SPE Brazil Flow Assurance Technology Congress
Rio de Janeiro, Brazil, November 06 – 08 2024

Experimental insights into Dense-Gas/Liquid two-phase flow in horizontal and inclined pipes

Carlos M. R. Diaz[1*], Alberto T. Postal[2], Oscar M. H. Rodriguez [1]

[1]Industrial Multiphase Flow Laboratory (LEMI), Mechanical Engineering Department, São Carlos School of Engineering (EESC), University of São Paulo (USP), São Carlos, SP, Brazil, [*]carlosruiz978@usp.br
[2]Research, Development and Innovation Center (CENPES), Petrobras, Rio de Janeiro, RJ, Brazil

Abstract
The research focused on the characterization of upward two-phase dense-gas/liquid flow with hydrodynamic conditions similar to the pre-salt production scenario, where the lack of experimental data poses a significant challenge for the avalilable predictive tools, which may result in substantial economic losses, and posing environmental and safety risks. Employing pressurized sulfur hexafluoride (SF_6), the investigation aimed to assess the influence of the presence of dense gas on various parameters, including total and frictional pressure gradient, holdup, and flow patterns. 115 experimental data points were collected at Industrial Multiphase Flow Laboratory (LEMI), filling up some information gaps in the field. A comprehensive set of flow patterns was observed, including stratified smooth, stratified wavy, intermittent, dispersed, pseudo-slug, and dual-continuous. The appearance of the dual-continuous flow pattern, notably present even at 5° and 10° upward inclinations, is one of the main findings. Methodical uncertainty analysis was undertaken for each parameter, specially for the the gamma-ray densitometer that was employed for in-sity volumetric fraction measurement.

Keywords
Dense-gas; two-phase flow; flow pattern; holdup; pressure gradient; experiments.

Introduction
Multiphase flows play a significant role in the oil and gas industry, which is the primary focus of our study. These flows are particularly prominent in the extraction of oil and gas in pre-salt fields, where high pressures result in dense gases. Therefore, the research is concentrated on two-phase flow, involving the combination of pressurized sulfur hexafluoride (SF_6) and oil. Characterizing these flows is challenging and highly elusive, given the limited availability of experimental data under conditions similar to those encountered in pre-salt reservoirs and with different inclinations from the horizontal [1].
The phenomenological modeling of dense-gas/liquid flow remains largely unexplored, as existing models for gas-liquid and liquid-liquid two-phase flow in horizontal [2], vertical [3], and inclined [4], [5] pipelines do not account for dense gases in their formulation. This limitation renders computational tools that may produce inadequate predictions, given that the data used to calibrate these models do not correspond to the specific pre-salt production conditions. This data gap compromises prediction accuracy, leading to potential economic losses and environmental and safety risks.

This study focuses on dense-gas/liquid two-phase flow utilizing sulfur hexafluoride (SF_6) to investigate its impact on flow patterns, given that the gas density is similar to that of a liquid. It is worth noting that the use of SF_6 represents a safe and relatively economic alternative to the study of dense-gas-liquid flow.

Methodology
The experimental data were obtained using the platform with adjustable inclination of the Industrial Multiphase Flow Laboratory (LEMI). This experimental setup comprises a large-scale platform capable of operating with SF_6 and oil in a closed-loop circuit. It is equipped with all necessary measurement devices and operational safety features to replicate various two-phase flow patterns encountered in practice with hydrodynamic similarity. The apparatus allows operation in pipes of 1 and 2 inches in internal diameter, specifically designed to convey dense-gas/oil two-phase flow under different pressure and temperature conditions. One can see in Tab. 1 an overview of the experimental apparatus capabilities.
During the tests, the liquid/gas density ratio was kept below 10 at ambient temperature, with a test line pressure reaching up to 15 bars. The liquid and

gas flows were controlled and measured upstream and before the mixing section.
The properties of the working fluids are presented in Tab. 2.

Table 1. Experimental apparatus capabilities.

Parameter	Measurement	Units
Internal diameter	50.8	mm
Inclination	- 90 to 90	deg
L/d	459 – 918	-
Max. Oil flow rate	40	m^3/h
Max. SF6 mass flow rate	3062	kg/h
Temperature range	17 - 31	°C
Absolute pressure	15	bar

Table 2. Physical properties of the fluids at 15 absolute bar and 25°C.

Phase	Fluid	Density [Kg/m3]	Viscosity [cP]
Oil	Turbine X 22	867,1	22
Dense-gas	Sulfur hexafluoride - SF_6	100,2	0,015

The apparatus extends over 30 meters, divided into two straight segments of 15 meters each. It can operate with inclinations ranging from 0 to 90 degrees, enabling the study of flows in any upward or downward inclination, given its inverted "U" configuration. Additionally, it features a gamma-ray densitometer capable of measuring the in-situ volumetric fraction, emitting gamma photons with a maximum energy of 660 keV. In this study, the horizontal and two upward configurations were used, i.e., 0º, +5° and +10°. The experimental platform positioned at various inclinations is depicted in Fig. (1).

(a) (b) (c)

Figure 1. Experimental setup in (a) horizontal; (b) inclined; and (c) vertical positions.

The flow map given by [1] served as the starting point to generate the test matrix for each inclination, providing a preliminary prediction of what could be experimentally obtained. 8 flow patterns were identified by [1]. For our case study, the model was programmed with the specific experimental conditions of our laboratory, considering the properties of our fluids under defined pressure and temperature. Considering the inclination of the platform, three flow maps were generated, corresponding to inclinations 0º, +5° and +10°.
The flow pattern map generated for the horizontal position allows for the preliminary identification of regions where the expected flow patterns should occur during the experiments, namely: Stratified Smooth (ST), Stratified Wavy (SW), Intermittent (I), Dispersed (D), Dual-continuous (DC), and Annular (A).
The flow pattern maps generated for +5° and +10° exhibited similar behavior; thus, the observed transition lines are nearly identical. It is important to note that at these inclinations, the region where the stratified smooth flow pattern commonly develops disappears, thus expanding the region of occurrence of intermittent and annular flow patterns.
The distribution of proposed experimental points for developing the test matrix with the platform in the horizontal and inclined positions (+5° and +10°) was devised considering the installed capacity of LEMI. This includes the measurement ranges of pressure sensors, temperature sensors, differential pressure sensors, turbine-type flowmeters, and Coriolis flowmeters, along with pneumatic control valves, quick-closing valves, and check valves to ensure a maximum absolute operating pressure of 15 bar and an approximate operating temperature of 25°C. These conditions were chosen to achieve a SF_6 density of approximately 100 kg/m³.

Results and Discussion

During the tests at the horizontal position, 18 points were collected, with data of pressure, temperature, superficial velocity, pressure drop, void fraction using a gamma ray densitometer, and high-speed-camera movies to characterize the flow patterns for each experimental point. The flow patterns observed in the horizontal position were stratified smooth (ST), 7 points, stratified wavy (SW), 3 points, intermittent (I), 3 points, stratified wavy with mixing at the interface (SW/MI), 3 points, dispersed (D), 1 point, and dual-continuous (DC), 1 point, Fig. (2).
46 experimental data points were obtained for inclination +5°, showing intermittent (I) flow, stratified wavy with mixing at the interface (SW/MI), dispersed (D), and possible dual-continuous (DC) and pseudo-slug (PSL).
For the inclination of +10°, 51 experimental data points were obtained, with points identified as intermittent flow (I), stratified wavy with mixing at the interface (SW/MI), and possible dual-continuous flow (DC), and pseudo-slug (PSL).
From the videos recorded with the high-speed camera, it was possible to visually determine each flow pattern obtained. It was possible to observe the appearance of the dual-continuous flow pattern for certain experimental conditions, not only for horizontal, but also for +5° and +10° inclinations. This flow pattern had not been observed previously in upward gas-liquid flow, considering that it is only

commonly observed in liquid/liquid two-phase flow [4].

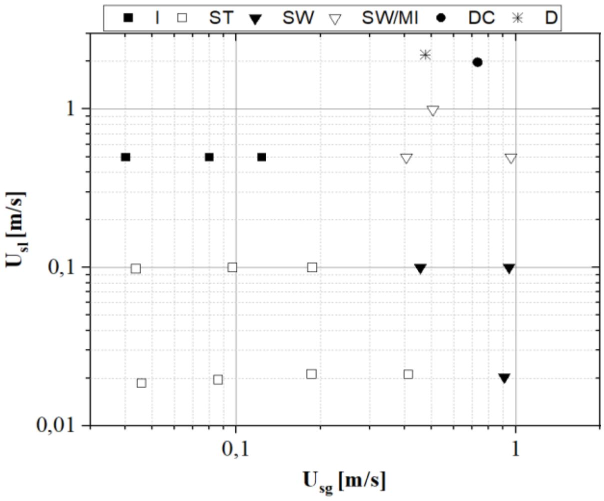
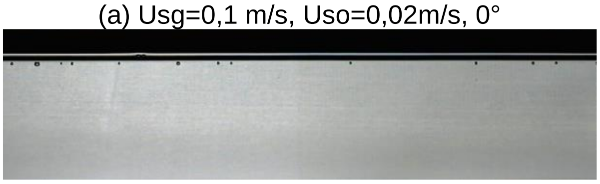


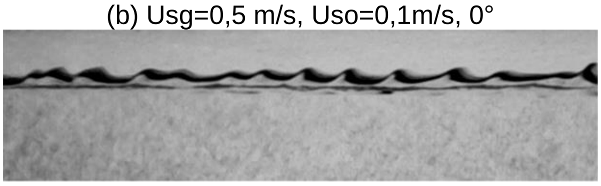
Figure 2. Experimental flow pattern map for 0°.

The study details how the inclination of the pipeline impacts flow patterns in dense gas-liquid two-phase systems. While smooth and stratified wavy patterns predominate in the horizontal position, at inclinations of +5° and +10° there is a greater presence of the intermittent pattern. The unusual appearance of the dual-continuous flow pattern under various experimental conditions, even at inclinations, suggests additional complexity in flow behavior. The six flow patterns observed during the experiments are presented in Fig. (3).

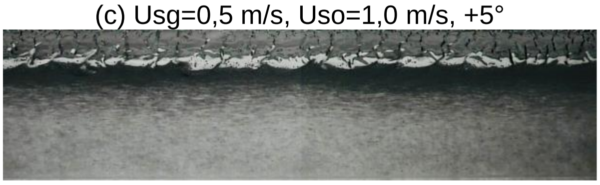
(a) Usg=0,1 m/s, Uso=0,02m/s, 0°



(b) Usg=0,5 m/s, Uso=0,1m/s, 0°

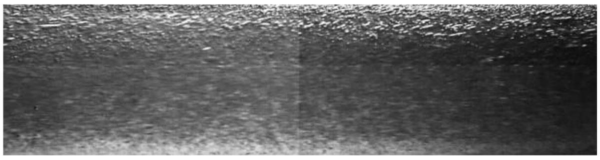


(c) Usg=0,5 m/s, Uso=1,0 m/s, +5°



(d) Usg=0,05 m/s, Uso=0,02 m/s, +5°

(e) Usg=0,2 m/s, Uso=2,0 m/s, +5°



(f) Usg=1,0 m/s, Uso=2,0 m/s, 0°

Figure 3. Flow patterns identified experimentally (a) ST; (b) SW; (c) SW/MI; (d) I; (e) D; (f) DC.

An interesting observation was the generation of liquid splash at the interface. The occurrence of splash was related to the increase of the dense gas superficial velocity. The experimental points that exhibited splash had gas superficial velocity exceeding 1 m/s at inclinations of +5° and +10°.

The phenomenon of splash refers to the detachment of liquid droplets from the liquid phase and their quasi-stable displacement into the gas phase, typically observed in upward gas-liquid flow configurations. This occurrence is often associated with the increase in the phases' relative velocity, leading to disturbances at the gas-liquid interface. The liquid droplets are massively detached from the wavy interface due to shear and exhibit varied sizes and trajectories, sometimes reaching the pipe's top side.

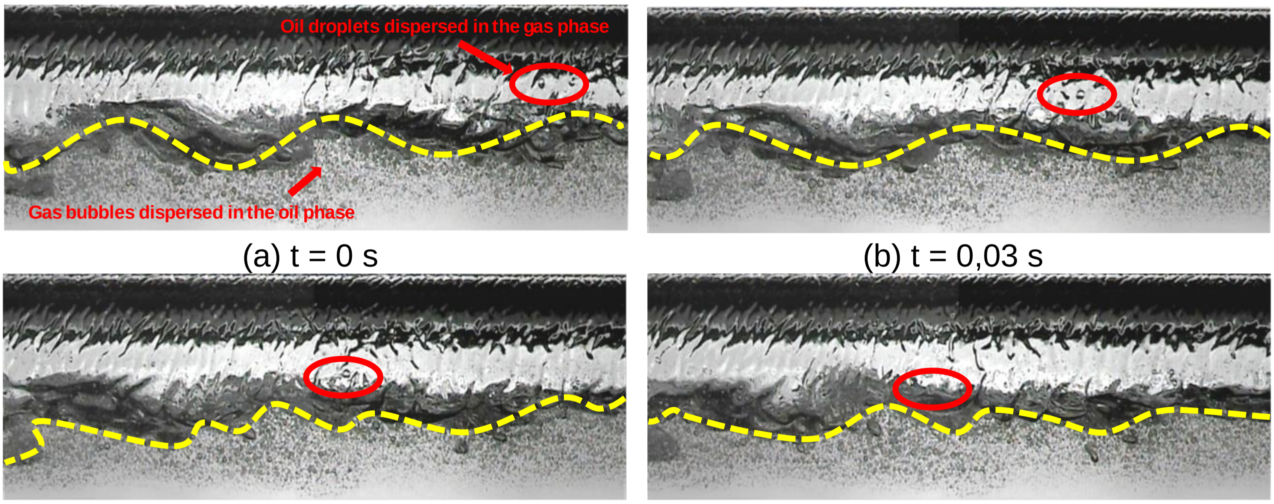
The formation of liquid splashes can significantly alter flow dynamics and may impact heat and mass transfer processes within the system. Understanding the mechanisms behind splash formation is crucial for predicting and mitigating potential flow instabilities and ensuring the reliable operation of stratified gas-liquid flow systems.

In Fig. (4) a temporal sequence of images can be seen, illustrating the phenomenon of splash on the interface and simultaneously showing the formation of a high-amplitude interfacial wave and the gas dispersion in the oil phase for specific experimental points.

The dual-continuous flow exhibits significant dispersion of one phase into the other, leading to high frictional pressure gradient values due to the imbalance created by bubbles and droplets inside the pipeline. The experimental values of holdup and frictional pressure gradient align with the values calculated using the homogeneous model.

Additionally, it is worth noting that the relative uncertainties in determining the holdup using the gamma ray densitometer were less than 8% for +5° and close to 10% for +10°.

The gamma ray densitometry technique, employed for determining holdup in gas-liquid two-phase flow systems, exhibits significant uncertainty at experimental points with low gas presence, irrespective of pipe inclination. The uncertainty stems from the method's difficulty in accurately detecting gas phases when gas content is low, resulting in imprecise holdup estimates.



(d) t = 0,08 s

Figure 4. Process of droplet separation at the interface captured with the high-speed camera: (a) development of a large amplitude interfacial wave, splash, and droplet detachment at the interface; (b) maintenance of the large amplitude interfacial wave, displacement of the reference droplet, splash; (c) deformed interfacial wave, reference droplet approaching the interface, splash; (d) deformed interfacial wave, coalescence of the reference droplet, splash.

Conclusions

During the experimental campaign with the platform positioned horizontally and inclined at 5° and 10° upward, a total of 115 experimental points were collected. Data set of pressure, temperature, velocity, pressure gradient, and holdup, along with visual observation of flow patterns was obtained. The flow patterns observed were stratified smooth, stratified wavy, intermittent, stratified wavy with mixing at the interface, dispersed, pseudo-slug, and dual-continuous flow. Of note is the unprecedented occurrence of the dual-continuous flow pattern with the platform at the upward position (+5° and +10°), revealing a unique behavior compared to previous studies involving gas/liquid two-phase flow. Additionally, the generation of liquid splash at the interface was observed under specific experimental conditions, related to high dense gas superficial velocity.

Acknowledgments

The authors would like to the University of São Paulo (USP), CNPq (162738/2021-8), PETROBRAS and ANP for their support in this research. Oscar Rodriguez would like to thank CNPq for the productivity grant (proc. 311057/2020-9).

Responsibility Notice

The authors are the only responsible for the paper content.

References

[1] A. M. . Quintino, R. da Fonseca Junior, and O. M. H. Rodriguez, “Experimental study of liquid/dense-gas pipe flow,” *Geoenergy Sci. Eng.*, vol. 230, no. July, p. 212179, Nov. 2023, doi: 10.1016/j.geoen.2023.212179.

[2] J. L. Trallero, C. Sarica, and J. P. Brill, “A Study of Oil/Water Flow Patterns in Horizontal Pipes,” *SPE Prod. Facil.*, vol. 12, no. 03, pp. 165–172, Aug. 1997, doi: 10.2118/36609-PA.

[3] A. R. Hasan and C. S. Kabir, “A Study of Multiphase Flow Behavior in Vertical Oil Wells: Part I - Theoretical Treatment,” in *SPE California Regional Meeting*, Apr. 1986, no. May, pp. 463–478, doi: 10.2118/15138-MS.

[4] O. M. H. Rodriguez and R. V. A. Oliemans, “Experimental study on oil–water flow in horizontal and slightly inclined pipes,” *Int. J. Multiph. Flow*, vol. 32, no. 3, pp. 323–343, Mar. 2006, doi: 10.1016/j.ijmultiphaseflow.2005.11.001.

[5] D. Barnea, “A unified model for predicting flow-pattern transitions for the whole range of pipe inclinations,” *Int. J. Multiph. Flow*, vol. 13, no. 1, pp. 1–12, Jan. 1987, doi: 10.1016/0301-9322(87)90002-4.