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COB-2021-0917 INVESTIGATION OF THE INFLUENCE OF GAS DENSITY ON TWO-PHASE FLOW FOR MINERAL OIL AND SF6 PRESSURIZED IN A ROCKING-FLOW CELL

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Abstract. *Gas-liquid two-phase flow has been widely investigated in the last decades. Most of the studies in this field focus on fluids at ambient conditions or high ratios of liquid density over gas density, e.g., water and air, mineral oil and light gases (air, N2), etc. However, in some industrial applications like offshore oil and gas production in deepwater, where the pressure is considerably high, the fluid densities are similar to each other and even of the same order of magnitude. Reproduce conditions like that in lab scale can be very challenging and risky because of the pressures involved, so in order to mimic this scenario at lower pressures, heavy gases at low pressure, e.g.,* SF_6*, are used to substitute the light gases at high pressure. In this paper, we will show the influence of pressure on the stratified flow using* SF_6 *and mineral oil to achieve small ratios of liquid density over gas density. Experiments were performed using a rocking-flow cell of 26 mm I.D. and 960 mm length that was pressurized up to 20 bar at ambient temperature, i.e., about 20ºC. The gas density ranged from 6 kg/m³ up to 176 kg/m³, resulting in density ratios of 141 to 5. Different rotational speeds for a liquid loading and an angular displacement amplitude were tested. Mixing rules were used to predict the influence of dissolved* SF_6 *over liquid properties. Recorded images of the experiments for low liquid loading show that the gas-liquid interface transition from a smooth surface to a wavy one as pressure increases, which is analyzed using Kelvin-Helmholtz instability theory.*

Keywords: *two-phase flow, stratified flow, rocking-flow cell, influence of gas density, instabilities of gas-liquid interface.*

1. INTRODUCTION

Multiphase flows are characterized by the simultaneous flow of two or more phases through the same pipe. This kind of flow occurs in natural environments, e.g., sediment transport in rivers, and in industrial areas such as the petroleum and nuclear industry. During the oil production and transportation, gases, liquids and even solid particles can be found. These flows are usually modeled as two-phase liquid and gas flows due to their complexity. The two-phase mixture can assume several distributions in the pipe, called flow patterns. The occurrence of a specific flow pattern depends upon many parameters, such as the flow rates, the physical properties of the two phases, and the geometrical characteristics of the pipe.

The flow characteristics in two-phase gas-liquid flow are strongly dependent on the flow pattern that prevails in the pipe. For the low velocities of gas and liquid at horizontal pipes, the flow pattern found is the stratified flow. This pattern is characterized by the flow of two phases, liquid and gas, separated from each other by a continuous interface. This pattern is dominated by the gravity force that causes the liquid to stratify at the bottom. This flow pattern can be observed in horizontal or slightly inclined pipelines. It is characterized by the interface structure that can be smooth or wavy according to the gas flow.

At low gas velocities, the interface between the two phases is smooth or can be rippled by small capillary waves a few millimeters long. As the gas velocity increases, regular waves of small amplitude appear. At high enough gas velocities, droplets can be dragged from the large-amplitude irregular waves and deposit on the wall or interface, called the roll waves.

In recent decades, the effects of properties on flow patterns and instabilities of the liquid-gas interface have been studied. Studies have reported that, in two-phase flows with gases with densities greater than that of air, there is a change in the transition between stratified and slug flows due to the influence of gas density on interfacial instabilities, increasing the set of superficial velocities of the phases in which the flow is in the stratified pattern.

One of the first studies that evaluated the effect of gas phase density on horizontal two-phase flow was Hoogerdorn and Buitellar (1961) using superheated Freon-11 as the gas phase. It was found that an increase in gas density does not affect the transition between slug and plug flow, but significantly decreases the onset of atomization, in which some droplets displace from the wave crest and deposit at pipe wall. Weisman et al. (1979) analyzed the effects of fluid properties and pipe diameter on two-phase flow patterns and proposed corrections for the flow map. However, the effect of gas density was not systematically isolated.

Nakamura (1996) analyzed the flow of saturated steam with water at pressures up to 12 MPa in horizontal tubes. The density of saturated steam at 12 MPa is about 60 kg/m³. Assessing the stratified and slug flow transitions, he found that the slug flow region in the flow map gradually reduced and eventually disappeared.

Likewise, Abduvayt et al. (2003) investigated the effects of pressure and pipe diameter on the behavior of two-phase gas-liquid flow for horizontal and slightly inclined pipelines. They acquired flow pattern, pressure drop and liquid retention data with a wide range of gas and liquid flow rates in a large diameter tube (106.4 mm ID) for two different pressures (592 and 2060 kPa). They found out that high pressure tends to shift the limits to the lower side of the superficial gas velocity in flow pattern maps.

Tzotzi et al. (2011) studied the effect of fluid properties on flow patterns, including gas density, using visual observations and a conductivity probe. They used two different gases, CO_2 and He, under atmospheric conditions and compared the experimental data with air-water experiments. They focused on stratified subregions and concluded that gas density strongly affects the transition to two-dimensional and Kelvin-Helmholtz waves, while the transition from stratified to slug flow remains almost unchanged.

To analyze the effect of gas density and pressure, Loh et al. (2016) carried out experiments varying the pressure between 0 and 10 bar in a horizontal pipeline. For all experimental points, the stratified-slug transition, once the liquid slugs have been eliminated one by one, increasing the pressure, and the flow pattern is wavy, there is a sudden increase in the average liquid height and then the average height of the liquid remains constant until the flow pattern becomes smooth stratified. Once it is smooth, it starts to decrease the height of liquid. This suggests that the energy (moment) of the denser gas acts first by dampening the interfacial waves and then lowering the liquid level.

Most of the studies in this field focus on fluids at ambient conditions or high ratios of liquid density over gas density, e.g., water and air, mineral oil and light gases (air, N_2), etc. However, in some industrial applications like offshore oil and gas production in deepwater, where the pressure is considerably high, the fluid densities are similar to each other and even of the same order of magnitude. Reproduce conditions like that in lab scale can be very challenging and risky because of the pressures involved, so to mimic this scenario at lower pressures, heavy gases at low pressure, e.g., SF_6, are used to substitute the light gases at high pressure. In this paper, we will show the influence of pressure on the stratified flow using SF_6 and mineral oil to achieve small ratios of liquid density over gas density.

2. FLUIDS PROPERTIES

The fluids used were SF_6 and mineral oil (LUBRAX HYDRA XP ISO 32). Following Henry's law, the amount of SF_6 dissolved in the mineral oil is proportional to its partial pressure. In the experiments, it was assumed that the gas is composed of only SF_6, so the pressure measured inside the cell (P) was used to evaluate the amount of SF_6 dissolved in the oil. From data carried out for this pair of fluids at NUEM/UTFPR (Miguel Junior et al., 2020), it has been estimated that the mass fraction of SF_6 in the oil is $x_{SF6} \approx P/309$. The fluids properties, i.e., density and viscosity, were evaluated using the software *Engineering Equation Solver* (*EES*). The gas phase was considered a single phase composed of SF_6 while the liquid phase was considered a mixture of mineral oil and dissolved SF_6, whose density is given by:

$$\frac{1}{\rho_{liquid\ phase}} = \frac{1-x_{SF6}}{\rho_{oil}} + \frac{x_{SF6}}{\rho_{SF6}}, \tag{1}$$

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

$$\ln\left[V_{liquid\ phase}\mu_{liquid\ phase}\right] = x_{oil}\ln\left[V_{oil}\mu_{oil}\right] + x_{SF6}\ln\left[V_{SF6}\mu_{SF6}\right] + x_{oil}x_{SF6}\frac{W}{RT}, \tag{2}$$

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.

Analyzing the results in Figure 1, it is noticeable that SF_6 has a minimum impact on the resulting liquid density. On the other hand, it severely reduces the resulting liquid viscosity. It is important to clarify that those values obtained here are estimations of the liquid phase properties and they will be used in this paper for qualitative analyses only. A detailed study should be performed in order to evaluate results that are more accurate.

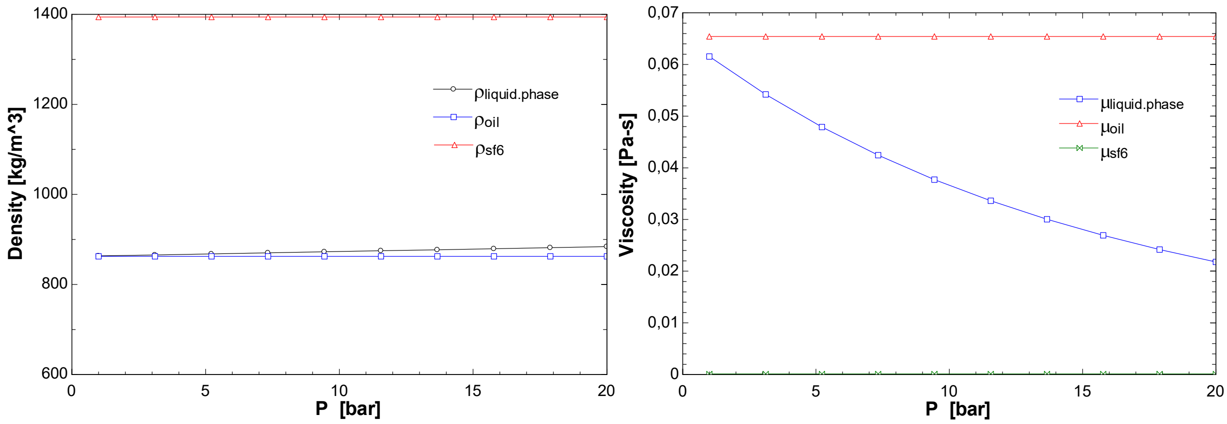

Figure 1. Density (left) and viscosity (right) of liquid phase.

3. ROCKING-FLOW CELL

A rocking-flow cell was used to perform the experiments and visualize the influence of pressure on the stratified flow. Figure 2 shows a picture of the rocking-flow cell apparatus. The cell is composed of two identical boxes of 500 mm in length with an acrylic tube inside of 26 mm ID rated to operate up to 27 bar. The boxes were connected to each other so that the combined length of the pipe available for the experiments was 960 mm. This modular construction allows experiments with different lengths and the box around the pipe allows the circulation of water, for example, from a chiller to control the temperature. A table pivoted at the bottom and connected to an electric motor with gear reducer using a simple mechanism (four-bar linkage) supported the cell. The tilt angle (maximum inclination angle) of the cell can be adjusted by changing the bars length of the mechanism and its period is controlled through a variable speed driver. Two cameras positioned in front of each cell's box recorded images of the flow, whereas a background illumination system provided proper light for the images. Fittings connected on the sides of the cell allowed the pressurization with SF_6 and the monitoring of pressure inside the cell.

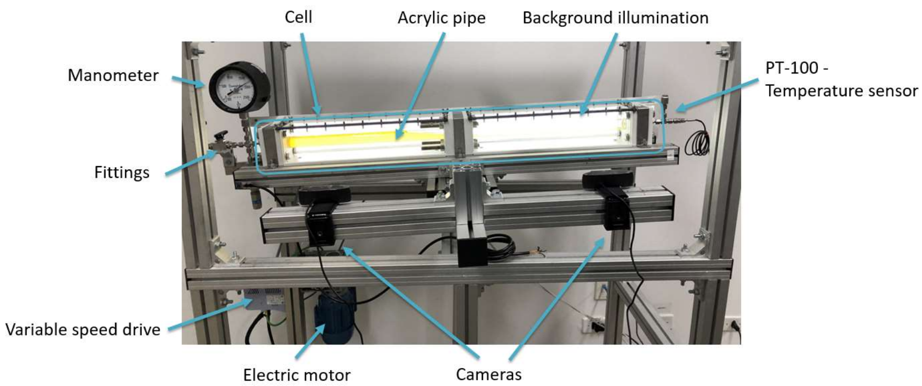

Figure 2. Rocking-flow cell.

This kind of experimental apparatus was chosen because of its simplicity and reduced size proportions (requires fewer resources) when compared to a flow loop, for example. Yet it provides good insights for the interactions between phases for a two-phase or even a multiphase flow. However, there are some limitations regarding the flow speeds that are possible to achieve in this equipment since the fluid motion is driven by gravity, which is proportional to the inclination of the cell, and only counter-current flow is possible. Nevertheless, it provided very interesting results for the study proposed in this paper, as will be showed herein.

The procedure to operate the cell was: (i) fill the cell with mineral oil; (ii) remove any gas dissolved in the oil or vapor in the cell using a vacuum pump; (iii) charge the cell with SF_6 up to the pressure of interest; and, (iv) wait for pressure stabilization of the system, since SF_6 solubilization process takes some time. The recording of the experiment started after the cell had already rotated a few cycles, so any influence of the start-up of the cell can be neglected. The room temperature was kept constant at 20ºC and the fluids used in the experiments were stored in the same room.

4. TEST GRID

Four different pressures were studied: 1, 5, 10 and 20 bar. The estimated properties of the fluids at these pressures are presented in Table 1. In the properties of the liquid phase are being consider the effects of gas solubilization with the increase of the pressure. The experiments were performed with a liquid loading in the pipe of 50%, a maximum inclination angle of 17.8° and 10 combinations of pressure and rotation speed as shown in Table 2.

Table 1. Properties of the fluids.

Fluid	Temperature (ºC)	Pressure (bar)	Density (kg/m³)	Viscosity (cP)
SF_6	20	1	6.1	0.016
		5	32	0.016
		10	69	0.017
		20	176	0.018
Liquid phase[(1)]	20	1	863	62
		5	868	49
		10	873	37
		20	884	22

[(1)] properties estimated using mixing rules for Lubrax Hydra XP ISO 32 and dissolved SF6

Table 2. Test grid for experiments.

Liquid volume fraction	Pressure (bar)	Maximum inclination angle	Rotation speed (rad/s)	Period (s)
0.5	1 5 10	17.8º	0.5, 1 and 1.5	12.5, 6.3 and 4.2
	20		0.5	12.5

5. RESULTS

As said in the previous section, a 50% liquid loading was chosen. This volumetric ratio of liquid and gas allows achieving a stratified-like flow within the rocking-flow cell, which can give some insights about the influence of pressure on the liquid-gas interface. Figure 3 shows the images of the liquid-gas interface for all pressures at rotational speed of 0.5 rad/s. The liquid-gas interface is smooth for 1 bar and 5 bar. For 10 bar some perturbations appears at the interface and for 20 bar it is very unstable. The intensification of the instabilities at the interface is explained based on the Kelvin-Helmholtz (K-H) instability theory. As the difference of the liquid and gas densities decreases for higher pressure, less energy is required to form waves. Furthermore, the dissipative effect associated with the liquid viscosity reduces because of larger amount of dissolved SF_6 in the oil. This result can be misleading, because a wavy interface could indicate that it is easier to form slugs. However, the wavelength of these ripple-like waves observed in the experiments is small and they are not associated to the mechanism of slug formation. Normally only small amplitude waves with large wavelength are able to evolve and result in slugs.

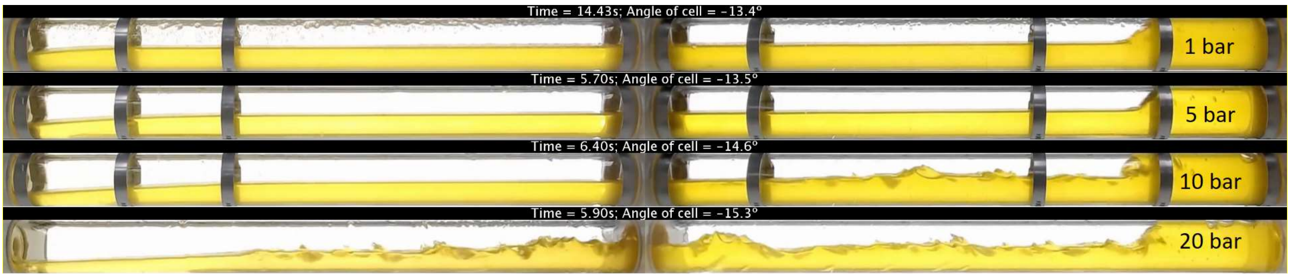

Figure 3. Influence of gas density on stratified flow – rotational speed of 0.5 rad/s.

Liquid and gas phase velocities are function of the rotation speed of the cell. The greater the rate of change of the tilt angle, the greater the acceleration the fluids will experience. As consequence, the fluids achieve higher velocities for higher rotation speed. Figure 4 presents the results for rotation speeds of 0.5, 1 and 1.5 rad/s at 10 bar. One can note that the liquid-gas interface is smooth for 0.5 rad/s, starts to exhibit smaller amplitude waves for 1 rad/s and lager amplitude waves for 1.5 rad/s. The reason for this is the greater velocity difference that the interface is subjected at faster rotation speeds, which promotes instabilities at the interface as predicted by the K-H instability theory.

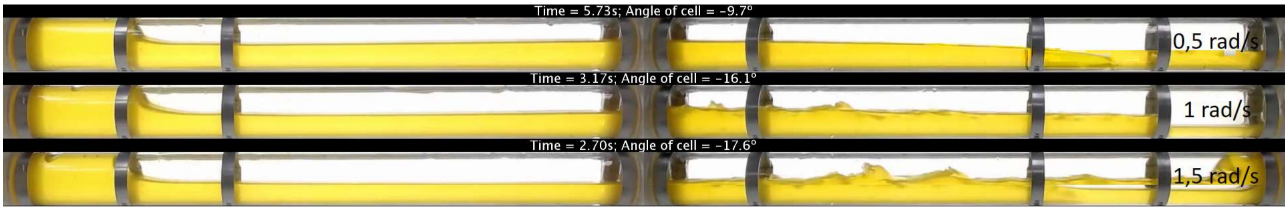

Figure 4. Influence of velocity of fluids on stratified flow – pressure 10 bar.

In Figure 5, it is again compared the results for the four pressures at 0.5 rad/s. However, the images of the flow are shown for the same tilt angle. At around -13.5º, the right side of the cell is lower than the left side, so the liquid phase is moving towards the right while the gas phase is moving towards the left. Besides the differences at the interface, it is interesting to note that the amount of liquid accumulated at the right side of the cell is inversely proportional to pressure. Just looking at the images, it may seem that the waves at the interface decreases the velocity of the liquid, however the 5 bar case does follow this same behavior despite its smooth interface. Considering that the liquid phase viscosity decreases with pressure, it would be expected that it would flow more easily for greater pressures. However, it seems that the counter effect of the massive increase of SF_6 density with pressure plays an opposite role decreasing the fluids velocity, since the higher the gas density, the higher its inertia is and lower its mobility. Usually the gas inertia is almost negligible compared to the liquid, but that is not the case when considering a high-pressure scenario. This behavior is not as noticeable as the appearing of perturbations at the interface, but it would still be interesting to investigate it further.

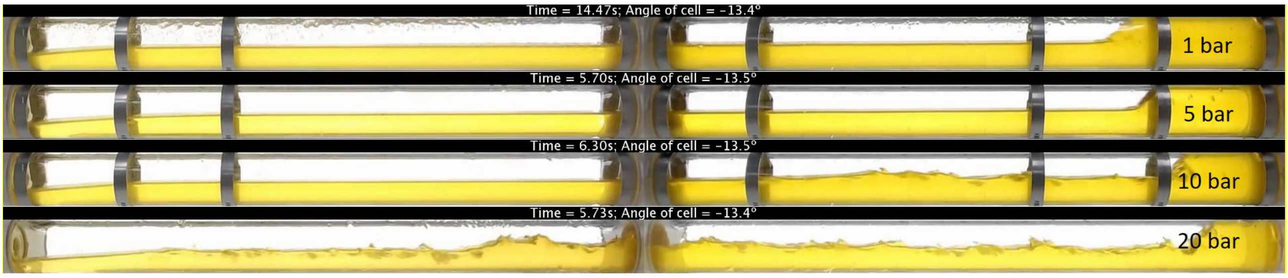

Figure 5. Influence of gas density on the displacement of fluids.

6. CONCLUSIONS

A study about the influence of pressure on stratified flow using a rocking-flow cell for mineral oil and SF_6 was presented. Simple mixing rules were used to estimate the liquid phase properties, considered mineral oil and dissolved SF_6. Four pressures were tested for three rotation speeds of the cell and a liquid loading of 50%. Wave-like disturbances appeared at the liquid-gas interface for 10 and 20 bar, while it remained smooth for 1 and 5 bar. With the increase in the pressure, there is an increase in the wave frequency. The rotation speed of the cell influenced the fluids velocity, which promoted instabilities at the interface for greater speeds. Finally, the SF_6 density increase with pressure appeared to affect the flow so the gas inertia may not be considered negligible for high-pressure scenarios.

The outlook for this research is to quantify these results using measurement techniques or via numerical simulation. Another interesting outcome would be to validate the theoretical explanations made in this paper through the application or modeling of the phenomenon using the Kelvin-Helmholtz instability theory.

7. ACKNOWLEDGEMENTS

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