

Experimental characterization of CO₂-oil slug flows near the supercritical state

E. P. Corrêa², J. B. R. Loureiro^{1,2} and A. P. Silva Freire^{1,2}

1: Interdisciplinary Center for Fluid Dynamics (NIDF/UFRJ), Federal University of Rio de Janeiro, R. Moniz Aragão No. 360, Bloco 2, 21941-972, Rio de Janeiro, Brazil

2: Mechanical Engineering Program (PEM/COPPE/UFRJ), Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Keywords: CO₂-oil slug flow, dense gas, Shadow Sizer, PIV, high-speed imaging

ABSTRACT

This work presents an experimental characterization of CO₂-oil two-phase flows at pressures and temperatures near the critical conditions of CO₂. A high-pressure test bench with a 30 m long, one-inch pipe was developed to investigate flow conditions relevant to carbon capture, utilization, and storage applications and to Brazilian Pre-salt oil production. Dense CO₂ was injected into a light oil stream, and the resulting flow was observed through optical windows rated up to 80 bar. High-speed imaging and a Shadow Sizer system were used to identify long bubbles and to obtain distributions of bubble velocity, liquid-slug length, and bubble length. Single-phase oil measurements were also performed to characterize the friction factor of the test section. For the conditions reported here, the CO₂ density was approximately 200 kg m⁻³, producing a much smaller oil-to-gas density ratio than in conventional air-oil flows. The results show how this reduced density ratio affects the morphology and dynamics of slug flows and provide experimental data for model development and validation of high-pressure CO₂-oil flows.

1. Introduction

The flow of CO₂ in pipes has been widely studied recently, mainly due to carbon capture, utilization, and storage applications (CCUS). The unique fluid properties of CO₂ and its thermodynamic behavior pose several measurement challenges (Andrade et al., 2022). Taking into account the operational conditions for carbon dioxide transport, the flow pattern can vary between single-phase liquid (e.g., temperature of 20°C and pressure around 57 bar), single-phase gas (e.g., ambient temperature and pressure around 20°C and 1 bar), two-phase liquid and gas, or supercritical fluid (temperature around 31.1°C and 73.9 bar). Above the critical point, the fluid is considered a dense gas, and small changes in temperature or pressure can result in large variations in viscosity and density. The presence of impurities or contaminants to the flow, like nitrogen or components of natural gas, also exerts an influence on the phase boundaries. The components and concentration of the contaminants can specifically change the two-phase region and the location of the critical point.

In the oil industry, especially in the Brazilian Pre-salt scenarios, the rock reservoirs are made of carbonate rocks and are located in deep offshore regions, under high pressures and temperatures. These conditions may result in a high content of carbon dioxide dissolved in liquids (oil and water). As production occurs and pressure decreases, CO₂ can exit the solution in the gas or dense-gas phase, giving rise to a two-phase gas-liquid flow pattern. The same phenomenon can happen in wells that re-inject the produced CO₂ back to the reservoir for enhanced oil recovery (to increase the well head pressure, maximizing the oil production). The extremely high CO₂ content gives rise to very complex flows in which the density of the gas phase is similar to that of the liquid phase (oil). This characteristic renders the existing correlations for predicting flow patterns and friction coefficients implemented in commercial codes no longer valid. In fact, the few experimental data available in the literature differ significantly from the results obtained using commercial CFD codes. Very few experimental results are available in literature for model development and validation (Hammer et al., 2021).

The purpose of this work is to investigate the two-phase flow of CO₂ and oil, focusing on the dispersed bubbles and slug flow patterns. The flow conditions were chosen to vary between low and high pressures to study the influence of changes in density between the gas and dense gas phases on the two-phase flow properties. High-speed filming and laser-based optical probes were used to characterize bubble size distributions, bubble velocities, passage frequency of slugs, and slug length distributions. Experiments are carried out for different mixture velocities in a one-inch pipe diameter. The operational conditions can vary between ambient pressure and temperature up to 80 bar and 30°C. Particle Image Velocimetry (PIV) is used to characterize the flow field of the continuous phase.

2. Experimental apparatus

The experimental setup is shown in Fig. 1. The test bench consists of a 30 m long, one-inch-in-diameter, schedule 160S pipe (20.7 mm internal diameter). The oil is pumped by a high-pressure triplex pump from a 2 m³ tank to the pipe inlet. The CO₂ is provided by 12 cylinders of 45 kg each. The gas inlet system is composed of a regulator valve, a Coriolis flow meter, and pressure and temperature measurements. The dense gas is injected at the inlet of the pipe through a T-junction. At the end of the loop, the flow is directed to a discharge tank, where the gas and oil are separated. A centrifugal pump is used to direct the oil to the inlet reservoir. The gas and oil flow rates and densities are measured by Coriolis flowmeters. Pressure transducers and Pt-100 temperature sensors were installed along the pipe to quantify the pressure drop and to monitor the state of the gas phase. Two polycarbonate windows were installed along the pipe length to allow optical measurements for pressures up to 80 bar. For the continuous phase, a light oil was chosen (Lubrax Turbina 10), which has the following properties: density of 852 kg m⁻³ and viscosity of 10 cSt at 40°C.

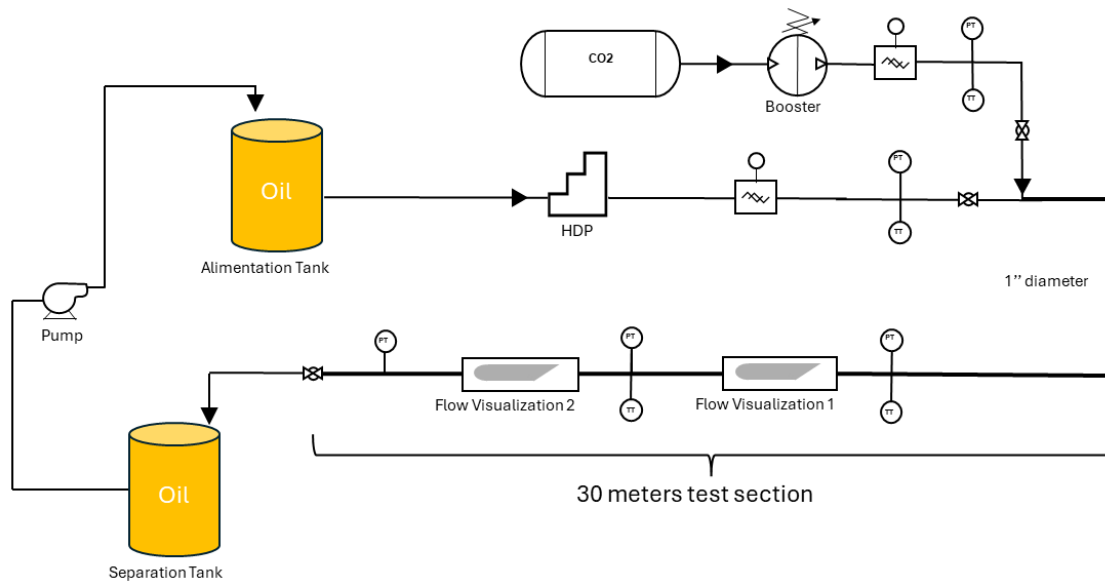


Figure 1. Experimental apparatus for the simulation of two-phase supercritical CO₂ and oil.

The characteristics of the two-phase flow were measured with the aid of a Shadow Sizer System from Dantec Dynamics. The system uses a backlight LED with a diffuser to promote uniformly illuminated images, increasing the contrast between the continuous and the dispersed phases. The high-speed camera used was a 12-bit Speed Sense M310 camera with a 60 mm Nikon lens.

3. Results

Prior to the two-phase flow experimental campaign, the friction factor was characterized for the single phase flow of oil. This result is shown in Figure 2a. The classical flow pattern map of Mandhane et al. (1974), shown in Fig. 2b, was used as a reference to illustrate the two experimental points that are presented and discussed below.

Figure 3 shows the oil and dense gas flowing through the optical window, on the left, and the high-speed camera image on the right-hand side.

The Shadow Sizer images were processed in Matlab to detect the contour of the long bubbles and then calculate relevant quantities for the characterization of two-phase flows. Results for the distributions of slug velocities, slug length, and bubble length are shown in Figures 4(a), 4(b) and 4(c), respectively.

For the present results, the density of the carbon dioxide was approximately 200 kg m⁻³. This means that the ratio between the density of the oil and the gas (ρ_{oil}/ρ_{gas}) is around 4. In comparison to compressed air under the same pressure and temperature (65 bar, 28°C), the density of the air would be approximately 70 kg m⁻³, increasing the density ratio to 12. For the typical ambient

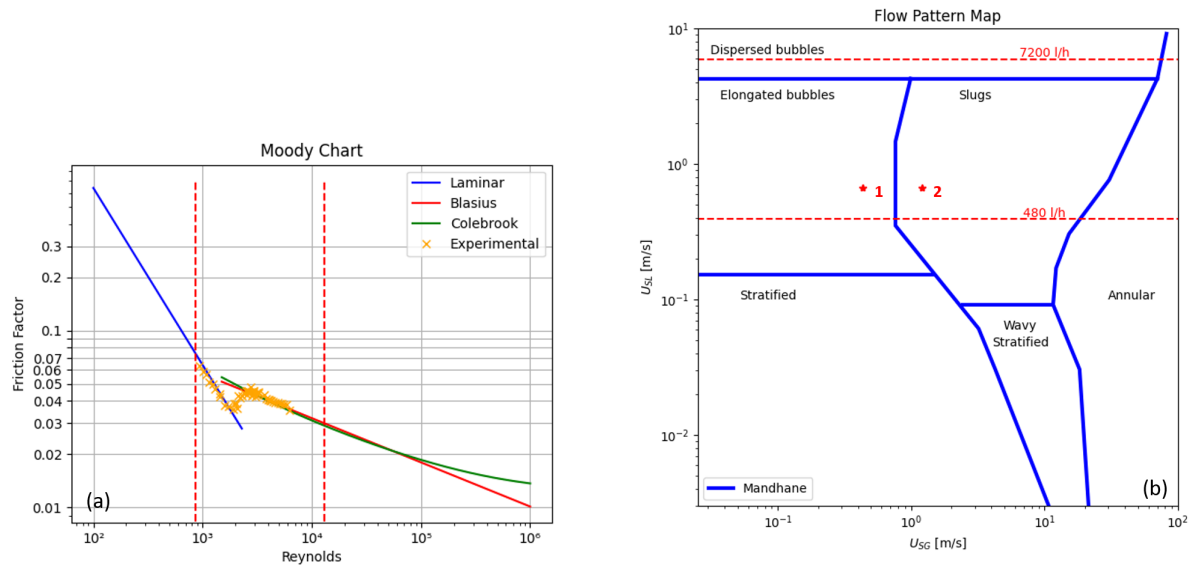


Figure 2. Friction factor for the oil single phase flow (a) and flow pattern map illustrating two typical measurement points (b).

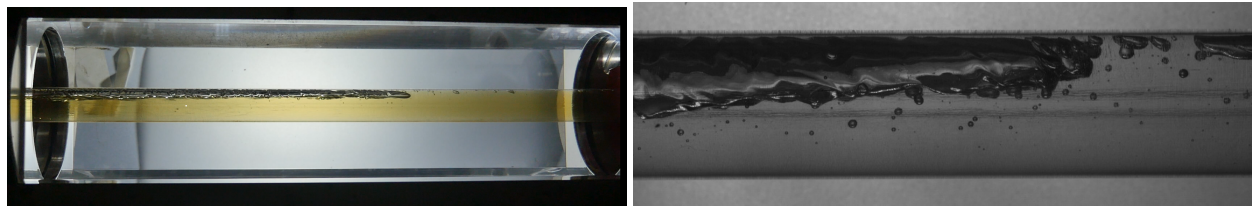


Figure 3. Optical window for high pressure flows (a) and Shadow Sizer image of a long bubble (b).

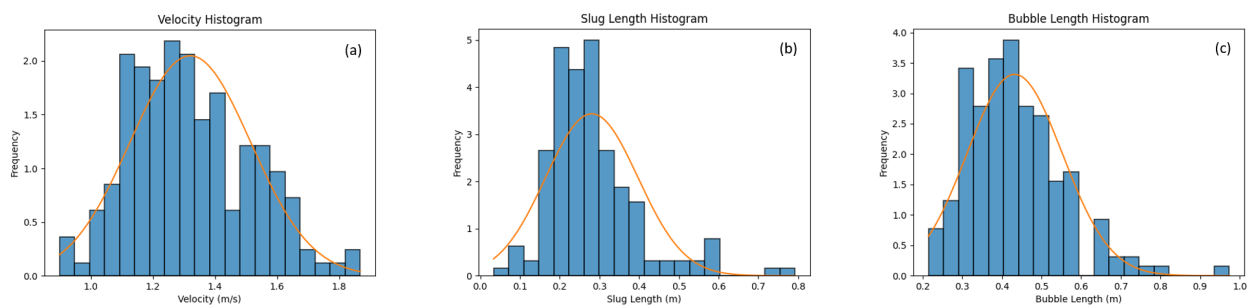


Figure 4. Results obtained from the high-speed filming and the Shadow Sizer System: distributions of (a) bubble velocity, (b) slug length and (c) bubble length.

temperature and pressure, $\rho_{air} = 1.16$, this ratio is around 724. The low density ratio between the oil and gas changes the flow pattern, the shape of the long bubbles, and the properties of the two-phase flow.

4. Final remarks

This work has shown a test bench developed to use optical techniques for the characterization of two-phase flows of oil and dense carbon dioxide. This problem is of interest to the oil industry and also for carbon capture, utilization, and storage (CCUS) applications.

High-speed filming and the Shadow Sizer Technique were used to characterize the distributions of velocities of the long bubbles, the length of the liquid slugs, and the bubble length. The full version of the manuscript will include results for the velocity field of the continuous phase.

References

- Andrade, L. A., Dutra, F. S., Lago, C. R., Pimentel, F. H., & Loureiro, J. B. R. (2022). Experimental study of flow measurement uncertainties in supercritical fluid with high content of CO_2 . In *Global flow measurement workshop 2022*.
- Hammer, M., Deng, H., Liu, L., Langsholt, M., & Munkejord, S. T. (2021). Upward and downward two-phase flow of CO_2 in a pipe: Comparison between experimental data and model predictions. *International Journal of Multiphase Flow*, 138, 103590.
- Mandhane, J., Gregory, G., & Aziz, K. (1974). A flow pattern map for gas-liquid flow in horizontal pipes. *International Journal of Multiphase Flow*, 1(4), 537–553.