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Experimental Study of Dense-gas/liquid Flow Pattern Transition in Horizontal Pipes

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Abstract

The pre-salt layer's oil and gas production plays a significant role in current Brazil's offshore scenario. Its importance is expected to increase dramatically in the near future. The fluids are transported through horizontal, inclined, and vertical wells of several thousand meters, and due to the environmental conditions at the reservoir, a dense-gas/liquid flow is observed in the pipelines. However, the flow of gas and liquid with densities of the same magnitude is uncommon in the literature. There is a lack of experimental data of this flow condition, which affects the accuracy of phenomenological models for flow pattern prediction. To improve the understanding, a new experimental apparatus was built at the Industrial Multiphase flow Laboratory (LEMI) of the University of São Paulo (USP) at São Carlos. Operating with sulfur hexafluoride and oil at medium pressures, a density ratio lower than ten was obtained in a wide range of gas and liquid flows. Overall, 41 experimental points were collected for horizontal operation, and the flow patterns observed were: stratified smooth, stratified wavy, intermittent, annular, dispersed, and dual-continuous.

Keywords

Flow Pattern; Dense-gas; Experiments.

Introduction

Two-phase gas-liquid flow is of common occurrence in the oil and gas industries. For the specific case of the oil and gas flow at the Brazilian pre-salt, due to the reservoir's environmental conditions, dense-gas and liquid flow are observed in the pipelines, where the density ratio between the phases is of the same order of magnitude [1]. The low-density ratio between liquid and gas affects the Kelvin-Helmholtz waves' generation responsible for the transition from stratified to hydrodynamic slugging. The oil and gas industry uses phenomenological models to predict important flow parameters such as flow pattern, pressure drop, and holdup. Those models demand closure relations obtained through experimental data, which is limited for dense-gas and liquid.

In recent decades, the experimental study of dense-gas and liquid has been evaluated, most notably using Tillers' experimental facilities in Norway. Results of density ratio between 15 to 22 were obtained for stratified, intermittent and dispersed flow in horizontal and slighted inclined flows [2]–[4]. However, there is still a gap in understanding of the conditions closer to pre-salt in terms of density ratio, pipe inclination, fluid velocities, and flow patterns.

To improve the understanding of dense-gas/liquid flow, a new experimental apparatus was built in the Industrial Multiphase Flow Laboratory (LEMI) of USP at São Carlos. This large-scale apparatus was prepared to operate with the simultaneous flow of sulfur hexafluoride and oil at medium pressure in a closed-loop. The experimental results aim to improve the understanding of dense-gas/liquid flows and support the development of phenomenological and machine learning predictive models.

Methodology

The new experimental apparatus is a medium pressure circuit that operates with sulfur hexafluoride (SF_6) and oil (LUBRAX Turbina 22) in a closed-loop. Pressure and temperature are monitored throughout the apparatus, and the pressure at the test section is controlled from 10 to 15 bar, resulting in a density ratio between the gas and liquid phase less than 10 at ambient temperature. The U-shape test section of pipe internal diameter 50.8 mm or 25.4 mm is supported by an inclinable structure that can operate from 0° to 90°. The test section flow inlet and outlet are interchangeable, allowing two-phase flow experiments from -90° to 90°. Storage vessels, compressors, pumps, control valves, and flow sensors are used to control the flows of each phase independently, and the two-phase flow pattern, pressure gradient, and holdup are measured at the test section. Table 1 provides an overview of the experimental apparatus capabilities. Table 2 the fluid properties used in this work, and it should be noted that the interfacial tension was not measured. Figure 1 provides an overview of the test section, the U-shape test section supported by the inclinable structure.

Table 1. Experimental apparatus capabilities summary

Parameter	Value
Max pressure	15 bar(a)
Temperature range	15ºC to 50 ºC
Max gas flow rate	463 Nm^3/h
Max oil flow rate	40 m^3/h
Oil	LUBRAX Turbina 22
Gas	Sulfur hexafluoride
Line sizes	1", 2"
L/D ratio	918, 459
Inclinations	-90º to 90º

Table 2. Oil and gas densities and viscosities

Fluid	Density $[kg/m^3]$	Viscosity $[Pa.s]$
Oil	850	0.027 to 0.035
SF_6	95 to 103	1.62x10^{-5} to 1.68x10^{-5}

Figure 1. Experimental apparatus test section overview

Each fluid flow is independently monitored, controlled, and mixed in a 45º Y-shape pipe. After the steady-state condition is obtained, the two-phase global parameters are measured. The two-phase flow pattern is observed in a 350 mm acrylic window and recorded using a high-speed black-and-white camera. The recorded frames-per-second are a function of the two-phase mixture velocity and ranged from 200 fps to 2000 fps. Figure 2 shows the two-phase flow recording process.

In total, 41 experimental points in the horizontal 50.8 mm pipe were collected. The operating conditions of the test matrix were selected to cover a wide range of superficial velocities and consequently provide a diverse result in terms of flow patterns. The ranges are provided in Table 3.

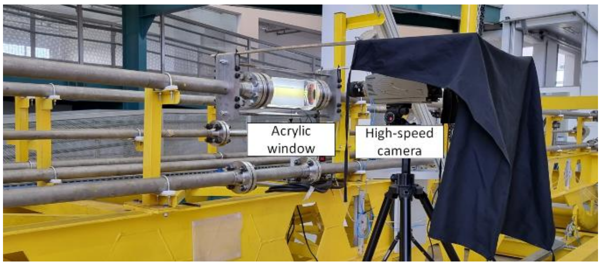

Figure 2. Two-phase dense-gas/liquid flow being recorded by the high-speed camera

Table 3: Oil and sulfur hexafluoride superficial velocities range

Fluid	Min. superficial velocity [m/s]	Max. superficial velocity [m/s]
Oil	0.02	2.1
SF_6	0.05	3.56

Results and Discussion

During the experimental campaign, six different flow patterns were observed: stratified smooth, stratified wavy, intermittent, annular, dispersed, and dual-continuous. The latter is a flow pattern typically observed in liquid-liquid flows [5].

The smooth stratified pattern is characterized by the segregation of phases due to gravity, the heavier phase (oil) flows at the bottom of the pipe, and the gas (SF_6) flows at the top. The interface between the phases does not present interfacial waves. (Fig. 3)

Figure 3. Smooth stratified flow pattern observed in the acrylic window

The wavy stratified pattern is characterized by the segregation of phases due to gravity, the heavier phase (oil) flows at the bottom of the pipe, and the gas (SF_6) flows at the top. The interface between the phases presents interfacial waves. (Fig. 4)

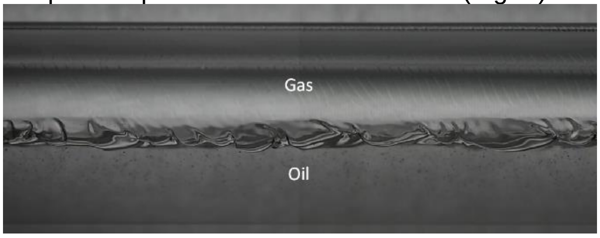

Figure 4. Wavy stratified flow pattern observed in the acrylic window

In the intermittent pattern, characterized by the alternating flow between liquid slugs and elongated gas bubbles, the liquid slug fills the entire cross-section of the pipe and is separated by pockets of gas and a layer of liquid at the bottom of the pipe. (Fig. 5)

Figure 5. Intermittent flow pattern observed in the acrylic window

The annular flow pattern is characterized by the flow of a film of liquid along the pipe wall and a gaseous core surrounded by the film of liquid. Due to the effect of gravity, there is an accumulation of liquid at the bottom of the pipe. (Fig. 6)

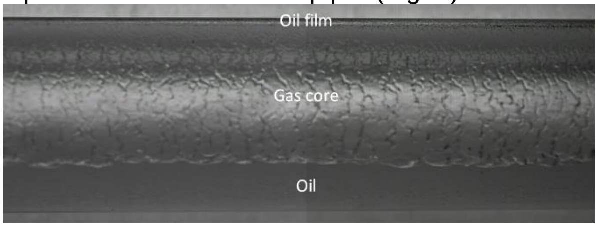

Figure 6. Annular flow pattern observed in the acrylic window

The dispersed flow pattern is characterized by a continuous phase of liquid, with gas bubbles dispersed in it. There is a higher concentration of bubbles in the upper part of the pipe due to gravity. (Fig. 7)

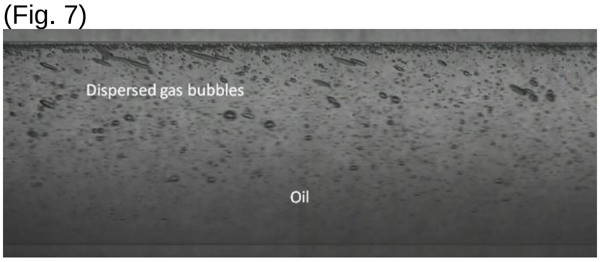

Figure 7. Dispersed flow pattern observed in the acrylic window

The dual-continuous flow pattern is characterized by the maintenance of gas and liquid continuity. However, a high dispersion between the phases is observed. The gas phase is concentrated at the top of the pipe, and the liquid phase is concentrated at the bottom of the pipe due to gravity. (Fig. 8)

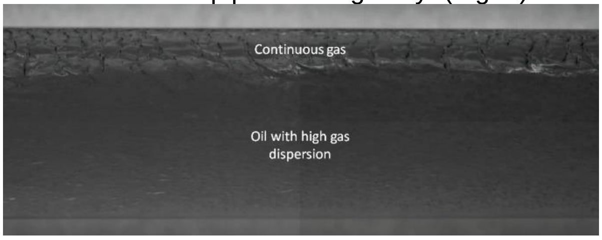

Figure 8. Dual-Continuous flow pattern observed in the acrylic window

In total, 18 smooth stratified, 8 wavy stratified, 8 intermittent, 4 annular, 2 dispersed, and 1 dual-continuous experimental points were collected. The flow pattern map is shown in Figure 9. The dots are the experimental data obtained in this work, and the continuous solid line is the flow pattern prediction based on the theoretical model proposed by Barnea [6], which was previously validated using air-water flows.

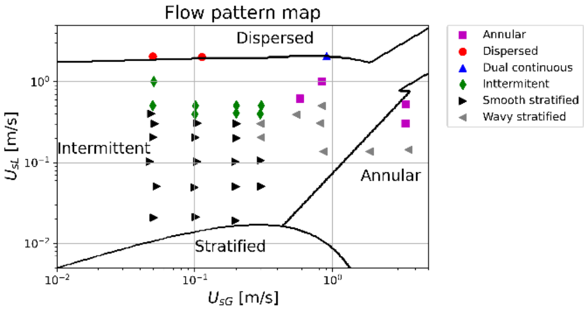

Figure 9. Flow pattern map for horizontal dense-gas/liquid flow in a 50.8 mm pipe

One can observe that the stratified region, both smooth and wavy, is underestimated by the phenomenological model if compared with the experimental results. In addition, the dual-continuous flow pattern is not predicted, and the intermittent region is overestimated. The dispersed flow pattern is correctly predicted. The results indicate that closure relation should be proposed to improve the flow-pattern predictions for dense-gas/liquid flows in horizontal pipes.

Conclusions

Dense-gas/liquid flow-pattern transitions in a horizontal pipe were studied. The experimental results were possible due to the new experimental apparatus built at the Industrial Multiphase flow Laboratory (LEMI) of the University of São Paulo (USP) at São Carlos. Six flow patterns were observed in a wide range of superficial velocities, and a flow-pattern map containing 41 experimental points is presented. A comparison with a well-established phenomenological model indicates that dedicated closure relations should be proposed for dense-gas/liquid flow to improve the prediction accuracy. Furthermore, the experimental work should be extended to a broader range of inclinations as observed in the Brazilian pre-salt oil-and-gas production scenario.

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Responsibility Notice

The authors are the only responsible for the paper content.

References

[1] J. N. E. Carneiro *et al.*, "Numerical simulations of high CO2 content flows in production wells, flowlines and risers," *OTC Brasil 2015: The Atlantic: From East to West - An Ocean of*

Innovation, pp. 1522–1533, 2015, doi: 10.4043/26231-ms.

[2] O. Kristiansen, "Experiments on the transition from stratified to slug flow in multiphase pipe flow," Norwegian University of Science and Technology, 2004.

[3] H. A. Khaledi, I. E. Smith, T. E. Unander, and J. Nossen, "Investigation of two-phase flow pattern, liquid holdup and pressure drop in viscous oil-gas flow," *International Journal of Multiphase Flow*, vol. 67, pp. 37–51, 2014, doi: 10.1016/j.ijmultiphaseflow.2014.07.006.

[4] A. Shmueli, T. E. Unander, and O. J. Nydal, "Characteristics of Gas/Water/Viscous Oil in Stratified-Annular Horizontal Pipe Flows," in *OTC Brasil*, Oct. 2015, pp. 1–18. doi: 10.4043/26176-MS.

[5] J. Lovick and P. Angeli, "Experimental studies on the dual continuous flow pattern in oil-water flows," *International Journal of Multiphase Flow*, vol. 30, no. 2, pp. 139–157, 2004, doi: 10.1016/j.ijmultiphaseflow.2003.11.011.

[6] D. Barnea, "A unified model for predicting transitions for the whole pipe inclinations," *International Journal of Multiphase Flow*, vol. 13, no. I, pp. 1–12, 1987.