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EXPERIMENTAL STUDY OF THE INFLUENCE OF GAS DENSITY ON TWO-PHASE FLOW IN A ROCKING-FLOW CELL

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Abstract. *Although two-phase flows have been extensively investigated over the last decades, most of the studies analyze the flow of fluids at ambient conditions or high liquid-gas density ratios. In deep water offshore oil and gas production, where pressures are considerably high, the fluid densities are similar to each other or even of the same order of magnitude. Reproducing such conditions in lab scale can be a quite challenging and risky enterprise because of the high-pressure levels involved. One of the options to reproduce those conditions is to reduce the pressure and use heavy gases, instead of light gases at high pressure. In this work, we will analyze the influence of gas density on stratified and slug flows by using fluid models, SF6 and mineral oil. Experiments were performed by using a 51-mm I.D., 500-mm long rocking-flow cell that was pressurized up to 35 bar at temperatures between 5ºC and 45ºC. The gas density ranged from 6 kg/m³ to 388 kg/m³, resulting in liquid-gas density ratios from 142 to 2.3. Liquid loadings of 0.4, 0.7 and 0.9 and rotational speeds between 0.5 and 1.5 rad/s were tested. The maximum inclination of the rocking-flow cell was 17º. Mixing rules were used to predict the influence of dissolved SF6 on liquid properties. Recorded images of the experiments show the gas-liquid interface transition from a smooth surface to a wavy one as the gas density and the rotation speed increases. Differences in the contact angle were also observed. An elongated bubble similar to that of slug flow pattern is observed for the highest liquid loading. For the liquid loading of 0.7, the influence of the gas density on the transition between the stratified and slug flow was observed.*

Keywords: *two-phase flow, influence of gas density, rocking-flow cell*

1. INTRODUCTION

Multiphase flow consists of two or more phases and their interfaces, flowing simultaneously. This type of flow can occur naturally, such as in volcanos, where lava and the expelled gases flow together; and in industrial applications, such as during oil and gas production.

Depending on the operational and/or environmental conditions, different phases can flow at the same time. During their transportation, phases can assume several spatial distributions along the pipe, the so-called flow patterns. For instance, in horizontal gas-liquid two-phase flow, if the mixture flow rate is low enough, the denser phase will flow on the lower part of the pipeline, while the lighter phase will flow on the upper part, characterizing a stratified flow. Eventually, depending on the velocity of the phases, the interface separating the fluids becomes disturbed, and the generated waves can reach the top of the pipeline forming a slug flow (Shoham, 2006).

These different topological arrangements, such as stratified and slug, deeply affect the flow behavior. Therefore, understanding the characteristics of each regime, the impact of the operational conditions, and the conditions in which they will occur is a fundamental topic in the multiphase flow field (Shoham, 2006).

Among the parameters that affect the behavior of multiphase flow patterns, the influence of the fluid properties has drawn the attention of different researchers in the last decades. The present work focus on high-pressure systems under stratified and slug flow condition. In this scenario, the gas density increases, even reaching values of the same order of magnitude than that of the liquid phase, while the liquid viscosity decreases reaching 1 cP in some cases. This condition can be found in deep water offshore oil and gas production operations.

Taitel and Dukler (1986) evaluated the influence of the liquid viscosity on the transition between the flow patterns. For this purpose, air and water-glycerin mixtures were used as fluids and the liquid viscosity was varied between 1 cP

and 65 cP. They showed that when viscosity is increased, there is a reduction in occurrence of the stratified flow pattern and an increase in the occurrence of intermittent pattern, which can be either slug or elongated bubble flow. When comparing the flow transitions between the viscosities of 90 and 160 cP, an increase in combinations of superficial velocities of the phases was observed in which the intermittent pattern occurs.

Following the same line, Andritsos et al. (1986) evaluated the influence of liquid viscosity between 1 cP and 100 cP in the transition between stratified and slug flow. The authors compared the transition curves of air and water to the transition of air and a fluid with viscosity of 4 cP. It was observed that there are changes in the flow pattern curves even with such a small change in fluid viscosity. For all viscosities evaluated by the authors, increasing viscosity increases the number of flow combinations in which occurs slug flow, in addition to reducing the occurrence of stratified flow pattern.

In this scenario, Nakamura (1996) worked with a gas phase with a density of 60 kg/m³ in a 4- and 8-in ID pipes and noticed that the slug flow region in the flow map gradually reduced its area and eventually disappeared above 8.6 MPa.

Likewise, Abduvayt et al. [3] investigated experimentally and theoretically the effects of pressure and pipe diameter on the behavior of the two-phase liquid-gas flow for horizontal and slightly inclined ducts. They gathered data on flow pattern, pressure drop and liquid retention over a wide range of gas and liquid flow rates in a large diameter pipe (106.4 mm) for two different pressures (592 and 2060 kPa). They noticed that high pressures tend to anticipate transition in the flow map to lower gas velocities.

To analyze two-phase flows at high pressures, Johnson at al. (2009) carried out experiments using SF6 at 8 bar, which corresponds to a gas phase density of approximately 50 kg/m³, in a 25-m long, 10-cm diameter pipe for inclinations from horizontal to 5°. The authors reported that the increase in pressure caused an increment in the speed of the roll waves. This was attributed to the shape of these waves.

Tzotzi et al. (2011) used visual observations and conductivity probe sensors to study the effect of fluid properties, including the gas density, on the flow patterns. Two different gases, He and CO2, with densities of 0.167 and 1.8 kg/m³ were used. Water was the liquid phase, and the experiments were performed under atmospheric conditions. The results were compared with air-water experiments. They analyzed the influence of the gas density on stratified flow sub-regions and concluded that the gas density affects the transitions between stratified and wavy stratified flow. Significant changes were not observed for the stratified-to-slug flow transition.

An experimental study of two-phase flow using SF6 and two different oils with viscosities of 32 and 100 cP was developed by Khaledi et al. (2014). The experiments were performed with pressures of 4 and 8 bar, in order to vary the density of the gas from 25 to 50 kg/m³. The authors observed the occurrence of stratified flow pattern at conditions in which slug flow was expected.

In 2016, Loh et al. (2016) analyzed the effect of the gas density and pressure in a horizontal pipeline by varying the pressure between 0 and 10 bar. The authors noticed that the increase in the pressure causes an increment in the frequency of the waves in the stratified flow and a decrease in their amplitude.

Wang et al. (2019) carried out experiments in a 50-mm ID pipe, varying the pressure up to 20 bar for air and water, obtaining a gas phase density of 23.4 kg/m³. Comparing experiments at 20 bar with those performed at atmospheric pressure, it was observed that the wave amplitude decreases from 0.02–6.0 mm to 0.015–2.0 mm, thus implying that the high pressure reduces the wave amplitude. For two-phase flow in a horizontal tube at 20 bar, an earlier transition between smooth and stratified wavy flow occurs, that is, at smaller superficial gas velocities. At the same time, the transition between stratified and slug flow starts to occur with higher liquid superficial velocities, increasing the stratified flow region in the flow map.

The increment in the gas density increases the interfacial instabilities. The increment in the liquid viscosity tends to reduce the instabilities in the interface. In this study, the influence of the gas density and the liquid viscosity in the interfacial instabilities in the stratified flow and the transitions between stratified and slug flowis experimentally analyzed. In the production of oil and gas, the pressure is considerably high and the fluid densities are of the same magnitude of the oil. Reproducing such conditions in lab scale can be a quite challenging and risky enterprise because of the high pressure levels involved. One of the options to reproduce those conditions is to reduce the pressure and use heavy gases, instead of light gases at high pressures. Therefore, in this work, the influence of gas density will be evaluated by using fluid models, SF6 and mineral oil in a rocking-flow cell.

2. EXPERIMENTAL METHODOLOGY

A rocking-flow cell, represented schematically in Fig. 1, was used to perform the experiments and investigate the influence of the gas density on two-phase flow. A syringe pump, powered by the gas, was used for pressurizing the system.
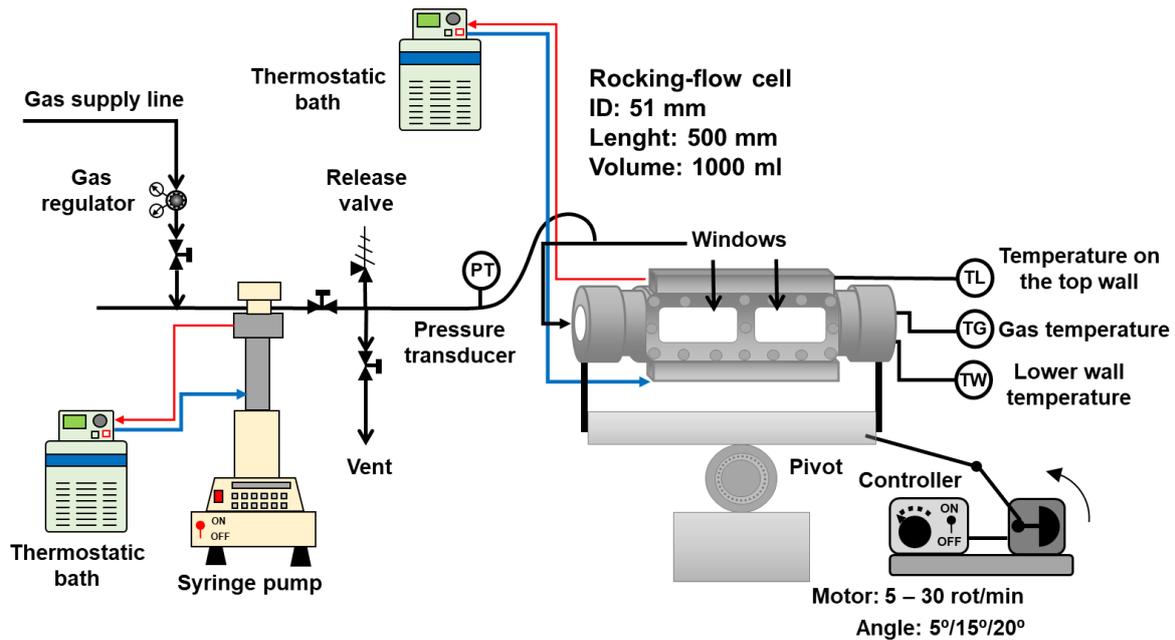
Figure 1. Experimental setup

The rocking-flow cell, which stands pressures up to 100 bar, consists of a 500-mm long cylinder with 51-mm ID. The cell has windows on its front, back and side, therefore allowing the visualization of the flow along the axial and cross-sectional directions. Three webcams were positioned facing the front (two) and side (one) windows.

Three different rotation speeds of 0.5, 1.0 and 1.5 rad/s and a maximum inclination angle of 17.6° were used to rock the cell. This simulates the flow in a pipe and causes the phases to mix because of gravity and the difference in their specific masses.

The working fluids were SF6 and mineral oil (LUBRAX HYDRA XP ISO 32), with three different liquid loadings of 40%, 70% and 90%.

Four temperatures were studied: 5, 15, 30 and 45°C and controlled by a thermostatic bath.

For each temperature, the maximum pressure tested was the highest one before the critical point of SF6.

In total, 63 combinations of pressure and rotation speed were investigated, as shown in Tab. 1.

Table 1. Test grid.

Liquid volume fraction (%)	Pressure (bar)	Temperature (°C)	Rotation speed (rad/s)
40, 70 and 90	1, 5 and 10	5	0.5, 1 and 1.5
	1, 5, 10 and 15	15	
	1, 5, 10, 15, 20 and 25	30	
	1, 5, 10, 15, 20, 25, 30 and 35	45	

2.1 Fluids Properties

The SF6 dissolves in the mineral oil; hence, it is necessary to estimate the properties of the liquid phase for each combination of temperature and pressure. According to Henry's law, the solubility of a gas in a liquid at constant temperature is directly proportional to the partial pressure of the gas above the liquid. It was considered that the gas phase was composed of molecules of SF6 only. With this consideration, the pressure measured inside the cell, P, was used to evaluate the amount of SF6 dissolved in the oil.

The estimation of the oil properties, namely density and viscosity, was made by using the software Engineering Equation Solver (EES). The gas phase was considered a single phase composed of SF6 whereas the liquid phase was considered a mixture of mineral oil and dissolved SF6. It has been estimated, from experimental data carried out for this pair of fluids at NUEM/UTFPR (Miguel Junior et al., 2020), that the mass fraction of SF6 in the oil is:

$$x_{SF_6} \approx \frac{P}{309} \tag{1}$$

The density of the liquid phase is given by:

$$\frac{1}{\rho_{liq}} = \frac{1 - x_{SF_6}}{\rho_{oil}} + \frac{x_{SF_6}}{\rho_{SF_6}} \tag{2}$$

where ρ is the density. The viscosity was calculated by the Katti-Chaudhri (1964) mixing rule:

$$\ln\left[V_{liq}\,\mu_{liq}\right] = x_{oil}\,\ln\left[V_{oil}\,\mu_{oil}\right] + x_{SF_6}\,\ln\left[V_{SF_6}\,\mu_{SF_6}\right] + x_{oil}\,x_{SF_6}\,\frac{W}{RT} \tag{3}$$

Where μ is the viscosity, V is the molar volume, W is the excess activation energy of the viscous flow, R is the gas constant and T is the temperature. In this study, W was considered equal to zero.

The liquid viscosity varied between 1.2 and 52.2 cP as shown in Table 2, and the liquid density between 856 and 888 kg/m³ as shown in Table 3. The gas viscosity varied between 0.016 and 0.024 cP as presented in Table 4, and the gas density, presented in Table 5, varied between 5.6 and 388.6 kg/m³.

Table 2. Liquid viscosity.

	1 bar	5 bar	10 bar	15 bar	20 bar	25 bar	30 bar	35 bar
5°C	52.16 cP	22.39 cP	4.15 cP	-	-	-	-	-
15°C	40.81 cP	23.03 cP	6.45 cP	2.36 cP	-	-	-	-
30°C	29.85 cP	19.46 cP	8.19 cP	4.28 cP	2.41 cP	1.27 cP	-	-
45°C	23.23 cP	13.47 cP	7.96 cP	5.07 cP	3.43 cP	2.41 cP	1.72 cP	1.21 cP

Table 3. Liquid density.

	1 bar	5 bar	10 bar	15 bar	20 bar	25 bar	30 bar	35 bar
5°C	865 kg/m³	869 kg/m³	874 kg/m³	-	-	-	-	-
15°C	863 kg/m³	868 kg/m³	873 kg/m³	879 kg/m³	-	-	-	-
30°C	860 kg/m³	864 kg/m³	869 kg/m³	873 kg/m³	878 kg/m³	882 kg/m³	-	-
45°C	856 kg/m³	861 kg/m³	865 kg/m³	869 kg/m³	874 kg/m³	878 kg/m³	883 kg/m³	888 kg/m³

Table 4. Gas viscosity.

	1 bar	5 bar	10 bar	15 bar	20 bar	25 bar	30 bar	35 bar
5°C	0.016 cP	0.016 cP	0.016 cP	-	-	-	-	-
15°C	0.016 cP	0.016 cP	0.016 cP	0.016 cP	-	-	-	-
30°C	0.017 cP	0.017 cP	0.017 cP	0.017 cP	0.018 cP	0.018 cP	-	-
45°C	0.018 cP	0.018 cP	0.018 cP	0.018 cP	0.019 cP	0.019 cP	0.020 cP	0.024 cP

Table 5. Gas density.

	1 bar	5 bar	10 bar	15 bar	20 bar	25 bar	30 bar	35 bar
5°C	6.4 kg/m³	34.1 kg/m³	75.3 kg/m³	-	-	-	-	-
15°C	6.2 kg/m³	32.6 kg/m³	70.9 kg/m³	118.8 kg/m³	-	-	-	-
30°C	5.9 kg/m³	30.7 kg/m³	65.5 kg/m³	106.5 kg/m³	157.8 kg/m³	231.6 kg/m³	-	-
45°C	5.6 kg/m³	29.0 kg/m³	61.1 kg/m³	97.6 kg/m³	140.2 kg/m³	192.4 kg/m³	262.5 kg/m³	388.6 kg/m³

3. RESULTS AND DISCUSSION

Figures 2, 3, 4 and 5 show images of the experiments for the liquid loading of 70% as function of gas density and rotation speed for the liquid viscosities of 23, 4.2, 2.4 and 1.2 cP, respectively. When the images are compared for the same rotation speed, it is noticed the increase in the interfacial instabilities with the increase of gas density.
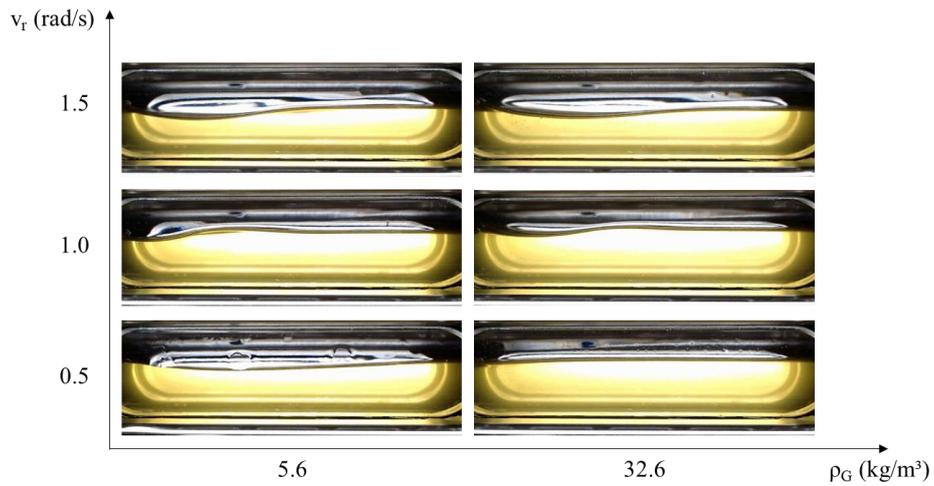
Figure 2. Interfacial instabilities as a function of gas density and rotation speed for the liquid loading of 70% for the liquid viscosity of 23 cP
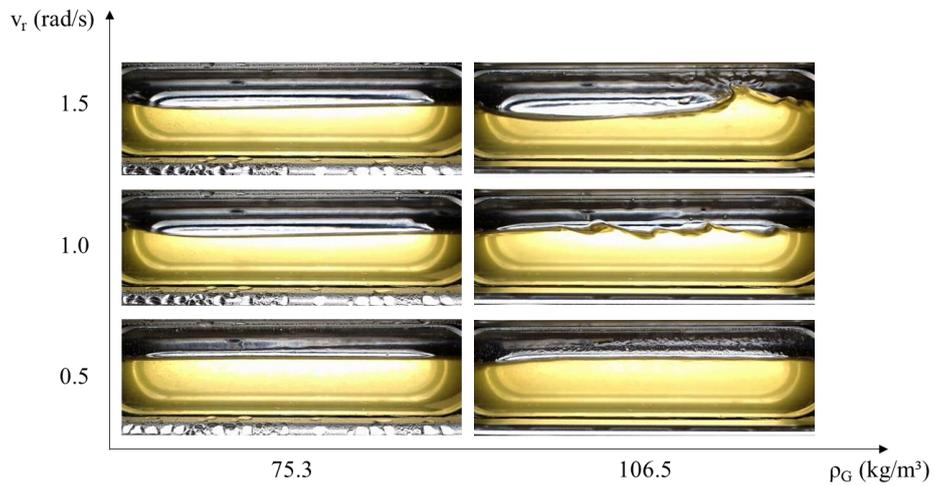

Figure 3. Interfacial instabilities as a function of gas density and rotation speed for the liquid loading of 70% for the liquid viscosity of 4.2 cP
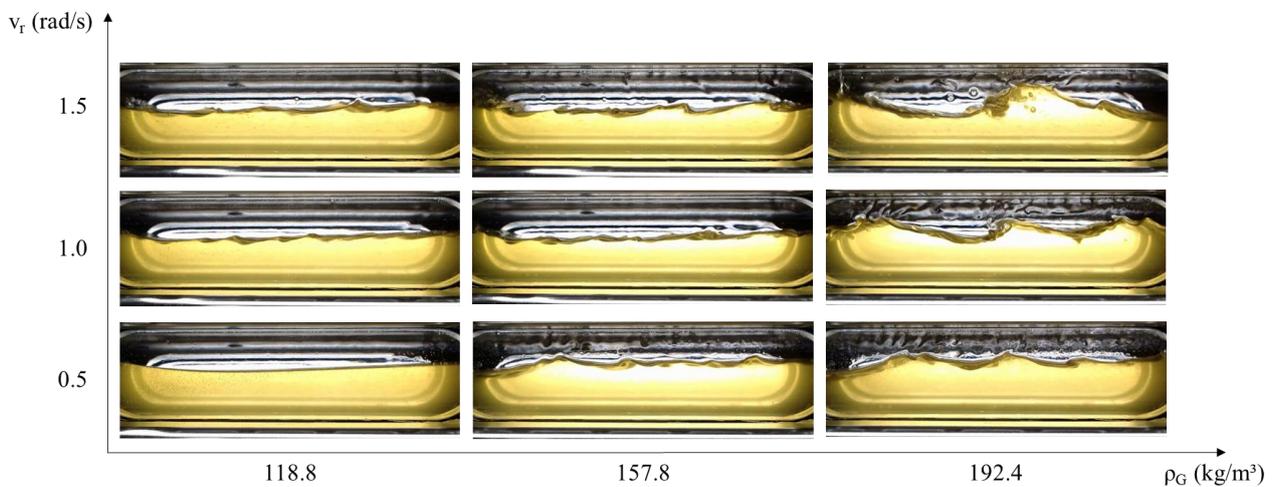

Figure 4. Interfacial instabilities as a function of gas density and rotation speed for the liquid loading of 70% for the liquid viscosity of 2.4 cP
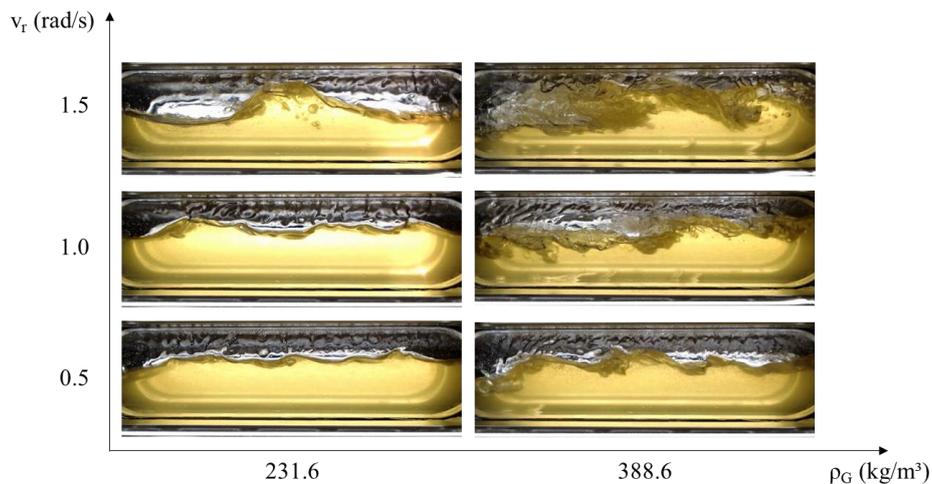
Figure 5. Interfacial instabilities as a function of gas density and rotation speed for the liquid loading of 70% for the liquid viscosity of 1.2 cP

In the Figure 2 are presented the images with the highest liquid viscosity and lowest gas density. It is observed that there is no waves at the interface because the momentum of the gas is not high enough to overcome the dissipation effect of the liquid viscosity.

The same effect can be seen in the Figure 3 for the gas density of 75.3 kg/m³. For the gas density of 106.5 kg/m³, it is possible to observe that there is no waves in the interface for the rotation speed of 0.5 rad/s, but, with the increase in the rotation speed, there are waves in the liquid-gas interface and a structure similar to an elongated bubble is formed.

In the Figure 4, there are the appearance of the waves in the interface with the increase in the gas density and with the increment in the rotation speed. For the gas density of 118.8 kg/m³, it is not possible to observe interfacial instabilities for the rotation speed of 0.5 rad/s. With the increase of the rotation speed, it is possible to see the appearance of waves at the interface. For the gas densities of 157.8 and 192.4 kg/m³, even for the rotation speed of 0.5 rad/s there are waves in the interface. The gas momentum is the principal mechanism of destabilization of the gas-liquid interface (Tzotzi et al, 2011). The increment in the gas density causes a significant increase in gas inertia, causing an increase in the destabilization of the interface and the growth of waves in the interface.

Furthermore, when gas density increases, a smaller difference between the gas and liquid densities is obtained since, as shown in the previous section, the density of the liquid phase remains almost unchanged. This reduction in the difference between phase densities causes an increase of interfacial instabilities. As the difference between the liquid and gas densities decreases, less energy is necessary to form waves.

As shown by Tzotzi et al. (2011), the increase in the gas density changes the wave regimes in the stratified flow for the same phase velocities, which can be associated to the appearance of waves in the gas-liquid interface for the same rotation speed.

The liquid and gas velocities are function of the rotation speed. As the rotation speed increases, the rate of change of the inclination angle becomes bigger as well as the acceleration and the difference between the velocities of the phases. As Figures 3, 4 and 5 show, the increment in the rotational speed results in more waves in the liquid-gas interface.

An increase in the rotational speed increases the velocity difference between the phases, causing an increase in the instabilities at the liquid-gas interface.

Although there is appearance of structure similar to an elongated bubble for the gas density of 106.5 kg/m³ and a liquid viscosity of 4.2 cP. Due to this competition of effects between the liquid viscosity and gas density, for the experiments with smaller liquid viscosities it was observed elongated bubbles with gas densities above 192.4 kg/m³. The decrease in the liquid viscosity requires less energy to form waves and to transition from stratified to slug flow. And the increase in the gas density increase the momentum transfer and the interface becomes wavier. With the increase in the gas density, there is also the effect of the weight of the gas, which tends to inhibit waves growth. Khaledi et al. (2014) has already shown that the increase in the gas density changes the transition between stratified and slug flow.

In the Figure 5 it is presented images of the experiments performed for the liquid viscosity of 1.2 cP. These images are for the highest gas density evaluated, and it is noticed the increase in the number of waves in the interface when compare to the images for the lowest gas densities presented in the other figures. This increase in the number of waves is due to the increment in the gas density and decrease in the liquid viscosity.

Comparing the results for three different rotation speeds, it is observed that there are some changes in the wave's characteristics, this is due the changes in the wave regimes.

4. CONCLUSIONS

This work presented an experimental study analyzing the influence of gas density on stratified flow and stratified-slug flow transition using a rocking-flow cell. Mixing rules were used for estimating the liquid properties, considering mineral oil and dissolved SF6 as the liquid phase. Four different temperatures and pressures between 1 and 35 bar were tested. The increase in the pressure causes an increase in the gas density and a decrease in the liquid viscosity, due to the solubilization of SF6 in the mineral oil.

An increase in the gas density and decrease in the liquid viscosity causes an increase in the interface destabilization. The increase in the gas density causes an increment in the momentum transfer in the interface. Although the increase in the gas density results in an increase in the number of waves at the interface, this does not mean that there is an increment in the wave's amplitude. The decrease in the liquid viscosity means less energy is needed for waves to grow at the interface.

The increase in the rotation speed changes the fluid velocities and results in higher interfacial shear stress, therefore leading to the more interfacial stabilities. The increase in the rotation speed increments the wave's amplitude. Also, with the increase in the phase's velocities, there is also changes in the wave's characteristics, due to the changes in the wave regime.

5. ACKNOWLEDGEMENTS

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