Global Flow Measurement Workshop
25 - 27 October 2022

Extended Abstract

Ultrasonic measurement of liquid carbon dioxide

Yessica Arellano, SINTEF Energy Research
Nicholas Mollo, Panametrics, a Baker Hughes business
Sigurd Weidemann Løvseth, SINTEF Energy Research
Hans Georg Jacob Stang, SINTEF Energy Research
Gerard Bottino, Panametrics, a Baker Hughes business

---

1 INTRODUCTION

In recent years, CCS (Carbon Capture and Storage) has gained attention as a possible means of meeting our global climate improvement goals. With CCS demonstration projects under development, there is a need to focus on the widespread deployment of CCS and the technologies needed to make it viable. Upscaling CCS demand reliable and accurate metering of CO_2 for fiscal, commercial, and regulatory purposes. Accurate measurement of CO_2 streams is crosscutting along the CCS value chain and is an enabler for CCS business. Dependable flow measurements are paramount to ensuring safe operation of CCS systems, complying with regulations, and enabling global fair trade of 5 Gt of CO_2 per year by 2050, ultimately warranting the CCS business model.

Several CCS projects are currently under development. The planning and construction of the infrastructure needed to transport CO_2 from industrial capture sites to the geological storage formations are well underway in various European locations. Throughout the CCS value chain, CO_2 will be transported in multiple fluid states (see Fig. 1), i. e. , (i) as a pressurised liquid or dense phase in export or offshore pipelines, (ii) as a refrigerated liquid for long-distance bulk shipping transport, and (iii) as pressurised gas for short-distance transport onshore. The present work focuses on the former two transport methods (i. e. liquid only).

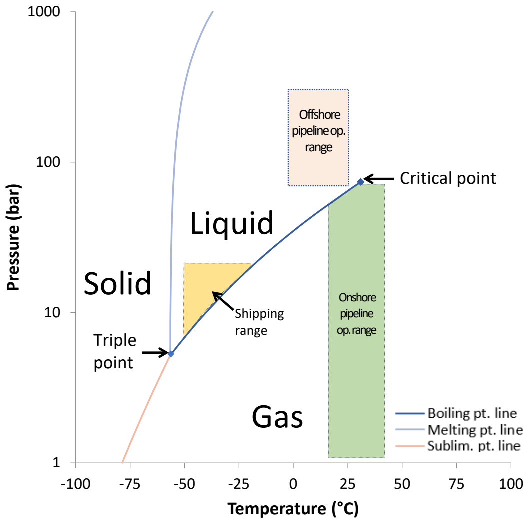


Fig. 1 – Operational conditions of CO_2 transport streams for CCS

Recent benchmarking studies agree that the CCS industry could benefit from the measurement capabilities developed and fostered in the oil and gas industry, where numerous metering techniques coexist [1, 2]. Ultrasonic flow measurement technology is promising for CCS, given the ability of such meters to handle large volumetric flow rates through large pipe sizes using a single metering unit. To date, verification tests of the ultrasonic technology for measuring liquid CO_2 have been limited to enhanced oil or gas recovery (EOR or EGR) operations or extraction of CO_2-rich natural gas. The potential use of ultrasonic meters for CCS has yet to be thoroughly tested and confirmed.

In this context, the present study highlights the capabilities and some areas of needed improvement to use such meters for liquid CO_2 service. This extended abstract derives from an experimental campaign undertaken by SINTEF Energy Research in collaboration with Panametrics, a Baker Hughes business. The work, available in [3], looked into the performance of a four-path ultrasonic flow meter during static liquid CO_2 testing. The observations discussed here and the challenges identified are a stepping stone towards understanding the implications of sound attenuation in CCS streams for ultrasonic meter technology.

2 Ultrasonic metering

Ultrasonic flow meters measure flow using the "time of flight" or transit-time method for calculating flow velocity and, therefore, volumetric flow rate. Every pair of facing transducers alternately sends and receives ultrasonic sound pulses. In every cycle, the electrical signal is converted into ultrasonic pulses at the transmitting side and then converted back to electrical energy by the receiving transducer. The transit times between the signals in the upstream and downstream directions are recorded. When the transducers are placed at an angle against the flow direction (θ), the signal sent in the downstream direction will have a shorter transit time than the signal sent in the upstream direction. Hence, the direct, linear relationship between the fluid velocity versus the recorded difference in transit times (also called "delta-t" or Δt). Multiple transducer pairs give increased confidence and accuracy in results. The ultrasonic meter used has four measurement paths arranged in chords across the meter body, as illustrated in Fig. 2.

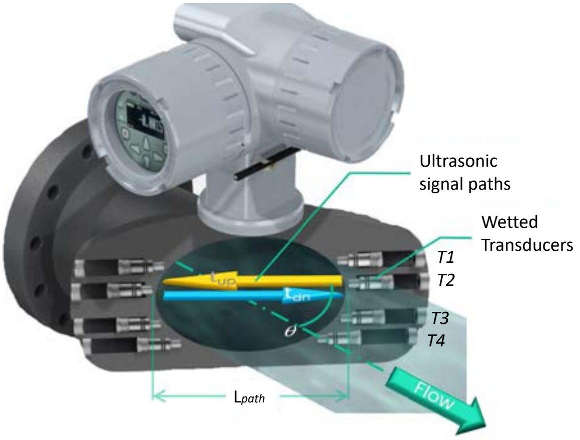


Fig. 2 – Cutout of the ultrasonic flow meter.

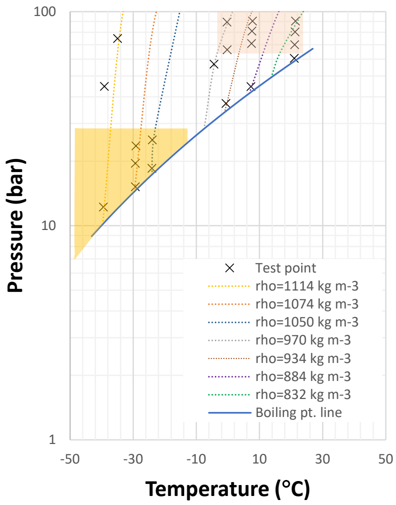


Fig. 3 – Tests points

Factors like fluid viscosity, temperature, pressure, and acoustic attenuation must be considered when calculating fluid velocity. The latter depends on the sound frequency and the properties of the specific fluid of interest. Experiments were undertaken to assess the performance of ultrasonic technology for liquid CO_2 measurements. The tests targeted CCS shipping and export pipeline conditions. Twenty static data points were collected at various fluid densities, see Fig. 3

The experiments were conducted at the laboratories of SINTEF in Trondheim, Norway. The unit was confined within a box with insulation and controlled heating. The enclosure was placed inside a temperature-controlled room, as illustrated in Fig. 4. The meter flowcell was filled with CO_2 (99.5% purity). Measurements were acquired in decreasing order of density, starting at the lowest temperature and moving towards higher temperatures and pressures. The data from the ultrasonic meter was acquired using PanaView®, the proprietary software with real-time flow data, historical tracking of diagnostics, and a full configuration audit trail.

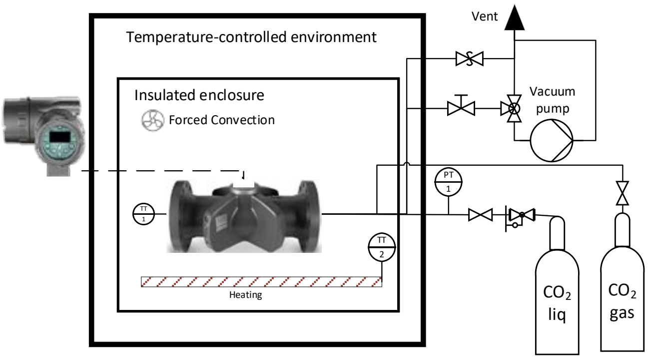


Fig. 4 – Sketch of the experimental setup

3 Preliminary results and challenges

The attenuation of ultrasound signals through CO_2, dominated by the fluid's molecular thermal relaxation properties [4], has previously been identified as a challenge for gaseous CO_2 service. Molecular thermal relaxation is less prominent for liquid than for gaseous CO_2. The relaxation frequency is approximately proportional to density up to 900 kg·m^{-3} [5, 6]. The ultrasonic signals were strong for most high-density points, enabling measurement through the medium. However, as the density of the liquid CO_2 decreased, approaching that of gas, the signal degraded significantly (see Fig. 5). This signal degradation could be due to the proximity of the saturation liquid line. The effect of phase transitions during operations can be potentially overcome by using transducers of different frequencies depending on the fluid conditions.

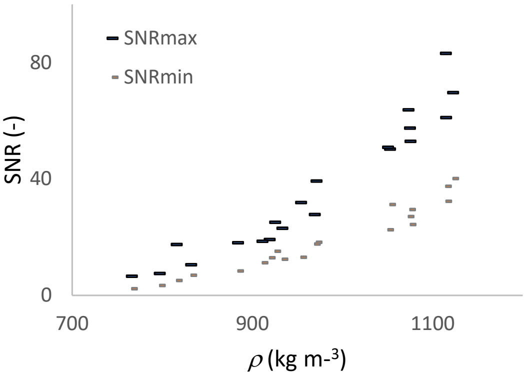


Fig. 5 – Maximum and minimum signal-to-noise (SNR) for all test points

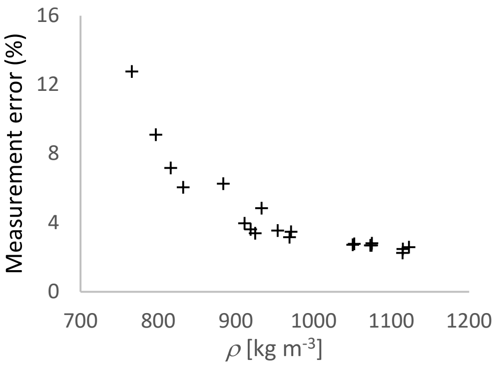
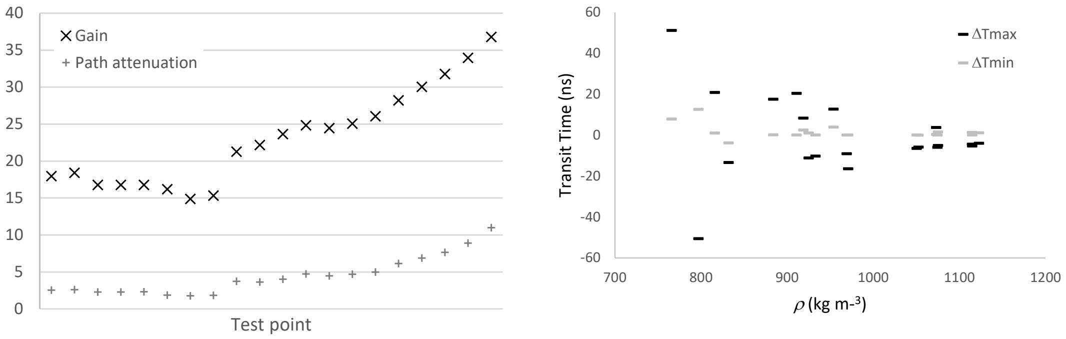


Fig. 6 – Deviation of speed of sound measurements from EOS

The speed of sound measurements showed a positive bias compared to theoretical values from Wagner-Span EOS [7]. The measurement error increases beyond 4% at densities below 900 kg m^{-3} (see Fig. 6).

Two other challenges were identified apart from the bias in the speed of sound from theory. Firstly, higher acoustic impedance and better coupling were observed at higher densities, as indicated by the improved signal gain. Yet, compared to theory [6] [8], there is increased signal attenuation for any given path length (see Fig. 7a). Secondly, the delta-time calculations, which under no-flow conditions should be very near to zero, present a more significant variance at lower densities (See Fig. 7b). The above further supports the hypothesis that possible changes in the fluid physical properties disrupt the ultrasonic signals' transmission causing signal degradation.



(a) (b)

Fig. 7 – (a) Measurements gain and theoretical path attenuation ($\alpha * L_{path}$) for all test points and transducer path T1 and (b) Maximum and minimum transit times across all transducer paths

Ensuring the quality of the processed signal is of paramount importance. Future experimental work should target conditions for CO_2 pipeline service for liquids at densities above 900 kg m^{-3} and close to saturated liquid conditions. The unique capabilities of ultrasonic flow meters (such as low-induced pressure drops and large flow capacities) make them valuable for use in the CCS chain. Hence, efforts are needed to overcome the technical challenges uncovered by this study. The value of such a study relies in a thorough analysis of the raw signals from which optimal processing of weaker acoustics can be realised.

4 NOTATION

The notation and symbols used in this paper are as follows:

Δt	Transit time difference between up- and down-stream times
t_{up}	Through fluid transmission time in the upstream direction
t_{dn}	Through fluid transmission time in the downstream direction
L_{path}	Path length between transducers
SNR	Signal-to-noise ratio
T1-T4	Transducers chords 1 to 4
V	Flow velocity
α	Sound attenuation coefficient
ρ	Fluid density (kg m^{-3})
θ	Transducer path angle

3 ACKNOWLEDGEMENT

This publication has been produced with support from the NCCS Research Centre, performed under the Norwegian research program Centres for Environment-friendly Energy Research (FME) and the Research Council of Norway (257579/E20).

4 REFERENCES

[1] S. W. Løvseth, Y. Arellano, H. Deng, F. Finotti, E. Jukes, and G. Bottino, "Enabling CCS via Fiscal Metering," presented at the Trondheim CCS 11 Proceedings, , Trondheim, 2021. [Online]. Available: https://www.sintef.no/globalassets/project/tccs-11/tccs-11/sproceedings-no-7.pdf.

[2] J. M. Kocbach, et al, "Where do we stand on flow metering for CO2 handling and storage?," presented at the 38th International North Sea Flow Measurement Workshop, 2020.

[3] Y. Arellano, N. Mollo, S. Løvseth, J. Stang, and G. Bottino, "Characterisation of an Ultrasonic Flowmeter for Liquid and Dense Phase Carbon Dioxide Under Static Conditions," *IEEE Sensors Journal,* vol. 22, no. 14, 14, pp. 14601-14609, 2022, doi: 10.1109/JSEN.2022.3180075.

[4] R. W. Leonard, "The Absorption of Sound in Carbon Dioxide," *Journal of the Acoustical Society of America,* vol. 12, pp. 241-244, 1940, doi: https://doi.org/10.1121/1.1916097.

[5] P. Giustetto *et al.*, "Heat Enhances Gas Delivery and Acoustic Attenuation in CO2 Filled Microbubbles," in *30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2008, pp. 2306-2309, doi: 10.1109/IEMBS.2008.4649659.

[6] C.-W. Lin and J. P. M. Trusler, "Speed of Sound in (Carbon Dioxide + Propane) and Derived Sound Speed of Pure Carbon Dioxide at Temperatures between (248 and 373) K and at Pressures up to 200 MPa," *Journal of Chemical & Engineering Data*
vol. 50, 12, pp. 4099-4109, 2014, doi: 10.1021/je5007407.

[7] R. Span and W. Wagner, "A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100 K at Pressures up to 800 MPa," *J. Phys. Chem. Data,* vol. 25, 6, 1996.

[8] H. Deng, S. W. Løvseth, and E. Jukes, "Benchmarking and a test plan for verification of selected relevant technologies for fiscal metering in CCS," 2018.