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Analysis of the Influence of the Gas Density on Two-Phase Slug Flow in Horizontal Pipes

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Abstract
The study of two-phase slug flow is relevant for several industrial operations, particularly the oil and gas production ones. The present study focuses on how the lower liquid/gas density ratio affects the slug flow. A 60-meter-long, 1-inch ID experimental loop was built. Sulfur hexafluoride (SF_6) and mineral oil were used as model fluids. A density ratio of approximately 18 was tested. The superficial velocities ranged from 0.02 to 1.0 m/s and from 0.07 to 0.5 m/s for the gas and liquid phases, respectively. The phenomenological behavior of a unit cell is analyzed on the basis of the flow images, obtained from the experiment with a high-speed camera and compared with other experimental data where the two-phase flows were a mixture of glycerin/air and water/air. The elongated bubble nose deformation, the interface instability, the shape of the plunging jets and the dispersed bubble shapes were investigated.

Keywords
Slug flow; dense gas, slug flow parameters.

Introduction
Multiphase flow consists of two or more phases flowing simultaneously in a pipe with different interface shapes. During their transportation, the phases can assume several spatial distributions along the pipe, the so-called flow patterns. These diverse topological arrangements deeply affect the flow behavior. Therefore, understanding the characteristics of each regime, the impact of the operational conditions and the conditions under which they occur is a fundamental topic in the study of multiphase flows. Among the parameters that affect the behavior of the multiphase flow patterns, the influence of the fluid properties has captured the attention of different researchers over the last decades.
The analysis of the slug flow pattern is often required in industrial, technological and scientific endeavors. In the oil industry, slug flows occur in production and transportation lines quite frequently. Slug flows are characterized by the intermittent transit of a liquid plug – which may contain gas bubbles, in which case they are known as aerated slugs – followed by an elongated gas bubble filling most of the cross-sectional area of the pipe. In the case of a flow in a horizontal pipe, the elongated bubble concentrates on the top of the pipe because of buoyancy and slides atop a liquid film [1].
Previous research has often concentrated on the influence of the liquid viscosity on the bubble translational velocities. Recent studies, such as [2], [3] and [4], have evaluated the effect of the viscosity on bubble characteristics and translational velocities, proposing new correlations to incorporate the viscosity impact.
However, none of the aforementioned articles have explored the impact of the gas density on the slug flow parameters, disclosing a noteworthy gap in existing data analyses.
The present work focuses on high-pressure systems with oil and a dense gas under slug flow conditions. In this scenario, the gas density increases, even reaching values of the same order of magnitude as the liquid phase. This condition can be found in deepwater oil and gas production such as Brazil's pre-salt fields, given the in situ conditions of the reservoir, dense gas and liquid flow.
This study aims to investigate the liquid/dense-gas pipe flows with low density ratios, comparing them to other experimental data and discussing the influence of gas density on slug parameters such as the elongated bubble velocity and the slug length.

Methodology

Fig. (1) presents the schematic diagram of the flow loop. This loop consists of a closed system divided into a gas circuit that supplies gas for the tests, a liquid circuit dedicated to supplying liquid to the system, the two-phase circuit where the measurements were taken and a multiphase separator at the outlet.

The horizontal test section has approximately 60 m (~2307D) of length, 26-mm inner diameter (D), and is made of stainless-steel pipe. The test section has seven measuring stations, each one is equipped with two capacitive sensors and one pressure transducer. The capacitive sensors measure the liquid height [5]. In addition, flow parameters are obtained through the processing of the data from the capacitive sensors. The high-speed camera (with a maximum speed of 250 frames per second) is located 53.8 m (~2069 D) downstream of the mixer. All the pipes are thermally insulated to reduce the thermal exchanges with the ambient.

The oil used for this application was a commercial mineral oil Lubrax Hydra XP32. The sulfur hexafluoride (SF_6) had a purity of 99.9%. The liquid density was 880 kg/m³ and the viscosity was 0.06 Pa·s. The gas density was 50 kg/m³ and the viscosity 0.0162 mPa·s. The surface tension was 28 mN/m.

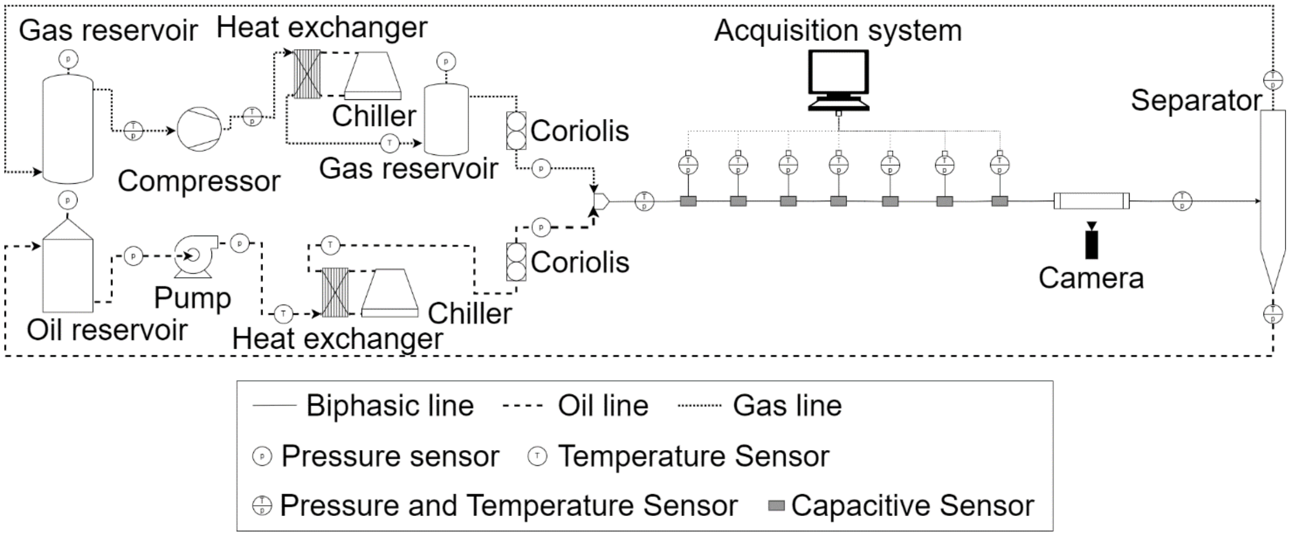

Figure 1. Schematic diagram of the flow loop.

Results and Discussion

The gas superficial velocities (J_G) ranged between 0.02-1.0 m/s while the liquid superficial velocities (J_L) ranged between 0.07-0.5 m/s. All experiments were performed considering $Fr_J < 3$. A total of forty-seven (47) pairs of liquid and gas superficial velocities were measured and the slug flow pattern was defined with the aid of the high-speed camera. In Fig. (2), the experimental points are presented and compared with [6] the transition lines on a flow pattern map. One can observe that the [6] map overpredicts the liquid superficial velocity determining the transition between stratified and intermittent flows. This might be attributed to the difference between the air/water density ratios - fluids used to build the original flow map - and those of the oil and SF_6 used in the experiments herein described. Although the higher gas inertia contributes to destabilizing waves, the smaller density ratio means that the potential energy required to produce the waves that can develop into slugs is smaller [7], thus contributing to the occurrence of intermittent flow for lower superficial velocities. Nevertheless, the transition between flow patterns has always been a very complex matter, with many different physical mechanisms working in opposite ways and intensities, not to mention the great influence of the physical properties of each phase.

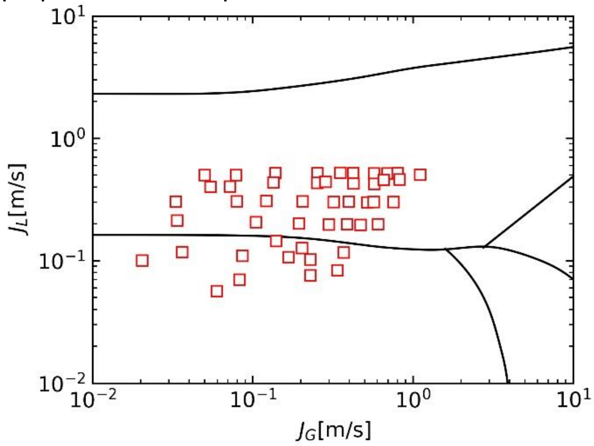

Figure 2. Experimental points on the [6] flow map.

Fig. (3) presents images of unit cells for three different fluids. Fig. (3a) and Fig. (3b) show experiments performed with air and water and air and a mixture of glycerin and water to achieve the liquid viscosity of 0.030 Pa·s, respectively [2]. Fig. (3c) shows the unit cell for mineral oil and SF_6. Those three experimental conditions have approximately the same superficial velocities of the phases, with gas and liquid superficial velocities at about 0.5 m/s.

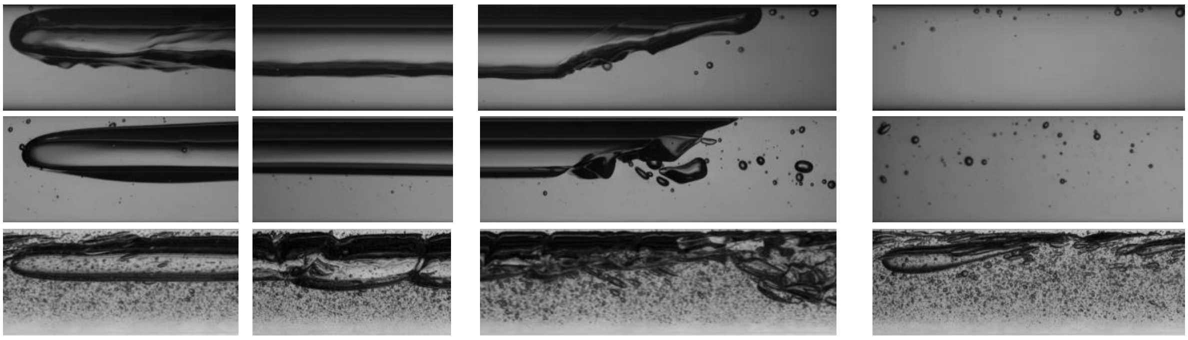

Figure 3. Images of sections of the unit cell for: a) air-water, b) air-water-glycerin, and c) mineral oil and SF_6.

When the images of the bubble noses are compared, one can observe the influence of the liquid viscosity making the nose narrower (Fig. 3a and b). When the effect of the gas density is accounted for, the nose detaches even further from the top of the pipe–an effect caused by the increase in the inertia.

The liquid viscosity dissipates the waves along the bubble, and thus the interface between the gas and the liquid becomes smooth. Waves appear on the interface with the increase in the gas density and the increment of the shear between the phases. The gas density reduces the amplitude of these waves, preventing the growth and formation of new slugs, and resulting in larger bubbles.

Plunging jets appear at the tail of the bubble with the increase in the liquid viscosity, because of the reduction in the surface tension which increases the penetration capacity of the cusp into the slug. The aeration of the liquid slug is impacted by the phenomena that occur at the elongated bubble tail. The shape of the dispersed bubbles is governed by the drag, buoyancy and the interfacial tension force. The elliptical shape of the necked dispersed bubble is the result of the combination of the increase in the shear of the phases and the low surface tension when compared to the air-water slug aeration.

Fig. (4) illustrates a comparison between the data from [2] for air-water and air-water-glycerin systems and the experimental data obtained in this study for slug length (L_S). Both air-water and air-water-glycerin systems share the same conditions, except for their viscosities, which are 1 cP and 30 cP respectively. Interestingly, it is observed that the higher viscosity leads to a reduction in slug length. Conversely, the experimental data from our study exhibit significantly longer slug lengths for a similar gas velocity range. This finding is intriguing, considering that the viscosity of SF_6-Oil used in our experiments is higher (60 cP) when compared to the viscosity values in [2] (SF_6-Oil 60 cP, air-water 1 cP, air-water-glycerin 30 cP), which would typically result in a smaller slug length. This suggests that the higher gas density contributes significantly to the increased slug length.

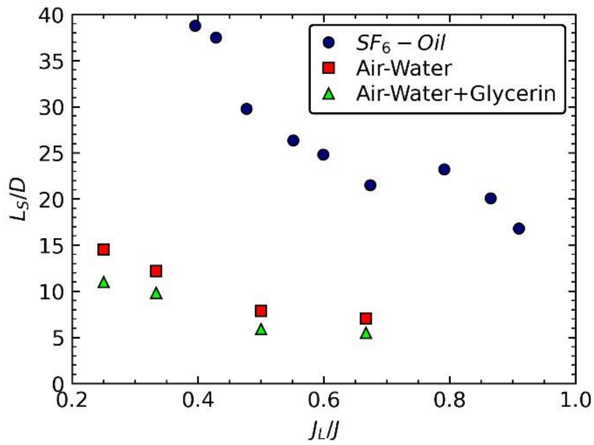

Figure 4. Slug lengths as a function of the ratio between the gas and the mixture superficial velocities, compared with air-water and air-water-glycerin [2] – superficial liquid velocity of 0.5 m/s and superficial gas velocity varying from 0.10 m/s to 0.8 m/s.

The increase in the slug length could be attributed to the difficult in slug formation. Consequently, when slugs do form, they contain a larger volume of liquid. Similarly, the bubble length (L_B) exhibits a trend similar to that of the slug length, as shown in Fig. (5). The bubble length for the presented experimental data is compared with the data from [2] for air-water and air-water-glycerin systems.

The impact of the gas density on the bubble length was associated to the increased energy required to make the liquid phase waves grow and to slug formation. As demonstrated earlier, although waves on the liquid-gas interface expanded with higher gas density, they lacked sufficient energy to develop into new slugs.

Conclusions

In this study, the influence of the superficial velocities of the phases and the gas density on the bubble nose, tail, and slug aeration were evaluated. The comparison between the experimental data for gas with small density shows that the elongated bubble began to show a narrower nose with a more accentuated detachment from the top of the pipe. Along the bubble, waves on the interface were observed with an increment in the gas density.

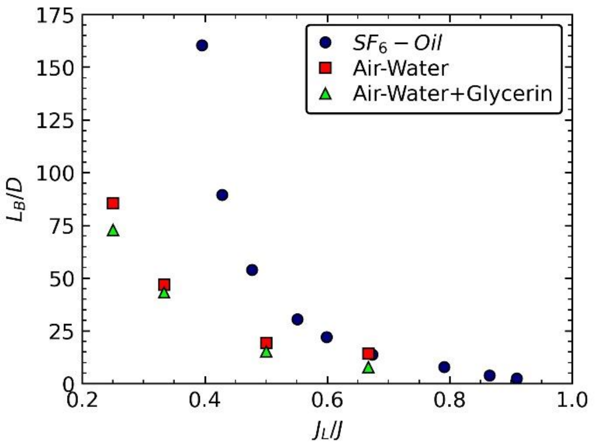

Figure 5. Bubble lengths as a function of the ratio between the gas and the mixture superficial velocities, compared with air-water and air-water-glycerin [2] – superficial liquid velocity of 0.5 m/s and superficial gas velocity varying from 0.10 m/s to 0.8 m/s.

The appearance of plunging jets was observed at the bubble tail. This phenomenon is related to the increase in the liquid viscosity and the reduction in the surface tension, which increases the capacity of the cusp to penetrate the slug. When analyzing the effect on the bubbles dispersed into the liquid slug, it is observed that these bubbles have larger sizes and a change in their shape. They no longer had the spherical shape of dispersed bubbles typically present in the air-water flow. Instead, they acquired an ellipsoidal shape, which was associated with a reduced resistance to deformation.

The impact of the gas density on the slug and bubble lengths is so significant that it overcomes the effect of the liquid viscosity. Nonetheless, a decrease in the slug and bubble lengths should be expected with the increase in the liquid viscosity. It was observed that raising the gas density causes an increase in the unit cell length.

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Responsibility Notice

The authors are the only ones responsible for the contents and opinions expressed in this article.

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