Flow meter performance under CO_2 gaseous conditions

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1 INTRODUCTION

The transport and energy measurement and billing of natural gas in pipeline systems is well understood in the gas industry. ISO standards and best practice specifications and procedures to facilitate transport and custody transfer are widely available and under constant improvement and review.

With decarbonization ambitions moving forward, the transport of CO_2 is becoming increasingly important to facilitate carbon capture, utilization, and storage (CCUS). As well as for natural gas systems, accurate measurement and subsequent billing for CCUS is required to show compliance with national and international emissions-reduction regulations, like the EU Emission Trading System (ETS). The ETS is based on the principle of cap and trade, meaning that the "capped" emission rights can be traded between parties. The ETS states that all CO_2 reported amounts above 500 kilotons/year should be within an uncertainty of 2.5% (k=2) independent of the thermodynamic state of the CO_2, i.e. gas, liquid or dense phase.

There are many ongoing CCUS projects especially in northwestern part of Europe, e.g. Northern Lights (Norway), Porthos & Aramis (Netherlands), Net Zero Teesside & Zero Carbon Humber (UK). Due to the complexity of the CO_2 value chain, accurate flow measurements are required in a variety of thermodynamic conditions ranging from low-pressure, low-temperature gas/liquid measurements to high-pressure liquid and dense phase measurements.

1.1 Porthos CCUS project

Porthos is developing a CCUS project in the Rotterdam harbour with storage offshore in the P18 gas fields, operated by TAQA. The project is a collaboration between Port of Rotterdam Authority, EBN and Gasunie. An important part of the transportation network of Porthos is the medium-pressure (<35 bar) onshore CO_2 gas transport, in a joint venture with Gasunie. This part of the network connects the different emitters (customers) before compression and offshore dense phase transportation towards the P18 fields. A schematic overview of the CCUS transportation system is given in Fig. 1.

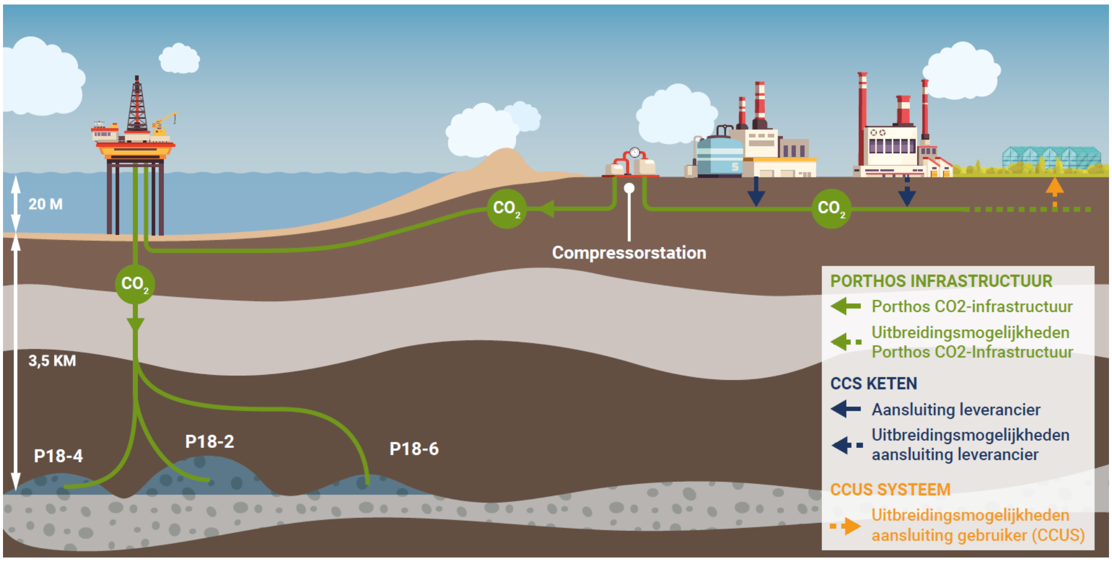

Fig. 1 – Schematic overview of Porthos transportation system (Dutch: taken from [8])

2 EXPERIMENTAL APPROACH

To evaluate the flow meters under these conditions, two types of tests were carried out: functional testing and flow performance testing.

The functional part of the test comprised a so-called zero-flow test, in which the meters under test are filled with a pre-defined CO_2-rich mixture under controlled pressure and temperature conditions. During these tests, the meter diagnostics are logged, and the health status of the flow meter can be monitored. Effects of impurities and pressure can be investigated rather easily by exchanging the gas composition and altering the pressure. Understanding of the meter response under zero-flow conditions can help optimization of the meter configuration for the application and aids in the specification of the useful range of flow conditions for the performance test.

The flow performance tests consisted of several flow metering technologies installed in series at DNV's MultiPhase Flow Laboratory in Groningen. The measurement principles used in the performance test were ultrasonic, turbine and Coriolis meters. These meters which were tested under natural gas and CO_2-rich mixtures under a range of pressures. The performance of the gas flow meters was assessed by comparing against a dedicated reference system consisting of a set of sonic nozzles, bearing-friction corrected turbine meters and Coriolis meters.

2.1 Zero-flow tests

Prior to the large-scale CO_2 flow tests, a series of zero-flow tests were carried out. A zero-flow test encompasses the filling of a closed section containing multiple meters under test with a pre-defined gas mixture and accurately controlling the pressure and temperature. The main advantage of this method is that multiple metering technology can be used simultaneously and changes in pressure conditions and gas compositions can be easily facilitated. An example of such a setup is provided in Fig. 2, where a Coriolis and ultrasonic meter are installed in series. The pressure and temperature are monitored in the pipe spool at the right-hand-side. The injection of the gas is done from the right side of the test section with a connection to the vent stack on the left side for purging purposes. Prior to injection of the test gas, the section is vacuumed to ensure that no residual gas is present. Also, the test section is purged several times and the resulting composition is measured by a GC. An internal circulation fan allows for fast temperature stabilization towards ambient temperature and is switched off when measurements are performed.

In the recent years, several different metering technologies were tested under multiple gas compositions (among which CO_2-rich gases) and based on this group of meters general conclusions can be drawn on the functional performance of these meters. Also, for ultrasonic meters, theoretical models are available that can calculate the attenuation of the ultrasonic signal. An example of such a model was initially proposed by Dain and Lueptow [1] and improved by Petculescu and Lueptow in [7].

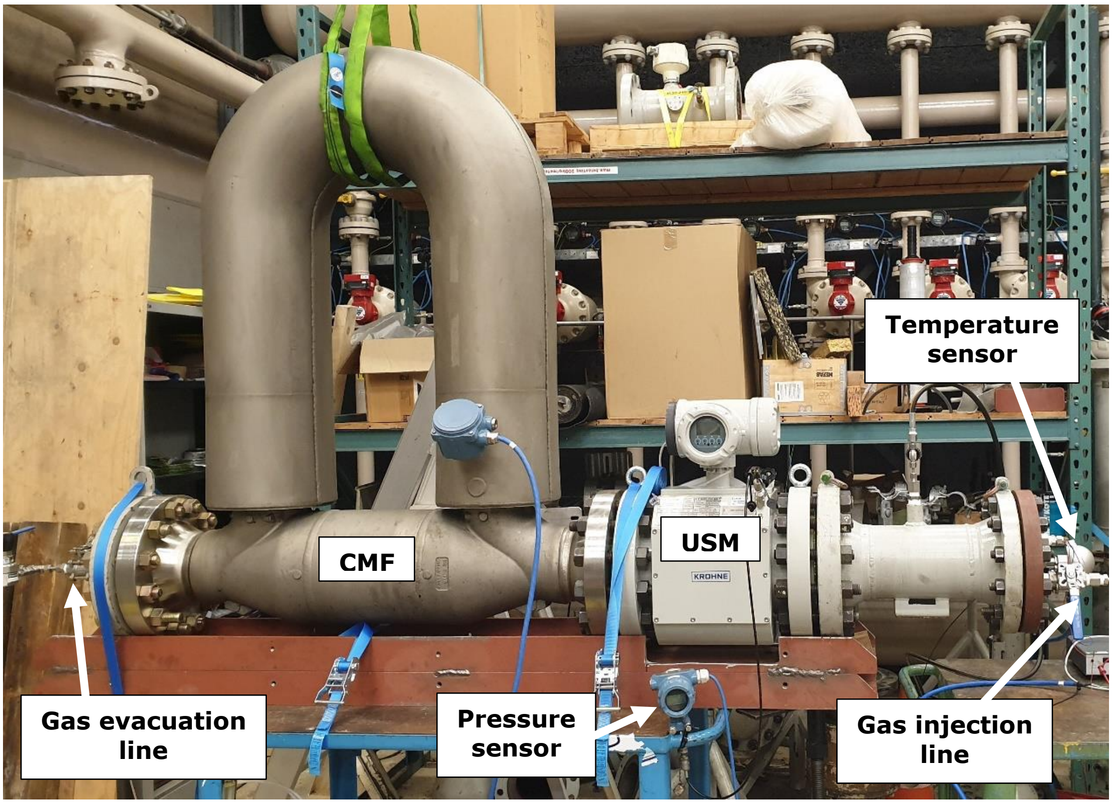

Fig. 2 – Typical setup of a zero-flow test with an Emerson Coriolis (CMF) and Krohne ultrasonic (USM) flow meter

2.1.1 Zero-flow test results

The response of the flow meters is based on the diagnostics logged for the Coriolis and ultrasonic technologies, since evidently, turbine meters do not provide any diagnostic capabilities under zero-flow conditions. Tests were executed with the focus on two CO_2-rich gases: 100% and 99.3% CO_2 with the remaining 0.7% natural gas. In some occasions, also tests with other concentrations and residual components were performed.

2.1.1.1 Ultrasonic meter

The used ultrasonic meter for the test was a standard custody transfer meter for natural gas applications and was not modified for the CO_2-rich mixtures. For the ultrasonic technology the speed of sound and gain were logged as primary diagnostic parameters of interest. The speed of sound can be compared to the theoretical speed of sound calculated by e.g. the GERG2008 [5] and all measurement paths should provide approximately equal numbers. If the speed of sound of a specific path is deviating (or even failing), one can assume that this measurement path can no longer be used for the flow calculation. The results for the speed of sound for the 100% CO_2 and 99.3% CO_2 are given in Fig. 3 as a function of pressure. As observed in the figure, the functioning of the meter depends strongly on the pressure and the concentration of CO_2. The pressure has two effects: reduction of the gas impedance (general effect for all gases) and increase of acoustic attenuation (specific for CO_2-rich gases). Also, the dependence on the path length is clearly visible, where the mid-plane path (path 3) fails first and the symmetric pairs (paths 2&4 and paths 1&5) fail at approximately the same pressure. Also test with 95% CO_2 and 5% N_2 were carried out giving approximately the same results as the 99.3% CO_2 case. It is remarkable that the apparent small difference between 100% CO_2 and high concentration CO_2 streams with small levels of contamination results in significantly different results for the ultrasonic transmission. This will be further addressed in the comparison with theory in Fig. 5.

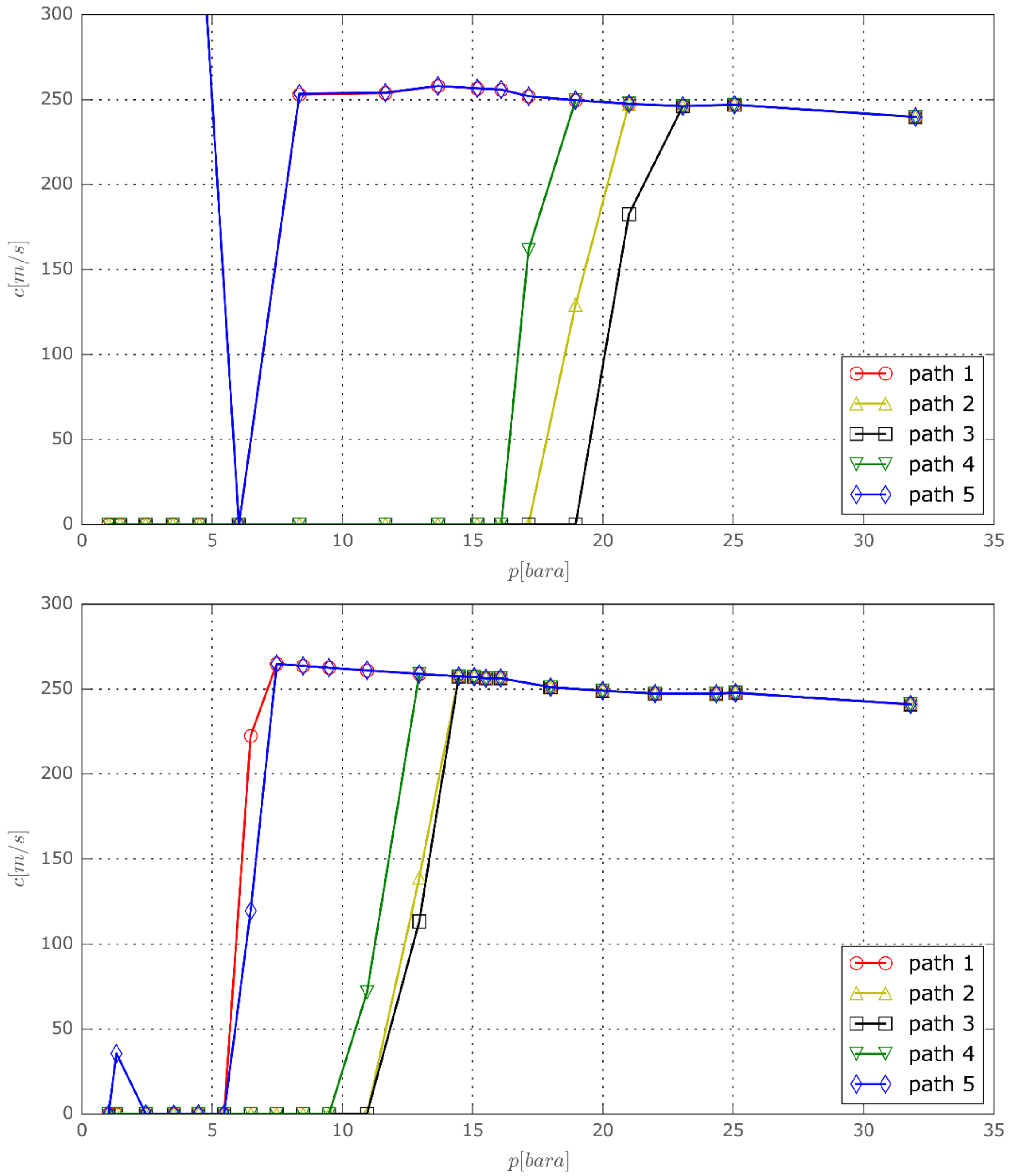

Fig. 3 – Speed of sound per measurement path for CO_2=100% (top) and CO_2=99.3% (bottom)

The same graphs can be made for the gain per measurement path, see Fig. 4. It is clear that when the maximum gain of a path is approached, this measurement path will start to fail. Therefore, knowing the maximum gain limits of the ultrasonic meter, the actual gain during measurement may provide a good health statistic.

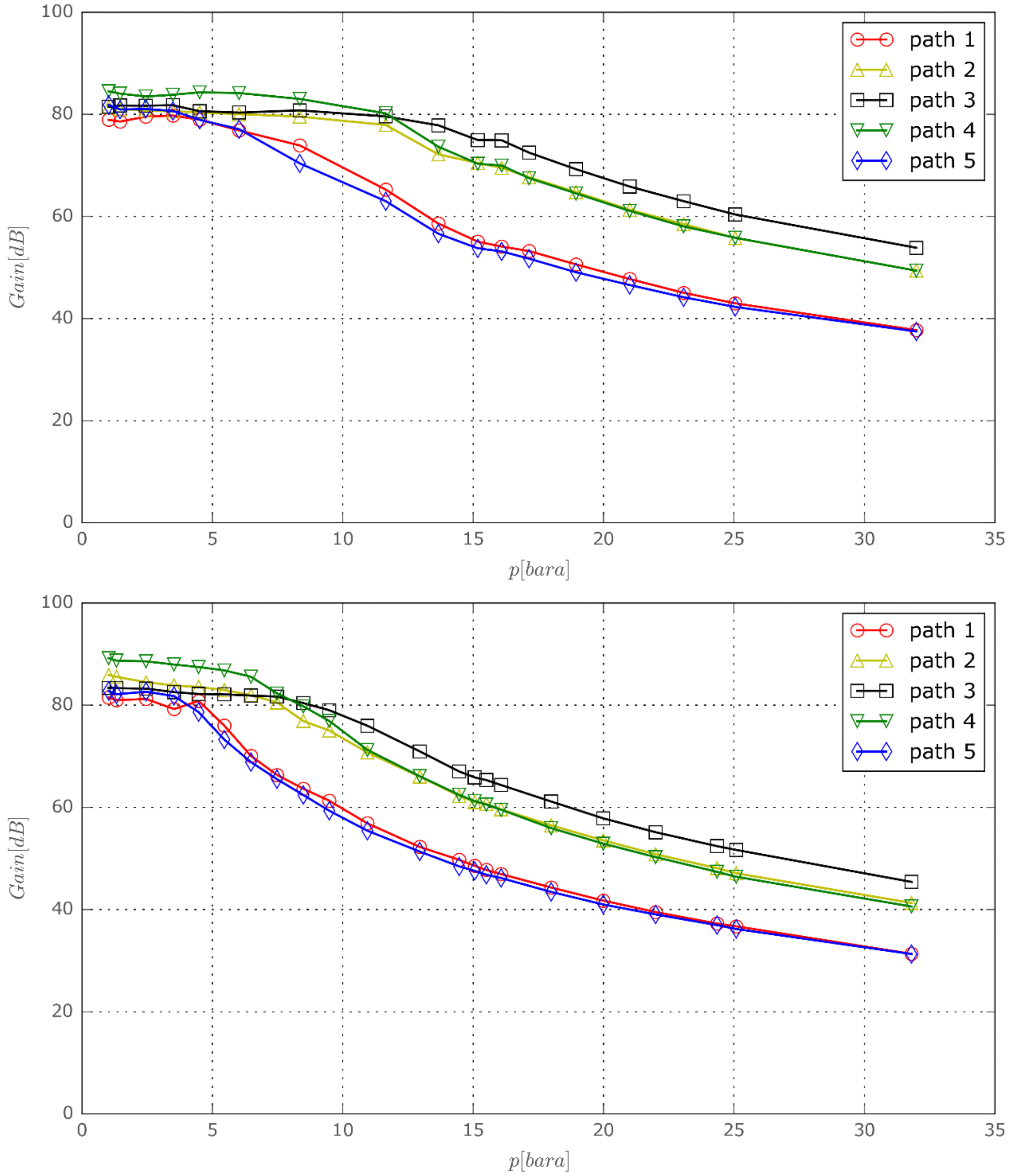

Fig. 4 – Gain per measurement path for CO_2=100% (top) and CO_2=99.3% (bottom)

The gain is a measure for the acoustic attenuation of the ultrasonic signal, i.e. the higher the attenuation of the gas the more the ultrasonic meter is trying to compensate by increasing the gain. The acoustic energy loss of the ultrasonic signal is due to several factors:

- impedance difference between transducer and gas
- wave dispersion of the signal along the ultrasonic path
- acoustic attenuation of the gas along the ultrasonic path

The transfer of the transducer surface towards the gas depends on the difference in the acoustic impedance of the transducer and gas and is equal for all measurement paths. The effect of the wave dispersion can be calculated to good approximation from theoretical models and depends on the path length. Therefore, using the multipath configuration with known path lengths, the acoustic attenuation can be estimated by using the gain per measurement paths. The acoustic attenuation is often presented in terms of the attenuation per wavelength ($\alpha\lambda$) as a function of frequency divided pressure (f/p) [1]. The frequency per pressure is a way of non-dimensioning the wave frequency with the collision frequency of the molecules (approximately linear with pressure). The results of the measurements compared to theory are given in Fig. 5. Since the meter has a 5-path configuration two separate sets of data can be used to estimate the attenuation: using path 1/5 & 3, and path 2/4 & 3. As shown in the figures both measurement set provide approximately the same results and match well with theory up to the failure of path 3, i.e. path 3 reaching it maximum gain. The same experiment was performed for 99.3% CO_2 with 0.7% nitrogen, resulting is approximately identical results as the bottom figure of Fig. 5.

From the theoretical results and their dependence on *f/p*, we can learn that operating at relatively high frequencies and low pressures the attenuation becomes more prominent and can cause problems with the signal transmission.

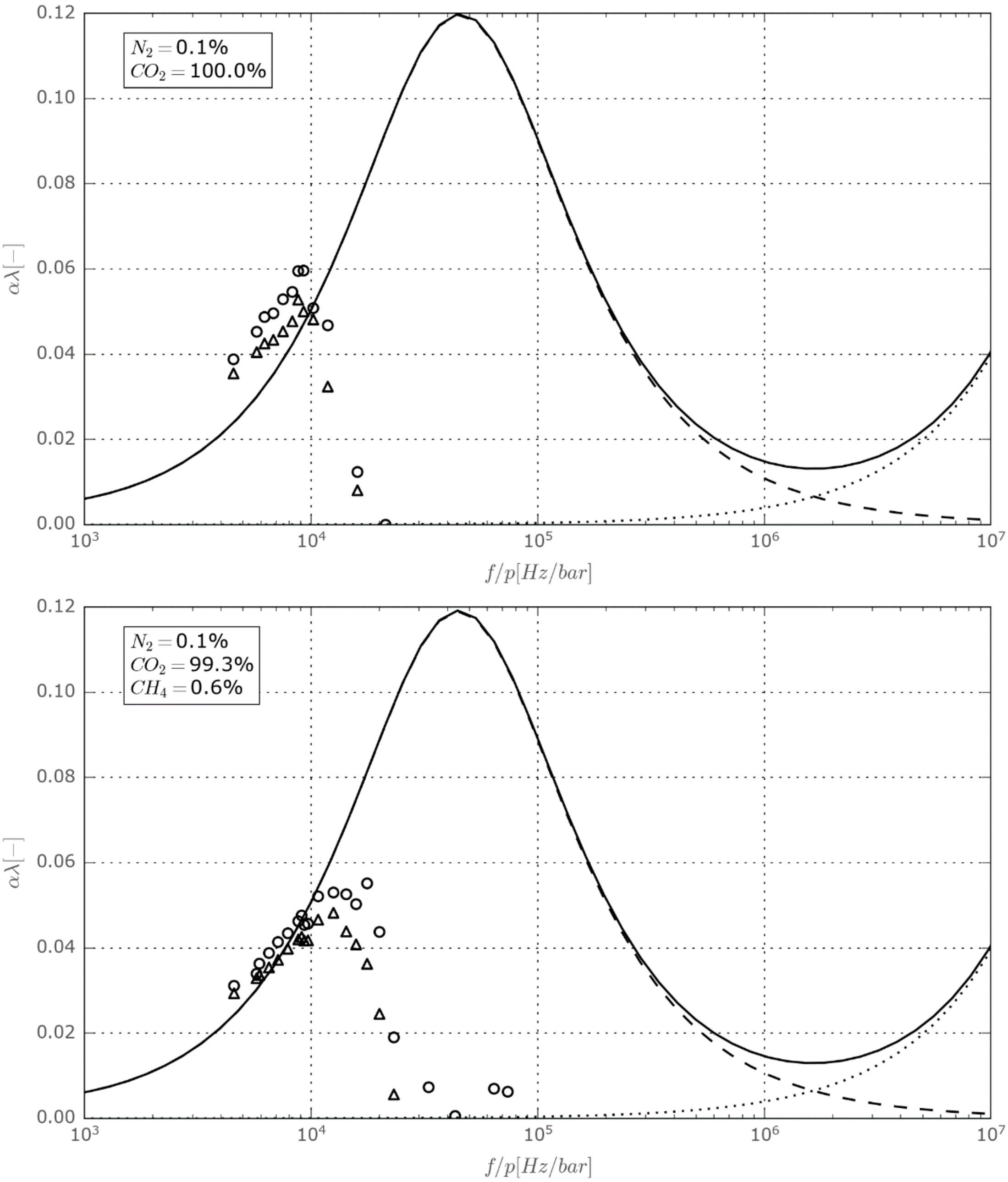

Fig. 5 – Acoustic attenuation for CO_2=100% (top) and CO_2=99.3% (bottom) by using path 1&2 (circles) and path 1&3 (triangles), and Dain and Lueptow model (solid line)

It is noted that the same model was used for determining the difference between pure methane and typical natural gas (blend of hydrocarbons and nitrogen). In experiment a large difference between these two mixtures is observed, where pure methane has a much higher attenuation. The model is not able to predict the difference between these two gas compositions.

It is known that the attenuation characteristics of the medium has an influence on the speed of sound as well [1], resulting in a low frequency limit (comparable to the GERG2008) and high frequency limit. During the depressurization in a zero-flow test, it is difficult to perform a representative temperature measurement. Therefore, the presented results in Fig. 6 should be considered qualitatively. Also, in the region of highest interest (the inflection region), the attenuation is highest, and the ultrasonic transmission is lost. Therefore, no data is recorded.

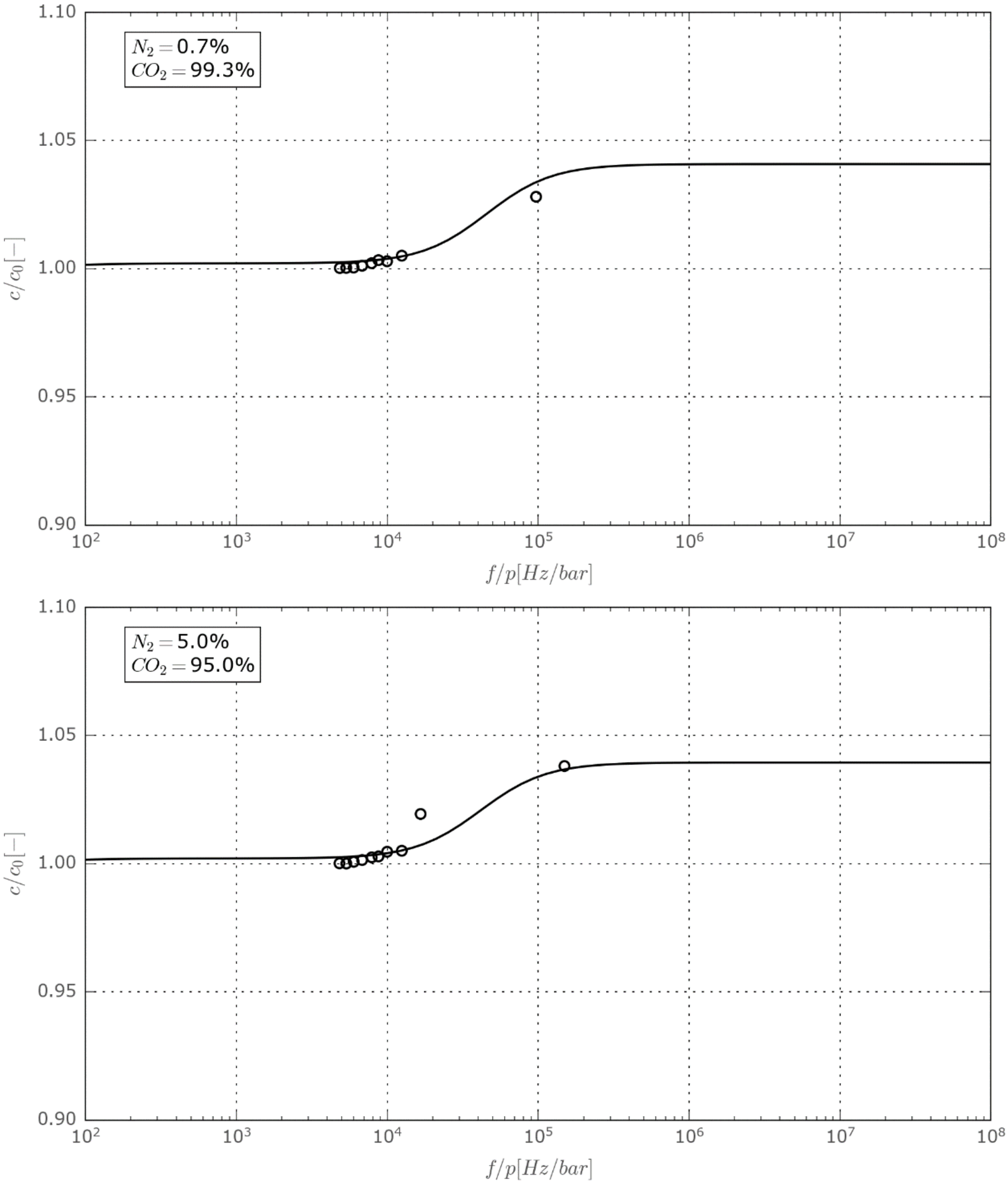

Fig. 6 – Relative speed of sound for CO_2=99.3% (top) and CO_2=95% (bottom) in circles, and Dain and Lueptow model (solid line)

2.1.1.2 Coriolis meter

One of the main diagnostics of a Coriolis meter is the drive gain. The drive gain is expected to be unaltered for different gases, which is confirmed in Fig. 7. In this figure, also the results of pure methane, nitrogen and helium are included.

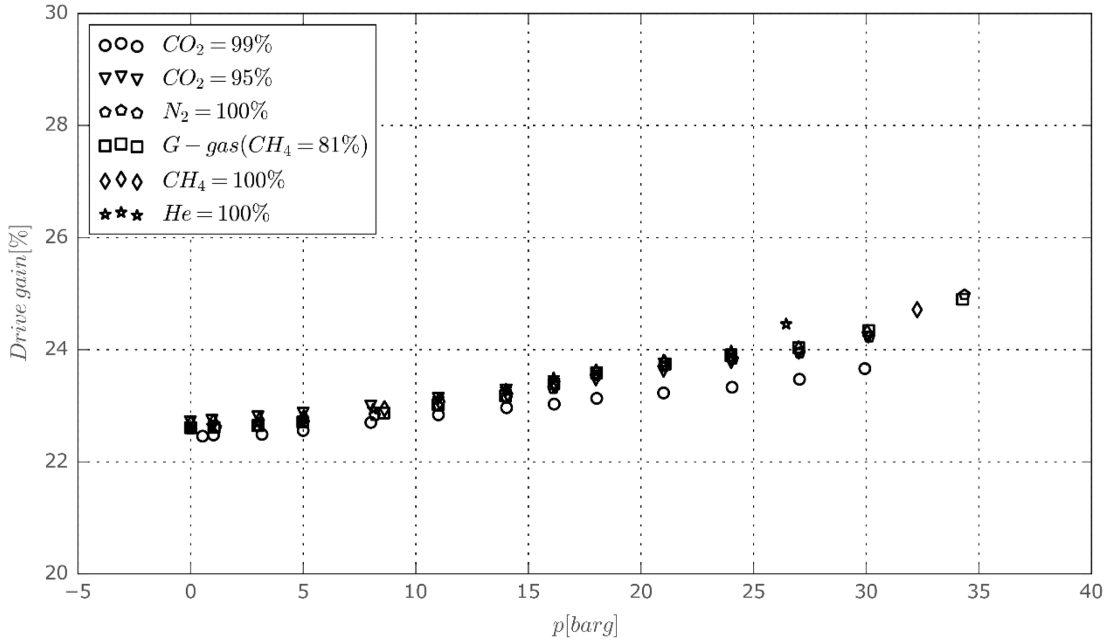

Fig. 7 – Drive gain of Coriolis meter for different gases as a function of pressure

For the same set of gases, the density error can also be plotted as a function of pressure, see Fig. 8. The reference density is calculated by the GERG2008. Although most of the results are well within 0.5 kg/m³, the temperature control during depressurization is much more difficult which may cause a higher deviation then under well controlled conditions.

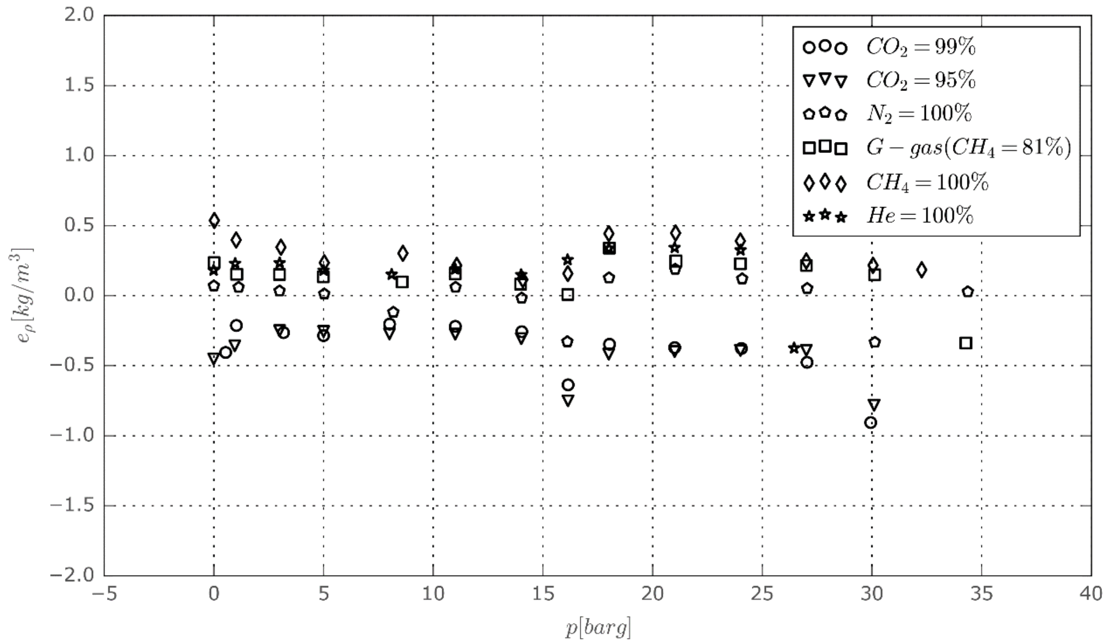

Fig. 8 – Density error of Coriolis meter for different gases as a function of pressure

2.2 Flow performance test

To cover the onshore transport part of the CO_2 value chain, CO_2 gas flow tests were carried out at the DNV test facility in Groningen in the range between 95-99% CO_2 at pressures up to 35 bara. The tests considered the main measurement principles used for custody transfer metering: ultrasonic and turbine meters; and included Coriolis mass flow meters. The performance of the gas flow meters was assessed by comparing against a dedicated reference system consisting of a set of sonic nozzles, bearing-friction corrected turbine meters and Coriolis meters. The CO_2 performance results were compared to their baseline test with natural gas.

2.2.1 Reference system design

The reference system used for the CO_2 test is shown in Fig. 9. It consists of a part with two lines of 4” and 6” with a Coriolis and turbine meter in series. These lines can be used in parallel or separately by using the block valves. The 4” line contains an Emerson Micromotion CMF200 and an FMG FMT-M400, the 6” line contains an Emerson Micromotion CMF300 and an FMG FMT-M1000. Downstream this section a 5-fold sonic nozzle system is installed. Each of the nozzles can be used by opening the block valves. A more elaborate description and its uncertainty claim is provided in [3].

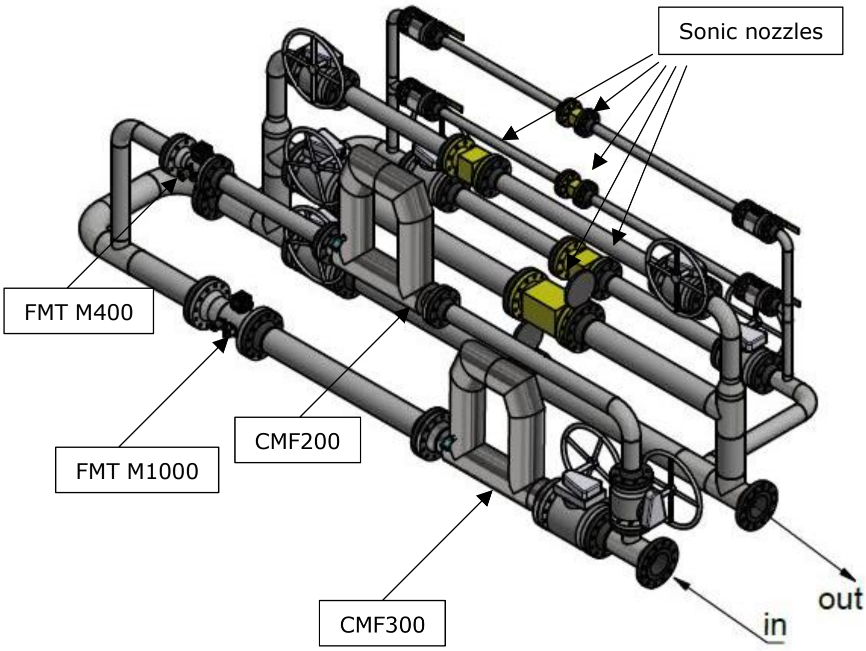

Fig. 9 – Gas reference system used for CO_2 tests at DNV facility

The analysis of the reference system can be performed by plotting the cross-plot of the turbine meter deviation (based on the sonic nozzle as the reference) versus the Coriolis meter deviation (based on the sonic nozzle as the reference)

$$\varepsilon_{TM} = \frac{\dot{m}_{TM} - \dot{m}_{SN}}{\dot{m}_{SN}}, \quad \varepsilon_{CMF} = \frac{\dot{m}_{CMF} - \dot{m}_{SN}}{\dot{m}_{SN}} \tag{1}$$

where $\dot{m}_{SN}$ is the mass flow from the sonic nozzles, $\dot{m}_{TM}$ is the mass flow from the (combined) turbine meters and $\dot{m}_{CMF}$ is the mass flow from the (combined) Coriolis mass flow meters.
The cross-plot is provided in Fig. 10, where the Groningen gas dataset is provided in red, the 95% CO_2 in grey and 99% CO_2 in black; the different pressures are distinguished by the symbols.

Not all flow conditions of the test facility could be run on the sonic nozzles due to the lower speed of sound of CO_2 and therefore this verification is done in the range between 50-600m^3/h. Also, the CO_2 test points at the highest pressure resulted in invalid nozzle reference flows with deviations up to -2% compared to the other reference systems. Analysis of the data showed that condensation of the CO_2 at the throat conditions may have caused the large negative bias. The isentropic expansion at the 35 bara and ambient temperature result in throat conditions at approximately -22°C and 18 bara. These conditions are very close to the saturation pressure curve of CO_2. Moreover, to ensure sonic conditions at the throat, the sonic nozzles are over-expanded (Mach>1) and the conditions downstream the throat enter the liquid region and under these conditions, CO_2 droplets will be formed. What the exact impact of these droplet are on the total mass flow is difficult to quantify, however it is known that a small fraction of droplets may decrease the speed of sound significantly [6]. This is in line with the negative bias observed in the results between the nozzles and the Coriolis/turbine meter system.

From the cross-plot, it is observed that the 95% CO_2 test points have a small systematic error of +0.1% for the turbine meters. Analysis of the measurement data for the small FMG turbine meter shows that a small Reynolds trend is still present in the data compared to the nozzle reference. This small offset is not compensated.

The results obtained from the reference system indicate that the claimed uncertainties of the turbine and Coriolis reference system (as stated by PTB [3]) still hold and can be used for the assessment of the meters under test in CO_2 conditions. The reference flows for the meters under test will be calculated based on a weighted average of the nozzle, turbine and Coriolis meter mass flow rate

$$\dot{m}_{ref} = w_{SN} \cdot \dot{m}_{SN} + w_{TM} \cdot \dot{m}_{TM} + w_{CMF} \cdot \dot{m}_{CMF}. \quad (2)$$

The weighting factors are based on the traceability uncertainties, and when all references are operational are given by

$$w_{SN} = 0.520, \;\; w_{TM} = 0.293, \;\; w_{CMF} = 0.187, \quad (3)$$

and when only the turbine and Coriolis meters are operational, are given by

$$w_{SN} = 0, \qquad w_{TM} = 0.61, \;\; w_{CMF} = 0.39. \quad (4)$$

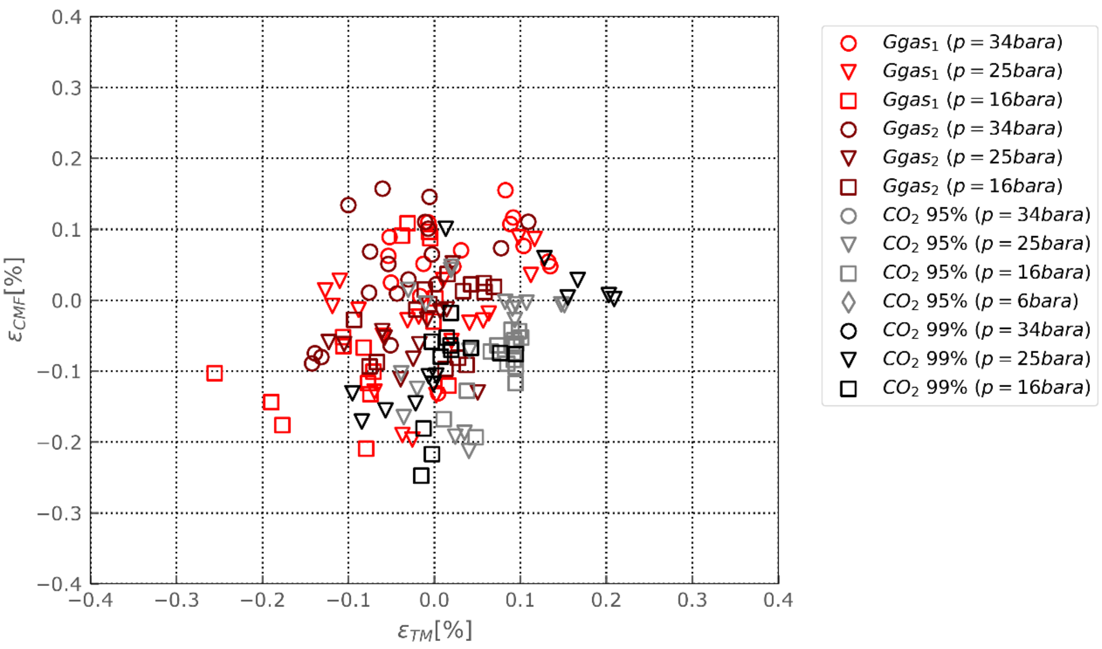

Fig. 10 – Cross-plot of the turbine meter versus the Coriolis meter with reference based on the sonic nozzles

The total claimed expanded uncertainty (k=2) of the flow reference system, denoted by U^*_{CMC}, differs when all reference meters are in operation or when only the turbine and Coriolis reference meters are used

$$U^*_{CMC}(\dot{m}_{ref}) = 0.23\%, \ \ ref = SN/TM/CMF$$
$$U^*_{CMC}(\dot{m}_{ref}) = 0.25\%, \ \ ref = TM/CMF. \qquad (5)$$

For the total uncertainty of the mass flow rate also the stability of the test point itself is taken into account by means of the repeatability of the flow rates and density. This typically leads to an operational reference system uncertainty of approximately 0.3%.

Part of the meter under test data is confidential, however the response of the reference meters (turbine and Coriolis) and the turbine meter under test can be analysed.

3 RESULTS AND DISCUSSION

The meters were tested at three different pressures: 16, 24 and 34 bara, for gas mixtures of natural gas (Groningen gas quality), 99.3% CO_2 with 0.7% natural gas and 95% CO_2 with 5% natural gas. The flow rates covered a range between 50 and 1000 m^3(a)/h. Each flow point was executed with three repeats and the series of natural gas were performed twice, resulting in a Groningen gas 1 and Groningen gas 2 data set, denoted by respectively $Ggas_1$ and $Ggas_2$. In the following sections, the results of a turbine meter, an ultrasonic meter and the reference Coriolis meters are presented.

3.1 Turbine meter

The response of the 8″ Elster turbine meter is given in Fig. 11 to Fig. 13. First the response of the meter as a function of flow rate is presented which clearly shows the typical behaviour of a turbine meter, i.e. the decrease of the measurement error at low flow rates due to the bearing friction. It is known that the bearing friction become more dominant at lower pressures, which is also observed in Fig. 11. The meter has a Q_{min} of 50 m^3/h, where the negative bias becomes lower than 0.5%.

Part of the deviations observed between the CO_2-rich data sets and the Groningen gas data set (when presented as function of flow rate) disappear when plotting the results as a function of Reynolds number, see Fig. 12. This demonstrates that the meter is a Reynolds meter and also that the difference in bearing friction effect is minimal for the current gas/pressure combinations. Fig. 13 shows the same data as a function of Reynolds number, however the repeat points are averaged; and the calibration curve on Groningen gas 1 and its uncertainty band is presented as well. Most of the test points are well within the uncertainty band of the calibration curve with one exception for high pressure 95% CO_2. Another important observation is that the CO_2 test sets contain values of the Reynolds number which are an approximate factor of 2 larger. This means that the calibration curve on the Groningen gas 1 data will be extrapolated and clearly the extrapolation is not following the CO_2 gas behaviour. Therefore, care should be taken when extrapolating a calibration curve outside it intended range.

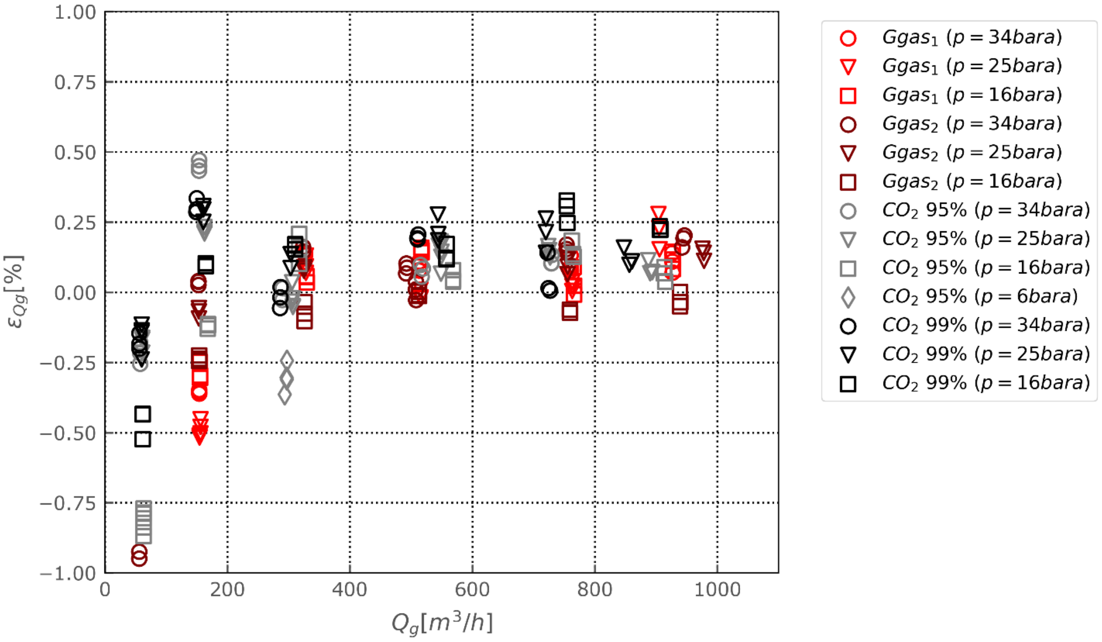

Fig. 11 – Deviation of Elster turbine meter as function of volume flow rate for different gases and pressures

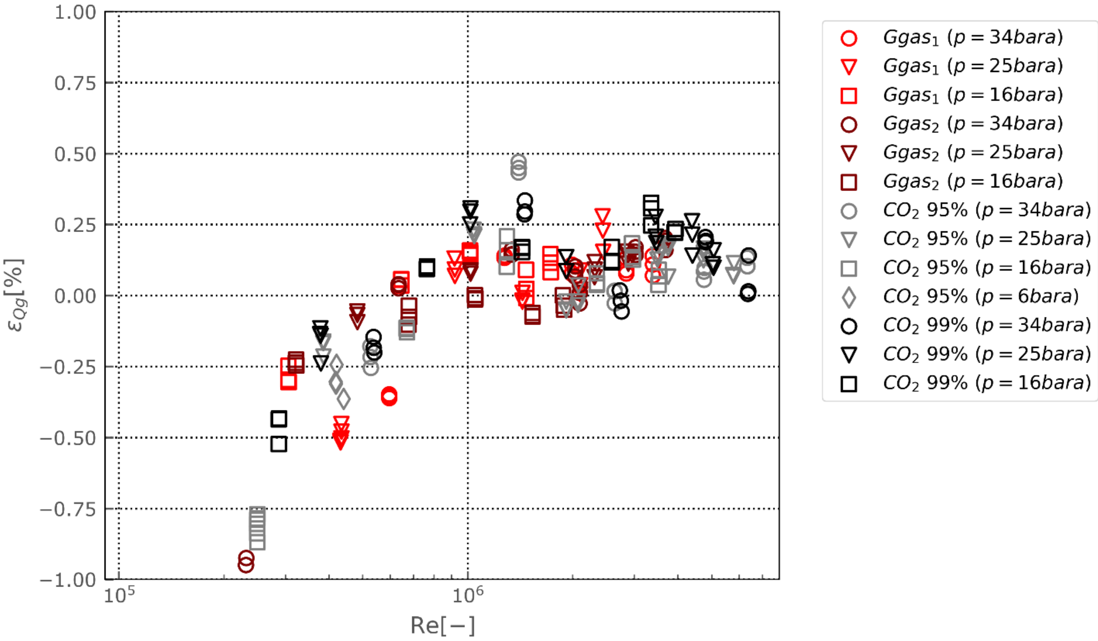

Fig. 12 – Deviation of Elster turbine meter as function of Reynolds number for different gases and pressures

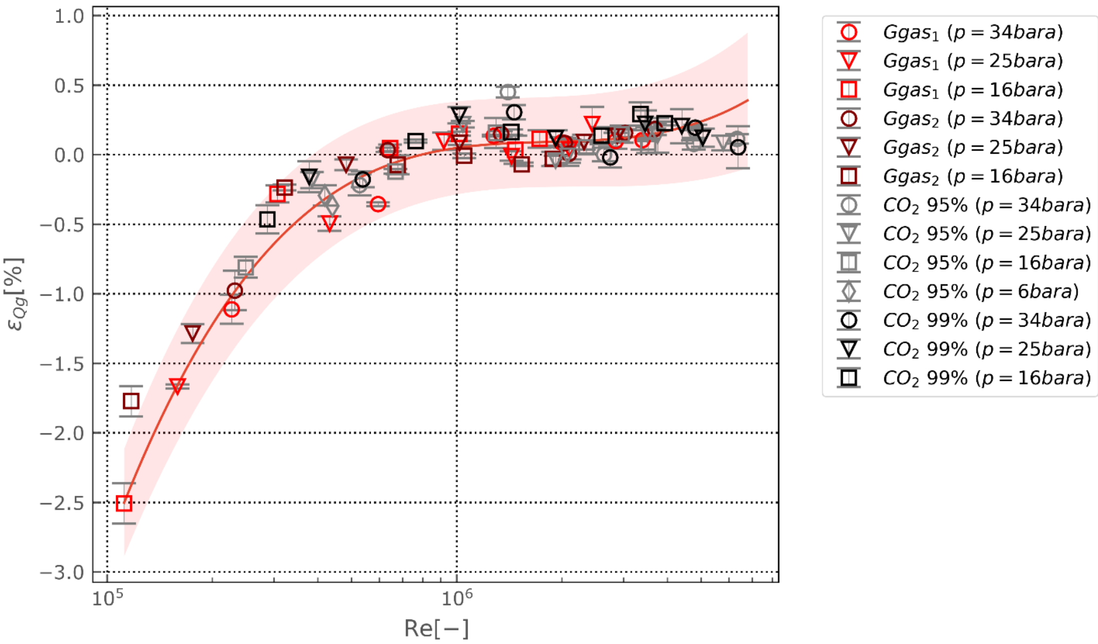

Fig. 13 – Deviation of Elster turbine meter as function of Reynolds number for different gases and pressures; red line indicates least square fit of Groningen gas 1 data, red shaded area indicates reference uncertainty, error bars indicate repeatability of measurement point

3.2 Ultrasonic meter

The Krohne ultrasonic flow meter used in the performance test is a standard custody transfer meter for natural gas applications and the meter was not physically modified for the CO_2-rich tests. The response of this ultrasonic meter is given in Fig. 14 to Fig. 16. First, the response of the meter as a function of flow rate is presented which shows an apparent offset between the natural gas and CO_2-rich results. This offset is partly due to the Reynolds behaviour of the ultrasonic meter and presenting the results as a function of Reynolds leads to more consistent results, see Fig. 15.

Plotting the results as a function of Reynolds number reveals a consistent trend between the Groningen gas 1 and the CO_2-rich data set. The Groningen gas 2 data set was run with the settings of the meter for CO_2-rich conditions, demonstrating the sensitivity of the meter to incorrect medium settings.

Fig. 16 shows the same data as a function of Reynolds number, however the repeat points are averaged; and the calibration curve on Groningen gas 1 and its uncertainty band is presented as well. Most of the CO_2-rich test points are well within the uncertainty band of the calibration curve. As for the turbine meter, the calibration curve is extrapolated to higher Reynolds numbers where it does not follow the trend of the CO_2-rich data points. Therefore, the same precautions need to be taken when using natural gas calibration curves for CO_2 applications.

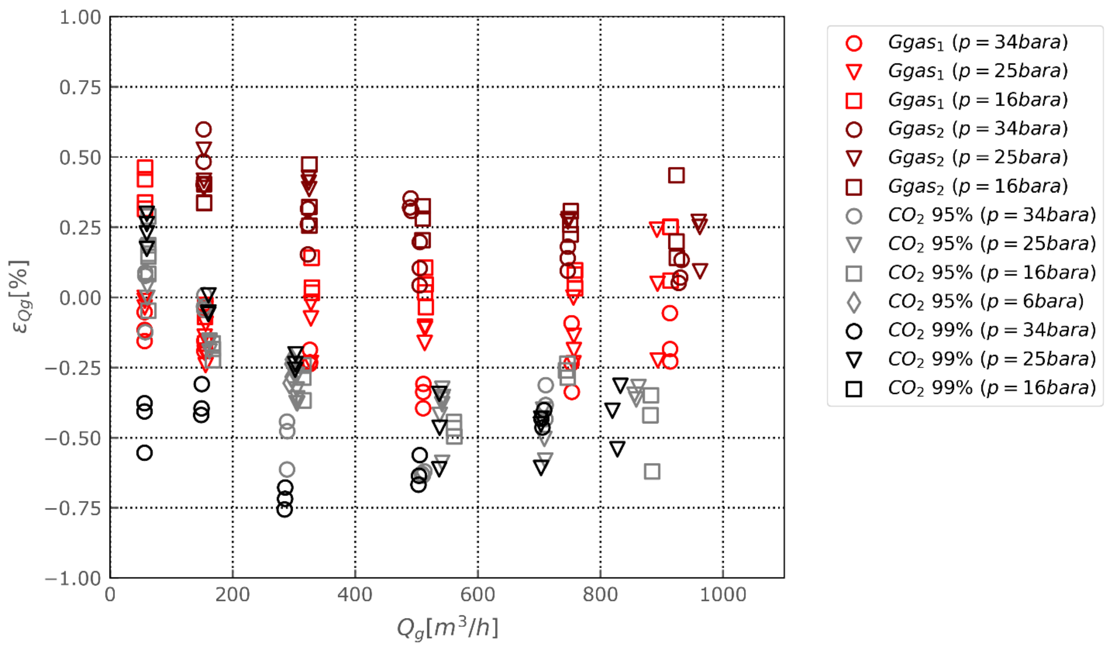

Fig. 14 – Deviation of Krohne ultrasonic meter as function of volume flow rate for different gases and pressures

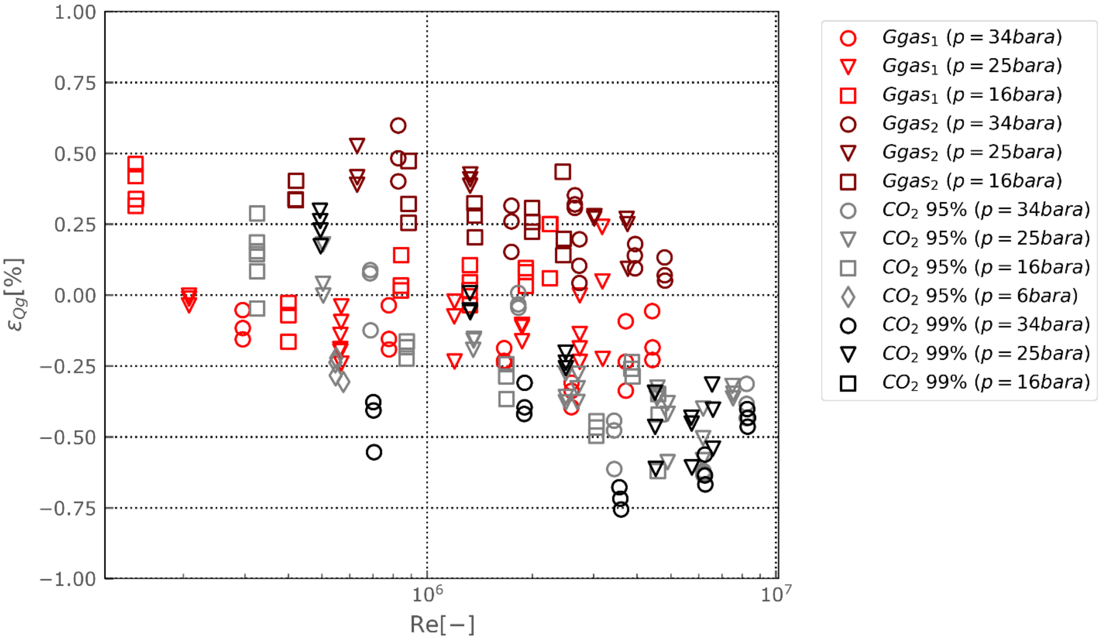

Fig. 15 – Deviation of Krohne ultrasonic meter as function of Reynolds number for different gases and pressures

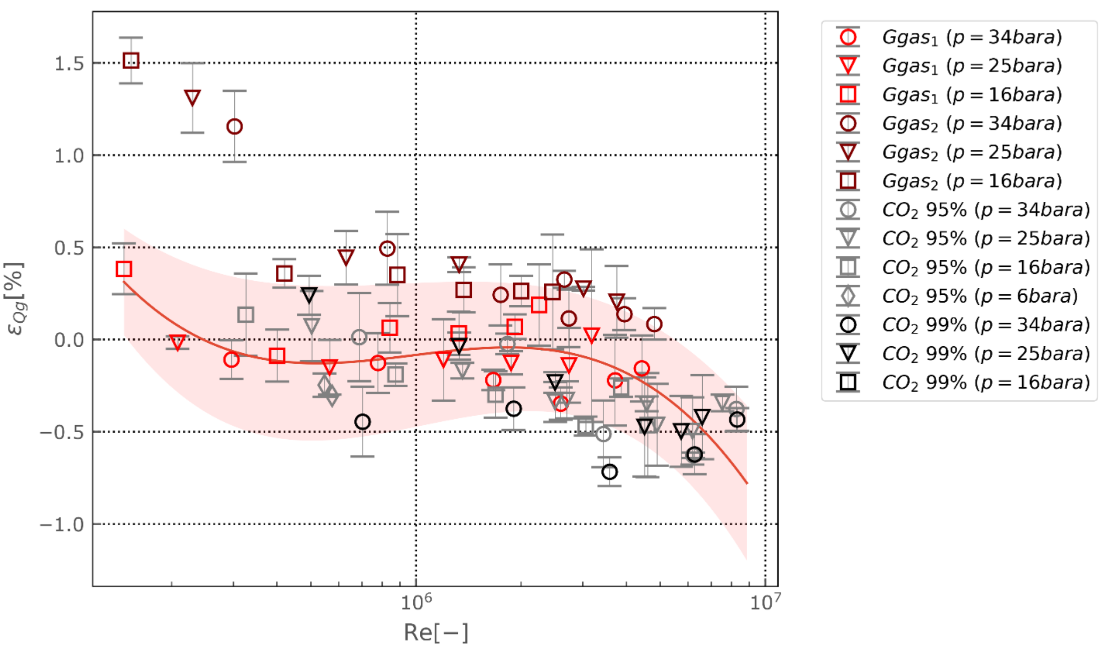

Fig. 16 – Deviation of Krohne ultrasonic meter as function of Reynolds number for different gases and pressures; red line indicates least square fit of Groningen gas 1 data, red shaded area indicates reference uncertainty, error bars indicate repeatability of measurement point

3.3 Coriolis meters

The response of the Coriolis reference meters is given in Fig. 17. Since these Coriolis meters are also part of the reference flow rates, the assessment is not fully independent. However, the weight factor of the Coriolis meters in the total reference flow is small. The response of the meter as a function of volume flow rate shows the use of the two different meters, where the CMF200 is used up to 300m^3/h, and above this flow rate both meters are used in parallel. Typically, 75% of the total flow rate is directed via the CMF300 line when operating in parallel.

The Coriolis meters were calibrated on water. For the application of the meters under multiple pressures and different gas mixtures, a pressure correction [2] and a speed of sound correction [4] was applied. Both corrections are based on initial input from the meter vendor before the test.

It is clear from Fig. 17 that the Coriolis meters produce repeatable results within 0.2%. Only a small negative bias of approximately -0.1% can be observed for the CMF200 for CO_2-rich gases, however, strong statistical conclusions cannot be drawn since the assessment method has a claimed uncertainty of ~0.3%. The pressure correction and speed of sound correction depend on the meter vendor and meter size and need to be quantified to enable the correction under CO_2-rich gases.

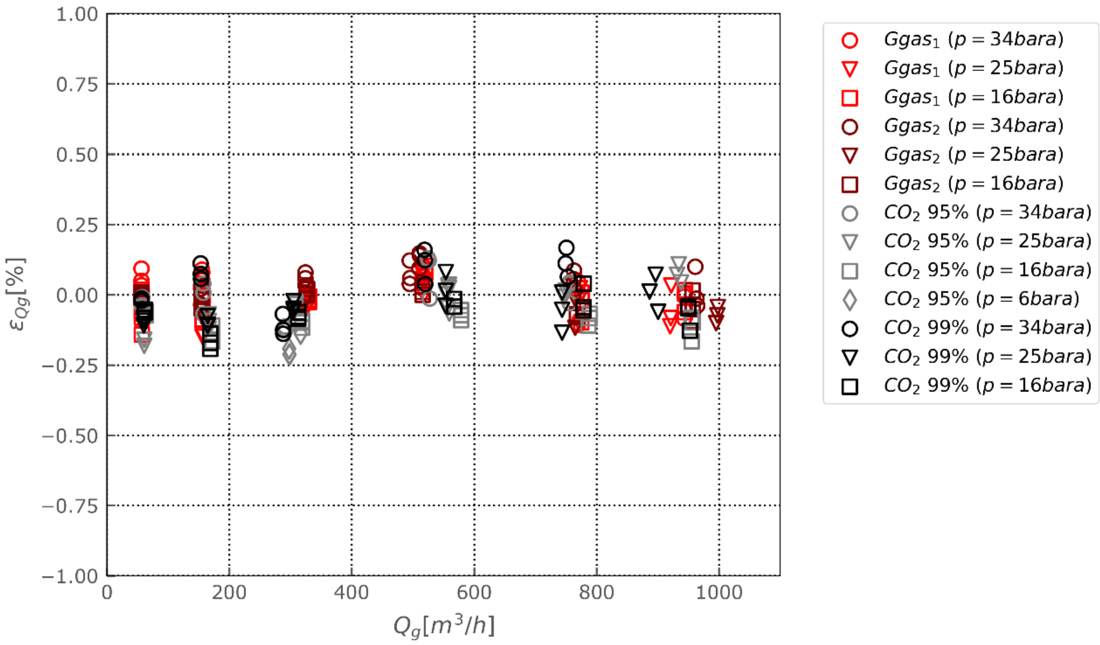

Fig. 17 – Deviation of Coriolis meter as function of volume flow rate for different gases and pressures

4 CONCLUSIONS

The effect of CO_2-rich gases on flow meters can be significant. Especially, flow meters that are affected by the molecular attenuation properties of CO_2, i.e. ultrasonic meters. Part of the influence can be reduced by proper transducer design and the choice of operating frequency. The influence of CO_2 on ultrasonic technology can be studied relatively easy by zero-flow tests. Also, small variations in operating conditions in term of pressure and CO_2 concentration can be investigated. The presented results showed that small variations in CO_2 concentration may lead to large differences in the signal transmission.

The performance of the turbine meter for the different gases was within the uncertainty claim of the facility. This further strengthens the confidence in the reference system and shows the good reproducibility and transferability of this technology under different gases.

The ultrasonic meter demonstrated the typical Reynolds behaviour, however with larger scatter than expected. The test sets of Groningen gas 1 and 2 did not reproduce well due to different meter settings. The difference of the meter response between Groningen gas 1 and CO_2-rich gases was within the uncertainty of the assessment method. This indicates that the settings of the meter have a larger impact on the meter performance than the transferability to different gases. Due to the challenging CO_2 conditions, the meter settings are important for ultrasonic meters.

The Coriolis technology required a pressure and speed of sound correction when applied to compressible gas streams. When applying these theoretical corrections, the tested Coriolis meters reproduce well at the tested conditions and showed a very consistent behaviour within 0.2% of the reference flow rates.

5 NOTATION

Abbreviations

CMC	calibration measurement capability
CMF	Coriolis mass flow
SN	sonic nozzles
TM	turbine meter

Latin symbols

c	speed of sound	[m/s]
f	transducer frequency	[Hz]
$\dot{m}$	mass flow rate	[kg/h]
p	pressure	[bara]
Q	volume flow rate	[m³/h]
Re	Reynolds number	[-]
U^*	relative expanded uncertainty	[-]
w	weight factor	[-]

Greek symbols

α	attenuation	[1/m]
ε	deviation	[%]
λ	wave length	[m]

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