Global Flow Measurement Workshop
25 - 27 October 2022

Extended Abstract

Experimental Study of Flow Measurement Uncertainties in Supercritical Fluid with High Content of CO2

Andrade, L. A., Cenpes/PETROBRAS
Dutra, F. S., Design & Engineering/PETROBRAS
Lago, C. R., NIDF/Federal University of Rio de Janeiro
Pimentel, F. H., NIDF/Federal University of Rio de Janeiro
Loureiro, J.B.R., NIDF/Federal University of Rio de Janeiro

---

1 INTRODUCTION

The complexity of the CO_2 behaviour poses a direct challenge for the flow rate measurement of fluid mixtures, especially near the critical point, where a slight change in pressure or temperature conditions can impose a dramatic change in fluid properties. Worldwide regulatory agencies are demanding higher accuracies for the flow rate measurements of CO_2 and CO_2 rich mixtures. This is particularly true in the exploration of the Brazilian Pre-Salt oil reserves, where fiscal meters should fulfil the strict criteria of 1.5% maximum uncertainty.

According to Kocbach et al. (2020), most of the available flow rate measurement equipment can only partially fulfil the requirements of the carbon capture and storage chain, considering both commercial and regulatory purposes. The authors investigated, for onshore and offshore pipeline applications, the measurement uncertainty at selected points and the impact on mass balance calculations. This work also surveyed the available test benches for testing flow meters on CO_2 process conditions, and highlighted the lack of accredited full-scale test facilities, capable of covering near real operational conditions.

Despite the broad need for CO_2 flow metering in industry, few laboratories are now capable of simulating high-pressure conditions with traceability in order to evaluate the response of different flow measurement principles in scenarios representative of field applications.

Hardie (2013) described the flow facilities under development at NEL for testing flow meters with CO_2, where orifice plates, ultrasonic and Coriolis meters have been tested. Although preliminary tests were promising, the author states that more tests are needed to confirm which metering technology is capable of achieving the levels of uncertainty required for CCS custody transfer applications.

Orifice plate meters are typically used in the oil industry for gas measurement, either for gas custody transfer or gas injection for enhanced oil recovery applications. Orifice plates are also widely used for liquid flow applications. As mentioned by Hardie (2013), the main limitation of the orifice plate for CO_2 applications is the need for an accurate density estimate, which is calculated through an equation of state and required for mass flow rate determination. The composition of the fluid mixture needs also to be accurately specified.

The presence of CO_2 in the fluid mixture adds much complexity to the flow as the phase change boundaries between gas, liquid and the critical point lie within the range of operational conditions of most pipelines and transportation systems. The critical point also changes with fluid composition (contamination). Regarding the density behaviour, even slightly small changes in pressure and temperature

conditions near the critical point can cause sharp and significant changes in this fluid property. This range of working conditions is thus very challenging for any flow rate measurement technique, particularly for the orifice plate type of meter.

In literature, some works have been devoted to the investigation of the performance of different equations of state for the calculation of gas density, especially for mixtures with high contents of CO_2 (Stewart et al. 2000, Mantovani et al. 2012, Glen et al. 2016, Farzaneh-Gord et al. 2018). The equation of state AGA8 detailed method is vastly used in industry for fluid properties calculation of natural gas supply. However, significant errors are achieved if this equation is used outside its range of validity, especially in terms of specified composition ranges. GERG-2008 has been proposed in order to broaden these ranges, in particular with regard to CO_2 content. Despite its benefits, literature shows that the lack of experimental validation, especially in regions of high pressures and temperatures, prevent a thorough quantification of uncertainty levels.

The purpose of the present work is to present the experimental apparatus developed to simulate turbulent flows of CO_2 mixtures at a range of high pressures up to the supercritical state. This test bench is then used to investigate the response of a typical orifice plate to turbulent flows of different contents of CO_2 near and at the supercritical state. The measurements obtained with the orifice meter have been compared with a reference Coriolis meter. The experimental conditions cover a wide range of the phase diagram, varying from gas flow, liquid flow to the supercritical state.

The main objective of this investigation was to evaluate the measurement uncertainty of an orifice plate near the critical point for different fluid mixtures. The reference flow rate has been measured through a previously calibrated Coriolis flowmeter installed simultaneously at the same flow loop. The influence of different equations of state (AGA8 and GERG-2008) on the flow rate uncertainty has also been evaluated. Experiments have been carried out for four fluid mixtures (pure CO_2, 92.7% CO_2 / 7.3% N_2, 90% CO_2 / 10% N_2 and 100% N_2). Temperature and pressure were varied so that vapour, liquid/vapour and supercritical states were achieved. As the density of the fluid can be kept constant at the facility, the uncertainty of the density measurement obtained from the Coriolis flowmeter could also be estimated for some tested conditions.

2 EXPERIMENTAL APPARATUS

The test bench was designed, installed and is currently operational at the Interdisciplinary Centre for Fluid Dynamics of the Federal University of Rio de Janeiro (NIDF/UFRJ). An overview of the experimental apparatus is shown in Fig. 1. The flow loop operates in closed loop and consists of 1, 2 and 3-inch pipe diameters. The maximum pressure and temperature are 150 bar and 80º Celsius, respectively. The working fluids are CO_2 and N_2.

Two gas boosters connect the CO_2 and N_2 reservoirs to its respective Coriolis flowmeters and then direct these individual lines to the test bench. A given measured mass of gas (or gas mixture) is then injected into the system from the feeding tanks. The initial pressure of the system is defined by the mass of gas injected at ambient conditions. A compressor drives the fluid through the flow loop to flow rates up to 60 cubic meters per hour. Temperature is monitored at different points along the pipe circuit.

For the present experimental investigation, the operational conditions were:

- Pressure [bar]: 30 to 100
- Temperature [ºC]: 20 to 100
- Mass flow [kg/h]: 300 to 4200
- Volumetric flow [m^3/h]: 2.3 to 25
- Molar composition CO_2 [%molar]: 90 to 100
- Mixture CO_2/N_2 gas: N_2 from 0 to 10%molar

Fig. 1 – Overview of the experimental apparatus.

As can be seen in Fig. 1, the compressor drives the flow to the reference Coriolis flowmeter (Endress-Hauser) and then to the evaluated orifice plate (Metroval) installed downstream.

As the flow loop has a fixed volume, for some conditions the density of the mixture could be independently estimated as the ratio of the mass inside the rig (measured by the inlet Coriolis flowmeters) to the total pipeline volume.

3 RESULTS

For the present experimental campaign, three different fluid compositions (molar fraction) were evaluated:

- 1st composition - 100% CO_2;
- 2nd composition - 92.7% CO_2 + 7.3% N_2;

In the following, results are shown for fluid properties (density) and flow rates (mass and volume flowrate) measured or calculated by:

- Orifice plate + AGA-8 equation of state;
- Orifice plate + GERG2008 equation of state;

- HFC302 flow computer (commercial software using AGA-8 detailed method and reading the pressure drop from the orifice plate);
- Reference Coriolis flowmeter.

The uncertainty estimates have been calculated using as reference the guide to the expression of uncertainty in measurement (ISO/IEC Guide 98-3) (JCGM100, 2010).

Fig. 2 illustrates the uncertainty calculation procedure. Systematic uncertainties (type B) are directly corrected from the measurements. Aleatory uncertainties (type A) are quantified from the measured standard deviations. Considering the effective degrees of freedom, the combined aleatory uncertainty is multiplied by the coverage factor for a 90% confidence interval to estimate the overall uncertainty. In the following figures, the overall uncertainty is expressed by the bars located around the measured data points.

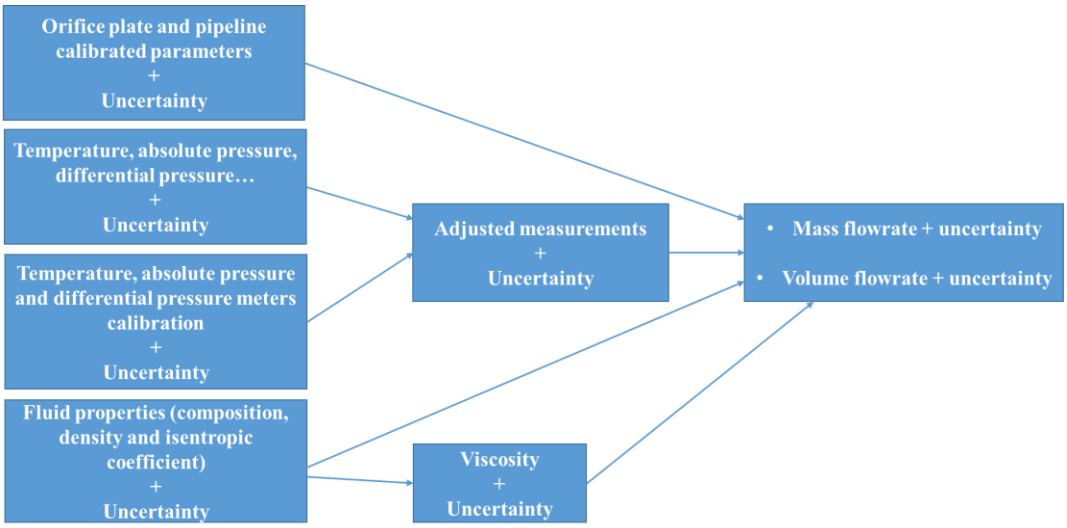

Fig. 2 – Illustration of the uncertainty calculation procedure.

3.1 Results for 100% CO_2 composition

The phase diagram for 100% CO_2 fluid composition is shown in Fig. 3. The phase diagram was obtained from the saturation curve calculated using NIST routines for an isochoric process (National Institute of Standards website). The red crosses reflect the measured experimental conditions. It can be noticed that the results were obtained for the liquid-vapour, vapour and supercritical states.

Figure 4a shows a comparison between the densities measured by the Coriolis meter, the value calculated from the orifice plate's HFC302 commercial flow computer and the values obtained through the equations of state AGA-8 detailed method and GERG-2008. The blue dotted line in Fig. 4a is an estimate calculated from the mass of fluid added on the test bench (measured by the inlet Coriolis flowmeters) and the volume of the pipe. This analysis could only be performed for some experimental conditions.

There is a systematic difference between the density measured by Coriolis and that calculated by the flow computer. Figure 4a shows that this difference is

Extended Abstract

smaller in the supercritical flow region compared to the transition region from the vapor phase to the supercritical phase (temperature below 35°C). The relative deviations, considering the Coriolis meter as a reference, are around 5% for the supercritical region and up to 50% for the liquid-vapor phase.

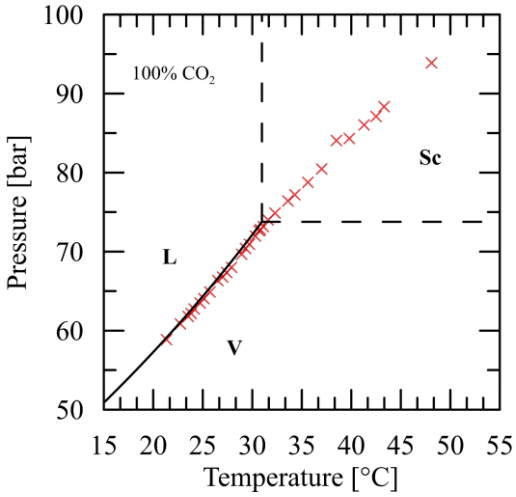

Fig. 3 – Phase diagram for 100% CO_2 fluid. The red crosses illustrate the measured conditions.

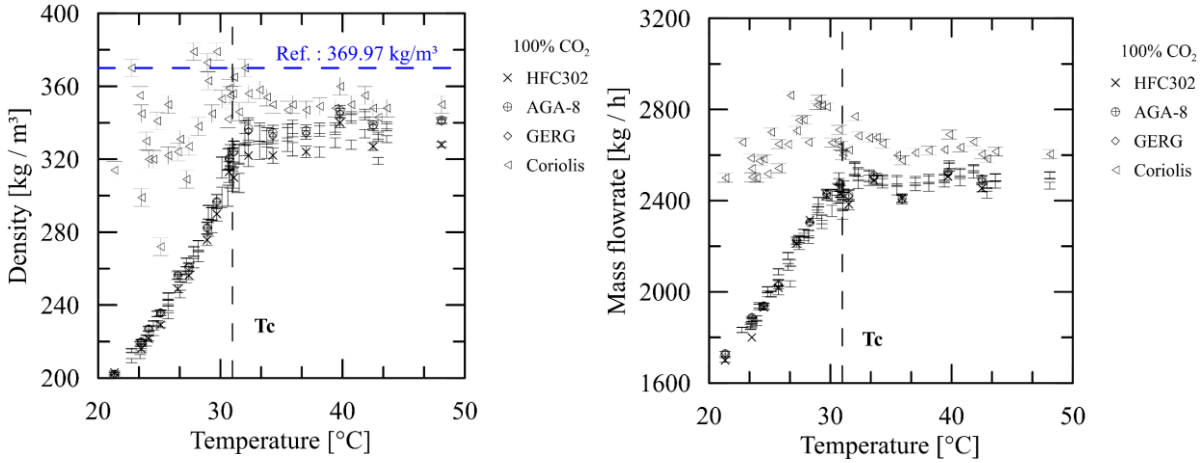

Fig. 4 – Measured and estimated densities for the different measurement points of the 100% CO_2 fluid composition (left) and measured mass flow rate (right).

The comparison between the mass flow measured by Coriolis flowmeter and the orifice plate is presented in Figure 4b (right). The difference observed between the mass flow measurements is essentially due to the deviation observed between the reference specific mass (measured by the Coriolis flowmeter) and the calculated specific mass by the flow computer (using AGA8 equation of state). When the volumetric flow rate is considered (not shown here), as the density is used to convert the mass values into volume, this difference decreases. In general, the observed deviations are less than 2.5%.

3.2 Results for 92.7% CO_2 + 7.3% N_2 composition

On the following, results are shown for the fluid mixture of 92.7% CO_2 and 7.3% N_2. As the control of N_2 injection on the test bench is done from the measured mass flow rate from the inlet Coriolis meter, the condition of the mixture was established from the addition of 5% of N_2 mass. After conducting a chromatography analysis, this amount then corresponds to 7.3% in terms of molar composition.

Figure 5 represents the state diagram for the mixture above referred; it was constructed from property data returned by the GPEC software. The experimental conditions, represented by the red crosses, varied from the vapor and liquid region to the supercritical state.

The comparison between the density value measured by Coriolis, the value calculated by the orifice plate HFC302 flow computer and those estimated by the equation of state AGA-08 and GERG-2008 for a mixture of CO_2 with 7.3% of N_2 is shown in Figure 6a. As mentioned in the previous section, the blue dashed line represents an estimate calculated from the inlet mass and the volume of the pipe. The observed behavior is similar to the pure CO_2 mixture. The discrepancy is higher for the temperatures that precede the entry into the supercritical state. The relative differences reach 20% for the region before the critical boundary and are less than 5% at most points within the supercritical state.

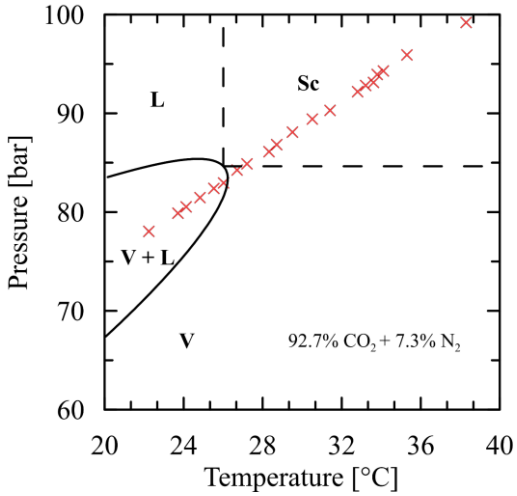

Fig. 5 – Phase diagram for 92.7% CO_2 + 7.3% N_2 fluid mixture. The red crosses illustrate the measured conditions.

The comparison for the mass flow is presented in Fig. 6b. Within the supercritical region, the systematic difference between the reading of the orifice plate and the value measured by Coriolis is similar to the ones observed at the vapour/liquid region.

The results indicate that the relative expanded uncertainty of the orifice plate measurement lies in the range of 0.50% for volumetric flow and 0.58% for the mass flow. However, the systematic error in the density measurement implies that the difference between the orifice plate reading and the Coriolis meter is of the order of 1.50% for the mass flow and 5.05% for the volumetric flow.

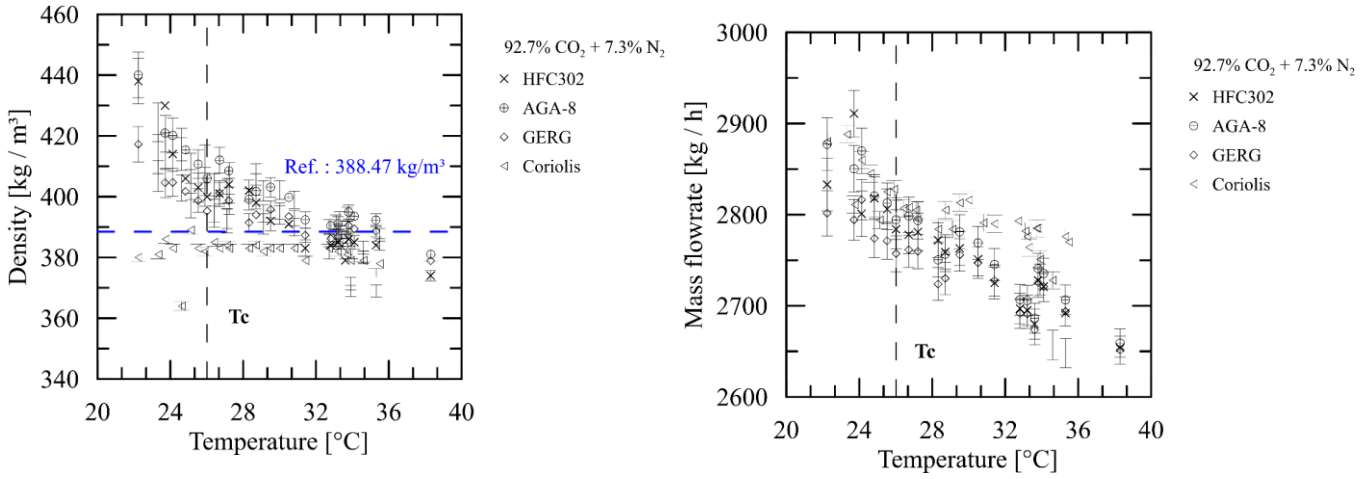

Fig. 6 – Measured and estimated densities for the different measurement points of the 92.7% CO_2 + 7.3% N_2 fluid composition (left) and measured mass flow rate (right).

4 FINAL REMARKS

This work has presented a test bench for the simulation of turbulent flows of fluid mixtures with different contents of CO_2. The operational conditions of the set up allows the simulation of flows at the vapour, liquid, vapour/liquid and supercritical states. To the authors knowledge, the results shown in the present work are original and show that the experimental apparatus can be used for different types of research on problems related to carbon capture and storage.

The results allowed the evaluation the measurement uncertainty of an orifice plate near the critical point for different fluid mixtures. The reference flow rate has been measured through a previously calibrated Coriolis flowmeter installed simultaneously at the same flow loop. The influence of different equations of state (AGA8 detailed method and GERG-2008) on the flow rate uncertainty has also been evaluated.

Experiments have been carried out for four fluid mixtures (pure CO_2, 92.7% CO_2 / 7.3% N_2, 90% CO_2 / 10% N_2 and 100% N_2). Only the first two sets of results have been discussed here and the other results will be detailed elsewhere. Temperature and pressure were varied so that vapour, liquid/vapour and supercritical states were achieved. As the density of the fluid can be kept constant at the facility, the uncertainty of the density measurement obtained from the Coriolis flowmeter could also be estimated for some tested conditions.

One of the main contributions for the overall uncertainty of the orifice plate stems from the density calculation, which depend on the choice of the equation of state and on the determination of the exact fluid composition. Indeed, the equations of state applied for mixtures with high CO_2 content under well injection conditions present significant errors in relation to the reference values obtained experimentally.

One alternative to be investigated is to install an in-line densimeter to provide the measured value to the commercial flow computer. An in-line chromatography

could also provide the fluid composition. This system would then be able to provide better accuracy for the orifice plate flow measurement.

5 REFERENCES

[1] J.M. KOCBACH, M.B. HOLSTAD, A.M. SKALVIK, K. FOLGERO, B. YSTAD, K.D. LOHNE, Eivind L. SOLDAL, S. LOSNEGARD, A. PAULSEN, G. MOUTON, L. Teberikler. Where do we stand on flow metering for CO_2 handling and storage? 38th International North Sea Flow Measurement Workshop, 26-29 October, 2020.

[2] C. HARDIE. Developing measurement facilities for carbon capture and storage, Measurement + Control, vol. 46, 2, 2013.

[3] D. G. STEWART, J. T. R. WATSON, A. M. VAIDYA. A new correlation for the critical mass flux of natural gas mixtures. Flow Measurement and Instrumentation, 11, 265-272, 2000.

[4] M. MANTOVANI, P. CHIESA, G. VALENTI, M. GATTI, S. CONSONNI. Supercritical pressure–density–temperature measurements on CO2–N2, CO2–O2 and CO2–Ar binary mixtures, Journal of Supercritical Fluids, 61, 34-43, 2012.

[5] N. F. GLEN, D. MILLS, D. GRIFFIN, S. FOSSE. Errors due to use of AGA8 equation of state outside its range of validity, Offshore Technology Conference, OTC-26662-MS, 2016.

[6] M. FARZANEH-GORD, B. MOHSENI-GHARYEHSAFAA, A. TOIKKAB, I. ZVEREVA. Sensitivity of natural gas flow measurement to AGA8 or GERG2008 equation of state utilization, Journal of Natural Gas Science and Engineering 57, 305–321, 2018.

[7] JCGM 100. Evaluation of measurement data – Guide to the expression of uncertainty in measurement (ISO/IEC Guide 98-3), 2010.