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EXPERIMENTAL INVESTIGATION OF HORIZONTAL TWO-PHASE SLUG FLOW WITH HIGH DENSITY GASES

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***Abstract.** During the offshore production of oil and gas, it is commonly observed multiphase flow. Due to the difficulty of modeling multiphase flow, it is common to simplify it to a two-phase liquid-gas phase flow. In this scenario, the gas phase is often of high density with similar magnitude to the liquid phase. This condition greatly differs from the regularly studied system of water and air, where the gas phase is of a much smaller density compared to the liquid one. Consequently, it is of great interest to investigate how the high gas density will affect the slug flow parameters, since this flow pattern is the most reported one to occur in oil and gas production in the petroleum companies. Slug flow is characterized by the intermittent repetition of the structure called unit cell, formed by an elongated bubble followed by a liquid slug. Therefore, this study aims to evaluate experimentally the liquid-gas two-phase slug flow for cases with density ratios ranging from 13.6 to 22.4, using mineral oil and sulfur hexafluoride (SF_6) as fluid models. Due to the increase in the pressure in the system, the liquid phase was considered a mixture of the mineral oil and sulfur hexafluoride dissolved in it. The liquid properties were estimated considering the dissolutions of SF_6 in the oil and the liquid viscosity varied between 7 and 22 cP. The pressures were 4.4 and 6.2 bar and temperature was 20°C. For each case, several phase velocities were applied and the slug flow parameters and the pressure gradient were obtained. The experimental loop consisted of 60-m long stainless steel circuit with a 26-mm I.D., with 5 measuring stations and one visualization window along the pipe. In the measuring stations were installed a pressure and temperature sensors and two capacitive sensors that allows to measure slug flow parameters such as bubble velocity, slug frequency, liquid holdup and slug and bubble lengths. It was observed that the slug flow region was much smaller compared with air-water experiments.*

Keywords: Experimental analysis, Slug Flow, Two-phase Flow, Influence of gas density

1. INTRODUCTION

In the production of oil and gas, the predominant flow regime observed is the slug flow (Shoham, 2006). Slug flow is characterized by the occurrence of intermittent liquid slugs followed by stretched gas bubbles. These bubbles occupy a significant portion of the pipeline's cross-sectional area. In horizontal pipelines, the elongated bubble tends to concentrate at the top due to buoyancy and flows on top a film of liquid.

In the conditions of offshore oil production, usually the gas phase presents a density closer to the density of the liquid one, different of what occurs in the flow of air and water. These characteristics motivated significant efforts in recent

decades to investigate the impact of gas density on two-phase flow. Several authors have reported that an increase in gas density leads to a reduction in the slug flow region within the flow map (Nakamura, 1996; Khaleedi et al., 2014; Wang et al., 2019).

The influence of gas density on flow map transitions was experimentally studied by Abduvayt et al. and Tzotzi et al. in 2011. They reported that for higher pressures the transition from smooth to wavy stratified flow occurs at lower gas velocities. Additionally, it has been observed an acceleration of roll waves when the gas density is more elevated (Johnson et al., 2009). They also saw an increase in the wave frequency of the stratified wavy flow, as well as a decrease in wave amplitude (Loh et al., 2016).

In this present work, SF₆ and mineral oil were used as model fluids. As the density of the SF₆ increases with the pressure, it is possible to simulate conditions in which the density ratios range from 2.3 to 142. In those scenarios, it was possible to analyze experimentally the influence of gas density on slug flow parameters such as bubble velocity, length, frequency, and pressure gradient.

2. EXPERIMENTAL METHODOLOGY

A flow loop was constructed to evaluate the flow characteristics in the aforementioned conditions. Figure 1 and Figure 2 presents respectively the loop and a schematic diagram of the flow loop used in the study. The liquid line comprises a liquid reservoir, a centrifugal pump, a heat exchanger, and a Coriolis mass flow meter. The gas phase line consists of a gas reservoir, a compressor, a heat exchanger, and a Coriolis mass flow meter.

The test section is composed of a horizontal stainless steel tube with a 26 mm internal diameter and a length of 2307D. Along the pipe there are five measuring stations and one visualization window as shown in Figure 3 and Figure 4. Each measuring station is equipped with two capacitive sensors and one pressure transducer. The capacitive sensors measure the liquid height and with data processing, obtained slug flow parameters such as bubble velocity and length, slug frequency and length (Dos Santos, 2023). The temperature is monitored with PT-100 sensors in the entrance, middle and exit of the tow-phase flow line.

All the pipes of the flow loop are thermal isolated in order to reduce the thermal exchanges with the ambient.

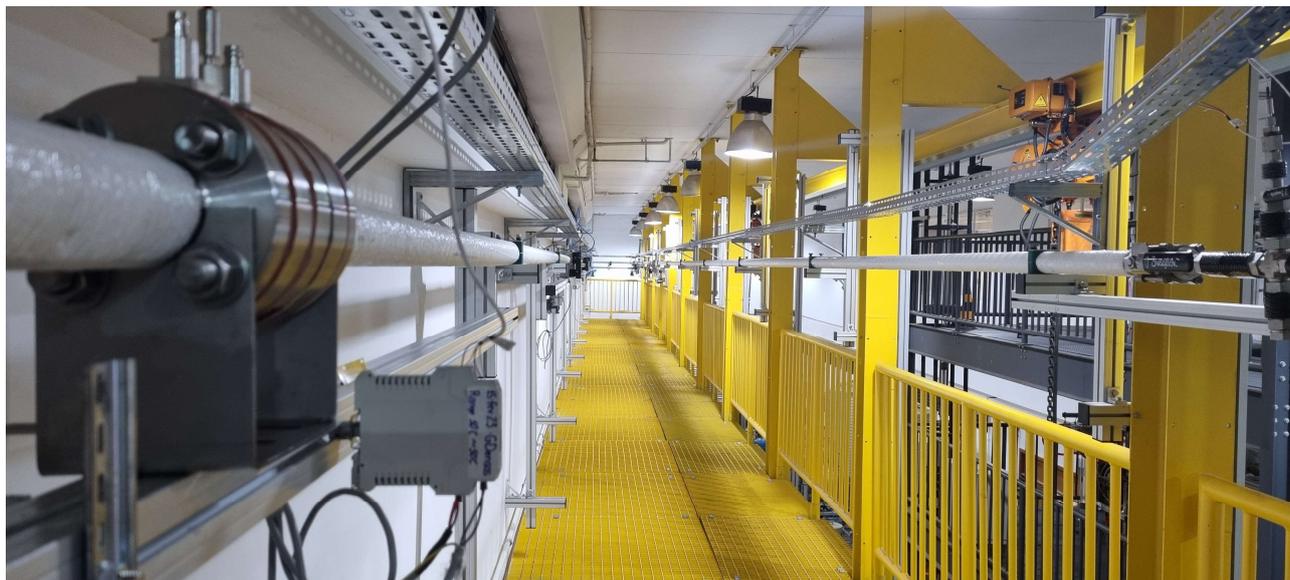


Figure 1. Experimental flow loop.

The oil utilized was a commercial mineral oil Lubrax Hydra XP32 and the SF₆ had a purity of 99,9%. It is necessary to account for the dissolution of SF₆ in the mineral oil and its impact in the thermodynamic properties. Naturally, the solubility is inherently dependent on both temperature and pressure. The solubility estimation was made according to the proposed by Miguel Junior (2020). The density of both phases was experimentally measured. The liquid viscosity was estimated according to Katti-Chaudhri (1964) mixing rule. The gas phase was considered to be a single-phase consisting of SF₆. The viscosity of the liquid was spanning from 7 to 21 cP, and its density was measured ranging from 872,5 to 874,5 kg/m³. The average gas phase viscosity was 0.016 cP and density ranged between 39 and 64 kg/m³.

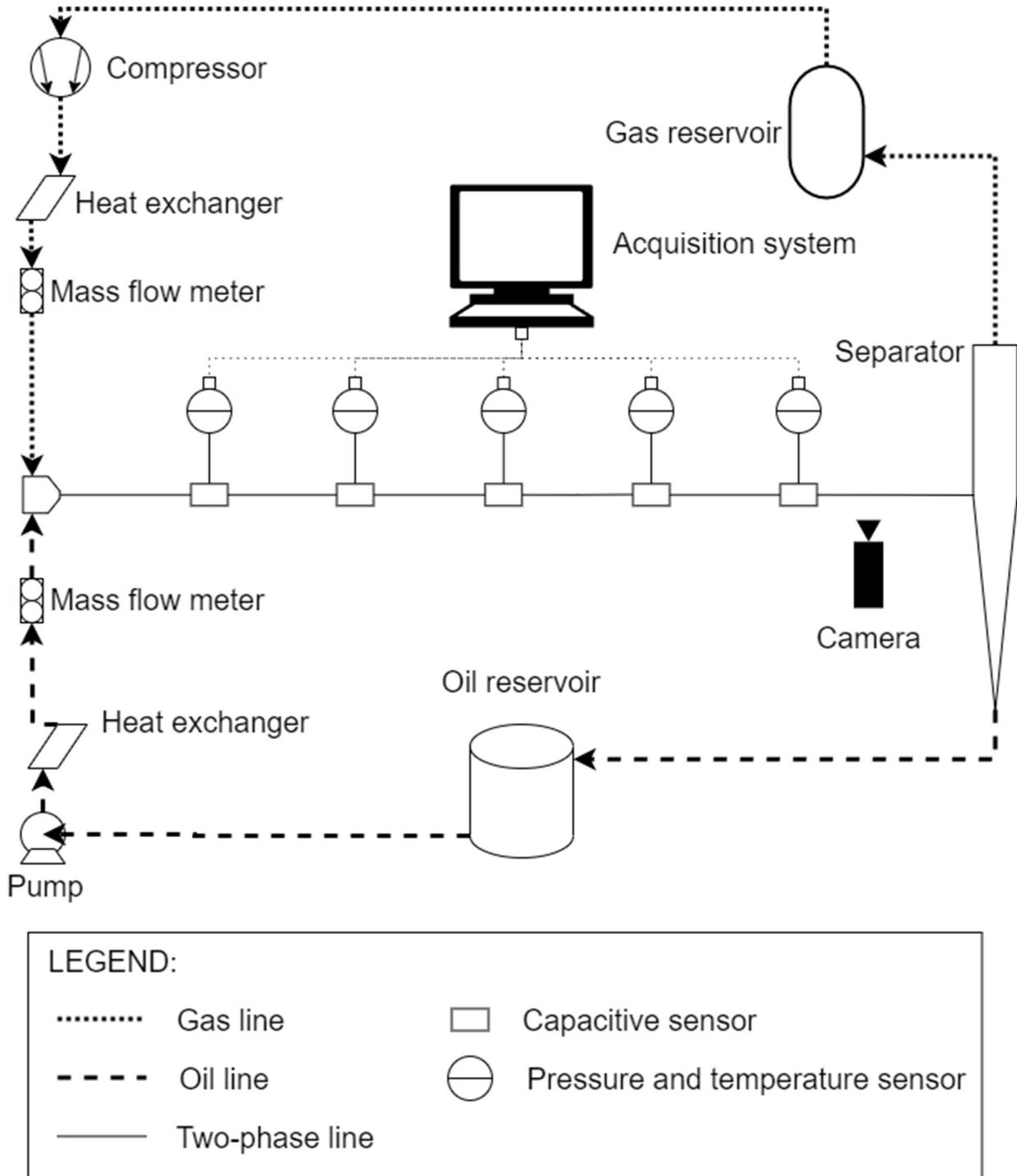


Figure 2. Schematic diagram flow loop.

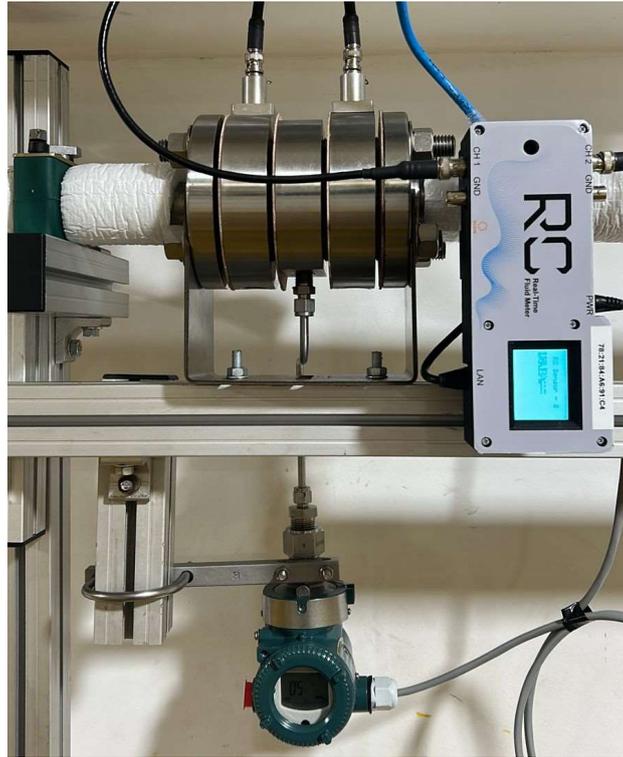


Figure 3 Measurement station.

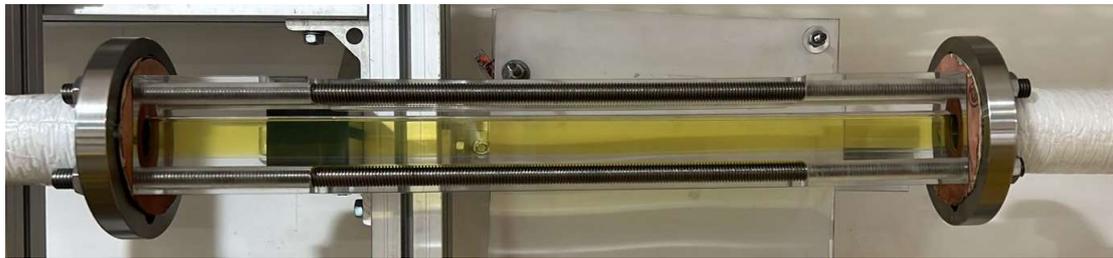


Figure 4. Visualization window.

3. RESULTS AND DISCUSSION

Two distinct thermodynamic conditions were tested, allowing observing the different flow behavior due the change of the density of the gas phase. In both conditions the temperature was kept at an average of 20 °C and the average pressure was 4.4 bar for the first condition and 6.2 for the second. The thermodynamics properties for each condition are presented in Table 1.

Table 1. Thermodynamic properties for each condition tested.

Pressure	4.4 bar	6.2 bar
Ratio ρ_L / ρ_G [-]	22.4	13.6
ρ_G [kg/m ³]	39	64
μ_G [cP]	0.016	0.016
ρ_L [kg/m ³]	875	873
μ_L [cP]	21	7

For each of these thermodynamic conditions nine combinations of gas and liquid superficial velocities were applied, with gas superficial velocities spanning from 0.08 m/s to 0.7 m/s and the liquid from 0.35 m/s to 0.79 m/s. The complete test grid is shown in Table 2. The cases were determined so all the points may present slug flow pattern.

Table 2. Velocities test grid.

Experimental Point	J_G [m/s]	J_L [m/s]	J [m/s]
P01	0,26	0,35	0,60
P02	0,08	0,35	0,43
P03	0,41	0,62	1,03
P04	0,60	0,59	1,19
P05	0,70	0,49	1,19
P06	0,50	0,62	1,12
P07	0,51	0,78	1,29
P08	0,48	0,71	1,19
P09	0,43	0,79	1,22

The interface between the elongated bubble and liquid film for the experimental point of P01 for the gas densities of (a) 39 kg/m³ and (b) 64 kg/m³ are presented on the Figure 5. It is possible to observe that the increase in the density of the gas phase and the reduction of the liquid viscosity have a direct impact on the behavior of the interface. There is the appearance of interface waves due to the increase in shear between the phases and due to the reduction of the wave dissipation effect of the viscosity of the liquid phase.

A large concentration of bubbles in the liquid phase was also observed for higher superficial gas velocities. This higher concentration is in line with the lower difference between the specific masses of the phases, and also with the viscosity of the oil. These two effects, however, should compete with each other, since with increasing pressure the difference between the specific masses decreases, facilitating the accumulation of bubbles, but also decreases the viscosity of the liquid phase due to the solubility of SF₆. Data for higher pressures, which will be explored in the future, will allow assessing how these effects will behave and their influence on the flow as a whole.

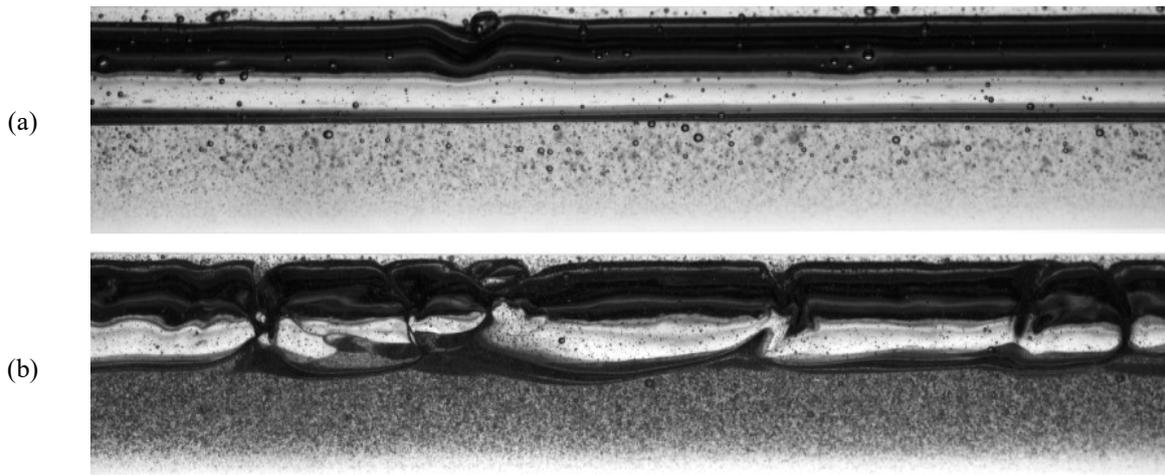


Figure 5. Images of the interface between the elongated bubble and liquid film for the experimental point of P01 for the gas densities of (a) 39 kg/m³ and (b) 64 kg/m³.

Figure 6 shows the interface between the elongated bubble and the liquid piston for the gas phase density of 64 kg/m³ and liquid viscosity of 7 cP for the experimental point of (a) P01 and (b) P02. The interface becomes more undulating with increasing surface velocity of the gaseous phase, due to the increase in gas inertia. It is also possible to notice a greater aeration of the liquid film with the increase in the superficial gas velocity.

The average pressure drop was measured for each condition, it was found that the pressure drop was slightly lower for the points of higher gas density, with the exception of the points P04 and P05. Both the points of higher gas velocity, above 0.6 m/s. One potential explanation for the lower pressure drop observed with higher gas density is that the increased density is a result of operating at higher pressure. Therefore, the higher pressure allows for a greater amount of SF₆ gas to dissolve in the oil. This increased amount of SF₆ dissolved in the oil leads to a decrease in viscosity, which in turn contributes to the observed lower pressure drop.

The measured pressure drops were also compared with Homogeneous and Lockhart-Martinelli (1949) models. Both models underestimate the pressure drop, with the homogeneous model being the less accurate of the two, underpredicting the pressure drop by approximately half for gas density of 64 kg/m³. The average deviation were 78% for the homogeneous model and 43% for the Lockhart-Martinelli (1949), considering all the points for both the gas densities. It was also observed that the deviations were consistently greater for the points of higher density (average deviations of

homogeneous for 39 kg/m³ were 74% and 82% for 64 kg/m³. For Lockhart-Martinelli the average deviations were 21% for 39 kg/m³ and 64% for 64 kg/m³, indicating that the models may need further optimizations in order to present better results for high density gas phases. Figure 7 show the pressure drop observed and calculated for the gas densities of (a) 39 kg/m³ and (b) 64 kg/m³ respectively.

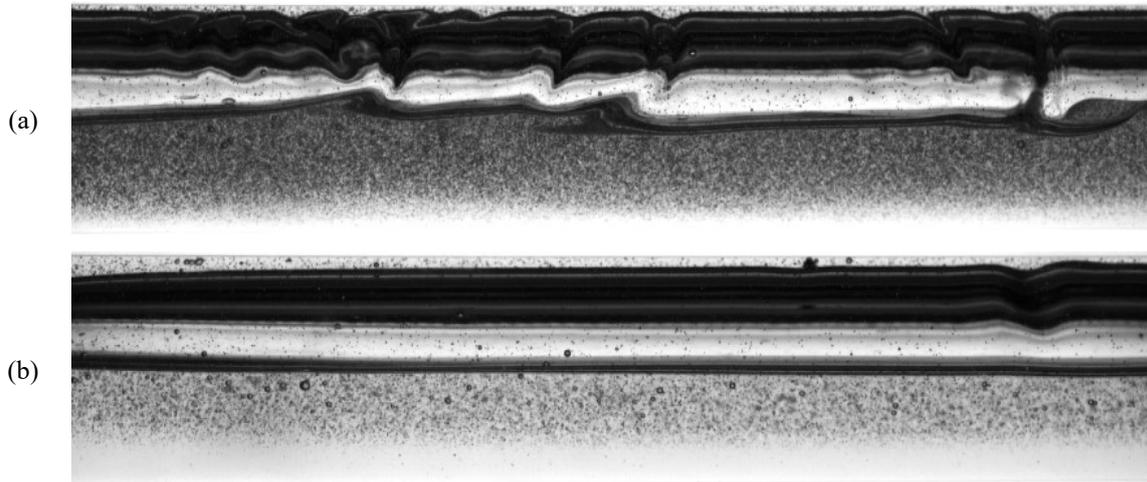


Figure 6. Images of the interface between the elongated bubble and the liquid piston for the gas phase density of 64 kg/m³ and liquid viscosity of 7 cP for the experimental point of (a) P01 and (b) P02.

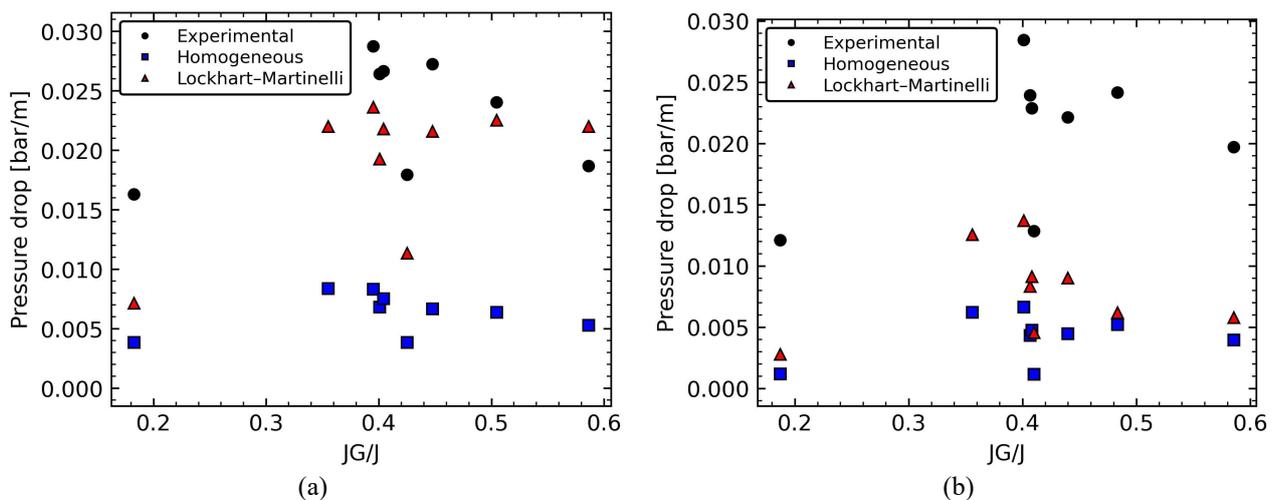


Figure 7. Pressure drop measured and calculated by homogeneous and Lockhart-Martinelli Models for gas density of (a) 39 and (b) 64 kg/m³.

The characteristics parameters of the slug flow were also measured experimentally with the capacitive sensors. Figure 8a presents the bubble length observed whereas Figure 8b shows the slug length. In both cases the higher gas density generally produced longer bubbles and slugs for most of the gas velocities tested. This increase in the bubble length is due the fact of the difficult of the form slugs as related by Khaledi et al. (2014) and Loh et al. (2016).

The normalized bubble velocity and frequency were also measured as shown in Figure 8c and Figure 8d. The bubble velocity was analyzed in terms of the Froude number. It was observed that the higher the gas density, higher the bubble velocity. A similar behavior is shown for the frequency, in particular for lower gas velocities.

4. CONCLUSION

This study presented an experimental investigation of the influence of gas density on two-phase gas-liquid slug flow in horizontal pipelines. The experiments were conducted in a 26mm a pipe and a length of 60 m. The model fluids used in the experiments were SF₆ and mineral oil. Five measuring stations were installed along the pipe, with each station equipped with a pressure transducer. Additionally, a visualization window was installed at the end of the two-phase flow pipe.

The impact of gas density was observed in the images showing instabilities at the interface between the gas bubble and the liquid film. There was a significant deviation between the experimental results for pressure drop and the predictions of the homogeneous and Lockhart Martinelli models. This discrepancy shows the need for further refinements in these models.

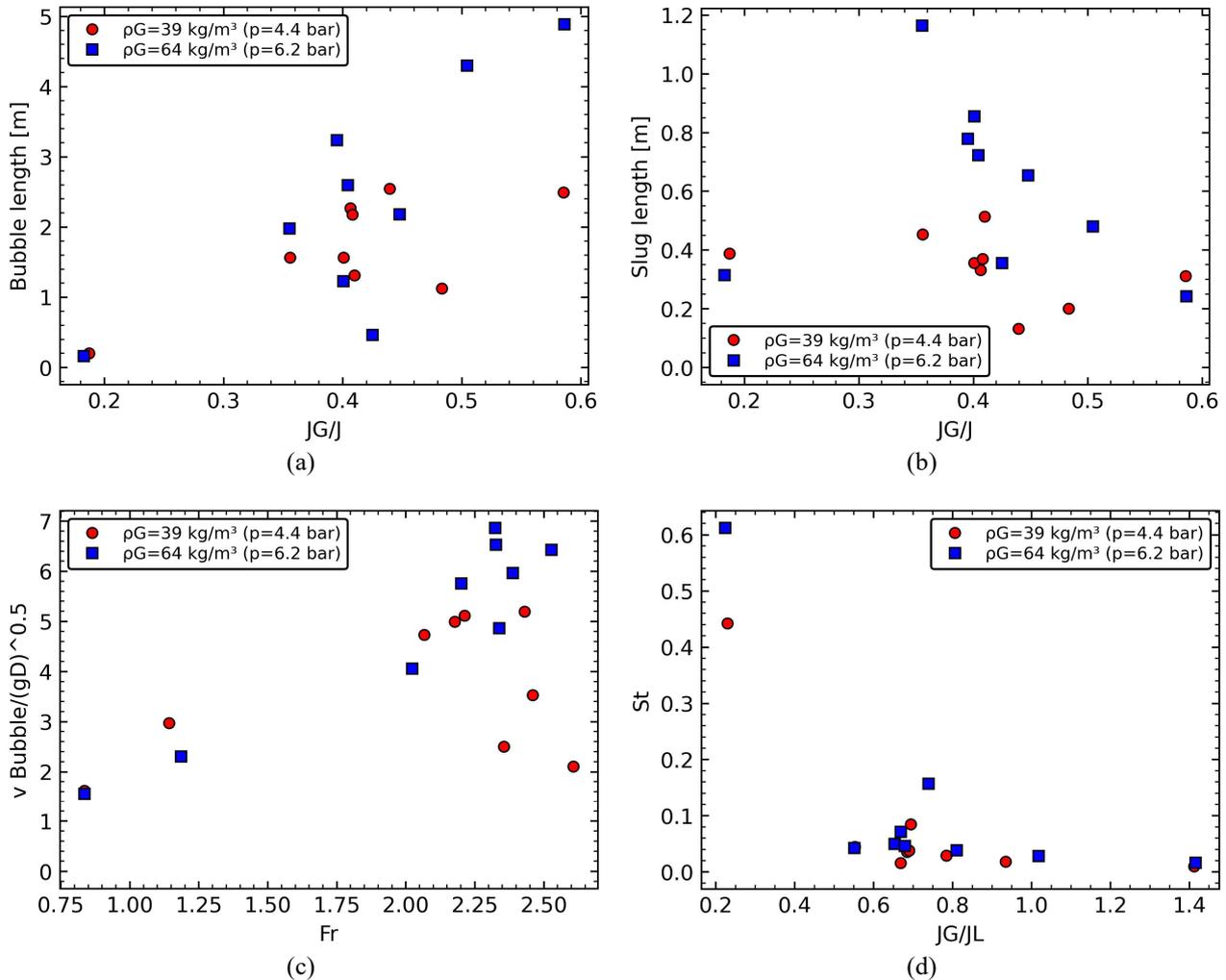


Figure 8. (a) Bubble length, (b) Slug length, (c) Bubble velocity and (d) Frequency for all the experimental points

5. ACKNOWLEDGEMENTS

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