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Technical Paper

Investigation of Coriolis Meter Performance under Liquid, Dense, and Supercritical CCS Transport Conditions

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1 INTRODUCTION

The commercial deployment of Carbon Capture and Storage (CCS) relies on an efficient operation of CO_2 Transport and Storage (T&S) networks. Several interconnected capture projects would require flexible and reliable networks for transporting CO_2 across CCS hubs and clusters and to the geological store [1]. Such an approach would enhance source/sink matching and accelerate commercialisation and deployment of CCS technology. Consequently, the operational activities of CCS infrastructures are expected to adhere to specific requirements set out by the regulator(s) and/or in commercial agreements. One of these activities is the flow measurement of CO_2 across the CCS chain, which represents a cash register for investment and government incentives pay-out, as well as to quantify and report annual emissions for regulatory purposes (e.g. UK or EU Emission Trading Scheme).

Accurate flow measurement of CO_2 is a prerequisite for commercialising CCS [2], [3]. Like in other process industries, investments in CCS transport and storage may lead to substantial financial exposures. However, CCS is a relatively new form of investment, with buisiness and market models currently under developement. Therefore, an assurance of minimal cross-chain performance risk across CCS networks becomes imperative. In practical terms, and in the context of custody transfer/fiscal measurement, an effective metering system is required to determine payments between the parties and ensure optimised and safe operations.

Presently, the transport conditions and thermodynamic behaviour of CO_2 make accurate measurement of CO_2 challenging. There is also a general lack of traceable experimental evidence to support the performance of flow meters and compositional analysers for CCS applications. As such, it is unclear whether current metering technologies can provide the required level of accuracy. Article 49 of the EU Monitoring and Reporting Regulation (MRR) 2018/2066 requires operators to measure the quantity of CO_2 transferred out of the installation to a capture installation, a transport network or a storage site, within ±2.5 % by mass

[4]. However, it is possible that a lower uncertainty requirement than ±2.5 % will be used for fiscal/custody transfer purposes if within current metering capabilities. It should be noted that this uncertainty requirement is for the overall metering skid and not for the flow meter(s) only. The overall metering skid uncertainty is obtained by appropriately combining the uncertainty of several primary and secondary measurements in what is called an uncertainty budget. It should also be noted that the overall uncertainty is for the CO_2 quantity and not for the total CO_2-rich flow stream (i.e. not for the flow of CO_2 and impurties together). This is quite an important point to underline as measurment of CO_2 will require measurement of the total stream composition.

There are several flow metering technologies on the market that could be potentially used for CCS applications. This work investigates one of these industry relevant and commercially available flow meters: a Coriolis mass flow meter. A Coriolis flow meter was tested under pressure and temperature conditions relevant for CCS transportation. The Coriolis flow meter perfromance was assessed against a novel gravimetric primary standard at Heriot-Watt University both with pure CO_2 and with a CO_2-rich mixture. The experimental findings are reported in this paper. To the best knowledge of the authors, this is the first time the performance of a Coriolis meter is assessed against a primary standard for dense, liquid & supercritical phase CO_2-rich mixture.

2 INVESTIGATED FLOW METER AND FLUID COMPOSITIONS

Of the available flow metering technologies, Coriolis flow metering is considered one of the commercially viable metering technologies to be deployed for CCS applications. One of the main advantages of a Coriolis meter, when compared to other technologies, is that it directly measures mass flow. Coriolis meters have the capability of handling two-phase bubbly flow [5] and are potentially immune to variation of fluid density, making them relevant in situations where determination of fluid properties is challenging. The Coriolis flow meter used in this work is a bi-directional dual tube type with a curved V-shape. The specification of the meter is summarised in Table 1. In addition, the meter is integrated with a totalizer and temperature sensor to obtain the totalized mass of fluid flowing through the measuring tubes and the temperature change in the tubes, respectively. The totalizer functions like a digital pulse counter, which is configured from the meter's transmitter. The set parameters of the totalizers are summarized in Table 2. While the meter comes with an in-built feature to automatically perform pressure compensation, no additional compensation was applied to the meter.

In the context of CCS flow measurement, flow conditions and stream compositions are the key factors to consider in CCS network operation. Although CO_2 transportion is prefered in single-phase [6], this requires maintaining the transport network within an operating window that can sustain the single-phase condition, regardless of the influence of impurities. To achieve this, CO_2 pipelines, for instance, must be operated above their cricondenbar regions (as dense fluid), or above critical point (as supercritical fluid), or below the gas-liquid transition boundary (as gaseous fluid).

Table 1 - Description of the Coriolis flow meter tested in the gravimetric CO_2 flow rig

Properties	Meter's specification
Design	OPTIMASS 6000 with MFC 400 output signal processor
Meter size	NPS - 1 inch (DN25)
Tube material	Stainless steel, 316/L
Fluid properties	Liquid, gas, slurries
Meter output	Mass flow, density, temperature, and volumetric flow
Nominal flow	600 kg/h
Nominal pressure	-1 to 100 bar
Process temperature	-70 to 230 ^oC

NPS – nominal pipe size in inches
DN – nominal diameter in mm

Table 2 - Counter setting for Krohne Coriolis mass flow totalizers

Parameters	Description
Low flow cut-off (kg/h)	0.65 ± 0.05
Time constant (s)	0.00
Preset value (kg)	2
Measurement direction	Incremental total

The presence of impurities generally alters both the thermodynamic and transport properties of CO_2 [2]. For instance, according to a study by Chapoy *et al*. [7], impurities from the capture or separation unit can lower the density of CO_2 stream by up to 35 %. This significantly affects the transport process, especially when the single flow condition of the stream is compromised. Hence, evaluating this potential impact on flow measurement of CO_2-rich streams would provide more understanding of CCS flow measurement.

The CO_2 composition detailed in this study, was selected considering the relevant non-condensable impurities associated with the oxy-combustion CO_2 capture technologies. The composition also reflects an impurity concentration within the framework of European CCS transport operation [8], [9]. A description of the mixture used in this investigation, and the pure CO_2, is highlighted in Table 3. Both the CO_2-rich mixture and pure CO_2 were supplied and certified by BOC. The supplier analytically validated the mixtures using gas chromatography as specified in ISO 6142.

Table 3 - Composition of the investigated CO_2 stream

Component	Pure CO_2 (mol%)	CO_2 Mixture (mol%)
CO_2	99.9995	97.496 (balance)
N_2	-	1.50 (1.46)
O_2	-	40 ppm (42)
Ar	-	1.00 (0.96)

Certified value of mixture in parenthesis

3. THERMODYNAMIC MODEL OF THE INVESTIGATED FLUIDS

The phase envelop of the CO_2-rich mixture was modelled using the National Institute of Standards and Technology (NIST) Reference Fluid Thermodynamics and Transport Properties (REFPROP) software [10]. The REFPROP software implements GERG-2008 [11] to predict the critical parameters - temperature and pressure, upon which a selected flow regime is best operated. For pure CO_2, the Span and Wager equation of state [12] assumed the default model in REFPROP. The predicted properties of the fluid are used in selecting the operating conditions of the targeted flow regimes. The phase envelope curves of the modelled stream are described in Figure 1. They represent a bubble and dew point curves that describe the conditions at which the fluids can exist under different temperatures and pressures.

The curves perfectly demonstrate the impact of impurities on T&S operation. For instance, as impurities are added to the pure CO_2 stream (left curve), a two-phase region opens up in the stream (right curve). The size of the two-phase region, which is determined by the amount and physical properties of impurities, affects the liquefaction condition of the stream. Although it is difficult to maintain a liquid or dense phase for a nonbinary CO_2 mixture, especially with %vol or %mol levels of impurities, the thermodynamic model gives an hypothetical condition at which a single phase can be maintained. In reality, the transport network must be operated above this condition to maintain a single liquid or dense phase flow.

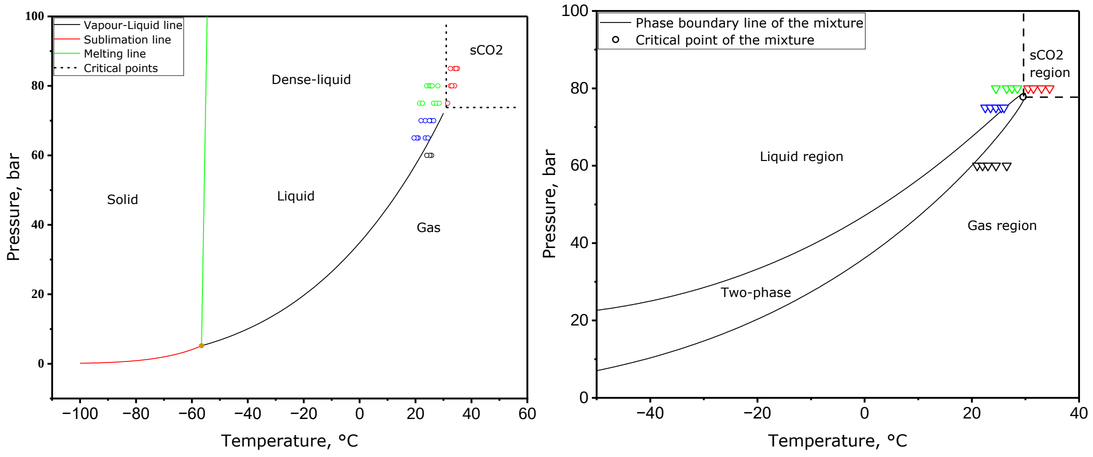

Fig. 1 - Phase curves of the investigated fluids and the flow measurement test points. The pure CO_2 on the left while the investigated CO_2-rich mixture on the right. The test points represent the average operating conditions at which the flow measurements for different flow regimes were conducted. (**O**) and (▽) are test points for pure CO_2 and the CO_2 mixture, respectively. The test points are colour-coded as black, blue, green, and red; for gas, liquid, dense, and supercritical (sCO_2) phases, respectively. It should be noted that results for gaseous test are not presented in this paper.

4. EXPERIMENTAL SET-UP AND TEST PROCEDURE

The flow measurement tests conducted in this study were based on a gravimetric principle. A gravimetric flow rig, originally developed for CO_2 flow measurement at Heriot-Watt University [13], was repurposed to allow flow measurement in dense and supercritical conditions. The Meter Under Test (MUT) was installed at the test section of the rig and was connected horizontally to the reference weighing system by small tubes (1/4" diameter). A P-700 back pressure controller incorporated with a Badger research control valve was installed downstream of the MUT. This control valve was used to regulate the flow output of the drive pump. Moreover, to minimise the flow fluctuation from the pump, a pulsation damper was installed in close proximity to the pump. The layout of the gravimetric rig is shown in Figure 2.

Crucially, the MUT was zeroed prior to starting the test once stable test conditions, particularly pressure, were reached. Zero calibration of the MUT was carried out according to the manufacturer's specifications. Zero calibration values ranging from 0.019 % - 0.035 % for the different test conditions were stored in the meter's transmitter.

To conduct a flow measurement run, CO_2 or a CO_2-rich mixture was pumped from the supply cylinder, through the MUT, to the receiving cylinder. The mass of the CO_2 or CO_2-rich mixture recovered from the MUT was compared to the totalised flow recorded by the MUT. Using Equation 1, the relative measurement error of the meter was then calculated.

$$u = 100\,(M_{rm} - \int M_t)\,/\,M_{rm} \quad (1)$$

Where $\int M_t$ represents the totalised mass from the MUT and M_{rm} represents the net weight reading from the reference weighing scale.

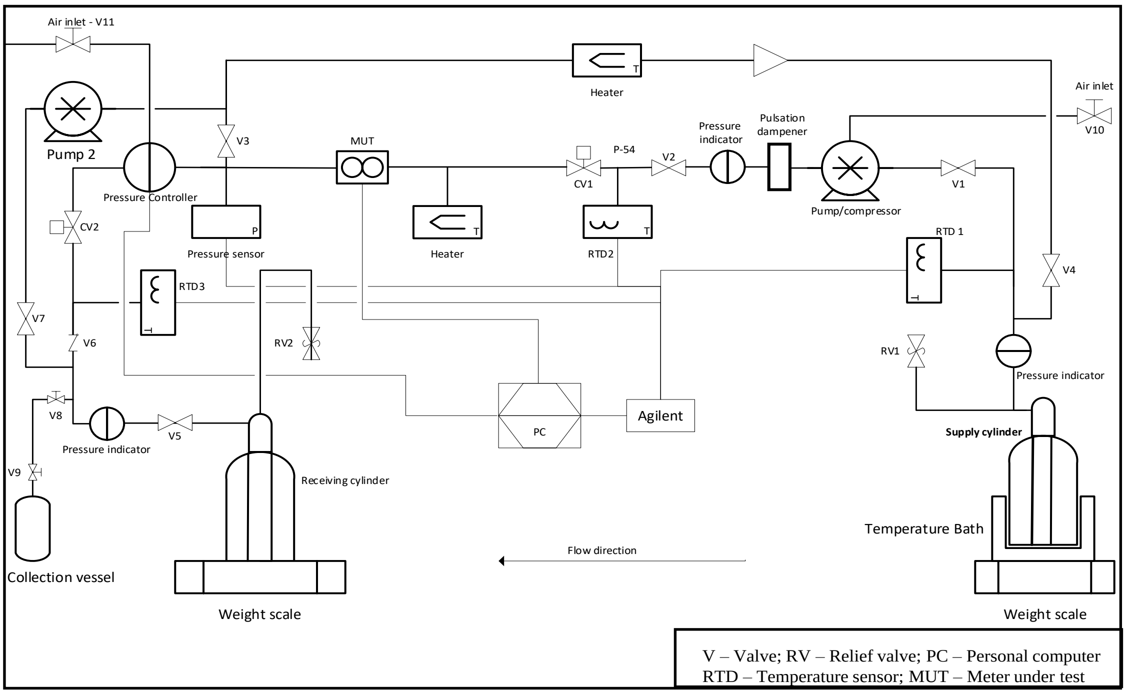

Fig. 2 - Schematic of the gravimetric flow rig designed for CO_2 flow measurement experiments.

5. RESULTS AND DISCUSSIONS

Tests were conducted with pure CO_2 and the CO_2-rich mixture in dense, liquid and supercritical states. The measurement errors of the MUT, calculated from Equation 1, are graphically presented in Figure 3. The liquid and dense phase pure CO_2 results were mostly within ±0.20 % error limits. However, for the supercritical phase, the errors offset by up to 0.25 % on the upper side, with the errors ranging from 0.37 % to 0.45 %. The measurement errors obtained for the supercritical flow also shows an under-reading behaviour of the MUT.

For the CO_2-rich mixture, the errors ranged from -0.27 % to +0.16 % for the liquid and dense phase, and 0.39 % to 0.59 % for the supercritical phase. The measurement errors for the CO_2-rich mixture at liquid, dense and supercritical conditions are not significantly different compared to that of their respective pure CO_2.

Even though some of the tests were conducted at conditions close to the phase boundary (two-phase region), all measurement errors obtained using the investigated fluid and across all the single phases are within a targeted limits of ±1 %.

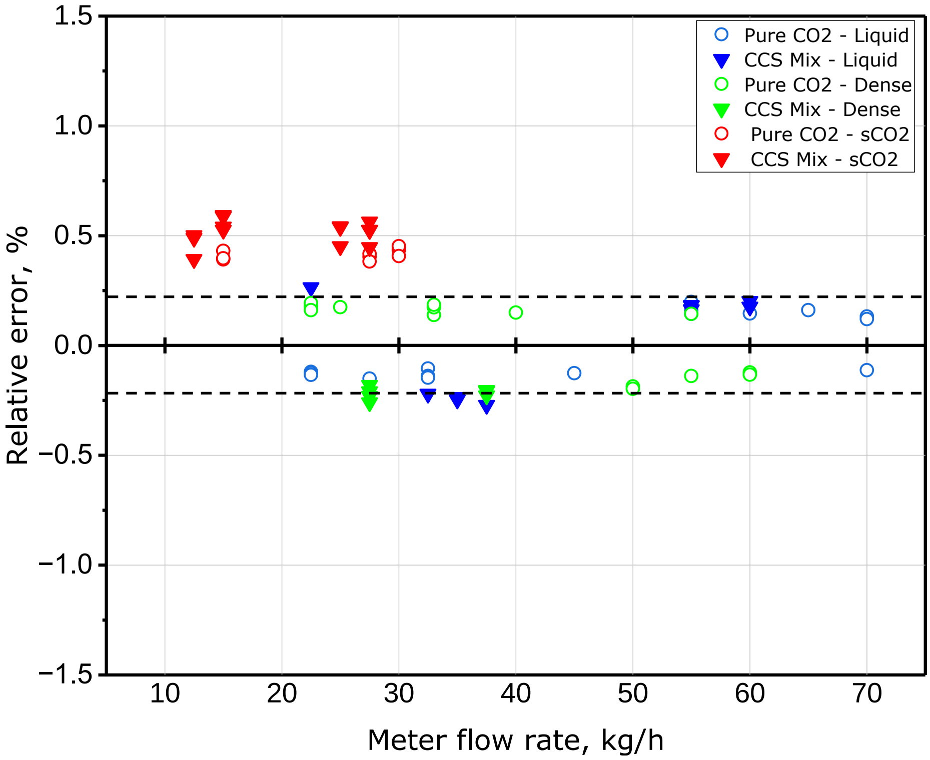

Fig. 3 - Measurement errors for the investigated Coriolis meter under liquid, dense, and supercritical conditions. (**O**) and (▼) are measurement errors for pure CO_2 and the CO_2 mixture, respectively. The blue, green, and red represent error values at liquid, dense, and supercritical conditions, while (--) represents an error limit of 0.20 %.

6. CONCLUSIONS AND FUTURE WORK

Flow measurement tests were conducted on a Coriolis flow meter using pure CO_2 and a CO_2-rich mixture in dense, liquid and supercritical conditions. The measurement results show that the flow meter performed well under each of the tested conditions, with the measurement errors well within ±1 % for all conditions, and within ±0.25 % for liquid and dense phase conditions. The measurement errors for the CO_2-rich mixture at liquid, dense and supercritical conditions are not significantly different compared to that of the pure CO_2. However, the measurement results for the supercritical conditions suggest that the meter is under-reading the flow under these conditions. Future tests would cover other industrially important candidate CO_2 flow meters and consider other impurities within the context of CCS transport. Also, tests are recommended to consider assessing the meter's performance under two-phase conditions.

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