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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. In this work, the influence of the gas density on stratified flow will be analyzed by using fluid models, sulfur hexafluoride (SF$_6$) and mineral oil. Experiments were performed by using a 51-mm I.D., 500-mm long rocking-flow cell pressurized up to 35 bar at temperatures between 5ºC and 45ºC. The gas density ranged from 6 kg/m^3 to 388 kg/m^3, resulting in liquid-gas density ratios from 142 to 2.3. Liquid loadings of 0.4, 0.7 and 0.9 and rotational speeds of 0.5, 1 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 the dissolved SF$_6$ on liquid properties. Recorded images of the experiments for low liquid loadings show that the gas-liquid interface transitions from a smooth surface to a wavy one as pressure increases.

Keywords

Two-phase flow; rocking-flow cell; interfacial instabilities.

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 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 [1].

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 operation conditions on them, and the conditions in which they will occur is a fundamental topic in the multiphase flow field [1].

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 flow condition. In this scenario, the gas density increases, even reaching values of the same order of magnitude than that of the liquid phase. This condition can be found in deep water offshore oil and gas production operations.

In this scenario, Nakamura [2], in a 4- and 8-in ID pipelines, working with a gas phase with a density of 60 kg/m^3 noticed that 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. [4] carried out experiments with SF$_6$ at 8 bar, with a gas phase density of approximately 50 kg/m^3 in a 25-m long, 10-cm diameter pipe, for inclinations from horizontal to 5º. 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. [5] 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 CO_2, 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 transition to two-dimensional and Kelvin-Helmholtz waves. Significant changes were not observed for the stratified-to-slug flow transition.

An experimental study of two-phase flow using high density SF_6 and two different oils with viscosities of 32 and 100 cP was developed by Khaledi et al. [6]. 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. [7] 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. [8] 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 surface gas velocities. At the same time, the transition between stratified and slug flow starts to occur with higher liquid surface velocities, increasing the stratified flow region in the flow map.

Most of the studies focused on the ambient conditions, or for high ratios between the liquid and gas densities. However, in the production of oil and gas, the pressure is considerably high and the fluid densities are of the same 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 pressures. The use of a rocking-flow cell allow high pressures experiments with reduced risk when compared with flow loops.

Therefore, in this work, the influence of gas density on stratified flow will be evaluated by using fluid models, SF_6 and mineral oil in a rocking-flow cell.

Methodology

Experimental Procedure

A rocking-flow cell, with schematic representation shown in Fig. (1) was used to perform the experiments and investigate the influence of the gas density on two-phase flow.

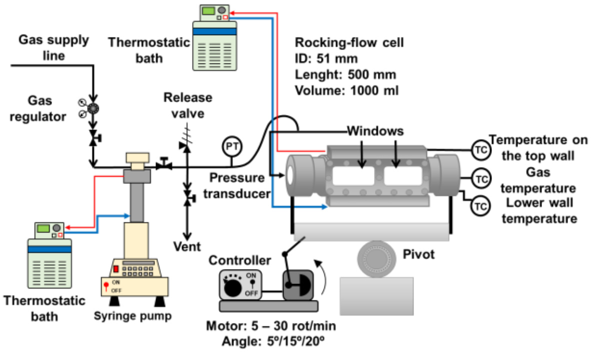

Figure 1. Experimental setup.

A syringe pump, powered by the gas, was used for pressurizing the system.

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 SF_6 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 means of a thermostatic bath.

For each temperature, the maximum pressure tested was the highest one before the critical point of SF_6.

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

Fluids Properties

The SF_6 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 SF_6 only. With this consideration, the pressure measured inside the cell, P, was used to evaluate the amount of SF_6 dissolved in the oil.

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	

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 SF_6 whereas the liquid phase was considered a mixture of mineral oil and dissolved SF_6. It has been estimated that the mass fraction of SF_6 in the oil is [9]:

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

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, and the liquid density between 865 and 888 kg/m³, as shown in Tab. 2. The gas viscosity varied between 0.016 and 0.024 cP, and the gas density between 5.6 and 388.6 kg/m³, as shown in Tab. 3.

Table 2. 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 3. 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

Results and Discussion

Fig. (2) shows images of the experiments as a function of gas density and rotation speed. When evaluating the effect of gas density, it can be observed that its increment increases the instabilities in the gas-liquid interface.

For the same rotation speed, it can be observed that there are more waves in the liquid-gas interface when the gas density is increased. For a gas density of 118.8 kg/m³ the interface for a rotation speed of 0.5 rad/s is smooth. Some waves can be seen at the interface for the same rotation speed and a gas density of 157.8 kg/m³. For 192.4 kg/m³ the interface becomes even more disturbed. As shown by [5], the increase in the gas density changes the wave regimes in the stratified flow for the same phase velocities, what it can be associate to the appearance of waves in the liquid-gas interface with the increment of gas density.

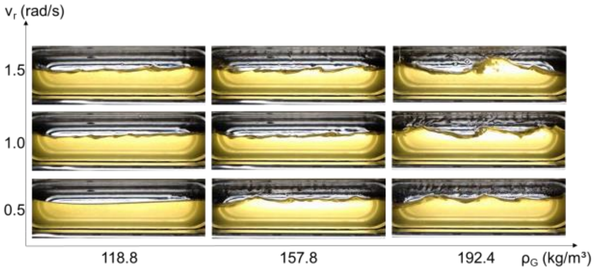

Figure 2. Interfacial instabilities as a function of gas density and rotation speed for the liquid loading of 40% and liquid viscosity of 2.4 cP.

The gas momentum is the principal mechanism of destabilization of the gas-liquid interface [5]. 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.

Fig (3) and (4) presents the interfacial instabilities as function of the density ratio between phases and the rotation speed. With an increasing gas density, 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 in interfacial instabilities. As the difference between the liquid and gas densities decreases, less energy is necessary to form waves.

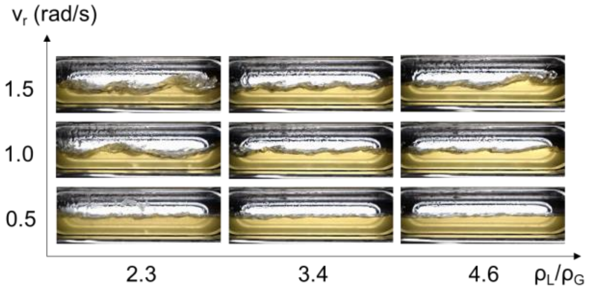

Figure 3. Interfacial instabilities as a function of density ratio between phases and rotation speed for the liquid loading of 40%.

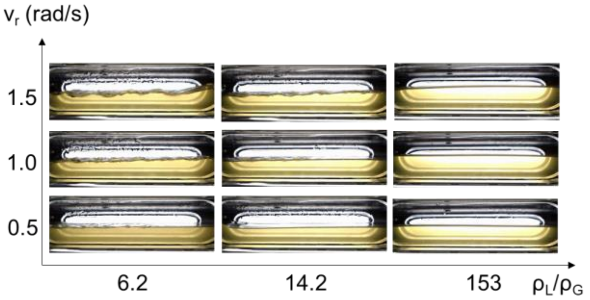

Figure 4. Interfacial instabilities as a function of density ratio between phases and rotation speed for the liquid loading of 40%.

The momentum transfer at the interface increases with the gas density. Therefore, a higher number of waves can be noticed. It is important to point out that although the amount of disturbances increased, their amplitudes do not necessarily become higher. As pointed out by [6], high-density gas results in an increase in the gravitational forces over the waves, inhibiting their growth.

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 Fig. (2), (3) and (4) shows, the increment in the rotational speed for the three gas densities presented results in more waves in the liquid-gas interface. An increase in the rotational speed increases the shear between the phases, causing an increase in the instabilities at the liquid-gas interface.

Conclusions

This work presented an experimental study analyzing the influence of gas density on stratified and slug gas-liquid flow using a rocking-flow cell. Mixing rules were used for estimating the liquid properties, considering mineral oil and dissolved SF_6 as the liquid phase. Four different temperatures and pressures between 1 and 35 bar were tested.

An increase in the pressure causes an increase in the interface destabilization. An increase in the rotation speed changed the fluid velocities and resulted in higher interfacial shear stress, therefore leading to the more interfacial stabilities.

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Responsibility Notice

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

References

[1] Shoham, O. *Mechanistic modeling of gas-liquid two-phase flow in pipes*, 2006.

[2] Nakamura, H. *Slug Flow Transitions in Horizontal Gas/Liquid Two-Phase Flows* (Dependence on Channel Height and System Pressure for Air/Water and Steam/Water Two-Phase Flow), JAERI-Research-96-022, JP9610, 1996.

[3] Abduvayt, P., Manabe, R.; Arihara, N. Effects of pressure and pipe diameter on gas-liquid two-phase flow behavior in pipelines. *SPE-84229-MS, 2003.*

[4] Johnson, G.W., Bertelsen, A.F., Nossen, *International Journal of Multiphase Flow* 35, 924-932, 2009.

[5] Tzotzi, C., Bontozoglou, V., Andritsos, N., and Vlachogiannis, M. *Industrial and Engineering Chemistry Research* 50, nº. 2, 645-655, 2011.

[6] Khaledi, A. H., Smith, I. E, Unander, T. E, Nossen, J. *International Journal of Multiphase Flow* 67, 37-51, 2014.

[7] Loh, W.L., Hernandez-Perez, V., Tam, N.D., Thiam, T.W., Yuqiao, Z., and Premanadhan, V.K. *International Journal of Multiphase Flow* 85, 196-208, 2016.

[8] Wang, Y., Liu, Z., Chang, Y., Zhao, X., Guo, L. *International Journal of Heat and Mass Transfer* 143, 118537, 2019.

[9] Miguel Junior, A.F., Vasconcelos, L.F., Kakitani, C., Ofuchi, C.Y., Marcelino Neto, M.A. and Morales, R.E.M. *18th Brazilian Congress of Thermal Sciences and Engineering, ENCIT*, 2020.