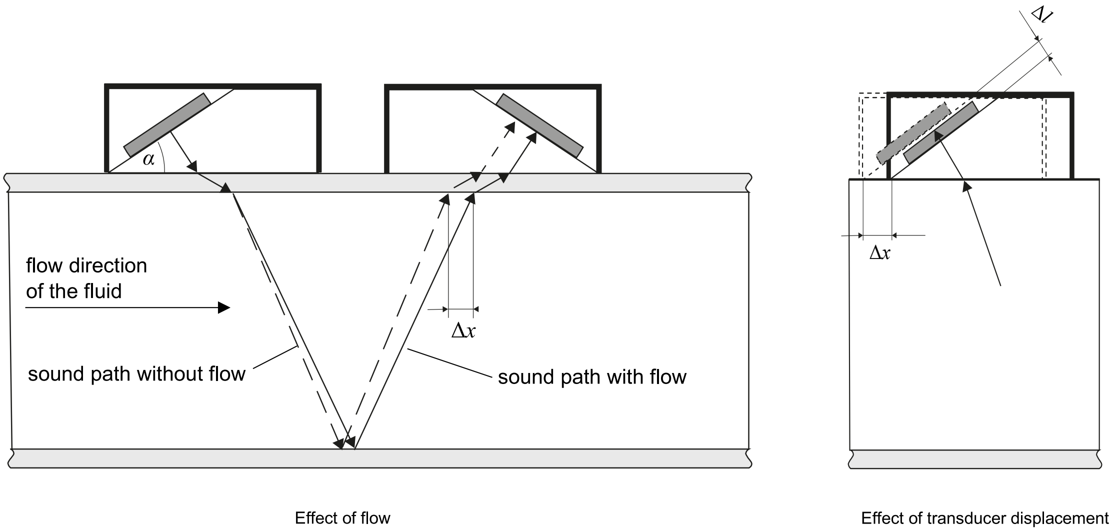


Figure 2 Calibration of the transducer

In a calibration facility, the beam displacement (transit-time difference) caused by a flow is simulated by precisely moving the ultrasonic transducers. Each pair of ultrasonic transducers is individually calibrated, and the result of the calibration can be transferred to any flow transmitter.

Moreover, the calibrations of the ultrasonic transducers and the flow transmitter can be applied to all process fluids that are measurable with the transit-time difference method. For this purpose, an optimal setup is recommended for each USCO measurement point. The selection of ultrasonic transducers and their positions on the measuring pipe is undertaken by user software and the flow transmitter itself. With the help of the operating software FluxDiag [1], a resulting measurement uncertainty for the flow according to ISO 24062 [2] can be calculated for each USCO measurement point.

2 Demonstration of a Hydrogen Measurement in a Flow Laboratory

How well this calibration can be transferred to hydrogen measurements was demonstrated about 2 years ago in a laboratory experiment at DNV. On a relatively small loop, measurements were taken with USCO against a turbine meter (TRZ, type SM-RI-X by Elster Instromet). The measurement uncertainty of the TRZ was about 0.2 to 0.3%.
Measurements were taken with 500 kHz ultrasonic transducers for gases in 4 sound paths on a 4" schedule 40 steel pipe. The flow velocities ranged from approximately 2 to 12 m/s with fluid pressures between 5 and 40 bar. Besides pure hydrogen (99.97%, class D), intentionally contaminated hydrogen (approximately 98%, class A) was also used. Additionally, calibrations with natural gas (G-gas, Groningen) and with nitrogen were performed. The following table shows the results in detail.

Series	Gas type	Pressure [bar]	Average error [%]	Average repeatab. [%]	# data points	FLUXUS c_{meas} [m/s]	diagn. Gain [dB]	value SCNR [dB]	remarks
1	pure H_2	30	0.18	0.06	8	1324	83	32	
2	pure H_2	20	0.21	0.06	5	1316	87	28	
3	pure H_2	10	0.45	0.05	5	1308	95	21	
4	pure N_2	6	-0.45	0.09	7	352	93	27	Re equivalent to series 6
5	pure N_2	4.5	-0.27	0.11	7	352	94	23	Re equivalent to series 1
6	pure H_2	40	0.02	0.05	8	1333	81	36	
7	pure H_2	30	0.16	0.04	4	1326	84	32	reproducibility of series 1
8	H_2|N_2|NG 98%|1%|1%	27	-0.01	0.06	8	1223	84	37	with setup for pure H_2
9	H_2|N_2|NG 98%|1%|1%	27	0.28	0.07	4	1217	88	35	with setup for 98% H_2
10	natural gas Ggas	6	-0.77	0.11	4	412	95	24	Re equivalent to series 6 low pressure limit for for natural gas out of spec
	pure H_2	6.5				1305	101	15	no calibration run, but max. flow velocity tested

Figure 8: Results of the flow comparison in pure hydrogen

To compare calibration measurement points that are equivalent in terms of Reynolds number with the typical calibration gases N_2 and natural gas, the pressure was reduced to between 4.5 and 6 bar. This is still within the extended specification limits of the USCO measurement in this configuration. To test the lower operating limit for fluid pressure in hydrogen applications, the pressure was reduced to 6.5 bar at maximum flow. The last complete calibration measurement with hydrogen was conducted at 10 bar. The diagnostic value of the SCNR, which is significant for measurement with FLUXUS, exceeds the value of 30 dB with hydrogen at a pressure of about 30 bar. This corresponds to the specified reference conditions for a good measurement within the specification. Furthermore, this confirms the hypothesis from the previous section, which suggests that the USCO measurement of hydrogen requires approximately three times the minimum pressure compared to other gases.

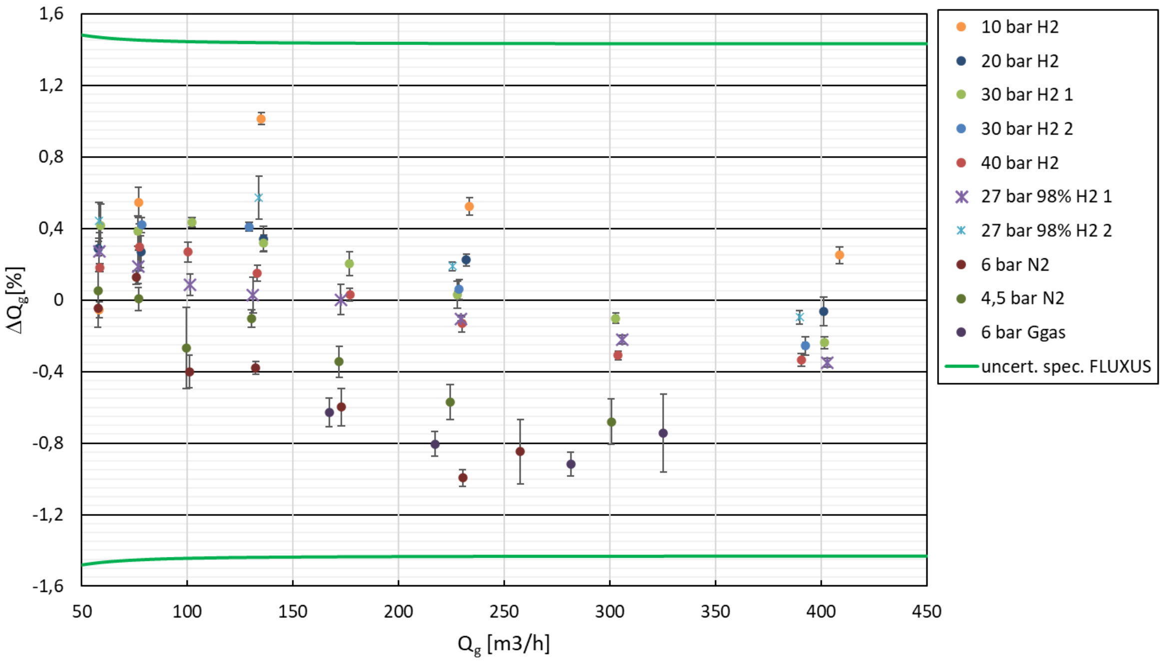


Figure 9 Deviation of the USCO vs reference in volume flow; green marking for expected uncertainty of the USCO

All measurement points are within the expected uncertainty.

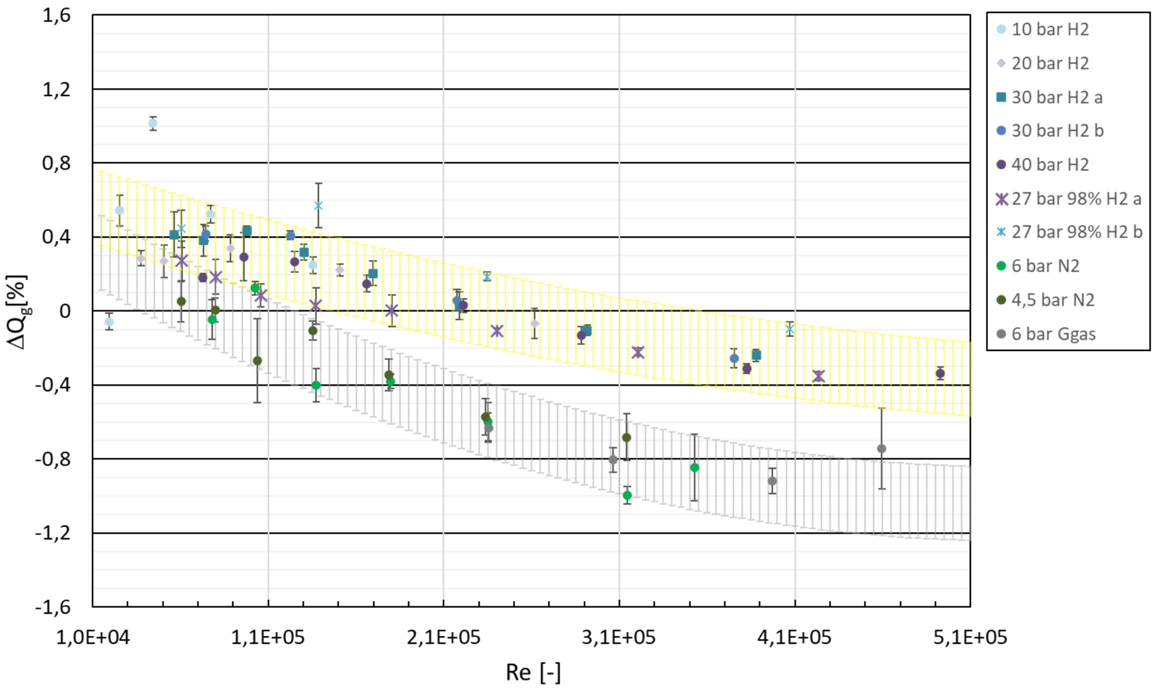


Figure 10 Deviation USCO against reference over Reynolds number.

In Figure 10, a characteristic trend of slight overreading transitioning to underreading at higher Reynolds numbers is plotted against the Reynolds number. This behaviour in comparison to the TRZ occurs with all types of gases and is somewhat more pronounced with nitrogen and natural gas than with hydrogen. The uncertainty of the TRZ is visually represented by a yellow or grey tube around the measurement points of the two gas types, "hydrogens" and "non-hydrogens."

For a clamp-on installation, the position of the ultrasonic transducers is determined by the pipe geometry and the fluid's sound velocity. Since the sound velocity for 98% pure H_2 differs by about 100 m/s from 100% pure H_2, different setups were tested for these calibration measurements; once with the ideal positioning of the ultrasonic transducers and once with a transducer position that is ideal for 100% H_2 but is slightly mispositioned for 98% H_2. In the results, both installations perform equally well, so good measurement results can also be achieved with an expected 100% H_2 quality even when only 98% H_2 is flowing in the pipe.

During the test runs, the observation of sound velocity was very useful in tracking how the admixture of other gases affects the sound velocity. Much faster than with the connected gas chromatograph, the purity of the hydrogen could be checked within seconds.

Summary of the USCO- Measurements at DNV

The laboratory measurements confirmed the expected measurement uncertainty of the USCO flow measurement with hydrogen as well as with other calibration gases. All measurements have been carried out with the same measurement system.

3 Field testing of a hydrogen measurement on a DN250 pipe

Flow measurement with USCO is particularly advantageous for large pipelines. There are not many large pipes filled with hydrogen yet but plans such as the hydrogen backbone network suggest significant developments in the future.
In Germany, Evonik has been operating a hydrogen pipeline with a nominal diameter (DN) of 250 mm for a long time. The pressure is about 18 bar. The operator uses a turbine meter (TRZ) to measure the flow rate. At the last Kötter workshop, the use of an inline ultrasonic flow meter (Inline-USM) at this measuring point was introduced and demonstrated, illustrating how ultrasonic flow measurement technology can be used in hydrogen applications [3]. Recently, we have set up our USCO measuring technology in the upstream section between the flow conditioner and the Inline-USM.

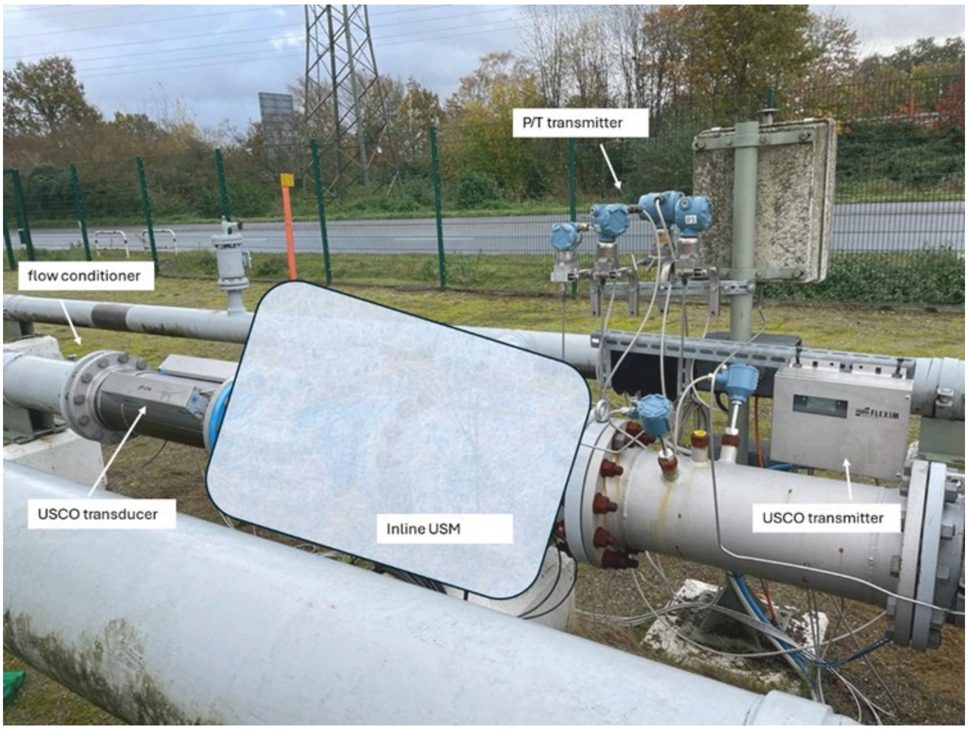


Figure 11 Measurement on a DN250 Hydrogen pipeline

The measurement described is in front of the chemical park in Marl, Germany. The USCO installation was a two-channel setup, using two acoustic paths with 500 kHz gas transducers. Additionally, at the measurement site, the fluid pressure and fluid temperature are recorded and fed into the transmitter. For this reason, the clamp-on measurement section was installed behind the flow conditioner in the upstream section, length 5D, of the inline ultrasonic flow meter (Inline-USM).

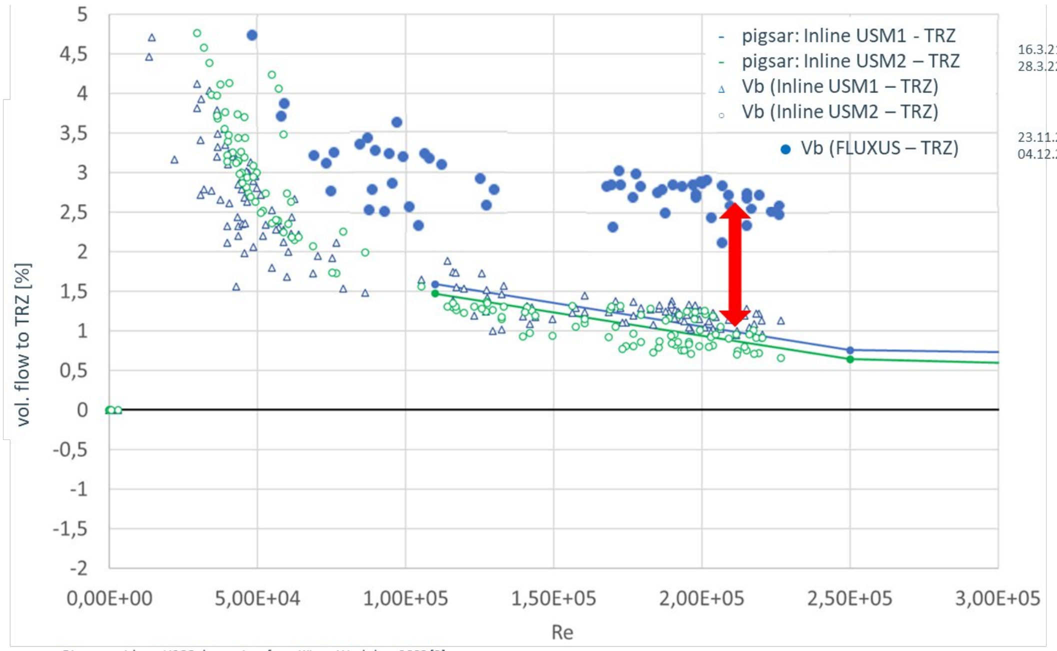


Figure 12 Clamp-on and Inline ultrasonic flow measurement over Reynolds number, 2D after flow conditioner.

Compared to the inline ultrasonic flow meter (Inline-USM), the USCO measurement shows an overreading of about 1.5% for the flow rate. The calculated measurement uncertainty of the USCO measuring point is approximately 1.47%. One possible cause for the overreading is the position of the USCO measurement point. The ultrasonic transducers were installed on the 5D upstream section between the flow conditioner and the first Inline-USM. The centre of the USCO measurement path is located about 2D behind the orifice plate flow conditioner.

However, a focus of this test trial was also on the measurement of sound velocity. At the Kötter Workshop 2022, it was reported and demonstrated in contribution [3] that sound velocity measurement can be usefully employed to monitor the purity of hydrogen directly in the pipeline. The USCO field testing is now intended to demonstrate that even a clamp-on sound velocity measurement is sufficiently precise to fulfil this task.

For regular flow measurements, sound velocity is primarily an important diagnostic parameter that, for example, indicates whether the clamp-on measurement point has been correctly parameterized. During the USCO-H_2 test measurement at Evonik, fluid pressure and fluid temperature were also fed into the transmitter and stored in the device memory. Along with the measured sound velocity, this information can be compared against a theoretical sound velocity of 100% pure or contaminated hydrogen with other gases, by calculating the theoretical sound velocity using NIST/REFPROP [4] equations of state according to GERG or AGA standards.

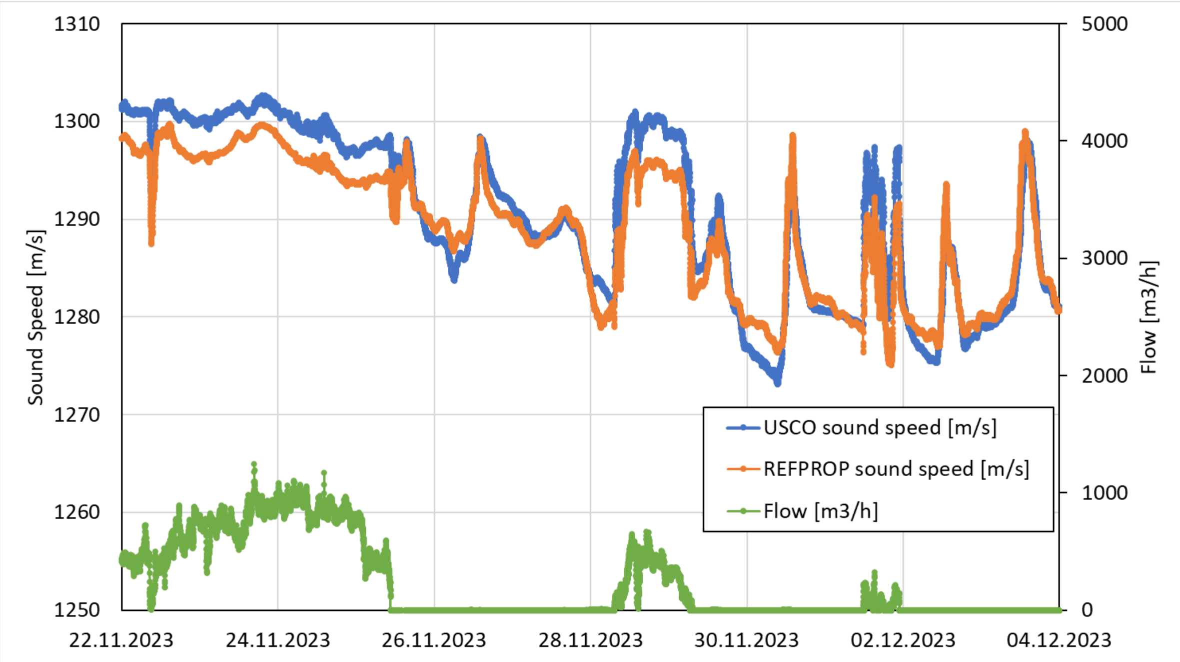


Figure 13 Comparison of measured and theoretical speed of sound (REFPROP); volume flow in green

A parallel trend can be observed between the theoretical and the measured sound velocity. This also indicates that the setup and parameterization of the clamp-on installation (position of the ultrasonic transducers, pipe geometry) were correctly applied. The fluctuations in the sound velocity are caused by variations in pressure and temperature and by changes in the quality of hydrogen.

In the depicted examples, another effect can be seen: Without flow (green curve), the difference between the measured and theoretical sound velocity is slightly different than when hydrogen is flowing through the pipe. This is mainly a temperature effect, as the temperature measurement point is located differently from the acoustic measurement path. When there is no flow, locally different temperatures can develop locally. When there is flow, these temperatures balance each other out.

The USCO measurement system FLUXUS can automatically perform a pressure and temperature correction with the integrated Dynamic Gas Meter (DGM) and output the molar mass. From the molar mass, the purity of the hydrogen can ultimately be determined if it is known which gas will contaminate the hydrogen. Assuming in this field test that it would be nitrogen, then the molar mass can also be converted into a purity in %H_2.

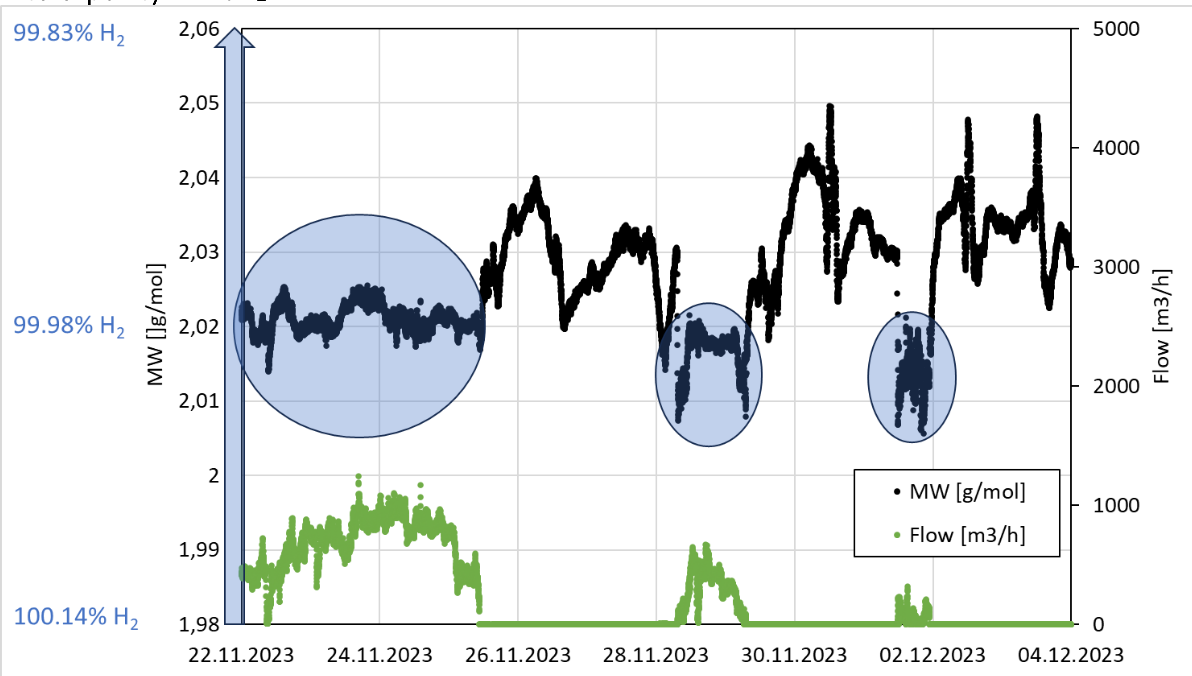


Figure 14 Calculation of molar mass from USCO; transferred to vol% of Hydrogen

The illustration shows the measured molar mass using the DGM, after an offset of +0.02 g/mol is applied to the original measurement. During the blue-marked periods, the pipe was in flow, so the local temperature measurement was well synchronized with the acoustic speed of sound measurement. Only very slight deviations in the hydrogen quality of a few hundred ppm (parts per million) are observable.

Summary Field Trial at Evonik in Marl

At Evonik, it was demonstrated on a DN250 pipeline with a pressure of 18 bar that a USCO flow meter could operate with comparable performance to US-Inline or TRZ, even with hydrogen as the process fluid. For this, no special "hydrogen version" of a USCO system is necessary. The measurements were carried out with a standard series device that is also used for conventional gases like natural gas or air.

Furthermore, the field trial showed the potential of a USCO measurement for monitoring H_2 purity. After field adjustment of an offset, USCO measurements can monitor H_2 purities in the 100 ppm range.

4 Joint testing with Emerson at RMA Hydrogen loop on DN400 pipe

The Emerson Coriolis Team requested Flexim to support their testing at the RMA Hydrogen loop in Rheinau as secondary sound speed measurement to validate the concentration and density measurement of the loop during the calibration of 3 different Coriolis meters as impurities from the nitrogen purge process might appear.

Each Coriolis meter has been tested at 25 bar and 50 bar, so in total 6 runs has been measurement.

Traceability to primary standards is currently implemented as follows: There is an PTB nozzle skid and there is an orifice plate measurement and a TRZ measurement. This provides the reference in the volume flow. Equations of state and the concentration of the hydrogen are used for conversion into a mass flow at the measuring point of the MUT.

Originally a λ-sensor (thermal conductivity) is installed inline with the reference system to monitor the hydrogen concentration. A flow comparison of the TRZ and orifice plate showed that the hydrogen concentration was not consistent with the λ-sensor. The λ-sensor was a commercial FTC 300 with factory calibration.

Under the guidance and with the support of PTB, the operator improved the concentration and density measurement with an inline system based on the speed of sound. This measurement is installed in the upstream section of a PTB nozzle skid, but in parallel to the position of the measuring device to be tested.

Test setup at RMA loop and sound speed uncertainty

The USCO meter was installed in series in the MUT line upstream of the Coriolis to be tested in order to validate the stability of the hydrogen concentration during the calibration of 3 different Coriolis systems. While the Coriolis meters are replaced during the tests, the Flexim meter remains installed on an identical DN400 spool supplied by RMA.

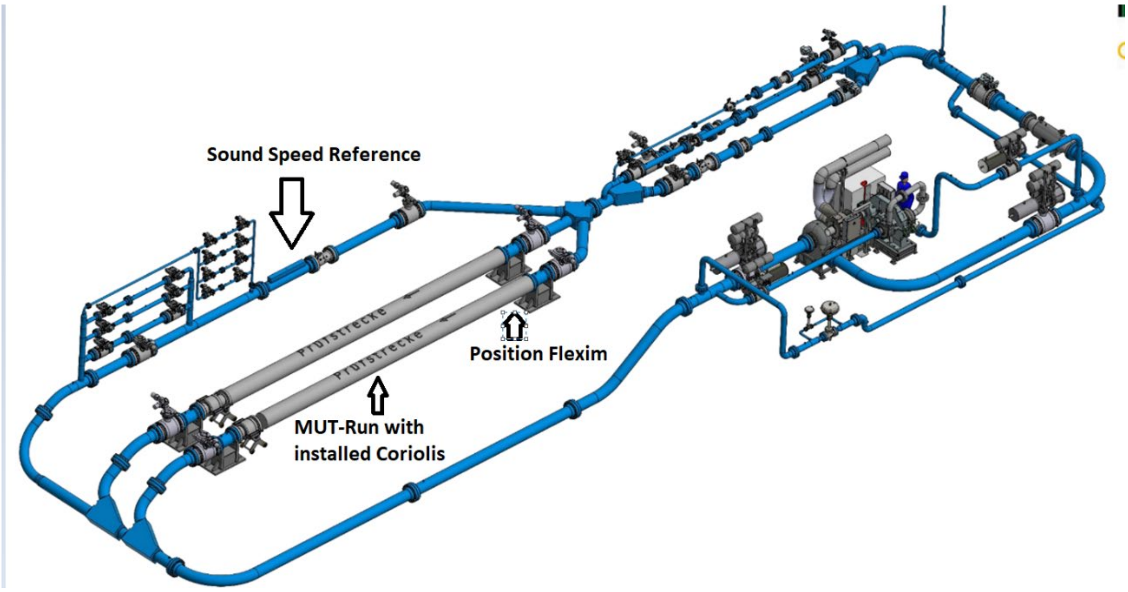


Figure 15 RMA flow loop with position of MUT (Coriolis), Flexim and sound speed reference (parallel run) [commented graphic from RMA]

As the Coriolis meters are replaced during the test of the different meters, but the USCO should remained unchanged, a position with limited straight run had to be chosen. The USCO meter has been installed directly upstream of a turbine meter with a flow conditioner, 2D after a pipe extension from DN300 to DN400, 4D after a shut off valve and 6D after the 45° bend (beam splitter).

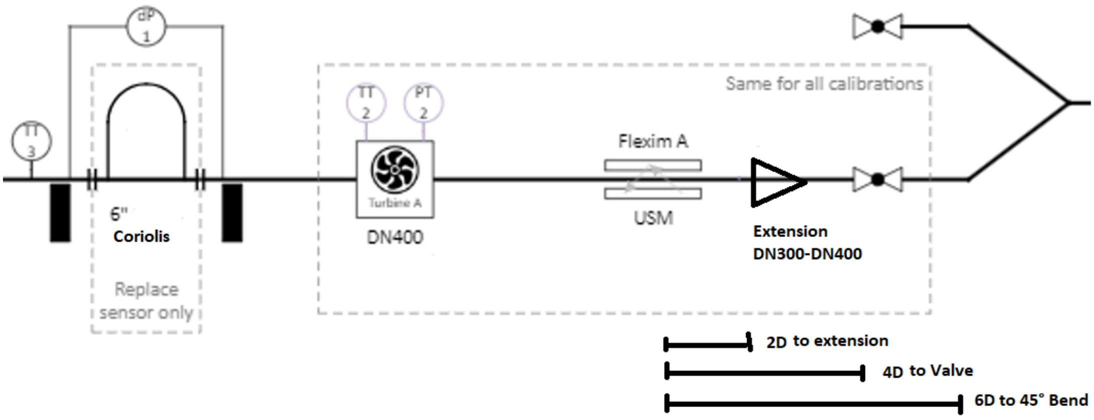


Figure 16 Position of the USCO in the Meter-Under-Test run

[commented graphic from RMA]

When installing the USCO, particular care was taken to ensure that the measurement uncertainty of the sound velocity measurement is low. This includes 3 measurements of the outside diameter with a circumferential measuring scale with nonius, 24 measurements of the wall thickness at the measuring positions and the distance measurement between the transducers with a caliper. With these measurements and a calibration of time measurement of the transmitter and acoustic calibration factor of the transducer in Flexim calibration loop, an overall uncertainty of sound speed measurement better than 4,3 m/s could be achieved for a two channel reflex set up with 300 kHz transducers on the DN400 pipe. No further correction has been applied on the sound speed measurement for DGM calculations.

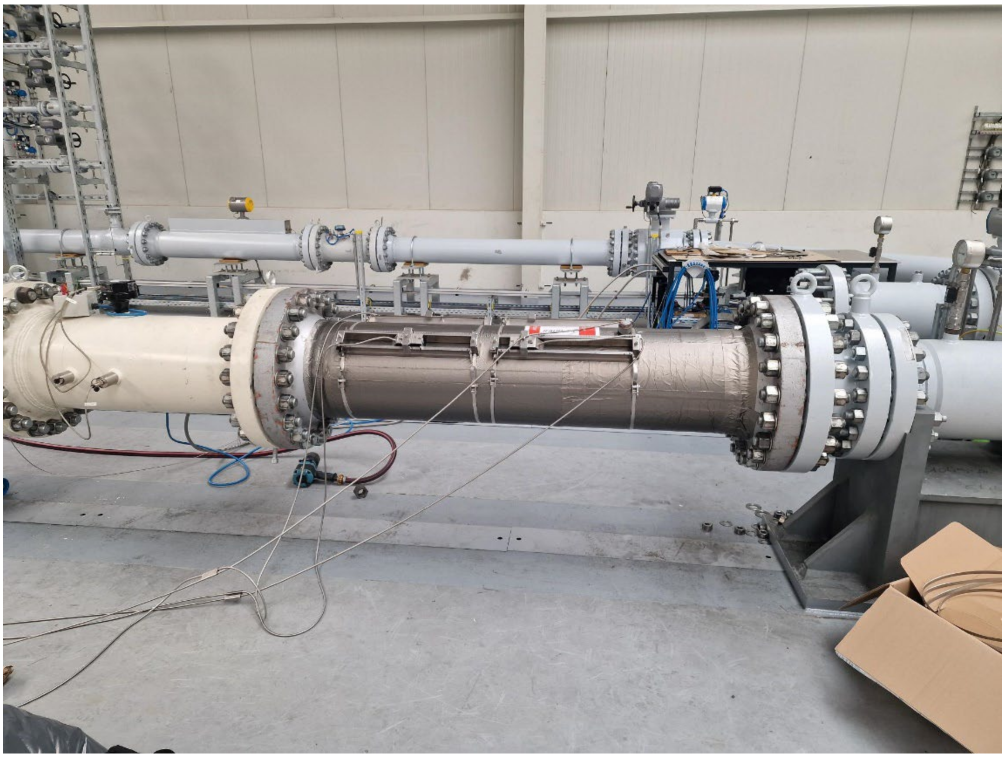


Figure 17 Flexim meter installed in the loop; in the background the sound speed reference meter

Results of the Molecular Weight and concentration measurement

The USCO uses its Dynamic Gas Meter function to calculate the molecular weight and density of the hydrogen stream from measured sound speed and temperature and pressure. A volume fraction of the hydrogen concentration can then be easily determined from the measured molecular weight and the molecular weight of the purge gas.

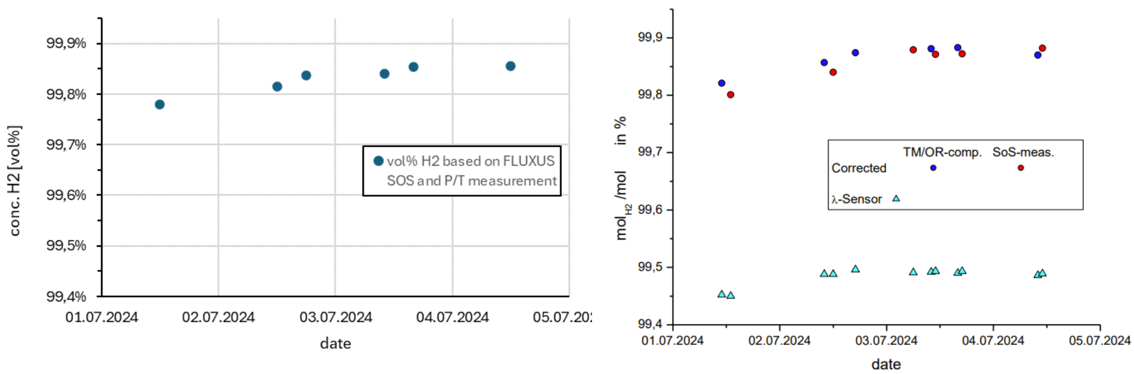


Figure 18 Concentration of hydrogen calculate by USCO (left) vs PTB evaluation with sound speed measurement and TM/OR model (right -

[source PTB - evalution of RMA Testing]**). The λ-sensor is also shown as a blue marker.**

Overall, a slight significant increase in the hydrogen concentration is observed during the multi-day calibrations. The purge gas still had a concentration of approx. 2000 ppm at the beginning and approx. 1500 ppm at the end.
In contrast to the previous λ-sensor measurement, the concentrations of the USCO and the inline sound measurement agree well, just as the comparative measurement from the orifice plate and TRZ is consistent with this.

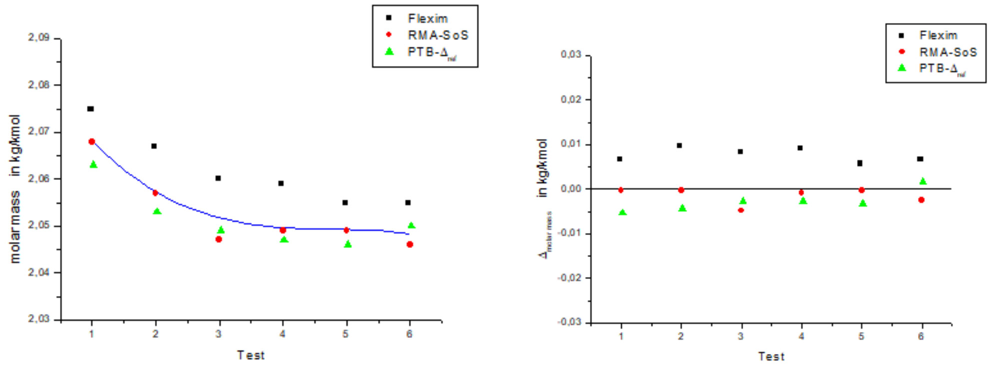


Figure 19 Concentration of Hydrogen calculate by USCO (left) vs PTB evaluation with sound speed measurement and TM/OR model (right). [source PTB – evalution of RMA Testing]

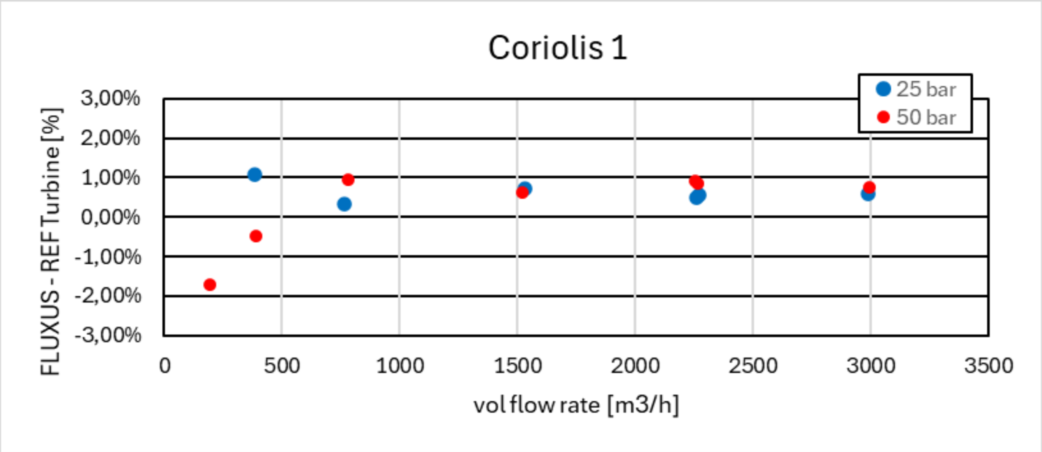
A stable deviation of less than 0,01 kg/kmol vs the sound speed reference could be observed. Recalculated in density this means a deviation of less than 0,5%.

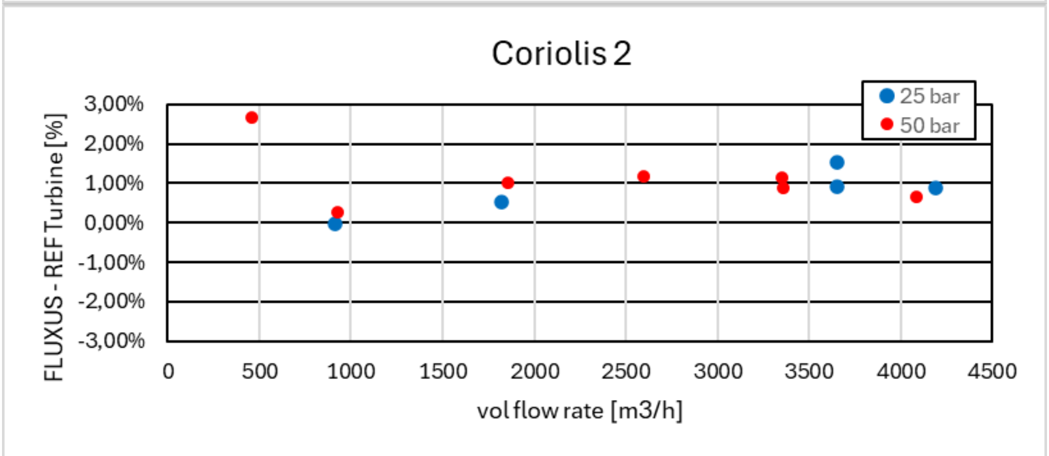
Flow results for USCO meter in volume flow vs. TRZ and in mass flow vs. Coriolis

During commissioning, the flow-mechanically unfavourable installation situation of the USCO was parameterized with a disturbance correction. For this purpose, the volume flow was adjusted against the TRZ at approx. 500 m3/h at 10 bar.

The calibrations with the Coriolis meters were carried out with volume flows between 200 and 5000 m3/h at 25 and 50 bar. The average deviations in the volume flow were plotted against the reference.

Operational volume flow vs Turbine Meter





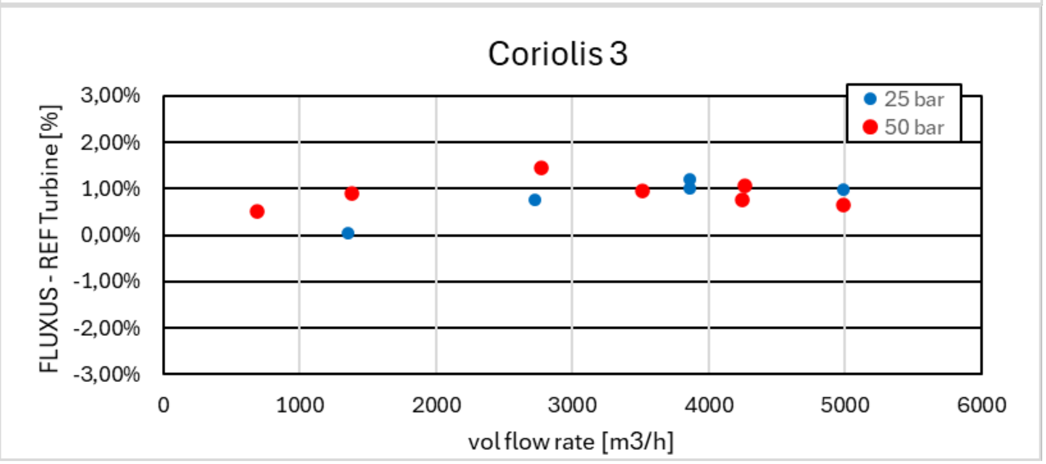


Figure 20 USCO volume flow measurement vs. reference turbine meter (naming related to Coriolis-Under-Test)

The flow-weighted mean average deviation (FWME) for volume flow is about 1% with an actual overreading of the USCO against the turbine meter.

	FWME
	[%]
Coriolis 1	0,65%
Coriolis 2	0,95%
Coriolis 3	0,92%

With the DGM-calculated molar mass und density, the USCO can output both the mass and the volume flow at the measuring point. This allows a direct mass flow comparison to the Coriolis meters without additional analytic equipment.

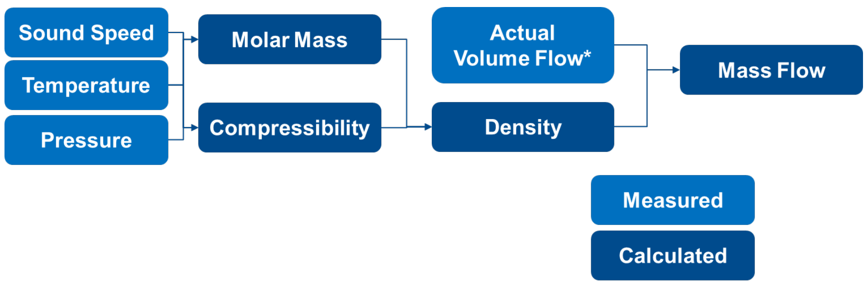


Figure 21 Calculation of mass flow directly in the USCO transmitter

Mass flow vs Coriolis meter

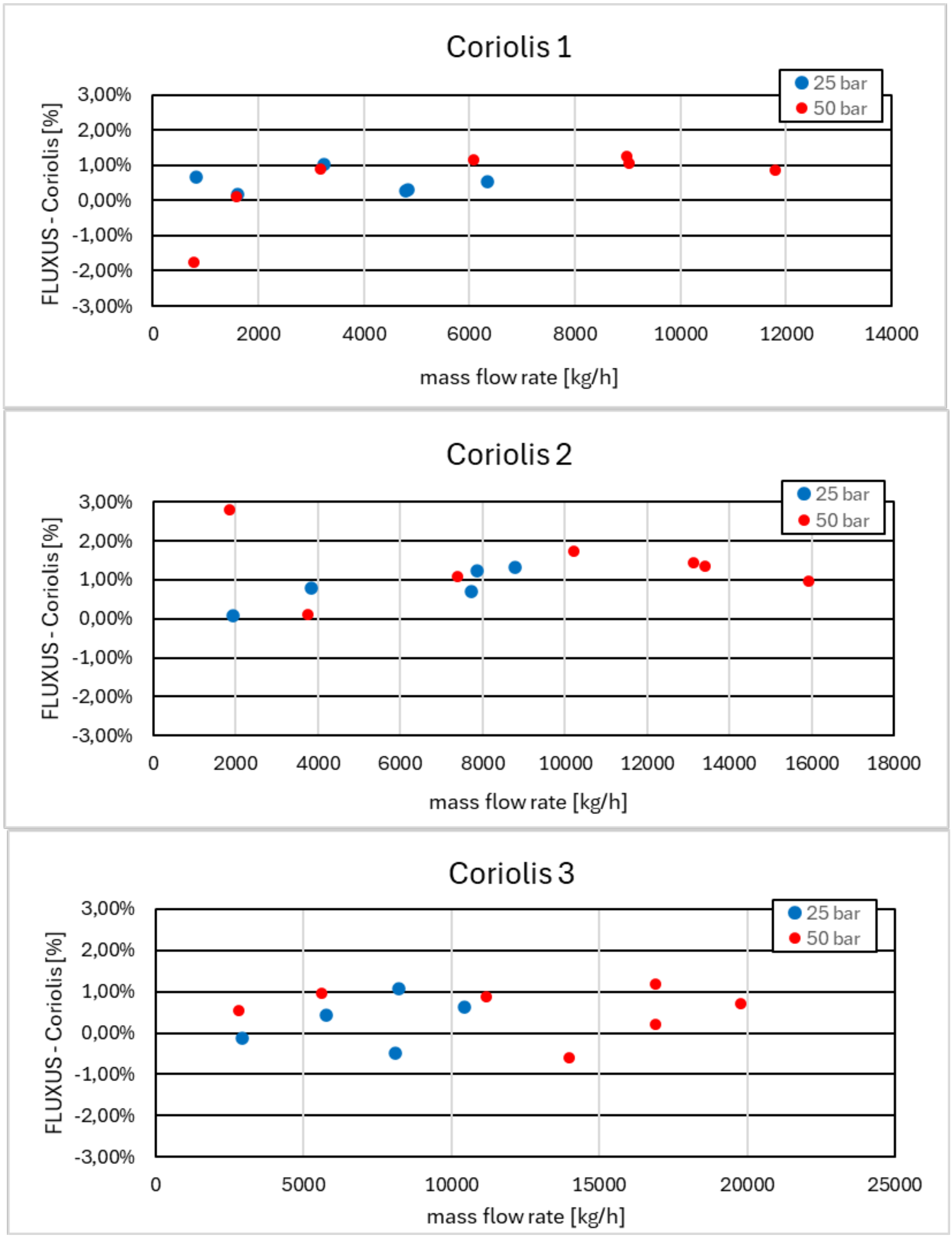


Figure 22 USCO mass flow measurement vs. Coriolis meters under test

The flow-weighted mean average deviation (FWME) for mass flow is about 1% with an actual overreading of the USCO against the Coriolis meter.

	FWME
	[%]
Coriolis 1	0,79%
Coriolis 2	1,18%
Coriolis 3	0,48%

Overall, there were no good statistics for the USCO flow measurements. This measurement was not recorded directly in the control room and only unaveraged measurements were available at 10s intervals from the internal data memory.
The pressure and temperature measurements from the turbine meter downstream the Flexim Meter has been used for calculations.

The comparison with the three Coriolis measuring devices shows no significant difference depending on the flow velocity respectively Reynolds number. There are only larger deviations at the lowest flow rate.

5 Summary

Hydrogen presents some unique challenges for the use of ultrasonic clamp-on flow measurement technology. Particularly due to its low density at comparable process pressures, hydrogen significantly differs from other gases used in the energy industry.

Experiences from field applications and in testing laboratories demonstrate that with USCO (Ultrasound Clamp-On), flow measurements with hydrogen can be carried out under various pressure conditions and across different nominal pipe diameters.

The factory calibrations of the USCO measurement system FLUXUS, including the calibration of ultrasonic transducers and the signal converter, can be transferred to hydrogen as the process fluid. Special hydrogen versions of the ultrasonic transducers are not necessary for this purpose. All measurements have been carried out with the conventional gas versions of the clamp-on ultrasonic transducers.

Due to the high speed of sound in hydrogen, USCO measurement technology is also suitable for monitoring the purity of H_2.

The DGM function in the USCO meter also provides a powerful function that converts volume flow into mass flow and also into standard volume flow in real time with high precision, even if the composition of the process gas changes.

8 Acknowledgments

The authors would like to thank the teams at DNV in Groningen, RMA in Rheinau, Emerson in Ede and the Evonik Team in Marl for their cooperation during the performed tests and their support during the evaluation.
We also thank Dr. Bodo Mickan, PTB Germany, for his support and cooperation for comparison calculation of purity and density during the RMA testing.

9 References

[1] FluxDiag, Version 2.22, 2023, FLEXIM GmbH
[2] ISO 24062, Measurement of fluid flow in closed conduits — Clamp-on ultrasonic transit-time meters for liquids and gases, 12/2023
[3] I. Krajcin, S. Chudoba, Untersuchungen von Ultraschall- und Turbinenradgaszählern mit reinem Wasserstoff, 11. Kötter Workshop Gasmengenmessung 2022, p. 143
[4] E.W. Lemmon, REFPROP Release 10, 2018