Laboratory and field experience, challenges and solutions in measuring hydrogen and CO_2 with ultrasonic (CT) gas flow meters

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1 INTRODUCTION

From the developments that take place as part of the energy transition, a variety of solutions emerge to produce, transfer and store both hydrogen and CO_2. Each solution has specific requirements for a suitable flow measurement technology.
For CT measurement of hydrogen accuracy class 1 is required acc. to MID MI002. For measurement of CO_2 an accuracy of 2,5% is required from the EER (European Emissions Regulation).
Ultrasonic flowmeters have a large flow range, are independent of fluid properties and lack pressure drop. They are recognized for their potential to fulfil the requirements for flow measurement of hydrogen and CO_2.
This drives the continuous further development and testing of ultrasonic flow measurement technology.
This paper will detail the experiences and insights gained from laboratory and field tests using ultrasonic flowmeters measuring hydrogen and CO_2.

2 Ultrasonic flowmeters, ready to measure hydrogen!

Through a number of laboratory tests, calibrations and field tests the potential of ultrasonic flowmeters to measure hydrogen has been proven. The ALTOSONIC V12 performed well during the DNV Renewable gases JIP in 2021 [ref. 1], where no significant effect on the measurement performance was observed for mixtures of up to 30% of hydrogen and 20% of CO_2 in natural gas. In 2022 a field test on pure hydrogen was started in cooperation with Evonik and OGE in Marl industry park in Germany [ref.2], [ref.3]. This demonstrated the principal suitability of ultrasonic transit time technology to measure hydrogen. Specifically the low flow performance in comparison to the installed turbine meter stood out as well as the potential of using speed of sound (SOS) measurement to verify hydrogen purity. The next step was to improve and prove the accuracy of the flowmeter.

2.1 Calibration with hydrogen

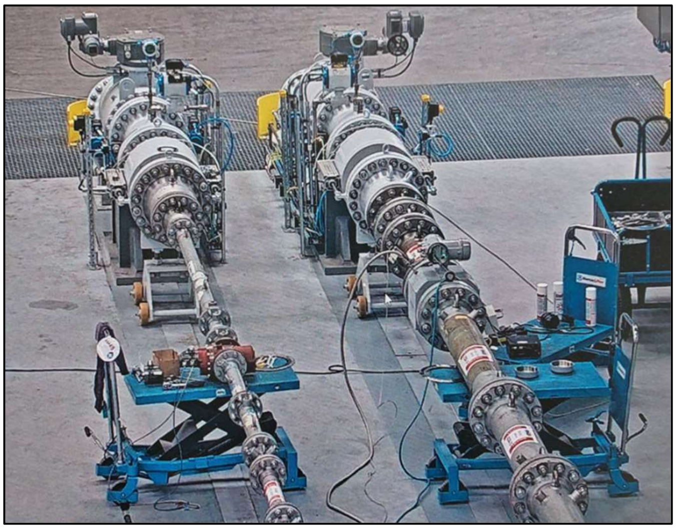

Fig. 1: Hydrogen calibration of an 8"/DN200 flowmeter.

In the past 2 years, calibrations have been conducted with hydrogen gas at the RMA hydrogen calibration facility [Ref. 5].
The status of RMA as a "nationally arranged calibration centre" for Germany allows for initial verification of flowmeters for hydrogen for custody transfer applications with Class 1 accuracy, as regulated by PTB-TRG 19 and DVGW-Information GAS Nr. 32.
The first calibration was done on May 15, 2024 with an 8"/DN200 ALTOSONIC V12.
The flowmeter was required to be calibrated at a min. flowrate of 40 m^3/h and a maximum flowrate of 4000 m^3/h. A min flowrate of 20 m^3/h was added to test the performance at Qmin as certified for natural gas.
After the hydrogen calibration the flowmeter was also to be verified on natural gas at Pigsar [Ref. 6]. This was done to investigate if natural gas can be used as a calibration gas for hydrogen service.

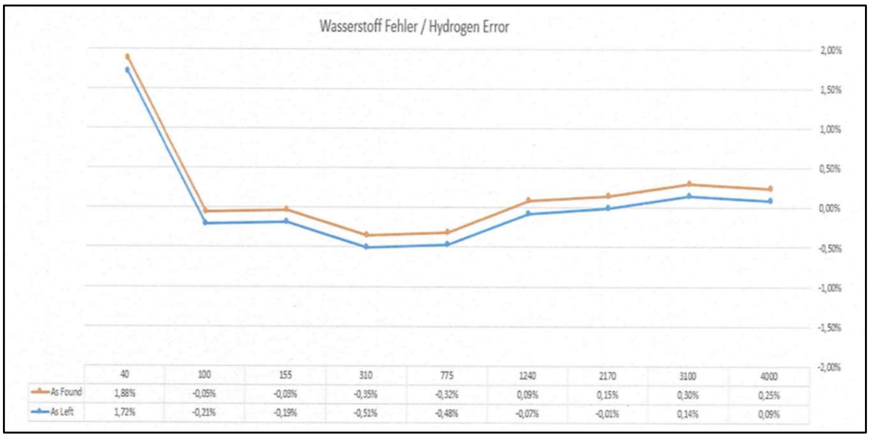

Fig. 2: Uncorrected and corrected calibration result of an 8"/DN200 ALTOSONIC V12 on hydrogen at RMA, deviation as a function of flowrate [m³/h] (copy from calibration certificate).

The hydrogen calibration result was corrected with a single k-factor to achieve a FWME of 0%. No linearisation was performed to enable a good comparison with the natural gas verification performed later. In Figure 2 the calibration results are plotted.
As expected the largest deviation was found at a low flowrate of 40m³/h (+1,72%). However this is still within the MPE. At 20 m³/h the deviation (+2,9%) was outside MPE and therefore this flow point was disregarded.

After the hydrogen calibration the flowmeter was calibrated at Pigsar on natural gas on a Reynolds range similar to that of the hydrogen calibration. In the chart showing the deviation as function of flowrate [Fig. 3], the deviation at Qmin is smaller at natural gas than at hydrogen. This is due to the lower SOS of natural gas compared to that of hydrogen, providing a longer transit time for natural gas than for hydrogen. The deviation shown at the natural gas calibration at the highest flowrates is caused by beam blow due to lower SOS as the flowmeter was tested beyond its Qmax as certified for natural gas (3100 m³/h for 8"/DN200).

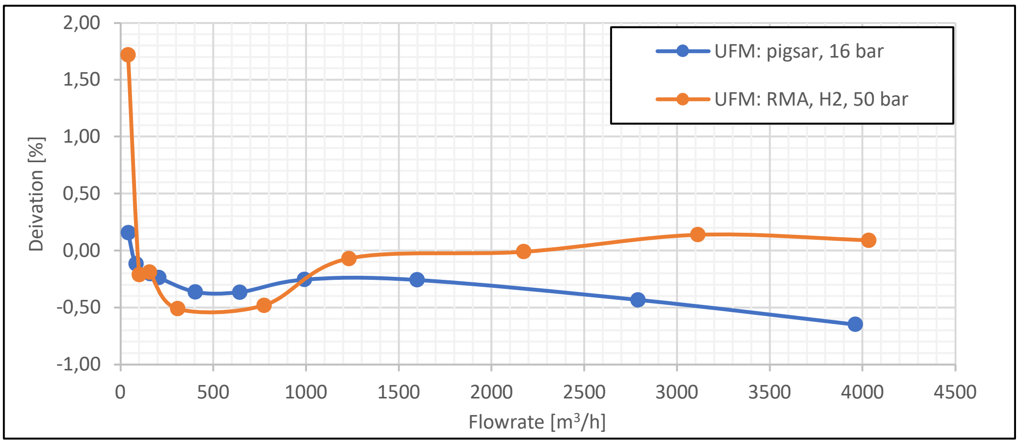

Fig. 3: Hydrogen and natural gas calibration result as a function of flow rate for an 8" ALTOSONIC V12.

The comparison between the hydrogen and natural gas calibration should best be made against Reynolds [Fig. 4]. As the performance of the flowmeter is Reynolds dependent a similar deviation may be expected at the same Reynolds number. The deviation over the entire range of overlap of Reynolds is around 0,3% which is small considering the uncertainties of the calibration laboratories and the significant differences in gas properties. From these results it can be concluded that a Reynolds calibration with natural gas has the potential to be used as an alternative for hydrogen calibration.

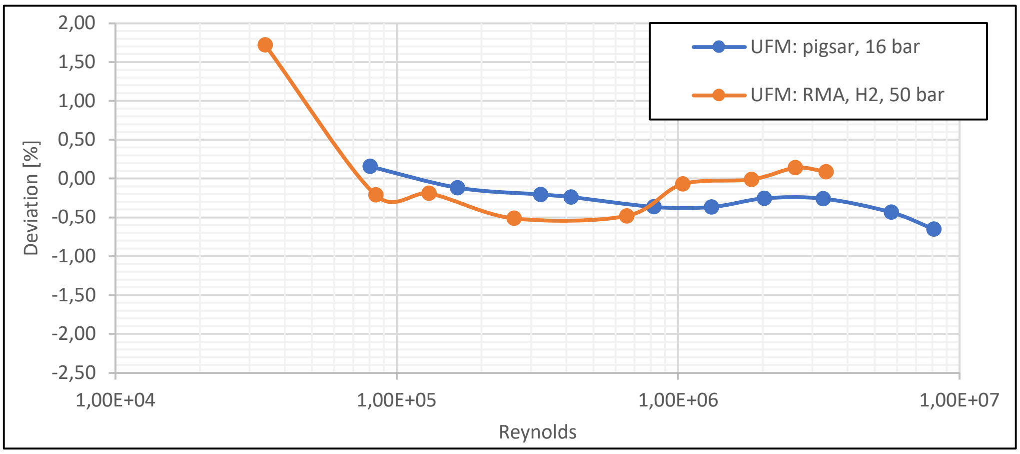

Fig. 4: Hydrogen and natural gas calibration result as a function of Reynolds for an 8" ALTOSONIC V12.

2.3 Laboratory tests

Fig. 5: A 4"/DN100 flowmeter at the DNV small hydrogen testloop.

Several laboratory tests were conducted to find the root causes of deviations found during hydrogen flow measurements and to reduce these.
Low flow deviation is one of those.
The high speed of sound of hydrogen gas causes a short transit time in the hydrogen gas. The delay time is the part of the transit time outside the gas, caused by the transducer and electronic circuits. The shorter the transit time, the more important errors in the delay time become. These must be identified and corrected to improve the low flow performance. This is best tested at small flowmeter diameters where the transit times are shortest.
Over time several tests were performed at the 4" hydrogen test loop at DNV [Ref. 7].

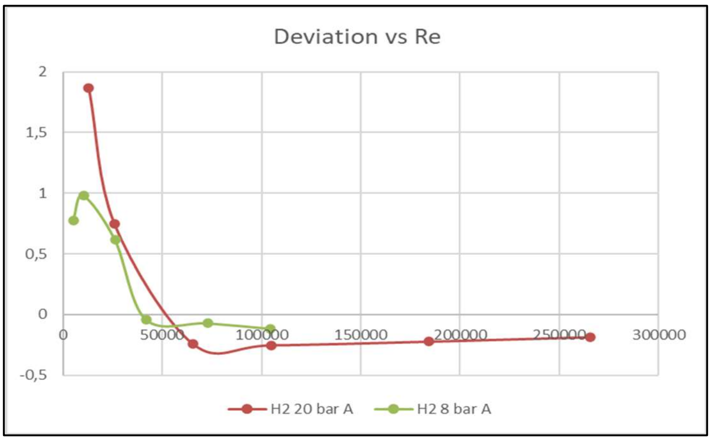

Fig. 6: Flow test result, deviation [%] as a function of Reynolds for a 4" ALTOSONIC V12.

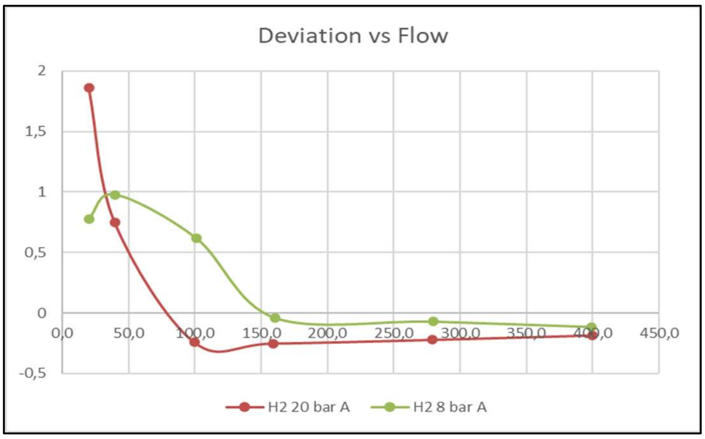

Fig. 7: Flow test result, deviation [%] as a function of flowrate [m^3/h] for a 4" ALTOSONIC V12.

The diagrams above [fig. 6 and 7] show the uncorrected results at 20 bar(a) and 8 bar(a). At 8 Bar(a) the lowest Reynolds number is 5240 and a Reynolds effect can be observed for the lowest 3 flowrates. It is important to differentiate between deviation caused by zero point accuracy and by low Reynolds number. At 20 bar(a) the lowest flowrate a deviation just below 2% can be observed, which is caused by zero point deviation. As a rule of thumb, the deviation should not be larger than MPE and the repeatability at these low flowrates should be within than 0,2%. This was improved to be the case at low flow at this test for a Qmin of 20m^3/h (0,7 m/s). Results of these tests were used to improve procedures for zero calibration which are executed in the factory before flow calibration. This will allow for lower values of Qmin at larger flowmeter diameters.

2.3 Further calibration with hydrogen

In December 2025, further calibrations were performed with ultrasonic flowmeters at RMA using one 8"/DN200 and two 10"/DN250. These flowmeters were pre-calibrated at static conditions at the factory using improved procedures in which the lessons learned from testing and earlier calibration were implemented.

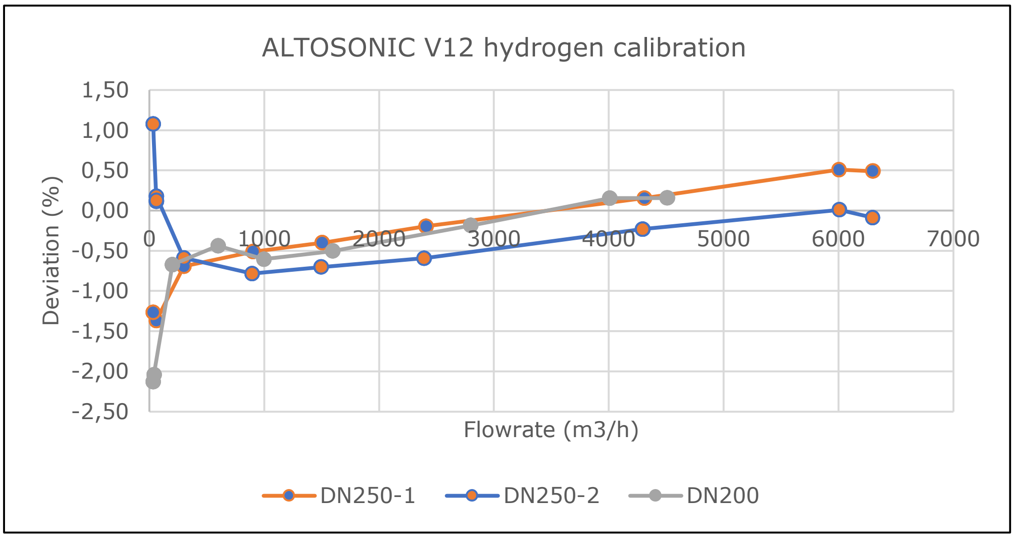

Fig. 8: Uncorrected flow calibration result for an 8" and 2x 10" ALTOSONIC V12 obtained at the RMA hydrogen calibration facility.

Table 1 - Typical parameters for one 8" and 2x10" ALTOSONIC V12 derived from the hydrogen calibration results.

Flowmeter	Qmin (m^3/h)	Uncorrected deviation (%)	Standard deviation (%)	Qmax (m^3/h / m/s)	Uncorrected deviation (%)	Standard deviation (%)	FWME uncorrected (%)
DN 10"/250-1	31	-1,27	0,18	6330 / 39,1	0,49	0,03	0,065
DN 10"/250-2	31	1,08	0,12	6295 / 39,0	0,4	0,02	-0,2745
DN 8"/200	31	-2,13	0,21	4500 / 43,63	0,16	0,1	-0,12

The calibration focussed on testing Qmin as well as Qmax. Compared to the first calibration the deviation at Qmin was reduced. The required minimum flow speed (Qmin) was 31 m^3/h at both the 8"/DN200 (= 0,4 m/s flow speed) and 10"/DN250 (0,2 = m/s flow speed), which is in the same range as with natural gas. The repeatability (calculated as standard deviation in the table [fig. 9]) at these low flowrates was good enough for correction of the deviation.
The maximum flow speed tested at 8"/DN200 was 43,63 m/s and at 10"/DN250, it was 39,1 m/s. The deviations at these flowrates were in line with the lower flow results and the standard deviation was well within specification. These figures enable a flow range (Qmax/Qmin) from just over 100:1 up to 200:1.

2.3 Adaptions to the flowmeter specific for hydrogen.

For the flow measurement on hydrogen our standard ultrasonic custody transfer gas flowmeter has been applied and specific adaptations for hydrogen have been made. The same, standard transducers are being used for natural gas. Also the electronics are not modified in any way. The adjustments for accurate hydrogen measurement are mainly achieved by finetuning of parameters for correction, transducer signal control and signal processing.
Materials used have been evaluated for hydrogen service. No incompliances were found. Transducers do not contain any titanium, which is known to be sensitive to hydrogen corrosion cracking.
However some improvements are being suggested for implementation:

- Stainless steel used in wetted transducer parts will be specified to contain at least 12% nickel (SS316 standard nickel content is minimal 10%).
- Wetted O-ring material will be changed to contain a compound that reduces ingress of hydrogen.

As hydrogen leakage is topic of concern, a transducer leakage test was conducted at a pressure of 50 Bar. The leakage rate found was 0,015 ml/h. Which results in a leakage of 1,6 Liter (0,144 grams) of hydrogen per year per flowmeter using the standard O-ring material, which is considered a very small amount considering the concerned flowmeter diameters and therefore within the limits as specified in ISO 15848-1 for industrial valves.

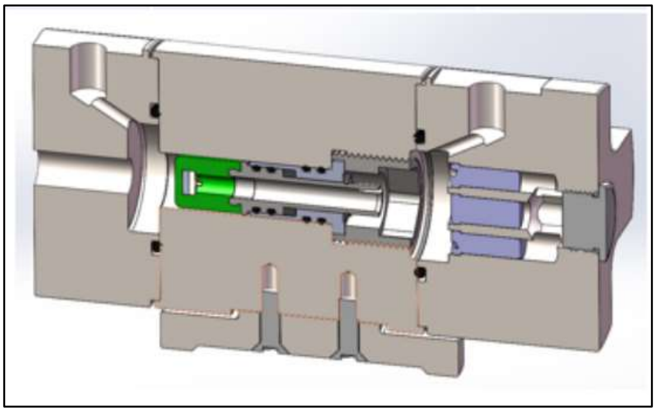

Fig. 10: Transducer leakage test setup.

3 Ultrasonic flowmeters, ready to measure CO_2?

In the logistic chain being established to store CO_2, it may appear in 3 phases; gas phase for (short distance) pipeline transport, liquid phase for ship transport and supercritical/dense phase for long distance pipeline transport and storage. For each situation a measurement solution is required, suitable for the specific properties for each phase.

CO_2 is notorious for its attenuation of acoustic signals and is therefore a challenging substance for the application of ultrasonic flowmeters with it. For CO_2 in the gas phase, the application is most straightforward. The relation of pressure and temperature to density and acoustic attenuation and are well known and therefore when the pressure, temperature and pipe diameter are known the suitability of the flowmeter can easily be checked.

In scenarios involving high-density and supercritical conditions, the interdependence between temperature, pressure, and properties such as density, speed of sound, and acoustic attenuation is complex and not readily apparent. These properties must be derived from Equation of State (EOS) models to accurately capture the thermodynamic behaviour of the system. To learn more about this a static test was performed.

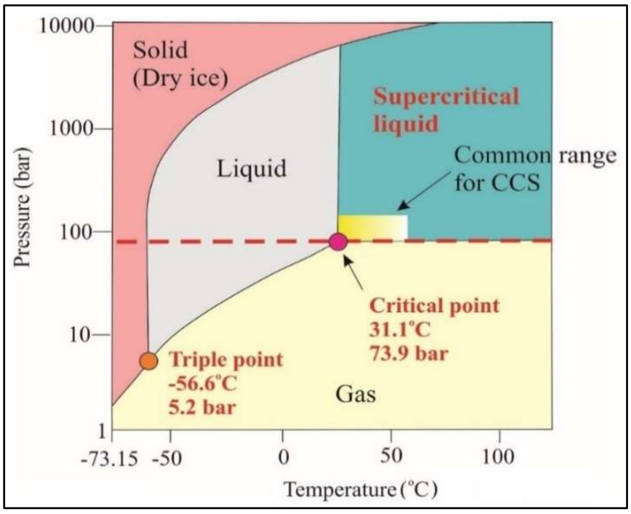

Fig. 11: CO_2 phase diagram.

3.1. Assessment of CO_2 properties relevant to ultrasonic flowmeters

To select the right flowmeter and define its configuration, the properties of CO_2 related to temperature and pressure must first be known. This was analysed for the dense and supercritical phase.

A model was developed to calculate the relevant properties like density, speed of sound and acoustic attenuation for various transducer types and frequencies as a function of pressure and temperature.

In the supercritical phase, at a pressure over 74bar(a) and a temperature over 31,1°C, all properties of the CO_2 show a high rate of change, even for small variation of temperature and pressure (see figure 12 and 13).

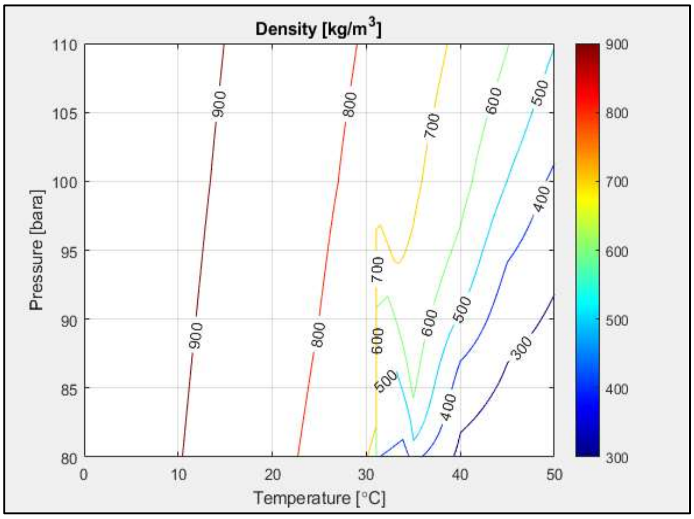

Fig. 12: Density of supercritical CO_2 shows a large variation as function of temperature specifically between 30 and 40°C.

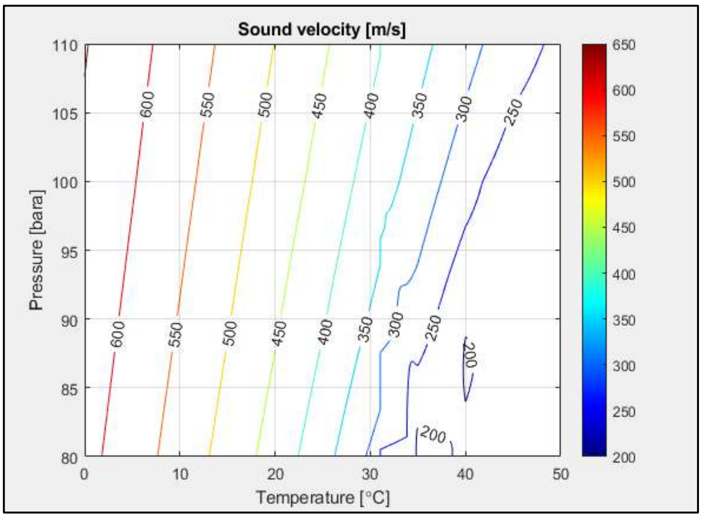

Fig. 13: Speed of sound as function of pressure and temperature for supercritical CO_2, shows a large variation over the entire test range.

Therefore the supercritical phase was considered in particular for the selection of the transducer.

The ultrasonic flowmeter must be able to adapt quickly to variations in the CO_2 properties . Given the range of values of density and speed of sound over the operation range of temperature and pressure a transducer with an intermediate frequency should be chosen.

The frequency should not be too low in order to prevent too much crosstalk at higher speed of sound and higher density. It should not be too high either, to prevent too much acoustic attenuation.

A G6 transducer type was selected for the measurement of CO2 in supercritical and dense phase. This is the same transducer as used for hydrogen flow measurement. This transducer has an operating frequency of 270 kHz. With a maximum acceptable attenuation for good signal quality of 70 db. When we consider a maximum damping of 320 dB/m, the maximum path length is 70/320 = 0,218m. This makes the diameter 6”/DN150 mm the maximum for a direct path flowmeter.

3.2 Static test

At DNV a static test was conducted with CO_2 at dense and supercritical conditions [fig. 14].
An 6”/DN150 ALTOSONIC V12 with a direct path, 600 lbs design, was used for the test.
The test area is shown in the phase diagram [fig. 13], the actual test points are shown in the T, p diagram [fig. 15].
The main objective available measurement parameter of such a static test is the speed of sound. The speed of sound can be compared with the calculated speed of sound.

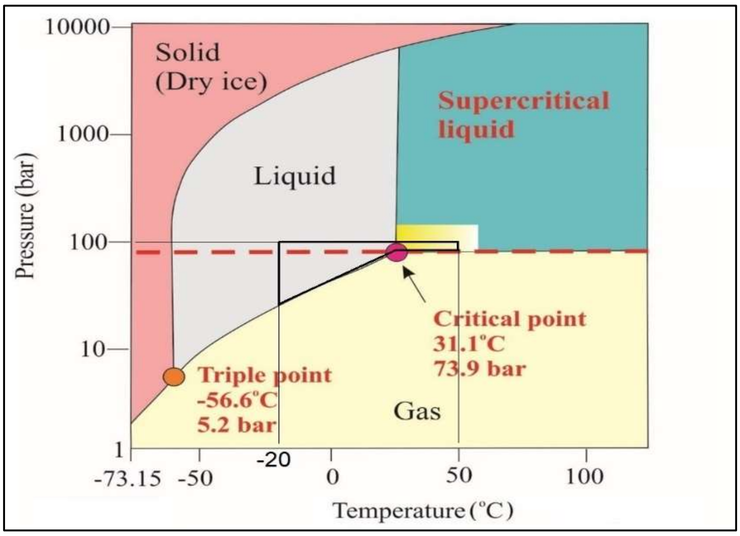

Fig. 13: Phase diagram of CO_2 with static testing area.

Fig. 14: The flowmeter in the static test setup at DNV.

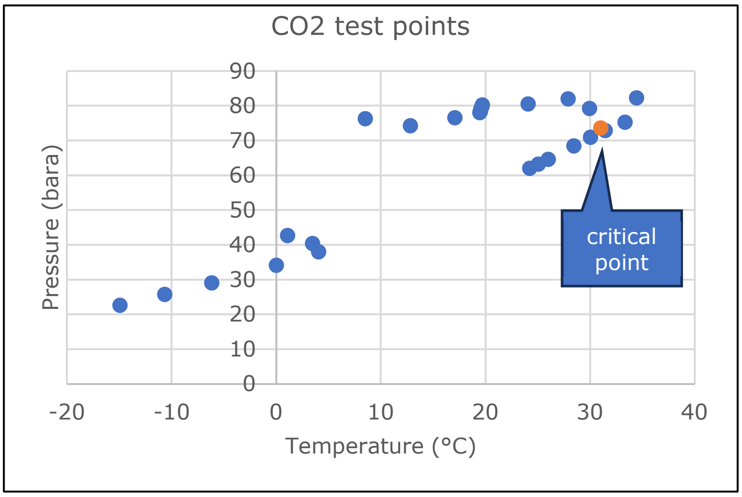

Fig. 15: Temperature and pressure of the test points of the DNV static tests.

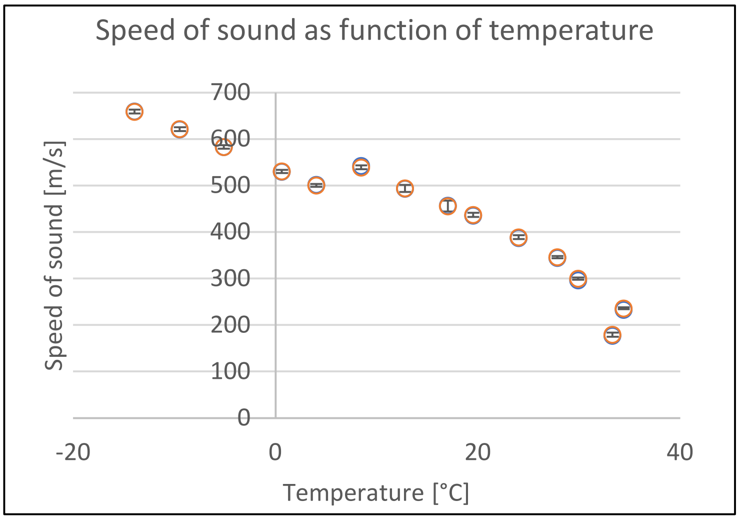

Fig. 16: Calculated and measured speed of sound of CO_2.

In the graph [fig. 16] in which the speed of sound as a function of the temperature is shown. The circles are the measured values, the error bars the calculated values. It can be observed that the calculated and measured value correlate very well.

Even in the temperature range between 15 and 35°C where the speed of sound varies significantly with temperature.

Based on the good static test result it may be expected that the ultrasonic flowmeter will show a good performance at dynamic (flow) measurements.

3.2 Signal quality and attenuation of acoustic signals in supercritical CO_2

The performance of the flowmeter depends on the quality of the acoustic signals, which is measured by the SNR. If this value is below 20dB, the performance at dynamic measurement will deteriorate. At all measurement points the SNR (signal to noise ratio) remained above 30dB.
The acoustic attenuation is indicated by the gain of the receiving transducer. During the test it reached a maximum value of 56dB, which is well within acceptable limit (<70 dB).
The measured values for attenuation were around 50% higher than initially calculated.
This an important result, which can be used to predict the limits for the proper functioning of a flowmeter for a specific CO_2 application.
In addition the results support further refining of our models during further research.

4 SUMMARY AND CONCLUSIONS

Summary

The transition to sustainable energy sources has necessitated the development of reliable methods for measuring hydrogen and CO_2 flow. Ultrasonic flowmeters have emerged as a promising technology due to their wide flow range, independence from fluid properties, and minimal pressure drop. This chapter explores the laboratory and field experiences, challenges, and solutions associated with using ultrasonic flowmeters for hydrogen and CO_2 measurement.

Hydrogen Measurement

Ultrasonic flowmeters have demonstrated their suitability for hydrogen measurement through extensive laboratory tests, calibrations, and field trials. The ALTOSONIC V12, in particular, has shown promising results, maintaining measurement accuracy even with hydrogen concentrations up to 30% in natural gas mixtures. Field tests conducted in Germany further confirmed the technology's capability to measure pure hydrogen, highlighting its superior low-flow performance compared to traditional turbine meters.

From the testing and calibration conducted with hydrogen, several key conclusions can be drawn about ultrasonic technology:

- It can fulfil custody transfer (CT) accuracy requirements, ensuring reliable measurement for commercial transactions.
- It can cover an application range that includes both pure hydrogen and natural gas using the same meter, offering versatility in mixed gas environments.
- It provides an extended flow range for hydrogen, achieving a range of 200:1, which enhances its applicability across various flow conditions.

Challenges in hydrogen measurement primarily stem from the short transit time in the gas, which amplifies the impact of delay time caused by transducers and electronic circuits. Laboratory tests have focused on identifying and correcting these deviations, leading to improved zero flow calibration and reduced measurement errors at low flow rates.

Calibration facilities, such as RMA in Germany, have played a crucial role in verifying the accuracy of ultrasonic flowmeters for hydrogen custody transfer applications. Despite initial deviations at low flow rates, ongoing refinements in calibration techniques have enhanced measurement precision. Adaptations specific to hydrogen, including material improvements and transducer leakage tests, have further optimized the flowmeters for hydrogen service.

CO_2 Measurement

CO_2 presents unique challenges for ultrasonic flowmeters due to its ability to exist in gaseous, liquid, and supercritical phases. The damping of acoustic signals by CO_2 complicates measurement, particularly under high-density and supercritical conditions. Accurate measurement requires a deep understanding of the interdependence between temperature, pressure, and fluid properties, which can be derived from Equation of State (EOS) models.

Static tests conducted with CO_2 under supercritical conditions have provided valuable insights into the behaviour of ultrasonic flowmeters. Notably, there is a very good correspondence between the measured and calculated speed of sound, demonstrating the flowmeter's capability to accurately capture this critical parameter. With the right frequency selection and flowmeter design, ultrasonic flowmeters are suited for application in supercritical CO_2 flow measurement, adapting effectively to rapid changes in fluid properties.

Conclusions

Ultrasonic flowmeters have proven to be a viable solution for measuring hydrogen and CO_2 flow, offering significant advantages in terms of accuracy and adaptability. For hydrogen, ongoing calibration improvements and material adaptations have enhanced measurement precision, making ultrasonic flowmeters suitable for custody transfer applications. The technology's ability to cover both pure hydrogen and natural gas with a single meter, along with its extended flow range, underscores its versatility and efficiency.

In the case of CO_2, the excellent correspondence between measured and calculated speed of sound, combined with appropriate frequency selection and flowmeter design, underscores the potential for successful application in supercritical CO_2 flow measurement. The ability to extend the application range beyond the state of aggregation further highlights the adaptability of ultrasonic flowmeters for diverse CO_2 conditions.

Future efforts should focus on refining calibration techniques, improving predictive models for CO_2 properties, and further adapting flowmeter materials and components to optimize performance across all phases. By addressing these challenges, ultrasonic flowmeters can play a pivotal role in the energy transition, facilitating the efficient measurement and management of hydrogen and CO_2 flows.

5 REFERENCES

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