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CHORDAL MEASUREMENT OF PHASE FRACTION DISTRIBUTION IN STRATIFIED FLOW PATTERN IN DENSE-GAS/LIQUID PIPE FLOW VIA GAMMA-RAY DENSITOMETRY.

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Abstract. *Gas/liquid two-phase flow is of common occurrence in the petroleum, nuclear, thermoelectric, and chemical industries. Stratified flow is one of the smoothest flows, because it occurs at low of liquid and gas flows, and these two immiscible phases are separated by gravity, with the liquid phase at the bottom of the pipe and the gas phase at the top of the pipe. Moreover, it is of common occurrence in the Brazilian offshore production scenario, in directional wells and subsea lines. An interesting feature of the pre-salt flow condition is that the gas has a density similar to that of the liquid due to the very high pressure, therefore a low liquid-gas density ratio is observed. The main objective of this work is performing experimental tests with dense gas (SF6) and mineral oil in the stratified flow pattern and develop chordal measurement of the cross-sectional phase fraction distribution in a horizontal 2"-i.d. 15-m-length stainless steel pipe. A specially designed collimator assures good spatial sensitivity, and a mechanical device allows for micrometric vertical displacement of a gamma-ray densitometry equipment. A high-speed camera was be used to obtain a detailed visualization of the flow pattern for validation purposes. The gamma-ray equipment consists of an emitting source of the isotope Celsium-137 (Cs^{137}) and a Scintillation NaI (TI) receiver.*

Keywords: gas-liquid flow, dense gas, gamma-ray densitometry, stratified flow, chordal phase fraction distribution

1. INTRODUCTION

The energy from the oil industry is one of the most important in the world, therefore, the process of oil extraction, production or transportation occurs in almost horizontal wells, in these processes the fluids involved adopt different spatial configurations, called flow patterns. These depend mainly on the geometry of the pipe (internal diameter and inclination), as well as the operating conditions (pressure, temperature, velocity and flow rate) and physical properties of the fluids (viscosity, surface tension and density) (Meng *et al.*, 2001). Consequently, in horizontal two-phase gas-liquid flow are commonly founded different kinds of flow patterns like stratified, intermittent, annular, and dispersed flow patterns. These patterns are very common in the oil industry, occurring throughout the production process from the reservoir to the platform, (Amundsen, 2011).

In the study of different flow patterns is the determination of the phase fraction distribution, where the technique of gamma ray densitometry (GRD) is used, which is a non-intrusive technique that emits ionizing radiation.This technique was implemented to study an inspection system based on gamma radiation transition using a Cesium-137 source, which showed the efficiency of the equipment in detecting obstructions in the duct and verifying volume levels inside the pipe, (Carneiro, 2006). Consequently, gamma-ray densitometry has also been implemented in other research for the determination of in-situ (Hold-up) volume fraction in two-phase water/oil flow, (Elseth, 2001), (Rodriguez and Oliemans, 2006) and (Amundsen, 2011). More recent research, used GRD to perform a chordal measurement along the pipe cross-section, starting at the top to the bottom of the pipe, and with obtained intensity data the phase fraction distribution in two-phase gas-liquid flow was determined, (Shmueli *et al.*, 2013), (Shmueli *et al.*, 2015) and (Vestøl *et al.*, 2018).

In the present research, experiments were developed in the experimental apparatus of the Laboratory of Industrial Multiphase Flows (LEMI), which has a 2"-i.d. diameter pipe and 15 m long. By performing a micrometric scan along the pipe cross-section, implementing the non-intrusive technique of collimated gamma ray densitometry, which allows a high spatial resolution. Thus, it was possible to determine the phase fraction distribution for two-phase gas/liquid flow, specifically in the stratified pattern.

2. EXPERIMENTAL APPARATUS AND METHODS

The development of this research took place in the Experimental Apparatus of LEMI (Industrial Multiphase Flow Laboratory) at the University of São Paulo (USP), São Carlos campus.

A U-shaped steel pipe is used in the experimental setup see Figure 1, allowing the fluids to return to their respective storage tanks, creating a closed-loop system. The pipe has an internal diameter of 2 inches and a length of 15 meters. The working fluids used in the experiment are dense gas (SF6) and turbine oil X-22. The test section consists of rapid closure valves, a bypass, a visualization section, a high-speed camera, a collimated gamma densitometer, a differential pressure sensor, and local pressure and temperature sensors. Figure 1 schematically depicts the test section with all the aforementioned components, and Tab. 1 presents the operational range of the experimental apparatus.
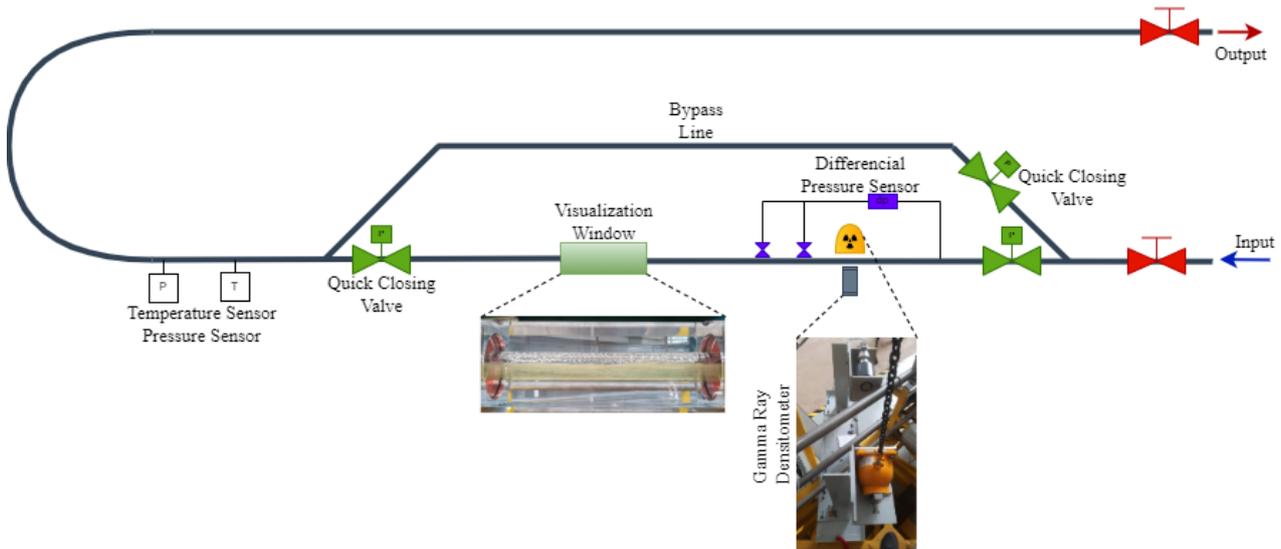

Figure 1. Schematic representation of the Dense-Gas (SF6)/Oil experimental setup.

Table 1. Operating ranges in the high pressure line.

Properties	Operating Data	Units
Operating Pressure	1500	kPa
Gas Flow Rate	463	Nm^3/h
Oil Flow Rate	40	Nm^3/h
Pipe Diameter	50.8	mm
Horizontal Length	15	m
L/D	449 and 918	-
Inclination	-90 to 90	deg
Gas Density	100	kg/m^3
Oil Density	867	kg/m^3
Gas Viscosity	1.617E-5	cP
Oil Viscosity	22	cP

2.1 Gamma Ray Densitometry

Gamma ray densitometry is one of the most widely used techniques for determining the phase fraction distribution in two-phase flows, whether it is liquid/liquid or liquid/gas. Additionally, it is also employed in determining the void fraction in liquid/gas flows. The gamma ray equipment used in this research consists of a radioactive source, Cesium-137, with particles having a maximum energy of 660 [keV]. For detection, a scintillator receiver, LB5441, is used, which consists of a Sodium-doped Thallium (NaI/Tl) crystal. In front of the receiver, there is a collimator with a 0.5 mm slit, ensuring good spatial resolution during the scanning process. Moreover, the equipment includes an LB 444-02 measurement system, used for acquiring the measured data and performing the necessary calibration.

To determine the phase fraction distribution in the SF6-Oil two-phase flow, the measured intensity data is correlated with Equation (1), also known as the attenuation law or Lambert-Beer law. This equation describes the phenomenon of ra-

diation absorption, where I_0 represents the initial intensity of emitted radiation, and I represent the measured transmission intensity by the receiver, that is, the attenuated intensity.

$$I = I_0 e^{-\gamma_1 X_1 - \gamma_2 X_2} \tag{1}$$

where

$$\gamma = \left(\frac{N_A}{A_M} \right) \rho \sigma \tag{2}$$

Thus, the variable X represents the thickness of the absorbing material [m], A_M is the atomic mass number of the material [kg/m^3], N_A is the Avogadro's number, ρ is the density, and σ is the atomic absorption section [kg/m^3].

From the attenuation law, as defined by (Stahl and von Rohr, 2004) and (Kumara *et al.*, 2010), when radiation emission occurs parallel to the fluid interphase, as shown in Figure 2 in case (a), a linear equation, Equation (3), is used to determine the void fraction. However, when the emitted radiation is perpendicular to the fluid interphase, as shown in Figure 2 in case (b), a logarithmic equation, Equation (4), is applied to determine the void fraction.
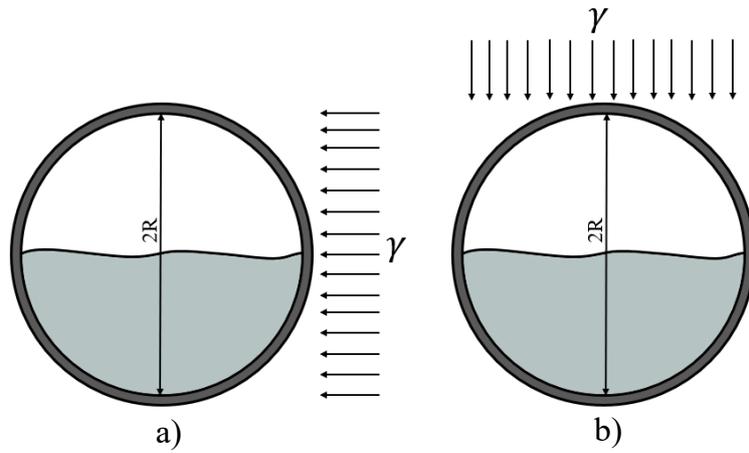

Figure 2. Schematic representation of gamma-ray incidence in two-phase flows.

$$\alpha_G = \frac{I_L - I}{I_L - I_G} \tag{3}$$

and

$$\alpha_G = \frac{ln\left(\frac{I}{I_L}\right)}{ln\left(\frac{I_G}{I_L}\right)} \tag{4}$$

Now, for the determination of the hold-up of the liquid (α_L) the following equation is used taking Equation (3) or Equation (4) into account:

$$\alpha_L = 1 - \alpha_G \tag{5}$$

2.2 Phase fraction distribution

Measuring the phase fraction distribution requires careful scanning along the pipe cross-section. For this purpose, an automated displacement system was developed, which enables a precise, controlled scan with millimeter accuracy. The displacement system consists of a stepper motor, drive module, and pulley and belt systems. This scanning is performed from the top to the bottom of the tube. Figure 3 illustrates the scanning process, showing that the string measurement is taken at predetermined points along the path. The distance between these points depends on the desired scanning resolution.

In the process of measuring the phase distribution, string measurements are performed to determine the fluid-specific calibration curves. It is observed that denser fluids tend to exhibit higher radiation absorption, resulting in an attenuation of the beam. Conversely, less dense fluids exhibit lower radiation absorption.
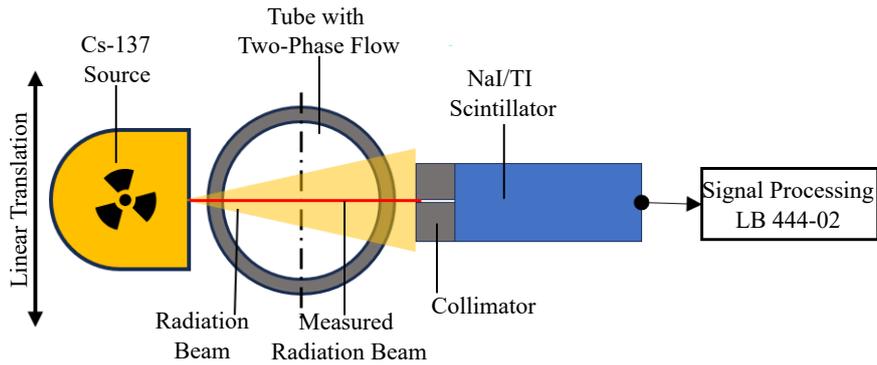
Figure 3. Schematic representation of gamma-ray.

2.3 Experimental Matrix

In developing the experiments, an experimental matrix was designed to investigate the phase fraction distribution of the stratified flow (ST) pattern in the gas/liquid system. This matrix was designed to suit the specific operating conditions of the experimental apparatus. Figure 4 illustrates the developed matrix, showing the respective surface velocities of each fluid.
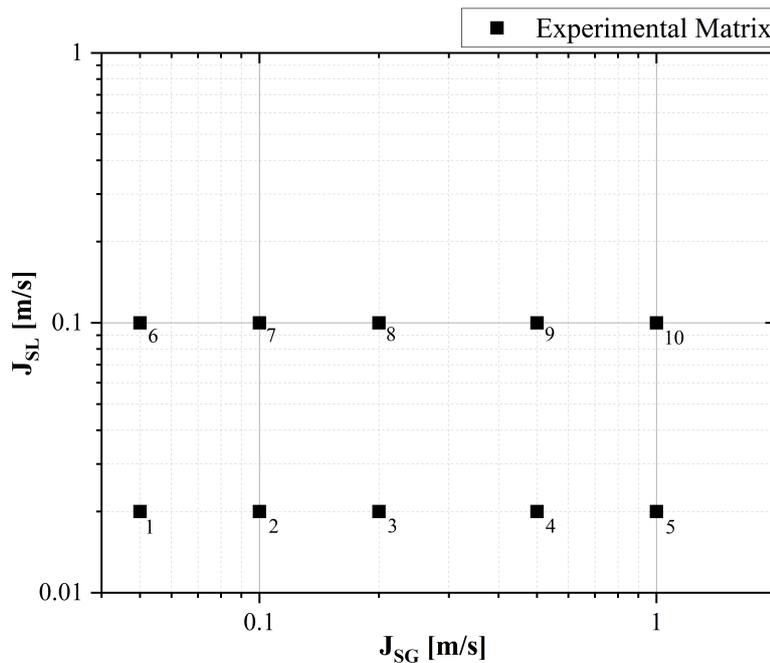

Figure 4. Experimental matrix for Dense-gas/Oil.

3. RESULTS AND DISCUSSION

The determination of the phase fraction distribution in the stratified pattern (ST) in two-phase gas/liquid (SF6-Oil) flow in a horizontal pipe is performed by incident gamma ray beams perpendicular to the fluid interface, as explained previously using the scanning technique. We present below the results obtained.

3.1 Phase fraction distribution in stratified gas/liquid flow

In the experimental process, tests were conducted on the experimental apparatus to study the different flow patterns. These tests were conducted with low surface velocities of the fluids, aiming to obtain the ST pattern. The main test points are shown in Figure 4. Based on these points, we selected some with different surface velocities to perform the characterization of the smooth stratified and wavy stratified patterns in the dense gas/oil flow.

Thus, the experimental matrix is presented in Figure 5, in which the red points represent the experimental locations studied in this work. In the front part of the matrix, the photos of the visualization window are displayed, which were used for the characterization of the patterns. Each point was individually characterized, resulting in the identification of different stratification types. Specifically, points 1 (P1) and 3 (P3) were classified as smooth stratified, while points 9 (P9) and 10 (P10) were categorized as wavy stratified.

For each of these points, chordal measurement was performed using a gamma ray densitometer in order to determine the phase fraction distribution. This distribution was determined using Equation (3) and Equation (5), resulting in the graphs shown in Figure 6. These graphs allowed the interface height within the pipe to be determined and subsequently the void fraction (α_G) to be calculated.

Each line represented in Figure 6 illustrates the distribution of the fraction of each phase in the pipe cross-section, for the experimental points 1, 3, 9 and 10, as mentioned earlier. It is observable that at points P1 and P3, which correspond to smooth stratification, the phase fraction lines show a flatter interface. However, at points P9 and P10, which correspond to wavy stratification, it is possible to notice a slope in the interfacial line.
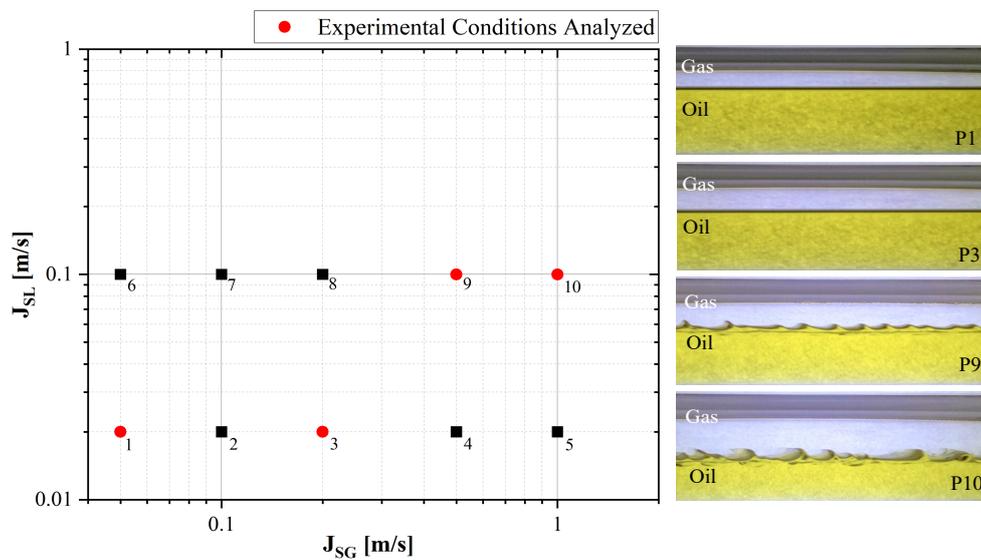

Figure 5. Experimental conditions analyzed and flow patterns in the visualization window.
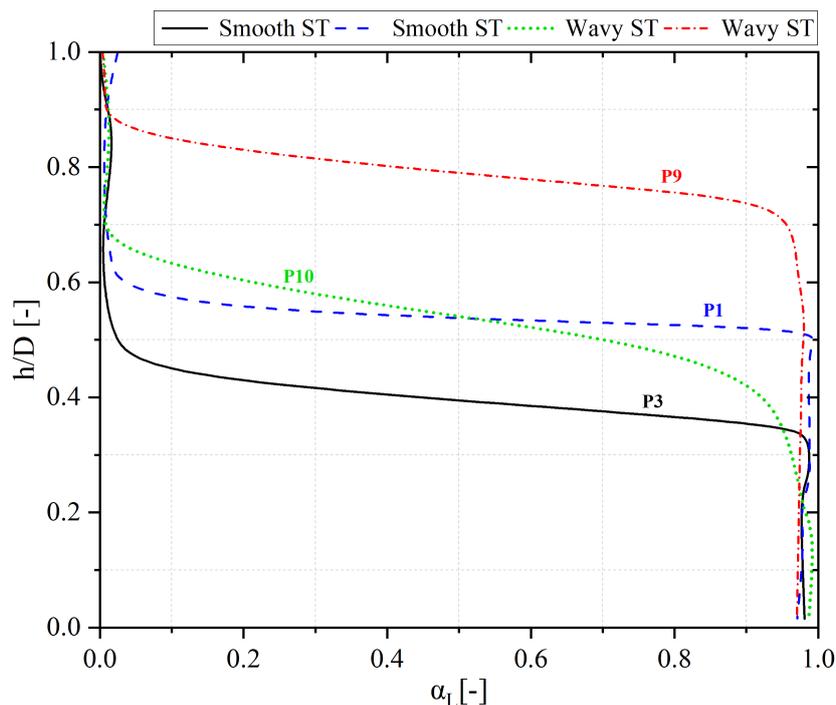

Figure 6. Phase fraction distribution in the cross-section of the stratified flow.

When determining the void fraction by viewing the window photo and using the data obtained by the gamma ray densitometer, it was possible to quantify the mean square error (MSE) by applying Equation (6). The results corresponding to the errors, both for the void fraction determined geometrically based on the height of the fluid viewed in the window, and for the void fraction determined from the gamma ray densitometer, are presented in Tab. 2.

$$MSE = \frac{1}{N} \sum (\alpha_{G_W} - \alpha_{G_{GRD}})^2 \tag{6}$$

Where α_{G_W} represents the void fraction determined from the visualization window, and $\alpha_{G_{GRD}}$ is the void fraction determined by gamma-ray densitometry

Table 2. MSE results for Void fraction values.

Experimental Point	α_{G_W}	$\alpha_{G_{GRD}}$	Error [%]
P1	0.40	0.38	0.40
P3	0.45	0.47	0.04
P9	0.25	0.24	0.01
P10	0.50	0.44	0.36

4. CONCLUSIONS

The experimental results presented in this study provided valuable information about the phase fraction distribution in the flow patterns investigated.

The use of the collimated gamma-ray densitometry technique to determine the fraction of each phase demonstrated high spatial resolution. Importantly, during the scanning process, the proximity between the source and the receiver are crucial to obtain a proper radiation incidence and a reliable measured signal intensity.

The plots representing the phase fraction distribution in the pipe cross-section, as shown in Figure 6, present a behavior consistent with the flow patterns described in Figure 5. It was observed that in the cases of wavy stratified flow, the phase distribution lines showed a characteristic slope. In addition, if it was of interest to obtain the wave amplitude from the chordal measurement, it is essential to perform a refined scan in the interface region.

Based on the data obtained, it was possible to determine the void fraction (α_G) using both the visual technique, through the analysis of the visualization window photo, and the experimental technique of gamma ray densitometry. When comparing the two techniques, the mean square error was calculated, revealing acceptable and coherent results, as presented in Tab. 2.

These findings reinforce the importance of combining measurement techniques to obtain a comprehensive and accurate understanding of the studied stratified flow patterns. The joint application of the visual technique and gamma-ray densitometry allows a more complete evaluation of the phase distribution and void fraction, contributing to a better understanding of the behavior of these flows and providing relevant information for practical applications.

5. ACKNOWLEDGEMENTS

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