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Technical Paper

Can a water flow calibration transfer to dense phase carbon dioxide with the presence of impurities?

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1. INTRODUCTION

The development of Carbon Capture, Utilisation and Storage (CCUS) has been gaining momentum in recent years as government incentives and commercial contracts are put in place to build the regulatory framework [1], [2]. This momentum has resulted in a near doubling in capture capacity in the last three years, a trend which is likely to continue [3]. To meet the regulatory and commercial requirements, the amount of CO_2 captured and stored needs to be measured accurately. For this accurate measurement to be validated, the custody transfer flow meters will require calibration in conditions which are analogous to their operating conditions. Currently, however, there are no liquid or dense phase CO_2 calibration facilities available which have ISO 17025 accreditation or that can meet the flow rates required to simulate CCUS pipeline flow [4]. It is therefore likely that CCUS operators will choose to calibrate these meters in an alternative fluid such as water.

Recent studies have given promising initial results to suggest that some flow meters can be calibrated in water for use in liquid and dense phase pure CO_2 [5], [6], [7]. To build confidence in the validity of this approach, it is imperative that further work is completed to corroborate and expand upon the previous research.

The CCUS transport and storage network is expected to cover the range of dense phase conditions up to and above 200 bar with temperatures into the thermodynamic supercritical phase. CCUS pipelines will also include small quantities (typically below 5% mole in total) of impurities relating to the process from which the CO_2 has been captured [4]. It is known that the presence of these impurities can open two-phase regions in the phase diagrams, however, very little is known about their effect on the accuracy of flow measurement and whether the inclusion of these impurities can render a water calibration unusable in these conditions.

To answer these questions the TÜV SÜD National Engineering Laboratory has undertaken an experimental campaign to build on their previous work on the transferability of calibration between water and CO_2 [5]. This work aims to validate the results published in 2024, extending the data available to a 2-inch Coriolis meter. The work then goes on to investigate whether a water calibration would still apply to a flow meter when selected impurities were present in the stream.

2. EXPERIMENTAL SETUP

A transfer package containing five flow meters, associated pipework and secondary instrumentation were installed at NEL's water calibration facility (ISO 17025 accredited) and calibrated against the facility reference meters at 20 °C, 30 °C and 40 °C across the range of 1 – 9 kg/s. A standalone mobile data acquisition enclosure (DAQ) was constructed and validated against the results from NEL's elevated pressure and temperature oil facility (EPAT) where a pressure correction for the Coriolis meters was also validated.

The transfer package contained one orifice meter, two ultrasonic clamp-on meters and two Coriolis meters in series. The flow meter package contained one Zanker type flow conditioner

8.5 straight pipe diameters upstream of the orifice plate. Upstream of the orifice flow conditioner there was approximately 86 pipe diameters of straight pipe. Two Coriolis meters were installed downstream of the orifice meter. The Coriolis results reported in this article are for the first Coriolis (FT3) located 15 straight pipe diameters downstream of the orifice plate. The results for the second Coriolis meter are not reported here.

The orifice plate had a nominal diameter ratio of β = 0.6, with an orifice diameter of 29.532 mm and the pipe internal diameter was 49.22 mm. The orifice plate and associated pipework was calibrated against the NEL water calibration facility in 2022 [5] to determine the measured discharge coefficient, and then validated against the NEL water calibration facility in 2024 to ensure the stability of the discharge coefficient. This calibrated discharge coefficient was then used in the calculation of the reported flow rate through the orifice. This meter was used as the reference flow meter for the reported results.

Two clamp-on ultrasonic meters and another 2-inch Coriolis were also included in the transfer package but are not reported here.

Table 1 - Transfer Package Specification

Tag Number	**Meter Type**	**Size**	**Manufacturer**	**Model**
FT1	Orifice 0.6 Beta	2 inch	McMennon	Compliant with ISO 5167
FT3	Coriolis	2 inch	KROHNE	Optimass 6400C H50

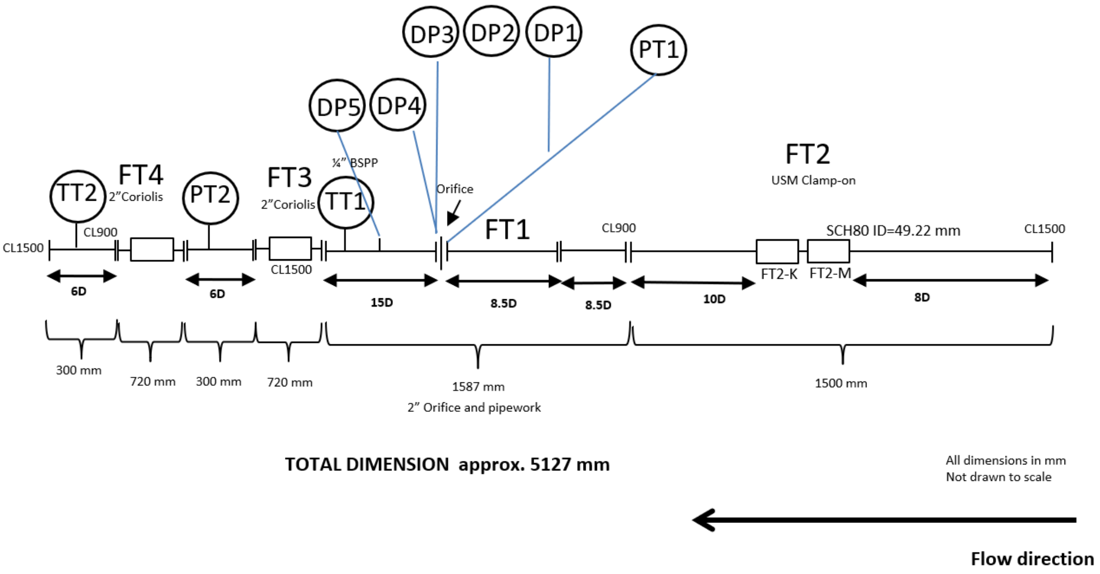

Figure 1 - Transfer Package Design Drawing

Before starting each test pressure and temperature condition, the Coriolis meters and the orifice meter differential pressure transmitters (DP) were zeroed, and their zero values recorded. The flow was then restarted and allowed to run until stability in pressure, temperature and flow was achieved. At this point the data recording was started for a period of 3 minutes and repeated 3 times to ensure stability and repeatability of the results. This procedure along with the transfer package setup was kept consistent between the test facilities and test conditions.

The data obtained from the water calibration was used as a baseline from which to compare the CO_2 results. No calibration offset was applied to the Coriolis meter and the data was recorded via the Modbus Mass Flow output.

Figure 2 - Test line setup at IFE, Oslo

2.1. CO_2 Test Conditions

To validate the conclusions of previous work, the transfer package was first tested in water at NEL and then tested with pure CO_2 (industrial grade) across eight pressure and temperature conditions as shown in Figure 3. The tests with CO_2 were carried out at Institute for Energy Technology's (IFE) FALCON liquid CO_2 flow facility in Kjeller, Norway. Once the tests in pure CO_2 were completed, impurities were added to the stream and the impurities levels checked with a gas chromatograph and a laser spectrometer (Optical Feedback Cavity Enhanced Absorption Spectroscopy). The measured composition is reported in Table 2.

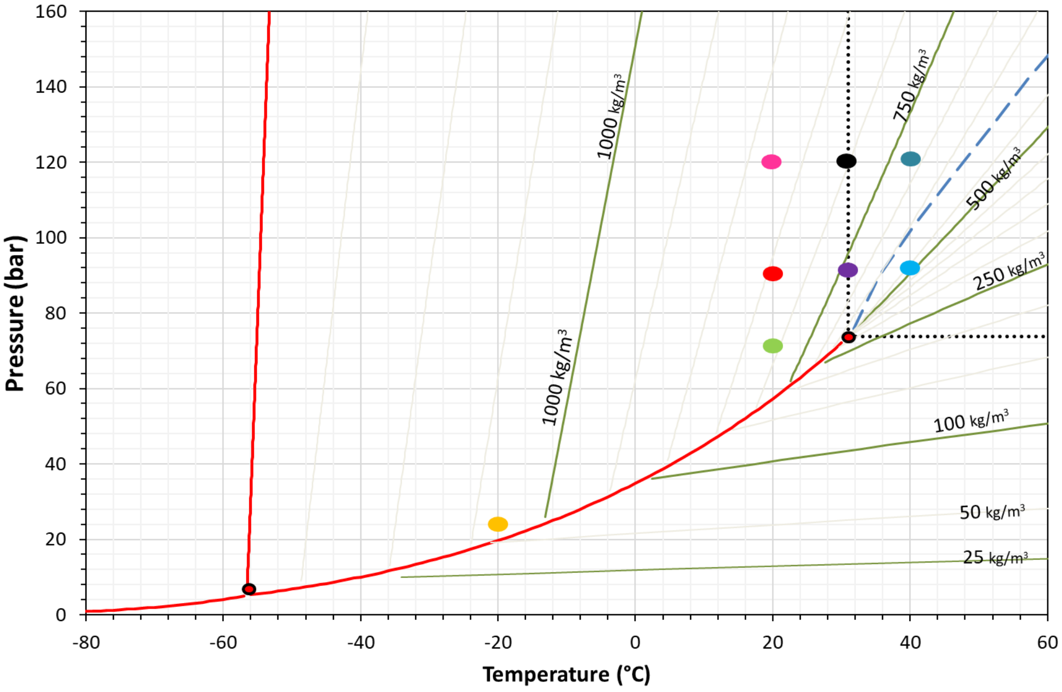

Figure 3 - Pure CO_2 phase diagram showing the locations of each set of each test conditions.

The addition of these impurities appeared to have a profound effect on the phase diagram, opening a large two-phase region and moving the critical point. To ensure the tests were conducted in single phase liquid or supercritical only, a select number of fluid conditions were repeated, these conditions are reported in Table 3. It should be noted that only a sample of the tests results collected in both pure CO_2 and CO_2 rich mixture are presented in this article, and the full dataset analysis will be presented in subsequent publications.

Table 2 - Measured Composition of CO_2 rich mixture

Component	Composition [mol%]
CO_2	94.83 %
N_2	2.28 %
CH_4	2.37 %

Table 3 - Conditions tested with CO_2 rich mixture.

Phase	Pressure [bar [g]	Temperature [ºC]	Nominal Density [kg/m³]	Flow Range [kg/s]	Results presented here
Liquid	50	-20	1033	1.5 - 6	No
Liquid (Dense Phase)	90	20	766	1 – 4.5	Yes
Liquid (Dense Phase)	90	30	634	1 – 3.3	No
Liquid (Dense Phase)	120	20	816	1.5 – 4.7	Yes
Supercritical	120	40	637	1.5 – 3.8	Yes

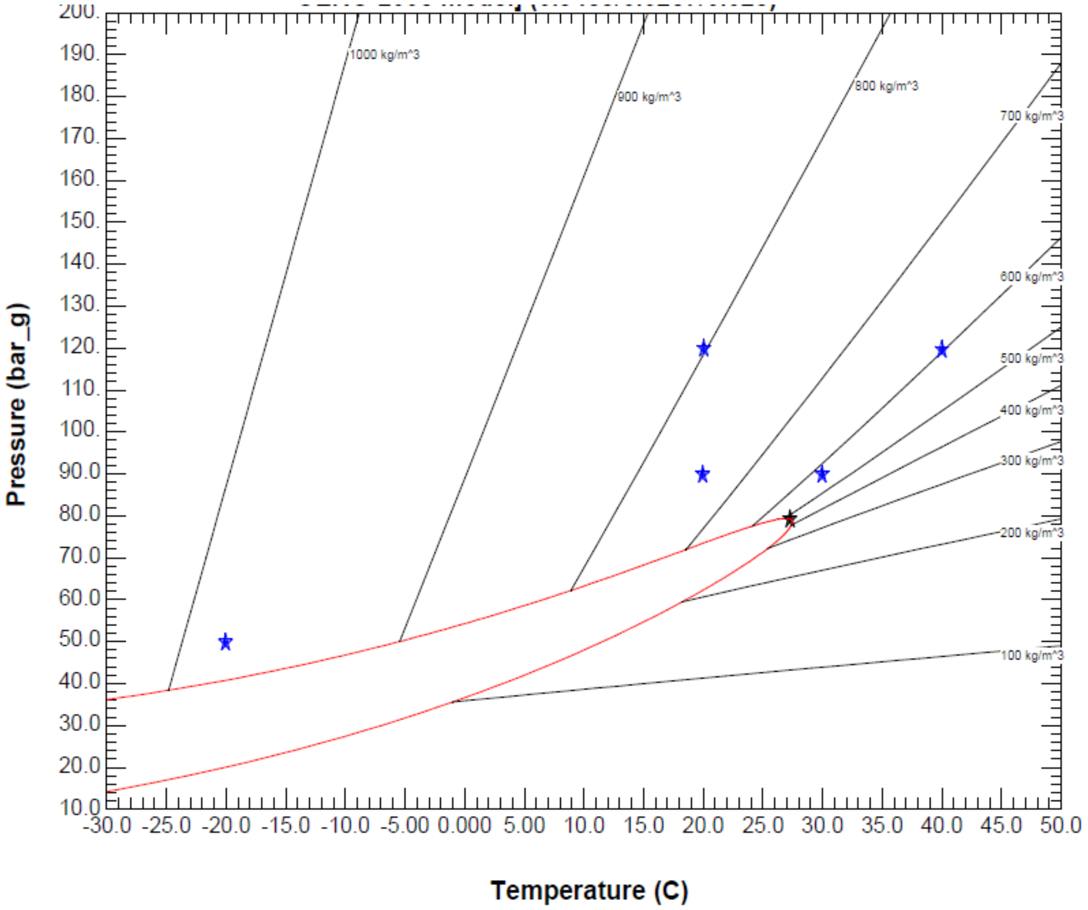

Figure 4 - Phase diagram of the tested CO_2 mixture with the tested conditions highlighted in blue. Diagram generated using the GERG-2008 Equation of State as implemented in REFPROP.

2.2. Calculations

The calculations used to determine the mass flow rate through the orifice are found in section 2.3 of reference [5], see equations 1 – 5.

The density output for the Coriolis meter was calibrated at the NEL densitometer calibration facility and a correction was applied.

The mass flow output was corrected for process pressure and compressibility effects as follows [8]:

$$q_{m,\ corrected} = q_{m,measured} \cdot \frac{1}{1 + a_p(p - p_{cal})} \cdot \frac{1}{1 + a_c \frac{1}{2}(\frac{\omega}{c} r)^2} \qquad \text{Equation 1}$$

Where $a_p = -0.005$ %/bar and is the manufacturer's pressure correction specification, p is the test pressure, p_{cal} is the factory calibration pressure and was equal to 0.58 bar. The coefficient,

a_c was taken as 1, while $\omega = 2\pi f_{tube}$ where f_{tube} is the Coriolis tube frequency, c is the fluid speed of sound and r is the Coriolis tube internal radius.

The error of the mass flow output from the Coriolis meter is reported in relative terms to the orifice meter using the equation below:

$$E_{\%} = \frac{q_{Coriolis} - q_{Orifice}}{q_{Orifice}} * 100 \qquad \text{Equation 2}$$

3. RESULTS

3.1. Reference Orifice Meter Calibration

The calibrated discharge coefficient developed from tests completed in 2022 [5] was validated against the NEL water calibration facility and NEL Gaseous CO_2 facility reference master meters. The orifice meter was calibrated across a Reynolds range of $4.5\text{x}10^4 – 3.2\text{x}10^6$ and the resulting measured discharge coefficient was within ±0.2 % of the fitted discharge coefficient developed in 2022. This orifice meter and calibrated discharge coefficient was subsequently used as the reference in the results reported below.

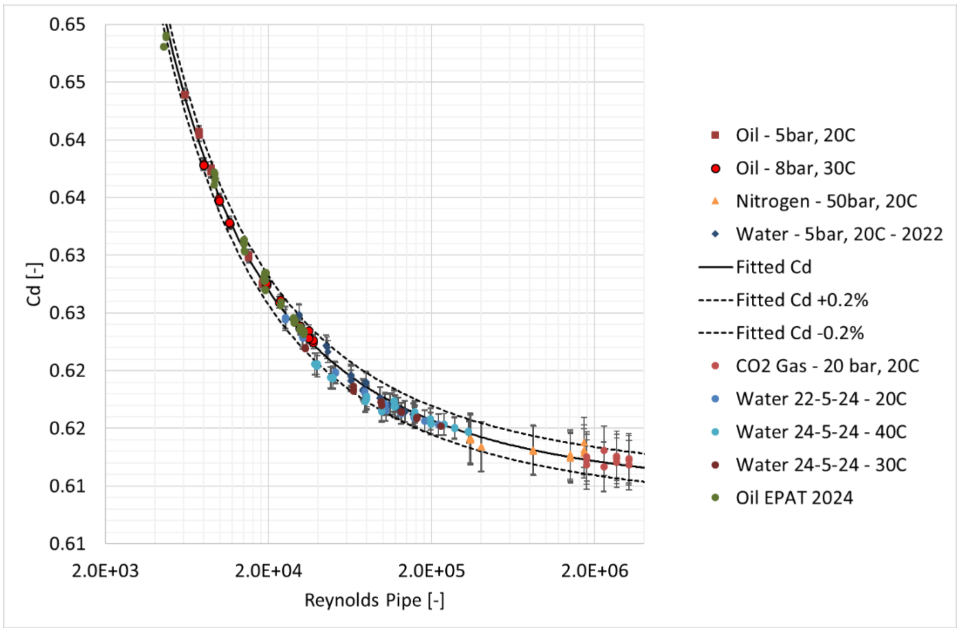

Figure 5 - 2-inch Orifice Discharge Coefficient Data

3.2. 2-inch Coriolis Meter Results in Pure CO_2

The 2-inch Coriolis meter shows good agreement to the orifice when tested in water at 20 ºC with a maximum discrepancy of ±0.067 %. For these tests the Coriolis meter was tested as out of the box except for a process pressure correction as described in Equation 1 and the zero procedure. The water results are well within the uncertainty for both the water facility and the orifice meter used as a reference in the CO_2 tests.

When tested in liquid CO_2 at 90 bar and 120 bar at 20 ºC the discrepancy between the orifice and Coriolis meter was within ±0.21 % and when tested in the supercritical region at 120 bar, 40 ºC the discrepancy was within ±0.17 %. Overall, no bias was observed between the results in water and the results presented in CO_2 across the three fluid conditions and any discrepancy in the results was within the uncertainty of the reference orifice meter, see Figure 6.

For the results presented in Figure 6, the density used in the reference orifice mass flow calculation came from the calibrated density output from the tested 2-inch Coriolis meter. The remaining fluid properties of viscosity and isentropic exponent came from the Span & Wagner equation of state for pure CO_2, using local measurements of pressure and temperature as the input.

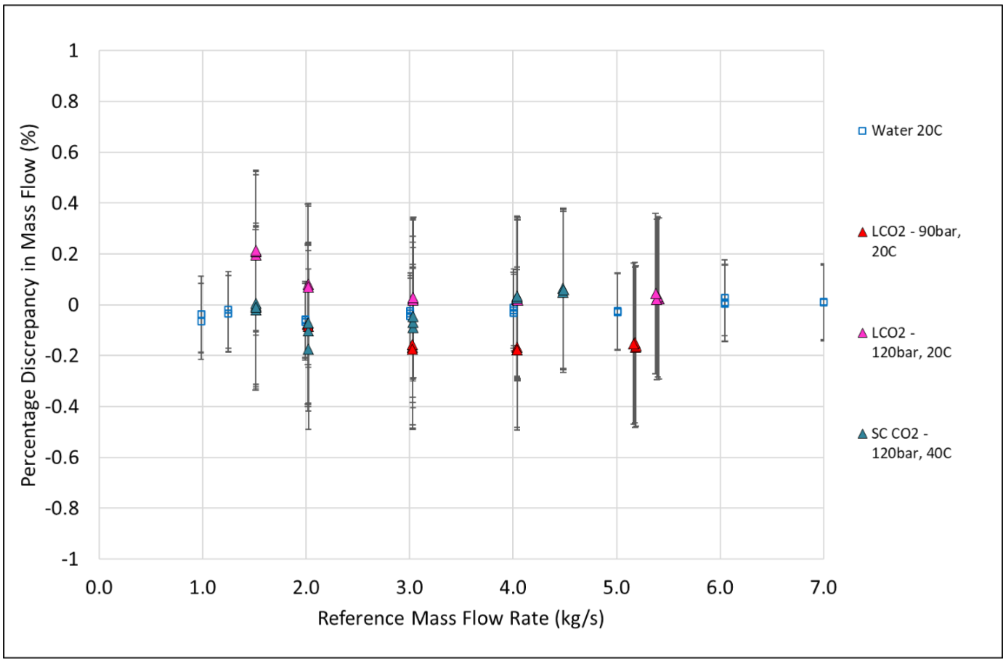

Figure 6 - Coriolis meter mass flow error in pure CO_2 when using the measured density input to the reference orifice meter equation.

3.3. 2-inch Coriolis Meter Results in CO_2 Rich Mixture

Following tests in pure CO_2, the impurities of nitrogen and methane were added to the CO_2 stream at the concentrations outlined in Table 2, the test conditions were repeated across the same flow range.

When the density used in the calculation of the reference orifice came from the Coriolis meter, the discrepancy was within ± 0.28% with no observable bias outside of the reference uncertainty, see Figure 7. The viscosity and isentropic exponent were determined by using the GERG-2008 Equation of State based on the impurity levels measured by the gas chromatograph and laser spectrometer at IFE.

When the GERG-2008 equation of state is employed for the determination of the density for use in the reference orifice equation, the resulting discrepancy shows a significant change, see Figure 8. The discrepancy shows a strong bias with decreasing density ranging from +0.6% at 120 bar, 20 ºC to +2 % at 120 bar, 40 ºC. No other changes are made in the preparation of these results beyond changing the source of density in the reference orifice calculation.

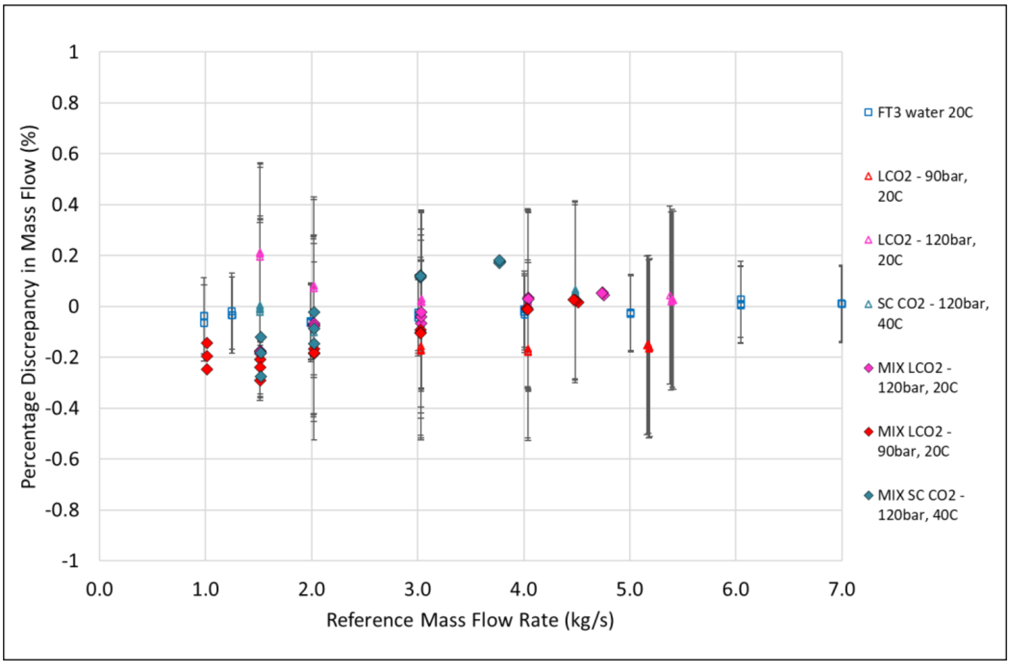

Figure 7 - Coriolis meter mass flow error in a CO_2 rich mixture when using the measured density input to the reference orifice meter equation.

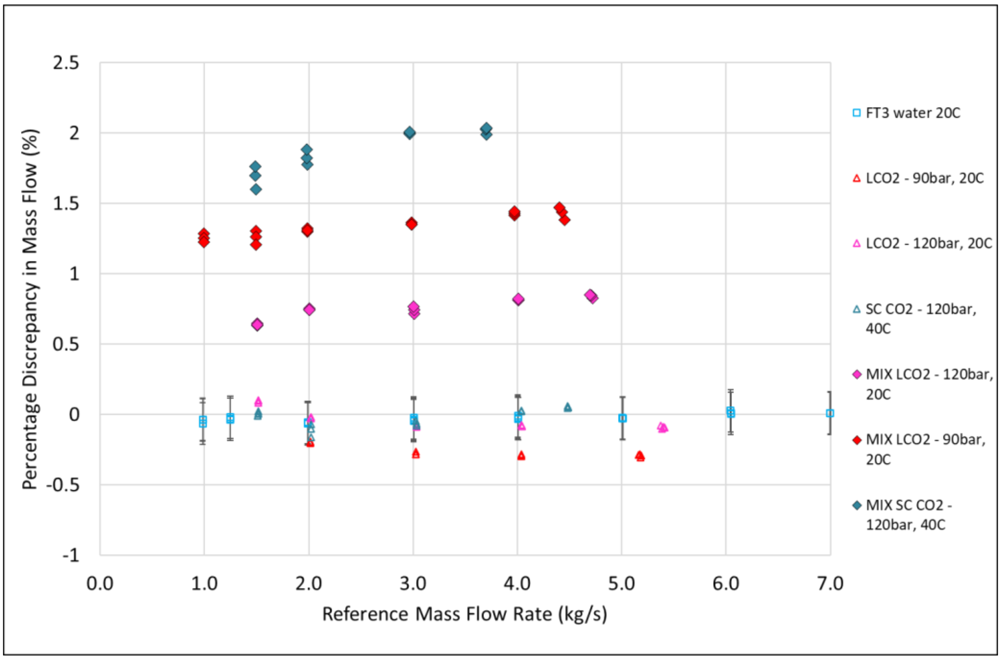

Figure 8 - Coriolis meter mass flow error in a CO_2 rich mixture when using the GERG-2008 density input to the reference orifice meter equation.

4. CONCLUSIONS

A 2-inch Coriolis meter was tested against a 2-inch 0.6 beta Orifice meter to determine whether a water calibration could be used in liquid and supercritical CO_2 with the presence of selected impurities. This follows on from a study completed by the authors with smaller meter sizes and using only pure CO2.

For this investigation, a transfer package was tested at the TÜV SÜD National Engineering Laboratory (NEL) in water and oil. The oil calibration was used to determine the response of the Coriolis meter to increasing process pressure which was then corrected for in the following CO_2 tests. The transfer package was then tested at the Institute for Energy Technology's (IFE) FALCON liquid CO_2 flow facility in Kjeller, Norway. In the absence of a traceable reference flow standard, the 2-inch orifice meter was calibrated at NEL with water, oil and nitrogen and used as the reference meter to conduct a relative comparison.

In water the discrepancy between the 2-inch Coriolis and orifice meters was within ±0.08 %. In pure CO_2, the discrepancy was within ±0.21 % with no observable bias from the water tests in the conditions presented. The results are well within the uncertainty of the reference orifice meter. These results agree with the observations made by the authors when testing a 1-inch Coriolis meter from a different manufacturer in similar conditions [5].

When Nitrogen and Methane were added to the CO_2 stream at concentrations of 2.28 % and 2.37 % respectively, the discrepancy stayed consistent with the results in pure CO_2 with a maximum discrepancy of ±0.28 % and no observable bias. For these results the density used in the orifice meter mass flow calculation came from the density output from the 2-inch Coriolis meter which had been calibrated at the NEL Densitometer facility.

When the GERG-2008 equation of state was employed for the density calculation at the orifice, including the additional impurities, the discrepancy increased significantly and showed some dependence on the density of the process fluid. This discrepancy range was 0.6 – 2.0 %. Currently more analysis of the results is needed to draw firm conclusions on the reason for the notable difference between the two methods of determining density. Notably, these results should prompt caution in relying solely on equations of state for determining density of liquid and supercritical CO_2, especially in the presence of impurities. Until these effects are fully understood, it is recommended to employ direct density measurement in cases where measurement uncertainty is critical.

When the density is measured directly, the results suggest that a water calibration of a 2-inch Coriolis meter can be effectively transferred to liquid and supercritical CO_2 flow measurement.

5. NOTATION

Notation should be included at the end of your paper and, if space is at a premium, it may be presented in two columns as follows:

a_p	Process pressure correction coefficient
CCUS	Carbon Capture, Utilisation and Storage
CO_2	Carbon Dioxide
DP	Differential Pressure Transmitter
$E_{\%}$	Percentage Error

p	Static Pressure
q_m	Mass Flow Rate
β	Orifice nominal diameter ratio

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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